ICWIM6

Proceedings of the
6th International Conference
on Weigh-in-Motion

Editors : Bernard Jacob, Anne-Marie McDonnell
& Franziska Schmidt, Wiley Cunagin

ISWIM

IFSTTAR

Dallas, June 4-7, 2012

6th International Conference on Weigh-In-Motion

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ICWIM 6

Proceedings

Edited by

Bernard Jacob
Anne-Marie McDonnell

Franziska Schmidt
Wiley Cunagin

Acknowledgement

The editors acknowledge the Organizing Committee members, the members the International Scientific Committees ISC-WIM for the abstract and paper reviews, and all the authors for their valuable contributions.

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Proceedings of the 6th International Conference on Weigh-In-Motion

Editors: Bernard JACOB, Anne-Marie MCDONNELL & Franziska SCHMIDT, Wiley CUNAGIN

Keywords: Heavy vehicles, heavy vehicle technology, lorries, truck equipment, road transport, Vehicle classification, weigh-in-motion, WIM, WIM technology, WIM systems, weight measurement, standards, specification, vehicle operation, vehicle control, weight and size enforcement, size and weight evaluation, traffic loads, road safety, freight mobility, road operation, road pricing, road, pavements, bridges, vehicle-infrastructure interaction, environment, testing, measurements, data quality, data management, regulations, enforcement, sensors, accuracy, durability, databases, tests.

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Institut Français des Sciences et Technologies des Transports, de l'Aménagement et des Réseaux, Publications, 2012

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PREFACE

The International Conference on Weigh-In-Motion (ICWIM6) returns to North America to join with NATMEC 2012, North American Travel Monitoring Exhibition and Conference. The first time was in 2002 (ICWIM3), in Orlando, Florida, with the support of the Iowa State University. The Transportation Research Board (TRB), in charge of NATMEC, brought a strong support to the International Society for Weigh-In-Motion (ISWIM) to join the efforts of the two Organizing Committees in preparing for a successful event.

NATMEC is the premier forum for travel monitoring in the United States. It began with the focus on weigh-in-motion (WIM) and has continued to bring together the WIM community for over forty years. The 2012 theme: "Improving Traffic Data Collection, Analysis, and Use," frames the shared conferences' goals. Bringing together the international WIM community with NATMEC provides an excellent opportunity for assessing state-of-the-practice, identifying future research needs and strengthening the WIM community for future progress. The proceedings provide an excellent reference to those interested in quantifying loadings and traffic using WIM. NATMEC 2012 is supported by the U.S. Department of Transportation, hosted by the Texas Department of Transportation, cosponsored by AASHTO and the North Central Texas Council of Governments and organized by Transportation Research Board.

ICWIM has a rich history, first held in Zürich (1995), and followed by Lisbon (1998), Orlando (2002), Taipei (2005) and Paris (2008). ICWIM has covered WIM technologies, standards, testing and applications of WIM to traffic monitoring, infrastructure engineering, enforcement and road pricing.

Freight transport delivered on road by commercial heavy vehicles is a key factor for development, trade and economical growth. However, the society has to face important challenges on the environment (CO2 and noxious emissions) and energy savings, and thus shall ensure harmonized and balanced development of all the transport modes. Therefore, it is crucial that all the heavy good vehicles comply with the legal limits and regulations, wherever they are travelling, to be operated at fair cost, to facilitate the inter-modality and to ensure a fair competition in freight transport. The issue has become timelier in many parts of the world, longer and heavier (higher capacity) vehicles are being introduced to improve the freight transport efficiency and to reduce congestion and CO2 emission. Road safety remains one of the priorities in all countries, but above all in the developing and emerging countries, where almost 1 million people are killed on roads every year. Overloaded trucks contribute to unsafety and severe accidents, above all for vulnerable users. With the financial crisis, governments, public authorities, road owners and operators have encountered difficulties to finance the construction and maintenance of road infrastructures. Thus, the general trend is to increase the infrastructure lifetimes and to cut the maintenance budgets. To keep a satisfactory quality it becomes necessary to avoid any overload, and thus to efficiently enforce the weight limits. WIM systems and technology is necessary to screen all the heavy vehicles and to help, if not to perform, the enforcement operations.

To optimize road infrastructure design and maintenance and minimize the related costs, it is necessary to get extensive and accurate data on weights and flows of axles and vehicles on each road section, as well as time based trends. Advanced bridge and pavement calculation models require more and more accurate data, as well as innovative road operation and pricing tools. Therefore, WIM becomes part of a global ITS trend for heavy traffic management, as developed in Australia with the Intelligent Access Programme (IAP). It is in this context, it appeared appropriate to merge again, 10 years after ICWIM3 and NATMEC 2002, the ICWIM6 and NATMEC 2012 conferences into a single larger event covering a wider domain and addressing a broader range of issues. It provides an opportunity to promote exchanges of experience between more scientists, researchers, engineers and other professionals.

The conference addresses the broad range of technical issues related to weight measurement sensors, technologies and systems, weight data management and quality assurance, enforcement, road operation and pricing and infrastructure related issues. It provides access to current research, best practice, and related policy issues. It is a multi-disciplinary, inter-agency supported event. It provides an international forum for WIM technology, WIM standards, research, policy and applications, and it reviews new developments since the last International conference (ICWIM5).

This conference promises to be more successful than ever, with almost 70 abstracts submitted, reviewed by the International scientific committee, with 50 papers accepted, from 20 countries. The conference is organised in 6 oral sessions, one poster session and 2 panel discussions, all of them open to all the delegates registered to ICWIM6 or NATMEC2012. These sessions cover a variety of topics including:

1. WIM Algorithms, Technology and Testing
2. WIM for Enforcement
3. WIM Standard, Calibration, Data Quality and Management
4. WIM Implementation, ITS, Traffic Monitoring, Safety and Environment
5. Application of WIM to Bridges
6. Application of WIM to Pavements

An industry exhibition is organised by NATMEC to facilitate the meeting of delegates with manufacturers and users of traffic data and monitoring systems, WIM and related technologies.

The conference is supported by International organisations such as the OECD/JTRC (Joint Transport Research Centre) and the FEHRL (Forum of European Highway Research Laboratories), the FHWA (US Federal Highways Administration) and the TRB (Transport Research Board).

We greatly appreciate the major sponsors of the conference: International Road Dynamics – IRD -, TDC Systems, Traffic Data Systems - TDS, Kistler and Indra Esteio Sistemas – IESSA -, and the regular sponsor (Sterela) for their support.

We welcome all delegates to Dallas and to the 6th International Conference on Weigh-In-Motion.

Anne-Marie McDonnell
ConnDOT, United States

Bernard Jacob
IFSTTAR, France

Conference ICWIM6 co-chairs

Thomas Palmerlee
TRB, United States
NATMEC 2012 chair

International Society for Weigh-in-Motion (ISWIM)

This is the sixth International Conference on Weigh-in-Motion (WIM) and the enthusiasm is there for delegates to travel to the farthest corners of the world to share experiences of WIM and hear about the latest developments. The International Society for Weigh-In-Motion (ISWIM), an international not-for-profit organisation based in Switzerland, was born in 2007 and officially launched in 2008, to welcome all with a common interest in WIM. It supports advances in WIM technologies and promotes more widespread use of WIM and its widespread applications.

Organizing WIM conferences and seminars is a major objective. ISWIM successfully held the 5th International conference ICWIM5 in Paris in May 2008, with the support of the French Laboratoire Central des Ponts et Chaussees (now IFSTTAR). In April 2011, with the support of the DNIT (Department of Transport of Brazil) and the Federal University of Santa Catarina, a very successful International Seminar was organized in Florianopolis (Santa Catarina, Brazil). Additionally the Latin American regional group of ISWIM was initiated. Furthermore, in North America, the TRB sub-committee on WIM is forming a regional group of ISWIM, and the European community of WIM carried out in the 1990's and 2000's important European cooperative projects (COST323, WAVE, REMOVE, FiWi).

ISWIM is active on the Internet through its web site (http://iswim.free.fr). This web site offers an International portal for WIM, with many resources, such as scientific and technical publications, links to WIM web sites, and facilitates exchanges of WIM experiences. The website also has details of affiliated vendors (i.e. The Vendor College). ISWIM has a scientific interest in WIM standardisation and in promoting common tests and assessment of WIM systems and an application interest in exposing end-users to the myriad of uses.

ISWIM consists of individual and corporate members. The Vendors College comprises 15 commercial enterprises, mainly WIM system manufacturers and vendors. There is a Board of 15 members which is elected by the General Assembly of all members. There is no membership fee for individuals. There is a membership fee for companies and organisations. So, please join us and become an active member of the ISWIM community by signing up on the ISWIM web site: http://iswim.free.fr.

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PANEL DISCUSSION 1
WIM FOR ENFORCEMENT

Chair: **Bernard JACOB**, Ifsttar, France
Co-chair: **Tom KEARNEY**, USDOT-FHWA, United States

Panelists: Joe CRABTREE (USA), Raul DIAZ (Chile), Chris KONIDITSIOTIS (Australia), Hans VAN LOO (Netherlands)

Around the world, the challenge that commercial motor vehicle safety program enforcement officials increasingly face is the ability to maintain current levels of enforcement capable of delivering an effective level of truck weight enforcement. The first objective is to ensure a fair competition between transport modes and transport companies, in a very competitive environment. Damage to pavement and bridge infrastructure caused by over loaded and illegally loaded trucks generates a cost to the general public that is more difficult to fund every day. Also, highway safety can be severely compromised by illegally loaded trucks at a time when highway program officials are redoubling their efforts to deliver the safest highway operating conditions in recent memory. Enforcing compliance of truck weight limits is daunting in light of current truck volumes and becomes increasingly challenging in light of truck volumes forecast over the short and medium term as increases in population and associated increases in consumption levels continue to grow. The ability of enforcement agencies to employ traditional approaches to truck enforcement program activities has become increasingly strained by the current levels of truck traffic and current public sector budgetary pressures, above all with high staff cut. If the number of large commercial vehicles using public roadways continues to grow at a rate that lessens the ratio of law enforcement personnel to trucks, the obvious conclusion is less ability to weigh trucks and less effective enforcement. And the consequences are more overloads, road and safety damages, and unfair competition.

The introduction of advanced technologies at the roadside has been identified in many countries as an important opportunity to increase the effectiveness of truck enforcement activities without increasing manpower. More intelligent, selective enforcement supports a modern highway transport model that uses enforcement resources effectively and does not compromise on ensuring fair transport costs, protecting pavement and bridge assets or highway safety. Technologies capable of conducting many of the inspections and measurements traditionally conducted at stationary site weigh stations have the potential of shifting tremendous pressure away from over strained weigh station sites. The use of automation in conducting truck enforcement activities has been identified as having the potential to support adequate levels of enforcement able to handle increases in truck travel and serve as a deterrent to illegal loading behavior. A key tool in this emerging technology based tool kit is Weigh-in-Motion (WIM) technology. WIM systems installed in roadway mainlines are increasingly being used by enforcement personnel to “pre-screen” trucks for compliance with legal weight limits and better target enforcement personnel efforts toward those vehicles requiring more extensive weight measurements on a static scale. That also allows preventing overloads by company profiling and warnings, as done in the Netherlands and France. Legally loaded vehicles can be excluded from enforcement queues contributing to higher levels of productivity in the transport sector as a result. On-board WIM complements the potential enforcement tools, and allows carriers to perform self-control and public authorities to make a wide survey of truck fleets. Australia is one of the most advanced country using on-board WIM in the Intelligent Access Program (IAP).

A new challenge is to develop, approve and implement fully automated WIM systems for enforcement, as initiated in Taiwan and Czech Republic. Beside the technological challenges on accuracy and reliability of the WIM systems, some metrological and legal issues are still to be resolved.

This session will present examples of how WIM can be and is being used as an automated enforcement tool. The benefits that can be generated through the inclusion of WIM technology in automated enforcement frameworks will also be presented.

PANEL DISCUSSION 2

APPLICATIONS OF WIM TO INFRASTRUCTURES

Chair: **Eugene OBRIEN**, UCD, Ireland
Co-chair: **Mike MORAVEC**, USDOT-FHWA, United States

Panelists: Mark HALLENBECK (USA), Lily POULIKAKOS (Switzerland), Valter TANI (Brazil), Eiki YAMAGUCHI (Japan)

WIM has been used for many years in a range of application areas relating to road transport infrastructure. The most significant development in the past decade has been the American Mechanistic-Empirical Pavement Design Guide and the need for U.S. state Departments of Transport to establish default histograms of axle weight data for pavement design and assessment. Elsewhere in the world, most countries are still using numbers of Equivalent Standard Axles to design their pavements. In research circles, more sophisticated approaches to pavement assessment are in development. The University of Nottingham is a leader in this area and has developed a general framework for pavement life assessment which it is promoting as a benchmark for other researchers. They have made their model freely available for download and are encouraging other researchers to participate in a worldwide comparison of the most sophisticated approaches.

WIM can also be used to assess the sensitivity of pavements to different types of tire. In ICWIM5, South African research was reported that showed measured tire pressure 'footprints' from different tire types. This shows the potential of WIM to be used to assess the road friendliness of tires.

WIM data is also used for bridge load assessment and for the development of bridge loading standards. Bridge safety is often assessed on the basis of an inspection of the bridge condition. However, accurate traffic loading information can greatly enhance this assessment and can identify sub-standard bridges that are safe because of bridge-friendly traffic. In recent years, computing power has made possible 'long run' simulation of traffic loading on bridges where lifetimes of traffic loading, calibrated using WIM, are simulated on computer. The results are much more accurate than early statistical studies that extrapolated characteristic load effects from small WIM databases. The long run simulation studies allow 'what if' questions to be answered such as 'what would be the implications for bridges if the allowable legal weight limit were increased'.

Long run simulations can be also used to identify typical maximum-in-lifetime traffic loading scenarios. This has opened up many new possibilities – dynamic simulation of typical maximum-in-lifetime loading scenarios is giving new insights into dynamic amplification. Early results are suggesting that the level of dynamic amplification used for bridge safety assessment is much less than previously assumed.

Development continues and, with the continuing improvement in access to large WIM databases, it seems that new uses for WIM data will continue to emerge.

Session 1

WIM Algorithms, Technology and Testing

Chair : ANNE-MARIE MCDONNELL (ConDOT, United States)

Co-chair : JESUS LEAL (CEDEX, Spain)

AN EXPERIMENTAL WIRELESS ACCELEROMETER-BASED SENSOR SYSTEM FOR APPLICATIONS TO WIM AND VEHICLE CLASSIFICATION

      

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Abstract
The paper describes an experimental wireless, accelerometer-based sensor system for WIM and vehicle classification. The system has four arrays of accelerometer sensors to measure pavement vibration, and interspersed magnetometer sensors to measure speed. Sensor output is wirelessly sent to a server, where it is processed to classify vehicles and estimate axle load. Four tests are reported. The first checks repeatability of sensor measurements. The second compares estimates of pavement displacements with those of deflection sensors. The third evaluates axle detection. The fourth compares estimates of axle load with those of a Caltrans WIM station on I-80W.

Keywords: Wireless sensor, accelerometer sensor, weigh-in-motion, vehicle classification, axle load, deflection.

Résumé
Cet exposé décrit un système de mesure expérimental pour la classification des véhicules et le pesage en marche. Le principe de mesure est basé sur un accéléromètre sans fil. Le système possède quatre rangées d'accéléromètres pour mesurer les vibrations de la chaussée et des magnétomètres pour mesurer la vitesse des véhicules. Les mesures collectées sont envoyées sans fil à un serveur informatique où elles sont traitées pour aboutir à la classification des véhicules et à une estimation du poids sur chaque essieu. Quatre tests sont décrits ci-dessous. Le premier évalue la répétabilité de la mesure. Le deuxième compare les estimations de déformation de chaussée avec des capteurs de flexion. Le troisième évalue la détection des essieux. Enfin le quatrième compare le poids par essieu donné par ce système avec la station de pesage, de l'exploitant Caltrans, installée sur l'autoroute I-80.

Mots-clés: Capteur sans fil, accéléromètre, pesage en marche, classification des véhicules, charge à l'essieu, flexion.

1. Introduction

Agencies like California Department of Transportation (Caltrans) use truck classification and weight data to enforce weight limits, charge fees and assess pavement damage. Today Caltrans has 70 static weigh stations and 106 weigh-in-motion or WIM stations to monitor California's 50,000 lane miles of highway and 12,488 bridges with a median age of 43 years. An adequate monitoring system for California needs many more weigh stations, but this need cannot be met by today's static or WIM stations, which are expensive to install and maintain.

This paper describes an *experimental* wireless, accelerometer-based system to classify vehicles and estimate axle load and pavement displacement. The system called 'Sensys Wireless WIM' or SW-WIM is still under development. It represents a promising approach toward an inexpensive, easy-to-install system made possible by recent advances in MEMS (Micro-Electro-Mechanical Systems) devices, and ultra-low power radios and microprocessors. The challenge is to make SW-WIM sufficiently accurate. The tests reported here suggest this is possible.

SW-WIM uses four arrays of accelerometer sensors to measure the pavement's vibration caused by a moving vehicle, together with magnetometer sensors to measure vehicle speed. Sensor measurements are wirelessly sent to an Access Point (APCC), which forwards the data via cellular modem. Signal processing algorithms work on the data to determine the number and spacing of a truck's axles, estimate the pavement displacement, and the load of each axle.

Four sets of test results are reported. The first evaluates repeatability of sensor measurements at a Heavy Vehicle Simulator at UC Davis. The second compares estimates of pavement displacement with those of deflection sensors in a Falling Weight Deflectometer experiment. The third evaluates axle detection using three accelerometers located downstream of a Caltrans weigh station on I-680S. The fourth compares SW-WIM's estimates of axle load with those from a Caltrans WIM station on I-80W.

The rest of the paper is organized as follows. Section 2 describes SW-WIM. Section 3 presents the test results. Section 4 summarizes our conclusions from this study.

2. SW-WIM

This section provides a description of the SW-WIM system configuration at the I-80 test site, the sensor design, and the signal processing algorithms.

2.1 System Configuration

Fig 1 is a schematic of SW-WIM deployed on lane 2 of westbound I-80 in Pinole, CA at the Appian Way exit. The test site is directly upstream of a Caltrans WIM station whose data serves as 'ground truth'. The left side of Fig 1 shows the sensor layout in the 3.66m (12ft) wide lane of the pavement (in the actual deployment each array has a small stagger to prevent 'shadowing' of the pavement vibrations).

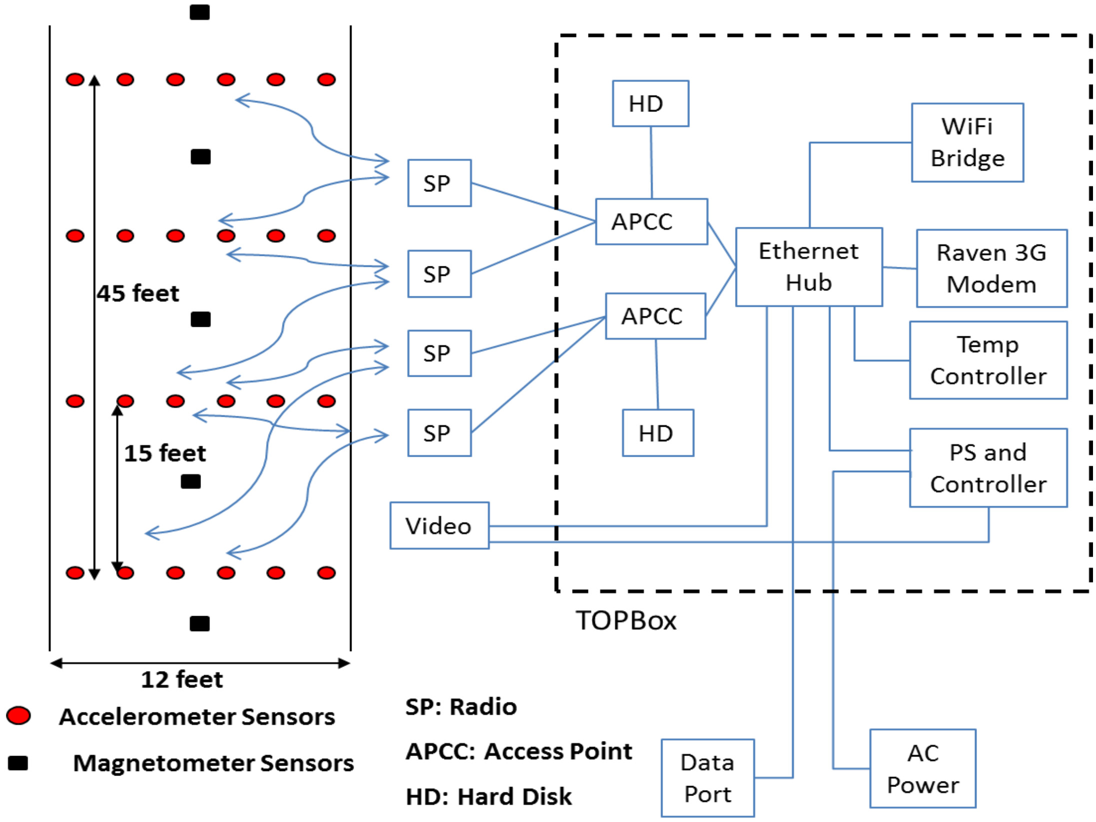


Figure 1 - SW-WIM test site on I-80 in Pinole, CA.

There are four arrays of accelerometer sensors (red circles) and five magnetometer sensors (black squares). The arrays are 4.6m (15ft) apart. The multiple array measurements permit separation of the dynamic and static axle load (Cebon, 2006). (Unlike SW-WIM, today's WIMs require a smooth pavement to reduce the dynamic component, but this is very expensive.) The six sensors in each array are redundant, but allow us to determine the sensitivity of the measurements to sensor placement. Each accelerometer sensor measures the vibration or acceleration of the pavement at the sensor location. The magnetometer sensors measure the arrival and departure times of each vehicle, from which one obtains vehicle speed, since the distance between two magnetometer sensors is fixed.

The rest of the equipment is mounted on a 5m (15ft) pole on the side of the highway inside a ruggedized 'TOPBox'. This equipment provides remote control and observation of the SW-WIM system. The equipment includes (i) two APCC processor modules with attached Hard Disk (HD) storage connected to the external SP radio modules that receive the sensor data; (ii) external Pan-Tilt-Zoom camera for video capture for validation; (iii) Power Supply (PS) and temperature controller for remote sub-system reset and monitoring; and (iv) cellular 3G modem, Wi-Fi bridge, and Ethernet data port for multiple ways of providing system and data access. The test system is a convenient and versatile platform for collecting pavement vibration data under a variety of traffic and environmental conditions. Data from the site can be collected 24 hours/day and 7 days/week.

2.2 Sensor Design

Each accelerometer sensor cube is comprised of a MEMS accelerometer, a temperature sensor, a microprocessor, memory, a radio transceiver, an antenna, a battery, and an electronic

PC board that interconnects these components, assembled as in Fig 2 (left). The assembly is placed in a hardened plastic 7.4 cm x 7.4 cm x 4.9 cm cube (middle), which is then filled with a potting material. The magnetometer sensor cube is virtually identical, except that the accelerometer is replaced by a magnetometer. Each cube is placed in a 10-cm radius, 5.7-cm deep hole in the pavement (Fig 2, right), which is then filled with fast-drying epoxy. The pavement needs no preparation and a sensor cube is installed in 10 minutes. (The system of Fig 1 was installed by a 4-person crew in four hours.) The analog accelerometer sensor measurements are low-pass-filtered at 50Hz, sampled at 512Hz and sent through a 12-bit A/D converter. The resulting bit stream is transmitted by the sensor radio to the APCC.

The APCC has a Linux processor and various communications interfaces as shown in Fig 1. The data from the APCCs and the camera can be stored locally and downloaded over the 3G network.

Figure 2 - Sensor cube assembly (left), package (middle), and installation (right).

2.3 Signal Processing

The APCC synchronizes all the sensor clocks, time stamps all measurements using the Internet NTP, and stores the data in the hard disk. The data are retrieved via a 3G cellular modem and processed offline. The processing algorithms are currently in Matlab. Eventually real time algorithms will be distributed among a server, the APCCs, and the sensors.

Let $y(x,t)$ be the displacement of the pavement caused by a truck at sensor location x at time t. The accelerometer sensor measurement $z(t)$ in mg is

$$z(t) = \eta \times \frac{\partial^2 y}{\partial t^2}(x,t) + w(t).$$

Here η is a characteristic of the accelerometer, and w is measurement noise. Let $\zeta = \{t \mapsto z(t), t \in (t_0, t_1)\}$ denote individual truck samples, obtained by the SEG algorithm.

SEG segments the continuous sensor measurements into samples ζ for each vehicle, using the magnetometer sensor to detect the arrival and departure of a vehicle (Haoui et al, 2008). Vehicle length is the product of its speed and the magnetometer occupancy time (departure time – arrival time). Vehicles longer than 7m (20ft) are treated as trucks. Non-truck samples are not used in this study which focuses on trucks. Non-truck data are recorded.

Three algorithms process ζ: NRED (Noise REDuction), ADET (Axle DETection), and LDC (Load and Displacement Computation).

NRED removes from ζ frequencies above 6.2 Hz or below 0.1 Hz; the cutoffs were arrived at empirically.

ADET identifies the occurrence of a negative peak with an individual axle. ADET passes the measured energy in ζ through a moving average filter and detects the peaks that are sufficiently spaced apart in time. The number and location of these peaks gives axle count and axle spacing for each truck. Most vehicle classification schemes are based on number and spacing of axles.

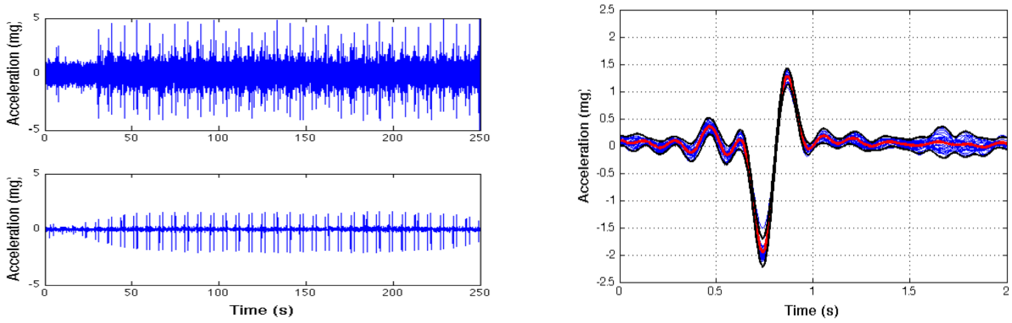
LDC double integrates the NRED-filtered response for each axle to estimate the deflection. However, the load estimation algorithms reported here are based only on acceleration. The use of displacement for load estimation is currently under study.

3. Test Results

Results of SW-WIM tests are reported in this section.

3.1 Repeatability

SW-WIM should give virtually identical pavement acceleration measurements from repeated motions of the same truck. The Heavy Vehicle Simulator (HVS) at University of California Pavement Research Center is used to simulate a single wheel moving repeatedly over a concrete road overlaid with a dense-graded polymer modified asphalt concrete layer at three speeds and with three wheel loads. Sixty trials were repeated for each speed-load combination.



(a) (b) *Multiple runs.*

Figure 3 - (a) Raw vs. filtered acceleration signal; (b) multiple trials.

Fig 3(a) is a record of the raw acceleration measurement (top) and its NRED-filtered version (bottom) for repeated runs. The latter reveals the back-and-forth passage of the single tire over the sensor but the passage is obscured in the raw signal. The attenuation of the filtered signal at the beginning and end of the record is due to transients in NRED. Fig 3(b) superimposes plots of several runs for 80 kN load at 5.41 mph. For this the variation in positive peaks, negative peaks, energy (as % of the mean) is 6.1, 7.4, and 4.3% respectively for one sensor and 4.0, 2.9, and 5.4% respectively for another sensor. Evidently SW-WIM measurements are similar under repeated loading conditions.

3.2 Pavement Deflection

A falling weight deflectometer (FWD) experiment can be used to gauge SW-WIM's estimates of deflection (displacement). The FWD imparts a load pulse by dropping a large weight onto the pavement through a circular load plate. Deflection sensors mounted away from the load plate measure the displacement of the pavement in response to the load. The displacement $h(x,t)$ measured at location x at time t is an estimate of the pavement impulse response.

A FWD experiment was conducted on the concrete pavement of Yolo County Road 32A. The plan on the left of Fig 4 indicates the locations at which the weight is dropped and where the pavement displacement is measured. A SW-WIM cube is located at the center (circle numbered 8,17). The plot on the right compares the FWD-measured displacement with that obtained by the LDC algorithm. The agreement is very good.

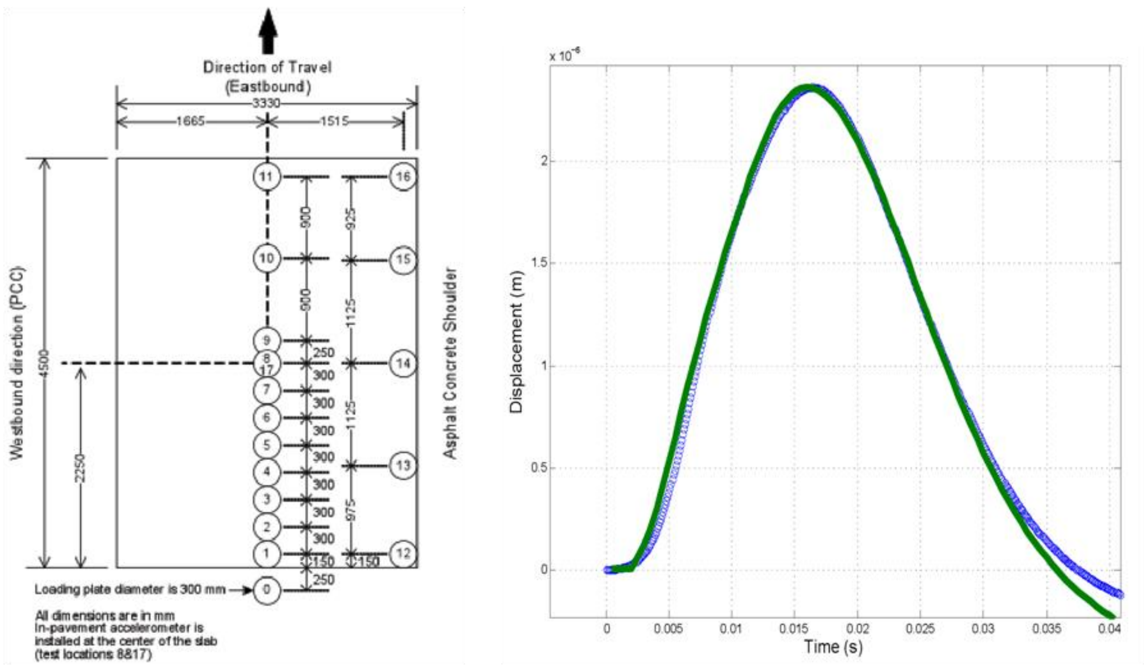
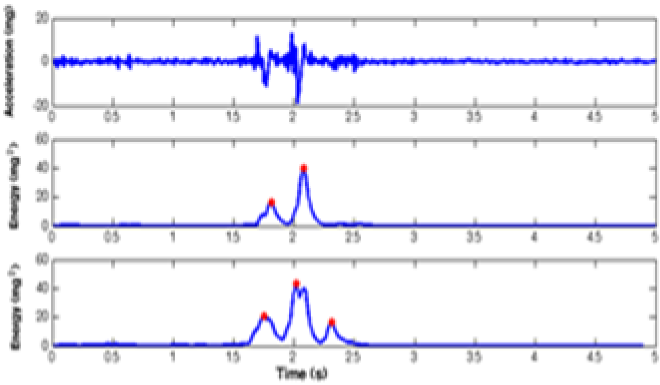


Figure 4 - Measurement plan of FWD experiment (left); comparison of FWD and SW-WIM measurements

3.3 Axle Detection

The ADET algorithm passes the measured energy of the signal through a moving average filter and peaks of the resulting signal that are at least 3ft apart are labeled as axle locations. The low pass filtering combined with this minimum separation constraint helps distinguish the real peaks corresponding to axles from any other peaks in the signal. The experimental site is downstream of the Caltrans weigh station at Sunol on I-680S. The left panel in Fig 5 displays three plots: the top plot is the raw signal from a single sensor, the middle plot shows the result when ADET is applied to the same sensor, and the bottom plot shows the result when ADET is applied to pointwise maximum of the signal from the three sensors. The single sensor detects two axles at the peaks (red dots) while the maximum detects all three axles. The table on the right gives the number of trucks whose axles are correctly or incorrectly counted.

Each individual sensor correctly counts the axles in 47 out of 53 trucks (errors are always from undercounting) whereas the pointwise maximum of the signals across three sensors correctly counts the axles in all 53 trucks. A detailed description of axle detection can be found in (Bajwa et al, 2011).



Count Err.	Sensor 1	Sensor 2	Sensor 3	Combined
-3	0	0	1	0
-2	1	2	1	0
-1	5	4	4	0
Correct	47	47	47	53
Performance	88.7%	88.7%	88.7%	100%

Figure 5 - (Left) Raw signal, NRED-processed signal from one sensor, and the maximum of three signals. (Right) Axle detection by each sensor and by their maximum.

3.4 Axle Load

We begin with a 'template' $\Psi(t)$ representing the pavement's response to a single, isolated axle. In practice, Ψ is obtained by averaging the responses of different sensors to an axle that is far from the other axles. Ψ is normalized, $\sum \Psi^2(t) = 1$. The ADET algorithm processes the measurement sample ζ of a truck and gives the number of axles and their locations. For example, 5 axles may pass over the sensor at $t_1, \cdots, t_5$. We find coefficients F_i by solving

$$\min_{F_i} \sum_t \left[\zeta(t) - \sum_i F_i \Psi(t - t_i)\right]^2. \tag{1}$$

(Below ζ is the average of the response of the three middle sensors.) We take F_i to be the force on the pavement exerted by axle i. The force depends linearly on axle load and increases with truck speed. Empirical considerations suggest removing dependence on speed V by taking the force as $x_i = F_i / V^{0.5}$. It remains to determine the *calibration coefficient* γ_i, which relates the measured force x_i to the true load w_i. Assuming that w_i is correctly measured by the Caltrans WIM station, γ_i is estimated via the regression model, (i is the axle index and n is the index for a 5-axle truck)

$$w_i^n = \gamma_i x_i^n + \epsilon_i^n, \; i = 1, \cdots, 5, \; n = 1, \cdots, N. \tag{2}$$

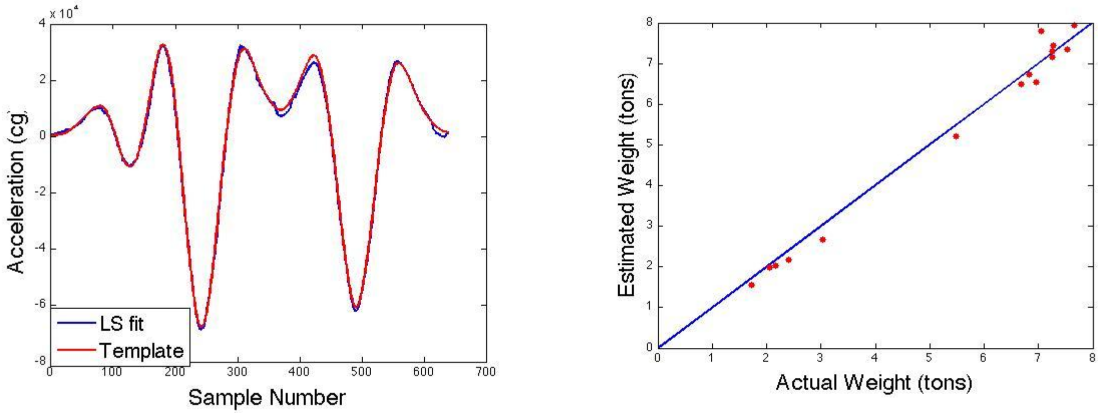


Figure 6 - (left) Sample ζ vs. least squares fit (1); (right) regression (2) for third axle.

We present results for a small set of $N = 15$ trucks. The left panel of Fig 6 compares one sample ζ with the least squares fit $\sum_i F_i \Psi(t - T_i)$ of (1). The right panel shows the scatter plot $(\gamma_i x_i^n, w_i^n)$ and the regression (2) for the third tandem axle of the 15 trucks in the sample.

Table 1 - Mean relative absolution error from regression (2)

μ_i	Axle 1	Axle 2/3	Axle 4/5	Axle 2	Axle 3	Axle 4	Axle 5
Individual	4.87			9.05	7.79	8.15	12.41
Joint	4.16	5.41	4.72	6.27	5.56	9.12	5.53

Table 1 gives the mean relative absolute error for each of five axles, defined as:

$$\mu_i = \frac{\sum_n |\epsilon_i^n|}{\sum_n w_i^n} = \frac{\sum_n |w_i^n - \gamma_i x_i^n|}{\sum_n w_i^n}. \tag{3}$$

Each entry in the first row labeled 'individual', gives μ_i from a separate regression for each axle. In the second row, three regressions are carried out: axle 1, and combined tandem axles 2/3 and 3/4. The estimated load for the combined axle 2/3 is then evenly allocated among axles 2 and 3; similarly the estimated load for 4/5 is evenly allocated among axles 4 and 5. Surprisingly, the errors in the 'joint' estimation are smaller than in the 'individual' estimation. This indicates a potential improvement in our approach to the determination of F_i from (1). Ongoing work is addressing this improvement, exploring methods to divide each axle's load between the left and right tires, and understanding how the calibration coefficients γ_i vary with temperature and pavement type.

4. Conclusions

SW-WIM represents a promising approach toward an inexpensive, easy-to-install system based on MEMS sensors, and ultra-low power radios and microprocessors. SW-WIM is under development. Tests indicate that it adequately classifies trucks and measures pavement displacement. Preliminary results suggest SW-WIM should be able to accurately estimate axle loads after improvements in the current algorithms.

5. Acknowledgement

The work reported here was made possible by NSF SBIR Phase I Award 0945919 and SBIR Phase II Award 1057566. We are grateful to Brian Fuller, Nathan Fraenkel, Mike Hui, Sebastian Lodahl and Wenteng Ma of Sensys Networks for their help.

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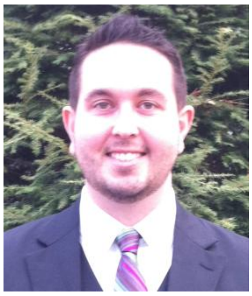
HIDDEN MARKOV MODELING FOR WEIGH-IN-MOTION ESTIMATION

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Abstract
This paper describes a hidden Markov model to assist in the weight measurement error that arises from complex vehicle oscillations of a system of discrete masses. Present reduction of oscillations is by a smooth, flat, level approach and constant, slow speed in a straight line. The model uses this inherent variability to assist in determining the true total weight and individual axle weights of a vehicle. The weight distribution dynamics of a generic moving vehicle were simulated. The model estimation converged to within 1% of the true mass for simulated data. The computational demands of this method, while much greater than simple averages, took only seconds to run on a desktop computer.
Keywords: Weigh-in-Motion, WIM, MS-WIM, Markov, Multiple sensors.

Résumé
Cet article décrit un modèle de Markov caché permettant de minimiser l’erreur dans l’estimation du poids du camion. Cette erreur vient des oscillations complexes du système de masses discrètes du véhicule. La réduction des oscillations se fait par une approche de lissage, plane et régulière à vitesse constante et lente en ligne droite. Le modèle utilise cette variabilité inhérente pour déterminer le poids total réel et le poids de chaque essieu d'un véhicule. L’oscillation dynamique de la distribution des masses d'un véhicule roulant a été simulée. Le modèle d’estimation converge à moins de 1% de la vraie masse pour les données simulées. Le temps de calcul de cette méthode, bien que beaucoup plus grand que celui de simples moyennes, est de seulement quelques secondes sur un ordinateur de bureau.
Mots-clés: Pesage en marche, WIM, MS-WIM, Markov, multi-capteurs.

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1. Introduction

Previous work has been performed to estimate static axle weights from multiple sensor WIM systems. These works include multiple algorithms varying from Maximum Likelihood (Stergioulas et al. 2000) to Kalman Filtering techniques (Sainte-Marie et al. 1998). More recent developments include a new Statistical Spatial Repeatability (SSR) algorithm that removes bias due to pavement (O'Brien et al. 2010) and impact factors (O'Brien et al. 2008, 2009). To this end, an effort to perform probabilistic modeling on Weigh-in-Motion (WIM) Gen II sensor data was performed in order to reduce error in the static weight measurement due to vehicle oscillation. These errors arise from oscillations as a vehicle traverses the WIM system and are a result of true dynamic forces acting on the sensors. These dynamics occur, because a vehicle is (i) a multi-body system of discrete masses (e.g., body, load, wheels) that are (ii) interconnected by springs (e.g., cab-load coupling, wheel suspensions) and are (iii) excited by various aperiodic external forces (e.g., uneven terrain, steering changes, acceleration, wind variability, load shifts in liquids, engine vibration) with (iv) nonlinear damping by slip-stick friction and shock absorbers. Lower-frequency oscillations (1-5 Hz) arise from vehicle dynamics (e.g., side-to-side rocking, front-to-back rocking, vertical bouncing of the load on the suspension, load-bed flexure, twisting about coupling points, and nonlinear couplings among them). Higher-frequency oscillations (9-14 Hz) depend on vehicle size (e.g., tire rotation). Accurate weights require minimization of these oscillations, which are presently reduced via a combination of: (a) minimal excitations by a smooth, flat, level approach, weighing, and exit; (b) constant, slow speed driving in a straight line; (c) several single-axle weight measurements as the vehicle crosses multiple weigh pads; and (d) continuous motion to foster dynamic friction, which reduces the slip-stick friction (Abercrombie et al., 2008).

The work focused on modeling simulated data of a Ford F-250 driving slowly in a straight line across a portable low speed Gen II measurement system shown in Figure 1 (Abercrombie et. al., 2008). Rather than focusing on reconstructing the original signal, the emphasis was to estimate the hidden parameters of the vehicle dynamics. A simplified model of the moving vehicle was created. The relevant differential equation for the simplified model was:

$$m\ddot{x}_t + g\dot{x}_t + kx_t = Ft \qquad (1)$$

where x_t is the distance of the vehicle's center of mass below its equilibrium point at time t, $\dot{x}_t$ and $\ddot{x}_t$ are the first and second time derivatives of x_t, m is the mass of the vehicle, γ is the damping coefficient, k is the spring coefficient, and F_t is the external (broadly defined) force pushing down on the vehicle at time t. The observations are not directly of x_t, but rather the readout of a sensor that has its own dynamics and includes measurement error. We chose a further simplification: to subsume the sensor dynamics into the sensor measurement error.

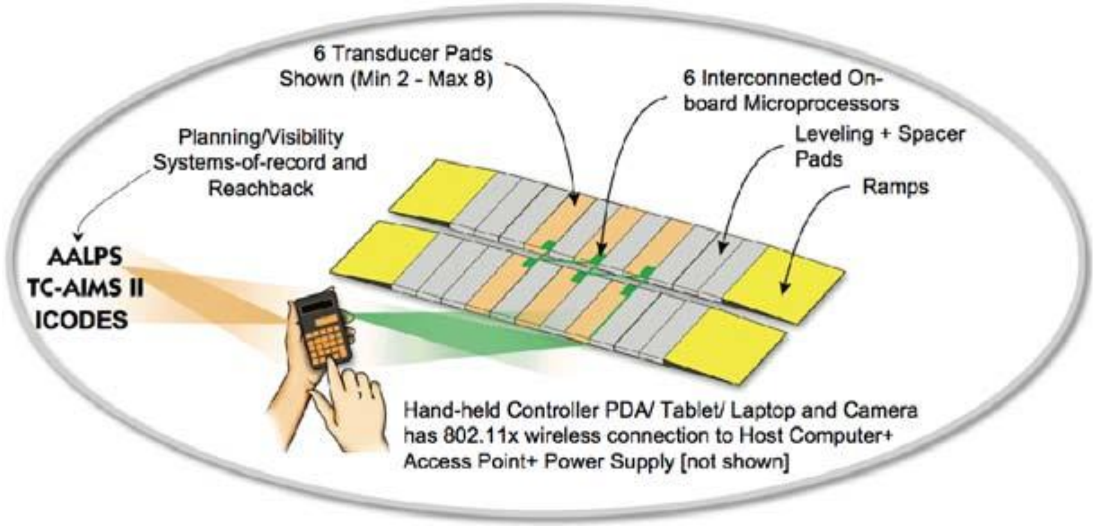

Figure 2 - WIM Gen II System diagram showing control/data management pathways

2. Hidden Markov Model

A hidden Markov model is a probabilistic model of observables (sensor readings) given in terms of a hidden state (vehicle position) that is subject to particular transition probabilities. These transition probabilities are determined from the differential equations that define the dynamics of the vehicular system. The observations include error. Our hidden Markov model discretizes both position and time. It differs from a Kalman filter primarily in the method by which the parameters are estimated.

The hidden Markov model is based on a Markov chain of the state $X = \{x_t\}$ which transitions over time according to the differential equation. We allow an arbitrary forcing function to act on the vehicle, but model it as independent identically distributed (i.i.d.) normal random variables with mean zero and known variance. The observations, S, of the hidden Markov model come from the sensor data. Given sensor observations, the approach is as follows: (1) choose an initial value of the parameters P, (m,γ,k), (2) use P and S to find the expected values of the position at each time, (3) use S and X to find P that maximizes the likelihood of the S given X and P (4) go back to step 2 and iterate until P converges. This has been implemented and it is possible to show that better estimates can be derived from poor initial starts.

The position and derivative of the position at time t+1 can be written in terms of the velocity and acceleration at times t and t+1 (as follows from the definition of the time derivative where a small time difference Δ between samples is assumed).

$$x_{t+1} = x_t + \frac{\Delta}{2}\left(\dot{x}_t + \dot{x}_{t+1}\right) \qquad (2)$$

$$\dot{x}_{t+1} = \dot{x}_t + \frac{D}{2}\left(\ddot{x}_t + \ddot{x}_{t+1}\right) \qquad (3)$$

The second derivative is determined by Newton's second law of motion using Equation 1 for the value of the acceleration:

$$\ddot{x}_t = \left(F_t + mg - kx_t - \gamma \dot{x}_t\right) / m \tag{4}$$

These equations can be used to write a relation between the x_t for three consecutive times, t. This allows for the development of the second derivative, which is necessary to include the force function and the parameters.

$$\left(1 + \frac{\Delta\gamma}{2m} + \frac{\Delta^2 k}{4m}\right) x_{t+2} + \left(-2 + 2\frac{\Delta^2 k}{4m}\right) x_{t+1} \left(1 - \frac{\Delta\gamma}{2m} + \frac{\Delta^2 k}{4m}\right) x_t = \frac{\Delta^2}{4m} \bar{F}_{t+1} + \Delta^2 g \tag{5}$$

where

$$\bar{F}_{t+1} = \frac{F_t + 2F_{t+1} + F_{t+2}}{4} \tag{6}$$

As a result, expected values for the sequence of positions and parameter estimates can be used to compute the smoothed forcing function $\bar{F}_t$. The log likelihood of that sequence is monotonically equivalent to the mean squared error of the sequence.

In estimating parameters of a hidden Markov model, it is also necessary to have a probability distribution of the observations given the hidden states. The sensor measurements are modeled as:

$$s_t = k\frac{x_t + x_{t+1}}{2} + \gamma\frac{x_{t+1} - x_t}{\Delta} + \varepsilon_t \tag{7}$$

where the ε_t are the sensor errors, which are modeled as independent and identically distributed (i.i.d.) normal with mean zero and known variance. (This is actually the expected sensor measurement for time t + ½. Using this offset simplifies the analysis.)

(Let $P = (m,\gamma,k)$ be the parameters, $X = \{x_t\}$ be the state, and $S = \{s_t\}$ be the sensor data.)

Now a key observation is that the F_t and ε_t error terms are linear in state, x_t, and also in the parameters m, γ, k after multiplying Equation (5) through by m. Therefore maximizing the likelihood of X given P or of P given X, because of the i.i.d. normality assumptions, is computationally a least squares regression. It is then possible to complete the following computations.

- Given P and S, find the most likely state sequence X.
- Given X and S, find the most likely parameters P.

In each case, the likelihood increases by iterating between the two leads to a locally optimal solution.

3. Simulated Analysis, Experiment, and Results

The analysis used 100 simulated measurements taken over 1 second. The sensor and forcing errors were given standard deviations of 100N, which was used as the known variance in the fitting. The forcing function values were created randomly according to their distribution. These values were then used to update the state x_t according to the update relation, Equation (5). At each point, a sensor observation was simulated using the sensor equation, Equation (7), wherein the error term was randomly generated according to its distribution. The sensor measurements were then input into the hidden Markov model estimation algorithm. The estimation algorithm also requires a preliminary "guess" of the parameters, which were intentionally selected to be very different from the true values.

Figure 3 shows the fit of the estimated forcing function (in red) as compared to the true values (in blue). The forcing function red line essentially overlaps with the horizontal axis in Figure 3. It can be seen that the estimate of the forcing function is generally much smaller than the actual forcing function.

Figure 4 shows the first of the estimated sensor measurements (in red) as compared to the true values (in blue). The initial low estimates of the observations were due to an underestimation of the forcing function. The initial low valley in the forcing function, when underestimated, results in an overestimate of the sensor error, which in turn leads to the low line toward the beginning. Despite the imperfect estimation of the forcing function, the sensor estimation was generally fairly good.

More important than the estimations of position and sensor error are the estimates of the vehicle parameters. The true, initial guess, and final estimate parameters are shown in Table 1. The mass estimate is shown to be within 1% of the true mass. The spring coefficient was not as good, being too high by 33%. The main shortcoming is in the damping coefficient, which was estimated at zero. It seems that to better estimate these values, more advanced methods need to be employed, such as incorporating prior distributions on the parameters.

The model is currently being implemented into a modified Gen II WIM System.

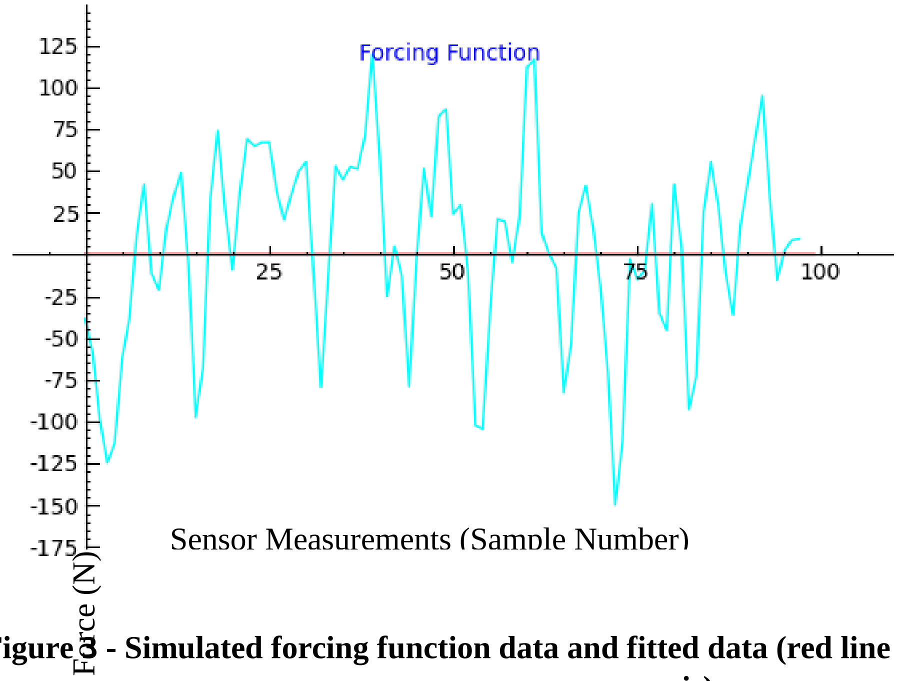

Figure 3 - Simulated forcing function data and fitted data (red line overlaying horizontal axis)

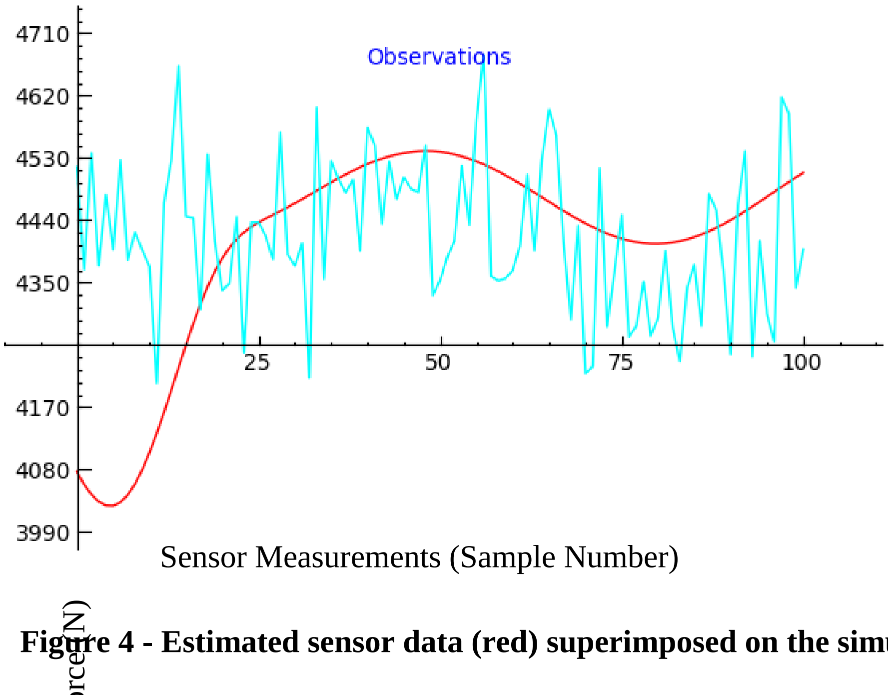

Figure 4 - Estimated sensor data (red) superimposed on the simulated sensor data

Table 2 - True, initial guess, and final estimate parameters (The initial guess was an arbitrary choice simply selected to be different from the true parameters)

	True	Initial	Final
Mass	450 kg	700 kg	454 kg
Damping Coefficient	7300 N/(m/s)	3000 N/(m/s)	0 N/(m/s)
Spring Coefficient	35000 N/m	70000 N/m	46563 N/m

4. Conclusions and Recommendations

A hidden Markov model was used on simulated data of a Ford F-250 driving slowly in a straight line across a portable low speed Gen II measurement system to assist in the weight measurement error that arises from complex vehicle oscillations of a system of discrete masses. The model estimation converged to within 1% of the true mass for simulated data. The computational demands of this method, while much greater than simple averages, took only seconds to run on a desktop computer. While our method appears to accurately estimate the mass coefficient, the effect of the spring and damping coefficient may be too subtle to estimate without longer runs of measurements. Recent research on sensor corrugated plates (Bin and Xinguo, 2010) may lend itself to the manufacture of larger sensors, thus allowing longer runs of measurements. Further research will investigate data requirements for these parameters and for parameters within more complex models of vehicle dynamics. Ongoing work is investigating extracting better estimates of uncertainty, and exploiting the learned spring coefficients associated with tires, as they may be useful for detecting under and over inflated tires. Additionally, ongoing work will apply this model to data taken from sensor measurements made in the field. Future goals include the implementation of this model into a next generation Weigh-In-Motion system with newly architected load cells. This work is ongoing and being funded under the US Army Small Business Innovation Research (SBIR) program. In cooperation with International Electronic Machine Corporation, the development of a Slow-speed Weigh-in-Motion Error Reduction System (SWIMERS) is being developed that will refine and implement the model discussed in this paper as well as algorithms and refinements used in the modified Gen II WIM System (Abercrombie et al. 2008).

5. Acknowledgements

The authors gratefully acknowledge funding from the U.S. Transportation Command, Department of the Army, and the ORNL Office of Technology Transfer. The authors would like to humbly thank the reviewers for the excellent suggestions during the preparation of this paper.

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AUTOMATIC VEHICLE CLASSIFICATION FOR WIM SYSTEMS

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Abstract

In the paper a new method of automatic vehicle classification called ALT (ALTernative) is presented. Its characteristic feature is open structure - a user can adjust the number of vehicle categories according to individual needs. It uses an algorithm employing data fusion methods and fuzzy sets. The presented method was compared with other axle-based classification schemes such as FHWA and LTPP. The high effectiveness of ALT classification while retaining high selectivity of divisions was proved by test results. The effective classification of all vehicles at the level of 95% and goods trucks of 100% is more than satisfactory. The ALT classification method requires accurate measurement of vehicle axle spacing and length, which may be considered as a drawback of this method.

Keywords: Automatic Vehicle Classification, ITS, Weigh-in-Motion, WIM, Fuzzy Sets, Data Fusion.

Résumé

Ce papier présente une nouvelle méthode de classification automatique des véhicules nommée ALT (à partir du mot “Alternative”). La particularité de cette méthode réside dans sa structure ouverte qui permet d’ajuster le nombre de catégories dans lesquelles classer les véhicules aux besoins individuels. L’algorithme pour l’identification automatique des véhicules utilise des méthodes de fusion de données et des ensembles flous. Cela assure un rendement élevé de la classification et en même temps la sélectivité élevée de l’algorithme.

Mots-clés: Classement automatique des véhicules, pesage en marche, ensembles flous, la fusion de données.

1. Overview of Existing Classification Schemes

Intelligent Transportation Systems (ITS) and particularly automatic weigh-in-motion (WIM) systems require a concurrent and unique classification of the vehicles in terms of both type and chassis characteristics. These needs result from law enforcement regulations determining, for example, the permissible axle loads depending on the axle configuration and spacing. Recent works resulted in developing several classification methods and automatic classification algorithms. The schemes differ in the number of vehicle categories that are based mainly on the vehicle functional features and its gross weight and mostly ignore the chassis characteristics.

Practical applications employ at least several vehicle classification schemes and a large number of specific methods developed for individual end-users. The most popular are: the American FHWA (FHWA, 1995) and LTPP (FHWA, 2010) classification, European EURO-13 and COST 323 (COST 323, 1999) classifications. The COST 323 solution is the least selective one; it comprises only 8 vehicle categories; for instance, two-axle and three-axle road tractors with single-axle or two-axle semi-trailers are categorized into one group. The EURO-13 classification is more detailed and a given category comprises vehicles of similar gross weight and overall dimensions. However, this classification scheme ignores the categorization according to the chassis type and therefore renders iy impractical. The FHWA and LTPP classification seems to be the most selective with respect to axle configuration. It differentiates two-axle vehicles into cars, delivery vehicles and lorries, and three-axle single vehicles are distinguished from vehicle combinations. However, articulated vehicles are divided in a manner that precludes their unique classification; moreover, this scheme also includes vehicles which can be hardly found on European and Polish roads. In (Cheng et al. 2005) automatic vehicle classification algorithms have been presented. Authors discuss a vehicle detection and classification system using model-based and fuzzy logic approaches based on video images.

Because vehicle outlines are differentiated by their functional design in addition to the number and configuration of axles, it can be concluded that the above classification schemes do not meet the selectivity requirements. Unfortunately, developing a single universal classification scheme, which would satisfy expectations of various user groups, is difficult or often infeasible because of a macro-scale diversity of vehicles. The traffic structure varies with the geographical situation and is dissimilar in various countries. Therefore a universal vehicle classification should not have a closed structure but should be characterized by:

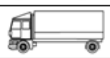
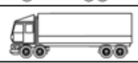
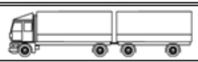
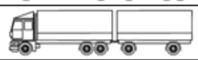
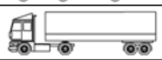
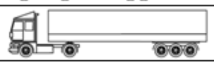
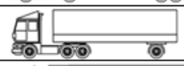
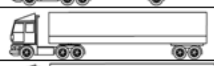
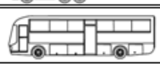
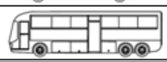
- high selectivity – associated with the applied vehicle classification scheme;
- high effectiveness – associated with the algorithm employed;
- high flexibility, i.e. capability to adjust vehicle categories to the traffic characteristic in a given area.

2. ALTernative Vehicle Classification

To satisfy the requirements for vehicle classification laid down for modern ITS systems and automatic weighing purposes, the author proposes a novel solution based on the ALT classification and an algorithm for automatic vehicle recognition employing data fusion methods and fuzzy sets. The basis for the ALT classification is the configuration of vehicle units (a single vehicle, articulated vehicle or vehicle combination) and the number and configuration of axles (Van Boxel et al., 2005). First, 8 basic groups of vehicle configurations have been selected. Some of them can occur only singly (e.g. cars) and some, like trailers, can only be coupled with other units. Each group is denoted by a letter symbol: M – Motorbike, C – Car, D – Delivery vehicle, L – Lorry, T – Tractor, R – Trailer, S – Semi trailer, B – Bus.The vehicle symbol is supplemented with the number of vehicle axles, e.g. a three-axle lorry is denoted 3L, and two-axle semi-trailer is denoted 2R.

Next, basing on an analysis of the vehicle types structure in Poland, the elements from the basic groups were formed into suitable combinations corresponding to vehicle outlines of the most frequent occurrence. For example, an articulated vehicle, which consists of a two-axle tractor and three-axle semi-trailer is classified into category 2T+3S, and a vehicle combination of two-axle lorry and two-axle trailer is categorized as 2L+2R. Twenty vehicle categories most frequently found in Poland are listed in Table 1.

Table 1 – Classification scheme and algorithm effectiveness

Vehicle type	Category Number	Outline	Effectiveness [%]:			No. of vehicles
			ALT	FHWA	LTPP	
Single vehicles	M		-	-	-	0
	2C		99.26	98.8	99.4	673
Vehicle combination	2C+1R		100	80.0	20.0	5
	2C+2R		100	0	100	3
Single vehicles	2D		75.6	76.9	48.7	156
	2L		89.7	43.8	78.9	57
	3L		100	100	100	14
	4L		100	0	0	7
Vehicle combination	2L+2R		100	No category	0	8
	2L+3R		100	No category	0	1
	3L+2R		100	No category	No category	5
	3L+3R		-	No category	No category	0
Articulated vehicles	2T+1S		-	-	-	0
	2T+2S		100	0	100	45
	2T+3S		100	100	63.3	109
	3T+1S		-	-	-	0
	3T+2S		100	0	100	1
	3T+3S		100	100	100	2
Single vehicles	2A		72.7	90.9	0	11
	3A		-	-	-	0
	Total of correctly classified vehicles:		95.0	85.0	84.3	total: 1097
	Total of not classified vehicles:		0.0	9.0	6.2	

The resultant categories uniquely characterize a vehicle for a given configuration of component units and the number of axles. The number of categories is not fixed and can be modified according to the given area traffic if required, what is an evident advantage of this method.

3. Automatic Vehicle Classification Systems

The basis for a vehicle classification process is the measurement of vehicle characteristic parameters, such as the number of axles and their spacings or the vehicle magnetic profile that form the so-called characteristic parameters vector. The decision whether a vehicle falls into a given category is taken by comparing the characteristic vector with the vector for the model of this category. The simplest case is a coarse division into large and small vehicles, based on measuring of only one parameter, i.e. length. The selectivity can be improved by increasing the number of parameters; e.g. in the case of division according to the number of axles, better selectivity is achieved by measuring the second parameter, i.e. axle spacing. The classification process is then a multi-stage and hierarchical one. The decision criteria used in classical logic (i.e., "true" or "false") , as will be demonstrated, is the reason for a low effectiveness of such classification algorithms.

3.1 Classical Logic and Fuzzy Sets

In the domain of classical logic the known algorithms for automatic classification are based on the definition of the conventional set, which can be written as a set of pairs:

$$A = \{(x, \varphi_A(x))\} \tag{1}$$

where:

- $X = \{x\}$ – is a certain wider set of values (in this case: the distance between axles or the vehicle length);
- $\varphi_A(x): X \to \{0,1\}$ – is referred to as the classical membership function that to each element of the space X assigns the number “0’ which means non-membership or “1” – membership.

Within the group of vehicles with the same number of axles, various types of vehicles with similar axle spacings can be specified. It is therefore not possible to define disjoint criteria, and inferring vehicle membership to a given category on the basis of classical logic has no meaning, as illustrated in Figure 1 for the parameter x_{12} – the axle spacing 1–2.

The classical approach lowers the effectiveness of classification, which in the presented form does not exceed 60–70%. Since unique assignment of an element to the set does not apply here, fuzzy logic should be employed as a measure of fuzzy, multiple-valued and imprecise concepts.

The fuzzy set B defined on X can be represented as the following set of pairs, see (Kacprzyk, 1986):

$$B = \{(\mu_B(x), x)\} \qquad \forall x \in X \tag{2}$$

where:

- $X = \{x\}$ – as in (1);
- $\mu_B : X \to [0,1]$ – is the membership function which to each element from space X assigns a degree of membership in the given fuzzy set: from non-membership ($\mu_B(x) = 0$) through partial membership ($0 < \mu_B(x) < 1$) to full membership ($\mu_B(x) = 1$).

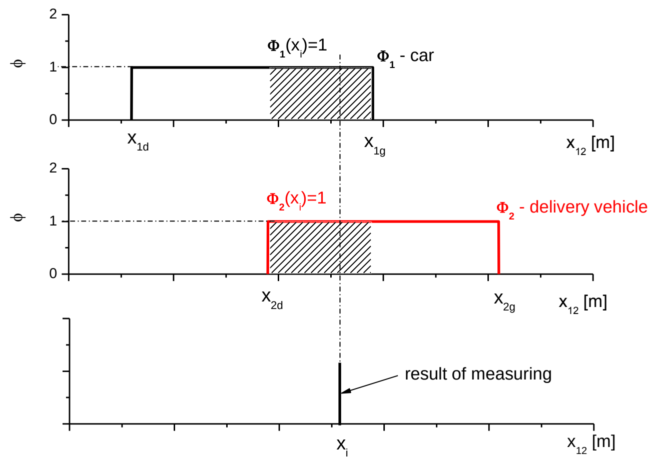


Figure 1 - An example illustrating the formulation of vehicle category models for rectangular (classic) membership functions and the procedure in the event a new result of measuring x_i is obtained.

In fuzzy set theory the transition from non-membership to membership is gradual rather than abrupt as in non-fuzzy sets. The shape of the membership function depends on the problem being considered, and may take form from a simple analytic function to complex relations that are combinations of many simple functions (Mathworks, 2011). At the same time there are no exact rules for choice of the optimum shape of the membership function; the procedure is largely subjective and non-formalized, which is the drawback of this method. For the purposes of the algorithm for automatic vehicle classification, triangular and trapezoidal shapes of the membership function were selected.

Aside from the "membership – non-membership" alternative, characteristic for classical logic, the case of partial membership also occurs. An example of the triangle membership function of the fuzzy set "axle spacing" – x_{12} is shown in Figure 2. Practically, the notion of a fuzzy set is equated with its membership function and this convention has been adopted by the author in this work.

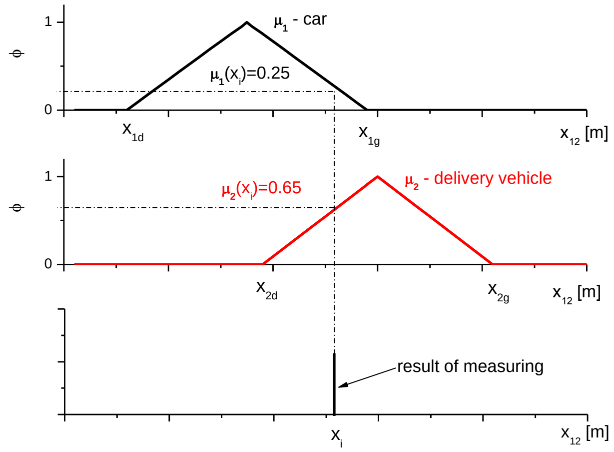


Figure 2 - An example illustrating the formulation of vehicle category models for triangular membership functions and the procedure in the event a new result of measuring x_i is obtained.

The use of triangular membership functions eliminates the ambiguity characteristic for non-fuzzy sets. The membership function values μ_1 and μ_2 obtained in this example should be interpreted as the measure of membership of a vehicle with the axle spacing x_{12} in one of the two categories: a car or delivery vehicle. The value ($\mu_2(x_i)=0.65$) > ($\mu_1(x_i)=0.25$) indicates that the vehicle with measured axle spacing of x_i, "better" matches the category of delivery vehicles than that of cars. The above considerations can be generalized to an arbitrary number *k* of vehicle categories and number *N* of measured parameters.

Each membership function should adequately represent the relation between the parameter value and the degree of membership, constituting the model of a given vehicle category. The models were formulated utilizing reference data from three sources:

a) vehicle manufacturer specifications – passenger vehicles and two-axle and three-axle lorries;
b) the Polish Committee for Road Transport – over 300 results of measurements and dimensions of lorries (mainly five-axle);
c) data acquired from the WIM system – over 5000 results of axle spacing measurement and the electrical equivalent length of a vehicle.

The model of the *k*-th vehicle category consists of a group of three membership functions determined for 3 selected parameters of a vehicle:

- axle spacing;
- length (evaluating on the basis of vehicle magnetic profile);
- the difference between the vehicle length and the distance between two outermost axles.

The coefficients of membership functions were determined by means of statistical analysis methods applied to the reference database and in that way the models for each category of vehicles were formulated.

3.2 Data Fusion

The classification algorithm consists of the use of the data fusion method. This notion will be understood as a set of operations whose purpose is to combine data from various sources in order to reach decisions, or achieve results better, in qualitative or quantitative terms than those obtained from an individual analysis of each source data separately (Sroka, 2008). The use of common information, "hidden" in the original measurement data, allows obtaining new or more comprehensive results that cannot be achieved by other methods. Data aggregation in the process of data fusion seems to be a particularly suitable method to be applied in automatic vehicle classification. The vector of characteristic parameters, obtained from the measurement has the length *N* that depends on the number of vehicle axles:

$$parameters=[d_l,\ d_{xl},\ x_{12},\ x_{23},\ldots]_{(1\text{x}N)}, \tag{3}$$

where: d_l is the vehicle length, x_{12} is the distance between axles 1 and 2, x_{23} between axles 2 and 3, etc. and d_{xl} is the difference between the vehicle length and the distance between the two outermost axles. The first stage of classification is the qualification of a vehicle into the group with a given number of axles. Next, the results of measurement of *N* parameters are compared with *K* membership functions that constitute the models for particular categories. As the result of the comparison *N* values of the membership function are obtained for each of *K* categories (see Figure 3).

The N values of the membership function obtained for a given category are combined by means of functions executing the data fusion. Two functions yielding the best results were found by testing:

$$f_1 = \frac{1}{N}\sum_{i=1}^{N}\mu_i(x_i)$$
$$f_2 = \bigcap_{i=1}^{N}\mu_i(x_i) = \min(\mu_1, \mu_2, \ldots, \mu_N) \qquad (4a, 4b)$$

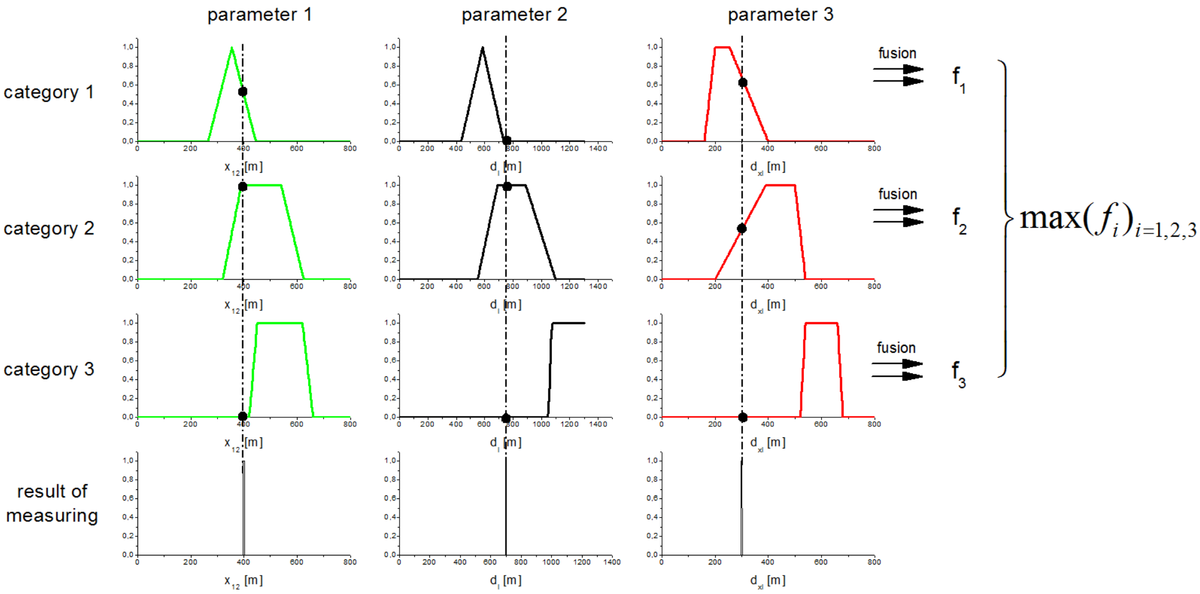


Figure 3 - An example illustrating models of three categories of vehicles, the procedure in the case of obtaining a new result, and data fusion.

The choice of the function depends on the number of axles of the vehicle. As the result of fusion one obtains one number for each category being considered. The largest value indicates the category to which the considered vehicle shall be assigned.

4. Test Results

The aim of the tests was the comparison of effectiveness of three algorithms for automatic vehicle classification:

– classical classification algorithm employing the FHWA scheme;
– classical classification algorithm employing the LTPP scheme;
– the algorithm employing data fusion methods and fuzzy sets for ALT classification.

For purposes of comparison, measurement data were used from the 16-sensor MS-WIM installed on road No. 81, in Gardawice. The system is provided with piezoelectric load sensors, evenly spaced at a distance of 1m from each other, as follows from modeling research (Burnos, et al. 2007)). A total of 1097 vehicles was recorded and, based on visual assessment, assigned to appropriate categories. The results of automatic classification were compared with the result of visual assessment of a vehicle. The ratio of the number of correctly classified vehicles to the total number of vehicles being tested in a given category was used as a measure of effectiveness. Results are shown in Table 1.

The effectiveness of the algorithm based on fuzzy measures and data fusion is significantly better than that of the classic algorithm. It should be particularly noted that no vehicles remained non-classified using ALT classification, whereas in the case of FHWA and LTPP algorithm almost 10% and 6% respectively of all results was non-classified. Moreover, despite the fact that the ALT classification is more selective (20 categories) than FHWA and LTPP (13 categories), the overall effectiveness of ALT classification is 10% higher than that of FHWA and LTPP. This proves the correctness of the concept of employing fuzzy logic and data fusion for automatic vehicle classification. Although the ALT classification scheme is currently in use in "Traffic-1" system (measuring system of road traffic parameters) it is considered a work in progress, subject to revision and enhancement.

5. Conclusion

The work described in this paper presents an alternative scheme of vehicle classification, ALT. Its characteristic feature is versatility resulting from its open structure. A user can adjust the number of vehicles and their categories according to individual requirements. Supplementing the ALT classification method with the algorithm based on fuzzy measures and data fusion enables high effectiveness of classification while retaining high selectivity of division, as proved by tests results. The effectiveness of classification of all vehicles at the level of 95% and goods trucks of 100% is more than satisfactory. The simplicity of the method (measuring the distance between the axles and vehicle length), its versatility and at the same time high effectiveness, allow for its implementation in autonomous WIM systems. The ALT classification method requires accurate measurement of vehicle axle spacing and its length and the choice of the optimum shape of the membership function is subjective and non-formalized. Both features may be considered as a drawback of this method.

6. Acknowledgment

The author would like thanks to: Janusz Gajda, Piotr Piwowar, Ryszard Sroka, Marek Stencel, Tadeusz Zeglen – a constructors of WIM system in Gardawice.

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EXPERIMENTATION OF A BRIDGE WIM SYSTEM IN FRANCE AND APPLICATIONS TO BRIDGE MONITORING AND OVERLOAD SCREENING

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Abstract
B-WIM systems have been studied and experiments have been conducted in France for 15 years, in the European WAVE project and for the Ministry of Transport. The two main applications are bridge monitoring and overload preselection. However, the type of instrumented bridge and the structural behavior are of great importance for WIM accuracy. This paper reports B-WIM results collected by LCPC and now IFSTTAR on reinforced concrete bridges and steel orthotropic deck bridges, from 1997 until 2010, and analyses the influence of the bridge type and the algorithm used by the weighing system. It also highlights the importance of sensor location to obtain accurate results. The challenges for bridge monitoring and maintenance are highlighted, using the IQOA, a French quality assessment system for bridges.

Keywords: B-WIM, reinforced concrete bridges, steel orthotropic deck, accuracy, trucks, traffic loads, enforcement, bridge monitoring.

Résumé
Des systèmes de pesage par pont instrumenté ont été étudiés et expérimentés en France depuis 15 ans, dans le projet européen WAVE et pour le ministère des transports. Les deux principales applications visées sont le suivi des ponts et la présélection des surcharges. Le type de pont instrumenté et le comportement structurel influent beaucoup sur la précision des résultats. Cet article présente des résultats recueillis par le LCPC puis l'IFSTTAR sur des ponts en béton armés et des dalles orthotropes métalliques, de 1997 à 2010, et analyse l'influence du type de pont, de l'algorithme de pesage et de la position des capteurs. Les enjeux pour la surveillance et la maintenance des ponts sont soulignés dans le cadre de la démarche IQOA, un système d'évaluation de l'état des ouvrages du réseau routier national français.

Mots-clés: Pesage par pont instrumenté, pont en béton armé, dalle orthotrope, poids lourds, charges du trafic, contrôle, surveillance des ponts.

1. Introduction

In France, engineers good knowledge of the structural health of bridges, primarily due to the 1995 adoption of the IQOA (Image and Quality of Structures) procedure as mandatory for the assessment of bridges on the National road system (Lefebvre et al., 2010). Each year, this procedure is applied to one third of the bridge stock, and every second year a general report on the state-owned bridge structural health is published.

In 2010, 11,930 bridges were inspected with a total deck surface area of 55,657,494 m^2 of which 1,477 are located in Paris region. A half of these bridges (5,771) are reinforced concrete structures, with a surface area of 1,549,629 m^2, and 2,218 are medium to long span pre-stressed bridges, with a surface area of 2,634,104 m^2.

Pre-stressed concrete bridges are not suitable for bridge WIM (B-WIM), because of their long spans and influence lines, which lead to frequent multiple presence events that are difficult or impossible to manage, and their low sensitivity to axle and single vehicle loads. Therefore experiments were carried out on reinforced concrete bridges, mainly on integral (frame and bent) bridges. In France, there are 2,550 integral bridges (440,000 m^2) and 1,754 slab bridges (604,000 m^2) (i.e. their structures are occur frequently and are of special interest for B-WIM).

The inspected bridges are categorized into 5 quality classes:
Class 1: good health according to a visual inspection, needing only routine maintenance.
Class 2: good health according to a visual inspection, but with defective equipment or protection elements, or bridges with small defects needing a non urgent specialized treatment.
Class 2E: same as class 2, but needing an urgent treatment.
Class 3: bridges with structural defects, needing a non-urgent repair.
Class 3U: bridges with important defects, needing urgent repair work.

Table 3 - Assessed health of French bridges (see (Lefebvre et al, 2010))

Class	1	2	2E	3	3U	Non assessed
Percentage	11%	47.4%	22.5%	5%	1.1%	13%

In 2010, most of the inspected bridges were in Class 2 (Table 1). Most of the defects do not concern equipment, but are localized on the bearings of the structure. This assessment demonstrates the need for preserving these structures, by monitoring their live loads - here the traffic loads - and behavior.

In 1997-99 the LCPC (IFSTTAR since 1/1//2011) developed and tested a B-WIM system on steel orthotropic bridges within the WAVE European project (Dempsey et al., 1999). Since 2005, the Slovenian SiWIM system was tested on integral concrete bridges and steel orthotropic deck bridges. This paper summarizes these experiments and the applications of the collected data to bridge monitoring and to overload screening.

2. Instrumented Bridges

2.1 Concrete Bridges

Nogent-sur-Seine

The SiWIM was tested on two frame bridges, on the National roads RN4 (Rozay-en-Brie) and RN19 (Nogent-sur-Seine). In both cases, the test was carried over 2 consecutive days with trucks from the traffic flow, weighed in a check area nearby with approved static scales. The latest bridge is located 100 km east of Paris, carries 2 lanes, one in each direction with approximately 1,500 trucks/day. It is a 10 m span frame bridge, 11 m in width with a slab deck of 0.60 m in depth (Figure 1), which is quite sensitive to the axle loads.

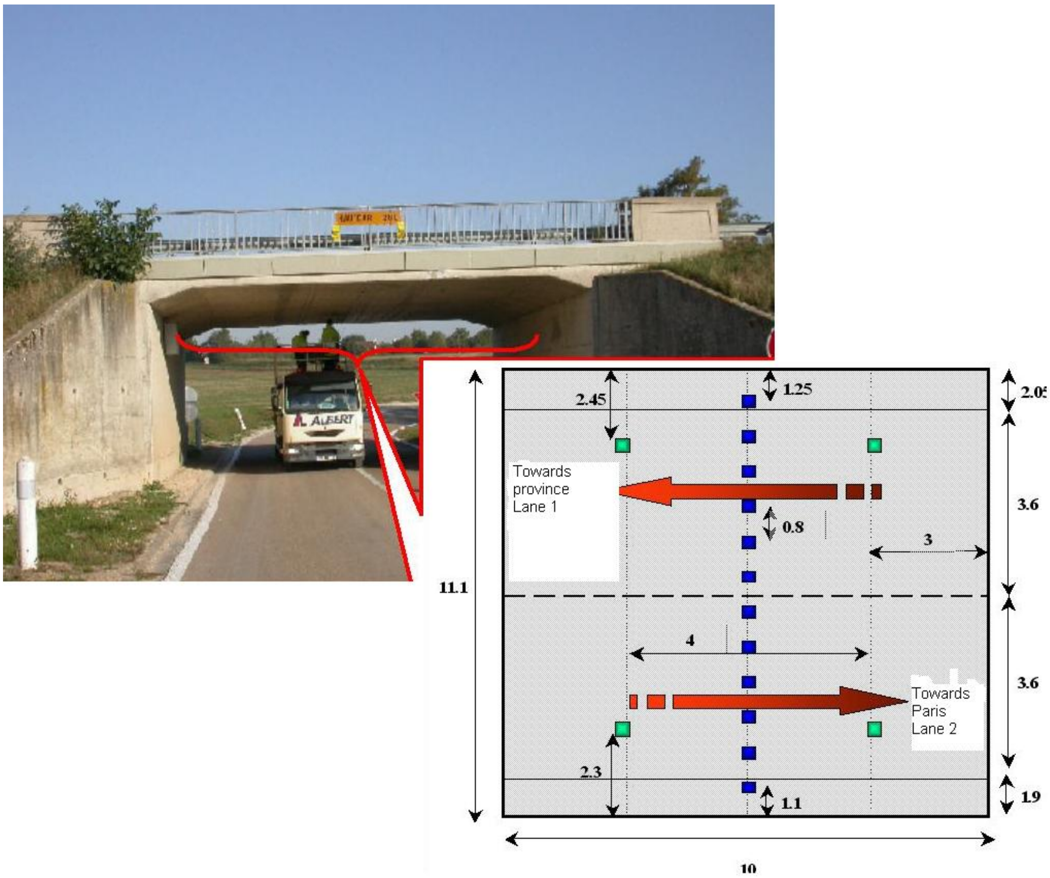


Figure 1 – B-WIM instrumented frame bridge on the RN19 near Nogent-sur-Seine

The test conditions were environmental repeatability (I) and full reproducibility (R2) for the test plan. The multiple presence events were removed manually, which led to rather good results with an accuracy in classes B(10) and C(15) according to the European Specifications COST323 (Jacob et al., 2002) depending on the lane (Table 2). The lower accuracy on lane 2 is explained by a bump prior to the bridge in this direction.

Table 2 - B-WIM accuracy on the bridge of Nogent-sur-Seine (RN19)

Conditions I/R2	GVW	Axle groups	Single axles	Axles in groups	Global
Lane 1	B(10)	B+(7)	B(10)	B+(7)	B(10)
Lane 2	C(15)	B(10)	B(10)	B(10)	C(15)

The sensor location was chosen according to the moment diagram for this kind of structure (Figure 2). The maximum strain is observed at mid-span. A node must be avoided and the best results are obtained near an antinode (Vabre and Ieng, 2011).

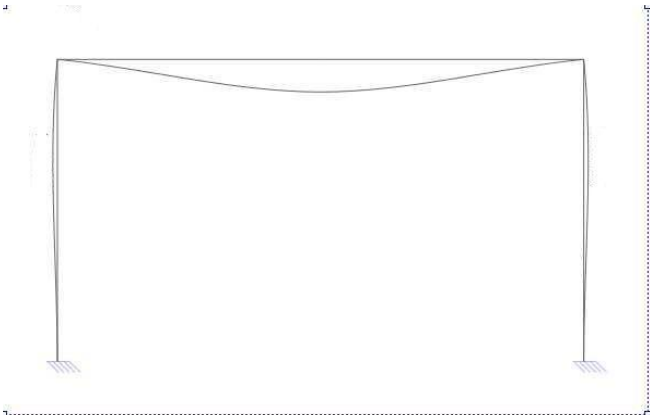


Figure 2: Moment diagram for a frame bridge, with fixed bearings

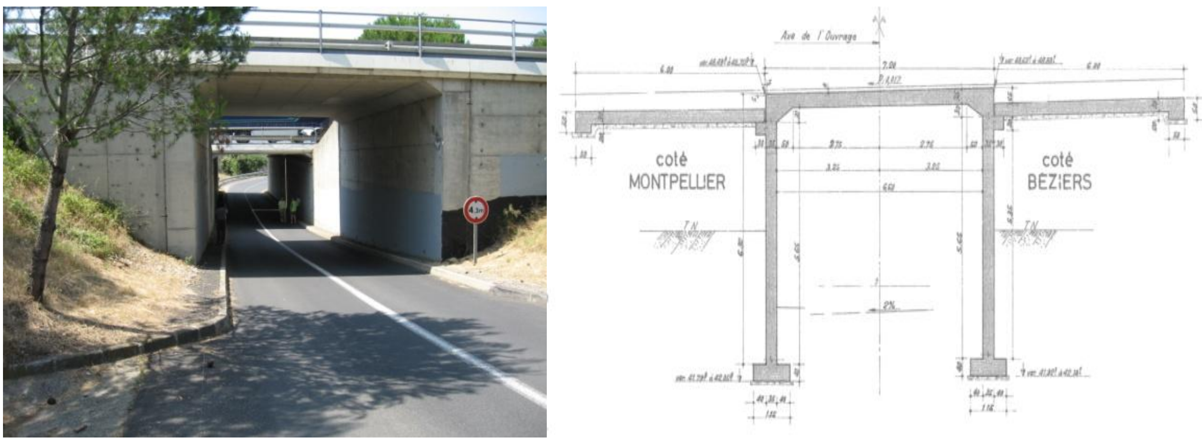
On the slightly skewed frame bridge of Rozay-en-Brie (RN4), the SiWIM accuracy was C(15). This accuracy is just enough for overload screening, but not for direct enforcement.

Fabregues-Montpellier

Bents in reinforced concrete are very frequent bridges on French roads. A simple bent is composed of a bridge sleeper fixed on the abutments, which lies on a spread footing or deep foundations.

The SiWIM experiment was conducted on a bent bridge at Fabregues, with hinges at the bearings, on the A9 motorway south of Montpellier (Figure 3). This bridge behaves very similarly to a frame bridge (Figure 2), but the rotations at the bearings are greater. The test was carried out on 2 consecutive days, in test conditions (I) and (R2), as described in Section 2.1 for Nogent.

The accuracy was in class D+(20) for the whole sample, but 3 trucks were doubtful with possible confusion between similar trucks, and without these outliers the accuracy became B(10) (Table 3). The statistics of the relative errors in % are given in Table 3, where n is the number of tested items, m is the mean of the unknown (GVW, weight of axle groups, etc), and s is its standard deviation..



(a) Bridge **(b) Sketch of the structure**

Figure 3 – B-WIM on a bent bridge of the A9 motorway near Montpellier

Table 3 - B-WIM accuracy on the bridge of Fabregues (A9) near Montpellier

Conditions I/R2	GVW	Axle groups	Single axles	Axles in groups	Global
Whole sample	n = 94 m = 2.61 s = 6.91 C(15)	n = 91 m = 3.77 s = 9.59 D+(20)	n = 188 m = 1.21 s = 6.74 B(10)	n = 273 m = 4.06 s = 12.26 D+(20)	D+(20)
Sample without 3 outliers	n = 91 m = 2.06 s = 4.35 B(10)	n = 88 m = 3.23 s = 5.28 B(10)	n = 182 m = 0.64 s = 4.99 B+(7)	n = 265 m = 3.51 s = 9.29 B(10)	B(10)

The above results show that reinforced concrete frame and bent concrete bridges are suitable for B-WIM, and therefore are appropriate locations for overload screening on highways and motorways. They are generally easy to access and to instrument (deck underside), without traffic disturbance, and multiple presence events are rare on such short span bridges. However, these structures are not of great interest for bridge monitoring.

2.2 Orthotropic Steel Bridges

Steel orthotropic decks are used for long span bridges because of their light weight. For example, there is the cable suspended Golden Gate bridge in San Francisco since 1985, when the corroded concrete deck was replaced by an orthotropic deck with a weight reduction of 11,160 tons, or cable stayed bridges such as Saint-Nazaire, Normandie and Millau in France. This type of bridge is also common for moveable structures, such as in the Netherlands over canals and in harbors. The first instrumented orthotropic deck in France for B-WIM was the Autreville viaduct on the A31 motorway in eastern France (Figure 4), between Metz and Nancy (Dempsey et al., 1999). It is a two girder bridge, with three spans of 60-90-60 m.

Autreville viaduct

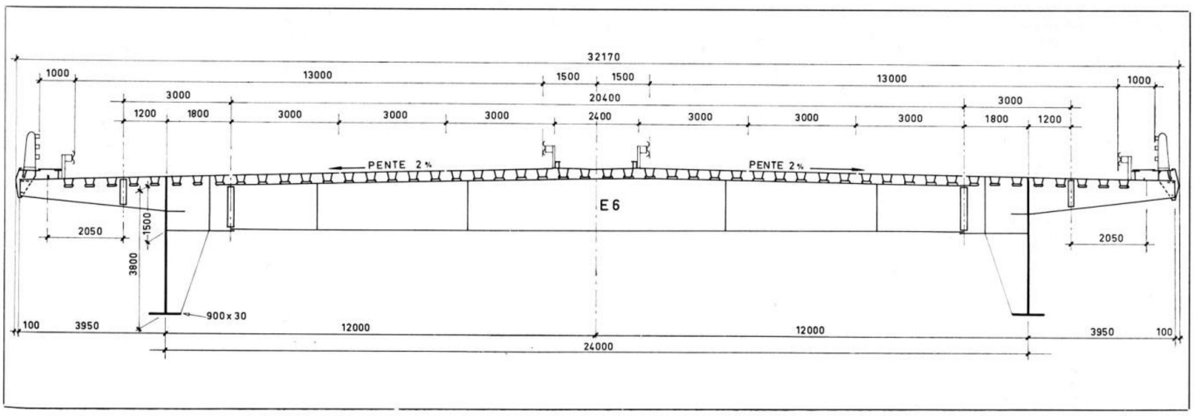


Figure 4 – Cross section of the Autreville viaduct

Strain gauges were attached to the bottom of the 13 longitudinal stiffeners under the two traffic lanes of the north-south directions, at mid-span between two cross beams at 4.2 m. separation. Therefore, the longitudinal bending moment influence lines are rather short (e.g. approximately 12 m if the two adjacent spans are considered - for other spans the signal vanishes quickly), which means that multiple presence events are mostly not an issue. Moreover, the short spacing between the two stiffeners (0.60 m) makes it possible to detect the lateral position of the wheels. However, such structures need a 2-D model and a suitable algorithm to correctly weigh the trucks, as shown in Table 4 and by (Schmidt et al., 2012) and

(Ieng et al., 2012). In 2008 the SiWIM was installed on the Autreville viaduct, but instead of strain gauges, it uses longer transducers developed by Cestel for concrete bridges, which were glued under the stiffeners at the same location as the former strain gauges. However, the glue was not strong enough and is not the right method to fix such sensors. Thus the signals were noisy and the results unusable. A new mounting technique was developed for the viaduct of Millau.

Table 4 - B-WIM accuracy on the Autreville viaduct in 1997-98 (A31)

Conditions I/R2	GVW	Axle groups	Single axles	Global
1-D bridge model	n = 44 m = 1.12 s = 7.61 C(15)	n = 44 m = -0.50 s = 10.12 D+(20)	n = 89 m = 3.79 s = 10.10 C(15)	D+(20)
2-D bridge model	n = 28 m = 0.55 s = 5.55 C(15)	n = 27 m = 0.17 s = 8.22 C(15)	n = 55 m = 0.79 s = 8.95 C(15)	C(15)

Millau viaduct

In 2009 and 2010 the SiWIM was tested on the cable stayed viaduct of Millau (Figures 5), which crosses the Tarn valley in southern France, 270 m above the bottom of the valley. The whole viaduct length is 2,460 m, with 7 spans of 340 m. The 32 m in width deck is a box orthotropic deck made of S355 and S460 steel plates (Figure 6), and carries two traffic lanes and one emergency lane in each direction of the A75 motorway (Clermont-Ferrand to Bezier and Montpellier). The 7 pier heights vary from 77 m to 245 m, with an additional height of 87 m for the pylons, which carry 11 cable stays on each side.

(a)  (b)

Figure 5 - (a) viaduct of Millau, (b) Instrumented longitudinal stiffenners under the deck inside the box, with extensometers

The results are given in Table 5 for both years. Each year trucks from the traffic stream were weighed over 2 consecutive days, and weighed in the toll area on an approved static scale. Thus, the test conditions are (I) and (R2). In 2010, the sample size was three time larger, because of a well trained staff and good weather conditions. The results of both years are very similar, in class D+(20). In 2010, one truck was considered as an outlier from a statistical point of view, with respective overweighing by 43% and 55% on the gross weight and tridem axles. That is due to some high dynamics for this empty truck. If this truck is eliminated, the sample size is only reduced to 126, while the accuracy class jumps into C(15). However, between 2009 and 2010, the standard deviation increased for the groups of axles and axles of the group, partly because of 11 tank trucks, which are more difficult to weigh because of the dynamics of the liquid.

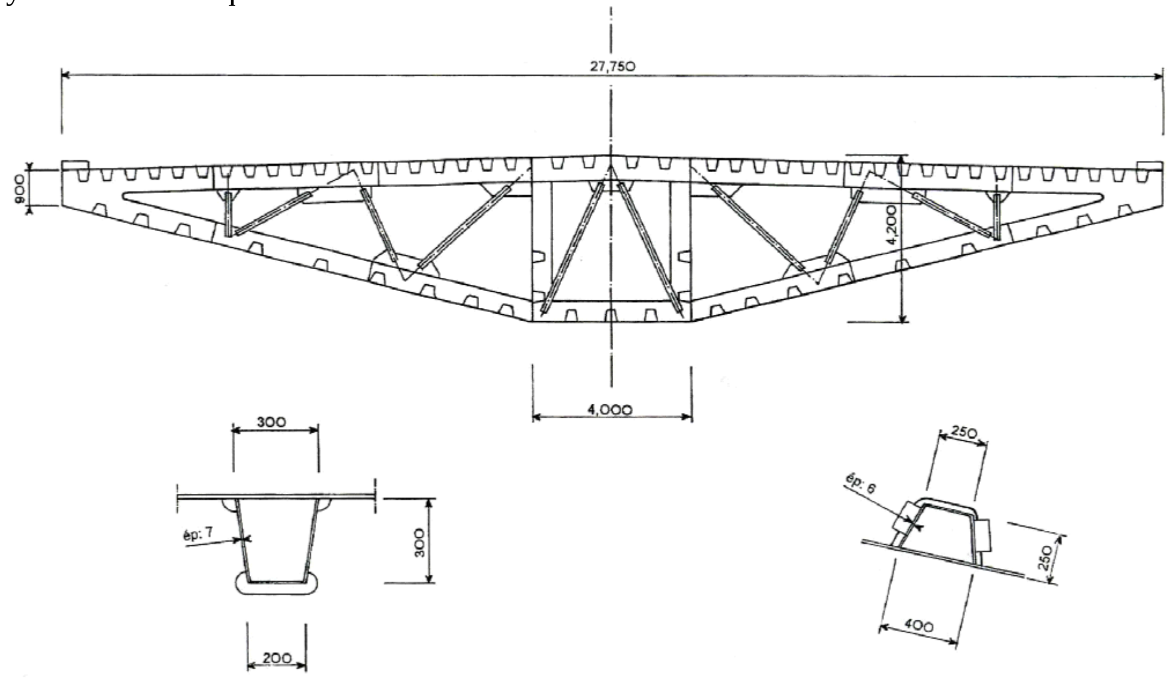


Figure 6 – Cross section of the orthotropic deck of the viaduct of Millau

Table 5 - B-WIM accuracy on Millau viaduct (A75) in 2009-2010, conditions I/R2

Year	GVW	Axle groups	Single axles	Axles in groups	Global
2009	n = 43 m = -3.24 s = 5.76 C(15)	n = 39 m = -8.01 s = 5.32 C(15)	n = 86 m = 1.09 s = 11.18 D+(20)	n = 115 m = -7.38 s = 10.43 D+(20)	D+(20)
2010	n = 127 m = -2.36 s = 6.67 C(15) *C(15)*	n = 119 m = -6.43 s = 8.44 D+(20) *C(15)*	n = 254 m = 1.14 s = 7.91 C(15) *B(10)*	n = 346 m = -6.47 s = 11.19 D+(20) *C(15)*	D+(20) *C(15)*

N.B.: the last line in italic gives the accuracy classes in 2010 without the outlier.

The accuracy obtained on the orthotropic decks is less (by one class in average) than the accuracy on concrete frame and bent bridges. This orthotropic structures needs a 2-D model (influence surface) and adapted algorithms to process the signals (Ieng et al., 2012), which are not yet built INTO the SiWIM system.

3. Infrastructure Manager Perspectives

The French and European infrastructure networks are aging. Many structures were built quickly after the destruction of World War II, and are reaching a critical state. Conversely, the structures built after 1995, and designed with the Eurocodes, are mostly in good shape (i.e. very rarely in class 3U). Most of them are in Class 2. The class split by period of construction is given in Table 6.

Table 6 - Classification of the structures according to their period of construction

Class	<1850	1850-1900	1901-1950	1951-1975	1976-1995	>1995
1	6.6%	6.3%	7.8%	4.7%	10.3%	24.6%
2	69%	73.2%	62.8%	66.4%	73.8%	63.7%
3	11.6%	7.3%	10.8%	8.3%	3.4%	1.3%
3U	3.5%	3.4%	3.1%	1.8%	0.5%	0.1%

While public funds are decreasing and these structures need maintenance, the repair work must be prioritized. Therefore, load effects, stresses and strains, due to traffic loads in our perspective, and structural behavior assessment is required. B-WIM is a useful tool which can provide vehicle weights and dimensions together with the strains induced in the structures. With such data, reliability and probabilistic methods can be used to calculate probabilities of failure and prioritize and orient repair work, adaptation of legislation on commercial vehicle weight and dimensions, specific regulations of some structures, etc.

4. Conclusion

This paper recalls experiments with B-WIM carried out in France by LCPC and now IFSTTAR, over more than a decade, and their implications on structural behavior and life. It is shown that the current B-WIM system gives good results for overload preselection on frame and bent concrete bridges, and for fatigue of steel bridge monitoring on orthotropic decks, but for this later type of bridges, even if the accuracy may be good enough for preselection, the accuracy may be further improved.

5. Acknowledgment

The authors thank the DGITM of the Ministry of Transport for its support to the WIM programme of IFSTTAR, the Languedoc and Midi-Pyrénées DREALs (JC. Mény & M. Jaury), the company CEVM/Eiffage (F. Dune, S. Gallice and C. Servant), and the contributors to the B-WIM measurements: X. Berdos, G. Burrier, SS. Ieng, F. Romboni, PJ. Vabre.

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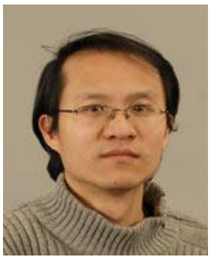
ANALYSIS OF B-WIM SIGNALS ACQUIRED IN MILLAU ORTHOTROPIC VIADUCT USING STATISTICAL CLASSIFICATION

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Abstract

Classical B-WIM systems are generally based on Moses' original work using influence line theory. The systems have been successfully tested on concrete bridges around the world. This paper presents an investigation of the use of B-WIM in the viaduct of Millau, which is a cable-stayed bridge with an orthotropic deck. We first show why the B-WIM system cannot be used directly because axle loads have a very localized influence on the structure. The majority of the signals is not useful and may be rejected instead of being used for the load estimation. The proposed method is based on statistical supervised classification algorithms to classify every signal into three different classes: clean signal, slightly noisy signal and strongly noisy signal classes. In this article only the two first classes should be used to estimate the axle load for some WIM applications such as the enforcement. The approach is tested by using data acquired on the Millau Viaduct in 2009.

Keywords: B-WIM, Orthotropic Deck, Millau Viaduct, Statistical Classification, Weigh-in-Motion, WIM.

Résumé

Les systèmes B-WIM classiques sont généralement fondés sur les travaux de Moses utilisant la notion de la ligne d'influence. Ces systèmes ont été testés avec succès sur les ponts en béton à travers le monde. Ce papier s'intéresse aux travaux de recherche concernant l'utilisation d'un système B-WIM sur le viaduc de Millau qui est un pont à haubans avec une à dalle orthotrope. Nous montrons d'abord qu'un système de B-WIM ne peut pas être utilisé directement sur ce type de pont sans adaptation des algorithmes à cause des effets très localisés des charges sur la structure. La majorité des signaux ne sont pas utilisables pour l'estimation des charges. La méthode proposée est fondée sur les algorithmes de classification statistiques pour identifier les signaux utiles des signaux bruités ou complètement noyés dans du bruit. Seuls les signaux utiles sont pris en compte dans l'estimation des charges des essieux pour certaines applications comme le contrôle-sanction des surcharges. L'algorithme a été testé sur les données recueillies sur le viaduc de Millau en 2009.

Mots-clés: B-WIM, Dalles orthotropes, Viaduc de Millau, Classification statistique, Pesage en marche, WIM.

1. Introduction

The concept of B-WIM was introduced by (Moses 1979). The principle is to calculate axle loads by analyzing measurements from strain sensors installed under the bridge when trucks cross the bridge above the sensors. Moses' algorithm consists of using the influence line of the measured effect to estimate the axle loads, as well as the speed and axle spacing measured separately by road sensors. Until now, most of the B-WIM tests and implementations were conducted on concrete integral bridges and beam bridges (Žnidarič 2005) and many recent improvements has been made for these kinds of bridge (Žnidarič 2010). A few experiments were conducted on steel orthotropic deck bridges (Dempsey 1999, Jacob 2010, Ieng 2010), when the LCPC launched the idea of using this type of bridge for B-WIM. Orthotropic decks are rather flexible structures, highly sensitive to wheel and axle loads which induce bending of the longitudinal stiffeners between two cross beams, spaced by 4 to 4.5 m. These stiffeners are generally spaced by 0.6 m, and thus mainly respond to a single or twin wheel load. Strain gauges or extensometers are fixed on the bottom of each stiffener under the traffic lanes.

Two signal analysis methods are of interest to:

- upgrade the influence line estimation to an influence surface estimation; however the task is not straightforward due to the surface modeling and because of the amount of calculation time that would be needed to solve the problem,
- identify the useful signals and only use these signals for axle load estimation.

The first method is the most complex one. It must first allow calibration of the B-WIM system by providing an accurate enough local influence surface estimation. The second method proposes some modifications of the existing algorithm. Its implementation is faster than the first method. The feasibility of this method has been shown herein. The work presented aims to evaluate the feasibility of this method and tries to answer to the following questions:
- How are the signals insensitive to the axle loads and what is their influence on B-WIM system accuracy?
- How many axle load sensitive signals can be found and used when a truck pass over the instrumented bridge section?
- Which are these signals? Are they provided by the stiffeners located under one or more wheels?

Our approach consists in classifying signals into three classes: the non load-sensitive signals class, the noisy signals class and the useful signals class. The classification is carried out by a Bayesian supervised algorithm and we experimentally show that hyperplanes can separate these classes. Once the signals are classified, we select useful signals and only use them for axle weight estimation. This work is based on the experiments conducted on the Millau Viaduct in 2009 and 2010.

2. Data acquisition

The SiWIM system was installed in Millau Viaduct which is a 2460m cable-stayed multiple span bridge, in the south of France. The system was only used for raw data acquisition in our investigation. The SiWIM algorithms were not used . The deck is a steel orthotropic box, 32m in width and 4.20m height. It carries two lanes and a hard shoulder in each direction. The average daily traffic is approximately 12,000 vehicles including 12 to 15% of trucks (i.e. 1500 trucks per day).

2.1 Sensor installation

The instrumented section is located in the first span, close to the north end of the viaduct, under the slow lane in the south-north direction. The trapezoidal stiffeners are numbered in Figure 1. The sensors (extensometers) are screwed to mounting plates that are glued on the bottom of the stiffeners 2 to 13, at the mid-span between two cross beams as it is shown in figure 1(a). We call the 16 sensors 'A' to 'P'. The sensors 'B' to 'G' and 'J' to 'O' covered the hard shoulder, Lane 1 (slow lane) and part of Lane 2 (fast lane). Four extensometers, namely 'A', 'H', 'I' and 'P' were installed on the stiffeners 4 to 7, 4m upstream. This sensors are used to detect heavy vehicles using the so-called Free of Axle Detector B-WIM system (FAD) that avoids installation of sensors in the pavement (Znidaric2005). The installation scheme is shown in figure 1(b).

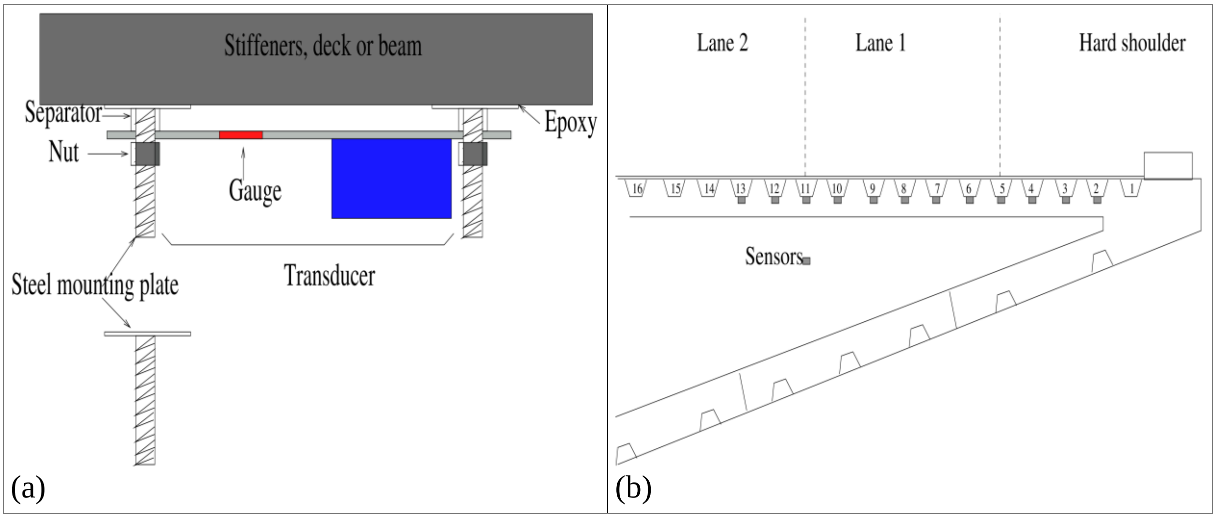


Figure 1– Sensor installation: (a) Sensors are screwed to mounting plates, (b) The sensors cover the hard shoulder, the lane 1 and part of lane 2.

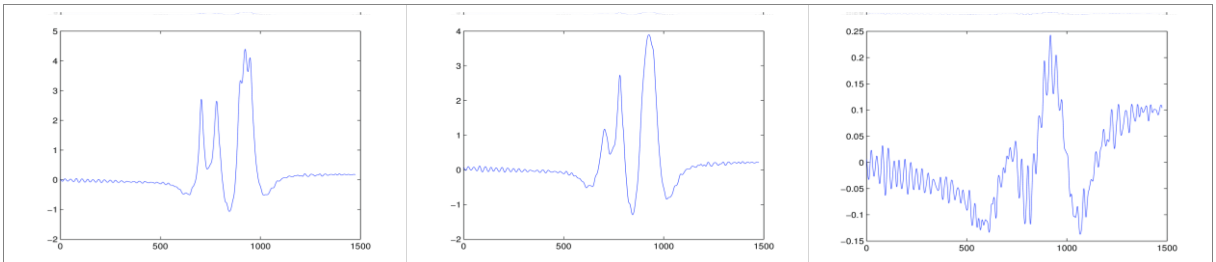
The measuring location was chosen upstream of the expansion join in order to avoid dynamic effects due to the expansion join. The SiWIM system was installed inside a box, well protected against rain and wind. However, communication means were important because the B-WIM system operator cannot see the vehicle on the bridge.

Only the vehicles passing on the Lane 1 were recorded, where nearly all trucks drive.

2.2 Data description

Data were acquired each time a truck passed on Lane 1. Sixteen signals provided by 16 sensors were saved and axle loads were estimated simultaneously. The accuracy of the system has been estimated as presented in (Jacob 2009). The worst accuracy is the single axle load which is classified as D+(20), for the other criteria (Gross weight, Group of axle and axle of group), the accuracies were C(15). A first fast observation of the raw signal provides an explanation of the low accuracy of the B-WIM system.

The effects of the loads are local, sensitive to the wheel transverse location, and the current algorithms do not take into account the transverse location. The axle loads are not estimated as accurately as required by the enforcement. Some noisy or unreliable signals should be removed from the load calculation process, because some sensors do not respond to the axle load but only to deck vibration, if they are too far from the wheel paths. Some other sensors only partially respond to the axle loads. In the Figure 2, three signals are displayed. They are acquired by the sensors 'L', 'M' and 'O', induced by the same vehicle. Thus, the sensors are quite close to each other. Despite of this, we can notice that the signals from sensors 'L' and 'M' are different: peaks corresponding to the tridem have disappeared in the signal of sensor 'M'. Moreover, comparing the signals from sensors 'L' and 'M', it is obvious that the peaks of the two first axles are also not similar. In the first signal, the two peaks have similar intensities but in the second signal, the first peak is abnormally low implying a very light axle compared to the second one.



Sensor 'L' | Sensor 'M' | Sensor 'O'

Figure 2–Three signals acquired at the same time are sorted and shown here: The most useful signal was provided by the sensor 'L', the sensor 'M' (near the 'L') provided a less influenced signal and the unreliable signal was provided by the sensor 'O' (zoomed 40 times).

Our first investigation was to classify the signals into three classes: the clean signal class, the slightly noisy signal class, and the strongly noisy signal class. For a more detailed classification, one should use more classes. Statistical classification algorithms can be applied to classify automatically each signal. We were interested in the well-known Bayesian classifier described in the next section.

3. Signal classification approach

Classification can be carried out using different kind of signal features that are characteristics of the trucks and their loads. We can also see a set of features as a 'signature' of the passing truck. If there is not a unique signature of the truck, we must select the most representative. One approach uses the well-known Principal Components Analysis (PCA) as it was proposed in (Ieng 2007) for the inductive loop applications. The most obvious signature is the raw signature acquired by the sensors. However, raw signals are noisy and contain too much data. A classifier using the raw signal will not be robust to the noise. The solution is to extract a set of a few features that are really representative of trucks.

3.1 Signature extraction

The features that are representative of a truck can be, for instance: the axle number, the axle spacings, the load of each axle. However, other features can be used. To extract the signature of a truck, two methods are tested:

1. the signal skeleton that provides the axle number, the axle spacings and the load distribution among the axles,

2. the number of peaks histogram that provides information on the the axle number, the load distribution among the axles, and the comparison of the axle load intensity.

For both methods, the basic operation is to note the intersection of the raw signal with horizontal line (constant value of the signal). Figure 3 displays two signal skeletons that are drawn with stars. It is interesting to notice the positions of the bifurcations and the number of axles. The second method shown in the diagram consists of counting how many occurrences of a given number of intersection of a horizontal straight line with the signal. The histogram corresponding to the useful signal has a very structured shape and on the contrary, the histogram corresponding to the unreliable signal seems to be more chaotic and bigger (Figure 4). Only a few interesting values are extracted from these two kinds of diagram.

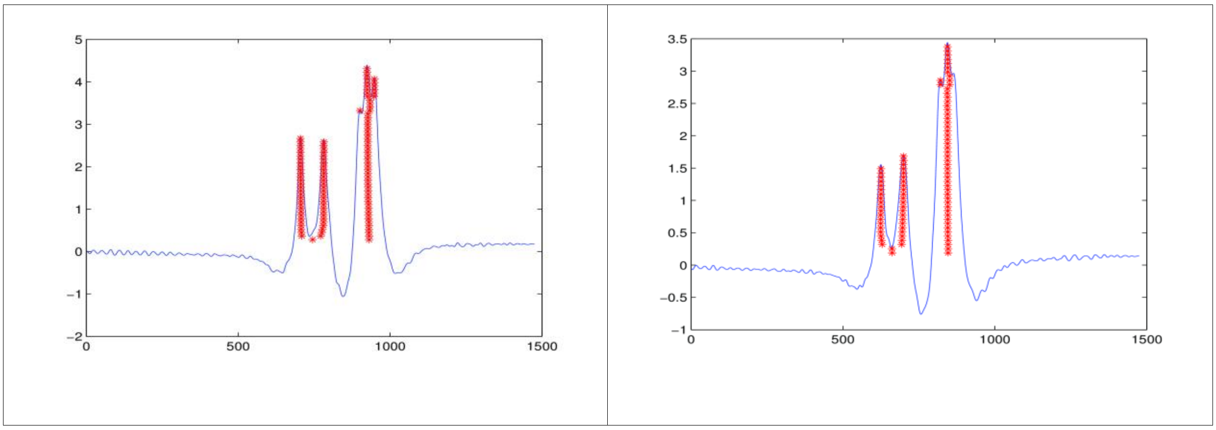


Figure 3–The signal skeletons provide a simple description of the signal shapes: peaks number, the peak length, bifurcation location and also the evenness of the shape.

3.2 Classification algorithm

The classification algorithms use the signatures as input and, together with a supervised learning procedure, they are able to separate the signature space into as many members as the class number. One classical classifier uses Bayesian theory(Ieng 2007). The learning process consists in using a 'learning' set of signatures to estimate the probability law for the signature which is assumed to be random. In many applications, the Gaussian assumption is suitable. For this application, we assume that the probability law is Gaussian and the parameters we need to learn are the mean *m* and the covariance matrix *P*. Once these parameters are learnt, we can derived the separating curve using a discriminant function (Ieng 2007):

$$g(x)=\frac{-1}{2}(X-m)^T \sum^{-1}(X-m)+\ln(P(C)) \quad (1)$$

where *X* is the signature vector and C is random variable corresponding to a given class.

The separating curve is $g(x)=0$. Following the sign of the discriminant function, the classifier would be able to classify signature for two given classes. For more than two classes, it is possible to iterate the classification using every couple of classes.

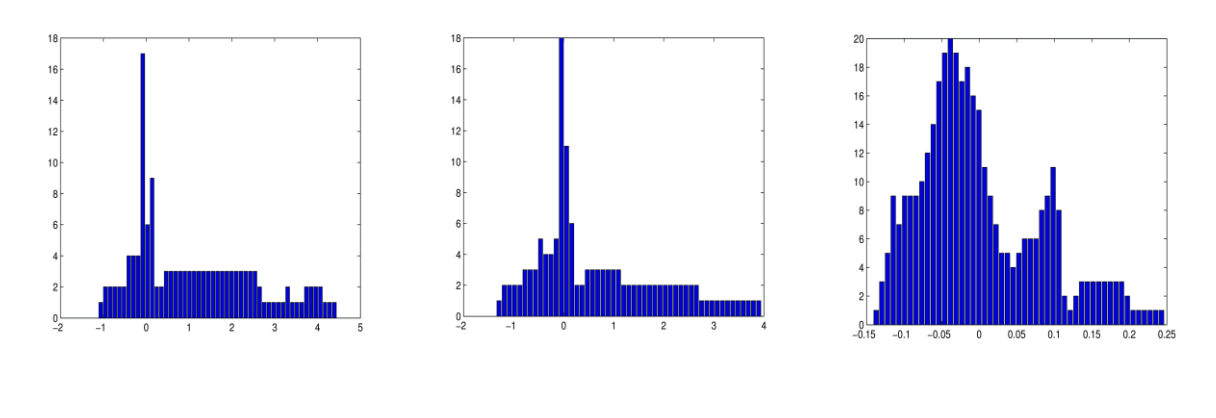


Figure 4–Three histograms derived from the signals shown in figure 2. Notice that the histogram corresponding to the unreliable signal is bigger.

3.3 Results

For signal selection in the B-WIM application, a classification map was built for the five-axle trucks (Figure 5). The class separating curves being known, new signals can be classified in real time by positioning the signature in this map. We can build a map for any kind of truck. In Figure 5, we can notice that the separation curves are actually hyperplanes. In that case, data are said to be linearly separable (Cristianini et al. 2000). Three classes are visible in Figure 5. At the left-hand side of the map, data are in the strongly noisy signal class and at the right-hand side of the map, data are in the clean signal class. The centre of the map represents the slightly noisy data class.

4. Applications of the classification algorithm

The output of the classification can be exploited to derive some interesting information on the vehicle location or the proportion of each signature class. One can also predict if a truck should be weighed or not.

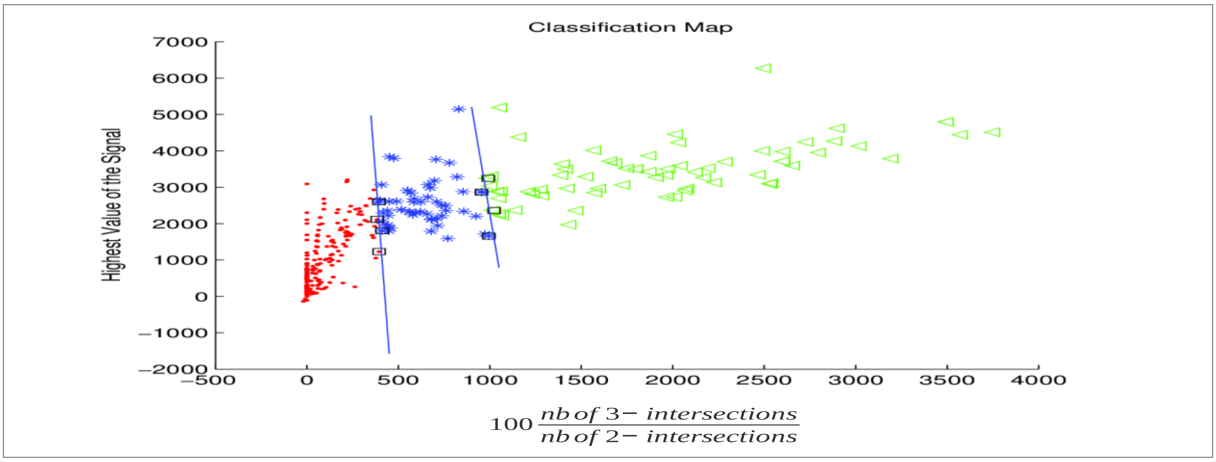


Figure 5–Classification Map that contents three classes. At the left-hand side, are strongly noisy signatures, in the centre, are the slightly noisy signatures and at the right-hand side are the noisy signatures.

The vehicle's transverse position influences the sensors considerably: only sensors that are very close to the wheels provide a clean or slightly noisy signal. The other signals are mainly perturbed by the structure's vibration. Thus, it seems to be obvious that only a few signals are perfectly useful to define our classes. Depending on the WIM application, the needed accuracy of the axle load estimation can be high or low. For the enforcement, one needs very high accuracy. Thus, one should detect the clean and the slightly noisy signals for the axle load estimation. The clean signal rate and the slightly noisy signal rate, together, can be used as a 'signal quality' indicator. Our assumption is confirmed by the proportion of signals for each class as shown in Table 1 for most of the trucks passing over the bridge. We have more clean signals (up to 32%) when the vehicles are very loaded (40 tons or more). In that case the number of slightly noisy signals decreased and the strongly noisy signal rate is almost invariant. It is appropriate not to use every signal for the axle load estimation and only select some interesting signals. This solution is motivated by the fact that 62% of the signals are strongly noisy.

Table 1 – The proportion of the signal of each class when a vehicle is passing

Clean signals	Slightly noisy signals	Strongly noisy signals
21%	17%	62%

Another use of the classification is to make a fast selection of the trucks to be weighed. The criteria is the number of clean signals. If only one clean signal or less is available, the confidence of the estimation is low. The axle load estimation would be reliable when there is at least one clean signal for each side of the vehicle (right-hand and left-hand side). The more numerous are the clean signals, the more reliable will be the axle estimation. By examining the classification map (Figure 5), a truck should be weighed if there are many signals classified in the right-hand side part of the map. On the contrary, if all the signals are classified into the strongly noisy class, the truck should not be weighed. As illustration, the data acquired in Millau Viaduct in 2009 were analyzed and signals were classified. Tables 2 and 3 provide the accuracy classification. The standard deviation decreases and the accuracy class for Single Axles is C(15). However, five trucks are not weighed because the signals are not reliable enough to be used for axle load estimation.

Table 2– Accuracy without using the classification map

	Gross Weight	Single Axle	Axle of Group	Group of Axle
number	43	86	115	39
Error mean(%)	-3.24	1.09	-7.93	-8.01
Stand. Dev. (%)	5.76	11.18	9.46	5.32
Class	C(15)	D+(20)	C(15)	C(15)

Table 3– Accuracy using the classification map

	Gross Weight	Single Axle	Axle of Group	Group of Axle
number	38	76	100	34
Error mean(%)	-3.5	0.13	-7.71	-7.73
Stand. Dev.(%)	5.2	8.84	9,00	4.78
Class	C(15)	C(15)	C(15)	C(15)

5. Conclusions

The classical B-WIM system is now a mature technology when it is used in concrete integral bridges. However, there is very little experimentation on steel orthotropic deck bridges and the efficiency of the system on such a kind of bridge is unknown. Experimentation carried out in the past provides encouraging but still low accuracies. In this paper, each signal is examined and we noticed that the majority of signals is not influenced by the axle load. For each vehicle, only 21% of the signals are useful and up to 62% signals are unreliable. This condition explains why the accuracy of the system is D+(20) at the Millau viaduct.
We proposed to identify signals that are classified in clean signal and slightly noisy signal classes before deciding whether the axle load estimation will be performed. Our approach is based on statistical classification methods and a numerical classification map is built. This map is split into three parts corresponding to the three classes of the signal. However, for a more effective result one should use more than three classes. Our work is aimed at study of the feasibility of the presented procedure. Every signal can be classified and plotted in this map and the useful signals are gathered together. When the number of useful signals is high enough, the axle load estimation will more likely be accurate, otherwise we should have less confidence on it. Following the needs of the WIM application, it would be wise to weigh the truck when the quality of the signal set is good enough if high accuracies are necessary.

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BRIDGE WEIGH-IN-MOTION BY STRAIN MEASUREMENT OF TRANSVERSE STIFFENERS



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Abstract
For constructing a good maintenance scheme of an existing bridge, it is essential to know the truck loads acting upon it. As many bridges age rapidly and the economy is troubled in Japan, one of the greatest needs for bridge maintenance is for the development of an economical yet practically acceptable WIM technique.
One method of WIM is BWIM, which is based on the deformation of a bridge. While the mainstay of the conventional BWIM is the strain of the main girder, extra measurements such as the strains of transverse stiffeners are required for supplemental information. In the present study, an effort is made to conduct BWIM only by the strains of transverse stiffeners. The study concludes that if the transverse stiffeners are carefully chosen, it is indeed possible to estimate truck loads with good accuracy using only the strains of transverse stiffeners. It is a BWIM based on the integration method with transverse stiffeners and is therefore called BWIM-IT. The proposed method is simple yet economical, reducing the cost significantly.
Keywords: Bridge-Weigh-In-Motion, Integration Method, Transverse Stiffener, 3-D FEA.

Résumé
Pour élaborer un plan de maintenance pour un pont existant, il est important de connaitre les charges de poids lourds s'exerçant sur celui-ci. Comme beaucoup de ponts vieillissent rapidement et que la situation économique au Japon est morose, une des plus grandes attentes pour assurer le maintien des ouvrages d'art existants est la mise au point d'un système de pesage en marche économique, mais fiable.
Une méthode pour réaliser ceci est le pesage par pont instrumenté, qui est basé sur les déformations du pont. Mais si le fonctionnement usuel du B-WIM repose sur les déformations de la structure principale du pont, des mesures supplémentaires telles les contraintes des poutres transversales, sont nécessaires. Dans ce papier, l'objectif est de réaliser le principe mais en utilisant seulement les contraintes des poutres transversales. C'est la méthode de pesage par pont instrumenté basée sur la méthode d'intégration avec des poutres transversales, elle est donc appelée BWIM-IT. La méthode proposée est simple mais efficace, réduisant les coûts de manière non négligeable.
Mots-clés: Pesage par pont instrumenté, méthode d'intégration, poutre transversale, modèle éléments finis en 3 dimensions.

1. Introduction

The information on actual truck weights on highways is essential to determine structural and maintenance requirements for the highways. Because of this, techniques that weigh trucks in motion without disturbing traffic flow have attracted many highway engineers and researchers. Those techniques are called collectively weigh-in-motion (WIM).

One of the WIM techniques is based on the deformation of a bridge and is called bridge-weigh-in-motion (BWIM). The technique was first explored by Moses (1979). Because of its lower cost than conventional pavement scales, much attention has been drawn to BWIM in Japanese bridge engineering community (Matsui & El-Hkim 1989, Ojio et al. 2001, Miki et al. 1987, 2001, Ishio et al 2002).

The authors have also conducted BWIM since 2002 (Yamaguchi et al. 2004). It was related to a project of investigating actual truck weights in National Highway 201, Japan. A problem encountered in this project was that a two-span continuous bridge with skew was the only bridge available to the project while a short, simply-supported steel bridge with no skew is ideal for BWIM. Therefore, a careful preliminary field test with trucks of known weights was conducted, having shown that even this type of bridge could be used for BWIM. The method for this BWIM is based on that employed in Miki et al. (1987, 2001). The estimate of truck weight is carried out by measuring the strains of main girders. But those strains are insufficient to conduct BWIM. Supplemental information such as truck velocity is required and needs be acquired by monitoring the strains of transverse stiffeners.

A good portion of a stock of bridges in Japan was constructed in the 1960s and the 1970s, which was the high-economic-growth period of Japan. This indicates that many bridges in Japan are aging rapidly; as a result, more bridge accidents are reported in recent years. Yet the current economic situation in Japan does not allow bridge owners to allocate enough budget to maintenance work. Especially, small cities and towns have trouble conducting sufficient maintenance work, as not only are their budgets very limited but many of them have no in-house engineers. Note that many small cities and towns own quite a few bridges vital to local activities. Therefore, it is crucial and critical to develop maintenance methods that even those small cities and towns can afford.

The objective of the present study is to explore the possibility to apply BWIM solely by using the strains of transverse stiffeners, which could lower the cost of BWIM considerably since the required measurements and the data manipulation are significantly reduced. It is BWIM based on the integration method with transverse stiffeners and is therefore called BWIM-IT. While more sophisticated WIM techniques are available in recent years (for example, Sivakumar 2007, Mini-Symposia 2010), the present research seek an economical WIM and tries to establish BWIM-IT to this end.

2. BWIM-IT

BWIM-IT employs the BWIM technique presented in Ojio et al. (2001). It involves the integration of the time-history response of strain and was originally associated with the strains of stringers. Herein it is associated with the strains of transverse stiffeners instead. Supplemental information such as truck velocity (which can be obtained in the same way as that of Yamaguchi et al.(2004) through the strains of transverse stiffeners) is needed with this BWIM as well. The basic idea of BWIM-IT is explained herein.

When a truck with n axles runs over a bridge, the strain at the point of interest $g(x)$ can be given generally as follows:

$$g(x) = \sum_{k=1}^{n} W_k \cdot f(x - L_k) \tag{1}$$

where x = position of the first axle; W_k = weight of the k-th axle; $f(x)$ = function of an influence line; and L_k = distance between the first axle and the k-th axle. In BWIM-IT, the following integration is carried out:

$$A = \int_{-\infty}^{\infty} g(x)dx = \sum_{k=1}^{n} W_k \cdot \int_{-\infty}^{\infty} f(x)dx = W \cdot \int_{-\infty}^{\infty} f(x)dx \tag{2}$$

where W = gross weight of the truck. The above integration corresponds to the area A surrounded by the x-axis and $g(x)$ in the x-$g(x)$ graph, which is called the influence area in the present study. Equation (2) indicates that the area A is proportional to the gross weight of the truck. Hence, if the influence area A_c due to a truck of known weight W_c is available, the weight of a truck W can be evaluated from the corresponding influence area A as follows:

$$W = \frac{A}{A_c} \cdot W_c \tag{3}$$

Strains are usually obtained as a time-history response. Therefore, when a truck runs with constant velocity V, the influence area A can be computed alternatively as

$$A = V \int_{-\infty}^{\infty} r(t)dt \tag{4}$$

where $r(t)$ is the time-history response of the strain.

The truck velocity is obtained by measuring the strains of two transverse stiffeners in each traffic lane. To that end, the identification of the strain responses due to the same truck is required. This is done by using the auto-correlation function.

3. Field Test and Result of BWIM-IT

The bridge used in this project on National Highway 201 is Sasaguri Bridge, which actually consists of two parallel bridges, the up-lane bridge and the down-lane bridge. The up-lane bridge is about 70 m long while the down-lane bridge is about 80 m long. Otherwise, they are very similar to each other. Both are a two-span continuous plate-girder bridge with five main girders. The plan is presented in Figure 1. The solid lines and the dotted lines in the direction perpendicular to the bridge axis indicate cross girders and cross frames, respectively. Each bridge has a side walk: it is located above the G5 girder in the up-lane bridge while it is above

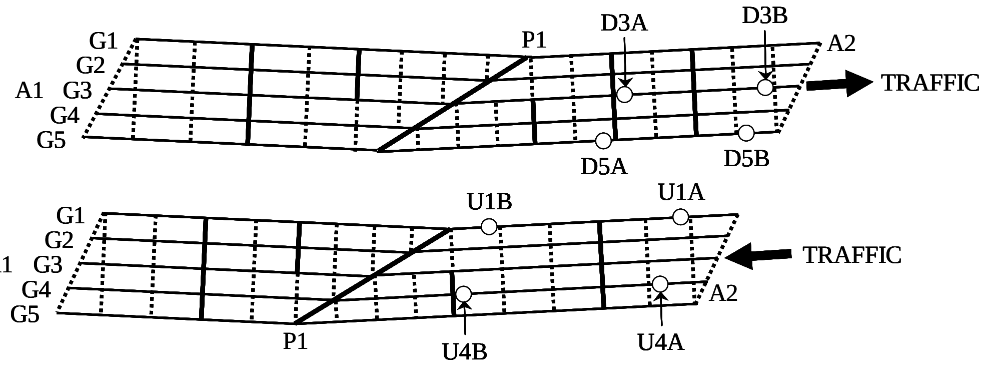
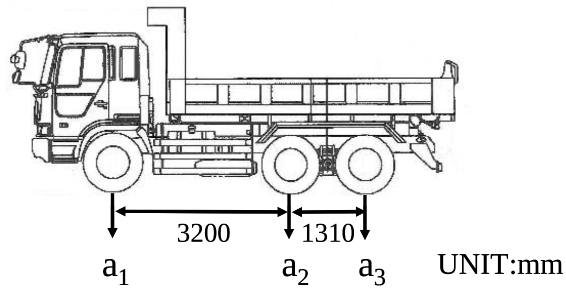


Figure 1 – Sasaguri Bridge (top: down-lane bridge; bottom: up-lane bridge)



	Axle weight			Gross weight
	a_1	a_2	a_3	
Truck A	50.4	73.7	74.5	198.6
Truck B	50.7	70.6	74.9	196.2
Truck C	43.6	51.3	56.7	151.6

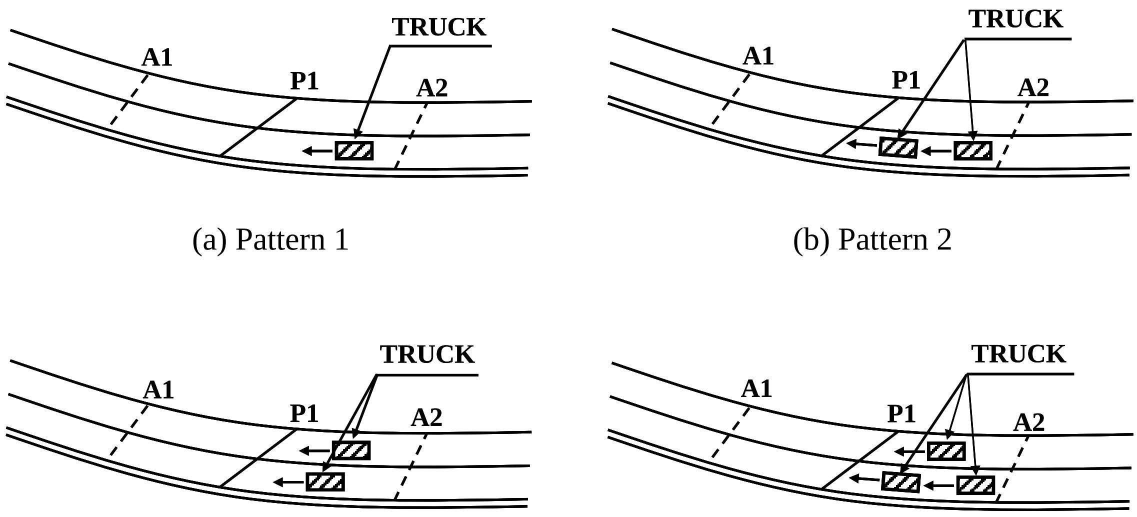
Figure 2 – Trucks for preliminary filed test

the G1 girder in the down-lane bridge. The bridges cross a river and the pier is inclined severely to the bridge axis, making the bridges quite skewed. While the axes of the girders are composed of line segments, the bridge decks and thus the traffic lanes are curved, so that the distances between running trucks and the girders vary along the bridge axis. The pavement condition as to smoothness was found good in both bridges at the time of the project.

At the initial stage of the project, the accuracy of BWIM was the major concern, since Sasaguri Bridge is by no means ideal for BWIM. Therefore, a preliminary field test was carefully conducted, in which the strains of the transverse stiffeners were measured for obtaining supplemental information. Three trucks of known weights were used in this test. The strains of the transverse stiffeners recorded in the test are utilized in the present study to explore the validity of BWIM-IT using the strains of transverse stiffeners.

The circles in Figure 1 show the locations of the transverse stiffeners whose strains were measured in the preliminary filed test. There are two measured transverse stiffeners in each lane for evaluating truck velocity. To avoid the effect of impact loading, the estimation of truck weight in the present study is based on those strains measured away from the expansion joints at the ends of the bridges: specifically, the strains measured at U1B, U4B, D3A and D5A are used. To assess the effect of dynamic response, several truck velocities were tested, revealing no significant difference in the measured strains.

The preliminary field test was conducted in May, 2002. Using three calibration trucks (Figure 2), the following four traffic patterns were considered in the preliminary field test:



(a) Pattern 1 (b) Pattern 2

(c) Pattern 3 (d) Pattern 4

Figure 3 – Traffic patterns in preliminary field test

Table 1 - Average percentage error of BWIM-IT

	Pattern 1	Pattern 2	Pattern 3	Pattern 4
Up-lane bridge	1.8 (2.7)	3.9 (8.3)	3.4 (7.6)	7.7 (11.9)
Down-lane bridge	1.6 (2.7)	6.6 (16.3)	37.0 (68.0)	34.7 (69.8)

( ): Maximum error

Pattern 1: Only one truck runs
Pattern 2: Two trucks run in the same lanes
Pattern 3: Two trucks run side by side
Pattern 4: Two trucks run in the same lane while the other runs in the other lane

Figure 3 illustrates the four patterns. Within each pattern, various combinations of trucks were considered and the test of the same traffic situation was repeated three times. The total number of the truck-running tests was 60. It is noted that in an effort to enhance the reliability of the field test data, traffic was controlled so that no public vehicles would run on the bridge during the truck-running tests.

For the estimation of truck weight, A_C in Equation (3) must be evaluated first. The measurements in Pattern 1 were used to this end. Since multiple truck-running tests were conducted within Pattern 1 and each test yields a unique value of A_C, the average was taken for the value of A_C to be applied for the BWIM-IT. It is however noted that the variation of A_C is quite small.

The results for the error in BWIM-IT are shown in Table 1. BWIM-IT yields satisfactory accuracy in the case of the up-lane bridge as the maximum error is only 11.9%. However, the error is large in the case of the down-lane bridge, especially so in Patterns 3 and 4, with the maximum error being about 70%. The smallest standard deviation is 1.0% of the average in the estimation of the weight of Truck A in Pattern 1 of the up-lane bridge while the largest is 13.8% of the average in the estimation of the weight of Truck B in Pattern 4 of the down-lane

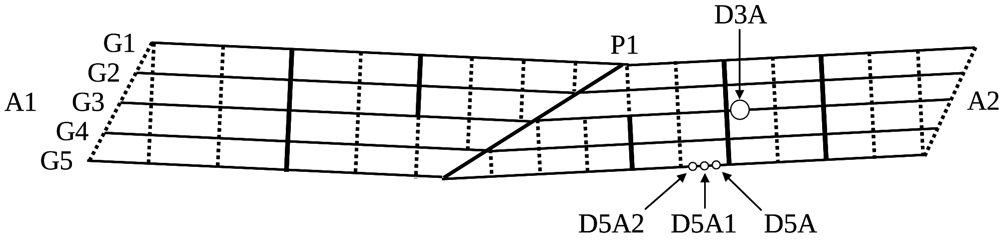


Figure 4 – The locations of three transverse stiffeners

bridge. There is a tendency for the standard deviation to be large where the estimation error is large.

By closely examining the strain measurements, the reason for the low accuracy in the down-lane bridge was identified as the influence of a truck in the adjacent lane on the strains of transverse stiffeners. When a truck runs in the cruising lane of the up-lane bridge, a large strain occurs at U4B while the strain at U1B is very small. On the other hand, when a truck runs in the cruising lane of the down-lane bridge, the strain at D5A is not negligible in comparison with that at D3A. The influence of a truck running in the adjacent lane is not expected in BWIM-IT and is considered a source of the error of BWIM-IT in the down-lane bridge.

4. Improvement of BWIM-IT

To find a way to improve the BWIM-IT with the down-lane bridge, a 3-dimensional finite element analysis (3-D FEA) of the down-lane bridge was conducted. Nastran (MSC.visual Nastran 2003)was used in this analysis.

4.1 Finite Element Model

The 3-D FE model of the down-lane bridge was constructed by applying 4-node shell elements to the main girders, cross beams, transverse stiffeners and horizontal stiffeners, 2-node beam elements to cross frames and lateral bracings, and 8-node solid elements to a concrete slab. As for material properties, Young's modulus and Poisson's ratio are assumed 2.0×10^5 N/mm^2 and 0.3, respectively, for steel, while for concrete they are 1/7 and for steel 0.167, respectively. A moving load is considered to simulate a running truck.

4.2 Strains of Transverse Stiffeners

There are three transverse stiffeners between the adjacent cross members. The three transverse stiffeners could be influenced differently by a truck running in the adjacent lane. In the present FEA, strains in the three transverse stiffeners shown in Figure 4 were evaluated to see the difference.

Figure 5 shows the FEA results. Strains at the three locations are indeed different from each other. The strain at D5A, the closest to the cross beam, is the largest, the strain at D5A2, the closest to the cross frame, is the second largest and the strain at D5A1 is the smallest. Apparently the cross beam and the cross frame play a role of initiating deformation in the transverse stiffeners due to a truck running in the adjacent lane. The smaller the influence of the truck in the adjacent lane, the better the accuracy of BWIM-IT: the strain in the transverse stiffener located in the middle between the adjacent cross members should be used for BWIM-IT.

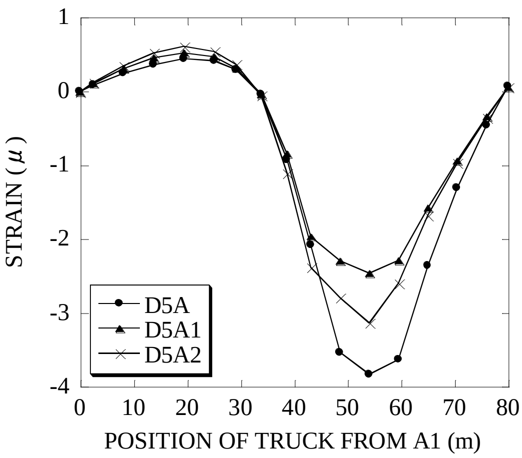


Figure 5 –Strains of three transverse stiffeners in Figure 3

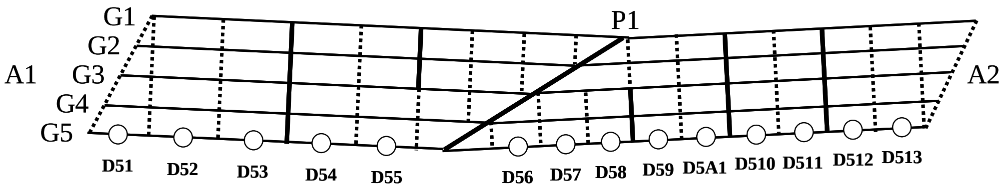


Figure 6 – Transverse stiffeners of interest

This observation further leads to the computation of the strains of the transverse stiffeners at such locations. There are 13 transverse stiffeners and their positions are illustrated in Figure 6. Te 3-D FEA then reveals that the strain at D57 is the smallest, indicating this strain is the best for BWIM-IT.

4.3 Improvement

The accuracy of BWIM-IT with the strain at D57 was investigated using the 3-D FEA. To this end, the 3-D FEA is conducted to simulate Pattern 1 with Truck A in the passing lane first. This is to obtain *Ac* in Equation (3). Pattern 3 with Truck A in the cruising lane and Truck C in the passing lane is then analyzed.

To see the validity of the 3-D FEA, BWIM-IT with the strain at D5A was also carried out. The result of the truck-weight estimation is 210.0 kN. Since the true weight of Truck C is 151.6 kN, the error turns out 38.5%. As Table 1 shows, the average error in the preliminary field test is 37.0%. The validity of the present FEA is thus confirmed.

BWIM-IT with the strain at D57 was then conducted, giving 165.8kN. The error was reduced to 9.4%: by using the strain at D57, the accuracy is thus improved considerably.

5. Concluding Remarks

BWIM-IT with only the strains of transverse stiffeners has been explored. A good result is obtained in one bridge while a large error is observed in the other. The reason behind this was identified as the influence of a truck in the adjacent lane on the strains of transverse stiffeners. A 3-D FEA was then conducted, revealing that this influence varies from transverse stiffener to transverse stiffener. The selection of a transverse stiffener to be used for BWIM-IT is therefore important. Further investigation of the 3-D FE simulation demonstrates that the proper selection of transverse stiffeners could make BWIM-IT with the strains of transverse stiffeners valid in practice.

6. Acknowledgments

The present research was assisted by Mr. Yoshihisa Takaki, a graduate student of Kyushu Institute of Technology, which is gratefully acknowledged.

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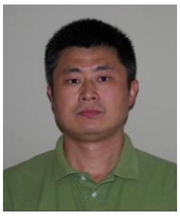
FIELD VERIFICATION OF A FILTERED MEASURED MOMENT STRAIN APPROACH TO THE BRIDGE WEIGH-IN-MOTION ALGORITHM



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Abstract
Most of the commercially available Bridge Weigh-in-Motion (B-WIM) systems are based on an algorithm developed by Moses (1979). The performance of this method is generally acceptable for estimating Gross Vehicle Weight, but can be unsatisfactory for estimating single axle loads. The new approach described in this paper filters the strain signal corresponding to the truck dynamic loads, boundary conditions and vibration etc, among others. Moses' algorithm is then applied to the filtered parts of the strain signals. The new approach is tested on a United States Interstate Highway 78 bridge structure in Alabama with a system called SiWIM. It is shown to result in a substantial improvement in accuracy. The results also provided a better understanding of the complicated effects of Highway Bridge.
Keywords: Bridge, Influence line, Moments Strain, Weigh-in-Motion, WIM, Wheel Axle Loads.

Résumé
La plupart des systèmes de pesage par pont instrumenté (B-WIM) disponibles sur le marché sont basés sur un algorithme développé par Moses (1979). La performance de cette méthode est généralement excellente pour l'estimation du poids total en charge du véhicule, mais peut être insatisfaisante pour l'estimation des charges sur un essieu simple. La nouvelle approche décrite dans ce papier filtre le signal de contraintes correspondant aux charges dynamiques de poids lourds, en prenant en compte les conditions aux limites, les vibrations, etc. En effet, l'algorithme de Moïse est encore appliqué, mais sur les parties filtrées des signaux. La nouvelle approche est testée sur une structure de l'Interstate Highway 78 dans l'Alabama avec un système appelé SiWIM. Il est montré qu'il permet d'aboutir à une amélioration substantielle de la précision, et ainsi d'offrir une meilleure compréhension de l'impact environnemental du trafic routier.
Mots-clés: Pont, ligne d'influence, contraintes de flexion, pesage en marche, WIM, charges à l'essieu.

1. Introduction

It is important that an authority charged with the keeping of a region's transport infrastructure have accurate estimates of the characteristics of the traffic fleet that make use of all the components of the infrastructure. This information has many applications, not just concerning planning, design and assessment in the area of transport, but is also of interest in relation to, for instance, the economic and social development of the area. With regard to the bridge stock of this infrastructure, the important characteristics of the traffic fleet are gross weight, axle loads, axle spacing (and wheelbase) and vehicle velocity. Bridge Weigh-in-Motion (BWIM) systems are one method of obtaining this data.

1.1 Weigh-in-Motion

Heavy vehicles can have adverse effects on road surfaces and bridges. Legal limits for loads per axle, Gross Vehicle Weight (GVW) and overload enforcement reduces the number of excessively heavy vehicles on a region's roads. Whether or not enforcement is effective, it is important to get unbiased, reliable data on the traffic fleet for design and assessment purposes. Pavement-based WIM systems and Bridge-based Weigh-in-Motion (B-WIM) pro-vide methods of automatically weighing trucks at full highway speeds, and in the case of Nothing-On-Road (NOR) B-WIM, this can be achieved without even the knowledge of the vehicle drivers.

1.2 Bridge-based Weigh-in-Motion

The concept of using bridges as weighing scales was first proposed by Moses (1979). B - WIM systems consist of strain transducers attached to the soffit of a bridge recording strain at set intervals defined by the scanning frequency of the system (typically 256Hz or 512Hz). Road surface mounted axle detectors, or extra strain transducers attached to the soffit in the case of NOR B-WIM (WAVE 2001) measure the vehicle velocity and axle spacing. An algorithm then uses these strain readings, axle spacing and velocity to infer the static axle loads. A detailed description of the process of inferring the static axle weights follows in section 2.

1.3 Dynamic Increment of Load

The use of a parameter to provide for dynamic amplification of the effect of traffic load is common among design guides and codes. There are many factors contributing to the magnitude of the dynamic load increment associated with a traffic loading event. These include vehicle characteristics (axle spacing, suspension parameters, etc.), vehicle velocity, bridge natural frequencies, boundary conditions and road profile. The Eurocode (2003) applies Dynamic Amplification Factors (DAFs) to traffic load models and AASHTO (1996) defines a Dynamic Load Allowance (DLA) that is applied to the static traffic load. These DAFs or DLAs are necessarily conservative to allow for the large variability in dynamic amplification.

A B-WIM system is particularly well suited to the study and quantification of the dynamic increment of load effect, as it measures directly the total load effect (total = dynamic + static) and can infer the static load effect using the calculated axle weights. There has been much work carried out studying the relationship between the dynamic increment and load effect (Hwang & Nowak 1991, Kirkegaard, Nielsen & Enevoldsen 1997, Heywood, Roberts & Boully 2001, SAMARIS 2006, OBrien et al. 2009).

Any direct measurement of dynamic increment is sensitive to the accuracy of the B-WIM estimate of static axle weights. By improving the accuracy of B-WIM systems, more accurate studies of the dynamic increment of load effect can be conducted.

2. B-WIM Algorithm

2.1 Moses Algorithm

The main advantage of B-WIM systems is that the vehicle is in contact with the apparatus (i.e., the bridge) for periods of the order of one second. B-WIM systems take advantage of this fact by smoothing out the dynamic component, even if there is no active attempt to remove it.

The algorithm developed by Moses in the late seventies remains the basis of modern B-WIM systems. The algorithm is based on the assumption that a moving load will induce strains in a structure proportional to the sum of products of axle weights and corresponding influence line ordinate values. The influence line refers to the point of measurement which is often taken as around mid-span, the point where strains are generally greatest. Recording strains at regular intervals, defined by the scan number, gives a typical number of strain values of the order of hundreds. An error function is defined as the sum of the squares of the differences between theory and measurement:

$$\varphi = \sum_{k=1}^{S} (M_k^m - M_k^{th})^2 \tag{1}$$

where S is the total number of scans; M_k^m = measured bending moment (proportional to strain) in scan k and M_k^{th} = theoretical bending moment in scan k.

The theoretical response used in Equation 1, M_k^{th} is calculated as the sum of products of the individual axle weights and the corresponding influence line ordinates for the location of each axle of the truck at the time of each scan. The influence line used for the calculations has a very significant bearing on the resulting axle weight calculations. For the 1-D theoretical simulations described herein (simulating a simply-supported structure), the influence line is the true influence line used to calculate the static response. Currently commercial system uses the Moses algorithm, so this testing method will be labeled "Algorithm #1" based on commercial equipment results.

2.2 A Filtered Measured Moment Strain Approach

Simulation Model

In reality, the influence line of a simply-supported bridge is not triangular and may lie closer to something between the simply-supported and fixed cases (Žnidariþ & Baumgärtner, 1998). This is due to support joints were not in "ideal" single support, and the actual connection has the ability to transfer the forces and the moments. The bridge is vibrating while the vehicle is moving over the bridge (single supported or continuous span) and in multi-span bridges in particular, each span's vibration has the interacting influence activated by the traffic vehicles. Additionally, the foundation support soil settlements and bridge horizontal movements during vehicle movement are sensitive parameters influencing the vibration related strains. In order to identify the true vibration related strains for each part of bridge, the following effects will be considered:

Loads Effects

Figure 1 shows the normal tire forces including vertical dynamic loads F_v and horizontal tire friction loads F_f when vehicle across the bridge. For the horizontal loads, at traffic status, the tire rolling friction coefficient is about 0.01- 0.015, but at fully brake status, the static friction coefficient is about 0.8. For vertical dynamic loads, the method of Tikhonov regularization (Tikhonov & Arsenin 1977) is employed to provide a bound to the error and smoother solutions to the Moving Force Identification problem (Law et al 2001, Law & Zhu 2000). A simplified model was applied in the paper (as shown in Figure 2), including the interaction of the bridge road roughness and vehicle suspension system, so that the tire response force can be obtained using Equations 4. The Figure 3 shows an example of a simulation results about the identification of the moving simulation force for one pre-weighted axle loads. At the bridge expansion joints, since the road roughness suddenly vary (raised up or drop down), the wheel would jump up or jump down, the activated wheel load to bridge slab would be suddenly increased or decreased with discontinued curve.

For vertical dynamic loads, simulation equations can be represented by Equation 2, 3 and 4 including the interaction with road roughness and vehicle suspension system:

$$U_g(t) = \sum_{i=1}^{n} (U_{go}^i \sin(\omega_i t + \phi_i)) \tag{2}$$

$$F_g(t) = -W + F_K + F_C \tag{3}$$

$$F_g(t) = -W + U_{st} R_d [K \sin(\omega t - \phi) + C\omega \cos(\omega t - \phi)] \tag{4}$$

Where; U_{go} is the displacement amplitude of harmonic ground motion; U_{st} is the wheel displacement; and R_d is the deformation response factor

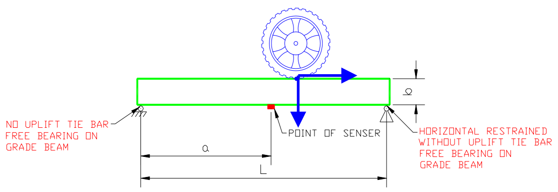

Figure 1 - Horizontal and vertical force model

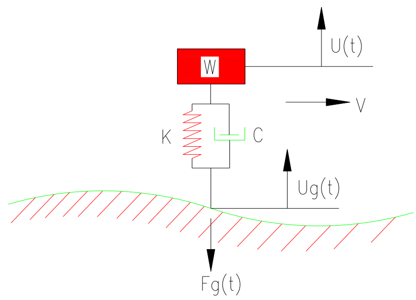

Figure 2 - Vehicle and road interaction model

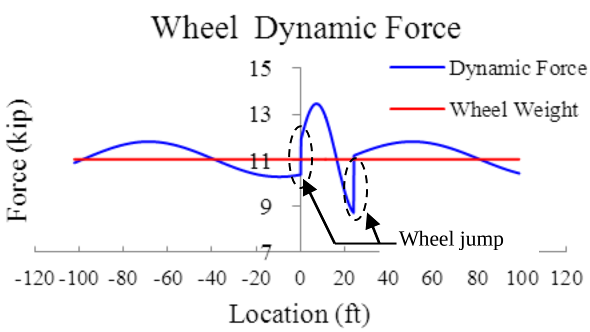

Figure 3 - Wheel loads simulation response for one axle

Boundary Conditions and Joint Rotations Effects

Boundary conditions and joint rotation during vehicle movement can influence the strain results from sensors. As an example, the boundary conditions of a US 78 bridge is shown in Figure 4. As shown in the left of Figure 4, there are no vertical tie and horizontal restraint at the expansion joint location. So the bridge has the potential to move along the horizontal direction; therefore a horizontal spring is provided in the simulation to restrain the horizontal movement and simulate the friction loads. In addition, at the fixed joint (Fig. 4 in the right), the vertical rebar, bridge girder and the support beams work together to restrain the vertical rotation, but this connection cannot fully transfer forces and the related moments. Therefore, these types of joints can be represented as a plastic joint where, it only can transfer partial moments and loads within the maximum limits where, the spring constant of expansion joint can be decided based on rebar and geometries of expansion joint. Moreover, the vertical springs are provided at each vertical support to identify the influence of the moment strain due to the foundation settlements depending on soil property, where, the spring constant of foundation can be decided by soil report and foundation pier types. In Figure 5, the dotted lines show the possible deflected shape of a US-78 bridge along with the horizontal and vertical springs provided to simulate the possible movements in the model.

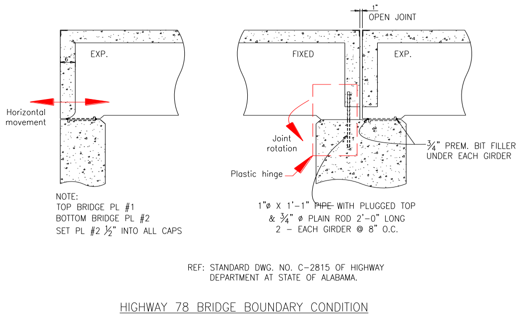

Figure 4. Boundary conditions of a US-78 Bridge

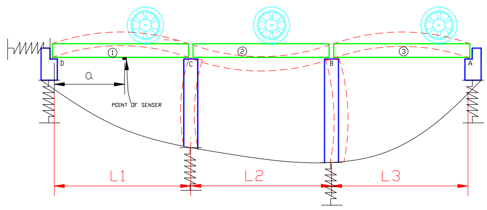

Figure 5. Simulation model for boundary conditions and joint rotation

Vibrations Effects

Once the vehicle tire touch the bridge, the tire force activates the bridge and the bridge will response with free vibration after the vehicle leave the bridge. Usually there are two types of free vibration: bending vibration in longitudinal direction and transverse vibrations at transverse direction. Figure 6 shows the 3D transverse vibration signals from WIM testing on US-78 bridge. It is obvious from the figure that both longitudinal and transverse vibrations would influence the strain sensor readings. At the same time, when the tire arrives at the expansion joints, the gap of expansion joint will cause the tire impacting the bridge in the horizontal direction; and this horizontal sudden impact forces may increase or decrease the free vibration amplitude, and may change the vibration directions.

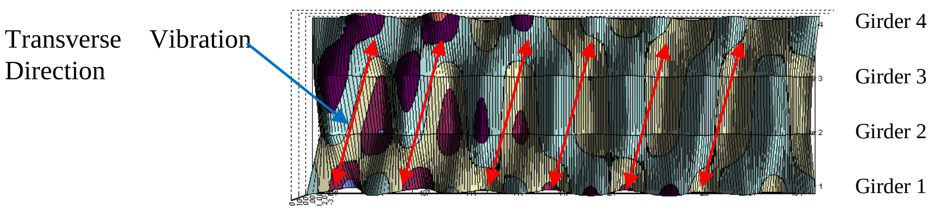

Figure 6 - 3D signal view of transverse Vibration

Elastic stiffness Effects

The bridge load capacity and deflection are controlled by the bridge stiffness. But the bridge stiffness is significantly affected by many factors including boundary conditions, concrete property and the integrity of bridge structure among many others. The bridge elastic stiffness may be predicted using the design information of bridge geometries. But the bridge elastic stiffness changes as bridge ages, and it is also affected by the changing of seasonal temperatures. Therefore, the actual elastic stiffness cannot be obtained based on design information only except by the field testing. Another method could be to obtain the elastic stiffness is by using bridge single degree freedom model, where the bridge bending moment domain frequency can be related to bridge elastic stiffness (Equation 5) with different boundary conditions as follows:

$$(EI)_n = \lambda_n \frac{m f_n^2 L^4}{\pi^2} \tag{5}$$

Where: m is the bridge unit mass; λ_n is the coefficient for different boundary conditions; f_n is the first bending moment domain frequency and L is bridge length.

Time Delay Effects

It takes some time for energy to transfer from wheel activated locations to the testing sensors. The concrete shear wave speed is about 3500 ~ 6000 *ft/s* and the testing sensor frequency is 512 *hz*. For example, if sensor location is 100 *ft* away from the wheel location, it will need a time delay Δt of about 0.019 ~ 0.027 second to transfer the wheel force effect to the sensors, so the sensor delay steps is about 8.7 ~ 14.7. That means the sensor cannot obtain the wheel force response at the same time; also it means the multi-wheel force cannot arrive to the sensors at same time. The dynamic force simulation model would be totally different from the ideal static force situations model. Therefore, the time difference or distance difference needs to be adjusted to fit the moment strains obtained from the sensors.

Summary of Effects

WIM testing moment can be assumed to be equal to the moments from the effects of loads, boundary conditions, vibration, elastic stiffness and time issues. The WIM testing moment can, therefore, be obtained from Equation (6);

$$M^{WIM} = M^{Load} + M^{Vibration} + M^{Stiffness} + M^{Boundary} + M^{Time} \tag{6}$$

Where: M^{WIM} is the moment from WIM testing; M^{Load} is the moment effect from loads; $M^{Vibration}$ is the moment effect from vibration; $M^{Stiffness}$ is the moment effect from elastic stiffness; $M^{Boundary}$ is the moment effect from boundary conditions; M^{Time} is the moment effect from time delay.

Simulation Mathematical Model

Based on the above assumptions, mathematical simulation model as shown in Figure 7 was developed to simulate the WIM testing in a US 78 bridge in Birmingham, Alabama. In this model, boundary conditions, joint rotations, dynamic loads, elastic stiffness, and time delay all are included. Using slope-deflection method, effects from each parameter can be obtained and the related moment at testing location also can be identified from the simulation model.

$$[\theta_A, \theta_B^L, \theta_B^R, \theta_C, \theta_D, \Delta_H, \Delta_A, \Delta_E, \Delta_F, \Delta_D]^T = [X]^{-1}[M] \tag{7}$$

Where: $\theta_A, \theta_B^L, \theta_B^R, \theta_C, \theta_D, \Delta_H, \Delta_A, \Delta_E, \Delta_F, \Delta_D$ are the parameters of simulation model, [X] is stiffness matrix, [M] is the end moments at each related end joint.

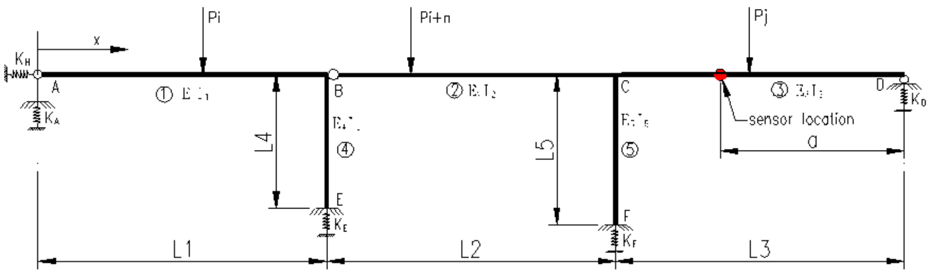

Figure 7 - Mathematical simulation model for highway 78

AASHTO based Model

Following the AAASHTO guide requirements, this bridge was designed as multi-single support beams as shown in Figure 8. For multi-moving loading, the moment at the testing location due to vehicle is identified in Equation 8 based on vehicle velocity *V*, time *t* and number of wheel axle *i* at different location.

$$M_T^{'} = \sum_{i=1}^{n} (P_i(Vt - \sum_{i=0}^{n-1} w_i))\,(1 - \tfrac{a}{L}) \qquad (a \geq P_i(Vt - \sum_{i=0}^{n-1} w_i))$$
$$M_T^{'} = \sum_{i=1}^{n} (P_i a(1 - \tfrac{1}{L}(Vt - \sum_{i=0}^{n-1} w_i)) \qquad (a < P_i(Vt - \sum_{i=0}^{n-1} w_i)) \tag{8}$$

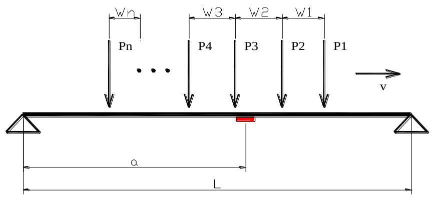

Figure 8 - AASHTO based model

WIM Testing Data Analysis

One of the US-78 highway bridge located at Graysville of Alabama, USA was used to perfrom BWIM testing using SiWIM equipment. This bridge has three single spans with each span of 42 ft. length. The sensors were mounted underneath mid-span of each girder as shown in Figure 9. Based on WIM moment strains, the individual girder moment, $M_{i,j}^{W}$, and the total moment, M_j^{W}, can be identified as shown in equations 9 and 10. Figure 10 shows the field testing the moment, $M_{i,j}^{W}$, at different girders and the sum of the whole bridge response moment, M_j^{W}.

$$M_{i,j}^{W} = \frac{EI\varepsilon_{i,j}}{r} \tag{9}$$

$$M_j^{W} = \frac{EI}{r} \sum_{i=1}^{n} \varepsilon_{i,j} \tag{10}$$

Where: $M_{i,j}^{W}$ is the moment at location *j* for girder *i*; $\varepsilon_{i,j}$ is the moment strain at location *j for girder i*; *EI* is the elastic stiffness; *i* is the number of the girder; *j* is the scan of the location; *n* is the total girder number.

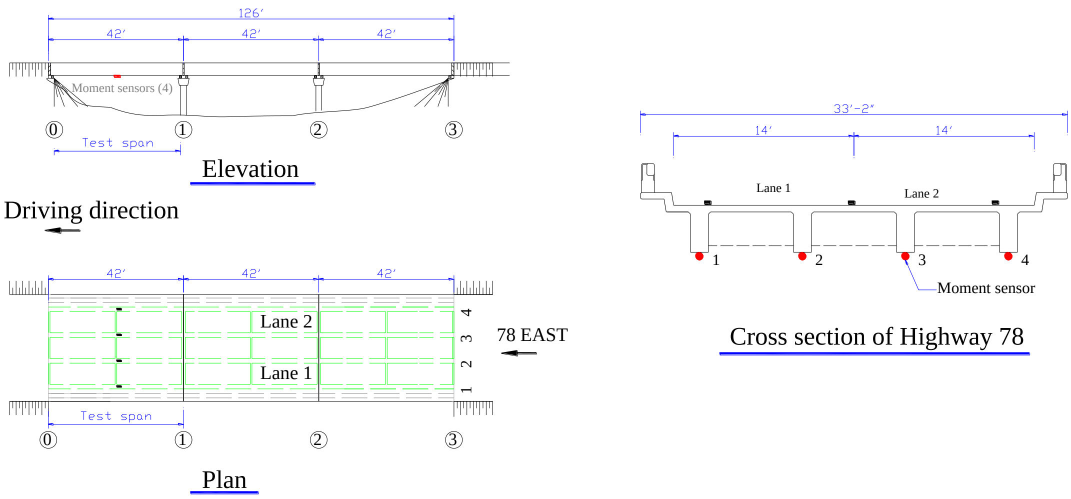

Figure 9 - Bridge WIM testing of Highway 78

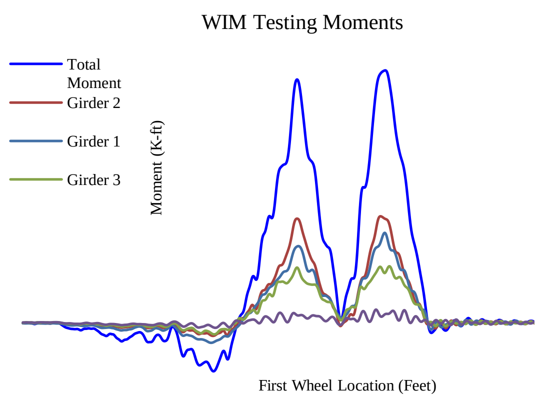

Figure 10 - WIM testing moment Result

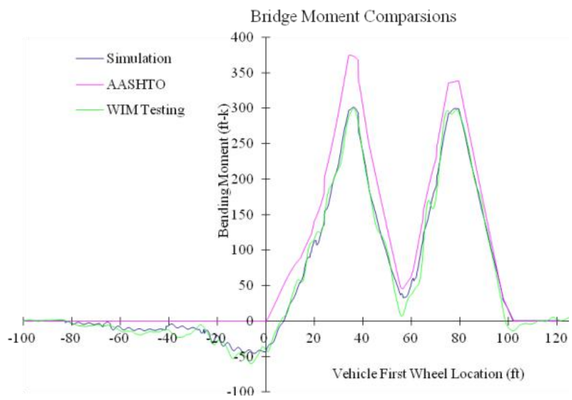

Figure 11 - Bridge moment comparisons

Moment Results Comparisons

Figure 11 presents the comparison among the simulation model moment, the AASHTO based model moment and WIM testing moment. From this figure, it shows that the AASHTO based model moment is significantly different than WIM testing moment, but the simulation model moment is very close to the WIM testing moment. Also, when the vehicle is at span 1 and span 2 (negative coordinates), the moments at testing location in span 3 is negative; which means that the connection joints are not actually ideal simple connections but partial moment connections. The results also confirmed the assumptions made in the simulation model that each part of bridge cannot work individually, and would be interacted by each other for multi-span bridges.

2.3 Filtered Measured Moment Strain Approach

As shown in equation 6, the WIM testing moment include effects from 5 contributing factors identified. So, to obtain the true vertical bending moment due to vehicle load, the WIM testing moment strain will be filtered from all the 5 contributing effects i.e., the moment form dynamic loads, boundary conditions, elastic stiffness, free vibration and time delay. The resulting filtered static moment $M^{Static\text{-}C}$ is then the sum of products of the individual axle weights and corresponding influence line, as shown in Equation 12.

$$M^{Static-C} = M^{WIM} - (M^{Dynamic-Load} + M^{Vibration} + M^{Stiffness} + M^{Boundary} + M^{Time}) \tag{11}$$

$$\{P_i\}\,\{X_i\} = \{M_{i,j}^{static-c}\} \tag{12}$$

Where: P_i is the i^{th} wheel axle load; i is the wheel axle number; X_j is the moment influence line at j^{th} location; j is the scan number of WIM testing.

But the equation 12 is ill conditioned equations, so the conventional matrix method cannot be used to obtain the solution. Therefore, the matrix SVD method is applied. This method would run all equations together to find out the best answers to match all equations. Using this method, the wheel axle load can be obtained. This method is labeled "Algorithm #2", Table 1 summarizes the two alternative B-WIM algorithms.

Table 1 - Description of the algorithms

Algorithm	Description
#1	Moses's Algorithm: Measured total response with exact triangular influence line.
#2	Filtered Method: Measured total response filtered moment strains, applied to related influence line

3. Results

The bridge BIN 7633 of US Highway 78 East in Graysville, Alabama was instrumented and tested using SiWIM BWIM testing equipment. This bridge is a three span simply supported T-beam concrete bridge with each span of 42 ft length having two lanes in each direction, and was built in 1960. Based on WIM testing and simulation model results, the summaries of the weight errors are presented in Table 2. From the table, it should be noted that the Algorithm #1 has as high as 37% and 16% errors for single axle and GVW. But Algorithm #2 predicted both single axle and GVW with significant improvement; the error being less than 5% and 1% for single axle and GVW.

4. Conclusions

A filtered based B-WIM algorithm was developed and verified based on field WIM data. Applying filters to the measured moment strain response by removing the effect resulting from bridge dynamic, multi-span interaction, time delays and boundary conditions true static response as required for WIM weight calibration was obtained. Based on the new approach, much better accurate prediction for the axle weight and GVW was possible.

5. Acknowledgements

The authors gratefully acknowledge funding and support provided by National Science Foundation (NSF) for this research project (CMMI-1100742).

Table 2 - Algorithm Errors of Axle Weight

Run	Vehicle	Type	Single Axle: Axle 1	Axle 2	Axle 3	Axle 4	Axle 5	GVW
1	1	Static Weight (kip)	11.05	15.65	16.1	18.2	18	79
		Simulation Weight (Kip)	10.76	15.91	15.84	18.28	17.71	78.5
		Error (%)-Alg. #1	7.7	12.7	37.7	0.8	23.2	16.7
		Error (%)-Alg. #2	-2.65	1.64	-1.61	0.45	-1.63	-0.6
2	1	Static Weight (kip)	11.05	15.65	16.1	18.2	18	79
		Simulation Weight (Kip)	11.36	16.01	15.57	18.01	18.46	79.4
		Error (%)-Alg. #1	-28.2	12.7	0.6	-18.5	-0.4	-12
		Error (%)-Alg. #2	2.77	2.33	-3.31	-1.06	2.58	0.52
6	2	Static Weight (kip)	10.05	16	15.8	18.3	18.05	78.2
		Simulation Weight (Kip)	10.31	16.25	15.38	18.99	17.58	78.5
		Error (%)-Alg. #1	1.9	-14	5.2	-8.2	12.2	-0.6
		Error (%)-Alg. #2	2.61	1.57	-2.64	3.76	-2.61	0.4
8	2	Static Weight (kip)	10.05	16	15.8	18.3	18.05	78.2
		Simulation Weight (Kip)	10.28	15.78	15.21	18.53	18.97	78.8
		Error (%)-Alg. #1	-1.5	-14.8	4.1	-8.8	11.5	-1.7
		Error (%)-Alg. #2	2.24	-1.36	-3.71	1.22	5.1	0.72

Note: Above Alg. #1 and Alg. #2 indicate the application of the algorithms 1 and 2 described in Table 1.

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STRATEGIES FOR AXLE DETECTION IN BRIDGE WEIGH-IN-MOTION SYSTEMS





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Abstract

To perform effectively, a Bridge Weigh-in-Motion (B-WIM) system requires accurate information on the location and speed of all axles on the bridge. In recent years, axle detection is by sensors under the bridge – so called Free-of-Axle-Detector or Nothing-On-Road (NOR) B-WIM. As axles pass over an axle detecting strain sensor, there is a peak in strain which can be detected by the data acquisition system. This approach works well for some bridges but there are challenges for beam-and-slab bridges where the beams are deep, a common form of construction in Alabama. The slabs in such bridges are therefore generally used for axle detection but the peaks in the slab strains are quite sensitive to the transverse position of the wheels over the beam. This paper describes a study into axle detection which tests alternative strategies for a range of bridge types and spans.

Keywords: Bridge, Weigh-in-Motion, WIM, B-WIM, BWIM, Axle, Detection, FAD, NOR.

Résumé

Pour fonctionner correctement, un système de pesage par pont instrumenté requiert une information correcte en ce qui concerne la position et la vitesse de tous les essieux du véhicule sur le pont. Ces dernières années, la détection d’essieux se réalisait par des capteurs sous chaussée, système qui est appelé pesage par pont instrumenté avec Free-of-Axle-Detector (FAD) ou Nothing-On-Road (NOR). Quand les essieux passent au-dessus d’un capteur de détection d’essieux, on observe un pic de contrainte qui peut être détecté par le système d’acquisition. Cette manière de faire fonctionne correctement pour certains types de ponts mais il reste des problèmes en ce qui concerne les ponts à poutres où les poutres ont une hauteur importante, ce qui est une structure commune en Alabama. Les dalles de ce type de ponts sont alors généralement utilisées pour la détection des essieux, mais les pics des contraintes mesurées dépendent fortement de la position transversale des pneus sur la poutre. Ce papier décrit une étude sur la détection des essieux pour différentes stratégies dépendant du type de ponts et de poutres.

Mots-clefs: Pont, pesage en marche, pesage par pont instrumenté, essieu, détection, FAD, NOR.

1. Introduction

The principle of Bridge Weigh-in-Motion (B-WIM) is to find the axle weights which give a least squares fit between theoretical and measured strains. For this calculation, the system needs accurate information on the location and speed of all axles on the bridge. The original system of Moses included electrical contact switches attached to the road surface. These were subsequently replaced by pressure sensitive air hoses that transmit a pulse of high pressure air when crossed by an axle.

In recent years it has become apparent that any form of axle detector on the road surface raises issues of safety and traffic disruption during installation and maintenance. Znidaric et al (2005) propose Free-of-Axle-Detector or Nothing-On-Road (NOR) B-WIM, where axles are detected using sensors attached to the underside of the bridge, i.e., no part of the system is on the road surface. These have proven to be extremely popular for operational reasons and there are now more than 1000 B-WIM sites, worldwide.

Despite its popularity, NOR B-WIM does raise some issues (Chatterjee et al 2006). The most common strategy is to locate sensors near the quarter points in a simply supported span. As axles pass overhead, there is a peak in strain which can be detected by the data acquisition system which typically operates at a scan rate in excess of 250 Hz. This approach works well for some bridges – short slender spans with a good road surface to minimise vehicle dynamics. However, the problem is more complex for beam-and-slab bridges where the beams are deep, a common form of construction in Alabama. The peak in strain on the underside of such beams is not very sharp and can be confused with other peaks due to, for example, bridge or vehicle vibration. The slabs in such bridges are therefore generally used for axle detection. However, the peaks in the slab strains are quite sensitive to the transverse position of the wheels over the beam. If a wheel passes over the slab between beams, it will generate local bending in the slab. However, if a wheel passes directly over the beam, there may be Vierendeel bending in the slab which can cause little or no direct strain mid-way between beams.

This paper describes one element in the *Next Generation Bridge WIM* project which will be carried out in the United States, Northern Ireland and the Republic of Ireland through 2011-2014. In this study, the issue of axle detection in Bridge WIM systems is addressed. Two approaches are considered:

- Better positioning of direct strain transducers: Complex 3-dimensional Finite Element models will be used to assess axle detection for a range of bridge types and transverse positions of wheels. The range of structural responses are considered and strategies are developed that will detect lighter axles in a greater number of cases.
- A novel shear strain sensor will be assessed to determine the feasibility of using shear as opposed to direct (axial) strain for axle detection. Again, 3-dimensional models will be used to determine the required accuracy of such a sensor and where it may best be placed.

Field trials are planned where axles will be detected by conventional means using low grade piezo sensors. The piezo sensors, located on either side of a test bridge, will be used to assess the effectiveness of alternative axle detection strategies.

2. Bridge Weigh-in-Motion

Bridge WIM is an alternative approach to weighing trucks in motion – an existing bridge is instrumented with strain sensors and these are used to calculate the weights of trucks passing overhead. Bridge WIM has a number of advantages – it is very accurate for gross weight, largely overcoming inaccuracies due to truck bouncing and rocking motions on rough road surfaces. It is also portable and can be moved from one bridge to another at relatively little cost.

A Bridge WIM system traditionally consists of two components: (i) a device which monitors a varying property of the bridge structure, usually longitudinal strain, using strain transducers; (ii) a device which detects the presence of an axle and hence finds the speed and axle spacing of the vehicles crossing the bridge. The passage of a vehicle is usually in the order of seconds which can help to reduce inaccuracies due to high frequency axle hopping motions in vehicles travelling at speed.

The conventional bridge weigh-in-motion (B-WIM) algorithm is credited to Moses (1979). It finds static axle weights by minimizing the sum of squares of differences between measured bridge strains and corresponding theoretical strains. Generally, two axle detectors in each lane were used to provide the times of occurrence of each axle of the vehicle and thus the axle spacing, velocity and vehicle class. In the original Bridge WIM systems, the axle detectors were tape switches or pneumatic hoses attached to the road surface (Figure 1(a)). However, in recent years, these have been replaced by sensors attached to the slab underneath the bridge (Figure 1(b)). This latter approach is the so-called 'Nothing-On-Road' (NOR) or 'Free-of-Axle-Detector' (FAD) Bridge WIM system. It has many advantages of durability and safety as no part of the Bridge WIM system is on the road surface. In the current NOR systems, strain transducers are used to detect bending in the bridge slab as axles pass overhead. Anecdotal evidence is that its success is mixed, i.e., it does not always work for lighter axles.

(a) Surface mounted detectors

(b) NOR axle detectors

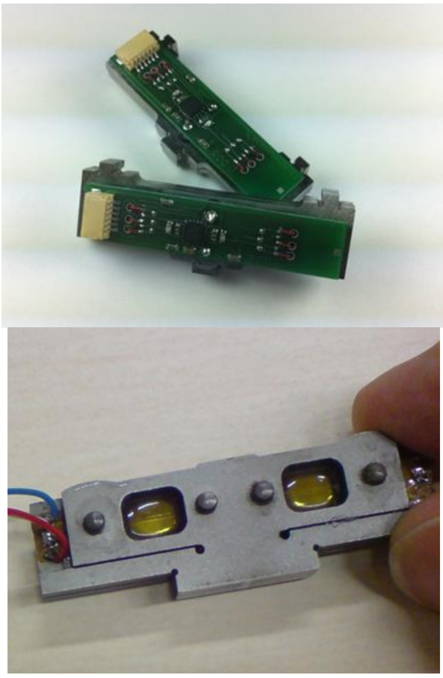
Figure 1 – Axle Detection

3. ROC Shear Strain Sensor

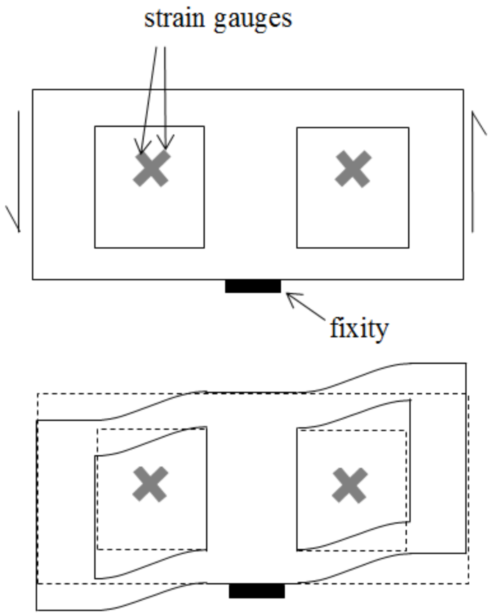
An electrical resistance strain gauge takes advantage of the physical property of electrical resistance and its relationship with the strain of the material. The WIM sensor developed by the ROC company in the European 7^{th} Framework *ASSET* project [1] uses four electrical resistance strain gauges to measure the shear deformation in a small plate – Figure 2. It is designed as a multipurpose measurement system.

In its usual configuration as a WIM sensor, the force is applied at the two corners on top. However, if subjected to a shear force, it will deform as illustrated, i.e., the right hand side will be pushed up and the left side down. The strain gauges are placed in a diagonal arrangement as shown and can therefore measure the angular distortion of the thin plate that makes up the central layer of the sensor.

The purpose of this study is to determine if it is feasible to use the ROC shear strain sensor as an axle detector in a NOR Bridge WIM system, i.e., to determine if there are sudden changes in shear strain as a wheel crosses the bridge. Finite Element modelling is used here to determine if this is the case and to find out where, in the bridge, the changes in shear strain are maximum.



(a) Photographs of sensor



(b) Diagrammatic view of sensor: Original geometry (above) and Deformed geometry (below)

Figure 2 – ROC Shear Strain Sensor

4. Bridge Model

A bridge and loading were selected to numerically test the concept of using the ROC shear strain sensor as an axle detection device. The effectiveness of the system will clearly depend on the geometry of the bridge and the location of the wheels over the main structural elements (over beam or slab). For the purposes of this study, one 'typical' simply supported bridge was selected – Figure 3. A span at the longer end of the range considered suitable for Bridge WIM was chosen, namely 30 m. A beam-and-slab configuration was chosen with the webs simplified as rectangular. A span/depth ratio of 1:20 was selected implying a depth of 1.5 m.

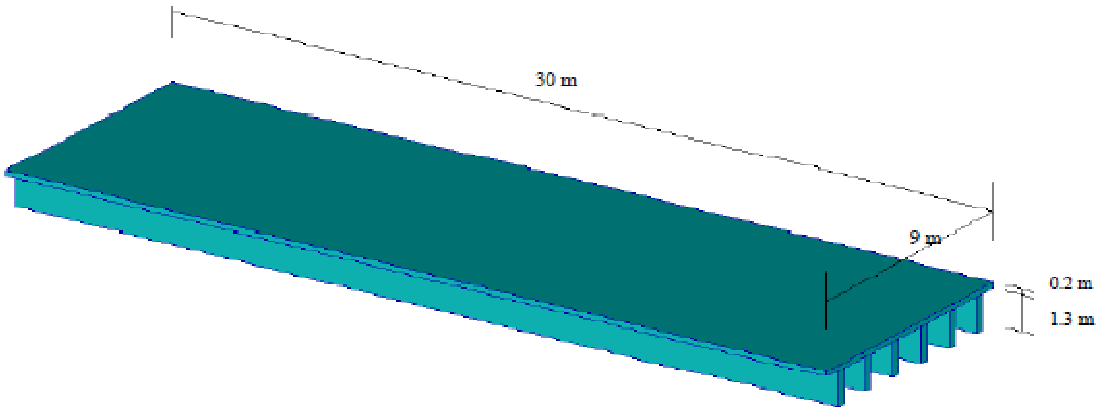


Figure 3 – Dimensions of bridge Finite Element model

The ‘Patran’ software was used for the analysis using 3-dimensional solid ‘brick’ elements. A simplified load case was considered of a knife edge load of magnitude 10 kN/m (900 kN in total) – Figure 4.

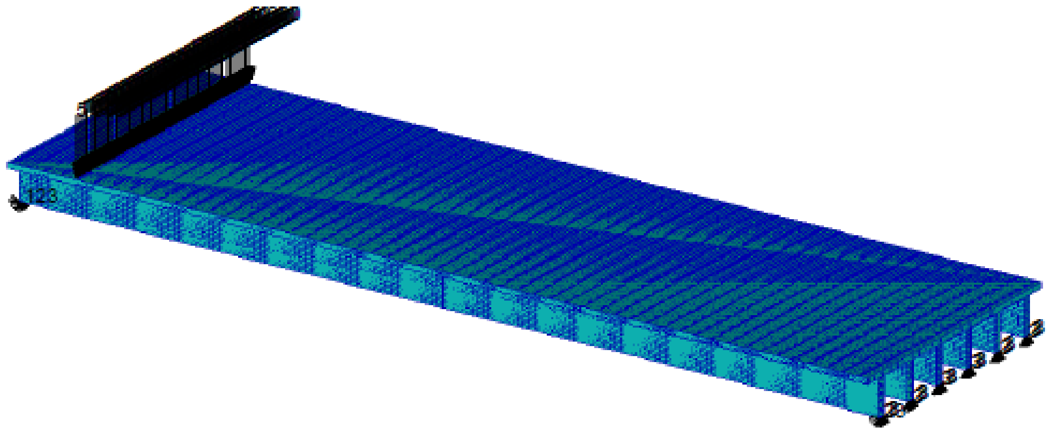


Figure 4 – Bridge loading and supports

The sign convention is illustrated in Figure 5 where X is longitudinal (direction of span), Y is transverse (perpendicular to span) and Z is vertical (out of plane). The shear stresses of interest are:

τ_{xz}: X-face and Z-direction

τ_{yx}, Y-face and X-direction

The former is the usual shear stress considered (for which shear links are usually provided) – it would be expected to vary parabolically with Z and to be a maximum about mid-depth in the web. Significantly, it will change sign as a knife edge load passes over that point, making it a good candidate for an axle detector.

The latter stress, τ_{yx}, is also known as interface shear stress. This is caused by the dispersion of longitudinal axial stresses into the flanges as bending moment increases. Again, it will change sign as a knife edge load passes as the situation changes from one of increasing moment (with X) to one of decreasing moment.

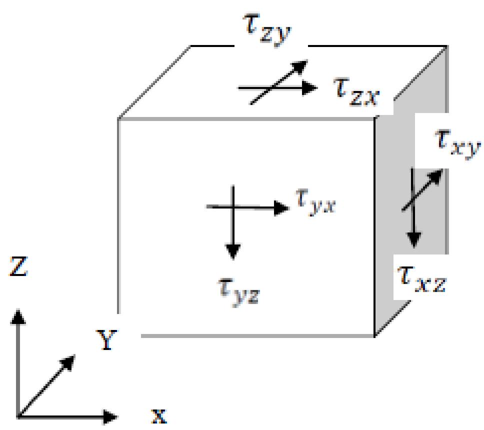
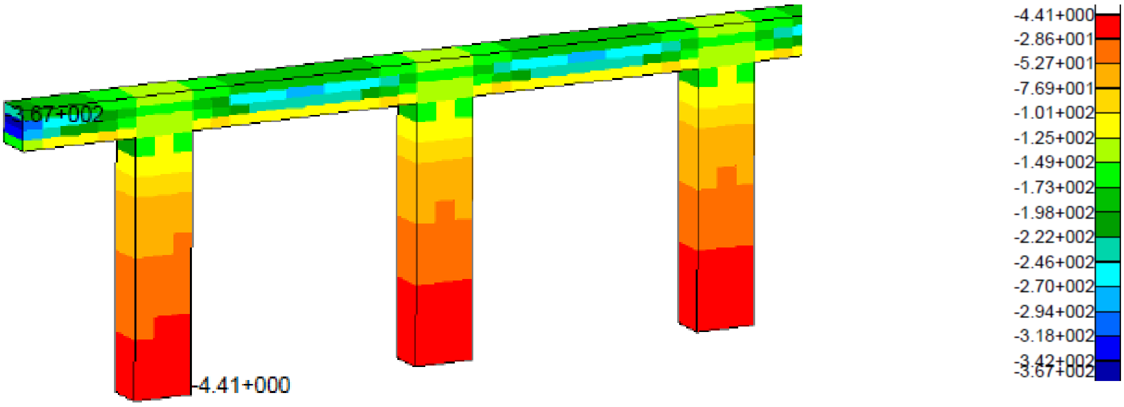


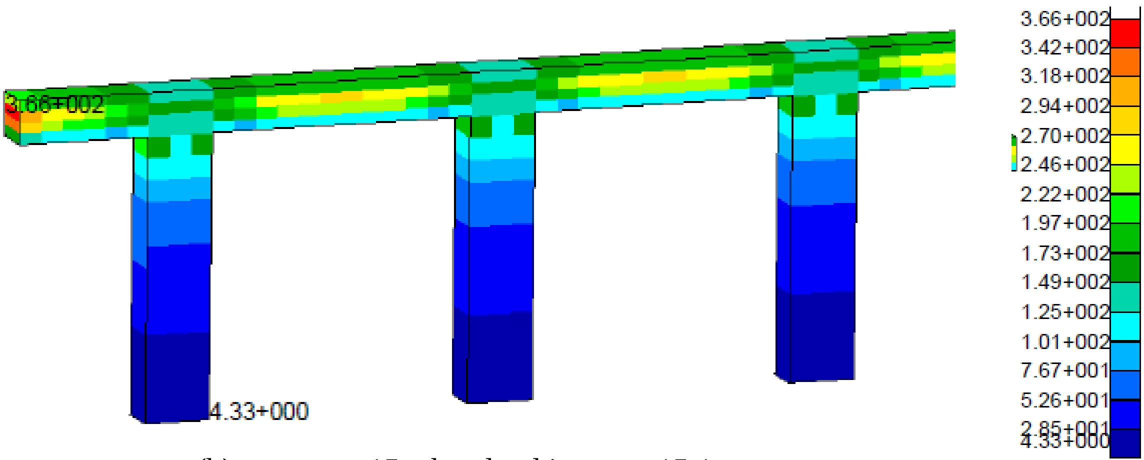
Figure 5 – Shear stresses

5. Preliminary Results

Figure 6(a) shows the distribution of vertical shear stress on the X-face at mid-span (*x* = 15 m) when the knife edge load is just before that point (*x* = 14.9 m). The stress does not vary parabolically with Z as might be expected – this is because of its proximity to the point of application of the load (it is parabolic 1m earlier). There is an extreme stress in the edge cantilever but this could not be easily measured. Apart from this local edge effect, the maximum stress in the web is near the top (where it meets the flange) and it is about 160 kN/m^2.



(a) τ_{xz}, at *x* = 15 when load is at *x* = 14.9

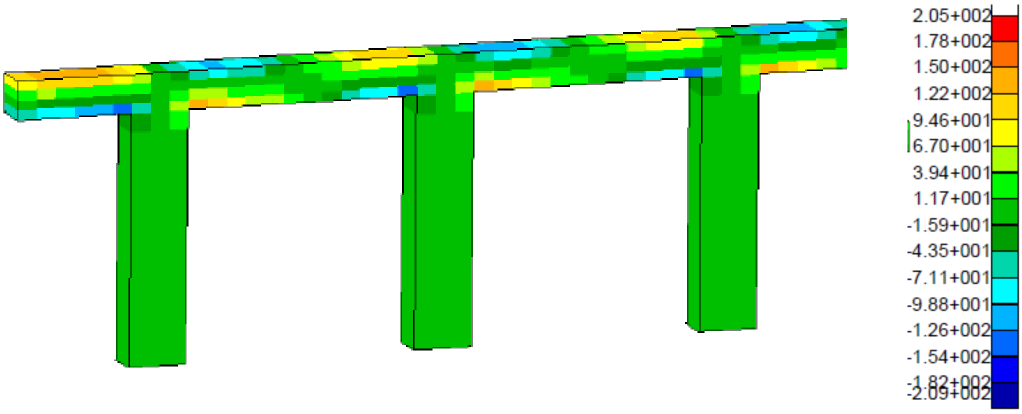


(b) τ_{xz}, at *x* = 15 when load is at *x* = 15.1

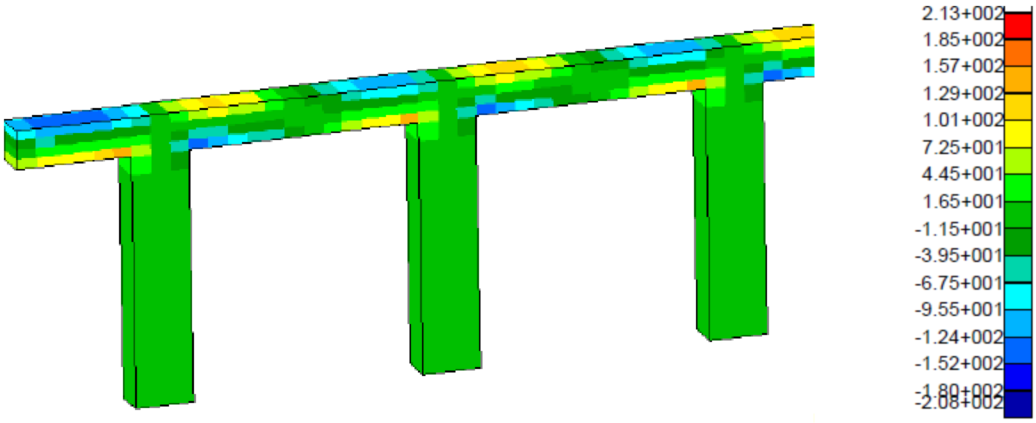
Figure 6 – Vertical shear stress distributions on X-face

Figure 6(b) shows the corresponding distribution at mid-span (*x* = 15 m) when the load has just passed that point (i.e., load at *x* = 15.1 m). This distribution is similar but of opposite sign to that when the load is approaching. Apart from the local minimum at the edge, the minimum in the web is where it meets the slab and is about -160 kN/m^2. It can be concluded that the shear stress changes from 160 to -160 as the 900 kN load passes, a change of 320 kN/m^2.

Figure 7 shows the interface shear stresses just before (Figure 7(a)) and just after (Figure 7(b)) the knife edge load passes. Again, there is a reversal in sign between them. The maximum stress evident in Figure 7(a) is about 180 kN/m^2, occurring in the slab just where it meets the web. This is matched by a stress of about -180 kN/m^2 at the same point, just after the load has passed. The difference is 360 kN/m^2 corresponding to a knife edge load of 900 kN. It would appear that the maximum shears in Figures 6 and 7 correspond to each other, i.e., there is a shear flow of about 170 kN/m^2 that changes from vertical to horizontal at the point where the web meets the flange. This changes sign as the load passes, giving a total change (in both the web and flange stresses) of about 340 kN/m^2.



(a) τ_{xy} (=τ_{yx}) at x = 15 when load is at x = 14.9



(b) τ_{xy} (=τ_{yx}) at x = 15 when load is at x = 15.1

Figure 7 – Interface shear stress distributions on X-face

Shear strain is $^{\tau}/_{G}$, where $G = \frac{E}{2(1+\upsilon)} = \frac{30\times10^6}{2(1+0.15)}$ = 13x10^6 kN/m^2. Hence, the change in shear strain as 900 kN axle passes is (340/13x10^6 =) 26 microstrain. As a 5 kN axle passes (representing a car axle), the expected change in shear strain is 0.14 microstrain. For a sensor that is 50 mm long, this change of 0.14 microstrain corresponds to a deformation of (50x0.14 =) 0.0072 mm.

6. Conclusions and Future Work

If the ROC shear strain sensor can consistently detect a change in shear strain of 0.14 microstrain, then it should be capable of detecting car axles as light as 5 kN in a 30 m span bridge of typical dimensions. Even if it fails this test, a less sensitive sensor could be used for truck axle detection. For example, a sensor 10 times less accurate would still have value as an axle detector in the Bridge WIM industry (as it could detect 50 kN axles).

The preliminary recommendation for the location of the axle detector is at the interface of the web and the flange, as illustrated in Figure 8.

These analyses are part of a preliminary study of the issue of axle detection. From 2011-2014, further Finite Element analysis will be carried out for a range of spans and transverse positions of the vehicle wheel. Field trials are planned for Northern Ireland, using a low-grade piezo WIM sensor to confirm axle detection made on the bridge.

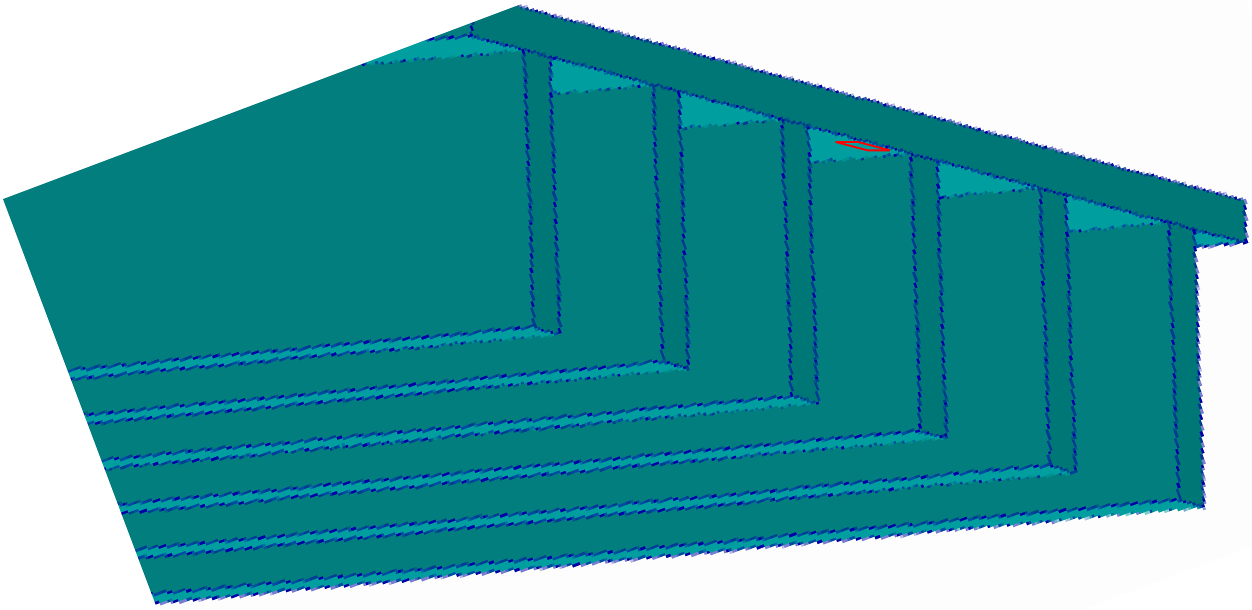


Figure 8 – Recommended sensor location

7. Acknowledgement

The authors acknowledge the financial support of the United States National Science Foundation, Invest Northern Ireland and Science Foundation Ireland for this project. The assistance of Drs. Emma Sheils (Roughan & O'Donovan) and Desmond Robinson (Queens University of Belfast) in developing this research is sincerely appreciated.

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USING STRIPS TO MITIGATE THE MULTIPLE-PRESENCE PROBLEM OF BWIM SYSTEMS

   

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Abstract
Bridge weigh-in-motion systems have for decades exhibited their accuracy and ease of installation. At the same time, one of their disadvantages which affects the accuracy of their results has been their inability to deal with more than one vehicle on the bridge at the same time, particularly if the vehicles meet close to the centre of the bridge span. The linear algorithms that are traditionally used for distributing the global loading effect among the different vehicles can potentially result in considerable errors. While on low-volume roads and on short-span bridges a percentage of such events can be neglected, the potential error increases rapidly on longer bridges and with higher traffic volumes. Because the theoretical solution using 2-dimensional influence surfaces would be difficult to implement, sensor strips were proposed as a compromise that takes into account the transverse position of vehicles on the bridge but keeps the calculation procedure reasonably simple and, above all, does not add complexity to the calibration procedure.
Keywords: Strips, Multiple Presence, Bridge, Weighing, Bridge Weigh-in-Motion, Weigh-in-Motion, WIM.

Résumé
Le pesage par pont instrumenté démontre depuis des décennies son potentiel, tant au niveau de la précision que de la facilité d'installation. Mais en même temps, un de ses grands inconvénients est son incapacité à traiter le cas de multi-présence sur le pont, en particulier si les véhicules se croisent à mi-portée. Les algorithmes traditionnels linéaires peuvent potentiellement mener à d'importantes erreurs, quand on répartit l'effet global de la charge sur divers véhicules. Même si sur des routes peu fréquentés et des travées courtes, ces phénomènes peuvent être négligés, cela n'est plus le cas pour des travées de ponts longues et des routes beaucoup fréquentées. Puisque la solution théorique consistant à utiliser des surfaces d'influence serait difficile à mettre en place, des barreaux sont proposés comme compromis qui prend en compte la position transversale des véhicules sur le pont, mais conserve des calculs raisonnement simples et n'apporte pas de complexification à la procédure de calibration.
Mots-clés: Barreaux, présence multiple, pont, pesage, pesage par pont instrumenté, pesage en marche, WIM.

1. Introduction

Multiple-presence (MP) of heavy vehicles on a bridge is a problem that can drastically reduce the accuracy of bridge Weigh-in-Motion (BWIM) results based on the traditional algorithm (Moses, 1979). In the traditional analysis, the signals from all strain transducers are summed together and the results (axle loads) are calculated from this global response of a bridge caused by all vehicles that are crossing it (WAVE, 2001). While this does not cause difficulties for vehicles following each other, it becomes a problem when two vehicles in adjacent lanes meet close to the centre of the bridge span (Figure 1). Then the basic bridge WIM algorithm has difficulty dividing the global response between the two vehicles. This is due to the definition of the problem (OBrien, Žnidarič, & Ojio, 2008) which is based on a linear model (influence line) and can be solved only when introducing an additional parameter into the mathematical description of the problem: the width of the bridge as the second dimension. Using an influence surface instead of influence lines may in theory almost completely eliminate the MP problem, but the calculations required would be extremely demanding. Furthermore, the procedure to calibrate such a system would be very complex, requiring far too many vehicle runs to be commercially viable. To overcome this situation an alternative approach, only marginally more complex than the basic BWIM methodology, was developed, implemented and verified.

Figure 1 – Multiple presence event on a bridge with two vehicles following each other (left) and driving side-by-side (right).

1.1 Definition of the problem

Typically, a BWIM bridge is instrumented with M strain transducers at appropriate locations, usually at mid-span or where bending moments and strains are the highest (Žnidarič, Lavrič, & Kalin, 2002). The passage of a truck with N axles deforms the bridge and the induced strains are transformed into voltages and read by data acquisition hardware. The entire passage of a truck is represented by $M \times K$ measurements where K is the number of samples needed to record the passage from the moment the first axle starts to exert influence on the bridge to the moment the last axle does not influence the bridge anymore. In the basic BWIM algorithm the measurements at time t_k are summed across sensors:

$$G(t_k) = \sum g_j(t_k) \tag{1}$$

where $g_j(t_k)$ is the measured signal on j^{th} sensor at time t_k (Moses, 1979).

The equation representing the influence of the truck on the bridge at time t_k can be written as:
$F(t_k) = \sum w_i . I. \left(v_i . (t_k - t_i)\right)$

(2)

where the sum is taken across N axles, $i = 1..N$, w_i are the individual axle loads, t_i is the time of passage of i^{th} axle, v_i is the speed of the vehicle to which the i^{th} axle belongs and I(x) is the influence line – the response of the bridge to a passage of a unit load, measured at the sensor location and dependent on the unit load position x. This type of model fits into the category of general linear least squares modeling of data, where the model is a linear combination of the so-called basis functions (Press, Teukolsky, Vetterling, & Flannery, 2007). The functions themselves can be arbitrary; of importance is the linear dependence of the model on the parameters w_i.

A merit function

$$\chi^2(w_1, w_2, \dots, w_N) = \sum\left(G(t_k) - F(t_k)\right)^2 \qquad (3)$$

is defined as a sum over all squares of differences between the measured and the fitted influences. The best-fit values of axle loads are obtained by minimizing the error function by varying the parameters, in this case the axle loads. To obtain the actual axle loads of an arbitrary vehicle, the bridge response is calibrated with multiple passages of a vehicle with known axle loads.

The quality of fit heavily depends upon the distinctiveness of the basis functions, i.e., influence lines for individual axles. For instance, if two axles in neighboring lanes arrive on the sensors at exactly the same time, if the vehicles' speeds are the same, and if the shapes of influence lines are the same for both lanes, it is mathematically impossible to determine weights for each axle. We can only solve for the sum of two weights, whereas the individual weights themselves are indeterminate since there are an infinite number of combinations that give the same sum. Even if the basis functions are not exactly the same, but are merely similar, the solution is very sensitive to the inevitable noise in the signal, where noise can be the result of true random noise, measuring errors, or dynamic components introduced by bridge and vehicle vibration. This is the main source of errors for the MP events when using a traditional bridge WIM algorithm.

The same reasoning is applicable to calculations on a bridge of which the length (and thus influence line) is long compared to the total wheelbase of the passing vehicles. In this case the gross weight can be calculated with a much higher accuracy than the axle loads which, depending on the user requirements, can be illogical and even negative.

1.2 The proposed solution

The most straightforward way to solve the MP problem is to use an influence surface. However, the calculation system then grows in both the number of equations and in complexity and is not solvable using linear methods. An additional difficulty with the use of an influence surface is the need for calibration at different transverse positions of the calibration vehicle. Even a conventional BWIM calibration, which is identical to a calibration procedure of a pavement WIM system, can easily take a half day or more; whereas to calibrate a bridge with an influence surface, multiple runs at many different transverse positions are needed and it could take a few days to calibrate a bridge properly. This clearly is not an acceptable solution for commercial applications.

The proposed *strips* method is an enhancement over the classical Moses method, but does not need extra calibration runs as would the solution applying the influence surface.

The basic principle behind the strips method is that instead of summing signals into one value for each time t_k, the sensors are separated into groups. Signals are then summed within groups of sensors that belong to individual lanes and this extra information is used to increase accuracy. For example, on a two lane bridge instrumented with 16 sensors, the two sums would typically be:

$G_1(t_k) = \sum g_j(t_k)\,; \quad j = 1..8$ and

$G_2(t_k) = \sum g_j(t_k)\,; \quad j = 9..16$ (4)

The reason for such grouping is straightforward: when a vehicle passes over the bridge in lane 1, the signals from sensors mounted underneath this lane will show a higher response than sensors mounted underneath lane 2 and, conversely, a vehicle in lane 2 will provoke a higher response on sensors underneath that lane. Just how much higher is unknown and, in principle, needs to be resolved. This results in a non-linear as opposed to a linear problem. However, the load distribution can be approximated across sensors by averaging load distributions from the random traffic. Use of this information, which describes how the influence of traffic is split between the lanes, can enhance the solvability of the equations using linear methods. The size of the system of equations used to solve for the weights is multiplied by the number of strips.

2. Experimental verification

To demonstrate and verify the strips method, tests and analyses of results were performed on a short slab bridge in Slovenia and on a longer beam bridge in Brazil.

2.1 A 7-m long slab bridge

The first test was performed on a 7-m long slab bridge (CE0122) instrumented with a SiWIM BWIM system on a heavily trafficked road in Slovenia (Figure 2). The traffic on the bridge was running in two lanes in opposite directions. Such short bridges are normally not critical from the MP point of view, as the probability of occurrence of two vehicles on them simultaneously is low. Yet, this bridge did experience a number of MP events even during the calibration runs, three in lane 1 and six in lane 2. This was a high of 36% of all of the runs in the data sample. Despite this high percentage the accuracy according to the COST 323 specifications (COST 323, 2002) was, due to the relatively short span, in a good accuracy class, B(10), in the smoother lane 1 and in a satisfactory class, C(15), in the noticeably less even lane 2 (Table 1).

Implementing strips

Prior to implementing the proposed procedure, the lateral distribution of the measured strains had to be defined. This was done in three stages:

1. the quality of all strain signals from individual transducers must be verified in order to eliminate or compensate for erroneous measurements, which can occur due to inadequate attachment of sensors on concrete structures or due to cracks in the concrete,

2. the contribution of each sensor per lane of traffic is evaluated by averaging the maximum responses of the sensors due to random traffic, and expressed as a percentage of the total strain response of all sensors (Figure 3), and
3. the individual sensors were assigned to the relevant strips; in the example in Figure 3 two strips were defined to describe two lanes of traffic.

Figure 2 – CE0122, a 7-m long skewed slab bridge with calibration truck and strain sensors underneath.

Analysis of results

In the case of bridge CE0122, the calibration vehicle was a three axle rigid truck that was statically weighed using portable static scales. Results of the initial calibration, evaluated in full repeatability and environmental repeatability according to the COST 323 WIM specifications (COST 323, 2002), are presented in Tables 1 and 2. The results exhibit considerable improvement in accuracy: improvement of one accuracy class in lane 1 with 25% of MP events, and improvement of almost 2 accuracy classes (criteria for gross vehicle weight only marginally exceeds threshold for class B+(7)) in lane 2 with 46% of MP events. This demonstrates that using strips can substantially improve the accuracy of bridge WIM results.

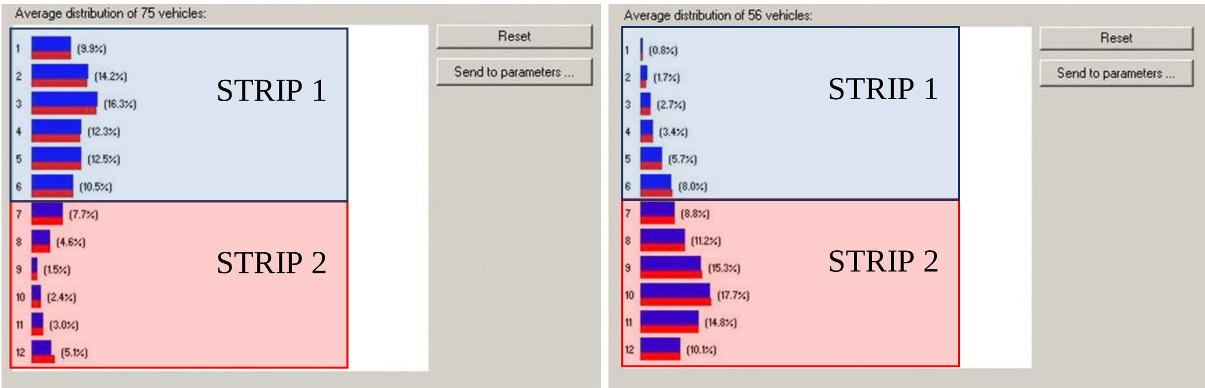

Figure 3 – Lateral distribution and defined strips for lanes 1 (left) and 2 (right) for the CE0122 slab bridge, as selected in the SiWIM software.

Table 1 – Accuracy without applying strips at CE0122 bridge – calibration runs

	Criteria	No.	Ident.	Mean	Std.	π_o	Class	δ	δ_{min}	δ_{crit}	δ_{class}	π	π	Acc.

			(%)	(%)	(%)	(%)		(%)	(%)	(%)		(%)	(%)	class
Lane 1	GVW	12	100%	0,00	2,42	95,9	B(10)	8,0	7,1	8,9	10	95,9	97,8	B(10)
	Group	12	100%	0,00	3,15	95,9	B(10)	10,4	9,3	8,1	10	95,9	97,8	
	Single	12	100%	0,00	3,34	95,9	B(10)	12,0	9,8	8,0	10	95,9	98,7	
Lane 2	GVW	13	100%	0,00	3,69	96,2	C(15)	12,0	10,8	13,5	15	96,2	97,9	C(15)
	Group	13	100%	0,00	4,33	96,2	C(15)	14,4	12,7	12,9	15	96,2	98,1	
	Single	13	100%	0,00	4,81	96,2	C(15)	16,0	14,1	12,0	15	96,2	98,1	

Table 2 - Accuracy after using strips at CE0122 bridge

	Criteria	No.	Ident.	Mean	Std.	π_o	Class	δ	δ_{min}	δ_{crit}	δ_{class}	π	π	Acc. class
			(%)	(%)	(%)	(%)		(%)	(%)	(%)		(%)	(%)	
Lane 1	GVW	12	100%	0,00	1,55	95,9	B+(7)	5,6	4,6	5,7	7	95,9	98,7	B+(7)
	Group	12	100%	0,00	2,51	95,9	B+(7)	8,0	7,4	6,5	7	95,9	97,3	
	Single	12	100%	0,00	2,54	95,9	B+(7)	8,7	7,5	5,9	7	95,9	98,3	
Lane 2	GVW	13	100%	0,00	2,02	96,2	B(10)	8,0	5,9	7,4	10	96,2	99,4	B(10)
	Group	13	100%	0,00	2,68	96,2	B+(7)	8,0	7,9	6,9	7	96,2	96,5	
	Single	13	100%	0,00	2,92	96,2	B+(7)	8,7	8,6	6,9	7	96,2	96,6	

2.2 A 31-m long beam-deck bridge

The second test was done on a heavily trafficked motorway at Araranguá in Brazil on a 31-m long three-span beam bridge instrumented with a SiWIM bridge-WIM system. The main 22-m span consisted of ten prefabricated reinforced concrete beams. Cross-beams at one third and two thirds of the main (center) span of the bridge were instrumented. The traffic on the bridge was running in two lanes in the same direction.

Implementing strips

After fine-tuning the strain sensors, the parameters for setting up the two strips were implemented using the same procedure as for the first bridge. Five strain sensors were allocated to lane 1 and the remaining five to lane 2. Figure 5 depicts a 3-dimensional representation of the responses from all 10 strain signals during a multiple presence event and, on both sides of the chart, depicts the contributions of the individual vehicles from lanes 1 and 2 (shown by the lines) within the total maximum beam responses of this loading event (shown by the bars).

Analysis of results

The initial calibration of the site was done with a 6-axle semi-trailer and no MP runs were recorded. After 5 days a test with 57 random vehicles from the traffic flow was performed. The vehicles were weighed on a static scale and results were compared to those obtained with the SiWIM system. Unfortunately, only the gross weights were recorded during the static weighing; therefore only this criterion could be compared. All statically weighed vehicles were using lane 2 which corresponded to the driving lane.

Figure 4 – Araranguá beam bridge and strain sensors installed on the beams

Among the 57 statically weighed vehicles, 5 multiple presence cases were identified. Each of the cases was examined and the results are presented in Table 3. All errors were reduced after implementing strips. The highest absolute improvement was attained in the first case where the two vehicles in the adjacent lanes were driving closest to each other.

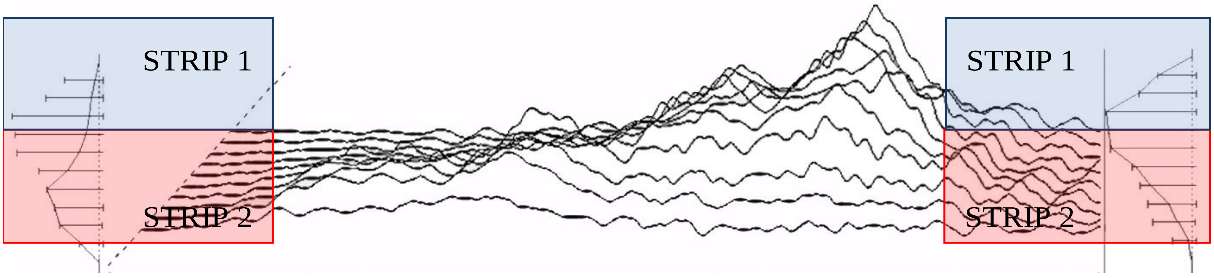

Figure 5 – Strain signals from individual strain transducer of a MP event with corresponding lateral distribution of each vehicle

Accuracy results under full reproducibility and environmental repeatability with and without strips are summarized in Table 3. Despite less than 10% of multiple-presence cases, which included some cases of one of the vehicles following the other vehicle in the same lane, the accuracy of gross weights according to the COST 323 specifications increased by one class, from B(10) to B+(7). In addition, the value of δ_{min} was close to 5%, which is the threshold for class A(5).

Table 3: Measured error of multiple-presence runs at Araranguá bridge.

Time	Static GVW	WIM error	
	t	No strips	Strips
11:36:44	22.76	-10.0%	-6.8%
15:40:59	20.76	-2.6%	-2.1%
13:29:53	44.91	-2.4%	-1.8%
15:12:50	44.26	-3.9%	-2.3%
15:17:25	52.06	-2.5%	-2.2%

Table 4: Accuracy of gross weights without and with strips at Araranguá bridge.

Method	No.	Ident. (%)	Mean (%)	Std. (%)	π_o (%)	Class	δ (%)	δ_{min} (%)	δ_{crit} (%)	δ_{class}	π (%)	π (%)
No strips	57	100%	-1.15	3.66	91.7	B(10)	10.0	7.73	7.73	10	91.7	97.9
Strips	57	100%	-0.44	2.81	91.7	B+(7)	7.0	5.77	5.77	7	91.7	96.8

3. Conclusion

A drawback of the traditional bridge WIM algorithms is the difficulty of dividing the global bridge response among the vehicles in a multiple-presence event, i.e. with several vehicles on the bridge at the same time. To mitigate this problem, the *strips* method has been developed and implemented in the SiWIM bridge weigh-in-motion system. Unlike implementing a full 2-dimensional influence surface which would require very complex calculations and system calibration, the proposed strips method is computationally efficient and does not require changing the conventional calibration procedure. The two examples in this paper demonstrate that using strips in BWIM calculation increases the accuracy of results. The degree of improvement is typically in the range of one accuracy class according to the COST 323 specifications and depends on the type of the structure (its length and stiffness) and on the density of the traffic which governs the frequency of multiple-presence events.

Using strips is the first step towards full implementation of the influence surface which is believed to be the ultimate solution not only for the multiple-presence events, but also to improve results on flexible superstructures (OBrien, Žnidarič, & Ojio, 2008). Using the traditional easy-to-perform calibration procedure, the strips can efficiently increase accuracy of bridge weigh-in-motion results.

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EXPERIMENTAL TESTING OF A MULTIPLE-SENSOR BRIDGE WEIGH-IN-MOTION ALGORITHM IN AN INTEGRAL BRIDGE




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Abstract
A new Bridge Weigh-in-Motion (WIM) algorithm which makes use of strain sensors at multiple longitudinal locations is tested using experimental data from an integral bridge in France. The optimisation procedure at the core of the proposed algorithm seeks to minimise the difference between static theory and measurement, a procedure common in the majority of Bridge WIM algorithms. In contrast to the single unique value calculated for each axle weight in common Bridge WIM algorithms, the algorithm implemented applies the optimisation procedure to a set of equations formulated at each scan of the Bridge WIM system, to give a time history of calculated static axle weights. Studying the determinant of the system of equations devised at each scan, those portions of the time history of calculated static axle weights for which the system of equations is poorly conditioned are removed from the final reckoning of the static axle weights. The proposed algorithm makes use of a robust moving average filter to remove much of the effects of dynamics. A calibration procedure based on using trucks from ambient traffic and the effect of the number of calibration vehicles on accuracy are investigated.
Keywords: Weigh-in-Motion, Bridge WIM, Integral Bridge, Experimental Testing, Algorithm.
Résumé
Un nouveau pont de pesage en mouvement (WIM) algorithme qui utilise des capteurs de déformation à plusieurs endroits longitudinale est testée en utilisant des données expérimentales à partir d'un pont ancré en France. La procédure d'optimisation à la base de l'algorithme proposé cherche à minimiser la différence entre la théorie statique et de mesure, une procédure courante dans la majorité des algorithmes de WIM Bridge. Contrairement à la seule valeur unique, calculé pour chaque essieu en commun algorithmes WIM Bridge, l'algorithme mis en œuvre la procédure d'optimisation s'applique à un ensemble d'équations formulées à chaque balayage du système de pont WIM, de donner une histoire du temps des poids par essieu calculé. Etudier le déterminant du système d'équations élaborées à chaque balayage, les portions de l'histoire du temps de calcul le poids par essieu pour lequel le système d'équations est mal conditionné sont retirés de la décompte final des poids par essieu. L'algorithme proposé permet l'utilisation d'un filtre à moyenne mobile robuste pour éliminer une grande partie des effets de la dynamique. Une procédure d'étalonnage basée sur l'utilisation de camions de la circulation ambiante et l'effet du nombre de véhicules sur la précision de l'étalonnage sont étudiées.
Mots-clés: Pesage en marche, Pont WIM, pont intégré, des essais expérimentaux, Algorithme.

1. Introduction

Bridge Weigh-In-Motion (WIM) systems measure the deformation of a bridge, most commonly in the form of strains, and use these measurements to estimate the characteristics of the traversing traffic loads. The data gathered at Bridge WIM stations can be used for many varying purposes: bridge monitoring, transport policy decisions, management of the bridge stock, the allocation of national resources and overload enforcement to name but a few. The ultimate end of the data gathered depends on the quality achievable, or the accuracy of the inferred axle weights. Only the most accurate of systems may be used for legal purposes or overload enforcement however, with slightly less accurate systems used to select trucks suspecting of being overweight, these trucks then being weighed on a static scales. This paper presents results of an experiment to test an algorithm proposed by González et al. (2011), which utilises bridge response readings (strains) at multiple longitudinal locations to provide an instantaneous calculation and a time history of applied forces for each axle. The experimental data is from a bridge in the south of France, and the algorithm is a further development of that implemented by Gonzalez et al. (2010). The multi-sensor algorithm is found to improve the accuracy of the system compared to the traditional algorithm based on a single longitudinal location, i.e., mid-span.

The stalwart algorithm proposed by Moses in the late seventies (1979) remains the basis of most modern Bridge WIM systems (OBrien et al. 2002, Rowley et al. 2008, Žnidarič et al. 2002). Moses' original algorithm is based on the minimisation of an objective function defined as the sum of the squared differences between theory (static response based on influence lines) and measurement (total strains) to provide a unique best value for each axle force. While the objective function of Moses is based on all readings at one given location for the entire period the vehicle is on the bridge, the objective function of the multiple-sensor algorithm tested herein is based on the readings of all sensors at one point in time. It is necessary to have a number of sensors equal or greater than the number of axles to be able to solve the system of equations that relate the expected (theoretical) response to the measured one. In the case of 5-axle trucks with a tridem as considered in this study, the axles of the tridem are assumed to carry equal load. This reduces the number of unknown axle weights from five to three. This assumption is justified by the fact that most modern trucks contain load sharing mechanisms for tandems and tridems. At each time-step, the determinant of system matrices (det(**G**)) is calculated, using this value as an indicator to remove those poorly conditioned sections from the ultimate prediction of static axle loads. The static axle weights are then estimated from those sections identified as being sufficiently well-conditioned.

2. Site Description

The experimental data was gathered from a bridge at Saint-Jean de Védas, approximately 7 km outside Montpellier. The bridge is located on the northbound passage of the A9 motorway, which links Barcelona and Montpellier. The bridge is a single 6.5m span integral structure; 14.4m wide with no skew and the road surface is in very good condition. An elevation of the bridge is shown in Figure 1.

Figure 1 – Photo of the elevation of Bridge at Saint-Jean de Védas

The bridge was instrumented with a Slovenian Bridge WIM system (SiWiM) (Žnidarič et al. 2002). The installation consisted of sixteen strain sensors, twelve located at mid-span and four off mid-span (two at approximately ¼-span and two at approximately ¾-span). Within the SiWIM system set up, the sensors at mid-span are those primarily used in determining axle weights, while those at the off mid-span locations are used for axle detection and calculating velocity. The sensor locations are shown in Figure 2.

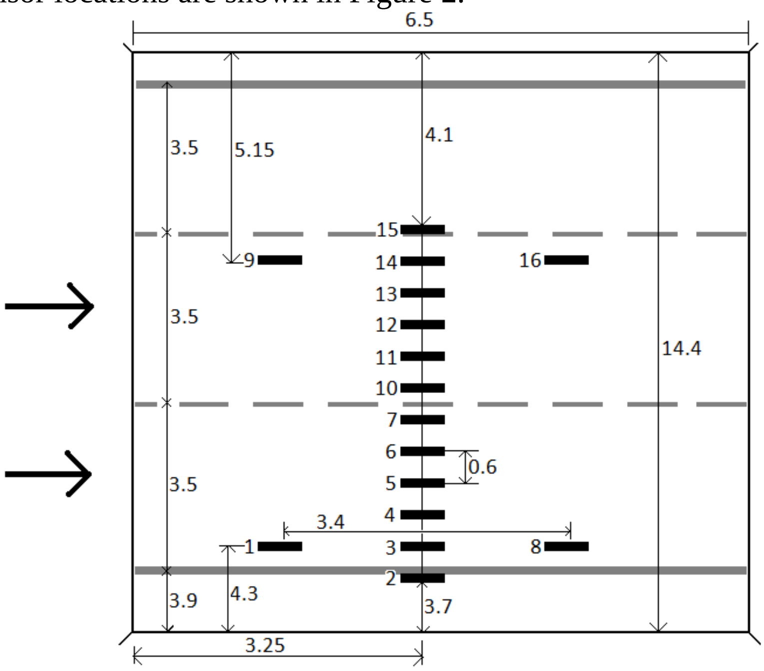

Figure 2 – Sensor Locations (showing road markings).

Located approximately 3 km downstream of the bridge is a toll plaza containing static weighing station. On 1st and 2nd December 2009, 79 5-axle trucks were identified crossing the bridge and pulled into the static weighing station to be weighed. As a result of this campaign, the complete strain records from sixteen sensors are available together with accurate static axle weights.

2.1 Bridge Response

The response of the bridge at Saint-Jean de Védas was found to contain very little dynamics. An example response is shown in Figure 3. Analysing strain readings from the bridge during a period of free vibration, the first natural frequency was found to be 35 Hz. The very high first frequency, of 35 Hz, is of the order that we would expect to see for very stiff integral structures such as this bridge and explains why there are very little dynamics evident in the measured response signals.

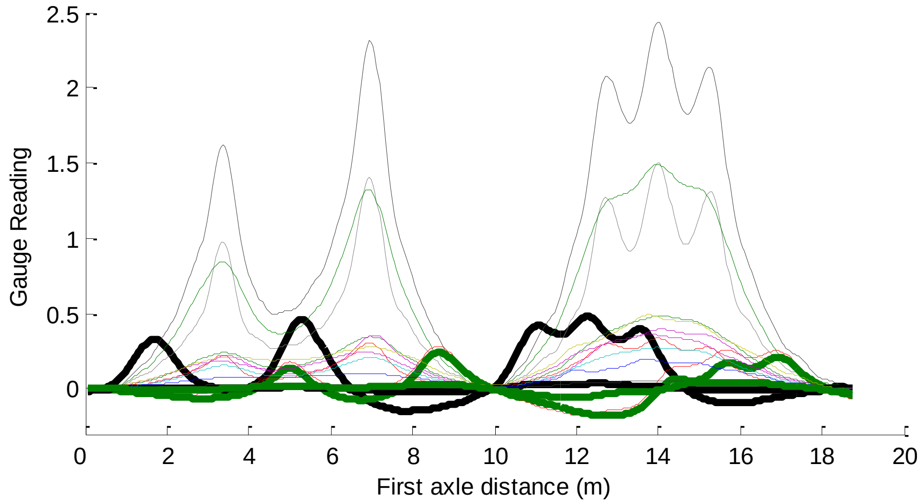

Figure 3 – Measured response from Site.

The off-mid-span measurements are plotted with heavier line-weights; there are two for each longitudinal location. There are twelve mid-span sensors, plotted with lighter line-weights in Figure 3.

2.2 Suitability of Site

The set-up of the instrumentation at the site is not the ideal testing conditions for the algorithm proposed in this paper; there are only three longitudinal locations instrumented and two of these locations have far less sensors than the mid-span location, two at each off-mid-span location and compared with twelve at mid-span. The span is so short that the period over which det(**G**) will be large enough so as to have a sufficiently high level of confidence in the predictions will be very short. However, despite the disadvantages of the experimental set up for this particular case, it will be shown that the proposed algorithm still offers an improvement over the original Bridge WIM algorithm.

3. Algorithm Influence Line

Implementing and testing the proposed Bridge WIM algorithm with a sample of 79 trucks, it is decided that 20 trucks are to be used in the calibration of the system. Figure 4 shows how a change in the number of trucks employed in the calibration affects the overall accuracy of the multiple-sensor Bridge WIM algorithm using the full sample of 79 trucks as a test population. The primary y-axis measures the sum of the squared differences between the influence line obtained using *n* trucks and the influence line obtained using *n*-1 trucks. The secondary y-axis shows the mean of the error in individual static axle weights obtained with the influence line calibrated with *n* trucks and it is represented with symbols in the figure.

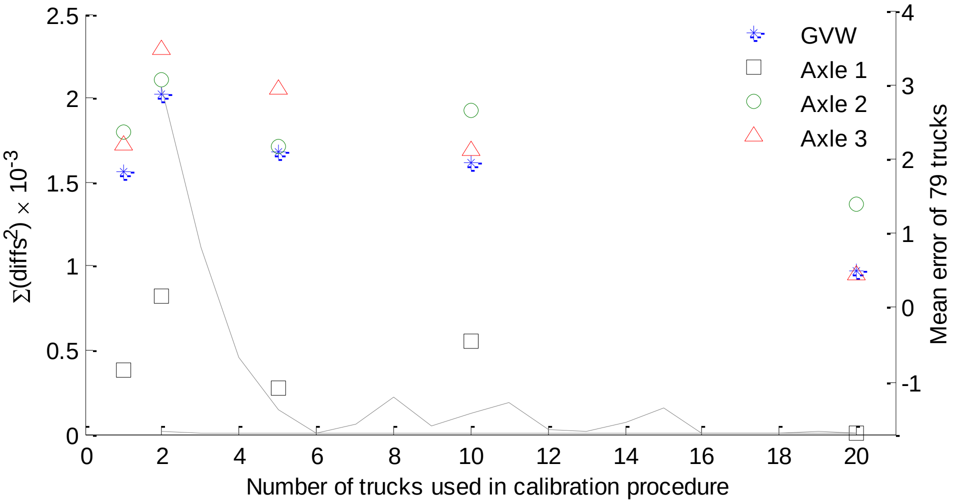

Figure 4 – Number of trucks used in calibration Vs error in predicted axle weights.

The influence lines providing the best results are the case when 20 trucks are used in the calibration procedure. This set of influence lines is provided in Figure 5 for reference.

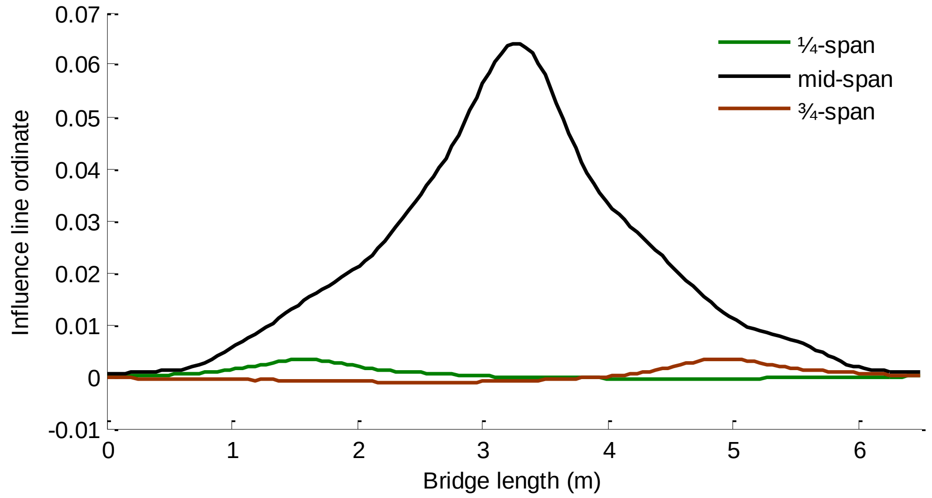

Figure 5 – Influence lines used in experimental Bridge WIM algorithm.

4. Limit of det(G)

The scale of the values of det(**G**) will be different for every bridge and every bridge location. In choosing the limit of det(**G**) for bridges as short as the bridge in this case, the state of the particularly small length of signal portion for which det(**G**) is large enough so as to inspire confidence in the predictions, must be considered in deciding the limit. A study of the errors obtained varying with the choice of det(**G**) limit is presented in Figure 6.

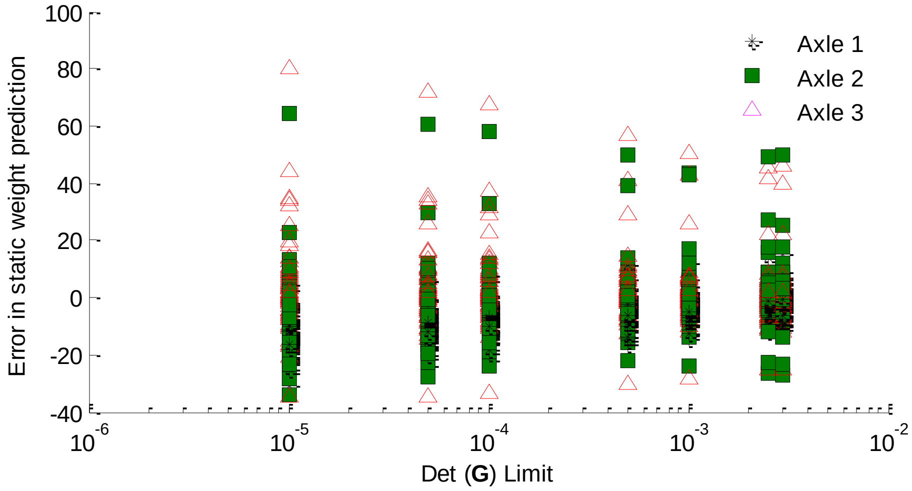

Figure 6 – Analysis of the limit of det(G).

In some cases for limits of above 0.03, imaginary predictions are returned, this means that for some axles there is no portion of the force history prediction for which det(**G**) > 0.03. The optimum limit of det(**G**) was found to be 0.025. This limit was used and the algorithm applied to the response of all 79 trucks. An example of the force history predictions is shown in Figure 7.

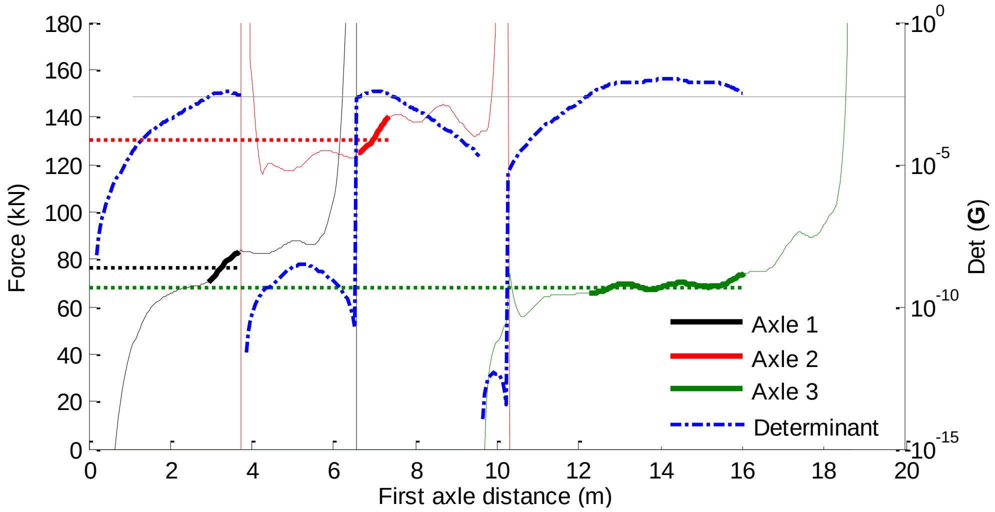

Figure 7 – Force predictions for a measured truck.

The plot style of Figure 7 is as follows: for each force predicted there is a heavy line-weight dotted line representing the actual weights recorded at the static weighing station; the light line-weight solid line is the entire extent of the force history predictions; the heavy line-weight solid section is the section of the force history prediction for which det(**G**) is above the limit of 0.025. The value of determinant is plotted with dash-dot line-type and values are on the secondary, right-side y-axis. The measured axle weights (dotted in Figure 7) are 76.5kN, 130.4kN and 67.7kN for the 1st, 2nd and 3rd axles respectively. The corresponding axles weights calculated by the proposed Bridge WIM algorithm were 77.2kN, 131.7kN and 68.9kN, giving errors of 0.9%, 1.0% and 3.8% for the 1st, 2nd and 3rd axles respectively in this case.

5. Method of Indentifying Outliers

The predicted force history of Figure 7 highlights the fact that for this experimental data the period of high det(**G**) values is very short; if it was longer, the force history predictions would 'settle down' and become less erratic as the distances between the transition zones of axles entering/ exiting the bridge, become longer. It would be advantageous to have, in any Bridge WIM system, a method of identifying those predictions which are likely to be erroneous. The proposed-WiM algorithm has a method, comprised of two indicators of identifying the potentially erroneous readings/ predictions. In ideal conditions the force history predictions will be horizontal straight lines and any deviation from horizontal or straight may indicate a poor prediction. When the section of the force history prediction for which det(**G**) > Limit has been identified, a straight line is fitted using least squares. The slope of this line is calculated as well as the sum of the differences squared between the time history prediction and the line of best fit, as a measure of the goodness of the fit, as demonstrated in Figure 8. In general, those runs with the worst slope/ correlation values contain the worst axle weight predictions.

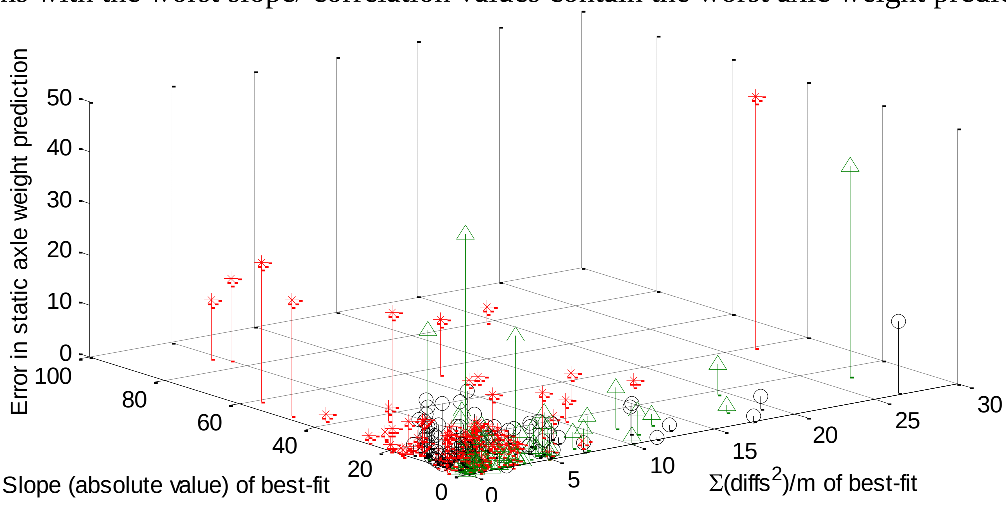

Figure 8 – Error in predicted axle weights Vs slope & Σ(diffs)^2 for line of best fit.

5.1 System Classification and Removing Outliers

COST323 (2002), in their final report presented a method classifying Bridge WIM systems based on the obtainable accuracy of the predicted axle weights in a number of categories. The classifications range from E in the worst case to B+(7) and A(5) at the upper end. Classifications A(5) and B+(7) are recommended for legal or enforcement purposes. The classifications are based on confidence intervals for the predicted weights, for example in the case of B+(7), the vast majority of individual static axle weights will be predicted within ±7% of their true values, while GVW and axle group weights (tridems, etc.) will be generally predicted within ±5% of their true values.

In the WIM standard (Clause 6.3.1), the user is permitted to remove up to 10% of the predicted results which can be shown to be potentially erroneous before classifying the system. Looking at slope and correlation of the line of best fit to the force history prediction, those seven trucks with the worst slope or correlation values were removed. The system was then classified as B+(7). The classification categories considered were Gross Vehicle Weight (GVW), individual axle and group of axles, the critical classification category of these was individual axle weight predictions. Classifications for GVW category, in all cases, were A(5). Bridge WIM systems are known to be more accurate in their predication of GVW then individual axles, and have difficulty distinguishing closely spaced axles like tandems and tridems (COST323 2002). The more critical categories of individual axles and group of axles will be focussed upon in presenting the results here. Comparing the predictions to those of the original Bridge WIM algorithm of Moses (1979), with an influence line calculated from direct measurements (OBrien et al. 2006), for the critical categories Table 1 is offered.

Table 1. Mean and standard deviation values after removing outliers.

	Individual Axles		Group of		Final Classification
	μ (%)	σ (%)	μ (%)	σ	
SiWiM Bridge WIM algorithm	1.7	4.2	3.2	4.1	B(10)
Proposed Bridge WIM algorithm	3.4	3.2	3.2	2.6	B+(7)

6. Conclusions

Using strain sensors at multiple longitudinal locations from the bridge near Montpellier, the accuracy of the axle weights calculated using a novel Bridge WIM has been improved. The algorithm has used ambient traffic for calibration. Parametric studies have been carried out on the key components of the system, such as the number of vehicles to be included in the calibration procedure and the value of determinant to be used in the selection of those portions of system matrices that are best conditioned. Furthermore, using a linear fit to the axle weight prediction histories for which the determinant of the system is above the limit, a method of identifying potentially erroneous predictions has also been presented.

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Session 2

WIM for Enforcement

Chair : CHIA-PEI CHOU (NTU, Taiwan)

Co-chair : VICTOR DOLCEMASCOLO (Ministry of Transport, France)

WIM SYSTEMS IN CHILE, A SUCCESSFUL EXPERIENCE

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Abstract

For 30 years, the use of WIM systems in Chile, which replaced static weighing systems, has allowed efficiency in vehicle weight control which has resulted in low overload rates. This has led to savings for the State in maintenance costs and road conservation. When the WIM technology was initially implemented, a rate of 15% overloaded vehicles were recorded; but in 2011 less than 2% overloaded vehicles were counted. There were just over one million vehicles in 1981, but the vehicle count reached 12 million in 2011.In the last 10 years the operating time has been greater than 98%, with accuracy below 1% error. The experience with the WIM systems in Chile is considered very positive because it has produced a progressive increase in the number of vehicles controlled for weight, which has obtained international recognition.As a result of this experience in Chile, many Latin-American countries have implemented similar WIM systems.
Keywords: WIM, overload, maintenance.

Résumé

Depuis 30 ans, le pesage en marche a remplacé au Chili les balances statiques. Le contrôle des charges en a été rendu plus efficace et montre une faible fréquence de surcharges, ce qui entraine des économies pour maintenir l'infrastructure dans un bon état de service. Quand cette technologie a été mise en place, une proportion de 15% de véhicules surcharges avait été constatée alors qu'en 2011, cette même proportion était de 2%. En 1981, le nombre de véhicules contrôlés était d'un nombre légèrement supérieur à 1 million, alors qu'en 2011 il atteignait les 12 millions, avec un taux de temps de fonctionnement de 98% et une précision avec une erreur inférieure à 1%. Ainsi l'expérience avec le pesage en marche est considérée comme très positive au Chili, parce que cette technologie a permis d'augmenter le nombre de poids lourds contrôlés et d'obtenir une reconnaissance internationale. Une grande partie des pays latino-américains a ainsi mis en place des systèmes similaires suite à cette expérience.
Mots-clés: Pesage en marche, surcharge, maintenance.

1. Fixed Weigh Stations

1.1 Description of the System

In Chile, there are 25 fixed weigh stations that operate every day of the year and are made up of a selection scale followed by a precision scale. They have been operating since 1981 and are frequently being modernized. The equipment is PAT Traffic brand. The selection scale is located on the side road to the highway and the vehicles pass over it at speeds of up to 60 km/h with a maximum error of 5%. The vehicles that exceed the weight limits are detoured to the precision scale, which operates with traffic speeds of up to 6 km/h with a maximum error of 2%. At the precision scale, the exact amount overweight is determined, the excess load is required to be removed and a fine is assessed. The vehicles that do not register as oveweight continue moving and return to the highway without major delay.

A processor exists for the selection scale that allows control of the weighing lane and additionally of the vehicle flow in the two normal travel lanes on the highway. In the main travel lanes, which are equipped with inductive loops, vehicles can be differentiated into 3 classes according to their size, which allows vehicles (trucks and buses) that are not required to be weighed to still be counted. The precision scale has a central processor that communicates with the controllers in both scales, an interface with the operator using the screen, the keyboard and manages storage of the weighing data, technical information and relevant operational information. The computers that control both scales are interconnected through the network with a third computer whose function is to centralize the overweight fine procedures. On the third computer screen the driver identification, vehicle owner and load dispatcher are entered and the overweight vehicle fines are automatically registered.

The automation includes an audio system with pre-recorded messages to communicate to the drivers without operator intervention about the correct procedure of weighing the vehicle and its detour to the parking area. The operating software works in a "Windows" environment, and has a maintenance management program incorporated that registers any technical interventions on the equipment and the weigh station system maintenance.

1.2 Selection Scale

The selection scale (Figure 1) is made up of four weight sensor bending plates and inductive loops for vehicle detection. The DAW 100 selective scale processor processes the signals and communicates information to the central computer through a serial data cable RS 422, Ethernet network connection or fiber optics cable to cover distances of approximately 200 m between the scale and the operations unit. It has the capacity to process the vehicles that travel over the scale and the two transit lanes on the highway, detecting long vehicles (trucks and buses) and sounding an alarm, and classifying and counting the vehicles that are not routed through the weigh station. Relays included in the electronics generate a signal with two displays (return to highway arrow or proceed to precision scale arrow, depending on the vehicle's weight). Additionally, vehicle height is controlled with an optical beam.

The selection scale screen (Figure 2) shows the summarized information of the weighed vehicle. This window can be activated to show a more detailed vehicle image and also to print weight information, if desired. The system is capable of differentiating between buses and trucks.

Table 1 - Precision and Capacity

Precision	Maximum Error +/- 5 % up to 60 km/h Maximum deviation 1 sigma
Nominal Capacity	20 Tons
Maximum Capacity	30 Tons

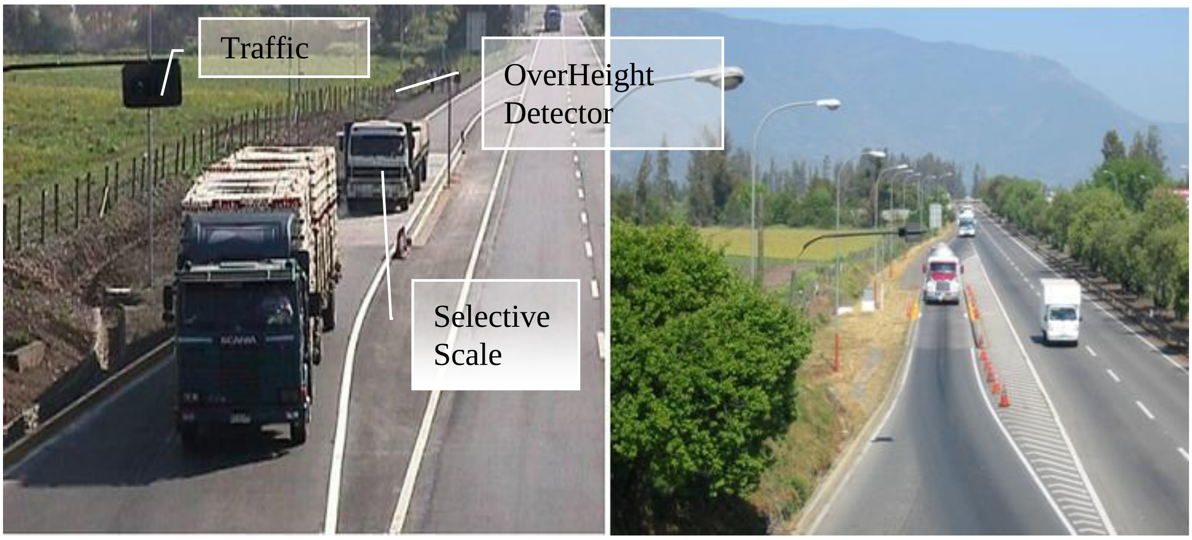
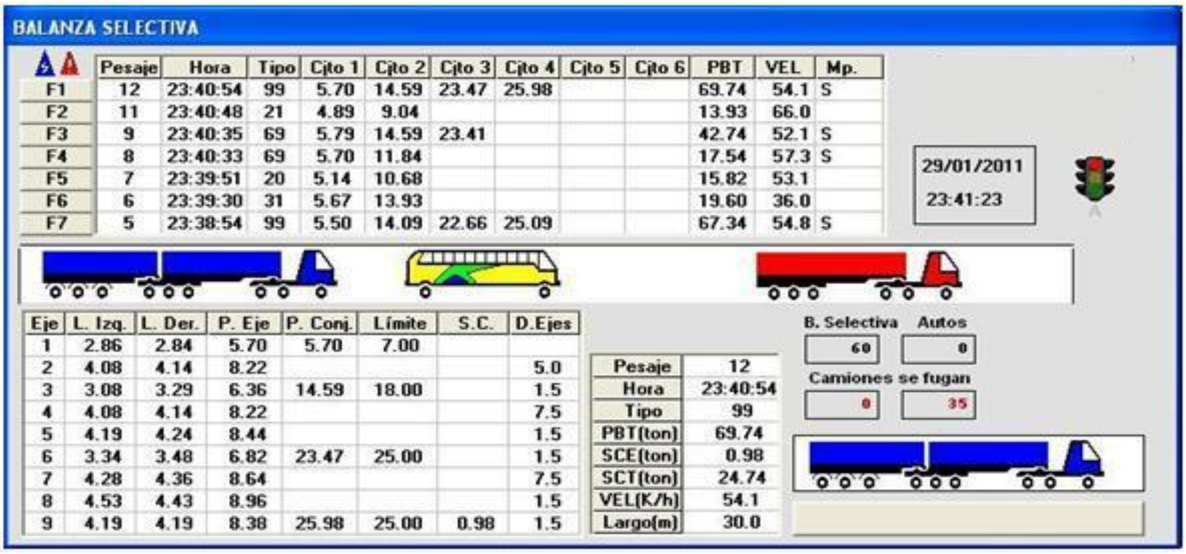


Figure 1 – Selection Scale



	Pesaje	Hora	Tipo	Cjto 1	Cjto 2	Cjto 3	Cjto 4	Cjto 5	Cjto 6	PBT	VEL	Mp.
F1	12	23:40:54	99	5.70	14.59	23.47	25.98			69.74	54.1	S
F2	11	23:40:48	21	4.89	9.04					13.93	66.0	
F3	9	23:40:35	69	5.79	14.59	23.41				42.74	52.1	S
F4	8	23:40:33	69	5.70	11.84					17.54	57.3	S
F5	7	23:39:51	20	5.14	10.68					15.82	53.1	
F6	6	23:39:30	31	5.67	13.93					19.60	36.0	
F7	5	23:38:54	99	5.50	14.09	22.66	25.09			67.34	54.8	S

Eje	L. Izq.	L. Der.	P. Eje	P. Conj.	Límite	S.C.	D.Ejes
1	2.86	2.84	5.70	5.70	7.00		
2	4.08	4.14	8.22				5.0
3	3.08	3.29	6.36	14.59	18.00		1.5
4	4.08	4.14	8.22				7.5
5	4.19	4.24	8.44				1.5
6	3.34	3.48	6.82	23.47	25.00		1.5
7	4.28	4.36	8.64				7.5
8	4.53	4.43	8.96				1.5
9	4.19	4.19	8.38	25.98	25.00	0.98	1.5

Pesaje	12
Hora	23:40:54
Tipo	99
PBT(ton)	69.74
SCE(ton)	0.98
SCT(ton)	24.74
VEL(K/h)	54.1
Largo(m)	30.0

Figure 2 - Selective Scale Screen

1.3 Precision Scale

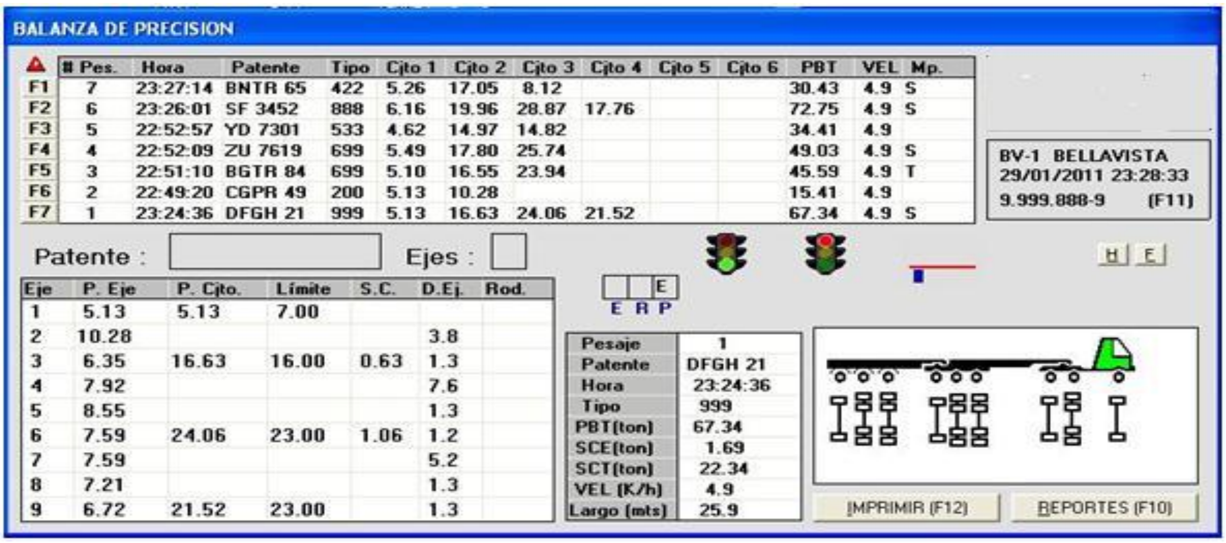
The precision scale is composed of a platform with four load cells and inductive loops for vehicle presence detection. The micro-computerized electronic model DAW50 contains analog amplification, digitalization and processing circuits, determines the weight information from the processed axles and sends it to the central computer through a serial interface. This

equipment contains relays for signal control, an automatic barrier, a height detector and a wheel classifier (which distinguishes between axles with four wheels from axles with two wheels).
Two video cameras are part of the system and register the weighing process, record a video clip of the vehicles that due to their overload must be fined, and automatically save an image record (see Figures 3 and 4).

Table 2 - Capacity and Precision

Dynamic Weighing	Maximum Error +/- 2 % up to 6 km/h, per axle or total weight
Static Weighing	2 Maximum Error +/- 1 % of the load over the platform
Nominal capacity	20 Tons
Maximum Capacity	30 Tons

Figure 3 – Precision Scale


BALANZA DE PRECISION

	# Pes.	Hora	Patente	Tipo	Cjto 1	Cjto 2	Cjto 3	Cjto 4	Cjto 5	Cjto 6	PBT	VEL	Mp.
F1	7	23:27:14	BNTR 65	422	5.26	17.05	8.12				30.43	4.9	S
F2	6	23:26:01	SF 3452	888	6.16	19.96	28.87	17.76			72.75	4.9	S
F3	5	22:52:57	YD 7301	533	4.62	14.97	14.82				34.41	4.9	
F4	4	22:52:09	ZU 7619	699	5.49	17.80	25.74				49.03	4.9	S
F5	3	22:51:10	BGTR 84	699	5.10	16.55	23.94				45.59	4.9	T
F6	2	22:49:20	CGPR 49	200	5.13	10.28					15.41	4.9	
F7	1	23:24:36	DFGH 21	999	5.13	16.63	24.06	21.52			67.34	4.9	S

BV-1 BELLAVISTA
29/01/2011 23:28:33
9.999.888-9 (F11)

Patente :
Ejes :
H E
E R P

Eje	P. Eje	P. Cjto.	Límite	S.C.	D.Ej.	Rod.
1	5.13	5.13	7.00			
2	10.28				3.8	
3	6.35	16.63	16.00	0.63	1.3	
4	7.92				7.6	
5	8.55				1.3	
6	7.59	24.06	23.00	1.06	1.2	
7	7.59				5.2	
8	7.21				1.3	
9	6.72	21.52	23.00		1.3	

Pesaje	1
Patente	DFGH 21
Hora	23:24:36
Tipo	999
PBT(ton)	67.34
SCE(ton)	1.69
SCT(ton)	22.34
VEL (K/h)	4.9
Largo (mts)	25.9

IMPRIMIR (F12)
REPORTES (F10)

Figure 4 - Precision Scale Screen

The system is designed for the operator to actively maintain the precision scale screen. The operator enters the vehicle license plate; the traffic light turns green so that the vehicle can move forward and begin the weighing process; the system automatically classifies the vehicle and the screen registers the weight, shows the established limits and the result of the control, and indicates whether the weight is within limits or the vehicle is overweight and the driver will be fined.

1.4 Parking Area

The overloaded vehicles are detoured using the exit traffic light and a barrier is activated which obligates the vehicles to drive to the parking area. There the vehicle weight is reduced to eliminate the overload in order for the vehicle to continue. The Chilean law prohibits overloaded vehicles from driving on the public roads. The system differentiates between buses and trucks, assigning them different code types than those assigned to vehicles.

2. Mobile Weigh Stations

2.1 Description of Mobile Weighing Equipment

In Chile two types of mobile weighing equipment of similar technical characteristics are utilized, the PAT Traffic model DAW-300 PC and the Captels model Alco CET10-4 (Figure 5). The first one has "bending plate" type sensor plates and the second has sensor plates with external load cells. The optimum vehicle speed for weighing is up to 6 km/h, with a maximum allowed error of up to 3%.

The sensor plates are connected to an electronic unit that transforms the analog signals to digital signals and executes the processes to determine the weights of the vehicle axles. The measurements are transmitted through an RS232 serial interface or an Ethernet network to a portable computer, where the software is executed indicating the data obtained from the weighing.

Figure 5 – Mobile Weight Stations

Leveling is a fundamental factor to obtain accurate measurements For this reason, leveling mats provided by the supplier are used as they have sufficient length so that the vehicle is totally leveled during the weighing process. Therefore, to obtain better precision, it has been necessary to construct recessed sections below the pavement level where the sensor plates are installed.

2.2 Equipment Components

The components of the equipment are:

- Electronic unit
- Weight sensor plates
- Portable Computer
- Printer
- Leveling ramp
- Battery unit 12 Volts
- Red-green traffic Light

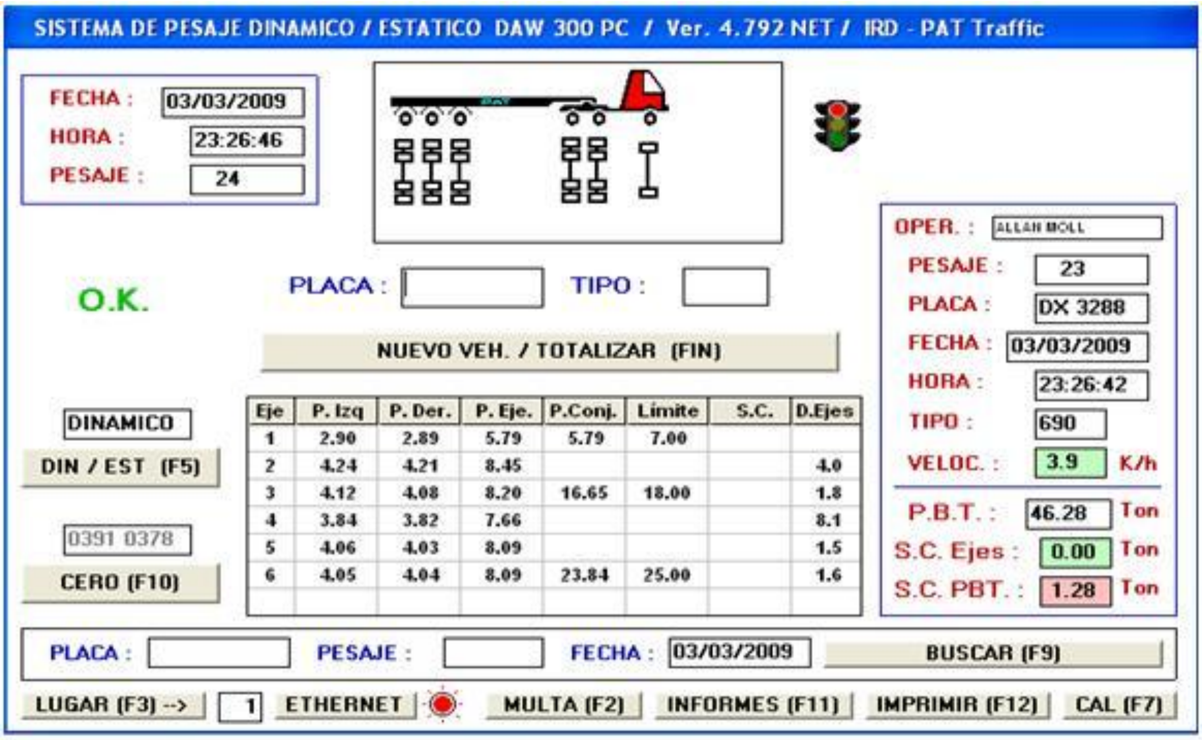


Figure 6 - Mobile Weight Operations Screen

2.3 Weight Records

The weight data are recorded in a storage unit (hard disk). The information includes the hour and the weight number, the vehicle license plate, the passing speed, vehicle type, overload status, and the weight of each group of axles (Figure 6).

For better control of truck weights in Chile, about 10 years ago mobile weighing units were created. They consist of van-type vehicles especially enabled to do field work. They contain automated electrical energy systems, exterior illumination devices, a traffic signal with electronic weight indicator panel, and transmission, data, and video lines.

3. Weighing System Calibration Laboratory

The implementation of a Calibrating Laboratory for Weigh in Motion systems (WIM) is fundamental to back up and validate the accuracy and precision of the scales that control the

total and axle weights. In order to obtain reliable, transparent and uniform operation of the network of weigh stations that will be accepted and respected by the truck drivers, it is necessary to apply international, systematic. and technically proficient protocols and traceability issued by credible and competent organizations.
The Calibrating Laboratory from the Chilean road department is officially accredited by the National Normalization Institute of Chile as a scale certification organization at the international level under ISO NCH 17025. The Calibrating Laboratory has professionals and technicians with specialized equipment, including a certified high precision scale (maximum error 10Kg. in a range of up to 45.000 Kg), composed of four independent and interconnected modules that allow the scale to simultaneously obtain the weight of each axle, the weight of each pair of axles, and the total weight of the trucks.

The scale calibration provides a statistical analysis of the data, linear parameters, eccentricity and instrumental uncertainty estimation. First for the static test, standard weight masses are used. Then tests are performed using standard calibration trucks travelling at different speeds to simulate the dynamic effect that the vehicles produce in WIM.

Besides validating the precision of the control system on the roads, the laboratory also controls the scales of the companies that utilize heavy trucks. In Chile by law it is required that the big companies that generate large truck loads control the weight of their own trucks in their loading area to avoid driving overloaded vehicles on public roads.

The technical protocols adjust to the OIML rules and the National Norm Standardization of Chile NCH ISO17025, in reference to the Laboratory Calibrations.

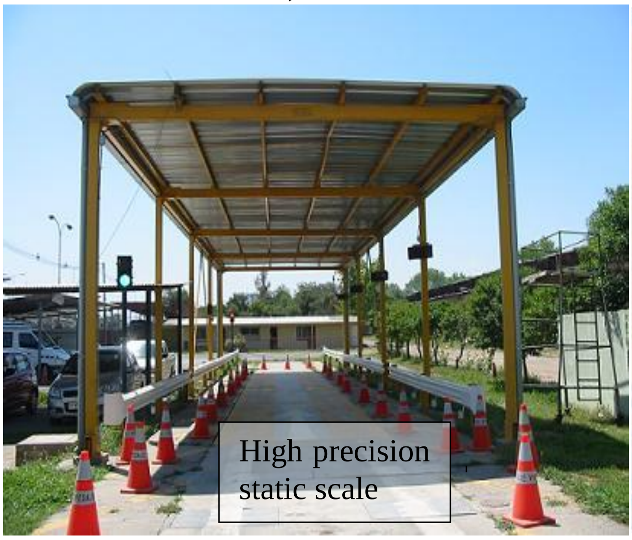


Figure 7 - Calibration Laboratory

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ANPR-MMR AND WIM FOR DETECTION OF OVERLOADED VEHICLES

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Abstract

Overloaded vehicles cause considerable damage to the roads and therefore reduce the length of their usability. They are also responsible for dangerous traffic accidents. Standard WIM solutions are designed to capture axle weight and gross vehicle weight. These parameters are used to detect vehicles that exceed allowed axle or gross vehicle weight. This allows detection of overloaded trucks but not overloaded vans, which are also responsible for the road damage and road accidents.

This document describes a solution which is a combination of video recognition and weight in motion solutions that allow the detection of overloaded vehicles.

Keywords: Overloaded truck and van, ANPR, MMR, WIM, Video detection.

Résumé

Les véhicules surchargés causent des dommages considérables aux routes et donc réduisent leur durée de vie. Ils sont également responsables d’accidents de la route. Les stations de pesage habituelles sont conçues pour enregistrer le poids par essieu et le poids total en charge du véhicule. Ces paramètres sont utilisés pour détecter les véhicules avec dépassement du poids autorisé du véhicule par essieu ou total. Cela permet de détecter des camions surchargés, mais pas les camionnettes surchargées, qui sont également responsables de la dégradation des routes et des accidents de la route.

Ce document décrit une solution qui est une combinaison de reconnaissance vidéo et de pesage en marche qui permet la détection des véhicules surchargés.

Mots-clés: Camion surchargé et van, ANPR, MMR, WIM, détection vidéo.

1. Introduction

Vehicles which are loaded above the maximum authorized weight cause not only considerable damage to the roads and therefore reduce the length of their usability but they are also responsible for dangerous traffic accidents. Standard WIM solutions are designed to capture axle weight and gross vehicle weight. These parameters are used to detect vehicles that exceed allowed axle or gross vehicle weight. This allows detection of overloaded trucks but not overloaded vans or other vehicles, which are also responsible for the road damage and road accidents.

One of the most tragic examples of accidents caused by an overloaded van was an accident that took place in Poland on 17.10.2010 on the national road No. 707 on the outskirts of Nowe Miasto on the Pilica river (Figure 1). In this crash a Volkswagen Bus collided with a truck. The accident killed 18 people, who were all van passengers. This case shows how thoughtless drivers can be.


Figure 1 - Tragic car accident near Nowe Miasto

The solution described below prevents damage to the roads caused by any kind of vehicle and at the same time prevents such dangerous accidents.

The solution uses two detection subsystems:

- Weigh in motion and
- Video identification which allows linense plate, make and model recognition.

The implemented solution uses the following components:

- Weigh in motion software and electronic equipment from Traffic Data Systems GmbH (Germany),
- LINEAS quartz sensors from Kistler Instrumente AG (Swiss),
- Video cameras from Bosch AG ,
- ANPR-MMR engine (automatic license plate, make and model recognition) and additional hardware and software from IBDiM and Neurosoft Ltd (both from Poland),
- Supervising software from Neurosoft Sp. z o.o.

The main idea of the solution is based on comparing two sources of data - real weight of a vehicle and legally allowed maximum vehicle weight (gross vehicle weight).

2. WIM subsystem

2.1 Quartz sensors

The main component of the system is a module for dynamic weighing which was constructed on the basis of specialized pressure Kistler Lineas Quartz Sensors (type 9195F) dedicated for calculation of WIM type pressure, see Figure 2a. This sort of pressure sensor is characterized

by very impressive metrological parameters - high precision in the full range measurement, low sensitivity to temperature changes (less than 0.02% per degree Celsius), and excellent linearity throughout the full range of measurement (deformation % FSO less than +-2). In addition during the mounting process these sensors require insignificant interference in a road surface which means that the damage to its structure is minor. For this reason these sensors can be successfully mounted in concrete as well as asphalt pavements.
Due to a good quality of pavement, special sensor construction as well as the double set of sensors, the system achieves the best available accuracy (A class) in accordance with the COST323 European Specification" (Jacob et. al., 2002).

2.2 WIM Computer

The WIM subsystem aggregates the loads of wheels, axles, axle groups and weight of vehicles. To improve the accuracy, an average value is calculated from the two rows of sensors provided. The two weight measurements are carried out independently. The inductive loop classifier is required for segmenting the stream of vehicles. An appropriate signal from the inductive loop classifier indicates the end of the vehicle, which would otherwise not be recognised in the pulse train from the row of sensors, especially in heavy traffic. The inductive loop classifier also provides the speed required for the weight calculation as well as classifying vehicles into 8+1, or 13+1 vehicle classes.

These provide data related to the wheel, axle, axle group and gross weight of the vehicle, from which a maximum load is determined. A very important component of the vehicle measuring system is a vehicle classification module using inductive loops mounted in the road surface, between the weight measuring sensors.

This module provides the following information:

- vehicle class,
- exact vehicle speed,
- total vehicle length and spacing between the axles,
- the total length of vehicle's passage through the measurement point (in milliseconds),
- distance between any two vehicles.

The WIM system uses the best available module for vehicle loop classification – TDS 821R made by Traffic Data Systems GmbH from Germany (see Figure 3). Device TDS821R is connected to the loop system in a configuration TLS Type 2 – this configuration is recommended for measurement points located on national roads, where vehicles travel at a moderate speed. This device is the only one in the world with a Class A1 quality certificate according to German standards (TLS, 2002). Among others this ensures accuracy of vehicle detection grater than 99% of all vehicles driving through the measurement point.

The TDS 821R module classifies vehicles according to the TLS (2002) to 8+1 categories. In addition to basic categories, a vehicle's shape classification is included. This classification indicates the way axles are group, including division for a vehicle and a trailer. As a result of this, the system assigns the studied vehicle into one of 56 specific classes defining its shape.

3. Video identification subsystem

The video subsystem is responsible for automatic identification of the vehicles based on their images generated by a video camera. Within the identification process for each vehicle the system determines the following parameters:

- content of the registration plate and the country of origin,
- affiliation with one of the vehicle classes (motorcycle, car, van, truck, coach),
- make, model and colour of the vehicle (MMR).

The system monitors all road traffic vehicles driving with a speed of up to 250 km/h. For the registration of a passing vehicle, the system does not require additional elements to trigger taking a photo (triggering). The identification is carried out only on the basis of analysis of photo sequences supplied by a video camera. Based on the generated photos the system detects the presence of the vehicle and then determines all of the parameters mentioned above. In each measurement point, two video cameras are mounted on a gantry located around 17 meters away from the sensors (see Figures 4 and 6):

- **Overview video camera** – registers a view of an entire road, including an overview of the controlled vehicle (Figure 7),
- **Measurement video camera** – captures the front view of the vehicle at the time of driving onto the weight sensors; this camera's task is to capture the content of the number plate and make & model of a vehicle, which must be automatically recognized (Figure 5).

The measurement video camera is equipped with a special infrared light radiator allowing receipt of clear images of the registration plates from vehicles driving at a high speed in the dark. This radiator creates a light completely invisible to the human eye (wave length - 940nm), with a 30 degree beam width. For this reason its light doesn't pose a threat to be mistakenly taken for a red traffic light above the traffic lane.

Figure 4 – ANPR Camera

Figure 5 - Picture from the ANPR camera

Depending on the vehicle speed and the way the camera is mounted, 3 to 20 images can be generated for each vehicle. If the camera is mounted in a standard way and a car is driving with the speed of 90 km/h, the registration plate will be visible on 7-9 photos.

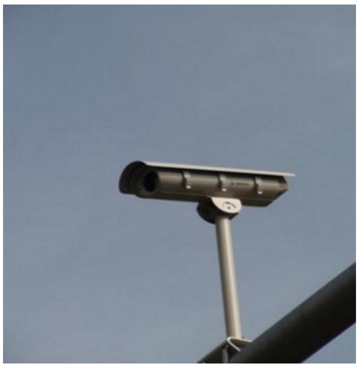

Figure 6 - Camera for overview picture

Figure 7 - Picture from the overview camera

For all passing vehicles the system finds and identifies the number plate and at the same time a special prepared neural network also recognizes the make and the model. The whole process of identification takes less than 40 milliseconds. Several dozen photos are generated for each vehicle depending on its speed, time of the day and season. The procedure of identification is performed for each photo (Figures 8 and 9), the result is classified, and finally the frame with the best identification result is chosen. An additional camera installed on the gantry delivers an overview picture with the site view of the vehicle.

Figure 8 - Region of interest for MMR – truck

Figure 9 - Region of interest for MMR - car

The quality of identification of the registration number depends on the lighting conditions and the scene geometry defined by a number of parameters: perspective rate, zoom, and turning angle. In good lighting conditions and with optimal adjustment the system shows the following effectiveness for a regular traffic:

- 99% correctly recognized registration plates,
- 98% correctly recognized types,
- 95% correctly recognized makes,
- 80% correctly recognized colours.

4. Supervising unit

All of the data from the video identification unit and from the WIM unit is time synchronized. The supervising unit prepares the data package which contains the following information:

- data delivered from a dynamic scale,
- recognized number plates,
- recognized make and model,
- pictures of the vehicles.

The supervising unit sends all of this information to the central system. Additionally the system compares the legally allowed maximum vehicle weight determined by a make and model with the real total vehicle weight delivered by the WIM system. If the real weight exceeds the allowed weight, the system generates alerts by SMS, SNMP, e-mail or directly via the warning screen in the user interface application.

4.1 Consolidating and archiving the measurements

Responsibility for joining all types of measurements from the different devices falls onto a module, which consolidates all the results and which is a part of NeuroCar 2.0 Terminal software. This module receives data from the recognition module and from the weighing and vehicle classification module. After receiving these data they are combined into an integrated information set about the vehicle – that way for each vehicle there is one set of measurement data saved as an XML file. To this XML file there is also added exact information about the location of the measurement point as well as the precisely defined time of capturing the vehicle (date, hour, minute and millisecond). To this measurement file are additionally added photos of the vehicle – one image from the measurement camera (front view of the car) and an appropriate image from the overview camera (overview of the car). After creating the data package containing the description of the single vehicle, the system analyzes the content of these data and determines whether a specific vehicle has committed an offense. If that is the case, the system forwards the entire package of data to a local offence register. Meanwhile a signal for the presentation module is generated, that another incident of offense has been recorded.

4.2 Presentation module

The main responsibility of the system is active control of passing trucks and catching those that exceed the allowed maximum weight (42t) or the allowed axle weight (11,5t). Additionally, all vehicles, including vans that exceed the allowed maximum weight, or which exceed the allowed speed or length can be also recorded in the offence register. Access to locally gathered information is possible thanks to the data presentation module which is a part of NeuroCar 2.0 Terminal software (see Figure 10).

This module provides data thanks to the internet server built into the system, which allows users to plug in via any web browser (MS Internet Explorer, Mozilla Firefox, Google Chrome, Apple Safari, Opera) to the system from any computer connected to the local network. The Java virtual machine is required to run Java applets. After opening an appropriate website the user has access to all functions of the system including:

- preview of the system's condition,
- preview of the last 10 recorded vehicles,
- preview of the last 10 vehicles recorded in the offence register,
- system configuration.

The website data is refreshed automatically (AJAX technology) immediately after each new incident appears (e.g. after recording another overweight vehicle).

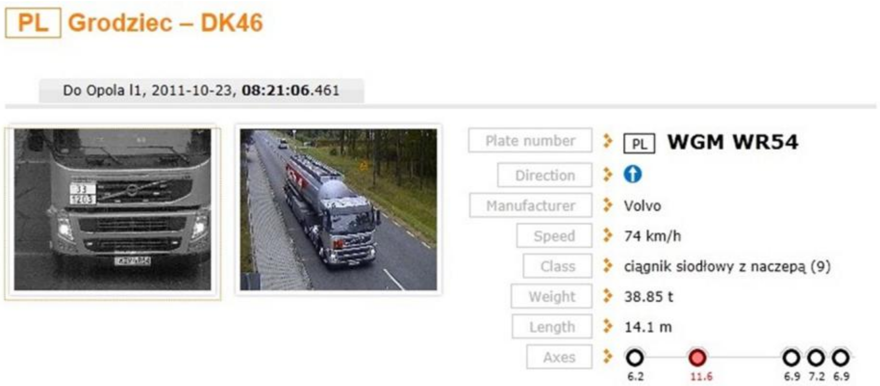

Figure 10 - Information about truck with exceeded axle weight

4.3 Data transmission module

The responsibility of the data transmission module is sending the measurement data to the central repository. Moreover all of the administrative and maintenance work can be carried out remotely. The module is a part of Neurosoft's NeuroCar 2.0 Terminal system. For data transmission, the system uses a different communication platform GPRS/EDGE/UMTS/CDMA, Wi-Fi, Ethernet, WiMax. All communication channels provide a safe connection of the system with a public Internet network but without an external IP address.

5. Results

There are 17 different locations with the installed WIM-P solution as described in this document. Each location is equipped with WIM and video identification subsystems. Below are some examples of overloaded vans or LGV (light good vehicles) and the statistics from the WIM-P system installed on the National Road No 1 in Wloclawek (Poland).

Picture 11 Overloaded Van/LGV

Table 1 Vans or LGVs – November 2011, national road no1 in Wloclawek (Poland)

Make & model	0 < weight < 4t	4t < weight < 6t	6t < weight < 8t	8t < weight	Sum
CHEVROLET	0	0	0	0	0
CITROEN	710	40	5	11	766
DAEWOO-LUBLIN	251	3	0	0	254
DAEWOO	120	2	0	0	122
FIAT	1540	54	4	14	1612
FORD-TRANSIT	2029	85	5	0	2119
HYUNDAI	51	0	0	0	51
IVECO	1140	368	51	4	1563
KIA	369	17	6	6	398
LDV	4	0	0	0	4
MERCEDES	2587	282	18	5	2892
MITSUBISHI	1	0	0	0	1
NISSAN	46	1	0	0	47
NYSA	3	0	0	0	3
OPEL	334	2	0	1	337
OPEL-VAUXHALL	1	0	0	0	1
OTHER NIGHT	6247	354	49	9	6659
OTHER	13	2	0	0	15
PEUGEOT	886	30	0	4	920
RENAULT	1982	212	15	12	2221
TOYOTA	72	3	0	0	75
VOLKSWAGEN	4330	202	17	7	4556
ZUK	4	0	0	0	4
	22720	1657	170	73	24620
	92,28%	6,73%	0,69%	0,30%	

6. Conclusion

For the correct detection of overloaded vehicles it is necessary to identify exactly the make and model for every passing vehicle, than determine the allowed gross vehicle weight (GVW) and compare it with real weight. Video identification allows correct identification of the make & model for every vehicle. In some cases this is not enough because there are LGVs (light gross vehicles) or vans with different versions of the same model and with different GVWs. For example, the Volkswagen Transport has a normal version with 3 m axle base and the long version with 3.4 m. The video system could distinguish between the Volkswagen Transporter and Crafter but it is not able to distinguish between normal and long version of the same model. In this case to determine correctly the version of the vehicle, it is necessary to take in the calculation of the make & model also the axle base which could be specified by the inductive loops of the WIM system.

Such a solution allows identification every overloaded vehicle – overloaded in the meaning of exceeding the allowed gross vehicle weight. It could help to prevent dangerous accidents with overloaded vehicles like the accident described in an introduction.

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ONE YEAR "WIM DIRECT ENFORCEMENT" EXPERIENCES IN CZECH REPUBLIC




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Abstract

Last year the Czech Republic (CZ) became the very first country in the European region and also in the world where the traffic law allowed the use of HS-WIM systems for direct enforcement concerning weighing road vehicles while the vehicles are moving along its route.
During the year 2011 different types of WIM systems were certified. These systems were certified (type approved and verified) in accordance with a Czech national regulation designed and elaborated by Czech Metrology Institute (CMI), elaborated taking into account the most important international documents used in the field of WIM (OIML, COST, ASTM and FIWI). The regulation represents a complex document according to which the testing for type approvals and verification is carried out.
The paper presents the most important parts of this document regarding the metrological and technical requirements as well as simulated functional laboratory tests carried out for verification of the system resistance to disruptive environmental effects and functional weigh-in-motion tests performed on location during road traffic which a manufacturer applying for a type approval certificate or verification shall undergo.
Keywords: Weigh-In-Motion, Type Approval, Certification, Initial Verification, In-Service Verification, Direct Enforcement, Overloading.

1. Introduction

By the amendment of the national traffic law in 2011 two ways of performing weighing as a part of the controls of overloading by road vehicles have been established in the Czech Republic (CZ):

- Weighing performed by high speed weighing-in-motion systems where the trucks to be controlled are not diverted from their route;
- Weighing performed in other ways, including low speed weighing-in-motion and weighing on static stales.

Through the new traffic law the high speed (HS-)WIM systems have become one of the weighing technologies that can be legally used for direct law enforcement. Although the use of the HS-WIM systems is not mandatory for relevant road authorities it offers another legal application of WIM for enforcement of overloading.

Since direct law enforcement is a field where only legally relevant measuring instruments can be used, HS-WIM systems fell into the instruments category intended for official periodic verification. By an amendment of a decree (legislation document connected to metrology law) published by the Czech Ministry of Trade and Industry such measuring instruments with mandatory type approvals and verification were listed and the accuracy defined.

Based on the Czech metrology law the Czech Metrology Institute (CMI) is the competent authority for type approvals, initial verifications and subsequent verifications. CMI elaborated a national regulation (designation 0111-OOP-C010-10) stipulating metrological and technical requirements, including test methods, for specified measuring devices: "HS-WIM road vehicle scales". The regulation represents a complex document according to which the testing for type approvals and verification is carried out.

2. System Requirements

The definitions used in this regulation are based on those used in (OIML 2006), (COST323, 1999), ASTM E1318 and (FiWi, 2010). HS-WIM systems for direct law enforcement are defined as: *“Automatic scales that measure the dynamic force on the tires of a moving vehicle and detect its presence on a pressure sensor over time, and calculate the total vehicle mass and load per axle or axle group, plus other vehicle parameters required by special legislation, while the vehicle is moving along its route”.*

The requirements for the measurement accuracy for weighing-in-motion correspond to a combination of the classes A(5) and B+(7) as mentioned in (COST323, 1999) and (FiWi, 2010). The maximum permissible errors for measurement of the vehicle mass, axle load and axle group load are specified in Table 1.

Tables 1, 2, 3 – Specifications for weighing ranges (1,2), and for scale intervals (3)

Max. Error	%
Axle and Axle Group Loads	± 11%
Vehicle Mass	± 5%

Weighing range	min [kg]	max [kg]
Axle load	1000	20,000
Vehicle mass	3500	≥ 48,000 or as specified by special legislation

Scale Interval	[kg]
Axle load	20 kg
Vehicle mass	50 kg

The requirements for the operation conditions are based on the requirements of recommendation OIML R-134-1 (OIML, 2006) and the Draft European Standard on Weigh-in-Motion of Road Vehicles (FiWi, 2010) and include Service conditions for: operating temperature range, operating speed and weighing range. The specifications for the weighing ranges are given in Table 2. The specifications for the scale intervals are given in Table 3.

The other technical requirements are based on the requirements of (OIML, 2006). Scales generally are an automatic measuring system composed of the following parts: load receptors installed in the roadway, vehicle recognition equipment, equipment for measuring vehicle speed, indication unit, and recording device, equipment for the optical identification of vehicles and auxiliary equipment. The system as a whole is capable of measuring dynamic forces on tires, detecting the presence of a moving vehicle on the load receptor over time and calculating total vehicle mass, axle loads, speed, plus other vehicle parameters required by specific legislation (e.g. axle separation, vehicle type, etc.).

Since HS-WIM systems are legally relevant measuring instruments disruptive external influences on the scales must not lead to measurement errors that would exceed the scales' maximum permissible error specified in the metrology legislation. The following external influences are specified: *Physical robustness, Weather resistance, Dust and water resistance, Electromagnetic compatibility (EMC).*

Also the software used in the scales must be presented in such a form that software cannot be changed without damaging a seal, or each change in software can be automatically recorded and its nature specified with the use of an ID code. All scale equipment including software, must be equipped with a housing or other suitable security means to prevent disconnection or removal by a user or other individual. It must be possible to seal housings after their closure; sealing points must be easy to access in all instances. All parts of the measuring system that cannot be protected by housings must be equipped with sufficiently effective means of preventing operations that tend to influence measuring accuracy. Each piece of scale equipment that could influence measuring results, especially equipment for calibration and adjustment of scales or for correction of measured values, must be sealed.

3. System design

The WIM systems consists of; two quartz crystal sensor rows (4 x Lineas 9195F411), one piezo sensor for detection of transversal wheel position, three temperature sensors in different layers for measuring of road temperature gradient and one accelerometer sensor. Figure 1 shows the layout of the system configuration including the use of different sensor types.

3.1 Validity of Measurement

Based on daily experiences, drivers of heavy overloaded trucks are often trying to confuse road sensors. They use several tricks, such as accelerating, sudden breaking or any other maneuvers just to make WIM sensors unable to measure their current weight precisely. Validity of Measurement is a unique procedure implemented in the WIM systems to identify information on the driver’s behavior, and more than that, to use this information to improve the accuracy of the measurement results. The use of the validity of measurement concept, is considered the key for the full integration of WIM into an automatic weighing system. From the user’s point of view, Validity of Measurement is one number in percentage indicating the success of measurement. In addition, this validity number is also followed by full list of factors having some exact influence during measurement process. End users can then easily interpret what has happened in system (Figure 2).

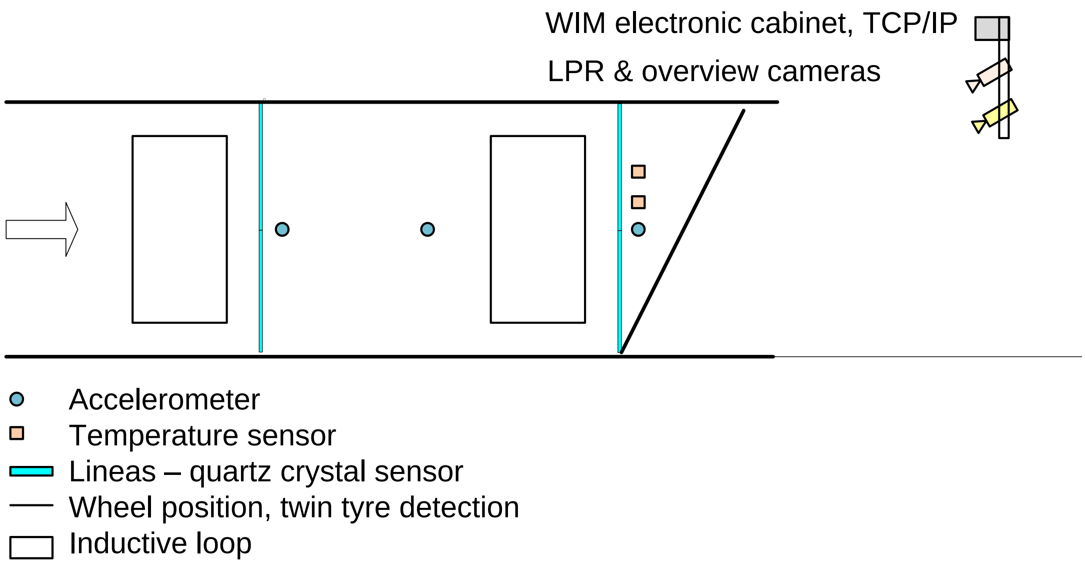

Figure 1 - WIM system configuration

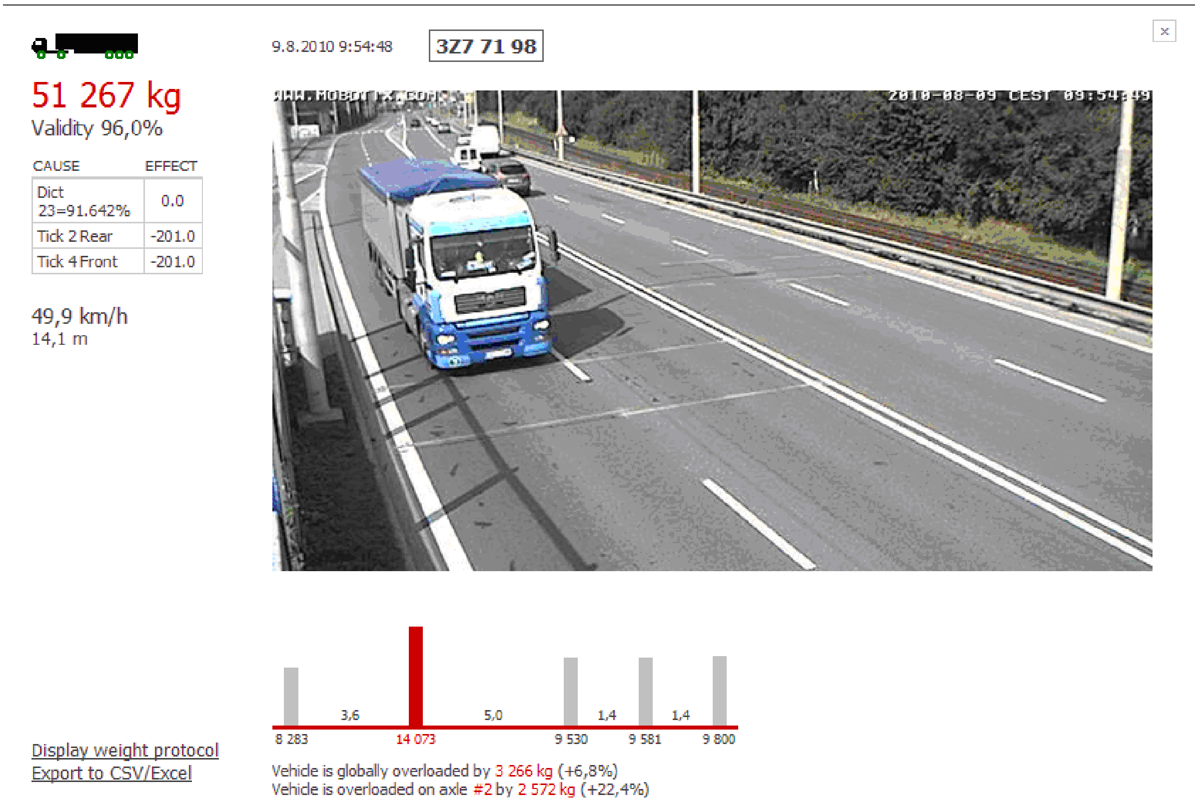

Figure 2 - Example of validity of measurement

3.2 Vehicle detection

Based on speed and weight data from each wheel and axle, and compared to time, WIM system is able to detect following vehicle maneuvers: acceleration/speed up. Even minor changes in each wheel speed can be detected. De-acceleration/brake actuating: in opposition on acceleration, even minor changes in each wheel speed can be detected. Slight turning left or right: if vehicle wheels have different speed on each axles and vehicle trail is turning aside, system will identify this. Sharp turning left or right: if vehicle is turning rapidly, system is able to recognize and identify that. Because of all of vehicle's events are stored in database (such as data from WIM sensors, data from loop detectors and other events), vehicles driving from one lane to another can be recognized and weighed properly. If some wheel information is missing in one lane, system will try to find out relevant information in connected lanes and pair all this information into one vehicle record. As result of lane pass detection, validity trace will include all necessary information for identifying incorrect vehicle drive.

For WIM system, each vehicle has a unique "signature". Signature is footprint of the vehicle mass moving over inductive loops. In classification model, each signature is then compared to special dictionary. Classification results can also have direct influence on validity value itself. The WIM system is equipped with an image recording unit to generate a video document recording the situation of weighing with secure identification of the weighed vehicle. The image recording unit operates automatically; a set up of mass limits for a record of a video document is done by the WIM application. The situation during weighing is taken by a digital camera. Outputs are single digital pictures stored in a data memory. On each single picture – video document following data are indicated:

- measured values of total mass, including the unit of measurement
- maximum permissible total mass value, including the unit of measurement
- measured values of axle or axle group load, including the unit of measurement
- maximum permissible axle or axle group load, including the unit of measurement
- the speed of the weighed vehicle including the unit of measurement
- number of axles of the weighed vehicle
- the time (resolution to the seconds) and date (day, month, year)
- type designation of the measuring instrument
- serial number of the measuring instrument
- serial number of the video document
- location of the measurement
- additional picture description

For digital images, image information and information regarding measured values are inseparably joined into one data file and integrated into the pixel structure of the digital image. To ensure integrity, the digital image data file has a digital signature. The authenticity of the entire digital image data file is uniquely identifiable via coding (the ID number of the video document, Figure 3).

3.3 Software security

Legally relevant part of the software is presented in such a form that software cannot be changed or each change in software is automatically recorded and its nature specified (e.g. with the use of an ID code).

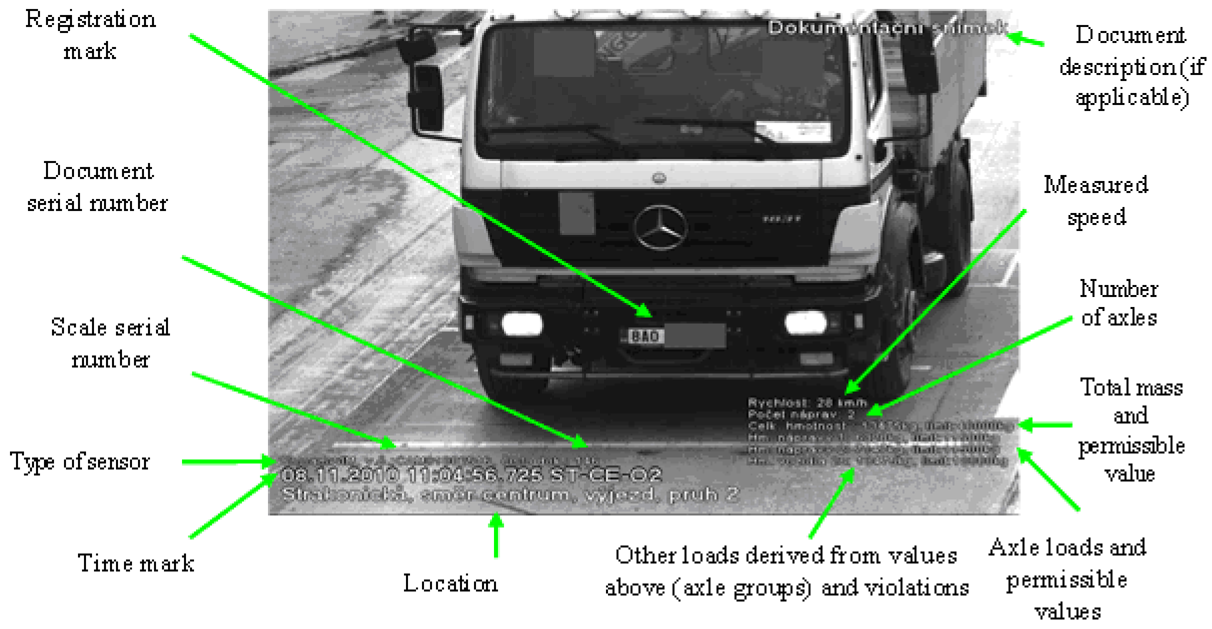

Figure 3 - Example of digital image with measurement data

Resources for securing software subject to metrological verification of measuring devices are as follows: only authorized individuals may be given access, using codes (passwords) that are changeable, the measuring device's memory stores all accesses, listing the date of the access, identification of the authorized individual performing the access, and the type of access, if memory capacity for access record storage is exhausted, no automatic erasure of any stored records can take place, it is possible to recall relevant access records to the full extent of information recorded, only authorized person can erase access records, downloading of software subject to metrological verification is possible only via an appropriate secure interface connected to the scales, the software includes identification of its version, which changes if any software version changes occur, functions that are performed or launched via a software interface meet the terms and conditions of relevant legislation.

4. Type approval tests

During the type approval test the following steps were performed:

- external inspection,
- tests of the scales' resistance to disruptive environmental effects,
- functional WIM tests on location during road traffic

4.1 Required test equipment

The reference vehicles were selected for weigh-in-motion tests so that they represent various axle configurations, truck/trailer configurations, truck/trailer connection systems and suspension systems. During testing the reference vehicles were used both unloaded and loaded in a way that two significantly different load levels are used, according to (FiWi, 2010). During testing, stand alone reference scales were available to determine the reference (or conventional true value) mass, the single-axle or axle group loads of each vehicle. The mass of the reference vehicles is determined by full-draught weighing scales with an error less than or equal to one third of the applicable MPE for weigh-in-motion. To determine the reference axle loads, portable static scales for weighing Class III or IV are used, or in case of low-speed scales of accuracy class 1 or better.

Reference scales are used to determine the GVW and axle load values for an unloaded and loaded reference vehicle. The reference scales are used to sequentially determine the load on each axle of the reference vehicle, with at least three to five test runs in both directions. The mean reference axle load is calculated as the arithmetic average of recorded values. To correct for the influence of the method used, the total vehicle mass (VM) is calculated as the sum of mean load values of the individual axles. The corrected mean load value per axle that is used as a reference value during the acceptance tests is calculated as:

$$CorrAxle_i = \overline{Axle}_i \times \frac{VM_{ref}}{VM} \tag{1}$$

VM_{ref} is the conventional value of each reference vehicle mass determined by full-draught weighing.

4.2 Test runs

Each reference vehicle, unloaded and then loaded, must perform at least five test runs at each of the three following speeds: near the maximum operating speed, v_{max}, near the minimum operating speed, v_{min}, near the middle of the operating speed range (each reference vehicle must thus perform a total of 30 test runs). For every five test runs at a given tests speed, the vehicle must be positioned above the centre of the load receptor three times, once on the left and once on the right side of the load receptor. Vehicle speed must be kept as constant as possible during each test run. Scales must indicate and record the speed of the tested vehicle as it passes over the load receptors.

4.3 Criteria for accuracy tests

The values of all vehicle mass indications and all axle load indications are recorded. For each recorded value (total vehicle mass, axle or axle group load), the relative error *d* is calculated in percent:

$$d = \frac{C - R}{R} \times 100\% \tag{2}$$

C the value measured by the scales,

R the corresponding reference value measured by the reference scales.

The percentage of relative errors *d* that exceed the maximum permissible error for each quantity is determined as follows:

$$P_{de} = \frac{n}{N} \times 100 \tag{3}$$

n the number of calculated differences exceeding the max. permissible error,

N the total number of recorded values for the given quantity.

The number of relative errors exceeding the maximum permissible error P_{de} must not be greater than 5%, with their distribution among individual vehicle types being recorded.

4.4 Speed tests

During the operating speed blocking test, a reference vehicle will pass the system at speeds outside the operating speed range. The scales must detect this and must react correctly.

- speed of least 5% higher than the maximum operating speed, v_{max},
- speed of least 5% lower than the minimum operating speed, v_{min}, (if the scales can be used for this).

To determine and test operating speed during a weigh-in-motion test, six test runs shall take place with an unloaded two-axle rigid reference vehicle across load receptors at a constant speed. Three runs must take place near the maximum operating speed v_{max}, and three additional runs must take place at exactly the listed minimum operating speed v_{min}. The indicated operating speed error must not exceed the error given in (FiWi, 2010).

4.5 Simulated laboratory tests

Simulated functional tests are performed to assess the resistance to the influence of external environment on the complete system. If the size and/or configuration of the scales make it impossible to test them in their complete form (in the laboratory), then it is allowed to perform to use a load signal generator taking the place of load receptors. The following simulated tests were performed:

- Shock resistance test, Weather resistance tests, Resistance to limit temperatures, Resistance to operating temperatures, Resistance to air humidity, Dust and water resistance
- Electromagnetic compatibility (EMC) tests: Resistance to interference caused by power lines, induced by high-frequency fields, Resistance to radiated high-frequency electromagnetic fields at radio frequencies, Resistance to electrostatic discharge, Resistance to electrical fast transients/bursts, Resistance to electrical surges, Resistance to power-frequency magnetic fields, Resistance to AC mains voltage dips

5. Results

- Two HS-WIM systems were approved by CMI approved: Cross a.s. (CZ) and Camea s.r.o (CZ). Both systems have been installed on the entrance motorway section city of Brno, I/52 Brno–Vienna and where directly connected with the toll collection.
- According to the results of the accuracy tests and with aspect to fulfilling of all other metrological test the systems received type approval for direct enforcement;
- The applied method “validity of measuring” gives a warranty for a fair direct enforcement of overloaded vehicles based on the WIM measuring. Accelerometer and temperature gradient outputs are used to put more precisely the axle load calculation in relation to actual road deflection.

6. Literature

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INTEGRATION OF WEIGH-IN-MOTION TECHNOLOGY INTO NIST'S HANDBOOK 44

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Abstract
The Federal Highway Administration's (FHWA's) Office of Freight Management and Operations recognized a need to encourage uniformity in the design, testing, installation, and performance of weigh-in-motion (WIM) technology and subsequently encourage acceptance by prosecution agencies (administrative or judicial) regarding the validity of WIM technology's role in supporting commercial motor vehicle (CMV) weight enforcement. In response to this need, FHWA is seeking to integrate WIM technology into the National Institute of Standards and Technology's (NIST's) *Handbook 44: Specification, Tolerances and Other Technical Requirements for Weighing and Measuring Devices*.
Keywords: Weigh-in-motion, enforcement, commercial motor vehicles.

Résumé
Le bureau de la gestion du fret de l'agence fédérale des autoroutes des Etats-Unis (FHWA) a reconnu le besoin d'encourager l'uniformisation dans la conception, l'installation et la précision des systèmes de pesage en marche, et ainsi encourager l'acception des agences de contrôle (administratives ou judicaires) en ce qui concerne la légitimité du pesage en marche pour le contrôle sanction. En conséquence, l'agence FHWA essaie d'intégrer le pesage en marche dans le manuel 44 de l'institut des normes et des technologies américain (NIST) : spécification, précision et autres requis techniques pour le pesage et la mesure.
Mots-clés: Pesage en marche, contrôle sanction, poids lourds commerciaux.

1. Introduction

The Federal Highway Administration's (FHWA's) Office of Freight Management and Operations recognized a need to encourage uniformity in the design, testing, installation, and performance of weigh-in-motion (WIM) technology and subsequently encourage acceptance by prosecution agencies (administrative or judicial) regarding the validity of WIM technology's role in supporting commercial motor vehicle (CMV) weight enforcement. In response to this need, FHWA is seeking to integrate WIM technology into the National Institute of Standards and Technology's (NIST's) *Handbook 44: Specification, Tolerances and Other Technical Requirements for Weighing and Measuring Devices* (*Handbook 44*).

The National Institute of Standards and Technology is a non-regulatory agency of the U.S. Department of Commerce, which, until 1988 was known as the Nation Bureau of Standards. At that time, the agency's responsibilities were expanded and the name changed. In the U.S., there are no federal regulations for commercial weighing and measuring *equipment* except in the areas of grain and livestock, where some applications are regulated by the U.S. Department of Agriculture. The authority for regulating commercial weighing and measuring equipment rests largely with State and local weights and measures jurisdictions.

The NIST Office of Weights and Measures (OWM) has the responsibility to promote uniform standards of weights and measures within the U.S. to facilitate commerce. OWM works in cooperation with States and the private sector to develop uniform weights and measures laws, regulations, device requirements, and test procedures. One of the things NIST does to promote uniformity is to publish *Handbook 44* on an annual basis.

While not a regulatory document in its own right, *Handbook 44* has been adopted by all U.S. State weights and measures jurisdictions, either by reference or through their State administrative procedures processes. As far as *Handbook 44* itself, it is comprised of a comprehensive set of requirements for weighing and measuring devices that are used in commerce as well as law enforcement. The goal is to try to eliminate any weighing or measuring device that will give inaccurate results or could be used to facilitate fraud so that the buyer does not receive what he or she has paid for or the seller does not receive fair payment for goods and services.

2. Motivation

Existing CMV weight enforcement efforts in the United States are characterized by:

- Limited enforcement resources with significant effort expended on compliant carriers—estimated overweight violation capture rates at continuously operated fixed weigh stations on the U.S. Interstate System approximate 1%.
- Infrequent and inconsistent use and maintenance of technology (including WIM systems) to support enforcement activities, leading to compromised data quality and a lack of "trust" in technology performance.
- A lack of coordination, shared technologies, and data exchange between and within agencies—including enforcement, transportation, prosecution, and regulatory agencies–that adds to enforcement costs.
- Ineffective penalties and prosecution procedures that encourage rather than discourage overloading as a routine business practice among industry components.

- Performance measures that are focused on activities (citations issued) rather than outcomes (reductions in overloading).

Despite the challenges facing CMV enforcement agencies in the U.S., certain industry organizations continue to press Congress to lift the freeze on longer combination vehicles and increase existing Federal truck weight limits. Congress directed that "pilot tests" be conducted in the States of Maine and Vermont to investigate the influence of allowing a temporary increase in truck weight limits. The tests were intended to assess impacts on safety, pavement and bridge service life, the environment, and economic implications tied to allowing heavier commercial motor vehicles. Since these pilots were very short in duration (one year in Maine and a two year pilot in Vermont), Congress recently extended them to cover a 20-year period.

Concurrent with industry pressures to increase allowable weight limits for CMVs, the Interstate system is approaching 50 years of service. The use of heavier trucks will accelerate the rate of pavement and bridge deterioration. These conditions of increased allowable weight limits on an aging infrastructure coupled with ineffective and inefficient CMV weight enforcement and the declining fiscal ability of States to maintain the infrastructure may result in unacceptable or unsafe roadway service levels.

There is a growing consensus among CMV weight enforcement agencies at State and Federal levels that the increased use of and reliance on key technologies, such as WIM systems, can significantly improve CMV weight enforcement effectiveness and efficiency. The expanded use of WIM technology is being supported and advanced at the State level through ongoing FHWA and FMCSA initiatives. Specifically, the expanded use of WIM and vehicle identification technologies is being facilitated through FHWA's Virtual Weigh Station (VWS) concept, FMCSA's Wireless Roadside Inspection (WRI), and Commercial Vehicle Information Services and Networks (CVISN) programs, and in partnership by FHWA/FMCSA through the Smart Roadside Initiative (SRI). The SRI and its associated technology deployments (including WIM technology) are expected to remain a high priority for both FHWA and FMCSA over the long term.

Despite the strong advocacy at the national level, State CMV weight enforcement agencies may be reluctant to embrace WIM technology for the following reasons:

- The performance of WIM technology in producing accurate and precise axle, axle set, and gross vehicle weight estimates has been observed to be highly variable under typical highway environment conditions. The observed performance of WIM, both perceived and actual, is often inappropriately attributed to shortcomings in technology design. More often, compromised WIM system performance can be associated with improper or inadequate installation, maintenance, calibration, and/or acceptance procedures, or vehicle dynamics. A lack of WIM technology end-user training coupled with a lack of manufacturer/vendor support can lead to noted performance issues with WIM equipment.
- Based in part on historic performance, WIM technology and the resulting weight measurements it provides are not anticipated to be accepted by prosecution agencies (administrative or judicial) responsible for issuing judgments and penalties for CMV weight violators. Already, prosecution agencies often reduce or dismiss fines for overweight transport without fully understanding the consequence of these actions. Some CMV weight enforcement agencies have successfully conducted targeted outreach in an attempt to educate judicial and administrative officials involved in adjudicating truck weight and encourage prosecution agencies to uphold penalties and institute uniform fine

schedules in court systems across multiple jurisdictions. Many more prosecution agencies remain unaware of the consequences of not penalizing CMV weight violators.

- Issues tied to the adequacy of WIM equipment used for truck weight enforcement purposes are not unique to the U.S. The press for an international set of equipment standards applied to WIM devices is occurring on a global basis. The promulgation of international standards for WIM equipment is being promoted by WIM device manufacturers.

The integration of WIM technology into NIST's *Handbook 44* would address these issues by lending consistency to existing WIM technology design, installation, acceptance testing, maintenance, and calibration procedures leading to enhanced accuracy and precision in weight measurements and subsequent acceptance by CMV weight enforcement and prosecution agencies.

3. Technical approach

The technical approach for this investigation consists of the following work tasks:

- Develop an initial, detailed Project Work Plan intended to guide activities, identify outcomes, allocate expenditures, and establish a communications protocol from project inception to successful project completion.
- Establish a working group from the WIM technology stakeholder community representing State departments of transportation, State law enforcement agencies, WIM technology manufacturers and vendors, academic researchers, and others to provide expertise and guidance throughout the project duration.
- Solicit input to support development of a proposed "WIM Scale Code" through meetings—involving the working group as a whole or focused sectors of the working group (e.g., State departments of transportation, State law enforcement agencies, WIM technology manufacturers and vendors, academic researchers, or other)—and various other information exchange mechanisms.
- Draft the proposed WIM Scale Code language, ensuring that it builds upon the existing state-of-knowledge expressed in existing standards and specifications, reflects WIM technology stakeholder community input, and is consistent with NIST's *Handbook 44* format and content requirements.
- Submit any and all supporting materials and documentation used in developing the proposed WIM Scale Code to FHWA and/or the broader project oversight team to allow for ready justification of the proposed amendment throughout the formal NIST/NCWM amendment process that will begin shortly after this project's completion.

3.1 Working Group

The project team established a working group representing the broad spectrum of the stakeholder community, including WIM equipment manufacturers/vendors and users of WIM technology. The working group includes the following entities:

- State department of transportation administrative and technical staff responsible for weight enforcement, WIM system calibration, planning and programming, and other functions.
- State law enforcement administrative and technical staff responsible for weight enforcement.

- Weights and measures regulatory officials who are responsible for testing devices once installed and who can assist in advancing a draft code through the NCWM adoption process.
- Equipment manufacturers and vendors producing and providing WIM technology and directing new developments for a variety of applications.
- Academic researchers and private consultants who have conducted detailed investigations related to WIM technology.
- Federal agencies, motor carrier representatives, and other organizations with a vested interest in WIM technology.
- International organizations directly involved with the use of WIM as an enforcement screening tool or, in limited cases, involved with WIM for direct enforcement.

3.2 Working Group Charter

During key planned meeting events and at various other times throughout the duration of this project, working group members will be asked to provide input on various aspects of the proposed WIM Scale Code. More specifically, working group members may be asked to approve individual changes or modifications to draft specification language, comprehensive draft specification language, or methods or approaches for advancing the draft WIM Scale Code. Because working group members represent diverse stakeholder communities and interests, consensus among all members may be unattainable. To ensure that this lack of consensus does not preclude progress toward developing a proposed WIM Scale Code, some general guidelines for decision making, including working group representation, voting eligibility and procedures, and general rules of order, have been established.

3.3 Draft WIM Code

The project team is in the process of drafting a WIM Scale Code, ensuring that it builds upon the existing state-of-knowledge expressed in existing standards and specifications. It will reflect the WIM technology stakeholder community's input, and will be consistent with NIST's *Handbook 44* format and content requirements. Five content areas, as identified by the OWM's staff, will be included as part of the proposed WIM Scale Code:

- Application.
- Specifications.
- Notes.
- Tolerances.
- User Requirements.

Although input from the working group will be sought for each of the five content areas, their input will be particularly beneficial when drafting the User Requirements section. As such, a first step in this task will organize, facilitate, and document a user requirements workshop. Although it is not the preferred option, the project team may choose to conduct the user requirements workshop using a Web-based format if in-person attendance is confirmed to be too low.

Irrespective of the format utilized, the project team will incorporate outcomes from the user requirements workshop into the User Requirements section of the proposed WIM Scale Code. Additional information to support development of the remaining content areas, as well as supplement the User Requirements section, will be obtained from various sources including but not limited to the following:

- The technical support team's own knowledge of state-of-the-practice WIM technology—including existing design, testing, and installation procedures and performance across various system/weight sensor types;
- Existing or proposed WIM technology standards and specifications, including but not limited to:
  - Title 23 Consolidated Federal Regulations (23 CFR) Part 500, Subpart B – Traffic Monitoring System.
  - Traffic Monitoring Guidelines; USDOT, FHWA Office of Highway Policy Information, FHWA-PL-01-021.
  - ASTM E1318—09 Standard Specification for Highway Weigh-in-Motion (WIM) Systems with User Requirements and Test Methods.
  - Ancillary ASTM standards and specifications, including but not limited to the following: ASTM E867-06 Standard Terminology Relating to Vehicle-Pavement Systems, ASTM E2415-05 Standard Practice for Installing Piezoelectric Highway Traffic Sensors, ASTM E2467-05 Standard Practice for Developing Axle Count Adjustment Factors, ASTM E2300-09 Standard Specification for Highway Traffic Monitoring Devices, ASTM E2665-08 Standard Specification for Archiving ITS-Generated Traffic Monitoring Data, and ASTM E2532-09 Standard Test Methods for Evaluating Performance of Highway Traffic Monitoring Devices.
  - The Long Term Pavement Performance Program Protocol for Calibrating Traffic Data Collection Equipment.
  - The European WIM Specification resulting from the COST 323 Weigh-in-Motion of Road Vehicles project.
  - The International Organization of Legal Metrology's (OIML's) Automatic Instruments for Weighing Road Vehicles in Motion and Measuring Axle Loads Part 1: Metrological and Technical Requirements—Tests (OIML R 134-1 Edition 2006 (E)) and Part 2: Test Report Format (OIML R 134-2 Edition 2009 (E)).
  - Expert technical advice and guidance offered by OWM's staff.

OWM's staff has been instrumental in providing procedural guidance throughout the duration of the project. These individuals possess unique knowledge related to amendment preparation and submittal requirements as well as technical content and language requirements that will greatly benefit this project's outcome and the subsequent success of the proposed WIM technology amendment through the formal NIST/National Conference on Weights and Measures amendment process.

3.4 National Conference on Weights and Measures

Handbook 44 requirements are based upon proposals developed through another organization—the National Conference on Weights and Measures or NCWM. The NCWM is a private nonprofit organization that was established by NIST in 1905. The NCWM brings together regulatory officials who enforce weight and measurement requirements, manufacturing companies and parties that use weighing and measuring equipment, and anyone else that might have an interest in developing standards that would apply to weighing and measuring equipment or packaged products. NIST first established the National

Conference to work with individuals with the idea that if everybody could agree upon a single standard, it might encourage uniform adoption and implementation in individual states. The way the National Conference works is that only regulatory officials can vote on proposals—those regulatory officials would then go back to their respective jurisdictions and adopt the updated sections of *Handbook 44* as approved by the National Conference. While regulatory officials are the only ones that can vote on the proposals, any member or any interested party can provide input and comment on any proposal put forward to the NCWM.

As to how *Handbook 44* becomes a regulatory document, most states adopt the document through referencing it in their weights and measures law. Some states adopt an earlier version of *Handbook 44* rather than adopt the handbook each and every year. That typically has to do with how they adopt the handbook in their particular jurisdiction. *Handbook 44* has been adopted by all states, but not necessarily the same version for commercial weighing and measuring applications.

The first task in the development of a new WIM Scale Code is to agree and to define the scope (or application) of that new code. The working group's overall approach will take a draft or straw man and refine it through an iterative process to request input from people affected by the code. Generally, the process builds upon the current state of knowledge—in this case the weigh in motion scales system standard. ASTM E1318-09 will be particularly useful for the working group as a starting point.

The iterative process would include getting input from stakeholders, discussing any issues that would arise from that input, making modifications to the draft, and achieving consensus that the draft reflects and supports the input that had been obtained. The process may go on until the working group achieves consensus on the final draft code. It is then ready to begin the process of adoption into *Handbook 44*. The NCWM is made up of weights and measures officials, manufacturers of equipment, users, and so forth. The proposed code must be presented to the NCWM to determine if it can be included in the handbook. Under the established process, a proposal to amend Handbook 44 has to be supported by at least one regional weights and measures association. If it is supported there, it can advance to the national level. At the national level, the Specifications and Tolerances Committee reviews and makes recommendations to do one of the following:

- Continue to develop the proposal.
- Retain as informational.
- Put it forward for a vote.
- Withdraw it.

Those decisions are made based upon input that is received in open hearings and in writing.
In summary, NIST publishes *Handbook 44* to promote uniformity. It has been widely adopted for commercial weights and measures application. It was seen as a good starting point for the effort undertaken by the Federal Highway Administration working group. The project is actively seeking input from stakeholders in the weights and measures community including officials, manufacturers, users, and others who have an interest. The final draft code will be submitted to the National Conference for consideration with additional comment through that forum.

4. Expected results

Expected results from this project include the following benefits for enforcement personnel:

- Enhanced national competitiveness through elimination of unnecessary delay in the national supply chain created when legally loaded vehicles are required to pull into compliance and inspection stations.
- Enhanced equity in the highway transport market through the elimination of the incentive to overload vehicles and underbid competitors.
- An increase in the total number of trucks having their weights measured.
- Enhanced judicial acceptance of the use of WIM technology in screening trucks for weight compliance while traveling at highway speeds.

Factors that could be used to quantify the improvements include:

- Costs: more maintenance, more calibration, and upgraded WIM in some cases.
- Savings attributed to reduced motor carrier delay, fuel usage, emissions, and noise.
- Savings attributed to reduced frequency of crashes at inspection and compliance sites.
- Savings attributed to reduced pavement/bridge damage and extended service life of highway infrastructure improvements.

One of the early projects initiating Intelligent Transportation Systems in the commercial vehicle arena was the HELP/Crescent Project in participating western states, where an evaluation of four technologies for screening transponder-equipped vehicles resulted in positive findings. The technologies included automatic vehicle identification, weigh-in-motion, automatic vehicle classification, and integrated communications systems and databases. The benefits data were developed as a projection of experience from the HELP/Crescent project. A full implementation of services examined in the Crescent project would yield a benefit-to-cost ratio of 4.8 for a typical state government over a 20-year period[2]. Less complete implementations will result in benefit-to-cost ratios for the government ranging from no benefits up to 12:1.

[2] http://www.itsbenefits.its.dot.gov/its/benecost.nsf/ID/36CFF2BCED3A6CCA852569610051E2AD?OpenDocument&Query=BApp accessed January 17, 2012.

Session 3

WIM Standard, Calibration, Data Quality and Management

Chair : RALPH GILLMANN (FHWA, United States)

Co-chair : MARCIO PAIVA (UFSC, Brazil)

STANDARDIZATION OF WEIGH-IN-MOTION IN EUROPE

Graduated of Ecole Polytechnique and Ecole Nationale des Ponts et Chaussées. Since 1982 with LCPC, as bridge engineer, expert in WIM and now deputy scientific director for transport, infrastructures and safety. Chaired the COST323 action, WAVE project and was involved in several projects and expert groups on trucks, OECD/DIVINE, truck performances, DG/MOVE...

A graduate in Electrical Engineering from the University of Twente. Since 1994 he has been involved with Weigh-in-Motion and traffic enforcement. He has been working for the Dutch National Traffic Police Agency, the Ministry of Transport and since 2006 for Kalibra-Cofely. He has been involved in a number of WIM-related project on both a national level.

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Abstract

This paper gives a review of recent developments in the standardization of Weigh-in-Motion systems in Europe. The output of the recent FiWi project - a FEHRL institute WIM initiative - is reported, i.e. the up-date and submission to the CEN (European Committee on Standardization) of the COST323 specifications, to form a full standard. The main developments are discussed. Finally the requirements and needs to develop a complementary standard, or to complete the current draft one, in order to address the direct enforcement by WIM are described.
Keywords: Weigh-in-Motion, WIM, Standards, Specification, Testing, International, Enforcement, Overloading, WIM Technology and Sensors.

Résumé

Cet article donne un aperçu des récents développements en matière de normalisation du pesage en marche en Europe. Les résultats du récent projet FiWi - initiative des institutes du FEHRL sur le pesage en marche - sont présentés en ce qui concerne la normalisation, à savoir la mise à jour et la soumission au CEN (Comité européen de normalisation) des spécifications COST323, pour constituer une vraie norme. Les principaux apports du nouveau projet de norme sont exposés. Enfin on esquisse les besoins pour mettre au point une norme complémentaire, ou compléter le projet actuel, pour couvrir le contrôle direct à l'aide du pesage en marche.
Mots-clés: Pesage en marche, norme, spécifications, essai, international, contrôle, surcharge, technologies et capteurs de pesage en marche.

1. Background

There have been considerable developments in the Weigh-in-Motion industry in Europe since the early 90's. In addition to technical improvements of WIM sensors and WIM systems there has been a considerable development in the applications of WIM. The development of WIM systems and their applications is reflected in a series of international projects: OECD/DIVINE (1997), COST323 (Jacob et al., 2002), WAVE (Jacob, 2002), Top-Trial (2002), REMOVE (2006) and most recently FiWi (2010).

1.1 Current WIM standards

At the moment there are three existing international sets of specifications on Weighing in Motion of road vehicles and a European Directive on measuring instruments:

- The COST323 European WIM Specification (Jacob et al., 2002); it applies to Low Speed (LS) and High Speed (HS) WIM systems, for all applications but trade, and is already widely used around the world by manufacturers and users. Even though formally it is not an official international standard it is widely used as a reference in the testing and acceptance of WIM systems.
- The ASTM E-1318 'Standard Specification for Highway Weigh-In-Motion Systems with User Requirements and Test Methods' (ASTM, 2009) from the American Society for Testing Materials defines and specifies four different types of WIM systems. Type IV systems are intended for Low-Speed weighing for enforcement purposes. ASTM E-1318 is intended to facilitate the relationship between a buyer and a vendor.
- The OIML R-134 (OIML, 2004 and 2006) from the International Organization for Legal Metrology is a recommendation for 'Automatic Instruments for weighing road vehicles in motion'. This recommendation is intended for use in enforcement and trade, however only for low speed weighing and weighing in controlled environment. This means restricted weighing areas and not on main roads.
- The Measuring Instrument Directive (MID, 2004)) is the EU-directive regularizing the construction and certification procedures of several measuring instruments in order to improve free trade of these devices across Europe. The MID is a set of uniform European specifications and a European framework for type and product approval. Recently OIML-R134 has been incorporated into the MID.

1.2 Need for an updated Standard

The COST323 Specification has been the de-facto European (and worldwide) pre-standard for WIM systems for the past 10 years. Formally it is neither an official European nor an International standard; however it is widely used as a reference in the testing and acceptance of WIM systems. This shows there is a need for such an international standard. Furthermore the considerable developments in the field of WIM over the last 10 years require an update of the content of the document. Finally the REMOVE project pointed out a strong need for a harmonized European WIM Specification for enforcement applications, especially direct enforcement. Direct enforcement means that the citation for an overloaded vehicle is directly based on the measurement by a WIM-system without human interaction.

2. Proposed European Standard

For of these reasons the Forum of European Highway Research Laboratories (FHHRL) initiated the FiWi project (i.e., FEHRL institutes WIM initiative). The participants were: LCPC (France, project manager), BAST (Germany), CEDEX (Spain), EMPA (Switzerland), RWS (The Netherlands), UCD (Ireland) and ZAG (Slovenia). The project ran over a 3-year period (2007-2010). The main goals of the project were:

- to make a general update of the COST323 specification;
- to add content on new developments like Bridge-WIM and WIM for direct enforcement; and
- to prepare a document that is suitable for official European standardization.

The FiWi project also provided a platform where FEHRL members and WIM research institutes and users could share information on all WIM projects in Europe. The procedure for official standardization remains with the European Committee for Standardization (CEN). However the updated version of COST323 was written by the project members in the format required for the CEN standardization procedure.

2.1 Scope of the proposed Standard

The draft European standard specifies the requirements for installation, calibration, performance and accuracy assessment, and test methods for Weigh-in-Motion (WIM) systems that are used to determine gross weights, axle and group of axle loads for road vehicles when they are weighed in motion. The standard applies to:

- WIM systems installed on road infrastructure (including bridges), but not to WIM systems installed on board vehicles;
- High speed WIM (HS-WIM) systems, i.e., systems installed in one or more traffic lane(s) of a road, and operated automatically under normal traffic conditions, and to low speed WIM (LS-WIM) systems (i.e., systems installed in a controlled weighing area, and operated under controlled conditions);
- WIM systems using either scales which are able to weigh standard masses statically, or other sensors which may measure the loads indirectly;
- On-site full WIM system performance assessment and model (type) approval, but excludes laboratory (product) tests or tests on parts of systems (e.g. sensors only).
- All WIM applications, except trade. For load enforcement of road vehicles, this standard or the OIML (International Organization for Legal Metrology) international recommendation R 134-1 and 134-2 (OIML, 2004 & 2006) may be applied, depending on national requirements and legislation.

The main differences between OIML recommendations R134-1 and R134-2 are that they apply to WIM systems used for trade in controlled weighing areas only, on a specified apron and where the vehicle speed is controlled. They mainly apply to WIM systems composed of scales, which are capable of weighing standard masses statically. The OIML recommendation is limited to the highest accuracy classes (0.2 to 10) and specifies the maximum permissible error (mpe), the tolerance for 100% of measurements.

The draft standard has been submitted to the European Committee, and successfully passed the first stage of the Preliminary Questionnaire (PQ) procedure. This means that the member state standardization organizations agreed on the need for a WIM standard, and to use this document as a draft standard, to be improved and submitted for a final vote.

2.2 Structure of the proposed Standard

The standard contains all three elements necessary for the successful installation: type approval, verification or assessment of accuracy, testing and operation of WIM systems (Figure 1).

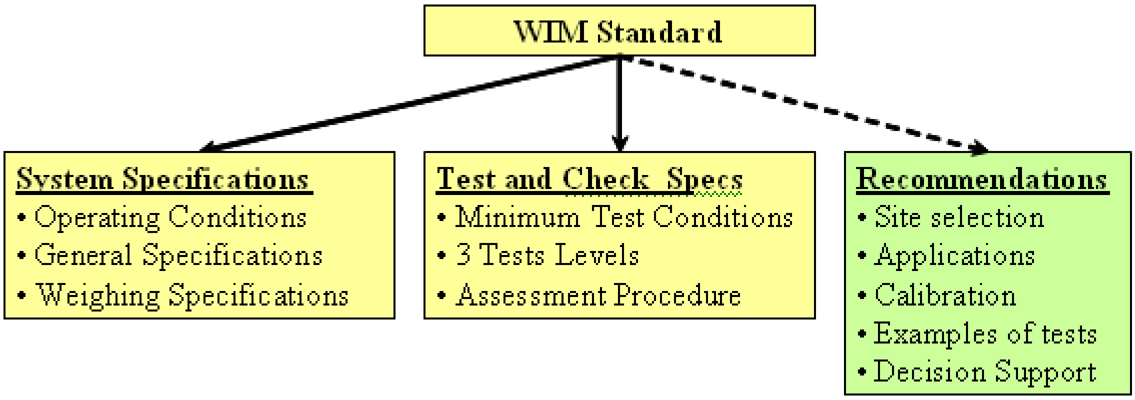

Figure 1 – Structure of the Draft Standard

System Specifications

The requirements to assess the performance of the system consist of the operating conditions, general specifications and weighing specifications:

- Operation conditions: within the rated operating conditions a WIM system shall perform according to the specifications. The operating conditions consist at least of ranges for traffic intensity, vehicle speeds, temperature, humidity, electromagnetic and mechanical conditions, as specified in chapter 5.
- Weighing specifications, consisting of the accuracy of the single axle load, axle of a group load, group of axles load, and gross vehicle weight, are specified in the chapter 6 by 6 classes: A(5), B+(7), B(10), C(51), D+(20) and D(25). Additional classes E(30) and below are given for low performance systems. The weighing intervals [min, max] where these specifications should be met are also specified, as well as the maximum scale interval per accuracy class.
- General Specifications, other specifications for non-weighing related measurements that are performed by the WIM system are given: minimum rate of detection (percentage of vehicles detected by the system), minimum rate of complete registration, axle spacing

and vehicle length and/or wheelbase accuracy, minimum rate of correct vehicle classification and time stamp accuracy.

Test and Checking Specifications

They describe how the test should be done in order to verify if the WIM system meets its specifications. Three different types of test are distinguished:

- Type Approval Test: first extensive test of a new type of WIM system where the performance of the system is tested extensively under the full operating ranges. The results of this test may be used as a European (or even international) reference. They will also form the basis for the other test types for the same type of systems. It is planned to further develop this section in future versions of the standard.
- Initial Verification: test made after installation or significant repair of a WIM system in order to assess the performance of this system under the specific conditions at the site where the system is installed. The results of this test are used for the acceptance decision by a buyer;
- In-Service Verification: test to verify if an in-operation system is still performing within the specifications. This is a relatively limited test carried out when a system has been operational for a period of time.

A standard procedure is given to assess the accuracy of a WIM system by testing. It describes how to analyze test results, and then, based on the sample statistics and test conditions, how to determine the accuracy class obtained.

Recommendations: non-mandatory but very useful practical information on the installation and operation of WIM systems based on decades of international experience is given. It contains information on site selection, possible applications, calibration procedures, standard test plans, alternative decision support procedures to check the accuracy by testing, and data storage and transmission format. The site selection specifications (chapter 4) are only mandatory to refer to an excellent, good or average site, in client specifications or call for tender prescriptions. Calibration methods are described in chapter 7 and are recommended, but other methods may be used.

2.3 Content of the proposed Standard

In order to satisfy the need for a simplified procedure without losing the valuable knowledge and flexibility of the original COST323 specifications (Jacob et al., 2002), the new standard was divided in two parts, as shown in Figure 2.

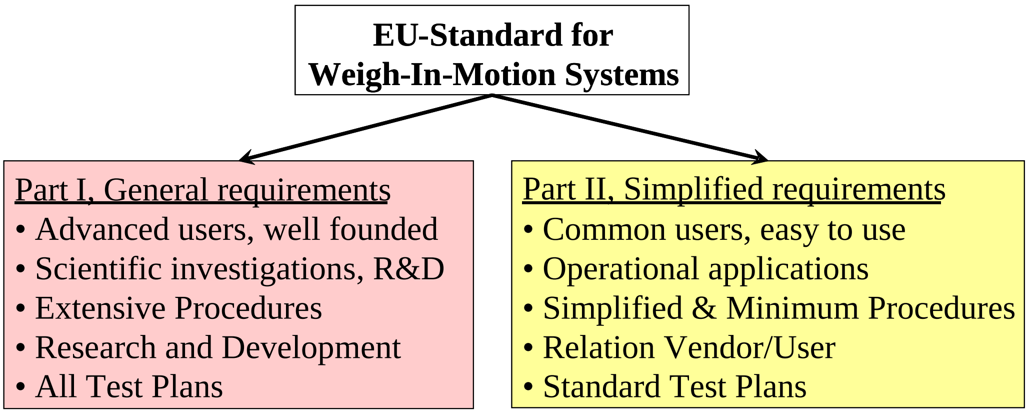

Figure 2 - Content of the proposed European Standard

Both Parts I and II are based on the same structure as described in §2.2, while some chapters or sections are common to both parts. To avoid unnecessary duplication of information some chapters are described only in Part I, and referenced in Part II. The document is divided into the following chapters:

Chapter	**Content**
1.	Scope
2.	Normative References
3.	Terminology and Symbols
4.	WIM Site Selection Criteria
5.	Operation Conditions and Environmental Requirements
6.	Accuracy Class Tolerances with Respect to the Weights (Accuracy Classes)
7.	On-Site Systems Checks and Calibration and Test Conditions
8.	Type (Model) Approval
9.	Initial and In-Service Verification
10.	Procedure to Check the Accuracy of a WIM System by Testing
11.	Data Storage and Transmission

Chapters 1, 2, 3, 4, 8, 9 and 11 are common to both parts. Chapter 5 is very similar in each part, with more clauses on sensor and electronic requirements in Part I. The accuracy classes defined by tolerances (with tolerance intervals) are common to both parts (chapter 6), as well as the definitions of environmental conditions E1 to E3, and vehicle sample conditions R1 to R4 (chapter 7).

2.4 Differences between Parts I and II

Part I provides general requirements that apply to any test conditions, sample size and types of vehicles, and therefore offers full flexibility. It gives detailed clauses to address all cases that may be encountered in practice, and a full procedure that allows in-depth analysis of any test results and discrimination of the performances of WIM systems. This procedure is based on statistical interval estimation procedures described in (Jacob, 2000). This part is needed for scientific investigations of WIM system behavior and performance assessment, analysis of the details of extensive tests, and understanding of the background information.

Part I provides formulae and tables to assess the accuracy class of a series of measurements, using the tolerances δ given in chapter 6, and comparing a confidence level (or estimated probability that the tolerance interval contains an individual measurement) calculated as a function of the sample statistics (n, m, s) of the relative errors[3], to a minimum required confidence level π_0 (given probability) with respect to the test conditions E1 to E3 and R1 to R4, and the sample size. Tables provide the π_0 values for each test conditions and sample size. The more repeatable the test conditions, the higher the required confidence level π_0; the larger the sample size, and the higher the required confidence level. The procedure is the same as in the COST323 specifications, and founded on a statistical background described in (Jacob, 2000) and (Jacob et al., 2000). If for a proposed accuracy class δ, $\pi \geq \pi_0$ the class is accepted. If not, and while π is an increasing function of δ, a lower accuracy class (for an increased tolerance δ) is used, and the test is repeated with the new π value, and so on. Alternatively, the lowest tolerance δ_{min} which exactly leads to $\pi = \pi_0$, is computed and gives the higher accepted accuracy.

Part II provides simplified minimum requirements of practical use.It is intended as an easy to use reference to facilitate the relation between buyers and vendors. Part II uses a default confidence level of 95%, which complies with four proposed standard test plans, with specified test vehicles, load and speed configurations and number of runs, and is justified by two reasons:

- Using a default confidence level makes it easy to compare the test results from different WIM systems while still using the well known – and easy to use - way of classification of WIM systems (classes A – E).
- The use of a tolerance interval combined with a standard confidence level of 95% is similar to the common description of measurement equipment specifying the 2σ interval around the mean error containing 95% of all measurements. This approach makes it easier for people with limited knowledge of WIM systems and/or test statistics to understand the outcome of an acceptance test.

Part II suggests two simplified methods to assess the accuracy class of a series of measurements collected following one of the four standard test plans, using the sample statistics (n, m, s). One method uses chart diagrams while the other uses simple formulae to calculate a "sample tolerance" to be compared to the standardized tolerances given in chapter 6. The accuracy class assessment may be performed by a pocket calculator using the chart diagrams or the simple formulae.

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[3] $\pi = \Phi(u_1) - \Phi(u_2)$, where $u_1 = (\delta - m)/s - t_{\nu,1-\alpha/2}/n^{1/2}$ and $u_2 = (-\delta - m)/s + t_{\nu,1-\alpha/2}/n^{1/2}$,

Φ is the cumulative distribution function for a Student-*t* distribution, and $t_{\nu,1-\alpha/2}$ is a Student variable with $\nu = n$-1 degrees of freedom. α is taken equal to 0.05

Part II suggests alternative procedures to assess the accuracy by testing using the sample statistics (n, m, s), (e.g. the Tolerance Interval Procedure (Lieshout, 2000)) and the YONA program (Slavik, 2008), called decision support programs.

2.5 Main Additions compared to the COST323 Specifications

The main additions with respect to the original COST323 specifications are:

- In the simplified requirements (part II), a default confidence level of 95% is specified.
- The vehicle sample conditions R1 to R4 replace the former repeatability and reproducibility conditions (r1, r2, R1 and R2).
- Minimum test conditions were specified (number of vehicles and runs, variations in the environmental conditions), with respect to the type of verification to be performed.

3. HS-WIM for direct Enforcement

The next step and challenge is to improve and adapt HS-WIM systems to direct enforcement purposes (Jacob and van Loo, 2011). There is a strong demand for that in Europe. If successful, that may open new markets for WIM vendors. Presently, there are several barriers preventing the use of HS-WIM for direct enforcement, such as a lack of appropriate certification. Therefore it will be necessary to develop a structure and procedures for the acceptance of WIM systems for overloading direct enforcement.

A potential description of a harmonized European procedure for the type approval, testing and certification of WIM systems by the legal metrology is given in Figure 3. That covers the organizational aspects of how the procedures will work in the future, the types of organizations that will be involved, and their roles in the process.

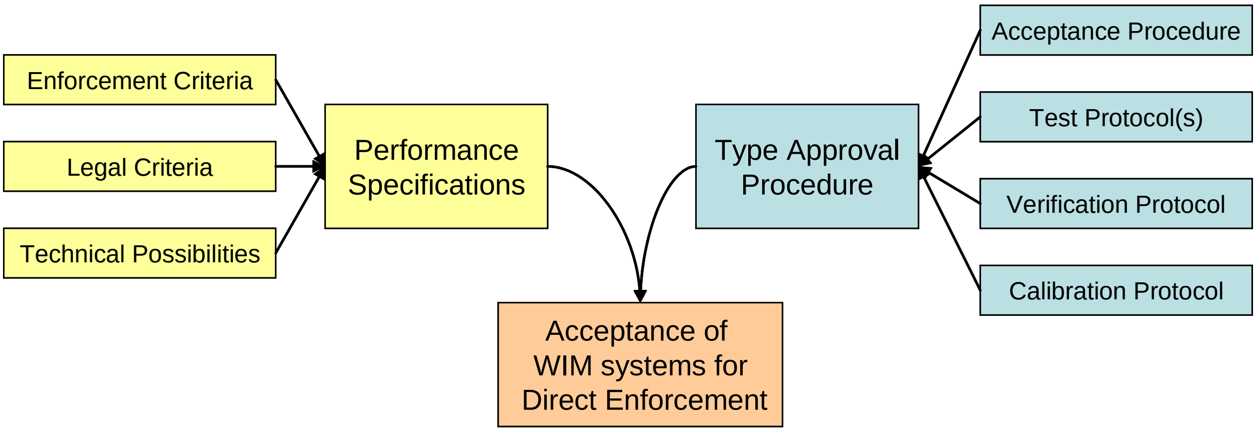

Figure 3 - Acceptance of WIM for direct enforcement

In 2011 the Czech Republic became the first European country to allow the use of HS-WIM systems for direct enforcement of overloading (Doupal and Kriz, 2011). Two different types of WIM systems were verified and type approved according with the new Czech national traffic law. The performance tests, evaluation and certification on were done by the Czech

Metrology Institute (CMI). The used test procedures are a compilation of the OIML R-134-1, ASTM E-1318, COST323 and FiWi documents.

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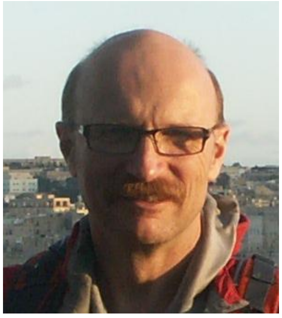
TESTING AND CERTIFICATION OF WIM SYSTEM

Obtained a Master of Science in Mechanical Engineering at the Swiss Federal Institute of Technology in Zurich (ETH). Currently employed at Kistler Instrumente AG as Manager of the Road and Traffic Market Segment, which includes the WIM technology.



Obtained a PhD degree in physics at the Swiss Federal Institute of Technology in Lausanne (EPFL). Currently head of the force, torque and pressure laboratory of METAS, the National Metrology Institute of Switzerland. Member of the work groups for force and for pressure of the Consultative Committee of Mass.

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Abstract

In recent years the development of new applications for WIM systems has resulted in an increased need for standards for performance assessment, testing and certification of WIM systems. This paper describes the results of extensive tests of a WIM system based on Lineas quartz sensors which were performed in a climatic chamber as well as on the road. The purposes of the tests were to assess the performance of the sensor and system according to different international standards and to evaluate possible differences among the standards as a basis for new certification procedures. The tests were performed by METAS (Swiss Federal Office of Metrology) according to the OIML R134 specifications. The results were then analyzed using other methods such as COST323, ASTM E1318 and YONA.

Keywords: Weigh-In-Motion, WIM, Performance, Specification, Testing, Certification, Norm, OIML R134, COST323, ASTM E1318, YONA.

Résumé

Ces dernières années, le développement de nouvelles applications pour le pesage en marche a entrainé un besoin accru d'évaluation des performances, de tests et de certification des systèmes de pesage en marche. Ce papier décrit les résultats d'importants tests réalisés sur un système de pesage en marche, avec des capteurs quartz, en conditions de laboratoire et in-situ. Les objectifs de ces tests étaient d'évaluer la performance de ces capteurs et de ce système, conformément aux normes internationales, ainsi que d'évaluer les différences entre les normes pour obtenir les bases d'une nouvelle procédure de certification. Ces tests ont été réalisés par METAS (l'Office Fédéral Suisse de métrologie), en suivant les spécifications de l'OIML R134. Les résultats ont alors été analysés avec d'autres méthodes, telles COST323, ASTM E1318, YONA.

Mots-clés: Pesage en marche, WIM, performance, spécification, test, certification, norme, OIML R134, COST323, ASTM E1318, YONA.

1. Background

Since the introduction of Weigh-In-Motion (WIM) decades ago, the main performance requirements for WIM sensors and systems have been the accuracy and repeatability of their measurements. Nowadays, these aspects of the performance of a WIM system remain of great interest for both users and suppliers; however, a third aspect has been added: reliability. Over the years, not only has WIM technology improved, but also the WIM applications have developed from 'Data Collection for Statistics' to 'Pre-selection for Enforcement', 'Tolling by Weight', and ultimately to 'Direct Enforcement'. These new high-end applications have resulted in a need for high-quality data which should be guaranteed over time. This means that there is a need for certification of WIM system performance. Such performance certifications must be based on national or international standards, specifying the system performance and the test procedures required to verify the performance.

In the field of WIM, a number of international norms or standards for vehicle weighing already exist, such as COST323, ASTM E1318 and OIML R134. However, all of these standards have their own specific advantages and disadvantages:

- The OIML R-134 recommendation (OIML, 2003) is widely accepted, as it is supported by the International Organization for Legal Metrology. However, the recommendation only applies to WIM systems installed in a controlled weighing area where the vehicle speed is controlled in order to eliminate the effects of vehicle dynamics. Some of the test methods described are applicable to WIM systems that are capable of measuring static loads.
- The COST323 Specification (COST323, 1999; Jacob et al., 2002) is widely used to assess WIM performance, but it is a non-normative document that was issued at the end of a European research project. During the FiWi (FEHRL institutes WIM initiative) project, an update of the COST323 specification (FiWi, 2010) was made and submitted to the members of the European Committee for Standardization (CEN) for public enquiry.
- The ASTM standard E1318 (ASTM, 2002) originates from North America and provides practical information on user requirements and test methods. It also contains minimum requirements for the quality of the pavement to ensure reproducible results. Although the quality of the pavement has a major impact on the performance of the WIM system, it is not part of the performance of the WIM system itself.

2. Introduction

To set a basis for future WIM certification, Kistler decided to perform an extensive test on one of its WIM systems. The purposes of the test were:

- to assess the performance of the quartz WIM system according to the OIML R134,
- to evaluate possible differences in the results when applying the COST323 and ASTM E1318 standards,

- to gain experience with the requirements and specific characteristics of the three different test procedures.

To guarantee quality and independence, the tests were performed by the Swiss Federal Office of Metrology (METAS). The tests consisted of two separate parts:

- Laboratory tests performed on the Lineas WIM sensor. In particular, linearity, temperature behavior and stability were tested according to the OIML R134.
- In-motion tests of the complete WIM system installed in the road pavement.

The OIML R134 recommendation inherits a lot of features from the OIML R60 recommendation, like the thermal stability test, the heat damp test and the long-term stability test. The OIML R134 has several classes of maximum permissible error: 0.2, 0.5, 1, 2, 5, 10. An important specification of OIML is that, for the system certification or for the initial verification all the measurements, 100% of the data sets must be within half of the maximum permissible error; thus, a sensor of class 10 shall not have any measurement with a relative error greater than 5% for all of the tests performed.

3. Climatic and long term stability tests

Climatic and long term stability tests are required by OIML-R134 and are performed using a static load:

- Measurement at 20°C, 62°C, -40°C, 5°C and 20°C in dry condition from 0 kg to 6000 kg in 500-kg steps.
- Measurement before, at the end of 48 hours at 60°C with at least 85% humidity, and after cooling back to room temperature.
- Long-term stability test over a time span of at least 28 days as well as before and after the climatic tests and for at least seven measurements.

Figure 2 shows that the error of the climatic test remained lower than 2% in agreement with the requirements of Class 5 for OIML 134.

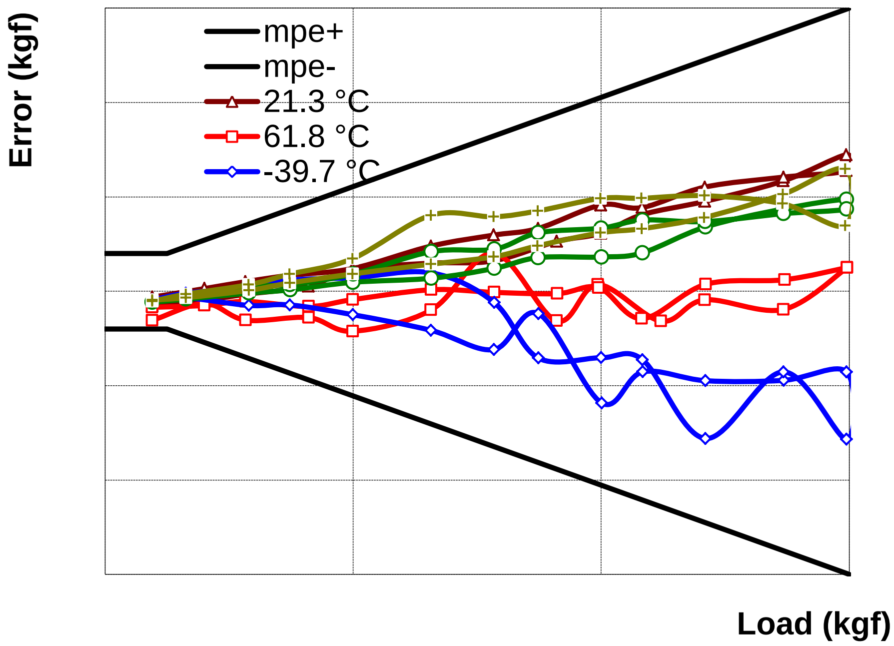

Figure 2 – Error for the several loading steps during the climatic test. The dark line shows a maximal permissible error of 2.5% as required for the Class 5 of OIML 134.

No significant difference was detected between the measurements made at 60° C and 90% relative humidity and those made at 60°C in dry air. The response of the sensor after the humidity test was similar to the response before it.

4. In-Motion Tests

4.1 Location and Test System

A special condition considered in the testing was the system performance at low speed. A minimum speed between 0 and 5 km/h was targeted. Therefore, a test location was selected in a former airfield near Interlaken, Switzerland. This location, being ideal for low speed, did not allow testing at speeds above 60 km/h with vehicles of 40 tons weight. Therefore, the speed range that was tested was 3 to 60 km/h.

For the test, a WIM system was used consisting of two sensor rows each with two 1.75m Lineas quartz WIM-sensors type 9195F411 and two induction loops laid as shown in Figure 3.

On the road side in the electronic cabinet, the sensor signals were processed through a 2-channel charge amplifier type 5038A2Y53 and then acquired and analyzed by a calculation unit. The road was an asphalt pavement in good condition, with a lateral slope of 2 %, a longitudinal slope of 0.5 % and with rutting maximum of 4 mm. The system was calibrated using a two-axle truck fully loaded, making 16 passes over the sensors at a speed of 11 km/h.

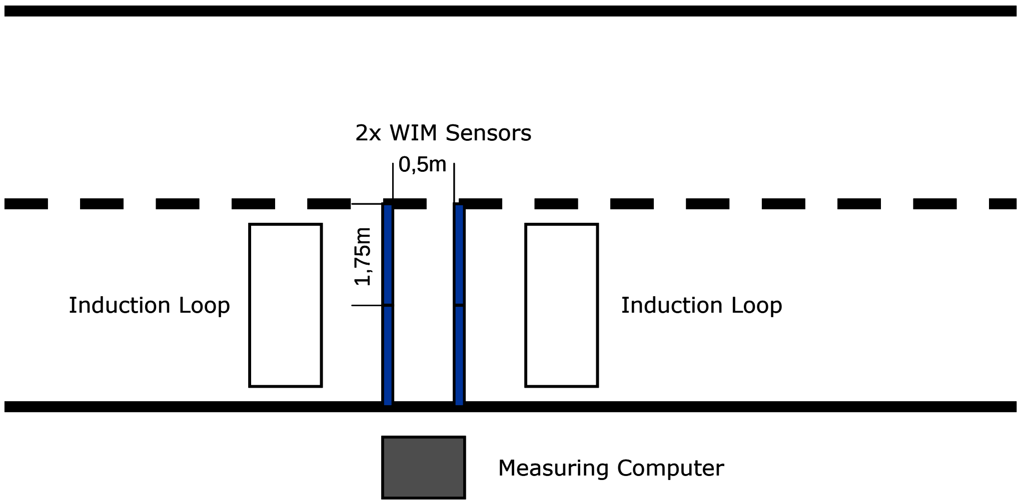

Figure 3 – Layout of test system.

4.2 Test procedure

The OIML R134 requires performing the in-motion tests at three different speeds: the minimum, the maximum and the middle speed (between minimum and maximum speed). In this case, the measurements were made at 3 km/h, 15 km/h, 30 km/h and 60 km/h to have a full set of results usable for an evaluation in different ranges with maximum speed of 30 km/h or 60 km/h.

According to the OIML R134, three different types of truck configuration must be used. The trucks selected were a rigid axle truck with two axles in order to assess the precision of the axle weighing, a four-axle leaf beam truck in order to qualify the system for use with leaf beam trucks, and a rigid 2-axle truck towing a 2-axle trailer.

Prior to the in-motion measurements, the trucks were statically weighed on four portable wheel scales (Dini Argeo, type: WWSE15T, uncertainty: 20 kg) calibrated using a dead-weight machine. Each wheel scale measured the load on a single wheel. Static determination of the weight was made in a place with less than 0.5% slope and by having the truck facing one direction for half of the measurements and facing the opposite direction for the other half of measurements (as prescribed in Annex A.9.3.1.3 of OIML R-134). The loads per axle and gross weights are listed in Table 1 with their respective uncertainties. The uncertainty is given as a combination of the uncertainty of the load cell and the repeatability of the measurement which has the largest contribution to the variation of the values. Despite the uncertainty of larger than 10 kg, the value of the load is given with 1 kg precision as this is required by the OIML R134 evaluation scheme.

Each truck was measured in an unloaded state and at maximum load capacity. For each speed, truck type and load, the test was performed twice on the left side, twice on the right side and five times on the centre of the sensor. The whole set of test results consisted of 216 measurements covering the different configurations of speed, type of truck and loads. A totlal of 720 individual axle load measurements was performed.

Table 1: Axle loads, gross weights, and their expanded uncertainties (k=2), measured using static scales and used as reference values.

Truck Type		Axle1	Axle2	Axle3	Axle4	GW
2 axles empty	Weight (kg)	5252	4368			9621
	U (kg)	25	25			20
2 axles loaded	Weight (kg)	7359	13209			20568
	U (kg)	100	100			50
4 axles empty	Weight (kg)	2716	3177	3969	3765	13618
	U (kg)	100	250	60	40	100
4 axles loaded	Weight (kg)	4607	5325	9365	9228	28527
	U (kg)	70	250	350	120	120
2 axles+ trailer empty	Weight (kg)	5252	4368	3527	3815	16963
	U (kg)	25	25	30	30	30
2 axles+ trailer loaded	Weight (kg)	7359	13209	9699	11563	41831
	U (kg)	100	100	160	180	70

5. Evaluation of in-Motion Tests

The measurement results of the in-motion tests were evaluated using four different methods: OIML R134, ASTM-1318, COST323 and YONA.

5.1 OIML R134

The in-motion measurements show that the maximum error with respect to the reference value for the gross weight is less than 5% (max. 4.76%) for all 216 measurements. Therefore, according to OIML R134, the system meets class 10. In a statistical analysis of the gross weight data, the standard deviation is 2.2 % and the mean value is 0.95%. For the axle weights, the maximum error is less than 15% (max. 14.69%) for all 720 measurements. The standard deviation is 3.5 % and the mean value is 0.85%.

The histogram in Figure 4 shows the distribution of the results for gross weights and axle loads. The x-axis shows the error (calculated as the relative errors between the weight measured in motion and that measured statically). The y-axis shows the number of measurements. Therefore, the curve indicates the distribution of the error.

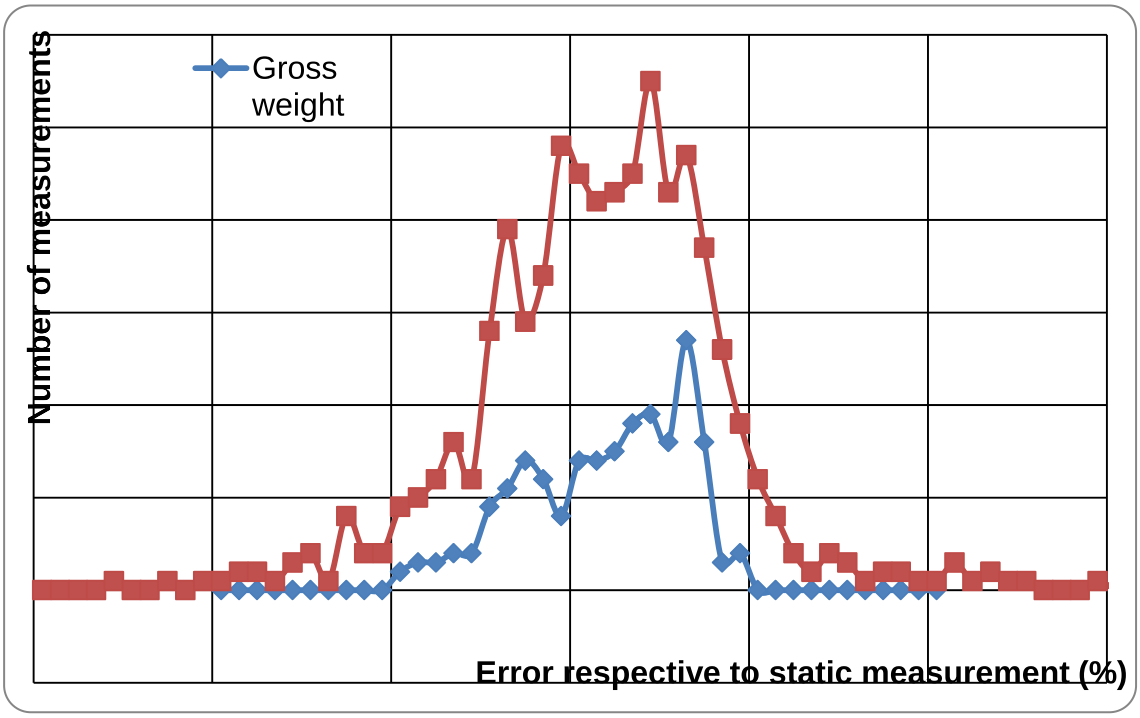

Figure 4 – Distribution of error for gross weights and axle loads. The standard deviation is 2.2 % for the gross weight and 3.5 % for the axle load.

The histogram of the relative error for the gross weight and the axle load is not a Gaussian distribution, but shows that several measurement populations are present. This is inherent to the requirement of OIML R-134 and the specific requirements of a limited set of measurements with drastically different conditions. The centre of gravity of the histogram is at +1 %, as the adjustment of the response of the sensor (calibration) has been made with a reduced set of variable conditions (just one vehicle, one load and one speed) compared to the variability used in the test. This offset is not a problem, since it is much smaller than the standard deviation of the measurements. Also it would be possible to reduce the offset to close to 0 % with a more sophisticated calibration procedure.

5.2 COST 323

The COST 323 recommendation gives a lot of freedom in the way the test of the system is conducted and provides some mathematics to determine the confidence interval based on the type of measurement. The way the dynamic test is required in OIML R134 is defined, in COST 323, as a measurement with limited reproducibility (R1) in environmental repeatability (I). The minimum level of confidence and the theoretical confidence level are given in Table 2. It appears that the results obtained comply with the requirements of COST 232 if all of the results are interpreted together. The sub-class of measurements made at 60 km/h fails to comply with the requirement of COST 323, presumably due to the dynamic effects of the vehicles at high speed. It has to be noted that the result for the gross weight fails in spite the fact that all of the points are within the tolerance of 5 %. This contradiction comes from the fact that in COST 323, a hypothesis on the distribution is made and the results are calculated based on the standard deviation and mean value. In this set of measurements at higher speed the measurements look more like a square distribution and are not well described by the hypothesis of COST 323. The difference is, however, marginal; it fails shortly in COST 323 while is complies with a tight margin in OIML-134.

Table 2: Analysis of the measurements, according to the mathematical model of COST 323. The two first lines include all of the measurements and are the conditions required by COST 323 while the two last lines are presented in order to compare the acceptance criteria.

Speed range	Gross weight / Axle	Sample (n)	Mean (m)	St.Dev. (s)	Tolerance A(5) (δ)	Min. Level. (π_0)	Theoretical confidence (π)
2 – 60 km/h	Gross	216	-0.95 %	2.23 %	5	96.0 %	96.1 %
2 – 60 km/h	Axle	720	-0.85 %	3.40 %	8	97.0 %	97.7 %
60 km/h	Gross	54	-0.65 %	2.62 %	5	93.7 %	93.2 %
60 km/h	Axle	180	-0.27 %	4.58 %	8	96.0 %	91.7 %

5.3 ASTM E1318

The ASTM E1318 standard defines several functional performance requirements. The Type III implies a maximum deviation of 6% for the gross weight and a maximum deviation of 15% for the axle load. Since both criteria are fulfilled, the system meets class ASTM Type III. However, it has to be mentioned that the maximum speed of the measurement is limited to
60 km/h in this test, while ASTM E1318 requires 130 km/h for class III.

5.4 YONA

The results of the test measurements were also evaluated using the YONA program (Slavik, 2008). YONA is not a standard, but a software tool for evaluating the performance of WIM systems. Based on the characteristics of a test sample, YONA provides a rating of the accuracy class for the system under test. The rating uses accuracy classes mentioned in the COST 323 recommendations for gross weight and single axle loads. As input, YONA requires information about:

- the test sample: sample size (n), mean error (m), standard deviation of error (s) and error source (vehicle mass or axle load measurements);
- the expected accuracy: delta (δ); this has no influence on the end result, only on the time the simulation needs to find the result;
- the settings for simulation: maximum percentage of excessive errors (Qcrit), minimum confidence level for the result of the assessment (Conf). For all evaluations, the values Qcrit = 5% and Conf = 95% were used, because this results in a value for delta where the accuracy interval [$-\delta$, $+\delta$] contains 95% of all measurements. This is similar to the [-2σ,$+2\sigma$] interval of the Normal distribution;

- the vendor risk (G) and buyer risk (B); for these values, default values were used, since they are not relevant for this type of evaluation.

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In this case, YONA was used to find the accuracy class (WIM rating) of the system under test for two situations: A) All speeds (5km/h, 15km/h, 30km/h, 60km/h) and B) High speed (only 60km/h). The results of the evaluation are shown in Table 3.

Table 3 – Results Assessment by YONA.

Speed range	Gross / Axle	Sample (n)	Mean (m)	St.Dev. (s)	Delta (δ)	Rating
2 – 60 km/h	Gross	216	-0.95 %	2.23 %	6%	B(6)
2 – 60 km/h	Axle	720	-0.85 %	3.40 %	8%	A(5)
60 km/h	Gross	54	-0.65 %	2.62 %	7%	B+(7)
60 km/h	Axle	180	-0.27 %	4.58 %	10%	B+(7)

The overall rating of the WIM system for all speeds is B(6), but for high speeds it is slightly lower, B(7). As can be seen in Table 3, the standard deviation for the (54 and 180, respectively) high-speed measurements is higher than that of all measurements together (high speed and lower speeds), due to dynamic effects as mentioned earlier. It must be noted that the rating obtained with YONA is very similar to the value obtained directly with COST 323.

5.5 Analysis

Table 4 – Rating Results for all Methods.

Method / Class	Vehicle Mass	Axle Loads
OIML R-134	Class 10	--
COST323 (2 – 60 km/h)	A(5)	A(5)
COST323 (60 km/h)	B+(7)	B+(7)
ASTM E1318	Type III	Type III
YONA (All)	B(6)	A(5)

Table 4 shows the rating results (accepted classes) from the different methods. The results from COST323, ASTM E1318 and YONA are similar. The rating of OIML R134 is almost 2 times higher, Class 10 instead of Class B(5) or B(6), respectively. The reason is that OIML R134 has separate requirements for initial verification that are 2 times stricter than those for in-service verification.

6. Conclusions and Recommendations

A WIM system consisting of two rows of Kistler Lineas WIM-sensors was tested and its performance was assessed; a total of 216 vehicle gross weights and 720 axle loads were measured by the WIM system and compared with the reference values measured by static scales, with results as follows:

- The system tested meets the OIML R134 requirements for Class 10 with a maximum measurement error of less than 5% for vehicle mass measurements.
- According to COST323, the system tested meets class A(5) for speed 3 – 60 km/h.
- The system tested meets the ASTM E1318 requirements for Type III systems; the maximum deviation is less than the required 6% for the gross weight and the maximum deviation is less than the required 15% for axle loads. However, this has been demonstrated only for speeds up to 60km/h instead of the required 130km/h.
- According to YONA, the system tested meets class B(6) for all speeds and class B(7) for high speeds (60km/h).

This test shows the differences in the rating results when different assessment methods are used. Difference has been noted between a recommendation that relies on the effective distribution of the measurements (OIML 134) versus recommendations that make assumptions on the distribution of the measurements (COST 323, YONA). WIM users need one internationally accepted reference for the performance of their systems that is both practical to use and scientifically well-founded. At the same time, this reference is equally essential for the WIM users to be able to confidently make an objective selection of which systems meet their requirements.

7. References

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MODERN CALIBRATION & VERIFICATION TECHNIQUES OF WIM DATA

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Abstract

With the evolvement of modern Weigh-In-Motion equipment both in the field of sensor and logger technology the way in which calibration and verification is undertaken has also changed. This paper discusses some traditional calibration and verification methods and suggests how to implement more reliable in-field and statistical calibration and verification methods.

Keywords: Weigh-in-Motion, WIM, Calibration, Verification, Front Axle Mass, FAM, Truck Tractor (TT) Method

Résumé

Avec l'évolution des systèmes modernes de pesage en marche tant au niveau de l'équipement que de la connectique, la manière dont sont réalisées la calibration et la vérification doit aussi changer. Ce papier discute de méthodes traditionnelles de calibration et de vérification, et suggère quelques manières statistiques et fiables pour réaliser ces mêmes opérations.

Mots-clés: Pesage en marche, WIM, calibration, vérification, charge sur premier essieu, FAM, méthode Truck Tractor (TT).

1. Introduction

With the evolution of Weigh-In-Motion equipment both in the field of sensor technologies and logger technologies, the way in which calibration and verification of WIM data is undertaken has changed. We discuss some aspects of these changes.

2. In-Field Calibration and Verification

Most of today's WIM systems use digital methods rather than a physical 'turn-the-knob' process to calibrate a WIM system. When a wheel moves over a given WIM sensor the signal from the sensor is digitized giving a set of signals (s_1, s_2, s_3… s_n) for the response generated by the wheel. These are then processed by the WIM logger using an appropriate signal processing relationship (f) to a single raw response (r) that is related to the weight of the wheel. The signal processing relationship (f) depends on the signals (s), on the type of sensors and may also depend on other variables, such as the speed, road surface deflection etc (variables x). The actual weight of the wheel (w) or axle is then related to this signal response through a calibration constant (C). One can thus write

$$w = C * r \qquad \text{where} \qquad r = f(s, x)$$

On old WIM systems this calibration 'value' (C) was set on the logger by physically turning a knob on a gain amplifier or by adjusting some resistor values. These adjustments were not digitized and often involved setting factors that were not linear. On many modern loggers, all adjustments are digitized and saved as part of the raw vehicle data or as part of the logger setup. The logger thus uses the digital calibration value C only to report on the final weight. It is thus possible to change the calibration value C in any given data set at any time by substituting the old value with a new value.

For modern WIM loggers this implies two things. Firstly one can use the same runs needed to calibrate the WIM system to also verify the WIM system. And secondly, the urgency of calibrating a WIM system after installation falls away as one can now post-calibrate all 'non-calibrated' WIM data after the WIM has been calibrated.

Since WIM systems measure the instantaneous in-flight weight, the weight measured by the WIM (w) differs from the static weight (W) from run to run. Under normal conditions this difference follows a normal distribution and the aim of the **calibration process** is to reduce the mean weight error or mean weight difference to zero.

The aim of the **verification process** is to determine the extent to which the WIM weights differ from the static weight. This is normally expressed as the standard deviation of WIM errors. This deviation gives information on how well the WIM performs and is used to determine the corrections required to relate a WIM weight distribution to the actual static weight distribution.

On WIM systems that required physical adjustments to the electronics a number of calibration runs had to be done, and the calibration 'knobs' turned, until the system was deemed calibrated; only then would one proceed with the verification runs. To get this calibration 'run' information is time consuming and also expensive. One is thus limited to the number of runs that one has available for either process and very often too few runs are actually done to determine the mean error (i.e. the calibration) with any degree of certainty. On a digital system one can use all runs to both calibrate and verify a system and thus increases the certainty without sacrificing any runs.

We now show, using classical statistics, how the number of runs affects the certainty with which we can determine the calibration and why it is advantageous to use both the 'calibration' and 'verification' run information as one set. The relative error (e_i) between the WIM weigh result (w_i) and that of the statically weighed vehicle result (W) is defined as (expressed as a percentage)

$$e_i = 100 * (w_i - W)/W$$

If we have (n) samples then the mean error ($\underline{x}$) and standard deviation of error (s) are given by

$$\underline{x} = (\sum e_i) / n \qquad \text{and} \qquad s = [\{ n (\sum e_i^2) - (\sum e_i)^2 \} / n (n-1)]^{½}$$

A WIM system is typically calibrated by adjusting the calibration factor C such that the mean error ($\underline{x}$) is ZERO. If one uses the individual axles for calibration, for example, then the calibration factor C is

$$C = (\sum W_a) / (\sum r_{ai})$$

If the number of samples (n) is large then the calculated mean error ($\underline{x}$) approximates the true mean error (μ) well, but if the number of samples is small then the difference between $\underline{x}$ and μ can be quite significant. The same applies to the accuracy with which the calculated standard deviation (s) approximates the true standard deviation σ. Classical statistics tells us that the confidence interval $A(1-\alpha)$ for the mean with n samples (and n small) is given by

$$\underline{x} - t_{\alpha/2}\, s / \sqrt{n} < \mu < \underline{x} + t_{\alpha/2}\, s / \sqrt{n}$$

where $t_{\alpha/2}$ is the value of the Students t distribution with n-1 degrees of freedom and leaving an area of $\alpha/2$ to the right of the distribution

Similarly the certainty with which we can determine the true standard deviation σ is also dependent on the sample size and the confidence interval is given by

$$(n-1)\, s^2 / \chi^2_{\alpha/2} < \sigma^2 < (n-1)\, s^2 / \chi^2_{1-\alpha/2}$$

where $\chi^2_{\alpha/2}$ is the chi square distribution with n-1 degrees of freedom leaving and area of α/2 to the right of the distribution

For example, if one is dealing with an ASTM Type I WIM system, then one expects that 95% of the individual axles weights fall between ±15% of the static weight i.e. one would expect a σ of no bigger than 7.6%. If one plots the expected uncertainty of the calibration at 95% confidence for the number of available samples then one gets the plot in Figure 1.

Typically, a 5 axle (122) vehicle is used to calibrate and verify a WIM system. Usually 2 runs are done to 'calibrate' the system and 10 runs to verify the system. If one uses the individual axles to calibrate the system, then each 'run' adds 5 samples to the sample set. After the first run we have a potential error on our calibration of 13%, after the 2nd run the error 7% while after 10 runs the potential error has reduced to 3% (Figure 1).

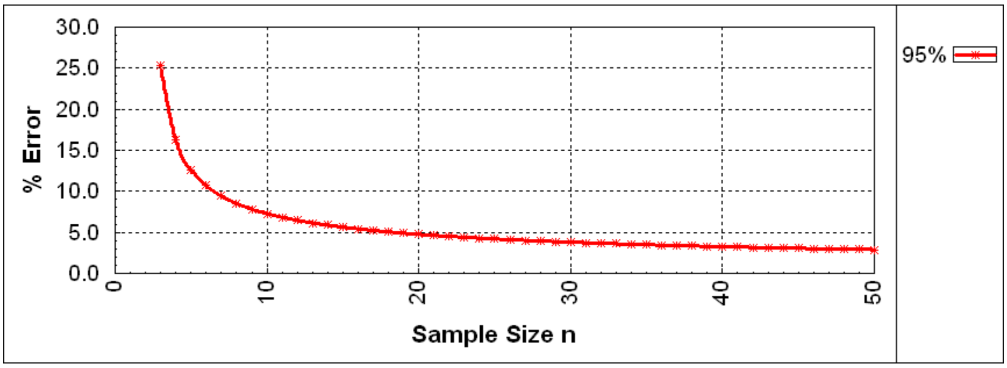

Figure 1 – % Error on the calibration of an ASTM Type I WIM as relates to sample size.

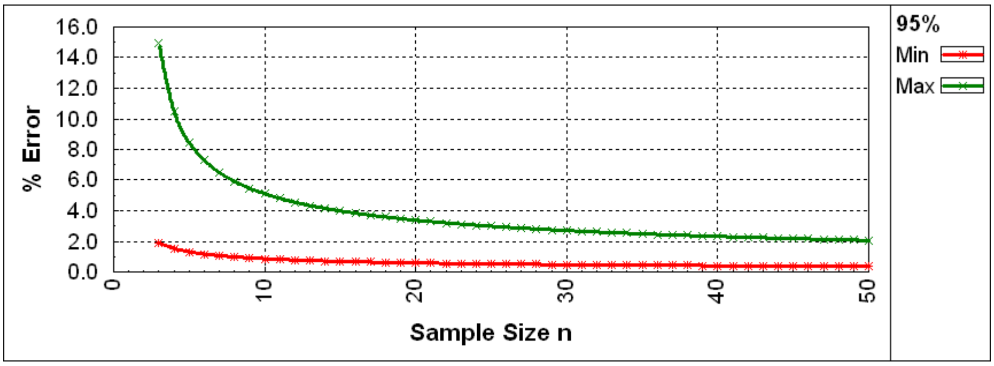

Figure 2 - % Error made when estimating the σ for axle weights on an ASTM Type I WIM

To determine whether a system performs within specification the system is verified using 10 runs, thus 50 axles. On an ASTM Type I WIM (15%) one could then end up overestimating the WIM performance (s) by 0.4% or underestimating its performance by 2% (Figure 2).

So, if one were to use only two runs to calibrate then there is a BIG chance that one does not get the calibration right. Clearly more effort should be placed on the calibration of the system, rather than verifying the system. If the system is fully digital, then all sample sets can be used for both the calibration and verification of the WIM system.

3. Statistical Verification and Statistical Calibration

The calibration of a WIM system can drift over time and the performance of the system can also degrade over time. One needs to correct for this drift and catch degradation in time. Traditionally most WIM users were using the average Front Axle Mass (FAM) from a given class of trucks as a reference to check the calibration of the WIM data and the standard deviation of the FAM to check for failure or degradation (not discussed here). This method is dependent on the loading of the selected trucks (full or empty) and also dependent on the location of the WIM (i.e. whether it is located on an incline or decline and what the cross-fall at the WIM site is). Never-the-less, with site specific knowledge on the behaviour of the FAM at a given site, this reference is still a good check to evaluate the drift and performance of a WIM system.

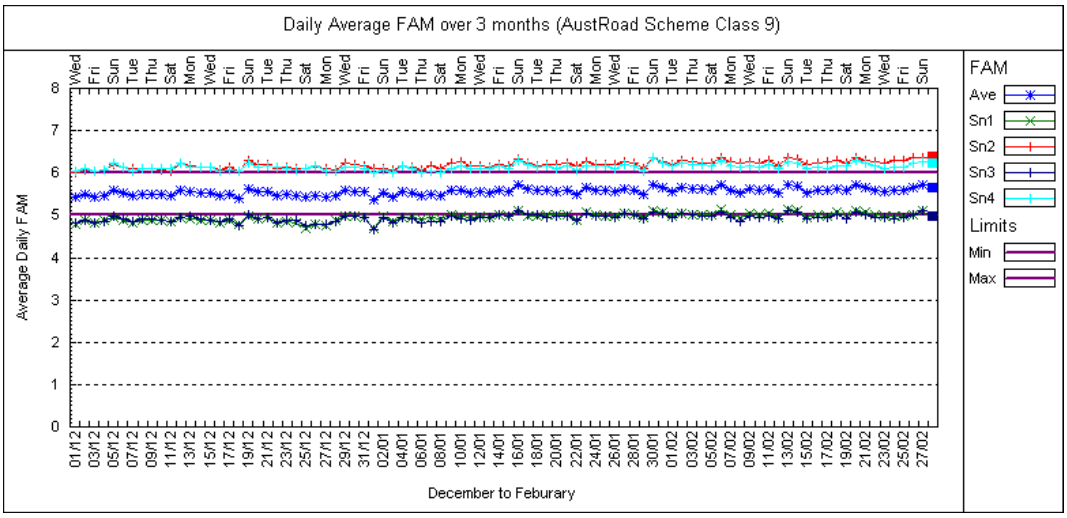

Figure 3 – Average daily FAM for 6 axle articulated vehicles (Dec 2010 to Feb. 2011)

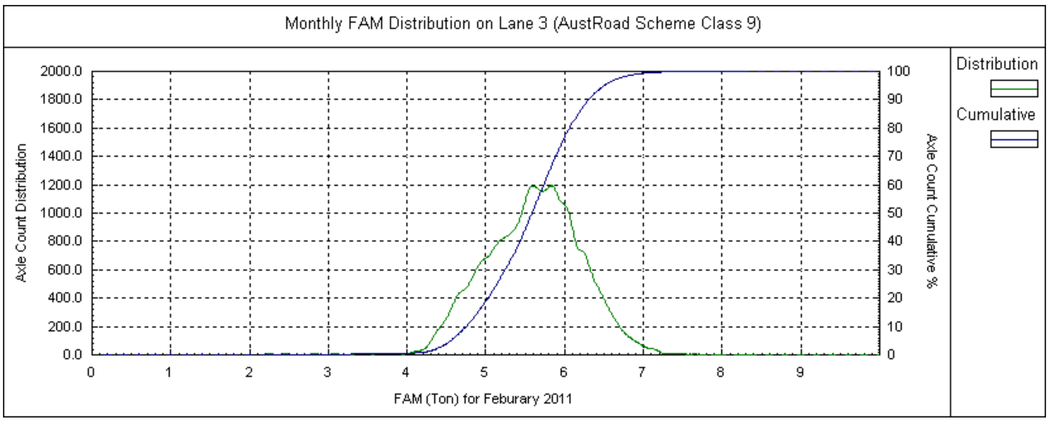

Figure 4 – Average FAM Frequency Distribution of 6 axle articulated vehicles

As an example the authors chose a WIM site in Australia that has 4 WIM sensors; sensors 1 & 3 in the left and 2 & 4 in right wheel track. The site was calibrated at the end of November 2010 using a 6 axle (123) uniformly loaded truck. Calibration was done by setting the GVM error on all 4 sensors to zero. In Figure 3 the daily average FAM of all 4 sensors for all 6 axle articulated trucks is plotted. The FAM is fairly stable over short periods (a month) except perhaps on Sundays and Mondays when it abruptly climbs. Over long term the FAM seems to rise. In Figure 4 the average FAM for February is shown as a frequency distribution. The mean FAM for these trucks is at around 5.6 Ton and has a standard deviation of 0.7 Ton.

If one splits up the trucks according to their loading as Full (>80% of GVM legal limit), Half (>50% but <80%) and Empty (<50%) and plots these in the same fashion then on sees that the FAM is load dependent (Figure 5). The mean FAM for Empty, Half and Full trucks are 5.3, 5.6 and 5.8 Ton respectively. Clearly the mean FAM will depend on the loading of the selected trucks on a particular day. In Figure 6 the % loading is plotted and one can see that on a Sunday the mix of trucks changes; there are more loaded trucks. This explains why the FAM climbs on a Sunday (Figure 3).

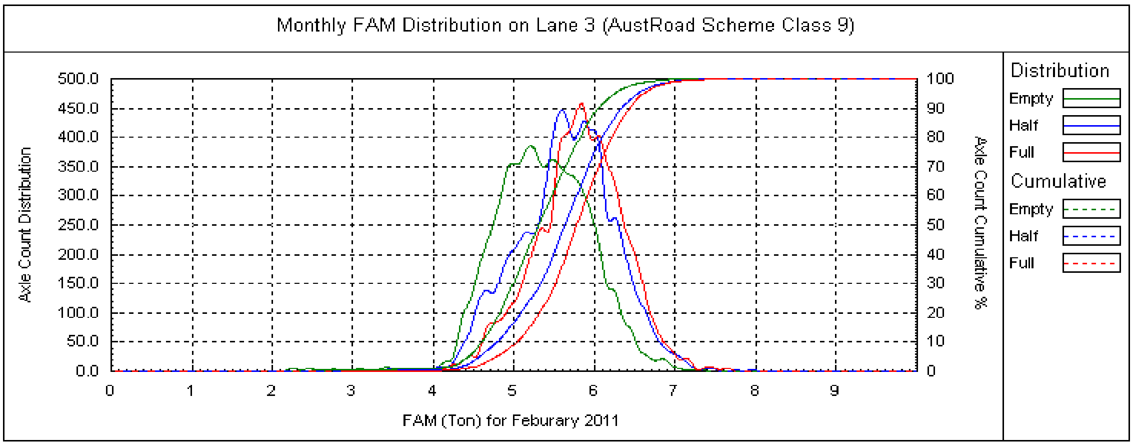

Figure 5 – FAM Frequency Distribution of Empty, Half and Fully loaded vehicles

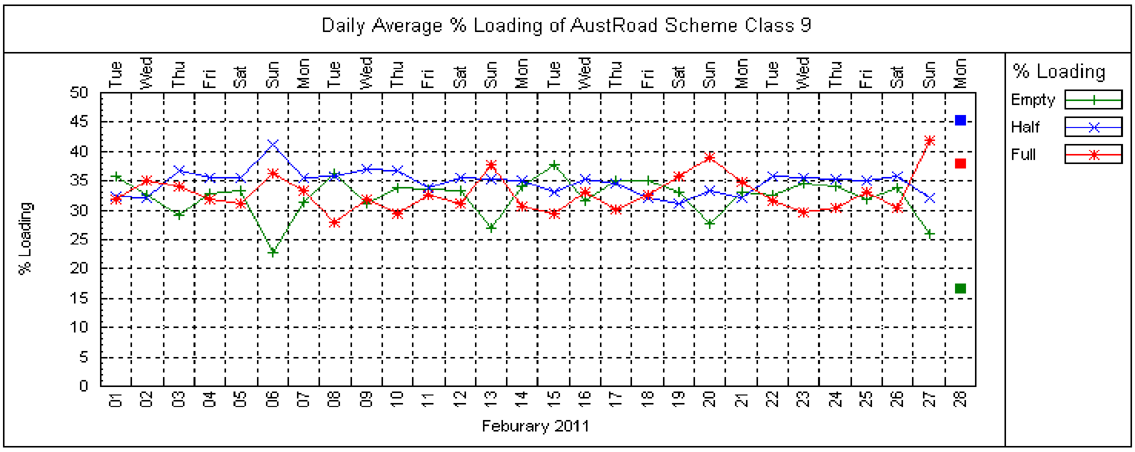

Figure 6 – Daily Average % Loading of Empty, Half and Fully loaded vehicles

If one looks at the FAM from each individual sensor then one observes that the sensors in the left wheel track ‘under weigh’ while those in the right wheel track ‘over weigh’ (see Figure 7). This is partially due to the fact that the calibration was done using static weights measured on a flat surface while the WIM site is at a camber. The mean FAM for the left sensors is approximately 4.95, while that for the right is approximately 6.25 and the average is at 5.6 Ton. This is a variation of ±10% between what the left and right sensors weigh for the front axle. The authors have observed these differences at a number of other sites in South Africa, Australia and the US too. In the US where trucks drive on the ‘other’ side of the road (compared to South Africa or Australia) the effect is the same except that left and right swaps. Great care and an understanding of the FAM limits must thus be taken when selecting the FAM as a parameter to check long term drift.

Notice that the means of sensor 2 and 4 do not coincide. When the system was calibrated at the end of November 2010 these did coincide (Figure 3). In Figure 3 one can observe a slow long term drift. The exact mechanism is not known but the drift can probably be attributed to settling of the WIM installation as the WIM was only installed in November 2010.

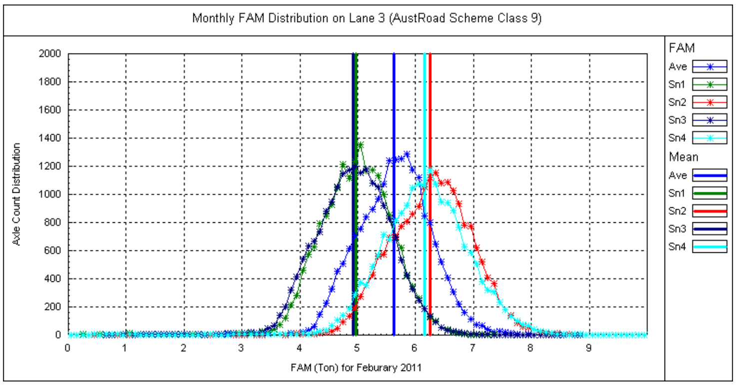

Figure 7 – FAM Frequency Distribution of individual WIM sensors (February 2010)

With the advent of faster computers, better methods, such as the Truck-Tractor (TT) method, have been developed (by De Wet and others) that allows one to verify WIM systems more reliably and to correct for long term drift. The principle of this method is that the whole tractor weight of a common loaded truck is used as a tracking and correction method. Their research had shown that the mean Truck Tractor weight of a large sample was 21.8 Ton. The correction method is based on a multi-pass process whereby the ‘calibration’ of the WIM data is adjusted by a factor k until the mean TT weight of the sample is 21.8 Ton. Two sample selection methods were proposed; one using a running count of trucks (say 600) and the other using a sample over fixed a period, say a month if there are sufficient loaded TT type trucks.

The method described by De Wet is for 6 and 7 axle trucks (123 and 1222) that are common in South Africa, but we found, not so common in Australia and the US. One has to adapt these methods. We have adapted the method to use 6 axle articulated trucks that are common in Australia and assumed, for now, that the target TT weight should be the same for left and right sensors. The actual target mass used by the authors (23.5 Ton) has still to be confirmed. In Figure 8 the frequency distribution of the Truck Tractor portion of the trucks is plotted as well as the selected loaded trucks for the raw data and in Figure 9 the same after post calibration was applied. The k factors for sensors 1 to 4 were respectively 1.072, 0.906, 1.092 and 0.934.

The same method was applied to the data from December and January. The result of the post-calibration is that the slow drift has been removed (see Figure 10 and compare to Figure 3), but the average FAM of the left sensors is still below that of the right sensors. Further investigations are required to explain this.

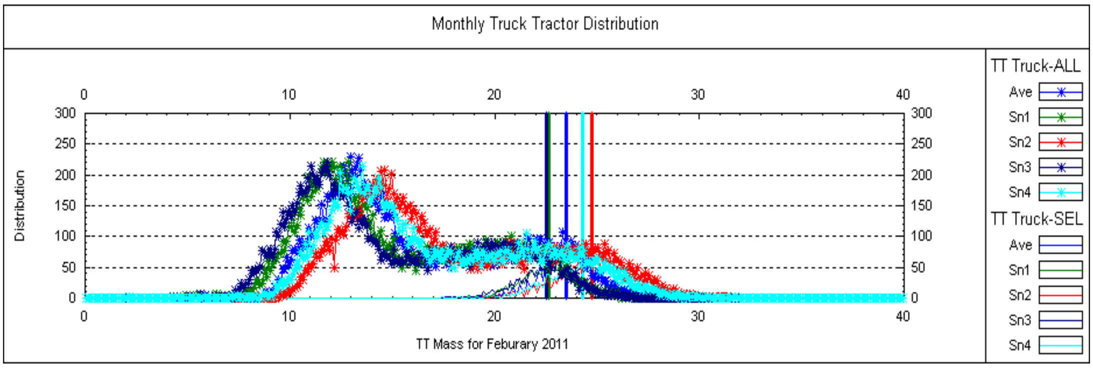

Figure 8 – TT Truck Frequency Distribution of the WIM sensors prior post calibration

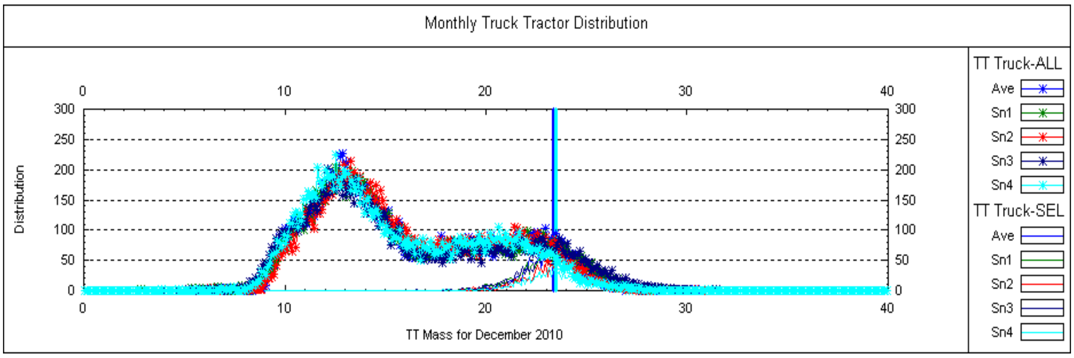

Figure 9 – TT Truck Frequency Distribution of the WIM sensors after post calibration

Statistical post calibration using the TT-Method can remove slow drifts in the calibration of a WIM system but further research is required on the TT target mass and on how to deal with sensor in the left and right wheel tracks for WIM sites that have a camber, as most sites do.

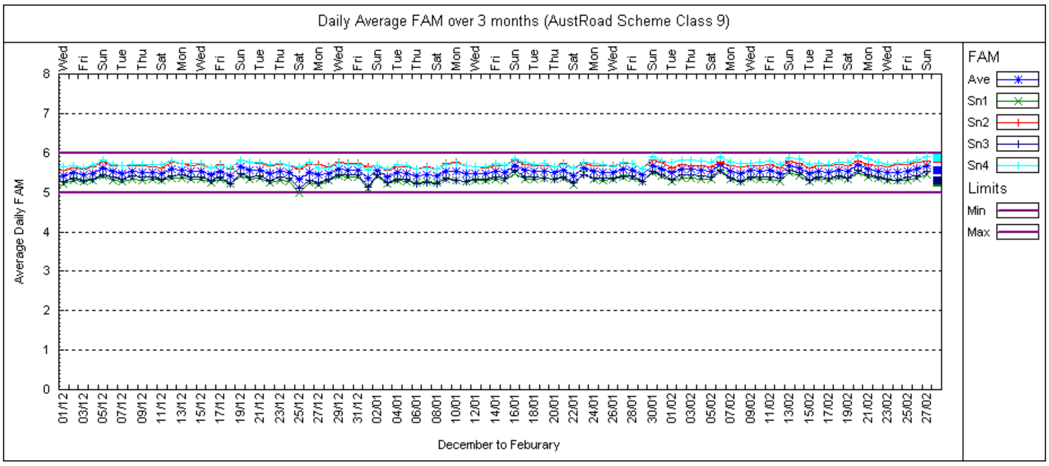

Figure 10 – Average daily FAM after post calibration using the TT Method

4. Conclusion

Providing the WIM data logger ensures the integrity of actual recorded raw data and no physical modification is done at a WIM site, modern statistical verification and calibration techniques can greatly improve the stability of WIM data. Ongoing research is still required to determine the role local traffic mix and vehicle configuration in the population plays in selecting reference values.

5. References

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ENHANCED AUTOCALIBRATION OF WIM SYSTEMS

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Abstract

This work presents the method of autocalibration of WIM systems. The algorithm allows for ongoing compensation of the influence of factors interfering with the system accuracy. Presented results of simulation tests have been supported with the results of measuring experiments on a WIM site equipped with two piezoelectric polymer load sensors. The results unequivocally prove predominance of the autocalibration method over the preliminarily weighed vehicles calibration method.

Keywords: Autocalibration, Weigh-in-Motion, HS-WIM

Résumé

Ce papier présente une méthode d'auto-calibration de systèmes WIM qui permet de compenser l'effet de facteurs affectant l'exactitude des résultats de pesage. Des résultats de simulations présentés sont obtenus par les conclusions des expérimentations de pesage sur des stations équipées de deux capteurs piézopolymères. Les résultats montrent clairement la supériorité de cette méthode sur la méthode classique d'auto-calibration utilisant des véhicules pré-pesés.

Mots-clés: Auto-calibration, pesage en marche, HS-WIM.

1. Overview of WIM System Calibration Methods

The aim of WIM system calibration is to determine the calibration coefficient C according to the equation:

$$y_s(i) = \frac{1}{C} \cdot y(i) \tag{1}$$

where:

$y_S(i)$ - calibrated result of weighing the i-th vehicle, i.e. evaluation of total mass of the vehicle or static load of a selected axle,

$y(i)$ - non calibrated result of weighing the i-th vehicle, i.e. the result of processing the signal from WIM system sensors.

In the process of calibration the key element is the reference value. The most often used method of WIM system calibration is preliminarily weighed vehicles, which is appropriate for the majority of weighing systems (Jacob et al., 2002). The whole process lasts between 5 and 8 hours and, despite the simplicity of the idea, it is hard to carry out due to many additional requirements (Huhtala, 1999). A different method consists in the use of an instrumented vehicle equipped with a measuring system that enables "self-weighing" (Kalibra, 2009). It is a significant advantage of the method that it enables precise determination of axle load on the sensor at the moment of measurement. Among the drawbacks of the method is the high cost of vehicle construction. Methods using static and dynamic force actuators are rarely used due to many disadvantages: e.g. it does not take into account the pavement/vehicle interaction. Described calibration methods are time-consuming and expensive and for these reasons are not normally carried out more often than every 6 months. Taking into consideration the fact that WIM systems with piezoelectric polymer sensors are nonstationary (LTPP, 2002) (Burnos, 2006), double calibration of the system in a year is not sufficient.

Increased frequency of calibration is possible by means of using a method that uses reference vehicles. Its grounds for the first time were formed in 1984 in the work (Stanczyk, 1984), and then developed in (Stanczyk, 1991): the idea of the method is based on the assumption that axle load or total mass of a characteristic vehicle group can be used as a reference value for WIM systems calibration.

2. Autocalibration

The autocalibration method consisted of a continuous estimation of the WIM system calibration coefficient and modification of weighing results according to the currently specified estimate. The basis of the method is the assumption that weighing results for a certain vehicle category participating in the traffic stream can be used as the reference value. The population of such vehicles should be characterised with the following features: 1) total mass or load of a given axle should have a known expected value and low relative random deviation, 2) the population of such vehicles should be large at the WIM site, 3) such vehicles should be easily recognisable by the calibrated system.

Vehicles that meet these terms will be referred to as the reference vehicles. This category of vehicles has been specified based on analysis of weighing results from a Multi-Sensor WIM (MS-WIM) system (Burnos et al., 2007) installed on road 81 in southern Poland (results of weighing over a million vehicles) and from the Polish Road Traffic Inspection Office (this institution uses precise static or low-speed scales with a legalisation certificate). Basis on statistical analysis of data, a category of five-axle articulated vehicles was specified, including a two-axle tractor with a three-axle semi-trailer, as a category of reference vehicle. Loading of the first axle of those vehicles is characterised by the lowest random variability among all examined categories of vehicles. Furthermore, this load is most weakly correlated with the loads of other axles and the total mass. This means that the load of this axle is relatively stable and insignificantly depends on carried load. A mean value μ_0= 61670 N of the first axle of reference vehicles was chosen as a reference value in autocalibration method.

2.1 Algorithm

Taking into consideration the fact that the calibration coefficient *C* should be specified in a continuous manner, a modified Weighted Recursive Least Squares algorithm with exponential forgetting factor (Vahidi et al., 2005) was used for computation. Modification of the algorithm was done by making the forgetting factor λ_n dependent on the time period between reference vehicles Δt_n by means of a weight function (Burnos, 2008).

3. Simulation Test

Sensitivity of the autocalibration method and the preliminarily weighed vehicles method (i.e., classic method) to 4 parameters of the weighing system was tested using simulation. The basis of the simulation tests was a model of a WIM system with special consideration for its nonstationarity. This model is excited with a simulated input, and its output is a simulated measurement result that undergoes calibration by means of the classic method or the autocalibration method. Comparison og the calibrated weighing result with the simulated excitation is the measure of system accuracy.

3.1 WIM System Model

The model of the WIM system has been assumed in the form described by equation (2). It gives consideration to three major reasons for errors of weighing results: system nonstationarity, changes of sensitivity along the load sensors and spatial repeatability of axle load.

$$\begin{aligned} y^j(i) &= p^j(i)\cdot\left[C\left(T_a^m\right)+\sigma_z\cdot z\ \ (i)+\rho\ \ \right] = \\ &= p^j(i)\cdot\left[k\cdot 10^{w\cdot T_a^m(i)}+\sigma_z\cdot z\ \ (i)+\rho\ \ \right] \end{aligned} \qquad (2)$$

where: $y^j(i)$ – simulated result of weighing of the i-th vehicle by the j-th system sensor, $p^j(i)$ – excitation model – e.g. load of the first axle of the i-th reference vehicle, $C(T_a^m)$ – calibration coefficient model which depends on model T_a^m – changes of asphalt temperature, k, w, d – model coefficients, σ_z – parameter determining relative (referred to μ_0) variability of sensitivity along the load sensor, $z(i)$ – random component with uniform distribution from interval [-0,5 ÷ 0,5], ρ – constant value – bias error load (Jacob and Dolcemascolo, 1998).

3.2 Model of Reference Vehicle Axles Load

Assuming that in the moment of weighing the vehicle moves with constant speed V and load sensors are arranged uniformly within mutual distances Δ, then the temporary axle load on the j-th sensor counting from the arrival direction, can be calculated according to formula (3).

$$p^j(i) = P_0(i) + \sum_{k=1}^{M} P_k(i) \cdot \sin\left(j \cdot 2 \cdot \pi \cdot f_k(i) \cdot \frac{\Delta}{V(i)} + \varphi_k(i) \right) \tag{3}$$

where: j = 1, 2, 3, .. , P_0 – constant component - static axle load, P_k, f_k, φ_k – models of parameters of the k-th dynamic component of the load signal, respectively (Cebon, 1999): amplitude (linear model assumed), frequency (random variable with normal distribution) and initial phase (random variable with uniform distribution).

3.3 Model of Asphalt Temperature Variability

The model of asphalt temperature variability has been specified in the basis of the analysis of the measuring data gathered at WIM site in Gardawice in southern Poland. Sinusoidal variability of daily fluctuations of this quantity with a long-term tendency resulting from the change of the mean value due to changes of the seasons of the year has been assumed.

3.4 Model of Algorithm of Static Load Estimation

In the classic WIM system configuration with two (j=2) polymer sensors, the algorithm for estimation of static load $y(i)$ for the i-th vehicle is reduced to the mean value estimator:

$$y(i) = \frac{1}{2} \sum_{j=1}^{2} y^j(i) \tag{4}$$

3.5 Criterion for Weighing Results Accuracy Evaluation

As a criterion for WIM system accuracy estimation, the relative root mean square error (r.m.s) was selected as defined with the following formula:

$$\delta = \sqrt{\frac{1}{N} \sum_{i=1}^{N} \left(\frac{y(i) - P_0(i)}{P_0(i)} \right)^2} \tag{5}$$

Simulation tests consisted of the evaluation of the sensitivity of the algorithms for classic calibration and autocalibration to changes in the 3 parameters of WIM system defined below. The influence of changes of each parameter value on the weighing results accuracy was examined independently, which means that in a given simulation the value of only one of them, was changed and the other ones were held constant.

a) Δt_n – time period between reference vehicles, (reference value 0,05 h)

b) $\delta\sigma_p = \frac{\sigma_p}{P_0}$ – relative standard deviation of the simulated first axle load of reference vehicles (reference value 10%), where: σ_p – standard deviation of the simulated axle load, P_0 - constant component – static load of the simulated axle load,

c) A_{Ta} – amplitude of asphalt temperature changes (reference value 8 °C),

4. Classical Calibration and Autocalibration– Evaluation of Properties of the Methods

As presented in Figure 1a, the characteristics clearly indicate that the classic calibration method does not work well in the case of nonstationary systems. The autocalibration method provides almost double the accuracy of weighing results in given measurement conditions characterised by the reference values of the WIM system parameters.

The quality of the road influences the amplitude of the vertical oscillations of a vehicle ($\delta\sigma_p$). Despite doubts, random variability of the reference value is not a critical parameter of autocalibration method (Figure 1b), which indicates its usability at WIM sites installed on the worst quality roads.

The amplitude of the asphalt temperature influences the range of calibration coefficient changes, and at the same time the degree of system nonstationarity.

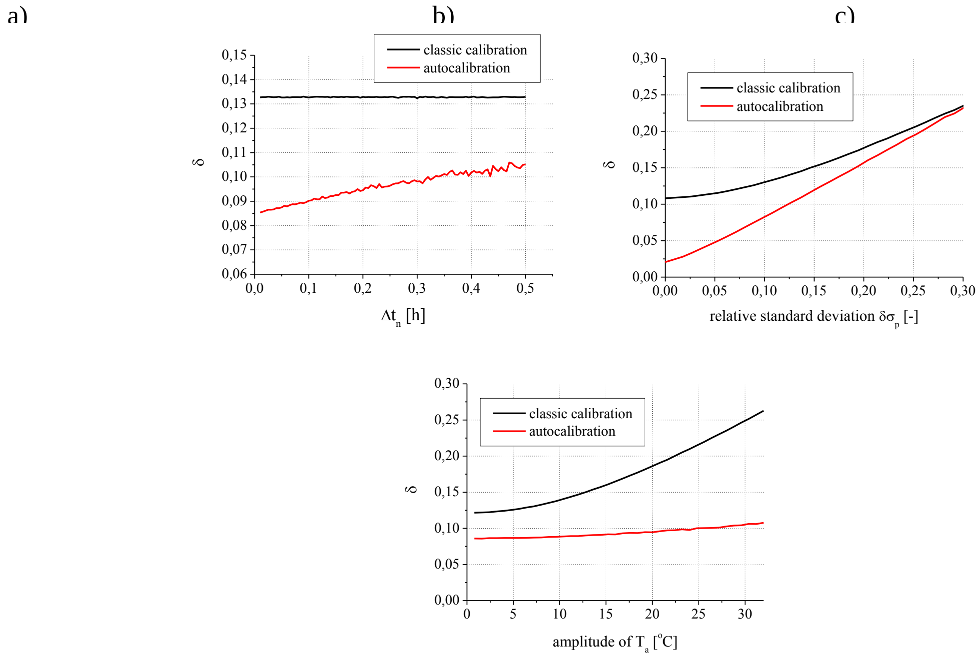

Figure 1 – Influence of: a) time periods Δt_n, b) relative variability of the load of the first axle of reference vehicles c) asphalt temperature amplitude on weighing results error.

The larger the amplitude, the higher is the nonstationarity of WIM system. The classic method of calibration indicates very high sensitivity to the changes of asphalt temperature amplitude (Figure 1c). The autocalibration method can be used in significantly nonstationary systems without major influence on calibration quality.

5. Experimental test – evaluation of WIM system accuracy

Evaluation of WIM system accuracy consists of comparing results for vehicles weighed with a WIM system with the results of weighing the same vehicles obtained using a static scale. Such an experiment was carried out one day in July 2008 in Gardawice between 4:30 a.m. and 8:00 a.m., as during the sunrise the largest changes of asphalt temperature occur. Unfortunately, due to particularly unfavourable weather conditions on that day (thick cloud cover), the asphalt temperature did not changed significantly until 8:00 a.m. With regard to organisational considerations, using preliminarily weighed vehicles was not possible after 8:00 a.m. Despite that, measurements were carried out until 12:00 p.m., and a few hundred weighing results of reference vehicles were recorded. Therefore, the experiment was carried out experiment in two stages: **Stage I** – 4:30 a.m. – 8:00 a.m. – 120 weighing results for preliminarily weighed vehicles and few dozen reference vehicles were recorded (due to thick cloud cover asphalt temperature did not change significantly within these hours); and **Stage II -** 8:00 a.m. – 12:00 p.m. – weighing results of reference vehicles passing through WIM station. During Stage II of the experiment weather conditions changed and the asphalt temperature grew rapidly (Figure 2).

a)

b)

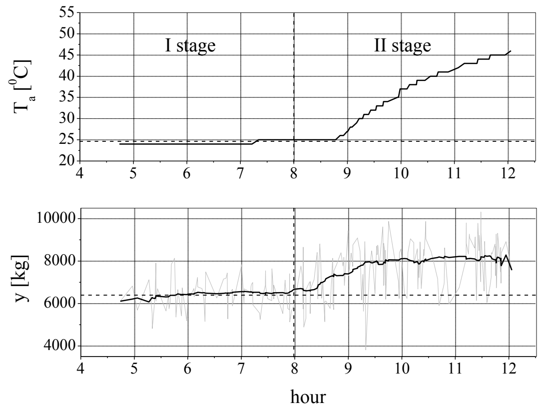

Figure 2 - a) Variability of asphalt temperature and b) load of the first axle of reference vehicles during the experiment.

R.M.S relative error was selected as the for evaluating WIM system accuracy, as shown in equation (5) where simulated results have been replaced with measured results. Additionally, in order to visualise the probability of occurrence of a specific value of relative error of weighing results, a reliability measure has been defined:

$$\Pr(\gamma) = 1 - P(\gamma) \tag{6}$$

where:

$\gamma = \left| \frac{y(i) - Ps(i)}{Ps(i)} \right|$ – absolute value of relative weighing error, $y(i)$ – result of weighing a given axle or estimation of the total mass of the *i*-th vehicle, $Ps(i)$ – result of static weighing a given axle (or the total mass) of the *i*-th vehicle, $P(\gamma)$ – distribution function of γ error.

5.1 Stage I

Three types of heavy vehicles with five axles were chosen for preliminarily weighed vehicles. According to the European Specification COST323 (Jacob et al., 2002), total masses of the vehicles selected to be 19980 kg, 26840 kg, and 35860 kg. Vehicles passed the calibrated WIM site 120 times at different speeds. Table 1 presents the evaluation of the accuracy of weighing results produced by a WIM system calibrated with the use of the classic method δ_{class} and autocalibration δ_{auto}, while Figure 3 presents the reliability characteristics. The obtained results indicate comparable accuracy of weighing results in a WIM system calibrated by the classic method and by autocalibration. However at this stage of the experiment asphalt temperature did not change; therefore, it is hard to generalise this conclusion for the case of a nonstationary system. The results, though, have demonstrated the usefulness of the autocalibration method as an alternative for the classic preliminarily weighed vehicles calibration method for WIM systems.

Table 1 - Weighing Accuracy of Preliminarily Weighed Vehicles – sample size: 120.

	δ_{class} [%]	δ_{auto} [%]
Axle I	7.5	8.5
Axle II	7.6	8.8
Axle III	10.8	9.1
Axle IV	6.2	5.9
Axle V	7.1	6.4
Total mass	4.7	5.4

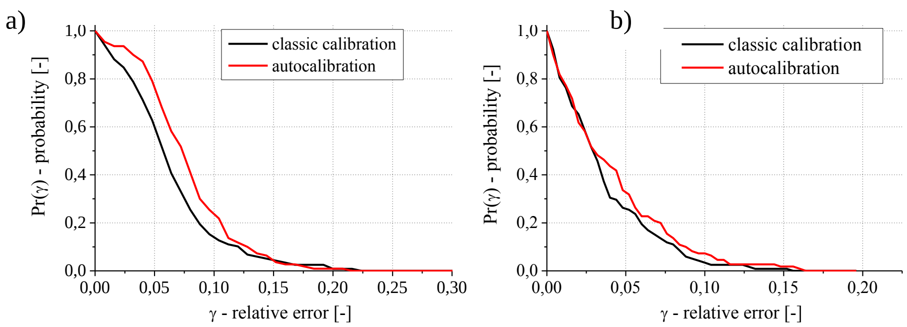

Figure 3 - Stage I: Reliability characteristics of weighing results a) the 1st axle of preliminarily weighed vehicles, b) total mass of weighed vehicles.

5.2 Stage II

From 4:30 a.m. until 12:00 p.m. in addition to the results of weighing preliminarily weighed vehicles, a few hundred weighing results for reference vehicles were recorded. Since the axle static loads of these vehicles were not known, an alternative method for evaluating system accuracy was used:

- Results of weighing reference vehicles gathered at Stage I were calibrated by means of the classic method, using the calibration coefficient specified at stage I,
- The mean value of the calibrated results of weighing the first axle of the reference vehicles was calculated at the first stage of the experiment. Since in this part of the experiment asphalt temperature did not change and the system was stationary, the calculated mean value has properties of a reference value and can be further used for evaluating accuracy of the system,
- Records of the results of weighing reference vehicles gathered at the second stage of the experiment (nonstationary system) were calibrated with the use of the classic method and the autocalibration method. Results obtained this way were compared with a reference value specified at the first stage.

In the second stage of the experiment, when asphalt temperature grew by 20 °C and the system was nonstationary, the distinct advantage of the autocalibration method in comparison to the classic method of WIM systems calibration is apparent. The accuracy of weighing results in the classic method is up to five times worse than in case of the method of autocalibration.

Table 2 - Weighing Accuracy of Reference Vehicles – sample size 222.

	δ_{class} [%]	δ_{auto} [%]
Axle I	18.0	3.6
Axle II	14.9	7.9
Axle III	21.5	8.0
Axle IV	22.0	8.8
Axle V	22.7	9.1
Total mass	19.1	6.7

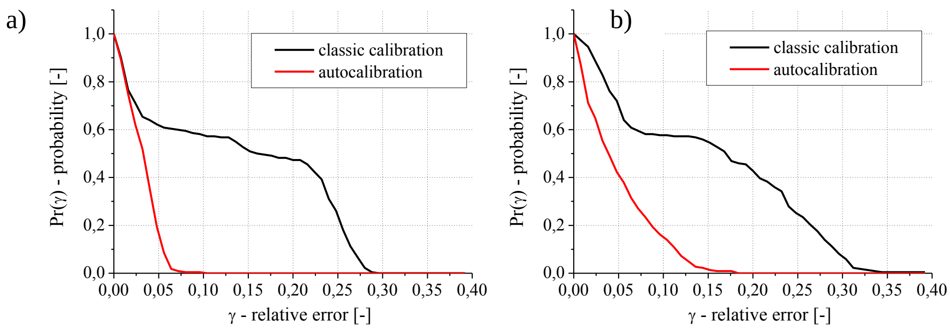

Figure 4 - Stage II: Reliability characteristics of weighing results a) the 1st axle of reference vehicles, b) total mass of reference vehicles.

6. Conclusion

The results of simulation tests and experiments presented in the work have proven that the uncertainty of weighing results in a system calibrated by means of the method of preliminarily weighed vehicles can reach several percent only a few hours after calibration. The method of autocalibration lacks this imperfection since the continuous calibration of the system limits the influence of nonstationarity on the accuracy of measuring results. Among other advantages of autocalibration is its autonomy, which causes this method to not require any preliminary actions in the weighing system. Furthermore, it can be used almost in every WIM system, even on roads with pavement of poor quality. It replaces the burdensome and expensive process of classic, periodical calibration of the WIM system.

7. Aknowledgement

Author would like to thank to: Janusz Gajda, Piotr Piwowar, Ryszard Sroka, Marek Stencel, Tadeusz Zeglen – a constructors of WIM system in Gardawice.

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DATA-BASED WIM CALIBRATION AND DATA QUALITY ASSESSMENT IN SOUTH AFRICA

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Abstract
Over the past three years there has been a shift towards using a data-based method for retrospective calibration and for assessing the quality of Weigh-in-Motion (WIM) data in South Africa. The Truck Tractor (TT) Method is currently being used for about 50 WIM systems located on the major toll roads in the country, totaling approximately 1 300 km of national roads. The most important data quality checking parameters that are used are the standard deviations of truck-tractor and front-axle loads, average front axle loads, stability of calibration factors and front-axle / truck-tractor load ratios (FTR). The value of the TT Method has already been proven in recent years, and the use thereof is gaining momentum. In addition, an error rating for axle spacing measurements (ERas23) was recently added to the suite of data quality checks.
Keywords: Weigh-in-Motion, WIM, data-based calibration, data quality, Truck Tractor (TT) Method
Résumé
Ces trois dernières années, les méthodes empiriques sont de plus en plus utilisées en Afrique du Sud pour calibration a posteriori et évaluation de la qualité des données de trafic. La méthode “Truck Tractor” (TT) est actuellement utilisée pour 50 stations de pesage situées sur les principales routes à péage du pays, ce qui représente environ 1300 km de route. Les paramètres les plus importants pour la vérification de la qualité des données de pesage sont l’écart-type des charges du tracteur et de la remorque, des charges sur le premier essieu, les moyennes des charges sur le premier essieu, la stabilité des facteurs de calibration, et le ratio entre les charges du premier essieu et de l’ensemble tracteur-remorque (appelé FTR). Cette méthode a été prouvée comme étant efficace et elle est de plus en plus utilisée. De plus, une méthode pour qualifier l’erreur, appelée Eras23, vient d’être ajoutée à la suite de vérifications de la précision.
Mots-clefs: Pesage en marche, WIM, calibration empirique, qualité des données, méthode Truck Tractor.

1. Introduction

Weigh-in-Motion (WIM) scales are installed on various higher-order South African roads to provide traffic loading information for pavement design, strategic planning and law enforcement. The inherent inaccuracy of WIM sometimes leads to the misinterpretation and misuse of data which may result in imbalances in pavement design and overload control efforts. Robust and effective tools are required to assess the accuracy and quality of WIM data on a routine basis.

Over the past three years there has been a shift towards using a data-based method for retrospective calibration and for assessing the quality of WIM data in South Africa. The Truck Tractor (TT) Method is currently being used for about 50 WIM systems located on the N1 North, N4 Maputo Corridor, Bakwena Platinum Corridor and the N3 toll road concessions, totaling approximately 1 300 km of national roads.

2. History of the Truck Tractor Method

The TT Method (De Wet, 2010) evolved from the FTR (Front-axle Truck-tractor Ratio) Method that was first presented at the International Conference on WIM in Paris in 2008 (De Wet & Slavik, 2008). It focuses on a sub-population of 6- and 7-axle articulated trucks with a single steering and double driving axles on the truck tractor, called Eligible Trucks. The Eligible Trucks with an average axle load between 6.5 t and 8.5 t, referred to as Selected Trucks, are used in the calibration process. An iterative procedure is used to determine the calibration factor, k_{TT}, that drives the monthly average truck-tractor loads for Selected Trucks to the target value of 21.8 t. The TT Method is remarkably accurate, and produces calibration factors correct to within approximately 3 % for a range of WIMs in appreciably different operating environments. Calibration of WIM data is done on a monthly basis. This interval is long enough to produce an adequate sample of Selected Trucks in remote locations, yet it is short enough that the user can act on irregularities as they arise.

The concept of data-based calibration was originally developed in France (Stanczyk, 1984). The TT Method follows a similar approach, except that calibration is performed on a monthly basis by a skilled professional in contrast to the more common automatic self-calibration procedures that are performed by roadside electronics. The originality of the TT Method lies in the fact that it was developed specifically for South African WIMs taking cognizance of the local truck fleet, pavement conditions and WIM equipment used. It also includes a series of unique data quality checks that allow the WIM data user without in-depth technical knowledge to determine whether loading measurements are reliable.

The technical details and algorithms of the TT Method and its data quality checking procedures have already been documented (De Wet, 2010). The latest addition to the suite of data quality checks, ERas23, focuses on the accuracy of axle spacing measurements. The concept of ERas23 was developed separately from the TT Method, and is documented in a technical paper at the ISWIM conference in Texas in 2012 (Slavik & De Wet, 2012). The following sections concentrate on the practical implementation and value of the TT Method and ERas23 data quality checks.

3. Application of the Data Quality Checking Procedures

The data quality checks are used to identify the symptoms of WIM failure. Although they cannot pin-point the cause, they do provide clues about the type of problem. WIMs that fail the data quality checks need to be inspected to identify and correct the root of the problem. The respective quality checks are discussed below.

3.1 Distributions of Truck Tractor Loads and Front Axle Loads

The distributions of truck tractor loads (T_{TT}) and front axle loads (F_{TT}) of Selected Trucks serve as the primary indicators of unacceptably large random WIM error. The standard deviations of F_{TT} and T_{TT} (also abbreviated S_{FTT} and S_{TTT}) for various South African WIMs were used to determine values to be expected from good and bad WIMs respectively. Warning and rejection thresholds for S_{TTT} and S_{FTT} were then developed, and they are currently used to flag WIMs that need to be investigated. Figure 1 shows the threshold values and how they relate to the values of S_{FTT} and S_{TTT} for good, suspect and bad WIM data. The warning thresholds reject practically all the bad data, but also reject some good data in the process. The rejection thresholds accept all the good data, but because of the more lenient approach they also pass some bad data. It should be noted that S_{TTT} is a more sensitive indicator than S_{FTT}, and generally provides the earlier indication of WIM performance deterioration.

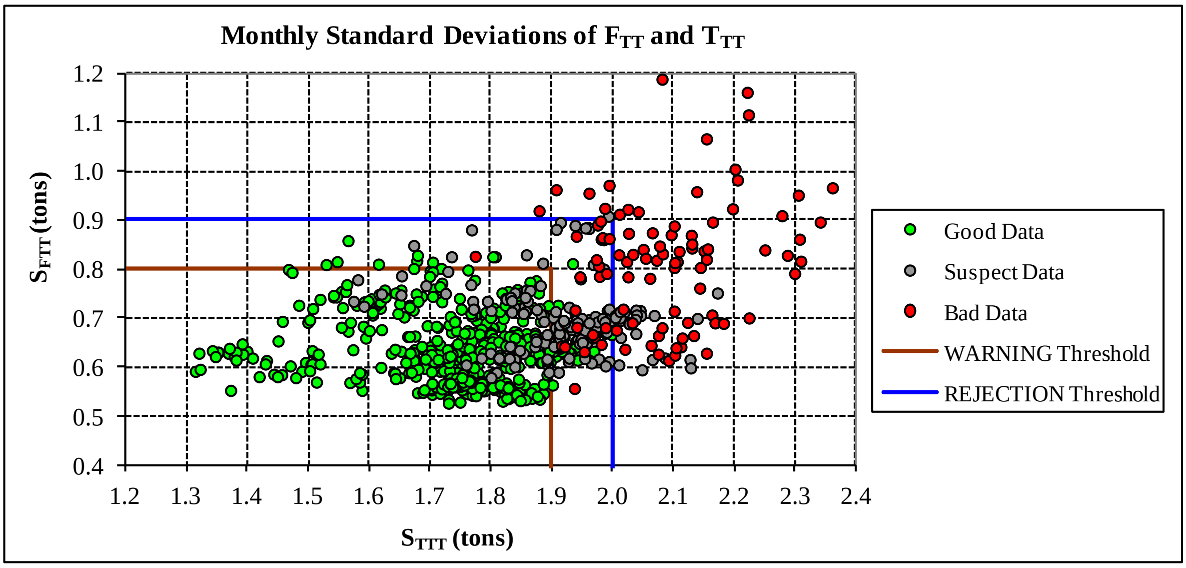


Figure 1 – Warning and Rejection Thresholds for S_{FTT} and S_{TTT}

Over the past few years, the evaluation of S_{TTT} and S_{FTT} already identified several cases of pavement failure, defective electronics, loose frames and levelness problems. This expedited the implementation of corrective action and consequently reduced the loss of data. As an example, Figure 2 shows the monthly trends of S_{TTT} for the six northbound WIMs on the N3 Toll Road between Johannesburg and Durban. The pavement in the vicinity of the Van Reenen WIM started to deteriorate in March 2010, and rapid failure set in during the following months. The pavement was repaired during July and August, and the WIM was reinstalled in a good road surface in September 2010.

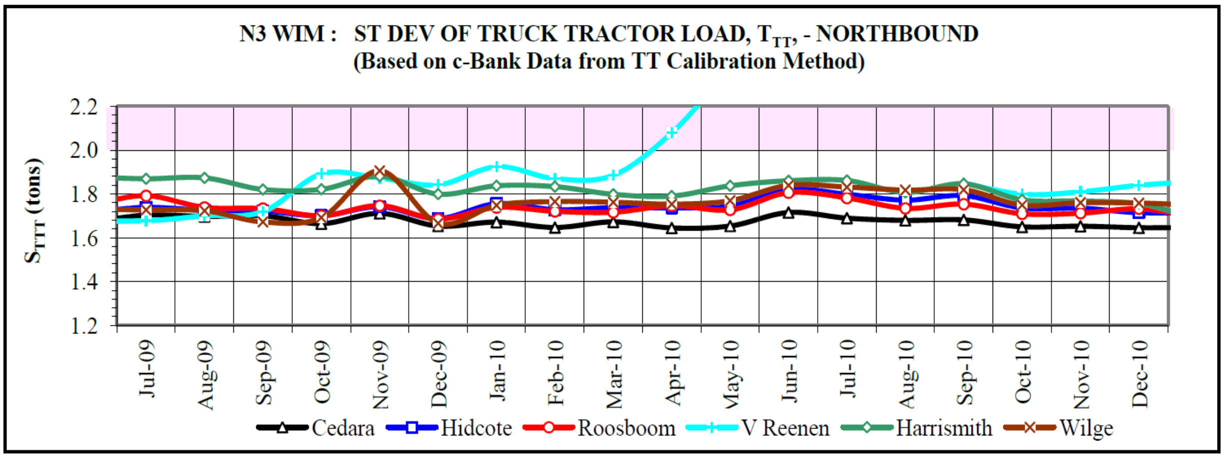


Figure 2 – Monthly Trends of S_{TTT} on the N3 Toll Road

3.2 Average Front Axle Load

Once calibrated using the TT Method, WIM systems produce average front axle loads of Selected Trucks, F_{TT}, in the range of 5.6 t to 6.6 t. Lower values are recorded by WIMs that are installed in uphill road sections or where acceleration takes place, while higher values of F_{TT} occur at WIMs on downgrades or where breaking takes place. Checking of the monthly F_{TT} trends serves as a basic check of WIM performance.

Figure 3 shows the monthly trends in F_{TT} for the northbound WIMs on the N3 Toll Road. The increase in F_{TT} at the Wilge WIM in September 2008 was caused by the installation of a flasher unit to deter motorists from speeding into the Wilge Toll Plaza. The implementation of this traffic calming measure caused vehicles to break on the WIM sensor which transfers load onto the steering axle. The trigger speed of the flashing unit was lowered in February 2009, which resulted in a further increase in F_{TT}. The Roosboom WIM is operated on an uphill section and the Hidcote WIM on a downhill section, which explains why their F_{TT} are respectively the highest and lowest on the graph.

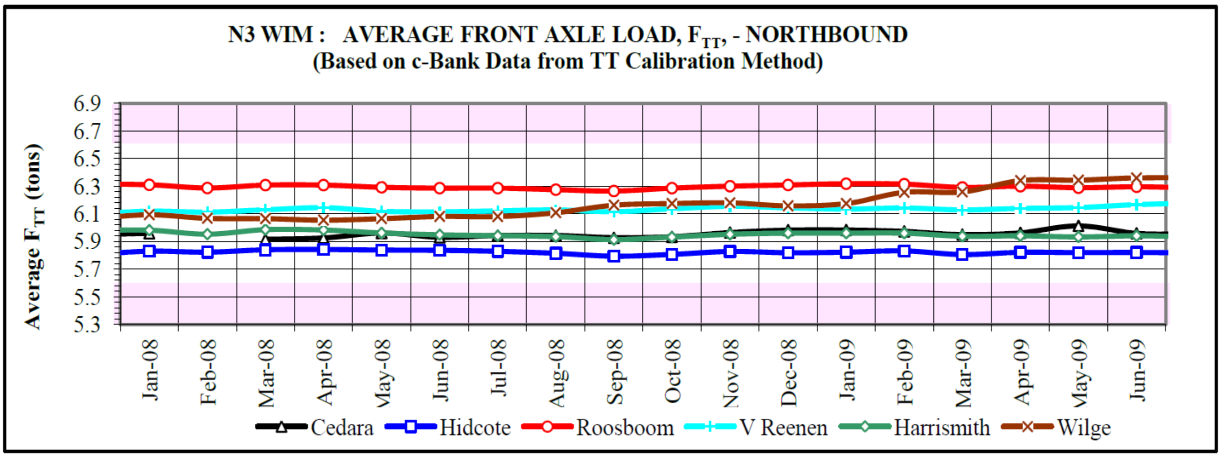


Figure 3 – Monthly Trends of F_{TT} on the N3 Toll Road

3.3 Stability of Calibration Factors

The stability of monthly calibration factors from the TT Method, k_{TT}, is used as an indicator of rapid changes at WIM installations. For stable WIM systems, the monthly calibration factors rarely differ by more than 3% from the average of the calibration factors for the preceding five months. Monthly calibration factors for WIM systems are plotted together with their rolling ± 3 % acceptance envelopes. These graphs are used to identify drift in calibration factors and to show instances where calibration factors suddenly crash out of their acceptance envelopes. The evaluation of calibration factor stability in recent years identified cases of loose WIM frames, rapid pavement failure at WIM installations, levelness problems as a result of poor pavement patching as well as temperature dependence of WIM sites where capacitive sensors were used. As an example, Figure 4 shows the monthly plot of k_{TT} at the Cedara northbound WIM on the N3 Toll Road.

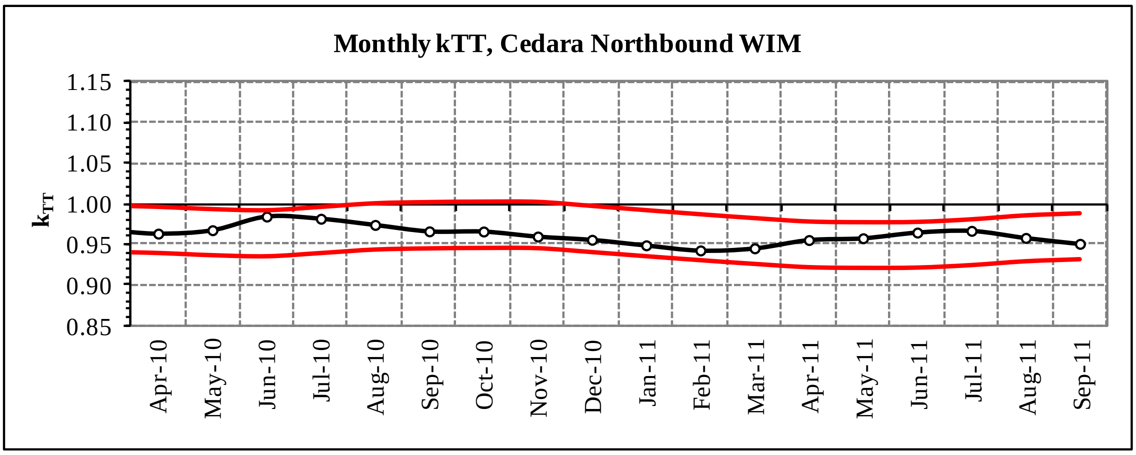


Figure 4 – Monthly Trends of k_{TT} at Cedara Northbound WIM

3.4 Lane Discipline

Lane discipline at a WIM installation is evaluated using the Front-axle Truck-tractor Ratio (FTR). The FTR is the front axle load, F, expressed as a ratio of the truck-tractor load, T, and is evaluated for Eligible Trucks. Half-lane WIM sensors are generally used in high-speed WIM systems in South Africa, and they are installed in the left wheel path only. Trucks that do not travel along the centre of the lane tend to stray into the shoulder of the road, causing a part of the wheel to clip the sensor and pass partly on the adjacent pavement. In most cases the mass of the steering axle (single wheel) is severely under-measured, while the under-measurement of the driving axles' dual wheels, although present, is less pronounced because only the outer wheel clips the sensor – see Figure 5. The result is an FTR that is uncharacteristically low for the truck's average axle load.

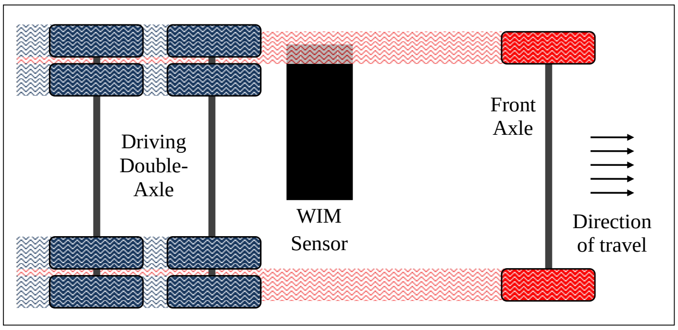


Figure 5 – WIM Sensor Clipping

A typical clipping identification line, called the C-line, was developed, and the percentage of vehicles with FTRs that protrude below this line is considered to be a good indicator of clipping. Figure 6 shows the FTR graph of the Machado WIM on the N4 Toll Road for September 2011. The lane discipline at this WIM is not particularly good – 8.1 % of FTRs are below the C-line.

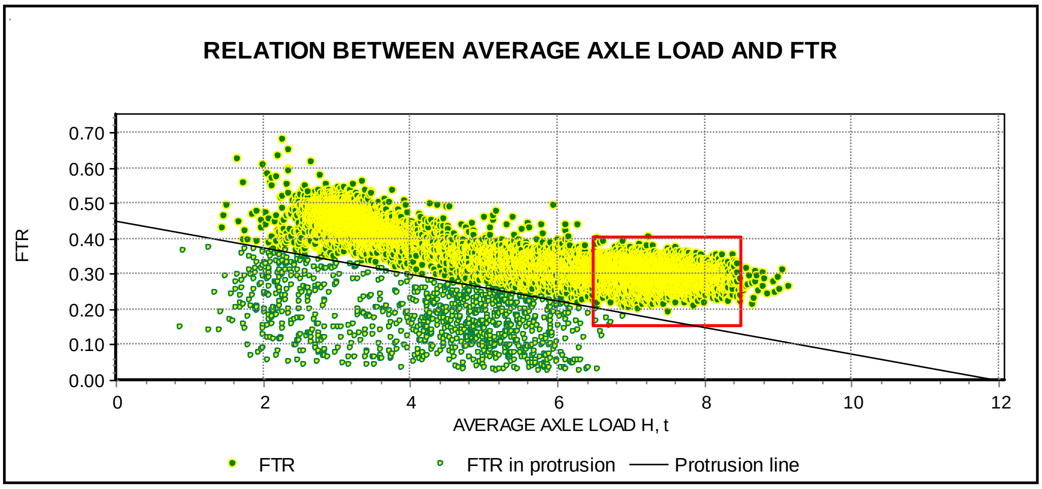
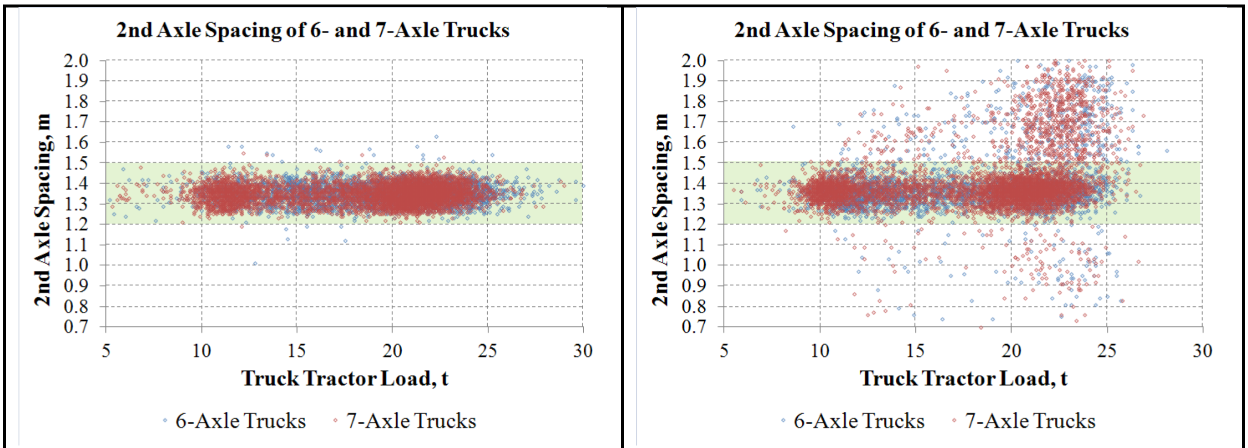


Figure 6 – Extent of Sensor Clipping based on FTR at Machado WIM

The extent of clipping is used to determine whether measures such as signage or rumble strips in the shoulder should be implemented to improve lane discipline. Sudden changes in the extent of clipping could also indicate loose frames or other problems that might cause under-weighing of the front axle.

3.5 Axle Spacing Measurements

As mentioned, the evaluation procedure for axle spacing measurements was developed separately from the TT Method, and is described in a paper presented at the International Conference on WIM in Texas (Slavik & De Wet, 2012). The accuracy of axle spacing measurements is reflected in the spread of measurement error of driving double-axle spacing. The actual spacing between axle 2 and 3 of Eligible Trucks is approximately 1 350 mm with a true standard deviation of about 40 mm. As an example, Figure 7 shows graphs of the second axle spacing of truck tractors plotted against the average truck tractor load for a WIM system with good and poor axle spacing measurement respectively.



Hidcote Nb WIM, Aug 2010
Good Axle Spacing Measurement

Farrefontein Eb WIM, Aug 2010
Poor Axle Spacing Measurement

Figure 7 – Example of Axle Spacing Measurements

The error rating of a WIM for axle spacing measurements between axle 2 and 3, called ERas23, is defined as the zero-centered interval, ±δ, containing 95 % of the percentage errors committed by WIM. The value of ERas23 should not exceed 7 %, and WIMs that fail this check are investigated and improved. Accurate axle spacing measurements are important not only to achieve good vehicle classification, but also to select the correct vehicles for WIM calibration. The evaluation of ERas23 was first implemented on a trial basis in the middle of 2011, and several problematic WIM stations were identified and checked. The evaluation of ERas23 shows promise as an indicator of malfunction related to inductive loops or WIM electronics.

4. Conclusion

Although developed for South African WIM systems, the TT Method also addresses several of the technical needs identified by WIM users in the USA (Papagiannakis, Quinly & Brandt, 2008). It offers a calibration method that doesn’t use test vehicles, which eliminates the need to relate the results from such vehicles to the general stream of truck traffic. The limitations of WIM data are duly recognized, and routine monitoring of data quality is done from a centralized office location using the data quality checks.

It appears that South Africa is on the verge of standardizing WIM calibration practices using the TT Method as the basis. The use of the method is gaining momentum on privately operated toll roads, and much of it is also being incorporated by the South African National Roads Agency into their model used to quantify the cost of overloading on South African toll concessions. Additional data-based quality checks such as ERas23 add to the selection of tools that ensure the integrity of loading information from WIM systems.

5. Acknowledgements

The South African National Roads Agency Ltd (SANRAL), Northern Toll Road Venture (NTRV), N3 Toll Concession (N3TC), Trans African Concessions (TRAC) and Bakwena Platinum Corridor Concession (BPCC) are thanked for the use of their data.

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EVALUATION OF SEVERAL PIEZOELECTRIC WIM SYSTEMS

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Abstract

In this paper a comparative study of the performance of three weigh-in-motion piezoelectric systems permanently installed in the road pavement is described, including the tests carried out in order to evaluate their initial (after calibration) and in-service (after a working period of 5 months) accuracies.

Keywords: Piezoelectric, piezopolymer, piezoceramic, weigh-in-motion, WIM.

Résumé

Ce papier décrit une étude comparative sur les performances de trois systèmes piézoélectriques de pesage en marche installés dans la chaussée de manière permanente, y compris les essais réalisés afin d'évaluer leurs exactitudes initiales (après étalonnage) et en service (après une période de fonctionnement de 5 mois).

Mots-clés: Piézoelectrique, piézopolymère, piézoceramique, pesage en marche, WIM.

1. Introduction

Following an assignment from the Planning Division of the General Roads Directorate (GRD) of Spain to find the most appropriate WIM systems for the traffic data acquisition network deployed throughout the national roads, CEDEX (Public Works Research and Experimentation Centre) undertook in 2008 a study for evaluating the performances and accuracies of several dynamic weighing systems which used piezoelectric technology, which was chosen as the most appropriate technology for obtaining statistical data about loads and detailed vehicle classification. In order to carry out the evaluation, three piezoelectric WIM systems were installed in the four lanes of the A-5 motorway in Badajoz (Spain), next to the Portuguese border, in February 2009.

The study of the WIM systems' performance and accuracies consisted of an initial assessment of the accuracy of the three piezoelectric systems carried out just after the calibration of the systems, a monitoring of the systems operation during more than 5 months and an in-service evaluation of the systems accuracies at the end of this period.

2. Selection of the WIM Systems Installed in Badajoz

The application of data on vehicle and axle weights collected with the WIM systems to be installed throughout the national road network would be to obtain statistical data for pavement design and maintenance, as well as for estimation of transported loads for transport studies.

In accordance with the requirements of the Planning Division of the GDR, the WIM systems would have to be installed at the traffic counting stations of the National Road Networkin order to take advantage of the existing infrastructure. Therefore, taking into account this requirement it was considered that piezoelectric technology would be the most appropriate. Among piezoelectric systems, those with piezoquartz sensors were discarded because of their relatively high cost. The three systems ultimately selected for installation used two types of piezoelectric sensors: two systems had piezopolymer sensors and the other one was of the piezoceramic type.

In view of these considerations, the systems marketed in Spain by three different companies (in alphabetical order: KINEO, SICE and TECBAS) were chosen. These companies were the agents in Spain of the following equipment manufacturers, also in alphabetical order:

- Piezopolymer type: MSI Road Trax (USA) - Quixote PEEK TRAFFIC (USA).
- Piezopolymer type: MSI Road Trax (USA) - TDC Systems Ltd (UK).
- Piezoceramic type: Vibracoax-STERELA (FR).

The test results of the systems' performances are presented in Section 7, but only the technology of the systems (piezopolymer or piezoceramic) is reported in order to maintain the confidentiality of the results for each of the commercial trademarks.

3. Installation

The installation of the three selected WIM systems was performed in the four lanes at km 407.7 of the A-5 motorway (Figure 1) next to a permanent traffic counting station located on the border with Portugal. The road section of the test site was inspected before installation, and rut depths of up to 1 cm were found in the right lanes of both directions. Therefore, the wearing course was removed and a new layer was applied. Once this operation had been finished, evenness in the outside lanes of both directions was measured using a laser profilometer, and the IRI (International Roughness Index) was calculated and compared with the requirements of the European WIM Specifications (Jacob et al., 2002). The IRI values measured in hectometres where the WIM systems were located ranged between 1.33 and 2.48 dm/hm; therefore, according to the European WIM Specifications, the section could be considered as "good" (i.e. having an IRI of up of 2.6).

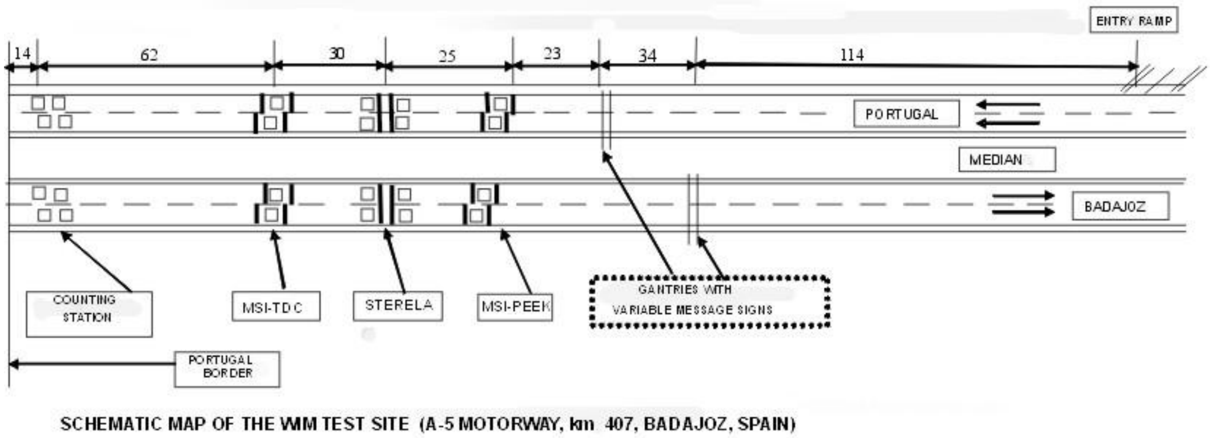

Figure 1 - Layout of the WIM systems tested in the A-5 at Badajoz site.

4. Calibration

The calibration of the WIM systems was carried out a few weeks after installation . For this purpose, four pre-weighed calibration trucks (two rigid and two articulated) representing the traffic on the site were used. Each vehicle passed about 20 times over the sensors of the WIM systems at its usual travelling speed. This operation was carried out by technicians of the manufacturing/vendor companies and consisted of matching the mean of the dynamic weights supplied by the systems of all the runs of each vehicle used in the operation with their static weight.

5. Tests for the Assessment of the Accuracy of the WIM Systems

On the day following the completion of the calibration, CEDEX, using the same four trucks, proceeded to conduct an initial verification test to evaluate the accuracy of all of the parameters registered by the WIM systems: vehicle counting, speed, silhouette, length and weight.

After 5 months of systems operation under high summer temperatures, with no recalibration, another test to verify the in-service accuracy of the systems was carried out. For this purpose, five pre-weighed trucks (two rigid, two articulated and a road train) were used. The main results of these tests are described in Section 7.

6. Monitoring of WIM Systems Operation during 5 Months

The objective of this task was to detect potential malfunction problems during a long period of continuous operation under different weather conditions (with air temperatures ranging from 0º C to more than 40º C in summer). This task was performed through a continuous checking of the data collected during this period. The assessment of the data provided by the WIM systems was inferred through a comparison between the results obtained by each of the systems with the results obtained by the other two systems, trying to detect which system had any problem on the basis of whether its data were deviating from those of the other two systems.

Regarding the existence of malfunction problems, it can be said that the monitored WIM systems worked properly during the 5 months except in cases where damage was observed. One of the variables that was checked was the accumulated total weight that travelled on the motorway each day; and it became obvious that the data obtained with the piezopolymer 1 system was remarkably deviating both from the other two WIM systems and from the accumulated weights relative to similar weekdays in previous weeks. Therefore it could be concluded that this system was losing calibration.

7. Results Obtained in the Verification of the Accuracy of the WIM Systems

The three piezoelectric systems were evaluated in terms of their ability not only to measure vehicle gross weights and axle loads, but also regarding vehicle counting, measurement of vehicle speed and length, and determination of a detailed traffic silhouette with 19 vehicle types. As the most specific function of a WIM system is weight measurement, the results for this variable are given in a separate subsection.

7.1 Results of Accuracy in Vehicle Counting, Speed, Length and Traffic Silhouette

Vehicle speed and length assessment refers only to the 5 pre-weighed vehicles used for the test, whereas traffic counting and silhouette refers to all vehicles passing through the motorway section of the test site. From the analysis of test results, the following can be said:

- Traffic counting: all of the systems performed with errors ranging from - 7% to + 4.3 % in the total traffic volume on the highway, mainly due to vehicles' changing lane.
- Speed: all of the systems measured speed correctly, showing an error lower than 2 %.
- Length: the piezopolymer 2 system obtained the best result, with an errors ranging between -0.9% and 5.2% for the different vehicles and lanes. The piezoceramic system measured all vehicles properly except road trains, whose length was underestimated by 8%. On the contrary, the piezopolymer 1 system was completely uncalibrated.
- Silhouette: the best system in estimating traffic silhouette was the piezopolymer 1, with an error of 6.7 % with respect to the total volume. The system which showed the highest

error was the piezoceramic, because it classified road trains as two different vehicles and also because some classification parameters regarding coaches had to be reset.

7.2 Bases for Analysis of Results of Weight Accuracy

The results obtained in the assessment of the performance of WIM systems regarding weight measurement are usually expressed in two different ways:
a) Based on the calculation of the average relative error (bias) obtained by the systems for each variable measured and the data scattering around the mean relative errors, expressed as standard deviation (in percentage).
b) By means of the proportion (probability) that an individual error falls within an specified confidence interval [–δ,+δ], which intends to measure the relative error that is within a given tolerance. This is the approach chosen by the European Specifications of Weighing in Motion (Jacob, O'Brien and Jehaes, 2002), and has the advantage that a single number (tolerance) gives an idea of the bias and dispersion of the results. The confidence interval represents the tolerance for a certain level of confidence (usually greater than 90%).

7.3 Results of Bias and Dispersion of Weight Measurements

Tables 1 and 2 show the mean relative errors and standard deviations of the dynamic gross weight of the pre-weighed vehicles supplied by the WIM systems in the test carried out just after calibration and after 5 months of operation respectively.

Table 1 – Mean relative errors (bias m in %) and dispersion (s %) of the GW of all test vehicles just after calibration (n = sample size)

	Lane 1			Lane 2			Lane 3			Lane 4		
System	n	m	s	n	m	S	n	m	s	n	m	s
Polymer 1	45	3.4	9.5	44	3.5	6.5	46	3.65	5.7	43	2.6	7.0
Polymer 2	70	10.0	10.2	45	-1.6	10.3	66	11.2	10.5	42	2.8	8.5
Ceramic	71	0.04	8.4	48	0.09	4.3	65	-2.0	4.7	44	- 2.5	6.2

Table 2 – Mean relative errors (bias) and dispersion (expressed as σ %) in the measurement of the gross weight of all test vehicles after 5 months from calibration

	Lane 1			Lane 2			Lane 3			Lane 4		
System	n	m	s	n	m	S	n	m	s	n	m	s
Polymer 1	246	12.2	29.7	152	125.4	71.8	223	13.7	18.6	167	29.6	27.4
Polymer 2	265	3.5	9.2	227	-11.2	11.8	192	-14.2	10.1	243	-23.4	10.1
Ceramic	128	-25.4	13.3	196	-1.2	5.0	214	1.6	3.7	213	3.0	5.7

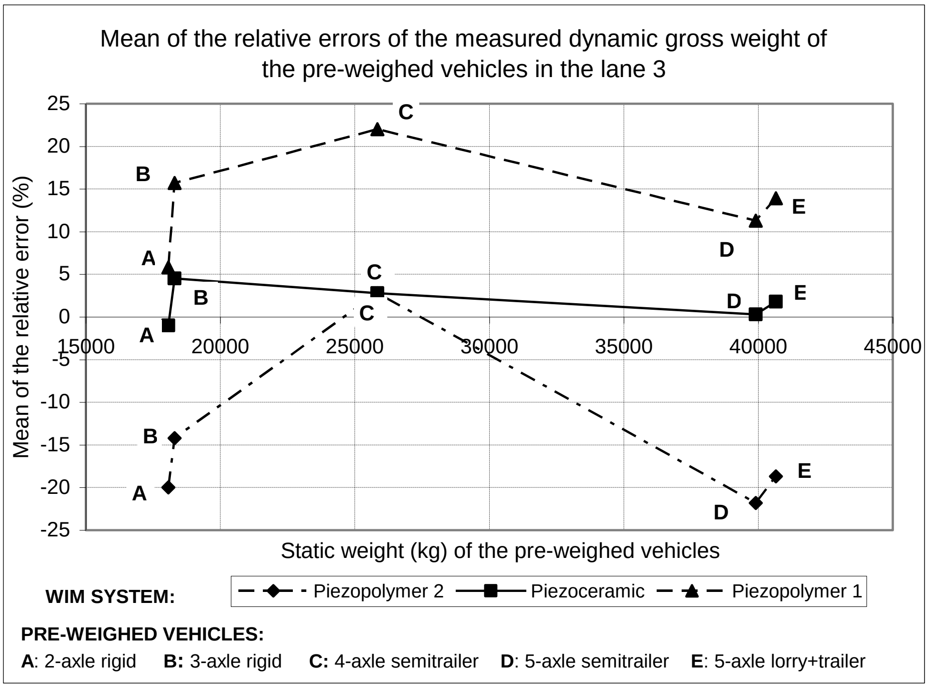

Figure 2 – Mean relative error obtained by the WIM systems tested in the measurement of the gross weight of each of the pre-weighed vehicles

As can be seen in Table 1, the piezopolymer 1 and the piezoceramic systems had rather small biases on the day after calibration, which indicates that the calibration was properly made; whereas the piezopolymer 2 system had a large bias in two of the four lanes even at this time. Five months after calibration (Table 2), only the piezoceramic system maintained a small bias in three of the four lanes, but the piezopolymer 1 system had completely lost its calibration and the standard deviation had also increased considerably, which indicates some type of system malfunction. The piezopolymer 2 system showed a large bias also in the two lanes that had a good initial calibration, although the standard deviation remained at the same level.

The graph in Figure 2 shows the mean relative error for the gross weights of each of the test vehicles obtained by the WIM systems after an operation period of 5 months. It can be noted that the shape of the polygonal lines for the piezopolymers 1 and 2 are very similar, but one is vertically displaced from the other. This may indicate that as both systems have the same type of sensors, their behavior is similar for each type of vehicle, and they only differ in calibration. As for the piezoceramic system, calibration is achieved more accurately, and the polygonal line approaches more closely to the x-axis with mean errors lower than 5% for all vehicles.

7.4 Classification of the Systems According to the European Specifications on WIM

An evaluation of the accuracy levels of the three piezoelectric WIM systems was made following the simplified method of estimation of π (the confidence level) with the sample proportion π' of individual relative error values found within the interval $[-\delta,+\delta]$, as described in section 11.4.6 of the European Specifications on WIM (Jacob, O'Brien and Jehaes, 2002).

Thus, for each accuracy class (A(5) to D(25)) defined in the specification, the probability π that an individual error falls within the specified confidence interval $[-\delta,+\delta]$ is estimated from the sample data. The appropriate accuracy class is the highest (i.e. the lowest δ) for which the calculated probability exceeds a specified minimum level of confidence π_0. The values of π_0 are given in the Tables 7, 8 and 9 of the European Specification on WIM for the different conditions of the test plans. As both tests (initial and in-service) were made in the environmental repeatability (I) condition, Table 7 in the specification applies. Then, entering that table with traffic conditions that were a limited reproduction of the traffic (R1), and sample sizes that were about 70 in the initial test and about 200 in the in-service test, the corresponding values of π_0 were 94.2% and 97 % respectively.

The results in Tables 3 and 4 show the percentages of vehicle runs (which gives an estimation of the confidence level) in which the relative error in the gross weight of vehicles is within the tolerance specified for each accuracy class (the number in brackets next to each class letter being the width of the confidence interval) according to the COST 323 European WIM specifications, obtained in tests both immediately after calibration and after 5 months of operation. In Tables 3 and 4, the percentages that exceed the corresponding values of π_0 are written in bold. In Table 3, it can be seen that, in the initial test, the piezoceramic system met in three lanes the requirements for a higher class (B(10)) than that required by CEDEX in the purchasing procedure, which was C(15), while from the first moment it seemed that lane 1 was not working properly. The piezopolymer 1 system met the required class in the initial test in lanes 2, 3 and 4, but it did not reach the required class in lane 1. The piezopolymer 2 system did not meet the required accuracy of class C(15) in any lane.

Table 3 - Test after calibration. Percentage (%) of vehicle passes with a gross weight within the interval of each accuracy class

	Piezopolymer 1				Piezopolymer 2				Piezoceramic			
Lane	1	2	3	4	1	2	3	4	1	2	3	4
A (5)	46.7	43.2	67.4	46.5	32.9	26.7	30.3	69.0	45.1	75.0	64.6	56.8
B (7)	62.2	59.1	78.3	58.1	50.0	37.8	42.4	54.8	66.2	87.5	83.1	93.2
B(10)	75.6	77.3	87.0	81.4	57.1	60.0	54.5	69.0	78.9	**97.9**	**96.9**	**97.7**
C(15)	91.1	**97.7**	**97.8**	**95.3**	70.0	84.4	68.2	83.3	**94.4**	**100**	**100**	**97.7**
D(20)	**95.6**	**100**	**97.8**	**100**	85.7	**97.8**	78.8	**100**	**97.2**	**100**	**100**	**97.7**
D(25)	**95.6**	**100**	**97.8**	**100**	88.6	**100**	84.8	**100**	**98.6**	**100**	**100**	**97.7**

Table 4 - Test after a working period of 5 months since calibration. Percentage (%) of vehicle passes with the gross weight within the interval of each accuracy class

	Piezopolymer 1				Piezopolymer 2				Piezoceramic			
Lane	1	2	3	4	1	2	3	4	1	2	3	4
A(5)	17.1	2.0	20.6	6.6	40.8	16.7	14.1	3.7	4.7	79.1	82.7	57.7
B(7)	24.8	2.0	26.9	10.2	52.5	23.3	17.2	5.3	5.5	92.3	95.3	89.7
B(10)	37.0	2.0	35.4	12.0	66.0	34.4	22.9	7.0	14.1	96.4	**98.1**	**97.2**
C(15)	52.4	5.9	52.5	19.8	86.4	60.4	42.2	17.3	26.6	**98.5**	**99.1**	**98.1**
D(20)	68.3	11.8	68.6	30.5	95.1	86.8	66.7	24.7	39.8	**98.5**	**100**	**97.7**
D(25)	76.0	13.8	78.0	40.1	**99.6**	92.5	89.1	48.1	51.6	**99.0**	**100**	**99.1**

Table 5 – Initial test after calibration. Accepted accuracy classes for the 4 criteria

	Piezopolymer 1				Piezopolymer 2				Piezoceramic			
Lane	1	2	3	4	1	2	3	4	1	2	3	4
GW	D(20)	C(15)	C(15)	C(15)	-	D(20)	-	D(20)	C(15)	B(10)	B(10)	B(10)
SA	D(25)	C(15)	C(15)	C(15)	D(20)	D(20)	-	C(15)	D(20)	B(10)	B(10)	B(7)
GoA	B(10)	C(15)	B(10)	C(15)	-	-	-	-	-	B(7)	B(10)	B(10)
AoG	C(15)	B(10)	B(10)	C(15)	-	-	-	-	-	C(15)	B(10)	B(10)

Table 6 – In service test 5 months after calibration. Accepted accuracy classes (4 criteria)

	Piezopolymer 1				Piezopolymer 2				Piezoceramic			
Lane	1	2	3	4	1	2	3	4	1	2	3	4
GW	-	-	-	-	D(25)	-	-	-	-	C(15)	B(10)	B(10)
SA	-	-	-	-	D(20)	-	-	-	-	B(10)	B(10)	B(10)
GoA	-	-	-	-	-	-	-	-	-	C(15)	B(10)	B(7)
AoG	-	-	-	-	-	D(25)	-	-	-	B(10)	B(7)	B(10)

After five months of operation, the defective operation of the piezoceramic system in lane 1 was confirmed; but in the other three lanes it met the requirements of the accuracy class C(15) and, in two of them, it even attained the class B(10). On the contrary, both piezopolymer systems were completely uncalibrated. The same analysis of the results of both tests (initial and in-service) was also performed considering the other criteria (single axles, group of axles and axle of a group loads) and the results were similar to those obtained with the gross weight, as can be seen in Tables 5 and 6.

8. Conclusions

The required accuracy for the systems purchased by CEDEX was to meet class C(15) requirements according to the European Specifications on WIM. The results obtained in the first test carried out just after the initial calibration (see Table 5) show that the system that approached the specification most closely was the piezoceramic, which fulfilled the class C(15) requirements in three lanes. The piezopolymer 1 system obtained correct results also in three lanes, whereas piezopolymer 2 only attained class C(15) in one lane and only for one criterion.

After 5 months of continuous operation without any recalibration (Table 6), only the piezo-ceramic system maintained its calibration and still met the requirements of class C(15) in three lanes (and in two lanes even fulfilled the class B(10) requirements), although it had some problems regarding vehicle classification because it considered road trains (rigid truck + trailer) as two separate vehicles. Alternatively, both piezopolymer systems were totally uncalibrated. These results suggest that piezopolymer systems still need to solve the loss of calibration problems if they are to be deployed throughout a road network.

9. References

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IMPROVEMENT OF WEIGH-IN-MOTION ACCURACY BY TAKING INTO ACCOUNT VEHICLE LATERAL POSITION



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Abstract

This paper reports research work done by IFSTTAR and CETE de l'Est to take into account the vehicle lateral position effect on road sensor Weigh-In-Motion (WIM) accuracy. The considered WIM sensors are piezoceramic strip sensors. Different methods and their results are discussed. Refinement of the automated calibration process is first studied, then an off-centered vehicle sorting out method is introduced, and finally a signal processing method is used. These results partially confirm previous theoretical and lab studies, and lead to a significant improvement in WIM accuracy by removing the bias due to the wheel lateral position.
Keywords: Weigh-in-motion (WIM), sensors, piezoceramic, wheel and vehicle lateral position, accuracy, heavy vehicles.

Résumé

Cet article présente les travaux de recherche réalisés par l'IFSTTAR et le CETE de l'Est sur la compensation de l'influence de la position latérale du véhicule sur la précision d'un système de pesage en marche utilisant des barreaux piézo-céramiques. Plusieurs méthodes et leurs résultats sont présentés. L'amélioration de la procédure d'étalonnage automatique est la première piste étudiée, puis la détection et l'élimination de véhicules excentrés dans la voie, et enfin une méthode de compensation directe des pesées. Ces résultats confirment en partie les précédentes études théoriques et menées en laboratoire, et conduisent à une nette amélioration de la précision des pesées par compensation des erreurs liées à aux roues excentrées.
Mots-clefs: Pesage en marche (WIM), capteurs, piézo-céramique, position latérale des roues et du véhicule, précision, poids lourds.

1. Introduction

Road sensor High Speed Weigh-In-Motion (HS-WIM) systems mostly use piezoceramic, piezoquartz or piezopolymer strip sensors. These sensors measure axle impact forces applied on the pavement, and the WIM system provides weight estimates for axles and vehicles.

In the late 90's, it was shown that the weighing accuracy of these HS-WIM systems depends on two types of factors (Scheuter, 1998):

- The sensor or system intrinsic errors, i.e. the differences between the true impact force applied by an axle on a sensor and the value provided by this sensor or by the whole system. These errors may result from several influencing factors such as sensor non-linearity or temperature drift.
- The difference between the static load of an axle and the dynamic impact factor applied on a sensor when passing on it. That is due to the dynamics of the vehicle, mainly induced by the pavement unevenness, but also by vehicle acceleration. The vehicle speed, suspensions, load, tire, etc. have influence on its dynamics.

Because of some heterogeneity of the sensors, but also of the road surface and pavement condition across a traffic lane, the wheel and vehicle lateral position may affect the WIM accuracy. However, as explained in the next section, the mechanical behaviour of the strip sensor also induces variations in its response with respect to the wheel position. This phenomenon has only been assessed in lab conditions until now, and was shown to have a significant effect on the response of most of the piezoelectric strip sensors.

2. Piezoceramic Sensor Lab Assessment

Theoretical studies on vehicle lateral position effects on piezoceramic strip sensors have been reported in (Iaquinta et al., 2004) and (Labry et al., 2005). These studies showed that the piezoceramic sensor response to an impact force is the sum of a vertical force component, independent of the wheel position, and a bending moment component which varies proportionally with the wheel lateral position. The bending moment component increases from 50% to 80% of the whole response when the wheel position moves from the sensor edge to its middle section. A correction formula was proposed to take into account this behavior.

3. Experimental Investigation on Vehicle lateral Position

Since 2008, CETE de l'Est has carried out field tests to investigate WIM errors induced by vehicle lateral position. Indeed, this effect is measurable and has an impact on the sensors' accuracy. This study was performed within the IFSTTAR research project on multiple sensors (MS-)WIM.

The field test was carried out on the Maulan open experimental site, on the RN4 highway, in eastern France (Jacob et al., 2008). Five piezoceramic strip sensors among 8 installed in an MS-WIM array were used, linked to a Sterela SWIMG© HS-WIM system.

Tests were carried out in 2010 on March 8th and May 15th, and in 2011 on May 16th. The references for the static weights were:

- Checking measurements on an approved by the legal metrology in the OIML Class 5 LS-WIM system (OIML, 2006); this applies for the trucks stopped by the police for control.
- Averaging the results of the 5 piezoceramic strip sensors; this applies for all trucks.

An additional piezoceramic strip sensor installed at an angle measured the vehicle lateral position; i.e. its relative position with respect to the lane mid-axis, denoted d (Figure2). The lateral position distributions for two days are given in Figure 3. On March 8th 2010, the distribution has approximately a symmetrical shape, close to a Gaussian shape, while on May 16th 2011, the distribution has a higher right tail, resulting from a different behavior of the trucks that may be due to the pavement deterioration after two harsh winters.

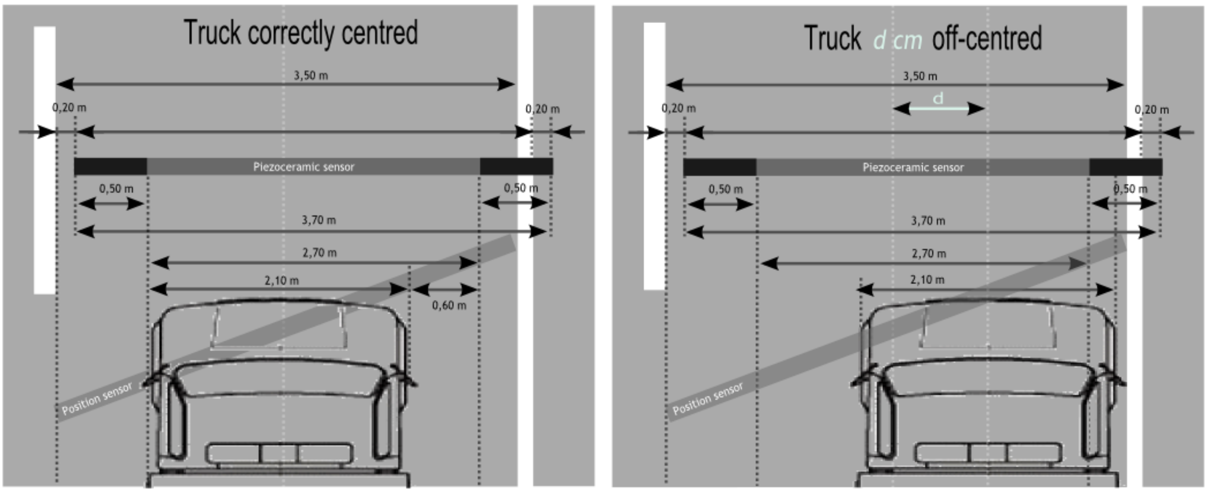

Figure 2 – Measurement of vehicle lateral position

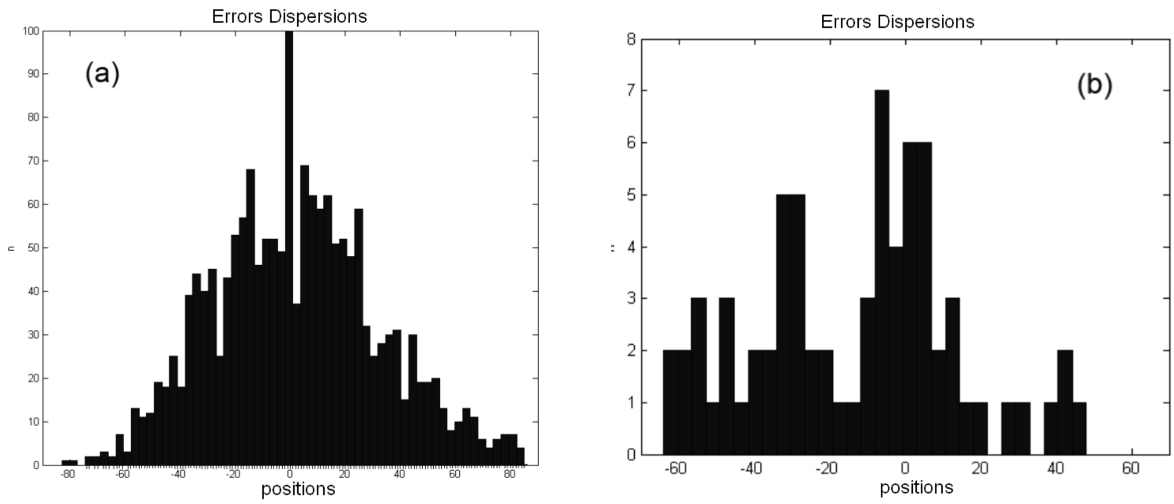

Figure 3 – Lateral positions: (a) 8/3/2010, (b) 16/5/2011

Relative errors for one single piezoceramic sensor against averaging 5 piezoceramic sensors (8/3/2010) or against the LS-WIM measurements, sorted by lateral position, are given in Figure 4 for four days (Figure 4(d) has an expanded vertical scale). Figures 4(b) and (c) for the same sensor, and days two month apart, show a very close shape. The same similarity is observed and confirmed for all the sensors in the array. The error distribution with respect to the lateral position is consistent in time, but differs from one sensor to another.

These data were then used for correction of errors due to the lateral vehicle position in subsequent weighing tests.

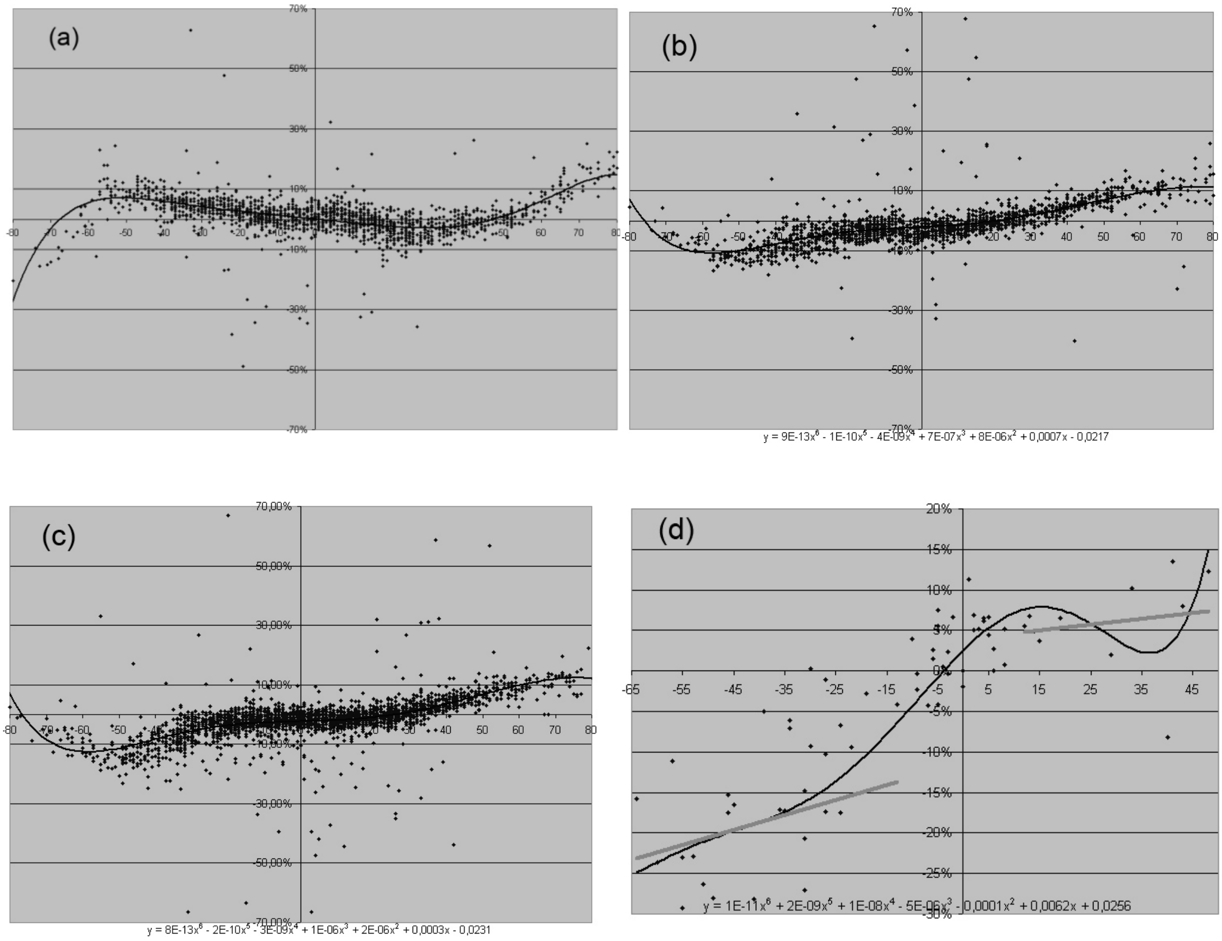

Figure 4 – Relative errors on GW: (a) 8/3/2010 against piezoceramic averaging, (b) 8/3/2010 against LS-WIM, (c) and (d) 15/5/2010 and 16/5/2011 against LS-WIM

4. Correction Methods for Vehicle lateral Position

Two correction methods are investigated and tested:

- Cancellation of measurement if the vehicle is positioned outside some limits for the automatic self-calibrating procedure.
- Using a correction function for off-centered vehicles.

4.1 Modifying the Automatic Self-calibration Procedure

Because of the sensor response attenuation when a wheel passes close to the sensor edge, due to the lower bending moment, off-centered heavy vehicles used for the self-calibration induce some bias through the calibration factor. Therefore, based on the previous theoretical and lab studies, vehicles driving outside a 2.70m wide virtual lane centered on the sensor mid-axis were eliminated from the self-calibration sample.

This improved self-calibration calibration coefficients where applied on four sensors during two test periods on March 8th and May 15th 2010. Significant accuracy improvements were found as shown in Figure 5. The mean biases were divided by 10 while the standard deviations are almost halved.

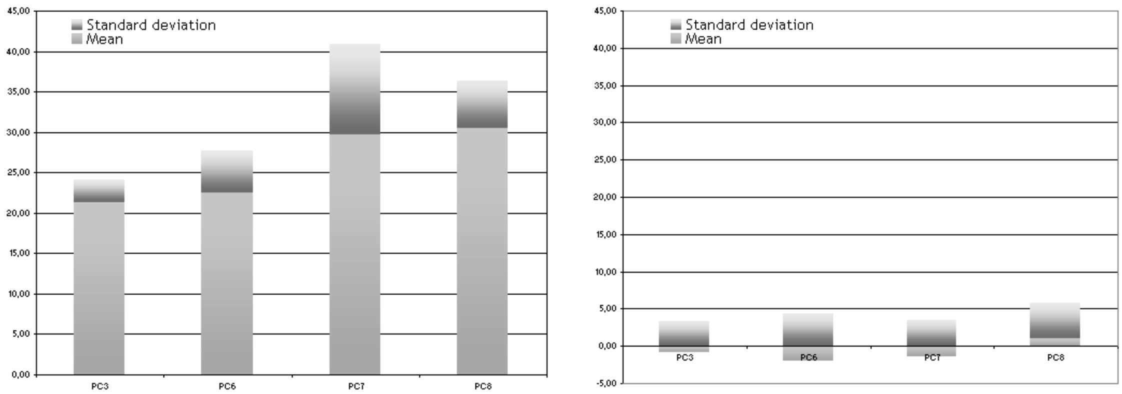

Figure 5 – WIM Accuracy with LS-WIM reference: (a) with the standard self-calibration on 15/5/2010, (b) with the improved self-calibration on 15/5/2010

4.2 Correction Function for Off-Centered Vehicles

Beside the improved self-calibration process, a simple correction model was developed to compensate for the errors due to vehicle lateral position variation. Correction coefficients were derived from the data collected over one day, applied to the vehicle total weights and then to individual axles and axle groups.

Using a 2,200 vehicle sample from the traffic flow measured on March 8th 2010, a sixth order polynomial function was fitted to the relative errors of the 5 piezoceramic sensors. This function was then used to calculate correction coefficients to be applied on the measured GVW of vehicles with lateral position deviating from the mid-lane axis by [-80cm,-10cm] and by [+10cm,+80cm]. A total of 160 correction coefficients were calculated by steps of 1 cm (Table 1). Despite the sensor position being off-centered, the correction was symmetrically applied. In this study, vehicles off-centered by more than ±80cm were not taken into account.

Table 1 – Correction factors derived from the polynomial function.

d (cm)	-80	-79	-78	-77	…	+77	+78	+79	+80
$f_c(d)$	9.1%	8.9%	8.85%	8.78%	…	6.3%	6.42%	6.45%	6.5%

Pol. Function: $f_c(d) = 9E\text{-}13d^6 – 1E\text{-}10d^5 – 4E\text{-}09d^4 + 7E\text{-}07d^3 + 8E\text{-}06d^2 + 0{,}0007d -0{,}0217$

The results of these correction factors for the data of May 15th 2010 are shown on Figure 6, and the gain of accuracy (mean and standard deviation) is shown on Figure 7. The self-calibration process based on the whole traffic sample was not inhibited during these measurements. The lateral position distributions observed on March 8th and May 15th 2010 were similar.

The correction procedure replaces the relative errors larger than 20% with the mean weight and then corrects measurements with respect to lateral positions ranging from ±10cm to ±80cm by applying the polynomial function. This method significantly improves the accuracy by halving both the mean and standard deviation of the relative errors (Figure 7).

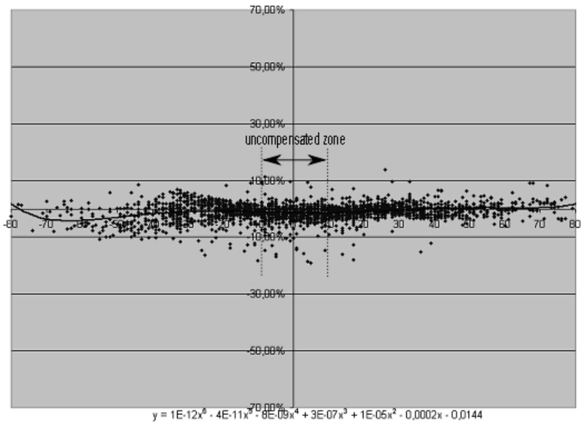

Figure 6 - Corrected errors, 15/5/2010

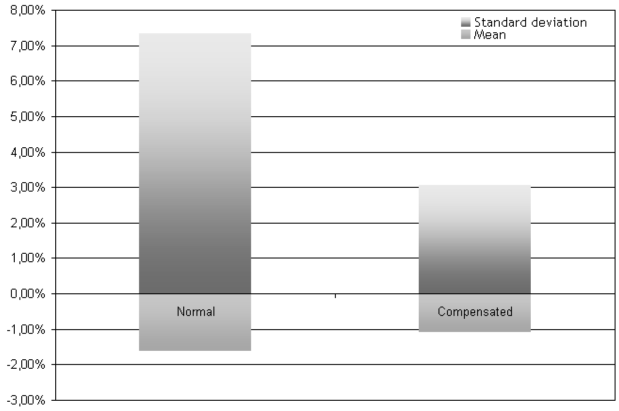

Figure 7 - Errors: Mean and deviation

The same correction factors were applied to another sample of 71 trucks one year later, in May 16th 2011. The lateral position distribution and relative errors against the LS-WIM reference are given in Figures 3(b) and 4(d). It is clear that the relative error distributions versus the LS-WIM and the average of 5 piezoceramic sensors are very similar. Therefore, the polynomial function can be calculated from either one or the other data set, and may be derived without static weighing. Figure 8 shows the corrected errors for the data of March 8th 2010 and May 16th 2011, using the correction factors derived from the sample of March 8th 2010. As above, the relative errors are highly reduced with again the mean error divided by 10 and the standard deviation by 2 (Table 2). According to the COST323 Specifications, the WIM system accuracy with the correction factors jumps by 3 classes.

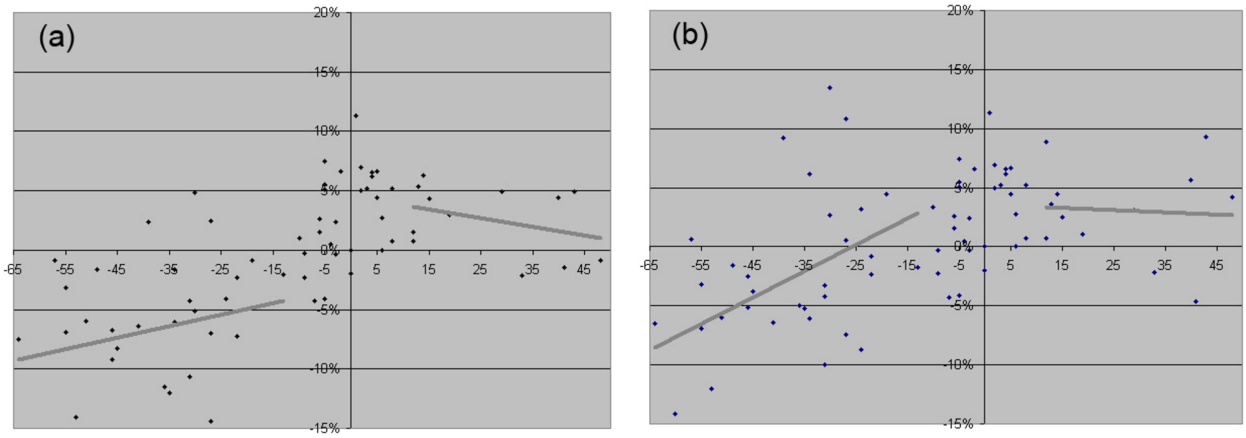

Figure 8 - Corrected errors: (a) 8/3/2010, (b) 16/5/2011

Table 2 – WIM accuracy before/after correction (May 17th 2011)

	n	m	s	Π_o	class	δ	δ_{min}	Π
Gross weight	71	-4.86	12.1	92.2	E(30)	30	26	96.0
GW corrected	71	0.42	6.06	92.2	C(15)	15	12.3	97.1

m, s, Π_o, δ, δ_{min}, Π are expressed in %.

5. Conclusions

As predicted by theoretical and lab studies, field tests confirmed that piezoceramic sensors are sensitive to wheel/vehicle lateral position. Beside the sensor and pavement related intrinsic errors, the main effect results from the bending moment induced in the strip sensor by a wheel vertical force, accounting for 20% to 80% of the total sensor response, depending on the distance between the wheel imprint and the sensor edge. However, the response of a sensor mounted in a pavement differs from its response recorded in lab, because of the simplifications of the pavement and load models.

First the automated self-calibration procedure was improved by eliminating the heavy vehicles with a too large off-set from the calibration sample. The accuracy improvement was significant, with a mean error divided by 10 and its standard deviation divided by 2.

Then a correction polynomial function of the lateral position was developed, by sensor, which led to a similar accuracy improvement. However, comparison over long time periods (2 months and more) showed that the correction function may need to be up-dated over time. Additional investigation will be needed to account for pavement temperature and road structure dynamic effects.

6. Acknowledgment

The authors deeply thank the ministry of Transport (DGITM) for its support to these research works and for its interest in the related projects.

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FINDINGS FROM LTPP SPS WIM SYSTEMS VALIDATION STUDY

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Abstract

This paper provides findings from the weigh-in-motion (WIM) validations conducted at 24 Long-Term Pavement Performance (LTPP) Specific Pavement Study (SPS) test sites in 21 States. It includes discussions of trends observed between sites equipped with different WIM systems and provides recommendations that can improve WIM system verification and calibration processes. The purpose of analyzing the SPS WIM equipment performance was to evaluate the ability of the installed equipment to provide research-quality data; determine whether the accuracy of the WIM systems is a function of pavement smoothness, speed, temperature, truck characteristics, and WIM sensor type; and evaluate the effectiveness of the current processes for validating the SPS WIM scales based on the results of the validations and provide recommendations for improving or enhancing the validation process.

Keywords: Weigh-in-Motion, WIM, calibration, validation, precision, bias, Long-Term Pavement Performance program, LTPP.

Résumé

Cet article présente les conclusions des tests de validation effectués sur 24 sites expérimentaux d'observation de la performance des chaussées à long terme, ainsi qu'une discussion des tendances et des modèles observés dans différents sites équipés de systèmes de pesage en marche différents. Il fournit également des recommandations qui peuvent améliorer le système de vérification et le processus d'étalonnage des stations de pesage en marche. Le but de cette analyse du rendement des appareils est triple: (1) évaluer la capacité de l'équipement installé à fournir des données de qualité suffisante pour la recherche; (2) déterminer si l'exactitude des stations de pesage est fonction du degré de lissage de la chaussée, de la vitesse, de la température, des caractéristiques du poids lourd et du type de capteur; (3) évaluer l'efficacité de l'actuel processus des classification des stations fondé sur les résultats de la validation et de fournir des recommandations pour améliorer ou renforcer le processus de validation.

Mots-clés: Pesage en marche, WIM, étalonnage, validation, précision, écart, programme de suivi de la performance des chaussées à long terme, LTPP.

1. Background

The objective of the Long-Term Pavement Performance (LTPP) Specific Pavement Studies (SPS) Traffic Data Collection Pooled-Fund Study is to improve the quality and increase the quantity of monitored traffic data (volumes, classifications, and weights) at the LTPP SPS-1, -2, -5, -6, and -8 test sites. Bending plate, load cell, and quartz-piezo sensor weigh-in-motion (WIM) sensors are being used to collect research-quality data. For the purpose of this study, research-quality data is defined as 210 days of data (in a year) of known calibration meeting LTPP's accuracy requirements for steering and tandem axles, gross vehicle weight, speed, and axle spacing.

Field calibrations and validations were conducted in 2010-2011 at 24 LTPP SPS WIM sites using the protocols in the LTPP Field Operations Guide for SPS WIM Sites (LTPP, 2009). The evaluated WIM systems included 11 bending plate sites, 11 quartz-piezo sites, and 2 mechanical load cell sites. The objectives for analyzing the performance of the LTPP SPS WIM equipment was three-fold: (1) evaluate the ability of the WIM systems to provide research-quality data; (2) determine whether the accuracy of the WIM systems is a function of pavement smoothness, speed, temperature, truck characteristics, and WIM sensor type; and (3) evaluate the effectiveness of the current processes for validating the SPS WIM systems and provide recommendations to improve or enhance the calibration and validation process.

2. Objective and Scope

The objectives of this paper is to collectively report on the findings and results of the WIM validations conducted at 24 LTPP SPS WIM sites over the course of the year; document trends and patterns observed across different WIM sites equipped with different WIM systems; and provide recommendations to improve WIM system calibration and validation processes.

3. Findings

The validation data were analyzed extensively, and this study resulted in several findings and lessons learned related to the WIM field calibration and validation process.

3.1 Analysis Results for GVW, Single, and Tandem Axle Weight Measurements

Axle weight and gross vehicle weight (GVW) data from validations conducted at each site using two test trucks were analyzed to see if there were differences between the equipment measurement accuracies achieved for different axle types and how effective the calibration was in improving the accuracy of WIM data. Values characterizing axle weight and GVW measurement accuracies were expressed in terms of percent error between WIM measured weight and the static weight. For comparison purposes, the percent errors were summarized using the following parameters:

1. Error due to equipment bias, computed as the mean percent error between static and WIM weight measurements, based on all passes of calibration trucks at each site.

2. Error due to equipment precision, computed as the maximum expected percentile deviation from the mean value for 95% of all observations at the site.
3. Overall error (WIM accuracy requirement), computed as the summation of the errors due to equipment bias and precision.

For single axles, all pre-validation and post-validation results were within LTPP's WIM accuracy requirements based on overall error values. Post-validation results had smaller overall errors compared to pre-validation results, demonstrating the benefit of system calibration efforts. All post-validation results for single axles showed that even tighter than current performance requirement for overall error, which is +/-20% error for 95% conformance (LTPP, 2009), was achieved at the LTPP SPS WIM sites. Maximum observed post-validation overall error was -14.6% for one of the sites. The spread of error due to equipment precision was similar between pre-and post-validation results, while a significant reduction in error due to equipment bias was observed across all sites as a result of WIM system calibration activities.

For tandem axles, all but two pre-validation results and all post-validation results were within LTPP's WIM accuracy requirements, which is +/-15% overall error for 95% conformance. Post-validation results had smaller overall errors compared to pre-validation results, demonstrating the benefit of system calibration efforts. The spread of error due to equipment precision was similar between pre-and post-validation results, while a significant reduction in the bias portion of error was observed across all sites as a result of WIM system calibration activities.

Bias in WIM weight measurements was observed at a number of sites, as determined by the mean error between the static and WIM-based weight measurements of calibration trucks from the 40 test truck runs. It was not possible to determine whether these errors were attributable to WIM system performance or caused, at least in part, by specific characteristics of calibration trucks. For cases where the bias in WIM weight measurement was observed for both lightly and heavily loaded calibration trucks, it was assumed that the bias was attributable to WIM system performance. Table 1 shows the distribution of errors due to WIM equipment bias observed at the LTPP sites.

Table 1 - Distribution of Errors Due to Equipment Bias Observed at LTPP SPS Sites

Measurement type	Errors due to bias in pre-validation measurements			Errors due to bias in post-validation measurements*		
	<2 %	2-5%	>5%	<2 %	2-5%	>5%
Steering Axle	7	12	5	14	8	1
Tandem Axle	10	8	6	22	1	0
GVW	10	8	6	22	1	0

*Post-validation results are based on 23 sites; one site was not calibrated due to equipment failure.

Errors due to bias were slightly less for GVW measurements compared to the individual axles. In some cases, negative and positive biases associated with single and tandem axle weight measurements were compensating each other in GVW bias calculation, once these measurements were combined to estimate GVW. Errors due to bias in steering axle measurements were higher than in tandem and GVW measurements. Errors due to bias in pre-calibration measurements were higher than in post-calibration measurements, indicating the benefit of routine WIM calibration. For post-calibration measurements, the majority of errors due to bias were less than 2%.

3.2 Analysis of Factors Affecting WIM Performance

The researchers analyzed the effect of speed, temperature, truck type, and sensor type, as well as pavement type and smoothness, on the weight errors associated with the various WIM systems installed at the LTPP SPS test sites.

Speed Data Analysis

Weight measurement error due to equipment bias is a function of the calibration. It is mitigated through the speed-based compensation factors and adjustment of those factors. Therefore, speed did not have an effect on weight measurement error due to equipment bias. However, the effect of speed on the range of weight measurement errors due to equipment precision was investigated. The operating speeds for the test trucks ranged from 45 to 70 mph. The variability in error for GVW appeared to increase as speed increased at 5 of the 23 sites, and tandem axle weight measurement appeared to increase as speed increased at 7 of the sites. For steering axle weights (10 sites), the range in error appears to decrease with increases in speed. The effect of speed had a statistically significant effect. Consequently, it is recommended that the validation continue across the widest possible range of truck operational speeds for the site.

None of the sensor types showed significantly higher sensitivity to speed than the others. However, bending plate sensors appear to provide more precise GVW measurements than other sensors throughout the speed range.

For asphalt pavements, the variation in GVW error appears to increase as speed increases. For those sensors installed in Portland cement concrete (PCC) pavements, the range in error is consistent throughout the speed range.

Temperature Data Analysis

During the validations, efforts were made to test the equipment over the highest range of temperatures possible. The target temperature variation was 30 degrees Fahrenheit. Temperature does not appear to have a significant effect on the mean error or variability in error for about two-thirds of WIM systems installed at the LTPP SPS sites. However, there were several sites (10 of 23 for GVW) that appeared to be affected significantly by pavement temperature. These sites were equipped with either quartz-piezo sensors or bending plates. Consequently, it is recommended that the validation be carried out at the greatest possible range of pavement temperatures for the sites equipped with these types of WIM sensors.

Truck Type Data Analysis

The effect of using two calibration trucks for evaluating the accuracy of WIM measurements was analyzed. The effect of truck type was found to be statistically significant in about 50 percent of all cases. Truck type appears to have a more significant impact on weight measurement than speed, pavement temperature, or pavement type. GVW and tandem axle weights for the heavily loaded "primary" truck were, on average, overestimated by the WIM equipment. GVW for the partially loaded "secondary" truck generally was underestimated. Variability in error appears to be consistently larger for all weight measurements involving partially loaded trucks. Based on these findings, the use of at least two test trucks, as recommended in the LTPP Field Operations Guide for SPS WIM Sites, was found to be important (LTPP, 2009). This finding also indicates higher variability in weight measurements associated with lighter vehicles.

WIM Sensor or Technology Type Analysis

Errors due to equipment bias for all weight measurements were analyzed with respect to sensor type (see Table 2). Error due to equipment bias provides an indication of consistent under- or overestimation in weight measurements from different passes of the calibration trucks. Analysis of pre-calibration measurements indicated that sites with quartz-piezo or bending plate sensors had higher weight measurement error due to equipment biases than load cell sites, except for steering axles. However, the analysis of post-calibration measurements indicated that load cell sites had the largest post-calibration weight measurement error due to equipment bias, indicating that these sites were more challenging to calibrate than sites with bending plate or quartz-piezo sensors. Load cell sites had the least change in weight measurement error between calibrations, indicating that performance of these systems is more stable between calibration visits.

Table 2 - Average of Errors Due To Equipment Bias Observed at LTPP SPS Sites with Different WIM Sensors

Measurement type	Errors due to bias in pre-validation measurements, %			Errors due to bias in post-validation measurements		
	Quartz-piezo	Bending plate	Load cell	Quartz-piezo	Bending plate	Load cell
Steering Axle	4.0	2.7	5.1	1.5	1.2	4.7
Tandem Axle	2.9	3.7	1.2	0.8	0.8	0.8
GVW	3.3	3.2	1.1	0.8	0.5	1.4

Error due to equipment precision provides a measure for a spread of errors in weight measurements from different passes of calibration trucks. Average errors due to equipment precision were computed and analyzed for different WIM technology types. They were computed by averaging errors due to equipment precision computed for individual sites with the same WIM technology type. The results, as shown in Table 3, indicate that errors due to equipment precision do not change much as a result of calibration. This is expected, as error due to equipment precision is not expected to be affected by the calibration process – it is a function of equipment type and site conditions. Among the three WIM technologies used, quartz-piezo showed highest spread of errors due to equipment precision while load cells showed the lowest spread of errors. All three technologies produced values well within the ASTM 1318 specification for Type I WIM systems (ASTM, 2002).

Table 3 - Average Weight Measurement Error Due to Equipment Precision Observed at LTPP SPS Sites with Different WIM Sensors

Measurement type	Average errors due to equipment precision observed during pre-validation, %			Average errors due to equipment precision observed during post-validation, %		
	Quartz-piezo	Bending plate	Load cell	Quartz-piezo	Bending plate	Load cell
Steering Axle	7.7	6.5	4.6	7.9	6.5	5.8
Tandem Axle	6.3	5.1	3.9	6.5	4.7	4.8
GVW	4.9	3.9	2.6	5	3.4	3.3

Smoothness and Pavement Type Analysis

Although the asphalt pavements were smoother, the WIM systems installed in asphalt pavements provided measurements which were, on average, less precise than those provided by WIM systems installed in the PCC pavements. Since all bending plate systems were installed in PCC pavements and the majority of the quartz-piezo sensor systems were installed in asphalt pavements, this counterintuitive finding may be attributable to the WIM sensor or technology type. In addition, pavement smoothness indices are based on the International Roughness Index (IRI) measurements and may be influenced by pavement type.

Evaluation of the WIM systems for the sites using bending plate technology installed in PCC pavement provided the greatest precision for all weight estimations, despite not being installed in the smoothest pavement sections. The sites using quartz-piezo sensors installed in asphalt pavement were more precise than those sites using quartz-piezo sensors installed in PCC pavements. This observation may be attributed to rougher PCC pavement at these sites.

4. Conclusions and Recommendations

For all the sites validated, it was possible to meet the overall tolerance limits specified in the LTPP Field Operations Guide for SPS WIM Sites (LTPP, 2009). Only one of the 24 sites had equipment issues that precluded WIM calibration/validation activities. This site is instrumented with a quartz-piezo sensor. Five of the 24 WIM sites did not require changes in calibration parameters based on assessment of the field performance. Of these sites, four were quartz-piezo sensors and one was a bending plate sensor.

Post-validation results showed smaller overall errors compared to pre-validation results, demonstrating the benefit of system calibration efforts. The weight measurement error due to equipment precision was similar between pre- and post-validation results, while a significant reduction in weight measurement error due to equipment bias was observed across all sites as a result of WIM system calibration activities.

Weight measurement error due to equipment bias associated with GVW measurement was consistently lower than weight measurement error due to equipment bias associated with individual axle weight measurements.

The following observations and recommendations are made regarding WIM system tolerance limits for WIM sites designated for collecting research-quality data:

- For the validations, it was possible to meet even more stringent requirements for single axle loads on a consistent basis (+/- 15% error). Although the SPS WIM tolerance limits can be met easily through calibration, it may not be easy to maintain these limits during the entire time period the equipment is collecting data, as was observed in the pre-validation studies at a limited number of sites. Therefore, the data obtained in this study provide support for different tolerance limits as set in ASTM 1318 (steering axles – 20%, tandem axles – 15%, and GVW – 10% (ASTM, 2002). Furthermore, the data indicate that these tolerances are proportionately correct.

- However, reduction in weight measurement error due to equipment bias associated with individual axle weight measurements becomes increasingly important in the United States, as pavement design and analysis procedures move from the use of a statistic representing gross loading estimate associated with the total truck traffic to specific axle load estimates used in the Mechanistic-Empirical Pavement Design Guide (MEPDG) methodology (AASHTO, 2008). The existing LTPP field operations procedures may need to be updated to emphasize the importance of reduction in not only GVW measurement error due to equipment bias but also the weight measurement bias associated with individual axle weight measurements.

- Weight measurement error due to WIM equipment bias increased between calibration visits. To avoid significant bias in axle weight data, auto-polled single and tandem axle load data for class 9 vehicles should be checked periodically against a comparison or reference data set collected right after calibration. It is suggested that this be done bi-weekly or monthly. Consistent shift by over one load bin in class 9 average single and/or tandem axle load spectra peaks would indicate that WIM system weight measurement error due to equipment bias is significantly different from zero and may not satisfy performance requirements.

Based on the results of the validations, the following are recommendations for changing the current calibration/validation procedures:

- The requirement for collecting and reporting speed data using a manual radar gun should be removed from the field and reporting requirements as outlined in the LTPP field operations guide (LTPP, 2009). Since the speed of the vehicles passing over the WIM system and the axle spacing measurements share identical computations, and the WIM system is calibrated for errors in the axle spacing measurement, the requirement for speed data collection using the manual speed gun is redundant. In addition, the speed guns are not accurate enough (+/- 1 mph) to provide the resolution needed to meet the requirements (also +/- 1 mph). Just one or two speeds outside of 1 mph results in a failure. However, the field validation team should continue to collect truck speeds from the WIM system to determine speed-related weight measurement error due to equipment bias.

- Based on the results obtained to date, it appears that the number of validation runs can be reduced for some sites. This possibility should be investigated further by analyzing data obtained from previous calibrations. This could be accomplished through a statistical analysis by reducing the number of runs and evaluating consequences of the reduced number of runs.

- The effect of pavement temperature on measurement errors sometimes is statistically significant. However, currently temperature compensation factors are not changed during calibration. In other words, the effect of pavement temperature is noted without doing anything about it. It may be beneficial to discuss with the WIM vendors how to take full advantage of this feature.

Several calibration/validation procedures currently in place are further endorsed based on the results of the WIM validations:

- Since the speed of test trucks often has a significant effect on measurement errors, and the axle weights obtained at different speeds are required for adjusting speed compensation factors, validation should continue to be carried out using the widest range of truck operating speeds, where possible.

- The use of at least two test trucks should continue because secondary (partially loaded) trucks typically have larger variability (standard error) in error estimates.

The data being collected and the information derived from the validations could be very useful for other studies, both as part of the LTPP SPS Traffic Data Collection Pooled-Fund Study and for other investigations. Supplemental data, if collected during the validation effort, along with past and future validation results could be valuable in support of future studies, such as:

- Analysis of historical and current WIM system validation data to determine the effect of factors such as pavement smoothness, sensor type, pavement type, and truck type on the variability of each weight measurement.

- Determination of the variability of error for single, tandem, tridem, and quad axle configurations and its effect on LTPP analyses that use axle weight data (such as MEPDG).

- Evaluating the current temperature compensation methodology for each type of WIM system configuration and incorporating temperature compensation into the WIM calibration process.

- Evaluating WIM sensor performance by considering not only sensor accuracy, but also other performance parameters (e.g., life cycle cost and user costs due to installation) and to evaluate the performance differences, in terms of the measurement accuracy, between the three types of WIM sensors used at the LTPP SPS sites.

- Analysis of historical validation information to determine which WIM systems may exhibit a tendency to drift lower (or higher) with time and increasingly underestimate (or overestimate) axle weights to determine the need and frequency for calibration/validation.

- Developing recommendations for minimum requirements for WIM installations and maintenance to collect research-quality data or data suitable for State-specific MEPDG loading defaults based on LTPP's experience.

- Developing an LTPP tool suite for States to use for WIM calibration based on sensitivity studies with LTPP validation results (fewer test truck runs, single test truck, etc.) to make calibration more economically feasible and promote more widespread use.

- Developing a "remote calibration verification" procedure based on LTPP's quality assurance processes that evaluate comparison data set against current data.

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WEIGH-IN-MOTION DATA: QUALITY CONTROL, AXLE LOAD SPECTRA, AND INFLUENCE ON PAVEMENT DESIGN

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Abstract

This research examines the quality of the traffic data collected by New Mexico Department of Transportation (NMDOT) and its influence on mechanistic-empirical pavement design. The weight data collected from five weigh-in-motion (WIM) sites during the year 2009 are used in this study. Quality of data is checked based on a set of algorithms implemented in Visual Basic Application. It is evident from this study that bending plate sites provide high quality WIM data compared to piezoelectric systems. The effect of data quality is evaluated by determining the influence of axle load spectra on the predicted pavement performance. An algorithm is used to produce a positive and negative calibration bias in the WIM data. The Mechanistic-Empirical Pavement Design Guide (MEPDG) is used to predict rutting, alligator cracking, longitudinal cracking, transverse cracking, and IRI.

Keywords: Weigh-in-Motion, WIM, Quality Control, Axle Load Spectra, MEPDG, distress.

Résumé

Ce document examine la qualité des données de trafic collectées par le Ministère de Transport de l'Etat de New Mexico (NMDOT) et son influence sur le guide de calcul mécanistique-empirique des chaussées. Les données de pesage recueillies par cinq stations de pesage durant l'année 2009 sont utilisées dans cette étude. La qualité des données de pesage est vérifiée par un ensemble d'algorithmes programmés en Visual Basic. Il ressort de cette étude que les sites avec barreaux fournissent des données de meilleure qualité que les systèmes piézoélectriques. L'effet de la qualité des données est évalué en déterminant l'influence des spectres des charges à l'essieu sur la performance des chaussées prédite dans MEPDG. Un algorithme est utilisé pour produire un biais d'étalonnage positif ou négatif dans les données de pesage. Le Guide de Calcul Mécanistique-Empirique de Pavées (MEPDG) est utilisé pour prédire la déformation permanente, la fissuration et la rugosité des chaussées.

Mots-clés: Pesage en marche, contrôle de qualité, spectre des charges à l'essieu, MEPDG, contraintes.

1. Introduction

Traffic is one of the most important inputs required for the design and analysis of pavements. It represents the magnitude and frequency of the loads applied during the pavement design life. The previous versions of the AASHTO Guide for Pavement Design characterized traffic by defining the equivalent single axle load (ESAL). However, the new Mechanistic-Empirical Pavement Design Guide for New and Rehabilitated Pavements (MEPDG) uses a more complex approach and requires a larger number of traffic inputs (ARA, Inc., and ERES Consultants Division, 2004). One of these inputs is the axle load spectra which can be only obtained from WIM data. Therefore, it is critical for highway state agencies to collect and process high quality weigh-in-motion data.

Weigh-in-motion (WIM) systems are installed in suitable sections of roads to collect classification and weight traffic data. For each truck vehicle passing, these equipments record a tabulation formed with the vehicle type (FHWA class 4 through 13) and the number, spacing, and weight of axles. There are different technologies for WIM systems such as load cell, bending plate, and piezo-sensor. The weight measured by these dynamic systems is not the same as the actual static weight, and their accuracy in conditions of use, i.e., under moving traffic tire loads, may only be defined in a statistical, as opposed to metrological, way (Jacob, 1997).

The equipment required to collect weigh-in-motion data is very expensive and often state highway agencies and their traffic monitoring programs are subjected to budget constraints. This usually results in lack of calibration of their WIM sites which directly affect the quality of data. Also, the type of sensor, the pavement condition, and the temperature in the case of piezo systems are factors affecting the accuracy and reliability of WIM sites. Therefore, it is very important to provide state highway agencies with a procedure to evaluate the quality of WIM data and to determine when a particular WIM site requires calibration.

With this study, the researchers pursue the following objectives:

- Develop a set of algorithms to perform quality control of weigh-in-motion data,
- Determine the influence of data quality on predicted pavement performance,
- Evaluate the effect of axle load spectra on predicted pavement performance.

2. Weigh-in-Motion Data in New Mexico State

Currently, fourteen WIM stations are collecting weight and classification data throughout New Mexico. These WIM sites are operated by New Mexico Department of Transportation (NMDOT). Three of them use bending plate systems (IRD 1058), and the remaining use piezoelectric sensors (Mikros Raktel 8000). The condition of the road surface, the calibration of the system, and the temperature in the case of piezoelectric sensors are factors that affect significantly the weight measurement. The data collected in five WIM sites during the year 2009 are used for these analyses. The WIM sites considered are: Cuba, San

Ysidro, and Bloomfield (bending plates); and Tucumcari, and Tularosa (piezoelectric sensors).

3. Quality Control Rules and Algorithms

A series of validation rules are defined to check whether the data are consistent and whether the data fall within acceptable ranges. These fifteen rules are implemented by means of algorithms in Visual Basic Application (VBA). This program is run for the desired weigh-in-motion data and every vehicle record has to pass each of these rules in order to be valid. If any of the rules is not fulfilled then an "ERROR" flag appears, and the user can remove that particular vehicle record. The details of the rules are described as follows (Ramachandran et al., 2011, Flinner, M., and Horsey, H., 1995):

1. The year is unique and correct, e.g. if Year ≠ 09 then "ERROR".
2. The month is correct, e.g. if Month ≠ 01 then "ERROR".
3. The day is correct, e.g. if Day ≠ 1 to 31 then "ERROR".
4. The time is correct, e.g. if Hour ≠ 0 to 23 then "ERROR".
5. The WIM site id is correct, e.g. if WIM Code ≠ 21020 then "ERROR".
6. The direction is correct, e.g. if Direction ≠ 1 or 5 then "ERROR".
7. The lane number is correct, e.g. if Lane Number ≠ 1 to 4 then "ERROR".
8. The vehicle class is correct, e.g. if Vehicle Class ≠ 4 to 13 then "ERROR".
9. The number of axles is consistent with the number of axle spaces, e.g. if Number of Axles ≠ Number of Axle Spaces + 1 then "ERROR".
10. The number of axles is consistent with the number of axle weights, e.g. if Number of Axles ≠ Number of Axle Weights then "ERROR".
11. The gross vehicle weight is consistent with the sum of axle weights, e.g. if Sum of Axle Weights ≠ GVW then "ERROR".
12. The number of axles is consistent with the vehicle class, e.g. if Number of Axles ≠ Range of Axles for that vehicle class then "ERROR".
13. The sum of axle spaces is consistent with the maximum length, e.g. if Sum of Axle Spaces > 35 m (115 ft) then "ERROR".
14. The axle weights are within acceptable range, e.g. if Axle Weight ≠ 200 kg (440 lbs) to 15,000 kg (33,000 lbs) then "ERROR".
15. The axle spaces are within acceptable range, e.g. if Axle Spacing ≠ 0.6 m (2 ft) to 15 m (50 ft) then "ERROR".

Finally, other algorithms are developed to make this program able to calculate the following frequency distributions which are very important for quality control of WIM data:

1. Gross Vehicle Weight Frequency Distribution by class,
2. Front Steering Axle Weight Frequency Distribution by class.

In the last step of this process, the gross vehicle weight and steering axle weight frequency distributions are subjected to the following criteria (FHWA, 2001):

- The class 9 gross vehicle weight distribution must have a peak due to unloaded vehicles within the range of 13,500 kg (30,000 lbs) to 18,000 kg (40,000 lbs) and another peak due to loaded trucks within the range of 31,500 kg (70,000 lbs) to 37,000 kg (80,000 lbs).

- The class 9 front steering axle weight distribution must have the majority of axles within the range of 3,600 kg (8,000 lbs) to 5,400 kg (12,000 lbs).

4. Quality Control Analysis

The set of quality control rules is run and less than 1% of the weight records are found to be invalid. The invalid records are removed, and then, the program calculates the previously mentioned frequency distributions. The gross vehicle weight frequency distribution for FHWA class 9 is plotted in Figure 1. This vehicle class comprises more than 50% of the total traffic stream. The three bending plate systems (Cuba, San Ysidro, and Bloomfield) present a distribution with peaks for unloaded and loaded trucks in the middle of the ranges recommended by the Traffic Monitoring Guide. Whereas the two piezoelectric sites (Tucumcari and Tularosa) do not have a peak for unloaded trucks which indicates that these WIM sites are assigning high weight to every truck passing, probably due to malfunction of the system.

The front steering axle weight frequency distribution for class 9 vehicles is shown in Figure 2. For the case of the three bending plates, most of the frequencies fall within the range recommended by the Traffic Monitoring Guide. The curves are totally out of the acceptable range in the case of piezoelectric systems.

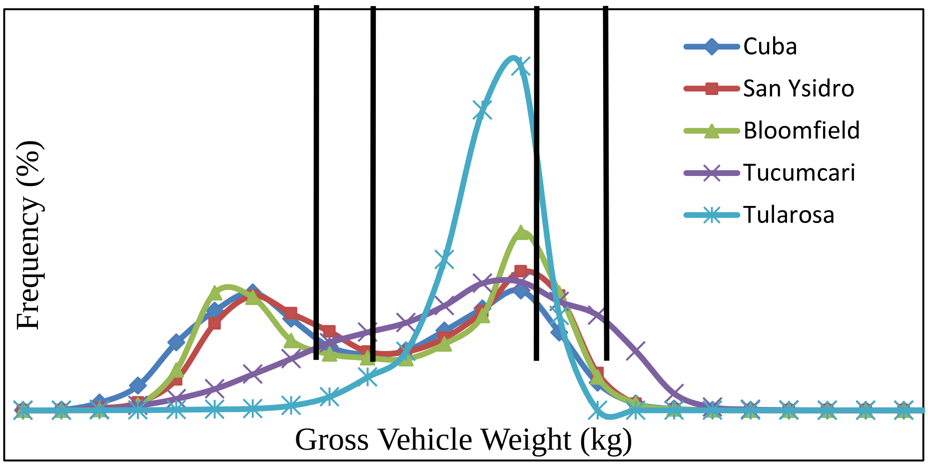

Figure 5 - Class 9 Gross Vehicle Weight Frequency Distribution

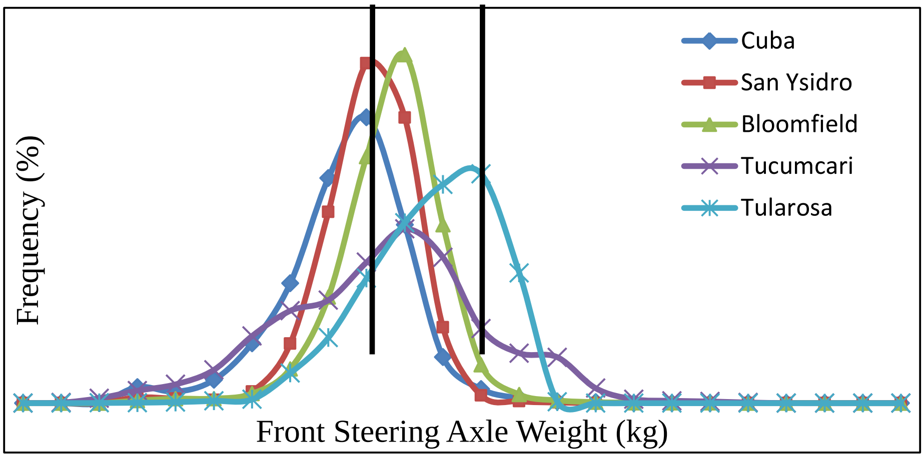

Figure 6 - Class 9 Front Steering Axle Weight Frequency Distribution

These results denote that Tucumcari and Tularosa sites are not providing good weigh-in-motion data, perhaps due to the lack of calibration or the effect of surface condition and temperature in piezoelectric sensors. On the other hand, Cuba, San Ysidro, and Bloomfield are collecting acceptable WIM data. Among the bending plate systems, the data collected by Cuba site is the most consistent, and therefore, are used in the following analyses.

5. Simulation of Measurement Bias

The weight measured in dynamic conditions by a WIM system is not the actual static weight. There is always some measurement error. Part of this error is random due to the inherent deviation associated to any measurement process. Also, error can be produced by a systematic bias in the measurement apparatus due to lack of calibration. The systematic bias results in a positive or negative deviation and can be quantified as a percentage.

An algorithm has been developed in VBA to simulate the systematic bias in a weigh-in-motion site due to lack of calibration. This subroutine increase or decrease the weight data collected at the WIM site by a given percentage. The algorithm is used to apply a positive and negative bias of 10%, 20%, and 30% to Cuba weigh-in-motion data.

The gross vehicle weight frequency distributions at Cuba for the cases of no bias and positive and negative 20% bias are calculated and plotted in Figure 3. As expected, a positive bias produces a displacement of the curve to the right and a negative bias a displacement to the left. The displacement of the curve is larger for loaded trucks.

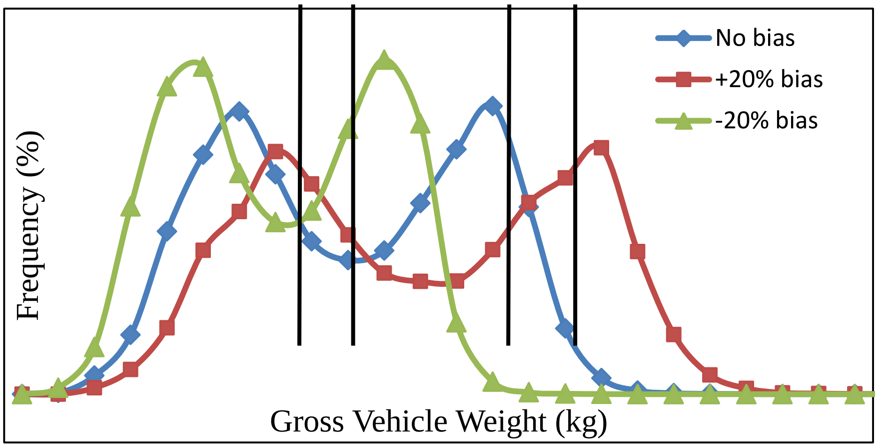

Figure 7 - Class 9 GVW distribution for no bias, positive, and negative bias

6. Development of Axle Load Spectra

Weigh-in-motion data has to be processed in order to obtain axle load spectra which are one of the most important inputs in pavement design. This process is external to MEPDG. TrafLoad v1.0.8 is software for processing and analysis of weigh-in-motion data that was created under NCHRP Project 1-39 (Cambridge Systematics, Inc., Washington State Transportation Center, and Chaparral Systems, Inc., 2005). In this case TrafLoad was tried but the data could not be successfully imported as in other cases reported in the literature (Tran, N.H., and Hall, K.D., 2007), (Smith, B. C., and Diefenderfer, B. K., 2010).Therefore, an algorithm has been implemented in VBA to process weigh-in-motion data and to compute the corresponding axle load spectra. This algorithm is based on the spacing between axles and the weight of each axle. This algorithm has been proved to reproduce correctly the axle configuration of most of the trucks being used currently in New Mexico roads. The subroutine is used to obtain the axle load spectra at Cuba WIM site for single, tandem, tridem and quad axles and for the cases of no bias and positive and negative bias as shown in Figure 4. These axle load spectra are used in the next section to predict the pavement performance with MEPDG.

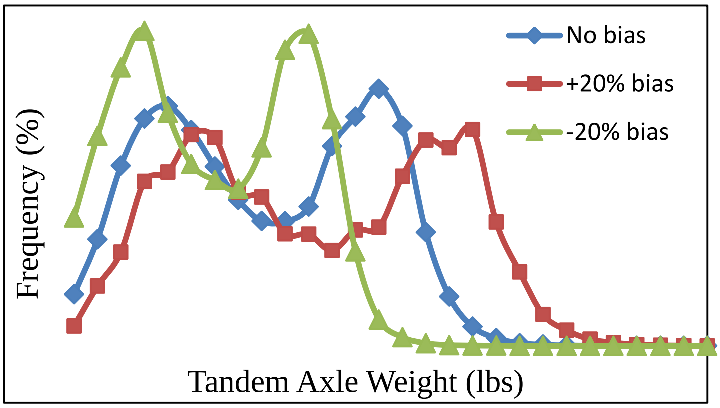

Figure 8 - Class 9 Tandem Axle Load Spectra for no bias, positive, and negative bias

7. Prediction of Pavement Performance

The MEPDG version 1.100 is used to predict the pavement performance of a section in the US-550 which is located close to Cuba WIM site. The data of the pavement section required to run MEPDG are obtained from the "Flexible Pavement Database for Local Calibration of MEPDG" which is currently being developed at the University of New Mexico. The simulation is performed for a design life of 20 years. All inputs are kept constant except axle load spectra which are varied to evaluate the influence of no bias, and positive and negative 10%, 20%, and 30% bias in the predicted pavement distresses (total rutting, longitudinal cracking, transverse cracking, alligator cracking, and IRI).

8. Influence on Pavement Performance

The total and AC permanent deformation are predicted and their sensitivity to bias in the weight measurement is plotted in Figure 5. The behavior of both total rutting and AC rutting is the same. A positive and negative bias of 1% results in an increase and decrease in the predicted rutting of 1% respectively. The relationship is linear.

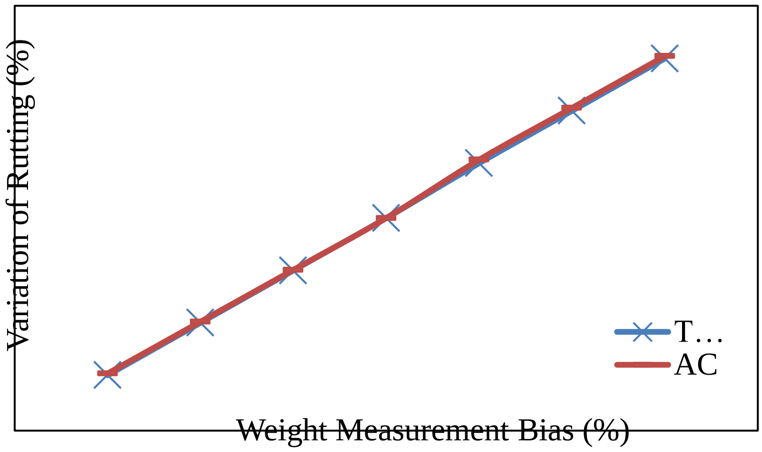

Figure 9 - Influence of Weight Measurement Bias on Predicted Rutting

Figure 6 shows weight measurement bias versus variation of longitudinal and alligator cracking. In both cases, the relationship is nonlinear in such a way that the influence of positive bias doubles that of negative bias. A negative weight measurement bias of 1% produces an average decrease in longitudinal cracking of 4%, while a positive bias of 1% results in an average increase of 9%. Similarly, a negative bias of 1% results in an average decrease in alligator cracking of 3% and a positive bias of 1% produces an average increase of 6%.

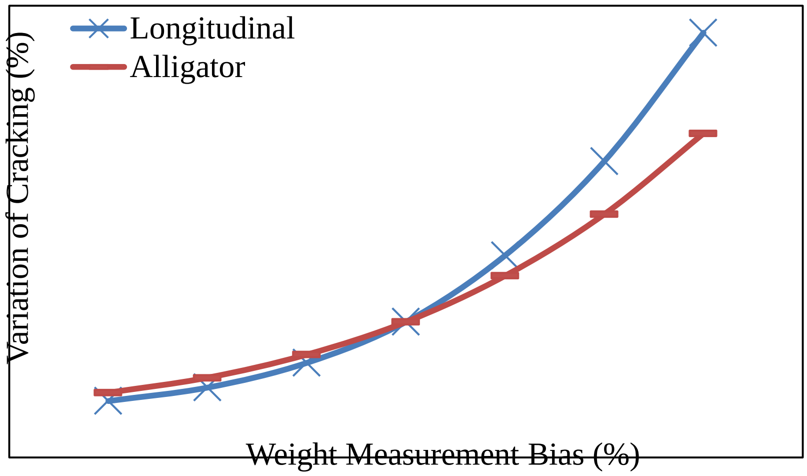

Figure 10 - Influence of Weight Measurement Bias on Predicted Cracking

The influence of weight measurement error on transverse cracking and IRI can be analyzed in Figure 7. As expected, weight measurement bias has no effect on transverse cracking because this distress depends mostly upon temperature. Similarly, the effect of bias on the international roughness index is negligible since 1% bias results in a variation of 0.1%.

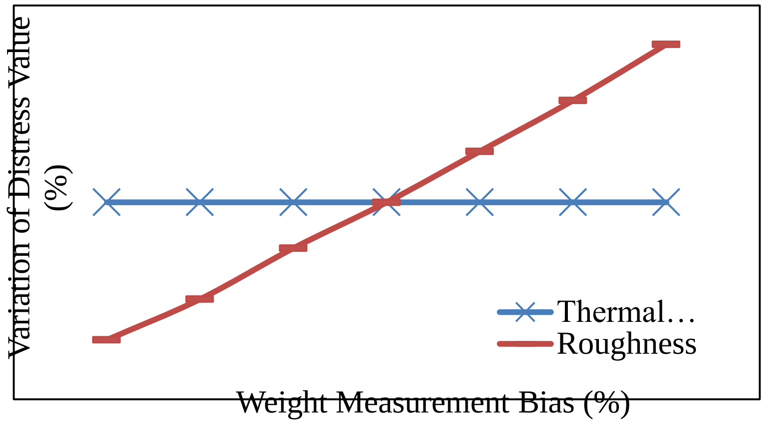

Figure 11 - Influence of Weight Measurement Bias on Predicted Thermal Crack. and IRI

9. Conclusions

From this research, the following conclusions can be made:

- The criteria based on gross vehicle weight and steering axle weight frequency distributions allow evaluating successfully the quality of weight data collected at WIM sites. In New Mexico, piezoelectric systems are not collecting consistent data, and thus, calibration of these WIM sites is required.
- Positive and negative bias of the weight measured at WIM sites can be simulated respectively by increasing and decreasing in a percentage the weight-in-motion data collected. A positive bias results in an increase of the weight frequency distributions and the axle load spectra. It goes the other way with a negative bias.
- The influence of weight measurement bias on predicted pavement performance can be analyzed using the axle load spectra for the cases of no bias, positive bias, and negative bias in the MEPDG in order to simulate the corresponding distresses.
- The effect of weight measurement error on predicted rutting is considerable but not critical. However, bias of weight data affects dramatically predicted longitudinal and alligator cracking (1% of bias can result in an increase of 9% in longitudinal cracking and 6% in alligator cracking). The influence of weight measurement bias on transverse cracking and IRI can be neglected.

It is important to collect accurate and reliable weigh-in-motion data since error in the measurement can lead to overestimate or underestimate the pavement thickness.

10. Recommendations

It is recommended to expand the WIM network as much as possible according to available budget and calibrate every WIM site at least twice a year.

11. Acknowledgment

The research team thanks the New Mexico Department of Transportation for funding and making possible this study.

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QUALITY CONTROL OF ALABAMA WEIGH-IN-MOTION DATA FROM DATA USER PERSPECTIVE AND DEVELOPMENT OF MEPDG TRAFFIC INPUTS



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Abstract

This paper presents a quality control (QC) procedure that was developed and then applied to raw WIM data from Alabama, and a process to develop reliable traffic inputs required by MEPDG. Data users' QC process should include simple threshold checks and more data-driven rational checks. Instead of using subjective visual comparisons of gross vehicle weight (GVW) curves, this research implements a QC process that includes an axle load spectra (ALS) peak-range check, an ALS peak-shift analysis and an ALS correlation analysis to quantify a rational approach to QC. To develop MEPDG traffic inputs in Alabama after WIM data QC, a process to convert raw TrafLoad outputs into MEPDG-recognized traffic inputs has been developed. WIM data collected from station 911 in Alabama from 2006 to 2008 were analyzed and then developed into MEPDG traffic inputs in this paper.

Keywords: Weigh-in-Motion, WIM, Quality Control, QC, Peak-range, Peak-shift, Correlation Analysis, MEPDG, Traffic Inputs, TrafLoad, Data Conversion.

Résumé

Ce papier présente une procédure de contrôle qualité (CQ) qui a été développée puis appliquée à des données brutes de l'Alabama, et un processus d'élaboration des entrées de trafic fiables requises par MEPDG. Processus de CQ utilisateurs de données devraient inclure des vérifications de seuil simple et plus guidée par les données vérifie rationnelle. Au lieu d'utiliser des comparaisons visuelles subjectives brute du poids des véhicules (GVW) des courbes, cette recherche met en œuvre un processus de CQ qui comprend une charge à l'essieu des spectres (SLA) vérifier pic de gamme, un SLA de pointe d'analyse et de changement d'une analyse de corrélation SLA pour quantifier une approche rationnelle de CQ. Pour développer le trafic MEPDG entrées en Alabama après les données détection CQ, un processus visant à convertir les sorties brutes en TrafLoad entrées du trafic MEPDG reconnu a été développé. Des données recueillies auprès de la station détection 911 dans l'Alabama de 2006 à 2008 ont été analysées puis développé en MEPDG entrées du trafic dans ce papier.

Mots-clés: Pesage en marche, contrôle qualité, CQ, amplitude des pics, changement des pics, analyse de corrélation, MEPDG, entrées de données de trafic, conversion de données.

1. Introduction

One of the major improvements with using the Mechanistic-Empirical Pavement Design Guide (MEPDG) occurs in its characterization of traffic. Instead of converting all Class 4 to Class 13 truck axles to 18 kips equivalent single axles, the MEPDG simulates every truck axle from a wide range of axle load spectra (axle load distribution). Then, the damage of every single pass is calculated and accumulated. The simulation will continue until the accumulated damage reaches a terminal serviceability point, and then the service life of the pavement is established.

The MEPDG requires significant amount of data inputs. Most of the traffic data inputs can be developed from Weigh-in-Motion (WIM) data. Even though WIM data provides support to the MEPDG, its quality is questionable. WIM data quality control (QC) is often incorporated into the data collection process, and it could be assumed that data users receive high quality WIM data through data collection. Even though WIM calibration recommendations through the Long Term Pavement Performance (LTPP) Program suggest local government agencies or data collectors calibrate WIM stations regularly, it is suspected that WIM stations may not be routinely calibrated (FHWA, 2001a).

Past studies have indicated that MEPDG pavement life estimation is highly sensitive to WIM data (Haider et al., 2010). To minimize the potential for “garbage in and garbage out” problem in WIM data analysis, quality control from data users’ perspective is crucial. Data users’ QC process should include simple threshold checks and more data-driven rational checks. Instead of using subjective visual comparisons of gross vehicle weight (GVW) curves, this research implements axle load spectra (ALS) peak range check, ALS peak-shift analysis and ALS correlation analysis to quantify the rational check process. This paper also details parameters for threshold checks.

Furthermore, problems have occurred when using TrafLoad to generate MEPDG traffic inputs from the quality controlled WIM data. One problem is that no C-Card (vehicle classification) format dataset is available. Another problem occurs when using only W-Card (axle weight) format data in that the resulting TrafLoad outputs could not be directly implemented in the MEPDG due to programming errors and format incompatibilities. Observations of both C-Card and W-Card datasets have found that most information stored in C-Card datasets can also be found in W-Card datasets, especially vehicle classification data. Thus, using only W-Card format data, TrafLoad is able to provide sufficient information to develop MEPDG traffic inputs. To develop MEPDG traffic inputs in Alabama, a process to convert raw TrafLoad outputs into MEPDG recognized traffic inputs has been developed.

2. TrafLoad, Its Limitations and Advantages

To generate traffic inputs required by the MEPDG software in an efficient way, the TrafLoad software was developed in 2004 as part of NCHRP Project 1-39 to serve as a principal source of traffic inputs for MEPDG software (Wilkinson, 2005). In recent years, little documentation has been published on QC procedures for WIM data. Some WIM data users may rely on TrafLoad to perform QC on their data. However, this is risky because TrafLoad only performs rudimentary checks for valid site IDs and lanes and direction values, and does not provide a sophisticated QC procedure.

TrafLoad has rigid format requirements regarding C-Card and W-Card datasets generated by WIM stations, and both types of datasets of each WIM station are required for TrafLoad to work. Thus, some state transportation agencies have found TrafLoad unusable due to format incompatibilities (Ramachandran et al., 2010; Tran and Hall, 2007). Another major limitation is an apparent non-responding output function of the software.

Despite the previously mentioned shortcomings, advantages of TrafLoad for the Alabama WIM data are significant. Even though TrafLoad is not programmed to manipulate automatic vehicle classification (AVC) data within the W-Card dataset, it stores these data in its database when monthly W-Card datasets are imported to the program. Thus, with the absence of C-Card format data, MEPDG traffic inputs can still be developed using TrafLoad. This information-rich database was stored in a Microsoft Access database format. By manipulating this database, the following items can still be developed from Alabama WIM data:

- AADTT traffic volume adjustment factor, etc, monthly and hourly
- Number axles per truck
- Vehicle class distribution
- Axle load distribution factor

3. WIM Systems in Alabama

ASTM E1318-02 (2002) has specified standards for highway WIM systems and their classifications (such as Type I, Type II and Type III) in North America. Under the Type-I requirement, WIM systems regardless of WIM sensor types should have the capability of producing high quality WIM data. These data elements recorded for every truck-traffic passing through the site includes:

- Date and Time
- Lane
- Speed
- Vehicle Classification
- Wheel Load
- Axle Load
- Axle Group Load
- GVW
- Individual Axle Spacing
- Vehicle Length
- Violation Code

Type I WIM systems should also meet the performance requirement established by ASTM E1318-02 (2002). The specification of Type I performance requirement is also shown in Table 1.

Table 1 – Functional performance requirements for Type I WIM systems (ASTM, 2002)

	Acceptable Tolerance at 95% Confidence Level					
Function	Wheel Load	Axle Load	Axle-Group	GVW	Speed	Axle-Spacing
Type I	± 25%	± 20%	± 15%	± 10%	± 1 mph	± 0.5 ft

All 12 WIM stations in Alabama were built by International Road Dynamics Inc. (IRD), and to meet the Type I WIM system requirements. WIM data collected from station 911 from 2006 to 2008 were analyzed in this paper. This station is located in Alexander City along US 280 and it uses bending plate technology as the weight sensor.

4. QC Methodology

The QC process applied herein consists of two phases: simple threshold checks and rational checks. Threshold checks eliminate dataset-file-size outliers of each WIM station and out-of-range values of each field within a dataset. Once an error is detected in any of these steps, the related row of data will be excluded or, for the file size check, the entire monthly data file will be excluded. Since tandem axles of vehicle class (VC) 9 are the most frequent heavy vehicle axle types and their ALS have identical two-peak shape, tandem ALS of VC 9 are developed by TrafLoad from threshold checked datasets and then used in the rational check phase. This phase focuses on patterns and relationships between datasets. These checks include a peak-range check, peak-shift check and correlation analysis of tandem ALS of vehicle class (VC) 9. These rational checks are performed on monthly datasets (one-month-worth of data), providing an extra level of caution in identifying and eliminating bad datasets. The overall QC process is also illustrated in Figure 1.

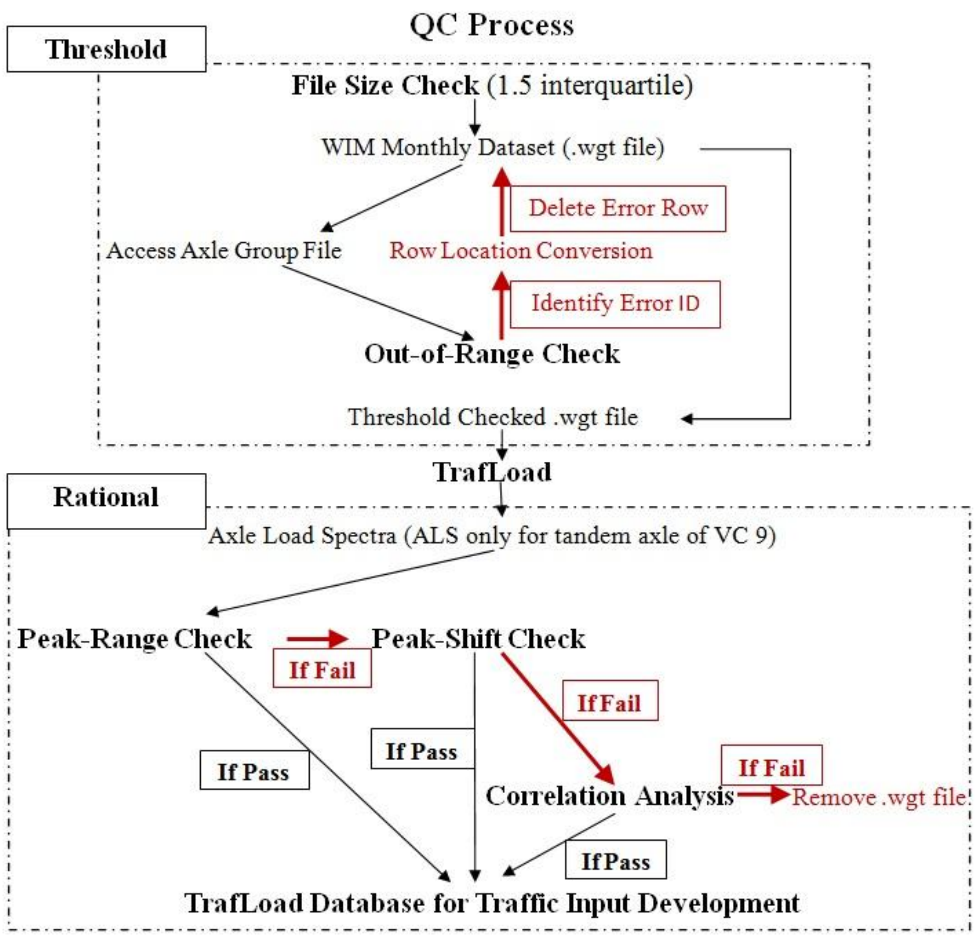

Figure 1 – Overall QC process

4.1 Threshold Check

The threshold check phase consists of two steps: (1) eliminating dataset-file-size outliers of each WIM station and (2) deleting out-of-range values of each field within a dataset. Dataset-file-size check is used to detect severe file size drops which represent substantial amounts of missing data. These drops might be due to WIM system failure, road maintenance, rehabilitation and so on. However, regardless of abnormal circumstances which lead to dataset-file-size outlier, disrupted truck traffic counting should not be used for further pavement design purposes. Therefore, monthly datasets with file-size outlier should be eliminated. On the second step of threshold check, the out-of-range check is to detect and remove extreme values caused by random system errors.

The scopes of these two threshold checks are very different. Dataset-file-size checks focus on 12 consecutive months of each year at a time, while the out-of-range checks look at every single truck pass. As the first step, the data-file-size check is performed to prescreen all WIM datasets and identify systematic errors before going to details of each dataset. Then, out-of-range check is used to identify defects of each dataset.

Dataset-file-size Check

A dataset-file-size check is recommended by the *FHWA WIM Data Analyst's Manual* (Quinley and Transtec Group, 2010); however, no detailed procedures are discussed. The term dataset-file-size herein means the file size of each ".wgt" text file that is directly from a WIM station containing one month of data and has not been QC checked. Dataset-file-size check assumes that file size has a positive linear relationship with the volume of truck traffic counted, and data-file-size outlier indicates systematic errors or abnormal circumstances occurred on the road.

Statistically, dataset-file-size outlier can be set to be 1.5 times (1.5 IQR) or 3 (3.0 IQR) times outside of the interquartile range. 1.5 IQR is used to detect outliers in normal practice, while 3.0 IQR is used to define extreme outlier (Navidi, 2010). It was assumed that the normal practice condition exists; therefore, it was determined that 1.5 times the interquartile range would be used in this check and file sizes beyond 1.5 times the interquartile range indicates severe data incompleteness during the monthly period. Therefore, dataset-file-size outlier can be defined if its file size is out of the range shown in Equation (1).

$$Q_1 - 1.5(Q_3 - Q_1) < \ R \ < \ Q_1 + 1.5(Q_3 - Q_1) \tag{1}$$

where,
R is the acceptable file size range
Q_1 is the first quartile of file sizes over 12 preceding months
Q_3 is the third quartile of file sizes over 12 preceding months
$(Q_3 - Q_1)$ is the interquartile

During the data-file-size check of WIM station 911, the December 2007 monthly dataset was found to have severe file size drop and therefore identified as outlier. The identification of this outlier is also shown in Figure 2.

Out-of-Range Check

The second step of the threshold check phase is remove vehicle records with out-of-range values. Errors detected by this step are believed to be random errors which occur individually with no effect on other rows of data. To eliminate random error in data analysis, the common practice is to remove erroneous records directly once detected. This is because random errors could happen for a variety of reasons with no consistent approach to correcting them.

In a WIM dataset, a proper value range of each field is set according to a review of past studies. When any fields within a row have out-of-range value, the whole row of data will be filtered for further analysis. A list of the out-of-range check criteria is shown in Table 2. Some criteria are set for data validation; while other criteria, such as speed and weight checks, are more sophisticated and are designed to filter out extreme random errors.

The *FHWA WIM Data Analyst's Manual* (Quinley and Transtec Group, 2010) *and Traffic Monitoring Guide* (FHWA, 2001b) suggest out-of-range check for axle loads; however, no specific range value is assigned. Local knowledge should be applied for these range values. For example, the North Carolina DOT QC rules determined proper range values of axles regardless of axle types to be from 0.2 metric ton (441 lb) to 20 metric ton (44100 lb), while the current federal legal axle load limit is 20000 lb for single axle and 34000 lb for tandem axle (Ramachandran et al., 2010).

Sta 911	
Month	File size, in KBs
Jan-07	3436
Feb-07	2941
Mar-07	3708
Apr-07	3433
May-07	3276
Jun-07	3597
Jul-07	3402
Aug-07	3394
Sep-07	3555
Oct-07	4013
Nov-07	3864
Dec-07	775
1st quartile	3335.00
3rd quartile	3652.50
lower outlier	2858.75
higher outlier	4128.75

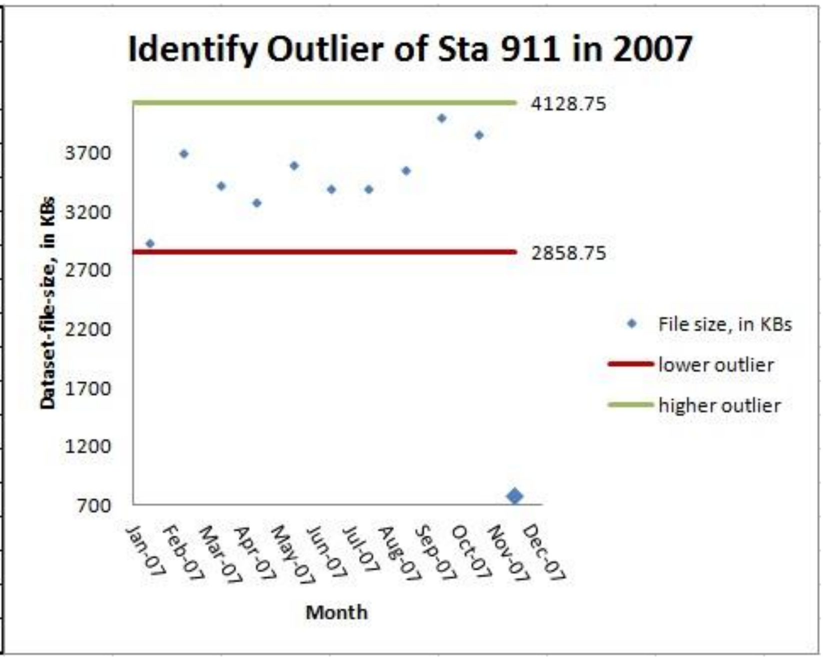

Figure 2 – Identification of outlier at WIM Station 911

However, this QC rule may ignore the extent of overweight trucks in other parts of the country and filter out too much "good" data for vehicles that damage pavement the most. Underestimating overweight truck volume is a major reason of premature pavement failure. The *FHWA WIM Data Analyst's Manual* (Quinley and Transtec Group, 2010) indicates that ratio of overweight truck could be as high as 25% in certain parts of the United States. Plus, trucks can obtain an overweight permit and travel on the road. Therefore, the axle loads range should be broad enough to include most of overweight trucks. In this QC procedure, it is suggested that an increase of 10 metric tons should be added for every extra axle in different axle types.

Table 2 – Out-of-range criteria

Check Field	Criteria with error
Axle Type	null or not 1, 2, 3, 4, 5,6 or 21
Direction	Null or not between 1 and 8
Lane Location	Null or not between 1 and 5

# Axle VS Axle Group	Number axles<Number axle Group
Steer Weight (mton)	< >0 And Not Between 0.2 And 20 or is null
Single Weight (mton)	< >0 And Not Between 0.2 And 30 or is null
Tandem Weight (mton)	< >0 And Not Between 0.2 And 36.3 or is null
Tridem Weight (mton)	< >0 And Not Between 0.2 And 40 or is null
Quad Weight (mton)	< >0 And Not Between 0.2 And 45 or is null
Penta Weight (mton)	< >0 And Not Between 0.2 And 45 or is null
Speed (km/h)	over 192 km/h, 0 km/h or is null
Year	not between 2006 and 2008
Month	not between 1 and 12
Day	not between 1 and 31
Hour	not between 0 and 23
State Code	not 1 or is null
Vehicle Class	not between 4 and 13 or is null

The out-of-range criteria for vehicle class check are set to exclude non-truck vehicle classification, such as VC 2, VC 3 and VC 14. Within the WIM system, vehicle classes are categorized based on axle spacing, making it difficult to differentiate between some single unit trucks (class 5 vehicles) and passenger vehicles (FHWA, 2001a). Therefore, heavy class 2 and 3 vehicles (GVW greater than or equal to 4,400 lb (2 metric tons)) were included. Vehicle class 14 is considered unclassifiable based on the axle spacing. However, in the MEPDG and TrafLoad, VC 2, VC 3 and VC 14 are not counted, and therefore should be excluded in the threshold check.

4.2 TrafLoad Process

To prepare for the next rational check phase, threshold checked WIM datasets are input into TrafLoad to develop tandem ALS curves of vehicle class (VC) 9. In MEPDG Level 1 data analysis (site specific), TrafLoad suggested that one week of data coverage for each month is sufficient enough to represent the monthly truck pattern. Thus, in reading the monthly W-Card format data, TrafLoad only extracts 7 consecutive days of each month starting from the first Sunday. For data validation purposes, weight data of each month has to contain at least 7 consecutive days of normal counting. To develop ALS for rational checks, at least 12 consecutive months of valid weight data are required.

4.3 Rational Check

The second phase of the QC process involves rational checks that focus on datasets with systematic errors, which can occur in a consecutive period of time, and every record collected within that given period could possibly be affected. In past rational check studies, there are only visual based methods to determine “abnormal” curve shapes of axle load spectra. This visual based method is a subjective manual audit to identify significant deviations in patterns that indicate equipment malfunction or invalid data sets (Ramachandran et al., 2010). However, the visual based method created an indistinct boundary between acceptable and unacceptable ALS curves. To quantify the extent of similarities between monthly datasets, ALS peak-range check, ALS peak-shift check and ALS correlation analysis are implemented.

ALS Peak-Range Check

ALS peak-range check focuses on load values of the low peak (when trucks are empty) and the high peak (when trucks are fully loaded). The final report of Transportation Pooled Fund Study *Traffic Data Editing Procedure: Traffic Data Quality "TDQ"* recommends the peak-range check and suggests peak ranges to be user defined and adapted to local traffic characteristics (Flinner and Horsey, 2000). According to the *Standard Data Release 25.0* of the LTPP, Alabama has a low peak range of 14 to 16 kips and a high peak range of 32 to 38 kips (LTPP, 2011). Table 3 illustrates the peak ranges for both peaks of tandem ALS of VC 9 in Alabama.

Also according to the *Standard Data Release 25.0* of the LTPP, the most frequent lowest point between two peaks occurs at 26 kips. Thus, axle load of 26 kips is set to be the boundary between low peak and high peak; axle loads from 6 kips to 26 kips are set to be the low peak area, while axle loads from 28 kips to 60 kips are determined to be the high peak area.

Table 3 – Peak values of low and high peaks for tandem ALS of VC 9 in Alabama

Low Peak Load Range, kips	14~16
High Peak Load Range, kips	32~38

The highest load ratios and their related peak values for both peaks of the same ALS are determined, then peak values are compared with their related peak-ranges shown in Table 3. A monthly dataset will be identified as potentially erroneous and then subjected to Peak-Shift checks if either its low peak or high peak is out of its respective range. If both its low peak and high peak are within peak ranges, the dataset passes the rational check.

Peak-Shift Check

The peak-shift check monitors peak patterns and compares the amount of peak shifting between datasets from the same month of different years. Potentially erroneous datasets detected by the peak-range check are sent to this step for further checks. To be considered as maintaining consistent peak patterns, low peak shifting should be not more than 2 kips, and 4 kips for high peaks. These allowable peak-shift values are based on observations of peak shifting of *Standard Data Release 25.0* of the LTPP in Alabama (LTPP, 2011). A third step, consisting of a correlation analysis, is applied to the dataset if either its low peak or high peak does not follow peak patterns.

From the previous peak-range check, peak values of both low and high peaks are determined. For the potentially erroneous datasets, their peak values are subtracted from related peak values from the same month of different years. When absolute values of subtractions of either peak exceeds the allowable shifting values as in Table 4, the target dataset is determined not following peak patterns and should be sent to correlation analysis. Figure 3 visualizes the peak-shift check while dataset of July 2006 of Station 911 is detected as potentially erroneous dataset from peak-range check in the previous step.

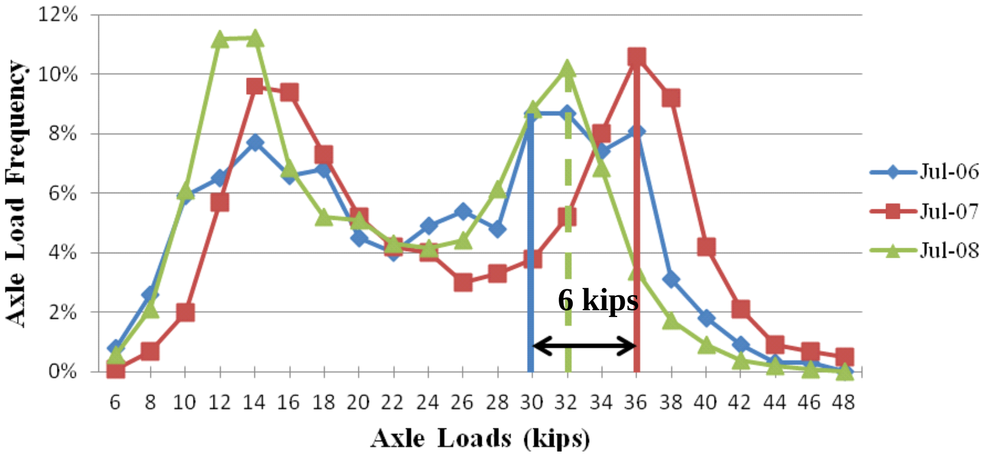

Figure 3 – Visualized peak-shift check of WIM Station 911

From the peak-shift check in Figure 3, the high peak-shift between Jul-06 and Jul-07 datasets is 6 kips (exceed allowable limit of 4 kips), while low peaks of two datasets match each other. However, when the July 2008 dataset is taken into consideration for cross-checking, the high peak-shift between July 2006 and July 2008 datasets is 2 kips, while that of the July 2007 and July 2008 datasets is 4 kips. Therefore, to be conservative, the July 2006 dataset passes the rational check.

Pearson's Correlation Analysis to Quantify Similarity

Pearson's correlation analysis is used as a statistical method to compare the similarity of two monthly ALS of different years in the rational check phase. In past practice, correlation analysis is recommended to evaluate similarity between objects when comparing pairs are ought to be similar and size displacement is not in the consideration (Romesburg, 1984). Everitt (1993) also indicated that Pearson Correlation could be a very useful measure of similarity in those situations where absolute "size" alone is seen as less important than "shape". The basic premise of this step is that the same monthly ALS curves of the same WIM station from different years should be similar to each other. Furthermore, ALS is distributed as a proportion, and the accumulated ratio of each curve must be 100%. Thus, no proportional size change is possible in ALS. Overall, Pearson's correlation analysis is an ideal tool to compare the similarity of monthly ALS in rational check.

The advantage of correlation analysis is that it compares all data points on both ALS instead of comparing merely peak values and provide a more sophisticated check. Statistically, this analysis is the major element to replace the subjective visual comparisons of past QC studies.

$$r = \frac{N\sum xy - (\sum x)(\sum y)}{\sqrt{[N\sum x^2 - (\sum x)^2][N\sum y^2 - (\sum y)^2]}} \quad (2)$$

The correlation coefficient r is the parameter to evaluate the similarity of two ALS curves. Equation (2) illustrates the correlation analysis equation. In that, the correlation coefficient r ranges from -1 to 1; a coefficient of 1.00 indicates two ALS match perfectly while -1 indicates two ALS are on absolute reverse positions. A correlation value of less than 0.85 was selected to indicate that two ALS do not match acceptably well. In this study, three years of data were obtained, thus, one dataset can compare with other two datasets of the same month. Since datasets subjected to correlation analysis have failed previous peak-range check and peak-shift check first. Thus, datasets with correlation coefficients less than 0.85 in both comparisons was considered to be erroneous, and should be removed for further analysis.

4.4 QC Results

In the QC of the 2,138,873 weighed vehicles recorded by WIM station 911 from 2006 to 2008, an overall 29.19% of data were filtered out. In that, 0.77% of data were detected by dataset-file-size checks, and the remaining 28.42% were identified as out-of-range errors. All threshold-checked data passed the rational checks.

5. Development of MEPDG Data Inputs from TrafLoad Database

Since TrafLoad would not function properly without C-Card dataset, MEPDG traffic inputs need to be processed manually through the raw TrafLoad database. By manipulating this database, MEPDG data inputs that can be developed were listed in Section 2 of this paper.

Some inputs are easier to obtain because they are already developed by TrafLoad, but recorded in incompatible formats. In these cases, simple format conversion procedures can solve the problem. Locations of these inputs remain unchanged in respective tables of TrafLoad database. These MEPDG inputs include hourly distribution factor (HDF) that can be obtained from the *hourly_dist_factor_2SM* table in the TrafLoad database, vehicle class distribution (VCD) factor from the *trfl_wim_final_agpv_ls_distribution* table, number axles per truck (NAPT) from the *trfl_wim_final_agpv_ls_distribution* table, and axle load spectra (ALS) from the *trfl-WIM-final-current-ls-distri* table.

Other MEPDG inputs, such as the monthly adjustment factor (MDF), are not developed and stored by TrafLoad. Thus, equations to develop these factors must be followed. From the MDF Equation (3), this factor is the ratio of specific monthly truck volume to average monthly truck volume in each vehicle class. Sufficient information to develop the monthly adjustment factor can be gathered from the *ls_avg* table.

$$MDF_{ij} = \frac{\sum(DTV_{ij})}{\{\sum(DTV_i)/12\}}$$

(3)

where,
MDF_{ij}= monthly distribution factor of class i in month j
DTV_{ij}= daily truck volume of class i in month j
DTV_i= daily truck volume of class i for weight data from 2006 to 2008

6. Conclusion

This paper presents the QC procedure from WIM data user perspective when calibration of WIM stations is beyond recall. Details of dataset-file-size check and correlation analysis are firstly introduced in WIM data QC. In the QC of WIM station 911, 29.19 % of data were filtered out, and this indicates that data users' QC is critical for WIM data and future pavement design applications. In the rational check process, even though peak-range check, peak-shift check and correlation analysis have not detected any systematic error in the data from the given WIM station, this process introduces a quantitative approach to replace previous subjective visual comparisons of GVW curves and therefore eliminate individual interpretation of the plotted curves as the key decision criterion for data quality. For future research, it is suggested that this QC procedure be implemented into several other WIM station datasets to examine the sufficiency of rational checks.

Also, the data development process used in this research can compensate for the limitations of TrafLoad, and develop MEPDG traffic inputs by using only W-Card datasets. This process can also prove that rigid data format requirements of TrafLoad are not necessary. TrafLoad was created with the intention of expediting the development of MEPDG traffic inputs; however, its limitations and rigid data format requirements, along with changes in computer operating systems since the initial release of TrafLoad, have created barricades for data users. Since the initial version of TrafLoad 1.0, no improvement to this software has been made. It is recommended that revision of TrafLoad is needed to better serve the MEPDG community.

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THE METAMORPHOSIS OF LTPP TRAFFIC DATA

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Abstract

This paper describes the transformation of the United States Federal Highway Administration's Long-Term Pavement Performance (LTPP) Program traffic data collection activities. The original plan, devised in the late 1980s, envisaged installation and management of low cost traffic data collection systems by highway agencies at approximately 2,500 LTPP tests sites. This plan proved unachievable and a revised plan was implemented to collect *research-quality* traffic data from a much smaller number of LTPP test sites. The revised plan has generated the largest repository of high-quality traffic data ever collected. This paper gives a brief history of traffic data collection for the LTPP program; describes the technical details of the revised traffic data collection plan and the novel financing and contracting arrangements; and summarizes the results.

Keywords: Weigh-in-Motion, WIM, assessment, calibration, validation, Long-Term Pavement Performance Program, LTPP, Specific Pavement Study, SPS, pooled fund study.

Résumé

Cet article décrit la transformation de l'activité de collecte de données de trafic du programme sur la performance à long terme de la chaussée (LTPP). Le plan original, conçu dans les années 1980, envisageait l'installation et la gestion de systèmes de collecte de données de trafic à faible coût sur environ 2 500 LTPP sites tests, par les agences d'autoroute. Cela s'est avéré irréalisable. Au lieu de cela, un plan révisé a été mis en place pour recueillir des données de qualité suffisante pour la recherche, mais sur un plus petit nombre de sites. Le plan révisé a généré le plus grand référentiel de données de qualité relatives au trafic jamais recueillies. Cet article décrit l'histoire de la collecte de données de trafic dans le programme LTPP, certains détails techniques du plan de collecte de données révisées de trafic, la méthode novatrice de financement et d'arrangements contractuels. Finalement il donne les résultats les plus importants.

Mots-clés: Pesage en mouvement, WIM, évaluation, calibration, validation, long-term Pavement Performance Program, LTPP.

1. Introduction

The LTPP program started out as an ambitious, 20-year study of in-service pavements in North America to examine how and why pavements perform as they do. The program was launched in 1987 and data collection started in 1989. Program management and data collection activities continue under the leadership of the Federal Highway Administration (FHWA). Approximately 2,500 pavement test sections in the United States and Canada were selected for monitoring the performance of different types of structures and materials in various climatic regions. Approximately 84 of these sites were for Specific Pavement Studies ('SPS') which were built to certain design standards and had an enhanced level of data collection (LTPP, 2011a). The remaining sites were denoted General Pavement Studies ('GPS') and these were pavements already built and in-service.

Monitoring these pavements over time is providing researchers with insights into their performance. Valuable lessons are gained for building better, longer-lasting, more cost-effective pavements. Because the traffic input is needed to understand the pavement performance information, traffic data collection is critical to the success of the LTPP program.

2. A National Plan

2.1 LTPP SPS Traffic Data Collection Pooled-Fund Study

In the early years of LTPP, traffic data was collected in a non-uniform manner and there were no quality control measures in place for traffic monitoring. So, the early planners of LTPP formed an expert task group to advise the LTPP program managers in collecting, processing, and storing traffic data for the LTPP test sites. This group was known as the Transportation Research Board (TRB) Expert Task Group (ETG) for LTPP Traffic Data Collection and Analysis (or Traffic ETG). It continues to advise the LTPP program on all issues concerning traffic data collection, quality control, and storage as well as, identifying traffic research projects and products.

In the process of developing a new strategy for collecting traffic data at the LTPP test sites, it became clear to LTPP and the Traffic ETG that installing permanent WIM systems at every LTPP test site was impossible to implement due to costs and the man-power needed to maintain, calibrate, and operate the systems properly. Consequently, LTPP decided to focus its efforts on collecting traffic loading data for only the SPS test sites, because these would yield the biggest return on investment. So, a national effort to collect traffic loading data at the SPS test sites was put in place. As part of this new plan to remedy the traffic loading issue (quantity and quality), the *Action Plan for Improving Quality of LTPP SPS Traffic Loading Data* was developed by LTPP in October 1999 (LTPP, 1999). This document recommended that the traffic data collection and processing be managed centrally to eliminate the quantity and quality issues that were associated with the earlier traffic data collection efforts. The plan also made reference to the type of WIM equipment to use in order to collect reliable loading data, gave a description of the ideal pavement structure in which to install the WIM equipment, and suggested the frequency in which the equipment should be calibrated.

As a result of the action plan to improve traffic loading data at the SPS test sites, protocols for verification of equipment performance; pavement smoothness requirements; WIM system specifications, including accuracy (Column 2 of Table 1) and construction guidelines; and data collection and processing procedures were developed by LTPP and the Traffic ETG.

Table 1 - Accuracy of Data (95% Confidence level) from Florida Field Validation Tests

Parameter	Accuracy Guideline (i)	Data from 2001 (ii)	Data from 2005 (iii)
Gross Weight	10%	-18% to +30%	0.2% +/- 8.2%
Tandem Axles	15%	-26% to +41%	0.0% +/- 10.2%
Single Axles	20%	-31% to +38%	1.2% +/- 10.0%

(i) Guideline from specification (LTPP, 2009)

(ii) Data collected from a Florida SPS WIM site in 2001 using piezo-ceramic sensors. (Same system used to collect the data shown in figure 1)

(iii) Data collected from the same WIM site 2005 using quartz sensors and the procedures specified by the LTPP SPS Traffic Data Collection Pooled-Fund Study protocols. (Same system used to collect the data shown in figure 2)

Five pilot studies were conducted to evaluate the protocols for the WIM installation process, field procedures for equipment performance, and pavement smoothness. The equipment performance specifications were shown to be achievable with current practice and technology and the recommended field calibration methods (including, accuracy, speeds, temperatures, and vehicle conditions) were validated. However, the pavement smoothness specification was too restrictive for field conditions and needed to be revised (FHWA, 2002). After further revisions and testing in various States, the smoothness specification developed by LTPP became the American Association of State Highway and Transportation Officials (AASHTO) Standard Specification for Smoothness of Pavement in Weigh-in-Motion (WIM) Systems MP 14-08 (AASHTO, 2008). Many of the protocols tested during the pilot studies were consolidated into what is known as the *LTPP Field Operations Guide for SPS WIM Sites* (LTPP, 2009). This guide has been the primary reference for collecting quality traffic data at the SPS sites since 2003.

Approximately two years after the development of the Action Plan, a national ‘pooled fund’ study was initiated to implement the ideas and concepts outlined in the plan. A pooled fund study combines the funds of multiple agencies to support a particular research effort. This study, known as the LTPP SPS Traffic Data Collection Pooled-Fund Study, TPF-5(004) (LTPP, 2011b) is led by FHWA in partnership with 27 States and 1 Canadian Province.

Unlike many pooled fund studies where all funds are combined and used for any area of the study, this one is unique because the money contributed by each of the 28 participating highway agencies is used for the data collection needs of the SPS site in that State or Province. SPS sites were included in the study if a State contributed funds and as long as there was adequate pavement performance and materials data collected at the site. Six of the 28 States recognized the value and potential advancement in their traffic data collection activities as a result of this multi-year study and decided to become 'donor States'. This gave FHWA the ability to use the donor money in other States where additional funds were needed.

2.2 Research-Quality Traffic Data Collection Begins

The objective of the traffic pooled fund study is to collect at least five years of *research-quality* traffic data (volumes, classifications, and weights) at the LTPP SPS-1, -2, -5, and -6 test sites. These high priority SPS sites, include the structural factors of flexible and rigid pavements (SPS-1 and -2) as well as the rehabilitation of these two pavements types (SPS-5 and -6). LTPP and its partners agreed to exclude the installation of WIM systems at the SPS-8 test sites, whose objective is to investigate how environmental effects impact a pavement structure in the absence of heavy loads.

For the purpose of this study, LTPP defines *research-quality* data to be *210 days of data (in a year) of known calibration, meeting LTPP's accuracy requirements for steering and tandem axles, gross vehicle weight, vehicle length (bumper-to-bumper), vehicle speed, and axle spacing* (LTPP, 2009). In addition, the recommended WIM technologies include bending plate, load cell, and quartz sensors, which all meet the specifications for a Type I WIM system as defined by ASTM E1318-02 (ASTM, 2002). Since data collection began in earnest in 2003, these WIM sensors have been collecting *research-quality data* for 28 of the 64 LTPP SPS-1, -2, -5, and -6 test sites.

2.3 Contractual Arrangements

LTPP did not want the contractor who installed the WIM system to be the contractor who also validated the system. So, two contractors were solicited to perform two different aspects or 'phases' of the research that run concurrently. Although the activities for each phase are distinctly different, collectively they ensure that the equipment is installed, calibrated, maintained, and operated correctly so that the highest quality of data is generated by the site.

Phase I – WIM System Field Calibration and Validation

The 'Phase I' activities involve site assessment, performance evaluation and calibration of WIM sites. In the early years of the study, SPS sites with existing WIM systems were assessed to determine if the equipment had the potential to meet LTPP's accuracy requirements (LTPP, 2009) and were likely to produce at least five years of quality data. If the assessment demonstrated that a site would not meet the requirements, then the Phase I Contractor provided a recommendation to LTPP and the highway agency to correct the issue. The Phase I Contractor was only responsible for reporting the issue, not resolving the issue. If corrective action was needed to the pavement, the highway agency was responsible for making that correction. If the corrective action was to replace the WIM system, then either the highway agency or LTPP (through the Phase II Contractor) was responsible for replacing the WIM system with one that would meet LTPP's accuracy requirements for quality loading data. Now that this national data collection is well underway, it is no longer necessary to perform assessments at the SPS test sites. The Phase I Contractor's primary focus is to make sure the WIM systems used to collect traffic data at the 28 SPS test sites are operating at peak performance by calibrating (if necessary) and validating them annually.

The field calibration and validation procedure consists of running two test trucks over the WIM site; a 'Class 9' fully loaded truck (5-axle tractor-semitrailer) because this is the predominant heavy vehicle on US highways and a partially loaded truck of a configuration that predominates on the particular site. These trucks are measured and weighed on certified scales prior to the site calibration/validation process. The drivers are directed to drive at speeds up to the posted speed limit, down the center of the traffic lane, without stopping or braking while crossing the WIM sensors. Making no adjustments to the WIM system, the Phase I Contractor does an initial performance evaluation of the system by having the drivers make a minimum of 20 runs per test vehicle at speeds ranging from 40-65 mph (64-104 kph) and temperatures ranging from 10-116 deg F (260.92-319.81 deg K) as outlined in the *LTPP Field Operations Guide for SPS WIM Sites* (LTPP, 2009).

If the initial performance evaluation shows the WIM system to be functioning with sufficient accuracy, then calibration is not necessary. The runs from the initial performance evaluation are used to complete the validation process. If, however, the initial performance evaluation show insufficient accuracy, the system is calibrated according to the equipment manufacturer's recommended procedures in order to achieve the best possible accuracy (LTPP, 2009). Depending on the availability of the test trucks, for newly installed WIM sites the initial performance evaluation is typically performed after the installation is completed or within a few weeks of the installation.

Immediately following calibration, validation of the WIM system begins. A minimum of ten further test vehicle passes (five passes per truck) is performed. The data from these passes are analyzed and the WIM system is recalibrated, if necessary. Once the WIM system is successfully calibrated, the validation process is completed by doing a minimum of 20 further runs per vehicle. If a WIM system does not successfully calibrate after three attempts, the validation activities stop. The Phase I Contractor records the statistical accuracy of the WIM system prior to leaving the site and provides LTPP with a detailed report on the field activities and findings for each site.

Phase II – Installation, Maintenance, and Data Services for WIM Systems

The 'Phase II' Contractor's responsibilities include site evaluation, equipment installation, ongoing maintenance, and daily quality control (QC) checks. At the beginning of the pooled fund study, the Phase II Contractor performed site evaluations at the participating

SPS sites to determine whether they were suitable for installing WIM systems. The evaluations considered the pavement condition and profile; the grade and alignment of the test section; the accessibility to utilities (power and telephone lines); and the observation of entry and exit ramps near the WIM site. Other major Phase II activities involved installing, calibrating, and maintaining the WIM system at the SPS test site, and providing a five-year warranty on site performance. As the work began, it quickly became apparent to LTPP that the data from these sites needed to be checked frequently. So, with the expert advice from the Traffic ETG, LTPP modified the Phase II contract to include daily download and QC checks of the data. The daily verification checks include: Total daily count by vehicle; No lane contains a value of 0 in a specific hour; No lane contains a traffic count value of 2,500 or greater in any specific hour; Percent count of error vehicles per day; Percent count of status clear vehicles per day; Total daily count of Class 9 vehicles per day; Percent count of Class 9 vehicles per day; Percent warning count of Class 9 vehicles per day; and Average Gross Vehicle Weight of Class 9 vehicles per day.

This contract modification also required that the Phase II Contractor provide the vendor software to the traffic engineers in the highway agencies where a new WIM system was installed. This ensures that the highway agencies are able to access the systems for their current and future use. At the conclusion of the pooled fund study, the WIM systems will become the responsibility of the highway agencies to maintain and calibrate.

For the past few years, the Phase II activities have focused more on maintaining and providing on-call repairs of the WIM systems, and performing the daily QC checks of the data. The Phase II contractor performs semi-annual maintenance for the WIM systems they installed. The WIM systems installed by the highway agencies are maintained by the highway agencies.

3. Results

Some key resources resulting from the pooled fund study are the *LTPP Field Operations Guide for SPS WIM Sites* (LTPP, 2009); glossary of WIM terms (LTPP, 2011b); LTPP Classification Scheme (LTPP, 2011b); WIM Smoothness Specification (AASHTO, 2008); and WIM Workshops (which are arranged upon request).

These resources are used by LTPP and are available to highway agencies. Developing such resources for the sole purpose of collecting quality traffic monitoring data, is in accordance with the data integrity philosophy that LTPP has practiced over the past 20 years with other pavement performance data collected directly by the program.

3.1 Data Quality Improvement

The data in columns 3 and 4 of table 1 are mean and ± 95% confidence interval values of weights generated during field validations for a Florida site in 2001 and 2005. The 2001 data was collected using ceramic piezoelectric cable sensors installed in 1995, while the 2005 data was collected with quartz piezoelectric sensors that were installed and calibrated in 2003 in accordance with the pooled fund study's protocols (LTPP, 2009). The dramatic improvement in accuracy and the near elimination of calibration drift is evident.

Figures 1 and 2 show histograms of gross vehicle weights for 'Class 9' trucks (3 axle tractor pulling a 2-axle semitrailer) travelling over this same Florida site in 2001 and 2005, respectively. Both figures show monthly totals for 12 months of the year. Both histograms show two peaks. The peak at a weight around 30,000 lbs (13,600 kg) corresponds to unladen vehicles, while the peak at a weight around 80,000 lbs (36,300 kg) corresponds to laden vehicles. The main difference between these two figures is that the results in figure 2 show much more consistency from month-to-month than the results in figure 1. The WIM system in figure 1 was installed before any standards were adopted, and is fairly typical of the data reported by ceramic piezoelectric WIM sensors. The data shown in figure 2 is typical of data collected at the 28 pooled fund sites for nearly the last five years of the study.

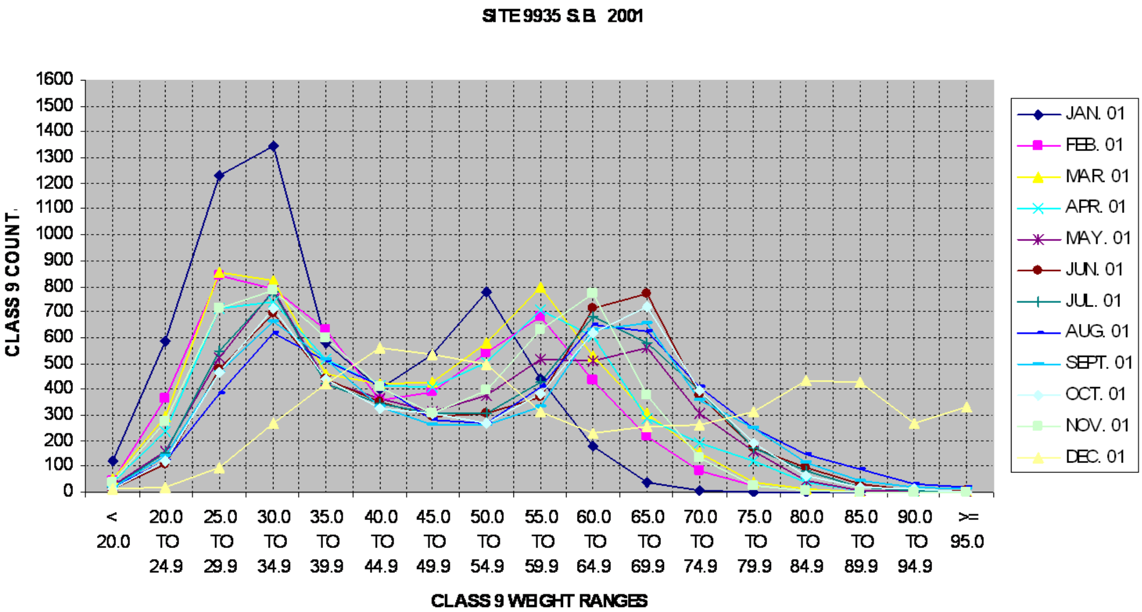

Figure 1 - Weight Data in 2001. Histogram of Gross Weights of Class 9 Trucks at a LTPP site in Florida Before Traffic Pooled-Fund Study Protocols.

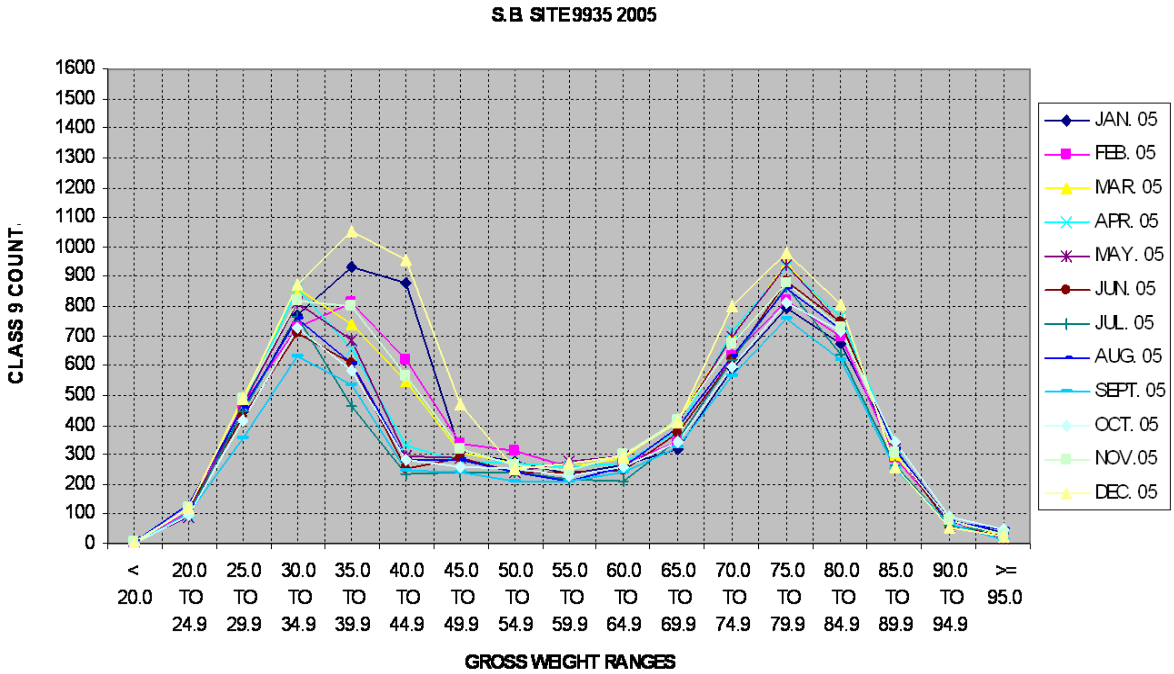

Figure 2 - Weight Data in 2005. Histogram of Gross Weights of Class 9 Trucks at a LTPP Site in Florida Using Traffic Pooled-Fund Study Protocols.

3.2 Some Statistics of the Study

The first field calibration and validation work performed by the Phase I Contractor occurred in 2003 at two agency-installed WIM systems in Florida, and the installation of the first WIM system by the Phase II Contractor was in 2005 in Illinois. Since the beginning of the pooled fund study, the Phase I Contractor has performed 89 field validations; and the Phase II Contractor has performed 37 site assessments to determine if a site was suitable for installing a WIM system, installed 19 WIM systems, and continues to maintain and provide daily QC checks of the data for these 19 sites. A few highway agencies played an active role in this project by installing the approved WIM sensors at the SPS sites in their States as recommended by the pooled-fund study protocols. Consequently, there are seven agency-installed WIM systems part of this study. All 26 WIM system installations are providing *research-quality* traffic data for 28 SPS sites (2 locations have adjacent SPS sites, so the traffic data is being shared).

As a result of closely monitoring these sites, in most years, *research-quality* classification and weight data have been collected for more than 90% of the days. This is dramatically different from equivalent statistics collected before the pooled fund study, when 0%-10% data availability was the norm. A total of 35,331 site-days of traffic data were collected through March 2011. This corresponds to approximately 350 million vehicle records and 2 billion individual axle load records. This is the largest quantity of *research-quality* traffic data ever collected. All of the raw and processed data is stored in LTPP's database. The data is available to researchers free of charge upon request, either in raw form or summarized into axle load probability distributions.

4. Conclusions

The LTPP SPS Traffic Data Collection Pooled-Fund Study has succeeded as collaboration between FHWA, 28 highway agencies, and many other participants and stakeholders. The study has transformed the quality and quantity of the traffic data collected for 28 LTPP SPS test sites.

Many important lessons have been learned about collecting traffic data. Protocols have been developed for site selection; surface smoothness; equipment installation, calibration, and validation; and quality control checks. In addition, the study created novel contracting arrangements so that two contractors could perform mutually exclusive but complementary phases of the project and could verify each other's work. Although the study turned out to be more challenging and costly than expected, it has shown that collecting *research-quality* traffic data with high availability over an extended period is possible. By the end of the study in December 2015, all 28 sites will have generated at least 5 years of *research-quality* data, with each site-year comprising at least 210 days of classification and loading data.

The action plan assembled in 1999, piloted in 2001, and implemented in 2003 has transformed traffic data collection, not only for LTPP, but for the entire traffic community. Although most highway agencies do not have the resources to implement all of the protocols for collecting *research-quality* data on their own test sites, many are able to apply and benefit from some of the protocols. In addition, the data collected from the pooled-fund study sites is being used by two traffic analysis projects. Without this data, these analysis projects could not be performed because the traffic data needed to complete them is not available elsewhere.

The metamorphosis of the LTPP traffic data project has yielded traffic data of unprecedented quality and quantity and has provided data that users can trust

5. Acknowledgements

The success of this work is a result of the unending support and commitment by the participating highway agencies, the current and past members of the Traffic ETG, the LTPP Contractors, TRB, and FHWA.

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Session 4

WIM Implementation, ITS, Traffic Monitoring, Safety and Environment

Chair : CHRIS KONIDITSIOTIS (TCA, Australia)

Co-chair : LILY POULIKAKOS (EMPA, Switzerland)

HIGH SPEED WEIGH-IN-MOTION IN THE UK

Worked for the UK Government for 35 years until the end of 2010 where he was head of the automatic traffic data collection (ATC) and WIM statistics branch in the Department for Transport. Now employed as Business Support Manager for TDC Systems Ltd.

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Abstract

The origins of high speed weigh-in-motion (WIM) in the United Kingdom lie in research projects carried out by the Transport Research Laboratory back in the 1960's. However, WIM was never fully employed as regularly used tool until a decision was taken in 1994 by the, then named, Department for Transport, Environment and the Regions, to begin installing a series of high speed weigh-in-motion (WIM) sites on the English trunk road network. The purpose of these sites was to provide data for a statistical survey and also background information for England's Highways Agency pavement design team. This paper re-visits those original sites and compares some of the data from 1997 to that collected 10 years on. This paper also discusses how the use of high speed WIM has expanded in the UK since 1994 and the purposes for which it is now being applied and the accuracy levels being achieved.

Keywords: Statistics, Heavy Vehicles, Piezo sensors, Weigh-in-Motion, WIM.

Résumé

Les origines du pesage en marche à grande vitesse (WIM) au Royaume-Uni remontent aux projets de recherche du Transport Research Laboratory, dans les années 60. Cependant, l'outil pesage en marche n'a jamais été vraiment utilisé, jusqu'à ce que la décision de commencer à installer une série de stations de pesage en marche sur le réseau anglais de route principale soit prise en 1994 par l'entité appelée en ce temps-là « département pour le transport, l'environnement et les régions ». Le but de ces emplacements était de fournir des données pour analyse statistique, ainsi que pour servir d'informations de fond pour l'équipe de conception des chaussées des routes de l'Angleterre. Cet article revisite ces emplacements originaux et compare les données rassemblées depuis 1997. Il discute également comment l'utilisation de WIM à grande vitesse a augmenté au Royaume Uni depuis 1994, les raisons pour lesquelles ces stations sont maintenant utilisées et les niveaux d'exactitude obtenus.

Mots-clés: Statistiques, poids lourds, capteurs piézo, pesage en marche, WIM.

1. Introduction

The United Kingdom has been involved in the field of weigh-in-motion for over 40 years when early research projects were carried out by the Transport Research Laboratory (Trott, et al, 1968). These projects concentrated on various scale, capacitive and piezoelectric systems which resulted in the adoption by the UK Government of a piece of equipment which satisfied their specific needs. Initially, three broad areas of interest resulted from these projects:

- Monitoring the variation in weights per axle and per vehicle for methods of pavement design and standards,
- Pre-selection of overloaded vehicles for enforcement,
- The automatic monitoring of overload violations.

It was the first of these areas of interest that resulted in an initial request in 1993 from the English Highways Agency (HA) to the, then named, Department for the Environment, Transport and the Regions (DETR) statistics branch – now Department for Transport (DfT). They were seeking assistance in creating a data collection system for the purpose of updating vehicle wear factors used in pavement design. This request then led to a fourth area of interest from dynamic WIM:

- A statistical survey into the degree of overloading on the roads in England.

The solution to this project lay in the enhancement of existing automatic traffic counting systems (ATC's) using inductive loops and axle sensors.

2. Background

The DfT has a long established history of traffic counting for statistical purposes with the background behind these traffic counts to provide data for the quarterly traffic statistics for Great Britain and also provide growth and expansion factors for the annual series. In the mid 1980's a decision was taken to establish a network of ATC's to replace over 250 manual count sites. The first of these ATC's was installed back in 1988 and the network grew steadily to 120 sites by 1990.

Following the request from the HA in 1993, a number of feasibility studies were carried out at major road sites in England where existing ATC's were located. These surveys looked at a number of aspects into the physical location of the site namely that they should attempt to meet as many of the recommendations that were ultimately adopted by COST323 (1999) for the successful operation of such sites. These were:

- Robust pavement construction,
- Free flowing movement of traffic, i.e. not subject to braking or acceleration,
- High percentage of heavy goods vehicle traffic.

Armed with the results of these surveys and the considerable knowledge and experience that the DfT had gained in collecting and analysing ATC data, the HA - an Executive Agency of the Department - and its pavement design team requested a number of these sites to be upgraded to WIM capability. The DfT were asked to collect and analyse this data on their behalf.

3. Description of the Original Survey

The following year a survey was implemented to supplement the traffic data already being collected by measuring the axle weights of heavy vehicles and monitoring changes in their levels using WIM equipment. The survey was designed to measure the individual axle weights of 12 different classes of vehicles. It was believed that the greatest difference between sites was likely caused by the mix of types of heavy vehicles, with average weights varying little between locations. Therefore, weighing a large number of vehicles at a few sites would be sufficient to allow suitable wear factors to be calculated with reasonable accuracy for any site. The average weights by vehicle type could then be combined with traffic flows and vehicle mix which were available for all ATC sites.

WIM equipment was installed in one lane at 14 sites on motorways and ‘A’ class roads and at an additional motorway site, two lanes were monitored. Each of the WIM sites were installed adjacent to the existing ATC array so a direct comparison could be obtained into the accuracy of the counting and classification of the equipment.

The initial phase of this survey employed equipment from three different companies so levels of performance could be compared. Two of these companies – PAT(CTI) and Trevor Deakin Consultants Ltd – chose to use piezo sensors whilst the third – Golden River Traffic – chose the capacitive strip.

3.1 Survey Performance Criteria

Each of the sites were calibrated by applying the recommended methodology of 10 passes over the array followed by 5 additional passes for the confirmation runs operated by three different statically weighed goods vehicles. The initial performance criteria demanded from these original sites was not particularly onerous compared to modern day standards; the all axle mean impact factor was to be unity ± 0.1 with a co-efficient of variation of less than ± 18%. As mentioned earlier, the aim of the survey was to provide statistical data and not to be applied for any form of enforcement or pre-selection.

3.2 Equipment Performance

It was soon found that the output of piezo polymer sensors were sensitive to the temperature of the road. This issue was dealt with by recording the road temperature using a thermistor installed adjacent to the array and appending the parameter to the individual vehicle record allowing a compensation factor for the variance in temperature to be calculated. However, the reliability and cost of these types of sensors proved to be the biggest bonus. The sensor, when installed correctly, becomes an integral part of the pavement body and it was found that the life span of these sensors was considerable. In some cases they have been in excess of 10 years and have been able to withstand the impact of millions of heavy goods vehicle axles during this period. Unfortunately the experience gained from the operation of the capacitive strips was poor in comparison, with frequent failures over periods of just a few months. This failure rate proved to be uneconomical to operate particularly when the cost of traffic management was taken into account to permit replacement.

Other problems were encountered with the operation of some of the equipment when it came to data download and analysis. One of the companies employed an MS-DOS based form of data retrieval which was slow, un-user friendly and archaic even by late 1990's standards whilst another company employed an intricate and over elaborate form of error checking procedure as each data packet was received. This proved to be a time consuming and expensive process during data download via the public service telephone network (PSTN). These two issues were felt uneconomical and inefficient to operate over a period of time using the PSTN particularly when dealing with large volumes of vehicle by vehicle data.

However, a number of these sites today are still providing data to the DfT. Since the initial trial the DfT has expanded its network of ATC's to over 300 and the WIM network to 21. It has also undergone an upgrade to the classification and recording equipment. In 2000, the DfT found that the original ATC and WIM classification equipment were becoming outdated and components obsolete as a result of technology improvement. DfT took the decision to find a suitable replacement and for the purposes of maximum efficiency, a single manufacturer should be appointed to provide a modern, technologically advanced solution to supply a combined ATC and WIM classifier. After a competitive tender within the industry, the contract was awarded to TDC Systems Ltd to provide both classification equipment and in-house telemetry software.

4. Data Analysis

The results from the original survey presenting vehicle numbers, average gross vehicle weights and average standard axles have been previously published (Davies, et al, 1998). However, it is interesting to compare some of the results obtained in 1997 with those from 2007 to see if there has been any radical change over the ten year period. During this decade, a number of significant events had occurred that may have had an affect on both quality of the data and the results being obtained. Firstly in January 1999 the weight limit for 5 axled articulated vehicles was raised from 38 to 40 tonnes and in February 2001, the limit for 6 axled articulated vehicles was also raised from 38 to 44 tonnes. The other event has already been mentioned above with the upgrade of both the WIM classification equipment and software in 2000.

Table 1 – Average gross vehicle weights (tonnes)

	Rigid		**Articulated Goods Vehicles**							
Site	4 – axle		4 – axle		2+3 axle		3+2 axle		6 axle	
	1997	2007	1997	2007	1997	2007	1997	2007	1997	2007
Motorways										
M1	20.3	18.8	17.6	18.5	25.7	24.8	26.7	21.8	27.8	33.5
M5	14.8	22.0	17.5	22.9	23.5	29.7	24.1	25.7	25.7	38.4
M40	21.9	16.5	17.8	16.0	24.0	20.3	26.4	20.1	27.1	27.6
M55	27.2	24.7	22.1	20.0	30.4	26.0	31.7	22.5	32.0	32.1
M180 (East)	22.6	26.5	17.0	20.5	22.0	26.3	21.8	22.0	27.7	39.2
M180 (West)	22.5	23.3	20.3	21.1	33.8	30.7	32.8	26.7	34.9	42.1
Roads										
A14	20.1	21.8	17.2	18.7	27.7	23.8	26.5	23.1	30.8	35.6
A39	22.6	18.3	19.3	15.6	23.0	22.1	22.1	17.6	25.8	30.5
A49	19.7	22.5	17.8	18.8	27.0	24.0	27.9	21.4	31.6	37.0

One clear area where there has been a change is in the level of heavy goods vehicle traffic. This has grown during the period, according to official statistics (Department for Transport, 2010) by approximately 7%. This equates to the number of heavy goods vehicle observations at the census sites to approximately 50.7 million per annum compared to the 1997 level of around 47.4 million vehicles.

As can be seen from Table 1, the raising of the weight limit on the larger vehicles has had a significant affect on the average loadings for these vehicle types where the aggregated weight has increased from approximately 30 tonnes to 35.1 tonnes on 6 axled vehicles. In addition, as a result of growth in heavy goods vehicle traffic, vehicle numbers in this category have also grown significantly in their passage over the census sites from 1.1 million in 1997 to 3.3 million in 2007.

Table 2 – Average Standard Axles

	Rigid		**Articulated Goods Vehicles**							
Site	4 - axle		4 – axle		2+3 axle		3+2 axle		6 axle	
	1997	2007	1997	2007	1997	2007	1997	2007	1997	2007
Motorways										
M1	1.62	0.77	0.65	0.80	1.73	1.22	1.92	1.02	1.25	2.13
M5	0.64	1.29	0.76	1.53	1.65	2.11	1.69	1.71	1.22	3.10
M40	1.62	0.53	0.66	0.53	1.44	0.67	1.86	0.77	1.15	1.21
M55	3.64	1.88	1.40	0.99	3.14	1.39	3.48	1.15	2.24	1.90
M180 (East)	2.63	2.18	0.69	1.21	1.57	1.49	1.44	1.21	1.52	3.37
M180 (West)	2.20	1.47	1.34	1.20	3.86	2.28	3.64	1.69	2.55	4.03
Roads										
A14	1.96	1.20	0.80	0.87	2.97	1.10	2.27	1.21	2.00	2.48
A39	1.90	0.71	0.90	0.50	1.19	0.85	0.88	0.64	1.59	1.60
A49	1.72	1.35	0.83	0.83	2.89	1.10	2.84	1.01	2.31	2.79

Table 2 presents the data by average standard axle. However as these are calculated on the basis of the fourth power law it has been found, both in the original analysis in 1998 and this latest one, that the results can be distorted by anomalous data especially very heavy axles or large numbers of very light axles. Where ever possible these have been identified and removed from the analysis but it is inevitable that some vehicles may have slipped through the validation procedure. In the original analysis of the data, it was commented on how vehicle weights at the M55 site appeared higher than the others. This apparent anomaly appears to have corrected itself and in the early days of the study this site may have been giving more false readings than had originally been identified.

However, one of the real benefits that this study has shown is the ability WIM has for identifying areas where road wear may be greater than had originally been anticipated. In the UK, road design is based on traffic flow that has been provided initially from traffic counts, generally manual, and aggregated to form an annual average daily flow for each vehicle type. What these flow rates do not show is the weight and potential damage being generated by the vehicles. Assumptions are made on average vehicle weight but as can be seen from the data in Tables 1 and 2, these weights can vary quite considerably depending on the direction of the flow. The M180 sites are a classic example. In the case of this road, it leads to a major port on the east coast of England and the data clearly shows that vehicles heading west from the port are heavier than those heading to the port. Without this information the road designer is completely unaware of the stress the carriageway is being subjected to purely from assumed traffic flows and as a result can legislate for improved road wear factors.
It is clear from analysis of the data that as a result of raising the weight limit in the UK on the larger vehicles, operators have made a transition to using more of these vehicles within their fleets which has made them more economically efficient when transporting large loads.

5. UK WIM Expansion

Although the DfT were at the forefront of high speed WIM back in the 1990's, their experiences have led to an expansion in the use of WIM in the UK. A number of manufacturers' products have been employed in the UK since the DfT survey was started although results have been mixed. One example is of an installation on an urban motorway in the north of England where sensor failure was frequent. As a consequence the results from the site were poor and the cost of sensor replacement became prohibitive for its continued operation to be economically viable. In addition, the manufacturer of the roadside classifiers software also proved to be clumsy to operate, particularly during the calibration process.

Calibration results being obtained from the DfT census are frequently meeting COST323 B(10) standards which has led to further progress in other areas of the UK. Transport Scotland, the Scottish equivalent of the HA, decided a network of WIM sites was necessary to monitor pavement performance on its own trunk road network and began the commissioning of 55 sites aimed at achieving the standards being obtained by the DfT. Pavement damage was a major area of concern in Scotland with a high number of articulated goods vehicles being employed for carrying freight from source along relatively small, but important, roads through small rural communities. Again, using the experiences of the DfT, they opted to appoint the same contractor to supply and install the equipment. Transport Scotland have also adopted similar techniques as those used in England to ensure the sites are adequately calibrated to the requisite COST323 standards

Soon after this project began, the Vehicle Operators and Services Agency (VOSA), another executive agency of the DfT, also became interested in the use of high speed WIM. Working in association with automatic number plate recognition (ANPR) cameras, there sites would act as a potential pre-selection tool for use prior to enforcement. They initiated a project called the Weight and Safety Partnership (WASP) which embraced a number of partners including enforcement agencies, manufacturers and the DfT to formulate a pilot system. The project aimed to utilize the principles and benefits of the existing Video-WIM concept which had been developed in the Netherlands. In addition they wanted to enhance the use of ANPR as VOSA already held a comprehensive database of vehicle specific maximum axle and gross vehicle weights for all UK registered vehicles. The trial period was carried out over two years and was considered an outstanding success (Jones, M,. 2008) and as a result VOSA and the HA developed a small network of these ANPR/WIM sites around the English trunk road network.

The improvements in high speed WIM technology and the success of the VOSA trial also attracted the attention of operators of major bridge crossings in the UK. Large bridges such as the Humber, Kessock, Severn and Erskine carry major roads which naturally have their fair share of heavy goods vehicles. Damage to bridge structure is of major concern and the operators needed to protect their bridges from unnecessary loadings. One bridge in particular, the Erskine, installed a similar system to the one employed by VOSA by combining WIM with ANPR to warn drivers, prior to crossing the bridge, if their vehicle was illegally overloaded. Of course, this system also proved ideal as it could also be utilised by VOSA at this location.

As for the future; High-speed WIM has always been seen in the UK as the preserve of central government agencies and private infrastructure owners such as bridge operators. However, not all roads in the UK are operated and managed by central government and, indeed, it has taken a long time for local authorities to realise that the roads they operate act as feeders to the main trunk road network and are being damaged prematurely by heavy goods vehicles. The damage to these roads by such vehicles is causing local authorities unnecessary and costly additional expenditure. A few are now beginning to realise the economical potential of WIM. Two large urban authorities are now seriously considering the implementation of WIM systems within the area similar to the systems being operated by VOSA to help alleviate the potential damage to the infrastructure and to assist with improvements to the local economy.

6. Conclusions

It was clear that in the early days of WIM in the UK the industry had become stagnated, the manufacturers had designed their systems and the customer was encouraged to use it as it stood. It has become apparent since those days that this has been the wrong way to approach the subject. The end-user should be clear in their requirements and what they want to achieve and they must encourage the industry to evolve and develop to meet these needs where possible.

High-speed WIM in the UK has been a long and slow process of education and, to some extent, trial and error. The vast majority of operators in the UK now insist on COST323 B(10) standards and are generally operating with one particular sensor type, the piezo polymer BL strip. A number of initial problems have been encountered over the years but these have been overcome such as the sensitivity of the piezo polymer sensor to road body temperature and the refinement of end-user software which has been developed to meet end-user requirements. Both end-users and manufacturers have worked closely together to develop WIM and shaped it to meet specific demands. This relationship should be encouraged and continue to develop.

Investing in ITS technology such as WIM provides long term benefits including government cost savings, economy wide productivity and improved quality of life. As a consequence it is encouraging to see that WIM is now beginning to expand in the UK away from its central government base. Local authorities have realised the economic benefits, both socially and environmentally, of operating such systems. It is now hoped that this upward trend in investment in WIM technology continues to expand to the benefit of everybody.

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TRENDS IN HGV PERFORMANCE IN THE MAIN GREEK ROAD NETWORK: LESSONS TO LEARN




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Abstract
The work presented in this paper reviews the findings of two major studies that were conducted in Greece over the period of four years (2000 - 2003) and concerned the determination of the dynamic characteristics of HGVs in the main interurban Greek road network using Weight-In-Motion (WIM) technology. The basic objective of this research work was to identify the trends in the values of the basic parameters that define the performance of HGVs operating on the principal Greek road network. Also an effort was made to develop a low-cost method to define the impact of HGVs on the road pavements using simple traffic volume and classification counts. Thus the values of the two impact coefficients (V.C.E.C. and A.E.C.) were calculated for the different vehicle class and sites. The analyses performed resulted to a series of descriptive statistical figures weight (gross and axle) of the HGVs per vehicle class.
Keywords: Weigh-in-motion, Heavy Goods Vehicles.

Résumé
Cet article liste les conclusions tirées de deux études majeures qui ont été réalisées en Grèce, sur une période de quatre ans (2000-2003) concernant la détermination des caractéristiques dynamiques des HGVs sur le réseau routier interurbain principal grec en utilisant la technologie du pesage en marche (WIM). L'objectif principal de cette étude est d'identifier les tendances par rapport aux valeurs des paramètres fondamentaux qui définissent la performance des HGVs fonctionnant sur le réseau routier principal grec. De plus, un effort a été fait pour développer une méthode à faible coût permettant de définir l'impact des HGVs sur les voies piétonnes en utilisant le volume de trafic et une classification simple. Ainsi, les valeurs des deux coefficients d'impact (V.C.E.C. et A.E.C.) ont été calculées pour les différentes catégories des véhicules et les différents sites. Les analyses effectuées aboutissent à une série de descriptifs statistiques des poids (total et par essieu) des HGVs par catégorie de véhicule.
Mots-clés: Pesage en marche, poids lourds de frêt.

1. Introduction

Two of the major road construction projects in Greece are the **P**atras-**A**thens-**Th**essaloniki-**E**vzonoi motorway (**PATHE)** and the Egnatia Road. The first project concerns the improvement of the motorway connecting the southern with the northern part of the country, having a length of 1,050 kilometers. The second project concerns the construction of a motorway connecting the western with the eastern part of the country, having a length of 680 kilometers. Egnatia Road also connects Greece with all neighboring Balkan countries. Both motorways play an important role in freight transport within the country. Within this framework the need to assess the impact of heavy goods vehicles on the national road network is essential. A research project was carried out during 1992 in the country concerning the collection and analysis of heavy goods vehicle traffic data along sections of the primary national road network (Mintsis G., 1992).

In 1998 the Ministry of Development, General Secretariat for Research and Technology assigned a research project (Dept. of Transportation and Hydraylic Engineering et.al. 2001) concerning the determination and assessment of the dynamic characteristics of HGVs and their impact to the national highway network, to the Department of Transportation and Hydraulic Engineering, Faculty of Rural and Surveying Engineering, Aristotle University of Thessaloniki, the Central Laboratory of Public Works (responsible authority for pavement quality), and Egnatia Road S.A. (responsible authority for the construction, operation and maintenance of the Egnatia Road).

The project included the following tasks:

- Recording the static and dynamic characteristics of heavy goods vehicles using Weigh-In-Motion technology, with reference to the two main road axes in the country (PATHE and Egnatia Road).
- Analysis and evaluation of the collected data in order to create a database, in accordance with the guidelines imposed by the European Action COST 323 (COST 323, 1997).
- Research on the characteristics of the overloaded heavy goods vehicles and their impact to the road network.
- Monitoring pavement performance due to the heavy goods vehicles loading.
- Forecasts of traffic loads in the two motorways.
- Development of a database for pavement management and support to the decision making process concerning the budget allocation for road construction, operation and maintenance.
- Design of guidelines for the evaluation of the impact of heavy goods vehicles on main roads.

Also, in February 2003 the Ministry of Environment and Public Works commissioned to the consortium Steer Davies Gleeve Ltd.–NAMA SA–SALFO EPE the project: “Traffic Advisor’s (TA) Motorway Concession Projects in Greece” (Traffic Advisor, JV SDG – NAMA - SAFLO, 2003). Among the tasks of the project was to measure the dynamic characteristics of commercial vehicles on specific principal roads in the country. In this context a Weight In Motion (WIM) database was created with data collected at five different sites of the principal Road Network of Greece.

The above mentioned projects constitute the only public efforts in the country in the last 15 years to identify measure and study the physical and dynamic characteristics of the commercial traffic in the principal Road Network in Greece, with no corresponding measurements on the secondary road network.

2. Data Collection Process

The main criterion for the selection of sites for the survey was that each one should be characterized by significant HGVs traffic. An attempt was made so that the number and position of these sites would secure the coverage in spatial terms of the principal National Road Network. The sites specially are presented in Figure 1. It was not possible to have simultaneous counts to all sites as it was originally scheduled due to the shortage of funds and therefore of the necessary instrumentation. Since the number of the available loggers was smaller than the number of the available sensors and loops, the loggers were removed from one site to another according to a predefined program of counts. The counting period for the research project started in August 2000 and ended in March 2001 and the measurements of the Traffic Advisor project occurred between August and November 2003. These sites are presented in Figure 1.

Figure 1 – Position of the WIM Sites in the National Road Network

Two types of Weigh-In-Motion (WIM) systems were installed. Both systems included sensors which were permanently placed under the road surface (in the pavement) at the specific road sections. Underground cabling was used to connect the sensors with the logger. In nine out of twelve sites PEEK TRAFFIC Ltd. sensors were used (sites 1 – 3 and 7 – 12, Table 1) while in the rest three sites the Electronique Controle Mesure (E.C.M.) sensors were used (sites 4 – 6, Table 1).
The layout of the installation consisted of two piezoelectric weight sensors having a length of 3.5 meters, another piezoelectric on scale sensor having a length of 0.5 to 0.8 meters and finally an inductive loop in order to measure other than loads traffic parameters as the class of the vehicle, speed, etc.

Repeated visits to the sites were necessary in order to transfer data from the logger to a portable personal computer and also to maintain power supply to the system. The frequency of these visits depended on the traffic volumes and on the batteries used. Measurements of the evenness were also made in each site in order to assess the quality of the pavement. These measurements were made for a distance of one kilometer before and after the exact position of the WIM systems. Apart from the field data collection process, an extended survey was conducted in order to collect data on the construction elements regarding the pavement (e.g., year of construction, type and year of last maintenance etc.), available traffic volumes, etc. In all cases special care was taken to secure the all site fulfilled the physical requirements set by the manufacturers such as slope, evenness of the pavement, temperature, etc.

Table 1: W.I.M. sites details in the national road network

Site code	Area	Site	National Highway Axis	WIM system (Direction)
1	Kavala	Agios Andreas	N.R. Thessaloniki – Kavala	both
2	Derveni	Agios Basilios	N.R. Thessaloniki - Kavala/ PATHE and Egnatia Road N.R.	both
3	Malgara	Kleidi Imathias	N.R. Athens - Thessaloniki/ PATHE and Egnatia Road	Athens – Thessaloniki
		Chalastra	N.R. Athens - Thessaloniki/ PATHE and Egnatia Road	Thessaloniki - Athens
4	Larisa	Larisa	N.R. Athens - Thessaloniki/ PATHE.	Thessaloniki - Athens
5	Oinofyta	Oinofyta	N.R. Athens - Thessaloniki/ PATHE.	Thessaloniki - Athens
6	Megara	Megara	N.R. Athens - Patra / PATHE.	Athens – Patra
7	Ioannina	Leykothea	N.R. Ioannina – Igoumenitsa/ Egnatia Road	Igoumenitsa - Ioannina
8	Volos	Killeler	N.R. Athens - Thessaloniki/ PATHE.	Athens – Thessaloniki
9	Atalanti	Tragana	N.R. Athens - Thessaloniki/ PATHE.	Athens – Thessaloniki
10	Xylokastro	Xylokastro	N.R. Athens - Patra / PATHE.	Athens – Patra
11	Nemea	Spathovouni	N.R. Athens - Tripolis	Athens – Tripolis
12	Mesologgi	Gavrolimni	N.R. Patra - Agrinio	Agrinio – Patra

3. Data Analysis

Due to the fact that two WIM systems were used within the framework of two different projects carried out at different time periods, there was incompatibility concerning the data obtained from the loggers. Concerning HGV vehicle classification ADR - Peek Traffic WIM system uses the Standard FHWA classification system while Hestia Station – ECM WIM system uses a more detailed classification system adopted by the manufacturer.

A significant number of false records were identified before the statistical analysis. Filters checking basic parameters of the WIM data were applied to identify false records. These filters checked the status code that the logger gives to each record, the vehicle speed, the wheelbase, the distances between axles and the axle weights. It was found that when HGV with extremely low or high values of parameters such axle loads, wheelbase size and speed were excluded than the sample only the 65% of the initial counting was used for further analysis. Due to the large amount of data, powerful tools were used in order to design the databases, to allow for computations and production of statistical results. Data analysis process considered all the analytical information from every site, every period of counts and every direction of vehicles. Finally, and after the application of filters to all the raw data received, 2.318.972 (1.943.384 + 375.588) total entries were remained, of which 799.089 (674.251 + 124.838) were commercial vehicles, used therefore in the analysis process.

The identification of the overloaded vehicles was made taking into account the values of the maximum allowed weights for the international transport as defined by the Ministry of Transport and Communications in Greece. The transformation of the axle loads to Equivalent Single Axle Loads (ESALs) of 8.155 tn (18.000 lbr) was made using the respective coefficients of the American Association of State Highway and Transportation Officials (AASHTO, 1993) Two coefficients were considered for the purposes of the analysis in order to express the “aggressiveness” of loads to the pavement. The first coefficient - Vehicle Class Equivalence Coefficient – V.C.E.C. - was defined as the ratio of the total number of equivalent axles per vehicle class over the total number of vehicles of the particular class (Dept. of Transportation and Hydraylic Engineering et.al. 2001). The second coefficient (Area Equivalence Coefficient – A.E.C.), with spatial reference, was defined as the ratio of the total number of equivalent axles over the total number of the heavy goods vehicles at a specific site. A.E.C. is intended to be used when ESALs are to be calculated from total HGV traffic volume data, with vehicle class not available. A geographic information systems technology was used in order to produce thematic maps with ESALs and overloaded vehicles.

The percentage of overloaded HGVs and the average daily number of ESALs at each site are presented in Figures 2 and 3. The percentages of the overloaded vehicles in Figure 2 refer to gross vehicle weight. The gross vehicles allowable weight limits used within the project are: for 2 axles vehicles is 18 tns, for 3 axles vehicles is 25 tns, for 4 axles vehicles is 32 tns and for 5+ axles vehicles is 40 tns. It’s obvious that the average percentage of the overloaded vehicles approximates 24%. This percentage is significantly high, compared with corresponding maximum values from surveys in other countries: Slovenia 12% (2004), Netherland 6.22% (2001), and Sweden 19% (2004, 2006 and 2009). It should be mentioned that for the percentages of overweight vehicles, as presented in Figure 2, there is a high concentration near the limit load, which for Class 9 with 5 axles ranges from 7,5% to 14% (interval weights from 40 to 44 tns) for all measured sites.

The average daily number of ESALs (Figure 3) varies considerably from site to site, taking peak in positions located near urban centers (sites 2,3,4 and 5) and clearly smaller values in lower hierarchy roads (sites 7,11 and 12). The average daily number of ESALs is more than 5.000 in sites 2 and 5 and less than 1.000 in sites 7 and 12. Also, the analysis showed that in some cases, a small percentage of axle systems correspond to a large percentage of ESALs (e.g., in site 3, 14% of the axle systems (tandem or triple axles) is responsible for the 59% of the ESALs).

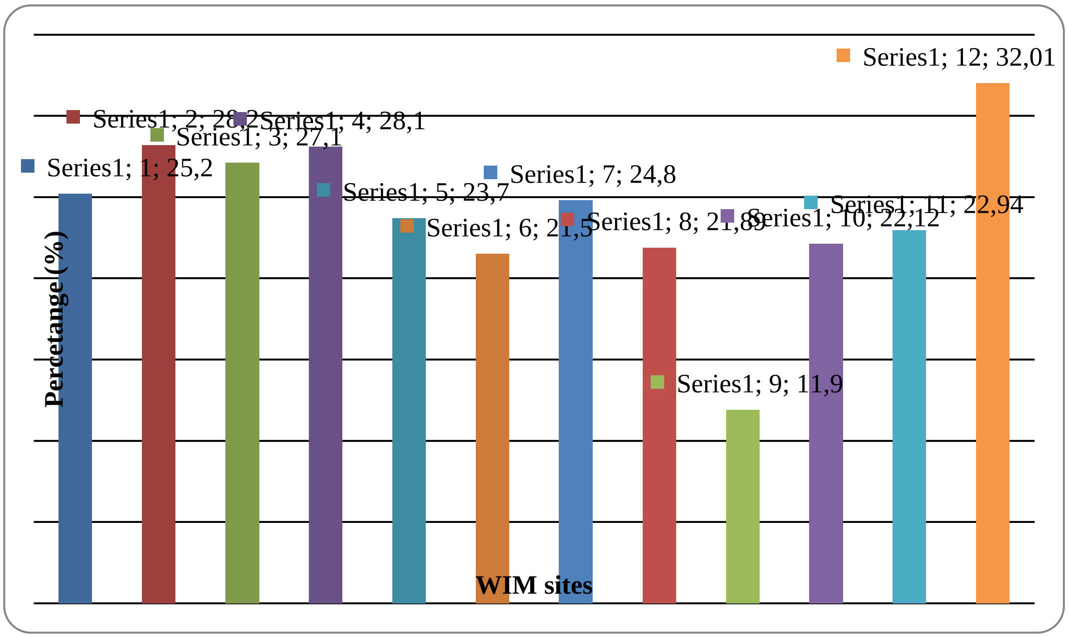

Figure 2 – Percentage (%) of Overloaded HGVs in Each Site

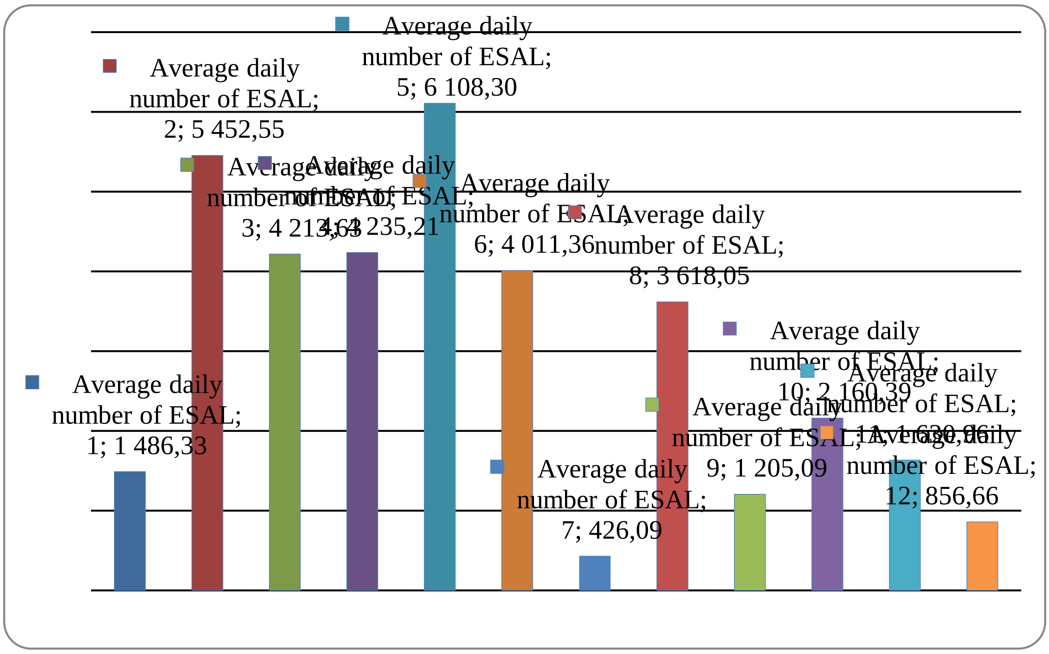

Figure 3 – Average Daily Number of ESALs in Each Site

Average weight per HGVs class (Table 2) in each site didn't change much between sites for the same vehicle class. It must be noted that, concerning the traffic composition in the national network, high percentages appear in class 9 with 5 axles (29.2%-49.6%), in class 8 with 4 axles (12.0%-16.8%), in class 5 with 2 axles (16.2%-29.5%) and in class 3 with 2 axles (6.1%-14.7%). On the contrary, the rest of the classes appear to have much smaller contribution to the traffic composition (e.g. class 11 and 12 do not appear in sites 4, 7, 8, 9, 10, 11 and 12).

Values of V.C.E.C. and A.E.C. coefficients (Table 3) appeared to have significant variation. Apart from certain vehicle class the finding is believed to be due to the absence of samples with considerable size. Only some of the values found for V.C.E.C. for specific vehicle classes can be considered reliable due to the fact that they were based on a large number of counts (class 9 with 5 axles, class 8 with 4 axles.

Table 2: Average Weight (in kgrs) Per HGVs Class in Each Site

C	A	Sites											
		1	2	3	4	5	6	7	8	9	10	11	12
	2	3.706	3.601	3.663	3.655	3.924	4.019	4.381	-	-	-	-	-
3	3	7.248	5.877	7.228	7.563	5.942	7.867	-	-	-	-	-	-
	4	11.752	12.336	10.389	13.786	12.590	12.471	6.256	-	-	-	-	-
4	2	15.127	16.116	15.021	14.773	13.741	15.666	15.694	13.602	13.683	13.814	15.662	10.346
	3	17.782	16.312	27.792	18.329	12.738	20.456	-	16.750	11.538	12.756	19.591	14.569
5	2	10.514	11.513	10.319	10.302	10.468	11.633	12.180	9.104	9.951	11.774	13.244	10.870
6	3	21.126	22.923	21.458	19.324	21.887	20.968	18.882	18.394	18.187	19.508	23.790	17.572
7	4	26.769	29.235	31.922	29.481	34.396	28.723	27.358	22.241	16.793	22.537	36.156	25.037
8	3	20.759	19.123	17.181	16.093	15.020	15.142	19.241	13.719	15.870	15.299	17.932	16.095
	4	26.007	26.904	26.152	23.584	25.208	22.421	26.098	21.354	20.938	20.627	23.832	20.577
9	5	33.599	35.904	34.387	33.562	33.244	29.610	35.307	31.431	31.763	31.679	37.847	29.157
10	6	35.743	41.026	37.964	36.052	35.724	31.094	39.379	34.443	29.694	32.275	32.116	28.611
11	5	29.392	25.780	27.458	-	-	-	-	-	-	-	-	-
12	6	44.037	46.817	46.984	-	-	-	-	-	-	-	-	-

C: class, A: Number of axles

Table 3: V.C.E.C. and A.E.C. Per Class and Per Site

	C	A	Sites											
			1	2	3	4	5	6	7	8	9	10	11	12
V.C.E.C.	3	2	0,01	0.01	0.01	0.01	0.01	0.01	0.02	-	-	-	-	-
		3	0,12	0.07	0.07	0.09	0.04	0.09	-	-	-	-	-	-
		4	0,16	0.16	0.11	0.22	0.18	0.14	0.01	-	-	-	-	-
	4	2	3,61	3.56	2.73	3.16	1.93	3.54	2.38	2.21	2.03	2.28	2.80	1.11
		3	1,43	1.94	4.70	0.85	0.25	1.74	-	1.21	0.33	0.52	1.36	0.81
	5	2	1,30	1.56	1.10	1.41	1.35	1.84	1.20	1.01	1.26	1.97	2.37	1.40
	6	3	2,87	3.40	2.48	2.04	3.01	2.42	1.51	1.84	2.03	1.86	3.24	1.38
	7	4	3,60	4.46	4.55	3.08	3.92	2.37	2.78	2.78	2.43	1.36	4.41	1.37
	8	3	4,29	1.65	1.28	1.71	0.96	0.82	2.15	0.88	2.86	1.44	2.42	1.68
		4	4,59	4.70	4.29	3.89	4.53	3.29	2.67	2.70	2.12	1.52	2.70	1.92
	9	5	5,03	5.77	4.64	5.41	4.92	3.77	3.67	4.72	4.54	3.92	5.61	3.19
	10	6	3,59	5.22	3.47	3.42	3.73	2.39	2.90	2.80	2.04	1.61	1.59	1.20
	11	5	4,26	2.06	3.42	-	-	-	-	-	-	-	-	-
	12	6	5,27	7.93	8.14	-	-	-	-	-	-	-	-	-
A.E.C. (HGV)			3,11	3.30	3.02	3.81	2.82	2.47	2.43	3.36	3.14	2.86	3.57	2.08

C: class, A: Number of axles

In the contrary when reference was made to A.E.C. its values were found not to present considerable deviation from a mean value close to 3,0 showing that at a mean level the impact of each HGV considered could be equal roughly to three ESALs.

4. Conclusion

The following main findings can be drawn from the data analysis for all the twelve sites studied during the two public projects conducted in different time periods:

- The roads and the sites considered represent an adequate, in physical – spatial terms, sample of the Greek principal Road Network.
- As it was expected a reasonable variation in average gross HGV per class was observed at each site considered. However it was obvious there were not sites where a systematic deviation of average gross weights from respective values from other site was observed for a large number of classes.
- The descriptive data analysis showed that the percentage of overloaded HGV with all classes considered ranged from 11,9% to 32%. Although it was possible to identify specific reasons for these findings it is considered that over the total data collection period a rough mean value for the percentage of overloaded HGV travelling along the principal Greek Road Network reaches the value of 25%. Also the counts made during the two counting periods presented no significant differences in any of the parameters considered in the analysis.
- The analysis also showed that when axle weigh was considered most overweight vehicles were recorded at the Athens – Thessaloniki motorway. Also that there is a

significant contribution of the overweighted vehicles to the total impact to the road pavement.

- V.C.E. coefficient values appeared to vary significantly among vehicle classes and sites considered. However, as it was expected A.E. coefficient showed consistently in its values among the different sites and time periods. However, it is believed that long period counts are needed if we are to reach reliable and safe for usage values for both coefficients.

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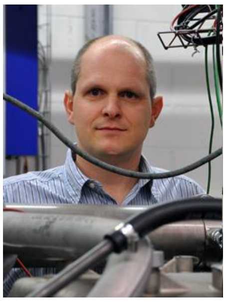
ENVIRONMENTAL IMPACT OF HEAVY VEHICLES BASED ON NOISE, AXLE LOAD AND GASEOUS EMISSIONS





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Abstract

All data indicate that the number of heavy vehicles is on the rise. For a sustainable transportation system there is an urgent need to develop means to reduce the environmental impact of these vehicles at the source. This paper delivers a detailed examination of vehicles from a combined Heavy Vehicle Fee (LSVA) and Weigh-in-Motion (WIM) site. In August 2009, WIM sensors were built parallel to an LSVA monitoring site on the A1 between Zürich and Bern, the main east west artery in Switzerland, at Oberbuchsiten. This provides a unique opportunity to combine many environmentally relevant heavy vehicle parameters.

Keywords: Heavy Vehicles, Noise, Weigh-in-Motion, WIM, Gaseous Emissions.

Résumé

Toutes les données indiquent que le nombre de véhicules lourds augmente. Pour un système de transport durable, il est urgent de développer des moyens pour réduire l'impact environnemental de ces véhicules à la source. Ce document fournit une étude détaillée des véhicules sur un site avec capture de la redevance sur le trafic des poids lourds liée aux prestations (RPLP) et de pesage en marche (WIM). Le site est situé à Oberbuchsiten sur l'A1 entre Zurich et Berne, la principale artère est-ouest en Suisse. Ceci fournit une occasion unique de combiner de nombreux paramètres pertinents de l'environnement des véhicules lourds.

Mots-clés: Véhicules lourds, bruit, pesage en marche, WIM, émissions gazeuses.

1. Introduction

All data indicate that the number of heavy vehicles is on the rise worldwide. Although this is a result of economic prosperity, the increase in heavy vehicles has a direct impact on the environment and infrastructure. For a sustainable transportation system there is an urgent need to develop means to reduce the environmental impact of vehicles at the source.

The European cooperative project Eureka Logchain Footprin E!2468 has developed methods to identify environmentally friendly vehicles for road and rail transport modes (Mayer et al, 2007). The parameters considered are dynamic load, noise, vibrations, and gaseous emissions. At the same time the Swiss heavy vehicle fee (HVF) or LSVA (the German acronym) has developed a bonus/malus system in effect since 2001, in order to encourage road vehicles with a small environmental footprint (Fair and Efficient, 2012). Parameters considered by the LSVA are declared transported mass, distance travelled, and Euro engine certification.

In August 2009, Weigh-in-Motion (WIM) sensors where built parallel to an LSVA monitoring site on the A1 motorway between Zürich and Bern, the main east west artery in Switzerland, at Oberbuchsiten. This provides a unique opportunity to combine many environmentally relevant heavy vehicle parameters. This paper delivers a detailed examination of vehicles from a combined LSVA site and WIM site.

2. Objectives

Detailed examination of vehicles chosen from the traffic stream as part of an earlier project Footprint phase II (hereafter referred to as Footprint II) has indicated that the parameters encouraged by the LSVA method are indeed at or below environmentally friendly limits whereas the additional parameters defined by the Footprint project are not affected (Poulikakos et al., 2010). Footprint II has shown that there are vehicles on the road with very high axle loads but gross vehicle weights that are within limits. There are vehicles with high noise emissions but engines that are up to the latest available technical standards for gaseous emissions. In summary, vehicles that - based on LSVA - would pay a reduced fee are not necessarily environmentally friendly when the footprint parameters are considered. Parameters that are currently controlled and their reduction encouraged such as gaseous emissions, axle loads and gross weight are for the most part below or close to acceptable limits. However, other important parameters such as tire pressure and noise remain higher than acceptable limits.

As of 2011, there are six WIM sites operated by the Federal Roads Office and fifteen LSVA sites operated by the Federal Customs Administration in Switzerland. This project has brought together existing synergies in order to find means to reduce the overall footprint of HGVs. The overall goal of this follow up project is to monitor the following parameters of interest: axle load, gross weight, noise, and engine type approval certification, in order to develop an overall footprint of individual vehicles for a statistically significant sample of vehicles. The results of the project can aid in developing a bonus/malus mechanism based on the "polluter pays principle" in order to reduce the environmental impact of vehicles at source.

3. Monitoring Site

The Footprint Monitoring Site (FMS) shown in Figure 1(a), is located on the major east-west artery in Switzerland as apparent by the thickness of the red line. It is located in Oberbuchsiten between Bern and Zürich, in the direction of Zürich. This site is a prototype combining WIM and LSVA allowing bringing together various monitoring activities. The original motivation for such a site was that in Switzerland, as discussed in Section 1, the heavy vehicle fee is based on declared mass, not actual carried mass, and it is suspected that some vehicles carry more than they have declared and paid for. Combining WIM with the LSVA data allows identification of such vehicles without disturbing the traffic stream.

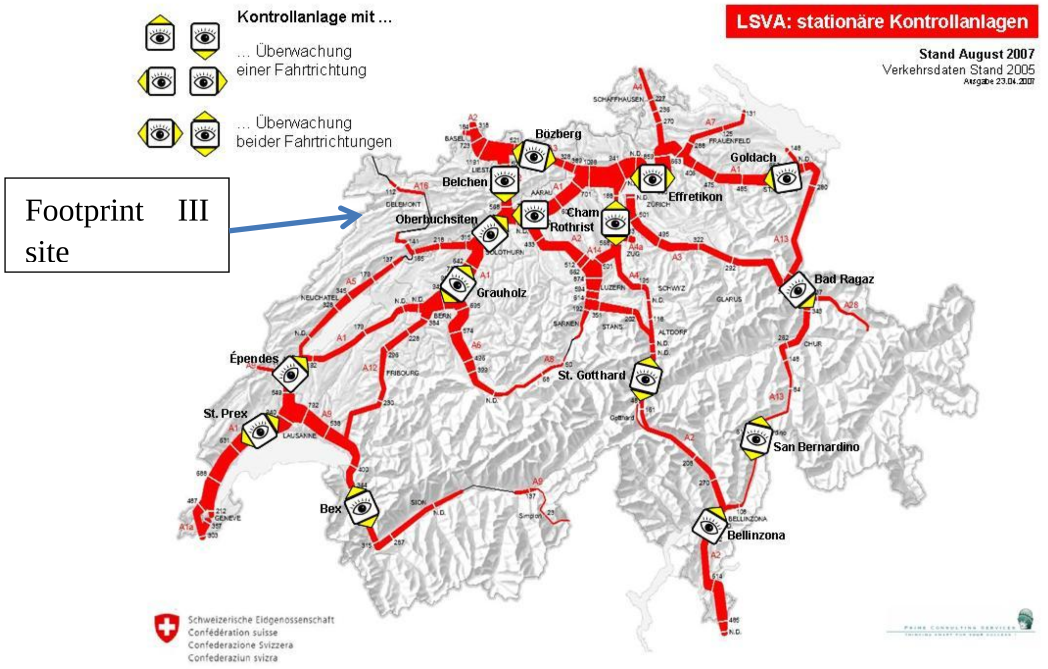

Figure 1(a) - Location of the Footprint III site combining LSVA,WIM and noise measurements in Oberbuchsiten, Switzerland.

As shown in Figure 1(b), the Dedicated Short Range Communication (DSRC), Laser scanner, and Cameras are located on the gantry. Cameras are used for recording front and back views as well as the license plate. The DSRC Antenna is used for communication with the LSVA on board unit (OBU). The Laser scanner is used for vehicle detection and classification. The noise measurements are made according to the European and International standards (EN ISO 11819-1) using a microphone. The microphone is mounted at a height of 3.0 m a distance of 7.5 m from the center of the inner lane

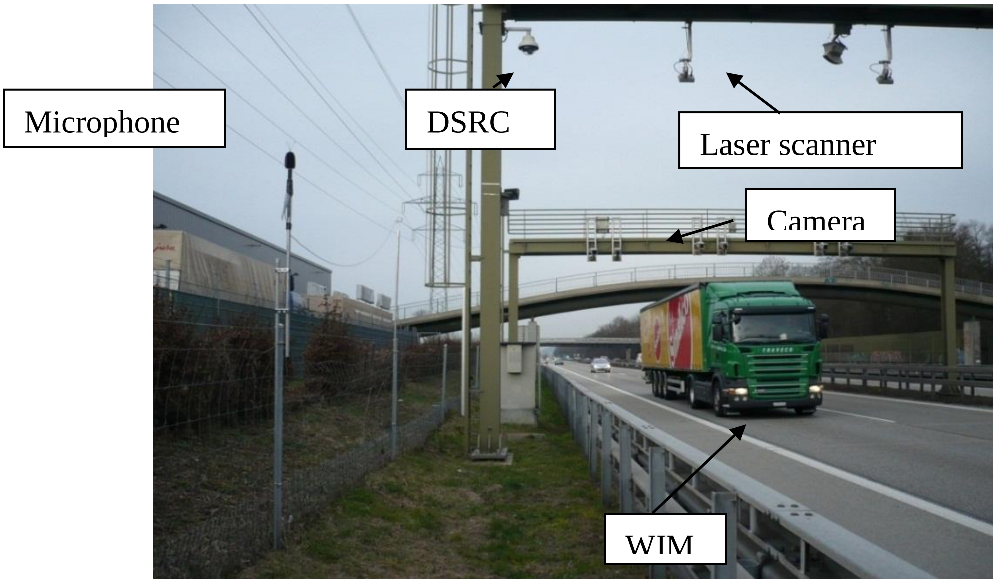

Figure 1(b) - Footprint III monitoring site.

4. Footprint Data

Table 4 shows a summary of the parameters collected using the various sensors described in Section 3. As shown, from the WIM sensors axle load, number of axles, gross weight, speed axle distance and Swiss 10 category are obtained. The microphone registers the sound pressure level (SPL) and the LSVA sensors and database deliver Euro engine type approval category, origin of vehicle, declared weight, and LSVA vehicle category as well as speed. Table 5 shows a summary of the Swiss10 vehicle categories.

Table 4 - Footprint parameters

Sensor/System	Parameter	Comments
WIM:	Axle load	
	Number of axles	1 - 9
	Gross weight	Maximum 99999 kg; Minimum 3500kg
	Speed	km/h
	Axle distance	
	Swiss 10 category	1 - 10
Microphone	Sound pressure level (SPL)	
LSVA	Gaseous emissions class	I – V
	EURO 0-V	< EURO I
	Domestic/Foreign	Country code (CH, D, A, F etc.)
	Declared gross weight	
	LSVA Veh. Category	
	Speed	m/s

Table 5 - Swiss10 Classification

Class	Vehicle Type
1	Buses and Coaches
2	Motorcycles
3	Personal Vehicles
4	Personal Vehicles with Trailers
5	Delivery / Pick-up Trucks (< 3.5 t)
6	Delivery / Pick-up Trucks with Trailers (< 3.5 t)
7	Articulated Delivery / Pick-up Trucks with Semi-Trailers (< 3.5 t)
8	Freight Trucks
9	Freight Trucks with Trailers
10	Articulated Freight Trucks with Semi-Trailers

Pollutant emissions of heavy duty engines in Europe are limited according to Euro categories. These pollutant emissions are measured on an engine test bench (i.e. the engine is directly coupled to a dynamometer) in exactly defined load patterns (i.e. engine speed and engine torque versus test time), and defined ambient conditions. The emissions are limited in a work-specific manner (i.e. in grams per kilowatt-hour of engine work). Starting from 2013, new engines will have to meet the most stringent emission limits ever (Euro-VI). Euro-VI will not only tighten the limits for all "classical" pollutants (carbon monoxide, hydrocarbons, oxides of nitrogen, and particle mass) but also a particle number emission limit is introduced which forces the use of highly efficient wall-flow particle filters. Additionally, Euro-VI introduces new in-use compliance measures (e.g. emissions can be controlled also on operating vehicles using portable emission measurement devices).

Figure depicts the emission limits from Euro-I to Euro-VI for the most important pollutants NOx and particle mass. It has to be mentioned that the test pattern from Euro-I to Euro-VI changed several times so that the numbers cannot be directly compared in an exact sense. However, it can be said in an approximate manner that five Euro-VI vehicles will produce about the same NOx emissions as one Euro-V vehicle. Accordingly, for particle number emissions, which are believed to have severe impacts on living organisms, the reduction is estimated to be even more pronounced: about 100 Euro-VI vehicles will emit about the same number of particles as one Euro-V vehicle without a particle filter.

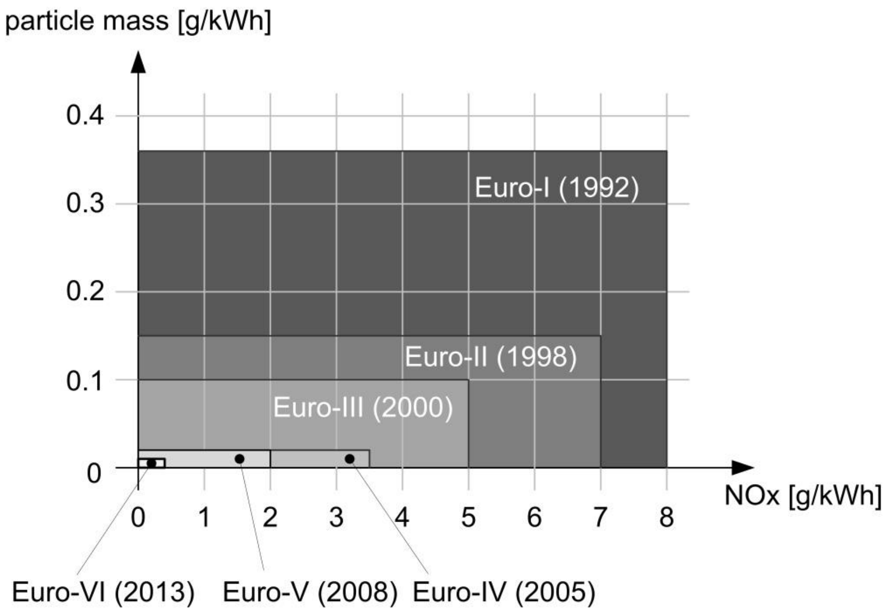

Figure 2- Nox and particle limits for heavy duty engines for the Euro-I to Euro-VI stages

5. Results

During the course of this phase of the project, data were collected for four full months in 2011. The representative sample of results shown for March 2011 for 120 643 vehicles indicate that the heavy vehicle fleet is primarily Swiss categories 10, 9 and 8 (Figure , Figure and Table 5). In order to profit from lower LSVA charges, fleets have been upgraded with vehicles complying with the Euro-III standard plus a smaller extent also to Euro IV standard [ARE 2007, Poulikakos et al 2010]. Since some major manufacturers did not introduce Euro-IV engine technologies but had already introduced Euro-V engines around the year 2005 (knowing that this will allow lower road user charges for their customers), Euro-IV engines are rather rare on the road. The distribution of emission classes in Figure shows that the vehicle fleet is tending to be more environmentally friendly and overwhelmingly having engines with Euro-V type approval classification, which is the most environmentally friendly engine technology on the market today (see Figure). These findings corroborate data reported by the office for special development indicating that one of the positive effects of the LSVA has been the reduction in air polluting emissions from HGVs.

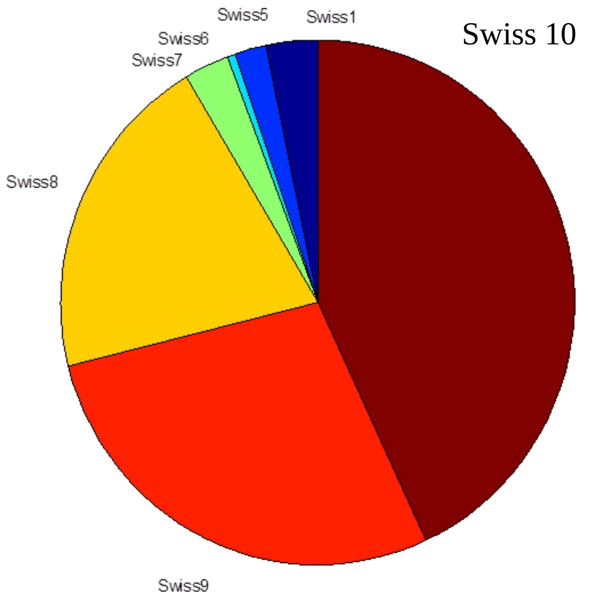

Figure 3 - Pie chart showing percent of Swiss10 category in March 2011

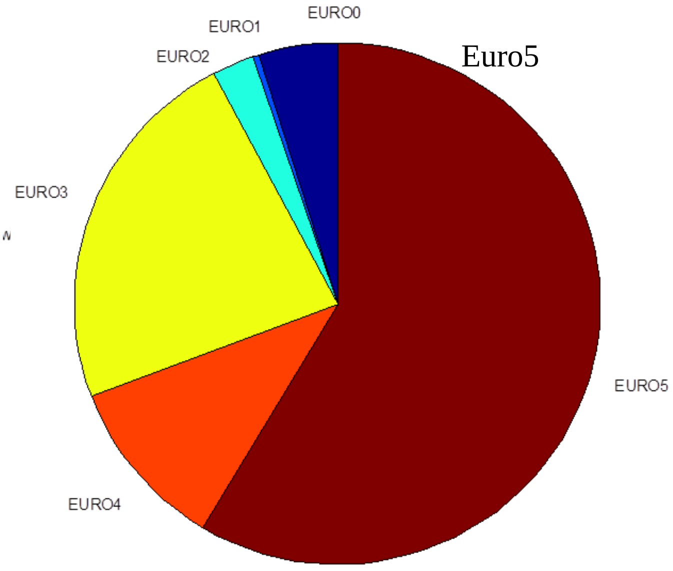

Figure 4 - Pie chart showing the distribution of Euro emission categories in March 2011

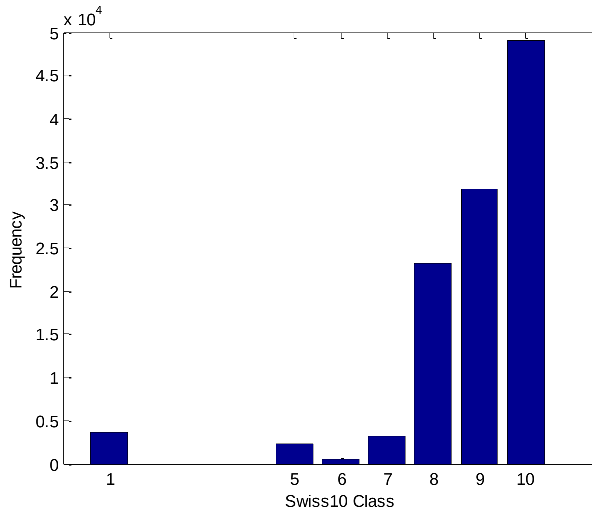

Figure 5 - Distribution of Swiss 10 categories in March 2011.

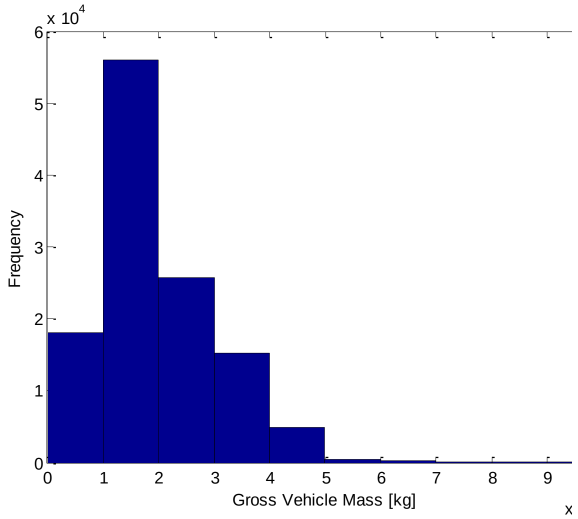

Figure 6 - Histogram showing the distribution of gross vehicle mass.

Figure and Figure show the distribution of gross vehicle mass for all investigated vehicles as well as for each category. It is clear that on average the vehicles are within allowable limits for gross vehicle mass which is 40 t in Switzerland. However there is a small percentage but nevertheless a significant number of vehicles in each category that are above this limit and cause disproportional damage to the pavement. Comparison of GVM between

Switzerland and the UK has shown that the median gross mass in the UK was higher than Switzerland for vehicles of a similar class. This trend is attributed to the higher allowable GVM in the UK which is 44t (Poulikakos et al 2009).

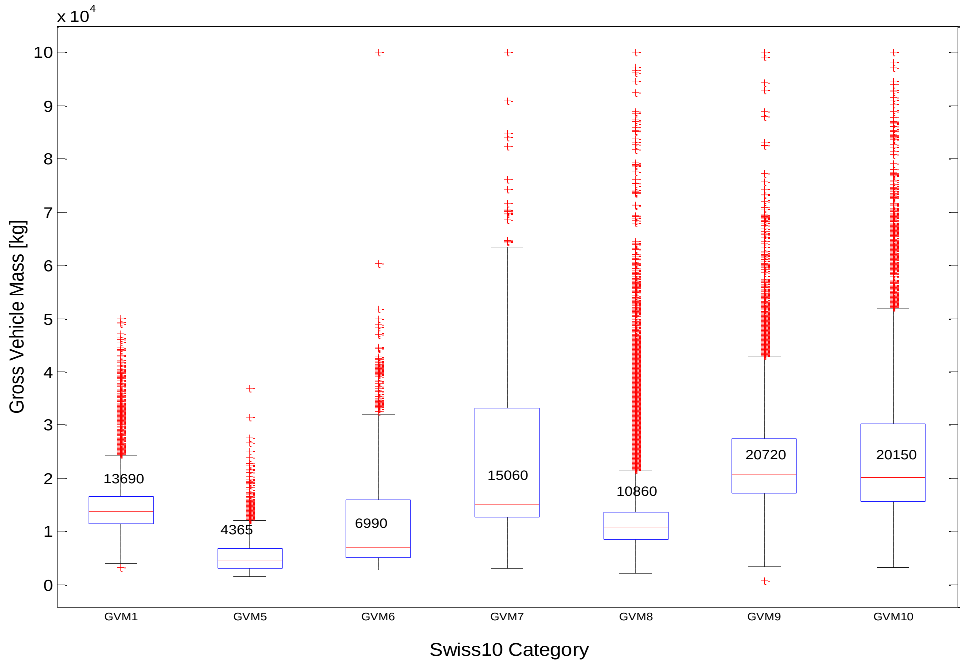

Figure 7 - Box plot showing distribution of Gross vehicle mass (GVM) and median values for each Swiss 10 category

Table 6 - Representative sound pressure levels

Sound pressure level [dBA]	Representative source
0	Threshold of human hearing
60	Human voice in 2 m distance
70	Road traffic in 10 m distance (1000 vehicles/h, 80 km/h)
120	Jet plane in 100 m distance

Table 7 - Average footprint for Swiss10 categories

Swiss10 Cat.	Gross Weight [kg]	Noise [dBA]
1	13’690	
5	4’365	85.4
6	6’990	86.7
7	15’060	88.0
8	10’860	87.0
9	20’720	88.6
10	20’150	88.4

Noise measurements at Oberbuchsiten (Figure) with averages summarized in Table 4 show the statistical distribution of noise emissions for five heavy vehicle categories (Swiss10) normalized for 80 km/h. Figure shows the distribution for Category 10 which are trucks with semi-trailers showing data similar to the those seen for overloaded vehicles, there is a significant number of vehicles which produce very high noise emissions. As demonstrated in

Table 6, as the decibel scale is logarithmic, a difference of 10 dBA is indicative of doubling or halving of the loudness.

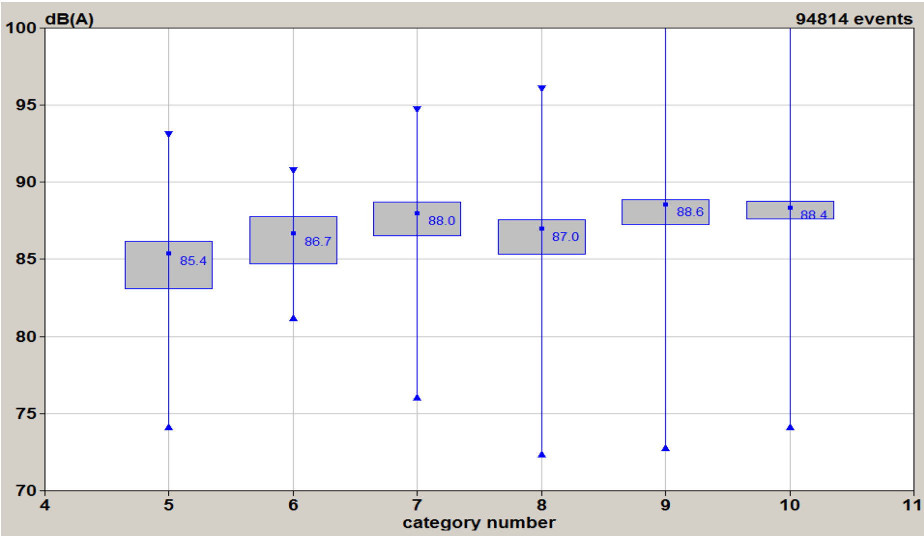

Figure 8 - Box plot showing distribution of SPL and median values for each Swiss 10 category, normalized for 80 km/h.

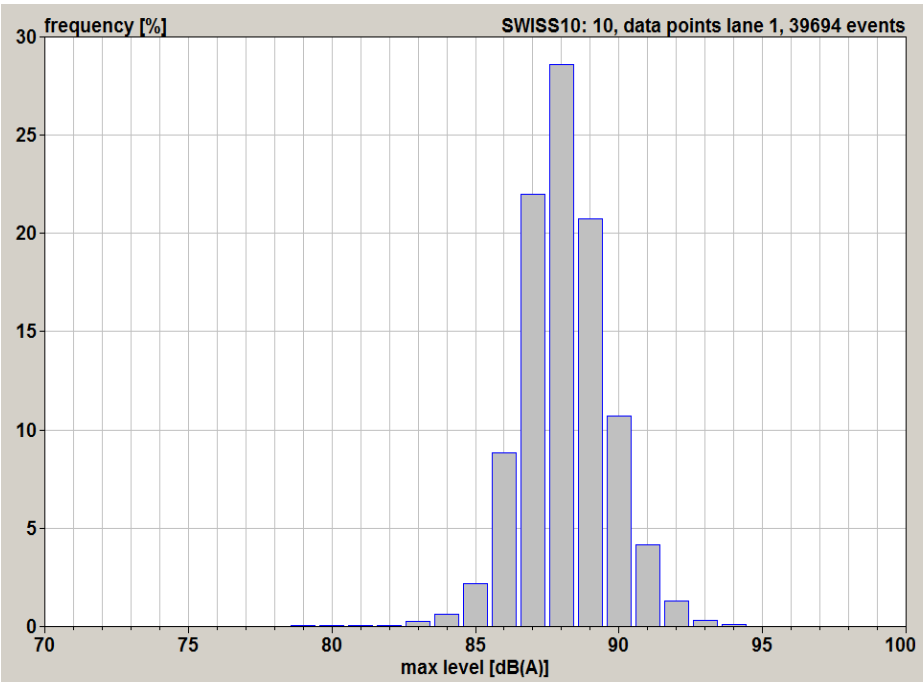

Figure 9 - Histogram showing the distribution of SPL for Swiss category 10 normalized for 80 km/h.

6. Conclusions

The analyzed sample data corroborated reported information that as a result of the introduction of the Swiss heavy vehicle fee, as intended, the vehicle fleet is becoming more environmentally friendly in terms of gaseous emissions and a further massive reduction is foreseeable with the introduction of Euro-VI engine technologies. However noise remains to be an environmental problem. In each vehicle category there is a small percentage of vehicles with high noise emissions and or gross vehicle weight. Any comprehensive bonus/malus program should take this fact into account.

7. Acknowledgements

The authors would like to thank the Federal Office for the Environment and the Federal Roads Office for financially supporting this project and the Federal Customs Administration for providing data.

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BRINGING HEAVY VEHICLE ON-BOARD MASS MONITORING TO MARKET



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Abstract

The Intelligent Access Program (IAP) is a voluntary program which provides heavy vehicles with access or improved access to the Australian road network. In return, heavy vehicles enrolled in the IAP will be monitored by vehicle telematics solutions for compliance with specific access conditions. The IAP is administered by Transport Certification Australia (TCA), on behalf of the Federal, State and Territory governments.

In addition to the administration of IAP, TCA is also involved in a range of regulatory telematics development including Heavy Vehicle On-Board Mass (OBM) monitoring. OBM, also known as on-board weighing, is a technology that monitors heavy vehicle weight using on-board sensors.

This paper provides an update on the Australian Intelligent Access Program and the development of On-Board Mass monitoring.

Keywords: WIM, IAP, OBM, Telematics.

Résumé

Le programme d'accès intelligent (IAP) est un programme qui fournit les poids lourds australiens volontaires avec des accès simples ou des accès privilégiés au réseau routier australien. En échange, ces poids lourds sont surveillés avec des solutions télématiques pour estimer leur obéissance à certaines règles d'accès à ces routes. Ce programme d'accès est administré par la direction australienne de certification, pour le compte des gouvernements fédéraux, national et territoriaux.

De plus, cette direction australienne de certification est impliquée dans une série de développements télématiques pour la surveillance embarquée des charges. En effet, cette technologie appelée OBM (On-Board Mass) permet de surveiller la charge des poids lourds avec des capteurs embarqués.

Ce papier donne des informations sur ce programme d'accès intelligent et le développement du pesage embarqué.

Mots-clés: Pesage en marche, programme d'accès intelligent, pesage embarqué, télématique.

1. Introduction

Heavy vehicle telematics has been heavily used by the private sector over the last twenty years. In recent years, governments have realised the great potential of heavy vehicle telematics and started using it as a tool in their road reform programs. The applications of telematics range from access regulation, driving hours monitoring, to toll collection. In Australia, telematics is used by the governments to improve heavy vehicle road access via the IAP.

The IAP is a voluntary program which provides heavy vehicles with access or improved access to the Australian road network. In return, heavy vehicles enrolled in the IAP will be monitored by vehicle telematics solutions for compliance with specific access conditions. The IAP is administered by TCA.

There are four key players involved in the IAP business model: Jurisdictions, Transport Operators, IAP Service Providers and TCA.

Jurisdictions are owners of IAP Applications which offer benefits for the Transport Operators enrolling with IAP.

A Transport Operator may elect to enrol in one or more IAP Applications as they see the potential benefits. An IAP Service Provider is a commercial third party telematics company which provides IAP services. An IAP Service Provider is engaged by the Transport Operator to monitor heavy vehicles against a set of conditions, and provide Non-Compliance Reports (NCR) to jurisdictions.

TCA was established by the jurisdictions and acts as an independent organisation to administer the IAP and provides certification and audit of the IAP Service Providers. The IAP technology can be broadly described in three components: the in-vehicle-unit (IVU), the IAP-SP System (Back Office), and the jurisdiction system. Figure 1 shows the data flow between these components.

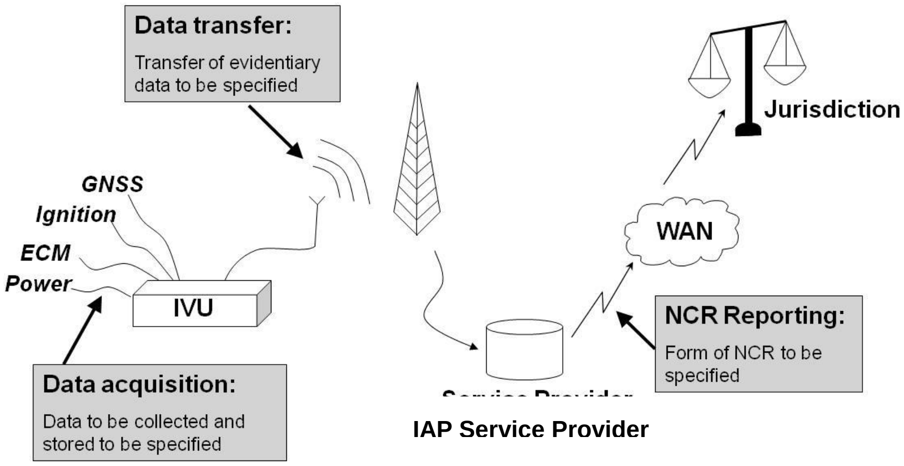

Figure 1 - IAP data flow

The IVU is installed in the vehicle. It collects location, time and speed information about the vehicle (using GNSS), and transmits the information to the Back Office. The IVU is also capable of receiving data from other sources such as on-board movement sensor, mass measurement sensor and driver self declaration and comments.

The Back Office stores the Intelligent Access Map (IAM)[4] as a reference and the Intelligent Access Conditions (IACs) with which the jurisdiction requires the vehicle to be monitored against. After receiving data from the IVU, the Back Office assesses the data against the IAM and conditions, and produces Non-compliance Reports (NCRs) which are sent to the associated jurisdiction.

The jurisdiction system is set up to enable secure and automated receipt of NCRs from IAP-SPs.

2. IAP Applications

Currently there are IAP Applications in five Australian states:

- Since July 2009, New South Wales and Queensland have provided Higher Mass Limits (HML)[5] schemes which allow heavy vehicles to carry additional load above the general mass limits on certain defined routes. IAP is one of the requirements for enrolling HML.

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[4] Intelligent Access Map (IAM) is a map in electronic form issued by TCA as the reference against which compliance with access conditions is assessed.

[5] Higher Mass Limits (HML) is an Australian nationally agreed scheme that permits approved heavy vehicles to operate with additional mass on certain types of axle groups, on a restricted road network and subject to specified conditions. (NTC, www.ntc.gov.au)

- In Victoria, heavy mobile cranes and pump trucks have been required to enrol in IAP since September 2008. Additionally, since April 2010 high productivity freight vehicles have also been required to enrol in IAP.
- From July 2010, South Australia extended HML network to transport operators with enrolment in IAP being one of the requirements.
- In New South Wales, IAP is a requirement for the Road Train Modernisation Program.
- Certain Performance Based Standard (PBS) [6] vehicles across Australia also require IAP as part of the operation conditions.
- In Tasmania with the monitoring of school buses.

As a transport operator, before making a decision to operate a vehicle under a scheme that requires the IAP, one needs to decide if the IAP provides a financial or operational benefit. The IAP may be relevant to a Transport Operator if:

- The business could benefit from carrying more mass,
- The business could benefit from operating longer vehicles,
- The vehicles could gain access to otherwise restricted roads or networks,
- The transport operator could gain benefit from operating with additional trailers,
- The transport operator would like to operate during specific hours,
- The transport operator would like to replace paper-based permits,
- The transport operator would like to be acknowledged as a compliant operator,
- The transport operator would like to demonstrate to customers their commitment to meeting chain of responsibility obligations.

Since the IAP became available, many Transport Operators have been enjoying the benefits it offers.

Barlow Agricultural Pty Ltd, a southern New South Wales based Transport Operator involved in grain production, trading, transport and storage, has been enjoying access to private roads and the HML network. The owner Mr Barlow says the IAP had proven to be a commercially viable proposition. "Operating at HML under IAP has enabled our trucks to increase payload by about 10%". Mr Barlow also suggests that aside from efficiency gains there are safety and environmental gains from operating under IAP. The IAP Service Provider is able to provide a range of commercial services in addition to the IAP services. The operator now can check where their trucks are, whether they are on the correct route, how long have the drivers been driving or resting. The number of truck trips to the operator's major clients has also been reduced by about 10%, and that leads to a direct reduction of emissions. Mr Barlow recommends any truck operator carrying a dense

[6] PBS brings a fresh alternative approach to heavy vehicle regulation. It focuses on how well the vehicle behaves on the road, rather than how big and heavy it is (eg length and mass), through a set of safety, road wear and bridge loading standards. (NTC, www.ntc.gov.au)

product to consider the IAP because it has been shown to deliver safety, productivity and environmental benefits in the business.

Riordan Grain Services, a Victoria based operator transporting grain and fertiliser in bulk, has a fleet of 10 company-owned B-doubles and hires another 30 sub-contractors who also operate B-doubles. The Transport Manager Joe Strawford says that IAP has been delivering benefits even though only about 25% of its business is conducted in New South Wales where IAP is required to gain HML access. The IAP allows Riordan Grain Services to have access to its storage facility at Lake Cargelligo as well as to a range of grain receival sites. The company has also secure access to three sites in Sydney and six in the Newcastle region. Mr Strawford said that they have been using GPS tracking for about six years. Enrolling in the IAP and changing their hardware to IAP compatible ones was purely a commercial decision. While this led to interruptions to the business, the transaction was conducted smoothly and the back office systems and existing fleet management systems were improved. Since enrolling in the IAP, Riordan Grain Services has been able to generate a range of benefits and as a result, has improved the levels of customer service.

The rural city of Dubbo is located in central western New South Wales at the junction of the Newell, Mitchell and Golden Highways. Dubbo, serving as the regional hub for one third of New South Wales, is increasingly the origin and destination of road freight movements. The city's economic growth is underpinned by its excellent transport links. Freight transfer issues arise as it is only possible to run road trains, AB-Triples and B-Triples on some of the New South Wales road network; either on or to the west of the Newell Highway, and there is no access for these vehicles east of the Newell Highway. These larger vehicles are often broken down there into smaller units like B-Doubles to continue their eastward journey and vice-versa on westbound journeys to western Queensland, the Northern Territory, South Australia and Western Australia. The IAP provided the Council with a high level of assurance that transport operators would comply with conditions to access approved routes. For Transport Operators using IAP, the Dubbo City Council has approved requests for HML access on a total of ten routes as well as quad axle access on one route. Better access for HML and quad axle vehicles has had the greatest impact on local livestock carriers, processed meat, grain hauliers, general freight, liquefied petroleum gas, quarried gravel, fuel and bitumen businesses by helping to lift operational efficiency.

Industry feedback has shown that the IAP lifts the standards of telematics and provides positive contribution to fleet management services. The IAP Specification was developed in close consultation with both telematics and transport industries. Therefore, it does not only address a specific public policy outcome, but also the needs of transport industry. The key driver for the program is the expanded network for use by heavy vehicles.

3. On-Board Mass Monitoring (OBM)

A review of the industry capability in OBM was undertaken in 2007, with focus on the current and expected future technologies as well as products and services associated with

OBM (Karl & Han 2007). The review identified two OBM sensors types that are commonly used on heavy vehicles, i.e. air pressure transducers (APT) and load cells as shown in Figure 2. An APT is suitable for vehicles with airbag suspension, while a load cell is designed for vehicles with mechanical suspension. The review also addressed a number of issues including the installation, calibration, operation and maintenance of OBM systems.

An APT measures the pressure in the airbag suspension and converts the pressure reading to a mass value. Note that the pressure in the airbag suspension is proportional to the weight of the axle group (hence the vehicle). A load cell is generally mounted under the turntable (fifth wheel) or above the chassis. A load cell directly measures the weight exerted on it, similar to a bathroom scale.

Figure 2 - APTs (left) and load cell (right)

In 2008, TCA conducted a test program on commercially available OBM systems in Australia. The program received full support from the domestic OBM industry. A total of twelve OBM systems from eight suppliers were tested across five Australian states in the course of seven months, commencing in April and finishing in October 2008. Both APT and load cell based systems were involved in the test.

Accuracy and repeatability of the OBM systems were tested against a static weighbridge as well as an on-board reference system (also an OBM system), by axle group and by gross mass. Multiple load conditions were tested with each system to examine their accuracy at different weights. Measurements were taken on level (flat) ground with the vehicle's brakes off and engine running. The overall results were positive. All systems tested provided an accuracy of ± 500kg for any axle group when compared to the weighbridge. This accuracy is equivalent to ± 2.5% on a 20 tonne axle group. The result is depicted in the box and whisker plot in Figure 3 (Karl et al 2009).

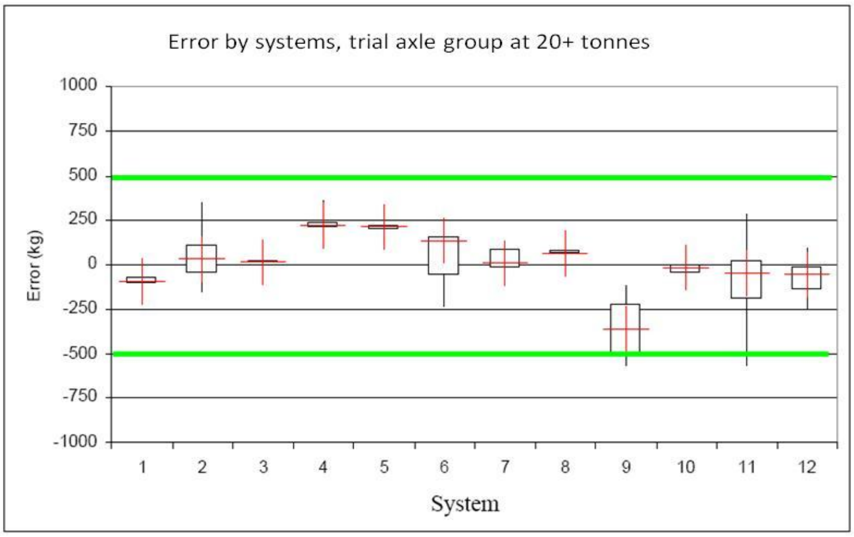

Figure 3 - Accuracy of OBM systems (Karl et al 2009)

Since an OBM system is installed on-board the vehicle, it is possible to continuously capture the weight even when the vehicle is moving. A study on the dynamic OBM measurement was also carried out with an aim to develop quality indicators for static OBM measurement.

In the commercial world, OBM systems have been used as an aid to the driver in making sure that the vehicle is within its legal mass limits. In this case, it is in the driver's best interest to take an accurate measurement using the OBM system. However if deployed in a regulatory environment there may be an incentive for drivers to seek to obtain misleading measurements (by tampering with the system or violating operation procedure). Therefore, quality indicators are critical as a measure of the integrity of OBM data.

Figure 12 shows an example of dynamic OBM data captured during the test. The data was captured at a frequency above 40Hz.

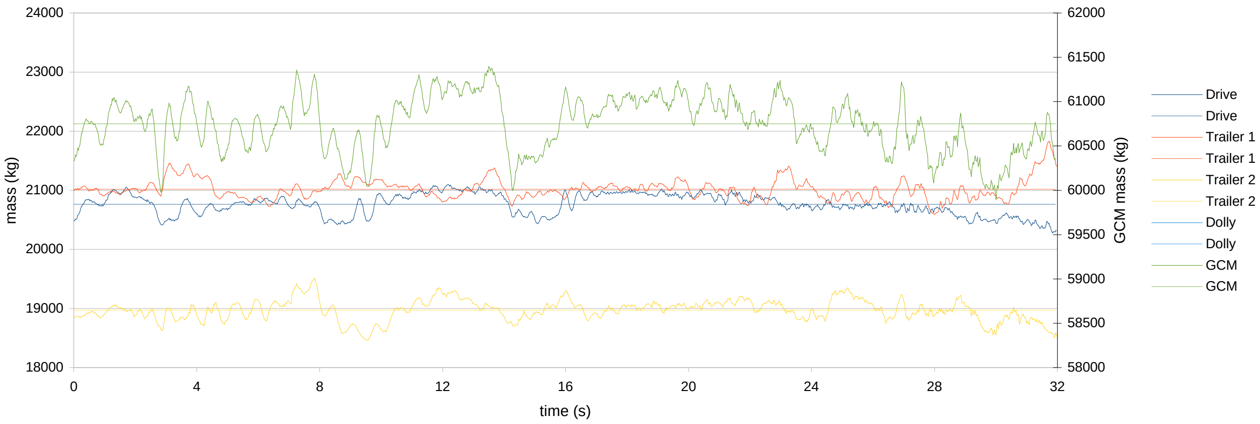

Figure 12 - Dynamic OBM data (Karl et al 2009)

It was observed that while the dynamic OBM data shows much fluctuation, and any instantaneous measurement may not provide useful information, many instantaneous measurements over a period of time can be averaged to provide an estimated static measurement. Under this observation, analysis was undertaken in averaging dynamic data and it was found that the 30 second average of dynamic data was able to provide an accuracy of ± 750kg.

Another investigation was carried out on the body bounce frequency of the vehicles. By assuming that road input is approximately equivalent to white noise in the frequency band of interest, it is possible to estimate the frequency response function of the system from analysis of the OBM system measurements. From this, it is possible to identify fundamental frequencies of the system, including the body bounce and axle hop frequencies. The body bounce frequency is most prominent and is fundamentally related to vehicle mass, but in a way that is completely independent of the magnitude of the measurement (Karl et al 2009).

The body bounce frequency is given approximately by:

$$f = \sqrt{(k/m)}$$

where f is the body bounce frequency, k is the airbag stiffness and m is the sprung mass on that suspension. The airbag stiffness, k, can be considered a constant as it depends only on the diameter of the airbags. Consequently, the frequently can be used to determine the mass and would be expected to vary with the square root of mass ratio. That is, if mass doubles, frequency would be reduced by a factor of $\sqrt{2}$ (Karl et al 2009).

This theory is demonstrated by a frequency analysis of dynamic OBM data as shown in Figure 5. It can be seen that as the load decreases, the peak body bounce frequency increases.

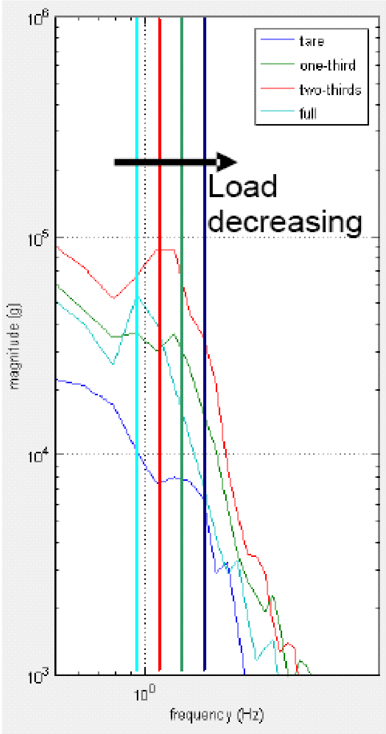

Figure 5 - Frequency shifts with changing mass (Karl et al 2009)

With the learning from the feasibility study, TCA developed a draft OBM specification in August 2009 (Karl & Cai 2009). The specification covers a range of requirements including accuracy of OBM systems, quality indicators, and procedures for installation, calibration, operation and maintenance.

In 2010, the National Measurement Institute (NMI) of Australia conducted a review on the draft OBM specification developed by TCA. NMI is the national body which approves measurement equipment for trade.

NMI in their review acknowledged that "The Specification establishes a very detailed and comprehensive set of requirements in relation to records related to the OBMMS (i.e. OBM monitoring system) and its relationship to the IAP, however it appears that there is a lack of detail particularly in regard to calibration procedures. It is possible that it is intended that the detail would be left to each OBM supplier and this may be adequate for uses not requiring trade/legal approval – however for trade use much more detailed procedures would be required. These would be dependent on the maximum permissible errors and test procedures decided, however it is expected that they would include matters such as the calibration status (traceability) and characteristics of the weighbridge used (e.g. scale interval relative to that of the OBMMS). It is also expected that testing at more than just empty and full conditions would be required." (NMI 2010).

NMI also acknowledged that "Although this report is aimed at the use of the OBMMS for static measurement (vehicle stationary), it is noted that The Specification includes provision for the collection of dynamic data, with the intention of potentially using this data as an additional means to identify possible tampering with the equipment, fraudulent activity (e.g. wedging to prevent the full load being applied to the OBMMS), or simply determining that equipment requires maintenance. NMI does not have previous experience with such an approach, but it does seem a worthwhile idea to pursue in the OBMMS context." (NMI 2010).

4. OBM Trials

Since the draft OBM Specification was developed, opportunities for Jurisdictions to initiate trials have emerged as higher productivity can be offered due to OBM instrumented vehicles affording jurisdictions greater confidence in heavy vehicle mass compliance.

In December 2010, Queensland Department of Transport and Main Roads (TMR) made a decision to approve the operation of Performance Based Standard (PBS) 2B vehicles (an example of these vehicles is shown in
Figure) on the route from Port of Brisbane to Toowoomba, with IAP and OBM as part of the conditions. This transport route is particularly important to the regional Queensland economy. The approval of PBS 2B vehicles operation on this route is expected to bring big benefits for industry, the community and the environment. Transport Operators can now carry up to two 40 foot containers on a PBS 2B vehicle whereas previously they could only operate on a single combination. Modelling undertaken by TMR has indicated that a Transport Operator would have needed to make 4,800 trips between Toowoomba and the Port of Brisbane to carry 120,000 tonne per annum. With PBS 2B vehicles, those trips could be reduced by up to 50% to 2,400 trips. Chairman of the Queensland Transport and Logistic Council, Neil Findlay, has supported and welcomed the decision, and acknowledged that this is a prime example of how government and industry can work together to deliver significant improvement in the freight sector (TCA, www.tca.gov.au).

Other Australian jurisdictions are also investigating OBM trials on other vehicles including buses.

Figure 6 - PBS 2B vehicle

5. OBM Data Analysis[7]

Since OBM trials were deployed, data has been collected from systems installed on operational vehicles.

Based on data collected from one truck and two buses installed with APT based OBM systems, TCA has performed a series of analysis attempting to identify any operational issues. Data used in the analysis are 30 second averages of high frequency dynamic OBM data including also GPS location and speed.

It was found that although the data generally agreed with the actual operational situations, filtering (or cleaning) of data is required in order to remove noise.

The basic assumptions for data filtering are:

- When a vehicle moves at low speed, it implies that frequent brake applications might have occurred. This in term affects the air pressure supplied to the airbag suspension system and hence the OBM system's APT(s) is not able to measure the correct air pressure.
- A vehicle cannot be loaded and unloaded in a short period of time (e.g. 30 seconds). Hence a single OBM reading that is significantly different from a series of consecutive readings may be caused by certain vehicle operations and does not represent a reliable value of vehicle mass.

Based on the above assumptions, two filtering processes were created:

1. Filtering of data with vehicle speed < 20 km/h (vehicle speed determined by GPS)
2. Filtering of data which is significantly different from the preceding and succeeding data.

The filtering processes were found to be effective in improving the data quality for all three vehicles. An example is shown throughout Figure 7, Figure and Figure 9. Figure shows all data collected for the truck for one day. Figure shows the data with speed < 20 km/h removed. Figure 9 shows the data with spikes further removed.

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[7] These data were provided to TCA for research purposes.

Figure 9 also clearly identifies three round trips the truck conducted between the mill and the port. The truck can legally transport a total combined mass (including the truck) up to 78 tonnes. Area A in Figure shows the mass (78 tonnes) of the truck carrying two fully loaded containers from the mill to the port. Areas B, C and D show the return trips from the port to the mill. It was observed that the truck carried a higher mass in trip B than in trip C and D.

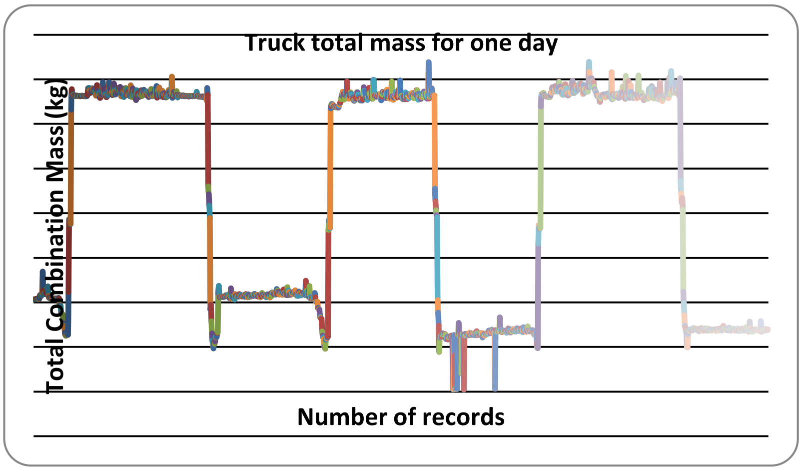

Figure 7 - Truck total mass data at 30 second interval

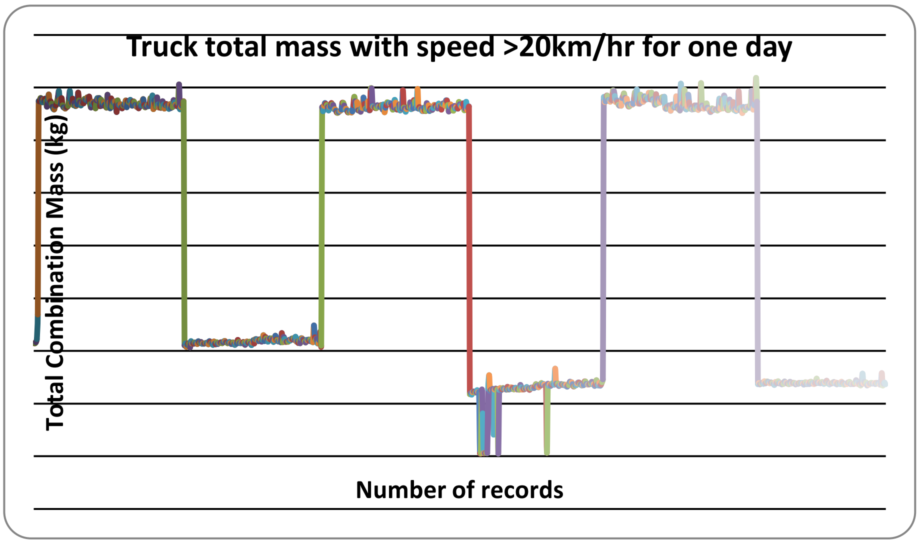

Figure 8 - Truck total mass for speed >20km/hr

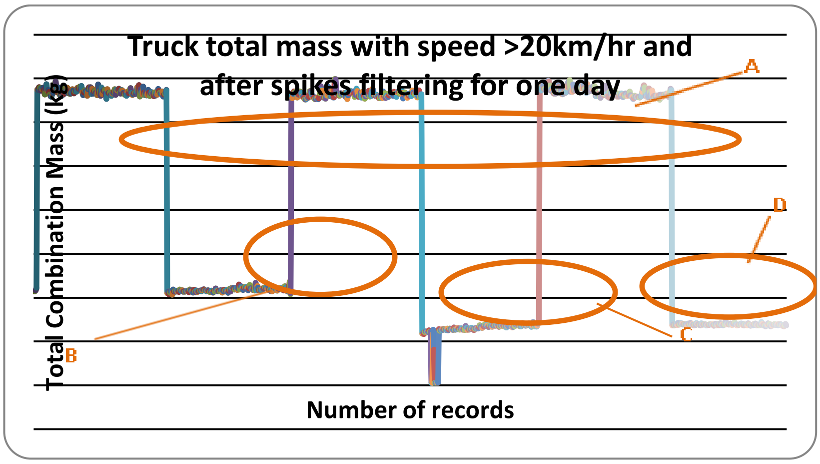

Figure 9 - Truck total mass with speed >20km/hr and after spikes filtering

One possible reason for this observation is that the truck might carry one empty container in trip B, and carry no container in trip C and D. At the beginning of trip C, it was also observed that a couple of downward spikes which went under the tare mass (about 22 tonnes) of the vehicle remained after the filtering processes. One reason for this could be that at the beginning of the trip the airbag suspensions were not inflated to the default operating level.

Furthermore, it was found that the accuracy of the OBM system was in alignment with the Draft OBM Specification.

The data for the two buses were also investigated to validate their operational behaviours. Figure 10 shows a full day of data from a trip bus which transported people and luggage between two fixed points. Unlike a truck, a trip bus can be expected to carry different numbers of people and different amounts of luggage in any single trip. Hence, the vehicle mass varied in all trips. Areas E and F in Figure 10 show two trips with relatively high mass.

Data collected from a route bus were also investigated. A route bus operates on a fixed route with many stops along the route. Passengers get on and off at each stop so that the mass of the bus can be expected to be almost random at any time, except at peak hours when the bus is usually at full. Figure 11 shows this unique behaviour of a route bus.

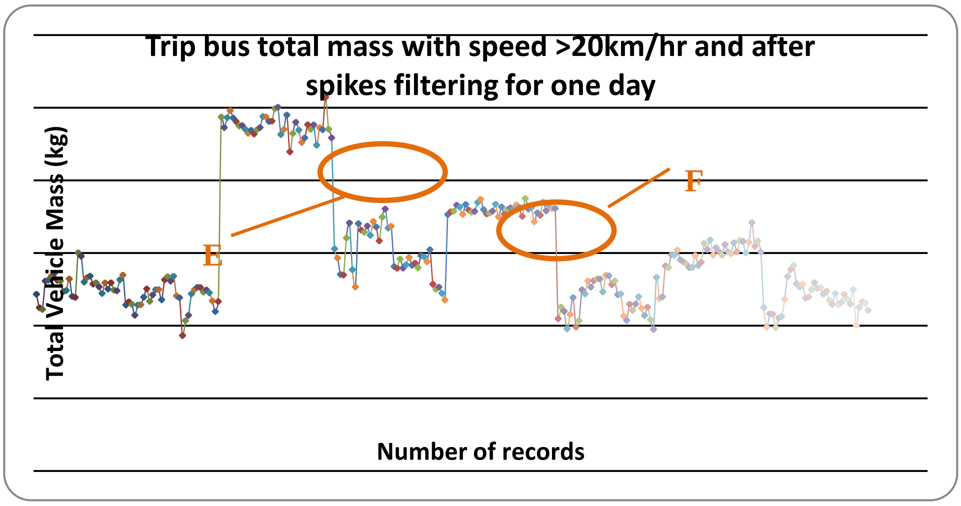

Figure 10 - Trip bus total mass with speed >20km/hr and after spikes filtering.

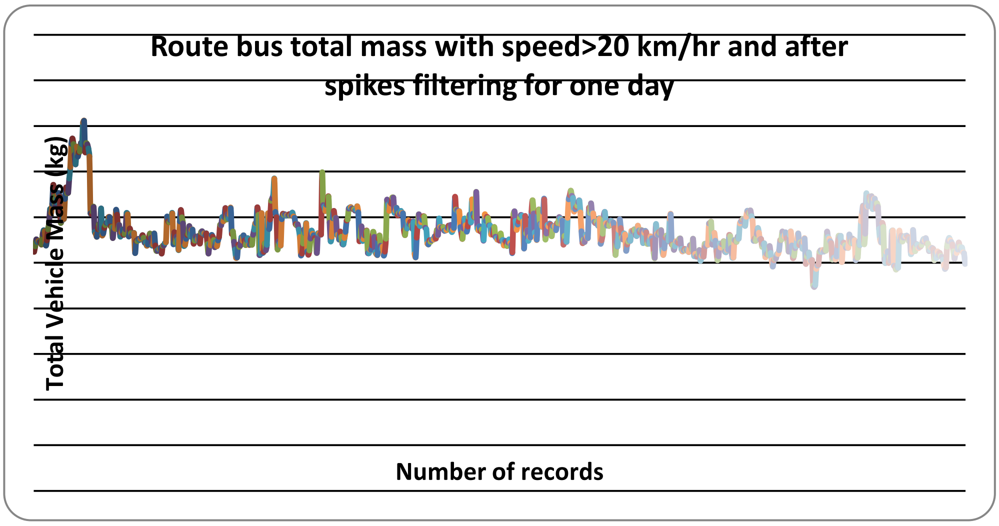

Figure 11 - Route bus total mass with speed >20km/hr and after spikes filtering.

6. OBM and WIM

There are many similarities between OBM and on-road Weigh-in-Motion (WIM). For example, both technologies measure heavy vehicle mass (or weight) without stopping the vehicle and hence reduce the inefficiency in compliance checking. However, compared to WIM, OBM has a number of unique aspects:

- OBM can provide continuous mass monitoring of vehicle,
- OBM can provide mass monitoring regardless of the vehicle location,
- OBM can provide higher accuracy (if procedures are followed),
- OBM stays with the vehicle, hence tamper monitoring is required for regulatory use,
- Calibration of OBM needs to be regularly verified. The period of verification typically varies from three to twelve months depending on the operating environment.

It is important to notice these differences and realise the great opportunities in integrating the two technologies. There are presently more than 150 WIM sites throughout Australia, given the WIM data and potentially the OBM data through IAP will be made available to the regulator for analysis, these system lend them selves to the performance of a corroborative function.

Operationally, the potential exists for multiple OBM installed vehicles passing a WIM site to be used to calibrate and/or verify the WIM equipment. Conversely a WIM site may be used to identify potential faulty or tampered OBM systems, i.e. if only one vehicle reports OBM data that is significantly different from the WIM data, further investigation on this vehicle may be initiated.

7. OBM Calibration and Verification

Development of OBM system calibration procedures remains the domain of the OBM system providers; this practice permits those familiar with the design and operation of the systems to detail installation and calibration procedures. TCA has drawn learning from present and past operational pilots when specifying appropriate frequencies for the calibration and verification of various OBM system types given their particular operating models; for example the PBS application studied in this paper requires the OBM systems to be recalibrated at 3 monthly intervals when deployed under normal operation circumstances.

To achieve ‘pattern approval’ (endorsement) for the OBM systems from the National Measurements Institute Australia (NMI) it becomes necessary to implement procedures for the licensing of testers to perform ‘verification’ inspections of the OBM systems in operation. These verifications are periodic tests conducted under controlled circumstances and within specified intervals. Such physical examinations are complimented by public weigh bridge certificates which are issued to the vehicle combinations as requirements for either a commercial (sales and trade) or a regulatory (a requirement of a road network access scheme e.g. the Concessional Mass Limits Scheme) application. The network of WIM sites, particularly those installed alongside number plate recognition equipment, serve as a secondary verification checks.

8. Next Steps – Taking OBM to Market

The use of heavy vehicle OBM monitoring as a regulatory enabler by jurisdictions has advanced with the commencement of operational pilots and limited trials in several Australian jurisdictions, including Queensland, New South Wales and Victoria. A nationally recognised framework for the delivery of OBM provides national policy makers with the ability to address their own policy requirements while leveraging a consistent operational approach to remove complexity, improve efficiency and drive safety and productivity gains in the use of the road network.

TCA is presently extending the IAP to include mass monitoring utilising OBM systems. The integration leverages the same infrastructure and operating environment that jurisdictions have become familiar with in operating their current IAP access applications. TCA will develop the necessary systems, processes, documentation and resources to perform the type-approval of OBM systems where an IAP Service Provider (IAP-SP) can be recertified for either: the delivery of IAP Services with OBM or type-approval of OBM systems for non-IAP commercial applications.

The implementation allows OBM to be delivered by existing IAP-SPs or by new Applicants who choose to enter the program and offer OBM services in the regulatory environment. Revising the performance based IAP Specification to include OBM functionality necessitated new provisions for:

- Interoperability of OBM systems,
- Trailer & configuration identification,
- Detection of physically (yet not electrically) connected trailers,
- Provisions for tamper detection.

Forging interoperability between the various OBM systems and existing in-vehicle units has some challenges. Industry has shown some leadership in this area by forging alliances between respective parties from both the telematics and scales sectors. Interoperability has already been established between a subset of the providers who have participated in trials. TCA is presently working with industry to ensure performance based interoperability requirements can be incorporated into the revised OBM specification.

Trailer & configuration identification is an important requirement for the program. A consideration for jurisdictions when permitting heavy vehicle access to their networks is vehicle configuration and carried mass. There are many local examples where applicable vehicles may be unladen yet incapable of negotiating segments of a network due to the configuration's physical length or breadth. A by-product of an OBM system currently being investigated is its ability, in some cases, to 'automatically' identify the vehicle configuration; achieved through the cross-communication of the axle group sensors and the OBM control unit. Such functionality serves to identify the configuration and order of trailer connection.

Detection of trailers physically connected to the prime mover is of importance for configuration identification, assurance in compliance monitoring, and potentially for tamper detection. TCA continues to work with industry to ensure a robust solution can be specified, current thinking leverages from existing best practice such as the application of security seals and the automated monitoring of connections through to the dynamic monitoring of chassis frequencies.

It is expected that two reviewed specifications will be delivered by TCA in 2012. The first specification, an update of the IAP Functional and Technical Specification, now expanded to incorporate OBM functionality, forms the reference for certification of new applicants and also for recertification of existing IAP-Service Providers to deliver OBM services. The second will be a stand-alone specification of OBM systems which will detail the requirements which need to be met for TCA type-approval – for commercial applications.

9. Conclusion

The Intelligent Access Program (IAP) serves as a nexus between the needs of the road transport industry - improved access, reduced trip times, higher permitted loads and the requirement of road authorities and government to protect their infrastructure assets, and the industry compliance needed to achieve this. The development and application of regulatory On-Board Mass (OBM) Monitoring enhances the use of IAP and provides further benefits for both the government and industries. OBM also has a great future in complementing on-road WIM to provide better visibility of vehicle mass.

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APPLICATION OF THE CENTER OF GRAVITY MEASUREMENT BASED ON THE DYNAMIC WHEEL LOADS MEASUREMENTS OF VEHICLES

    

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Abstract

Generally, the driver of a semi-trailer truck does not know the spatial distribution of freight inside a marine transport container. Sometimes the semi-trailer truck turns sideways due to dislocation of the freight, thereby causing a social problem in Japan. Considering that there should be a device to detect dislocation of the freight through measurement of dislocation of the centroid of truck, the authors conducted running tests by utilizing KYOWA LS-WIM technology. The results enabled authors to verify that a 3-dimensional position of the centroid of a running truck can be obtained by weighing wheel loads and calculating a slight inclination between the loads. This paper reports dynamic measurement of the centroid of a running truck.

Keywords: Centroid (center of gravity), 3-dimensional measurement, Wheel loads, Axle load, Inclination angle.

Résumé

Généralement, le chauffeur d'un poids lourd à semi-remorque ne peut pas appréhender les conditions du chargement à l'intérieur d'un conteneur maritime. Parfois la semi-remorque se renverse à cause d'un déplacement du chargement, ce qui pose des problèmes sociaux au Japon. Il devient alors nécessaire de disposer d'un moyen de détection du déplacement du chargement par une mesure du centre de gravité du poids lourd. Les auteurs ont réalisé un essai avec la technologie de pesage à basse vitesse de Kyowa. Le résultat a permis aux auteurs de vérifier que la position en 3 dimensions du centre de gravité d'un poids lourd en mouvement pouvait être obtenue en pesant les roues et en calculant les faibles écarts entre ces charges. Cet article présente des mesures dynamiques du centre de gravité d'un poids lourd en marche.

Mots-clés: Centre de gravité, mesures en 3 dimensions, charges de roue, charge d'essieu, angle d'inclinaison.

1. Introduction

In land transport, overload or dislocation of the freight causes accidental hazards such as dropping of the freight or causing the vehicle to turn sideways. An overload can be checked by a conventional general WIM device. However, to prevent a truck from turning sideways, it is required to let the driver recognize the truck's centroid position so that he/she may pay attention to the running speed on a curved road. The centroid position can easily be obtained by weighing wheel loads and calculating them. The authors conducted the tests described in this paper where wheel loads of a freight transport truck were weighed with the LS-WIM system and the centroid position was calculated for verification.

2. Centroid Measurement Principle

2.1 Method of Calculating Lateral Centroid Position of Truck under Horizontal Status

Through comparison between left and right wheel load waveforms and measurement with the wheel load weighing system, a relation between left and right wheel loads is as expressed in Equation (1):

$$W_L = aW_R \tag{1}$$

where, W_L: Left wheel load, W_R: Right wheel load, a : Ratio of W_L to W_R

For the lateral dislocation of the centroid position from the center of the tire tread, suppose the tread position is l_T. Then, the centroid position, C_l, of each axle from the center of the tread is as expressed in Equation (2):

$$C_l = \frac{W_L}{W_L + W_R} \times l_T - \frac{l_T}{2} \tag{2}$$

Substitute Equation (1) into Equation (2). Then, the centroid position of each axle is as expressed in Equation (3):

$$C_l = \frac{a}{a+1} \times l_T - \frac{l_T}{2} = \frac{a-1}{2(a+1)} l_T \tag{3}$$

The centroid position of a 2-axle truck is as shown Figure 2 and Equation (4):

$$C_i = \frac{\frac{a_1 - 1}{2(a_1+1)} l_{T1} \times W_{a1} + \frac{a_2 - 1}{2(a_2+1)} l_{T2} \times W_{a2}}{W_{a1} + W_{a2}} \tag{4}$$

Similarly, the centroid position of an n-axle truck is as expressed in Equation (5):

$$C_l = \frac{\sum_{i=1}^{n} \left(\frac{a_i - 1}{2(a_i+1)} l_{Ti} \times W_{ai} \right)}{\sum_{i=1}^{n} W_{ai}} \tag{5}$$

where, a_i: ratio of left wheel load to right wheel load of each axle, l_{Ti}: tread location of each axle, W_{ai}: axle load.

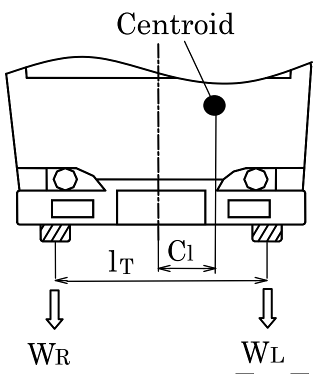


Figure 1 - Lateral Centroid Position

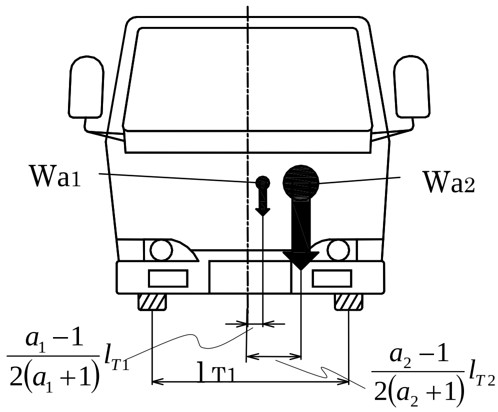


Figure 2 - Lateral Centroid Position of 2-Axle Truck

2.2 Method of Calculating Longitudinal Centroid Position

The longitudinal centroid position, Cl, comes at the position where front and rear axle loads are balanced.

Suppose the reference position is put at the last rear axle. Then, Cl of 2-axle truck shown in Figure 3 is as expressed in Equation (6), and Cl of n-axle truck is as expressed in Equation (7).

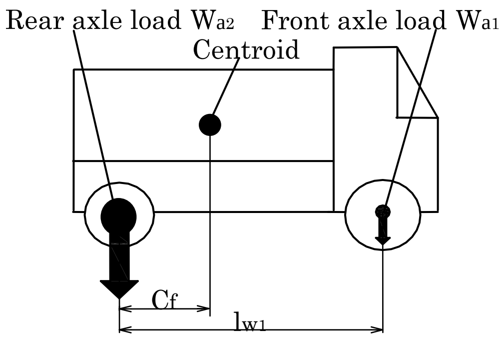


Figure 3 - Longitudinal Centroid Position

$$C_f = \frac{W_{a1}}{W_{a1}+W_{a2}} l_{W1} \quad (6)$$

$$C_f = \frac{\sum_{i=1}^{n-1}(l_{Wi} \times W_{ai})}{\sum_{i=1}^{n} W_{ai}} \quad (7)$$

2.3 Method of Calculating Lateral and Vertical Centroid Positions

Suppose an inclination angle of a running truck on a flat road surface is θ_0, that on a road sloping from the left viewed from the running direction is θ_1, and that on a road sloping from the right is θ_2 (see Figure 4). Then, the lateral centroid positions of the truck running on roads sloping from the left and right are C_{l1} and C_{l2}, respectively, in place of C_l in Equation (5). Using these parameters θ_0, θ_1, θ_2, C_{l1} and C_{l2}, lateral centroid position, C_{lN}, and vertical centroid position, C_h, of the truck running on a flat road surface are calculated as follows.

$$C_{lN} = \frac{C_{l1}\tan\left|\theta_2-\theta_0\right| + C_{l2}\tan\left|\theta_1-\theta_0\right|}{\tan\left|\theta_2-\theta_0\right| + \tan\left|\theta_1-\theta_0\right|} \quad (8)$$

$$C_h = \frac{C_{lN} - C_{l1}}{\tan|\theta_1 - \theta_0|} = \frac{C_{l2} - C_{lN}}{\tan|\theta_2 - \theta_0|} \qquad (9)$$

$$C_h = \frac{C_{l2} - C_{l1}}{\tan|\theta_2 - \theta_0| + \tan|\theta_1 - \theta_0|} \qquad (10)$$

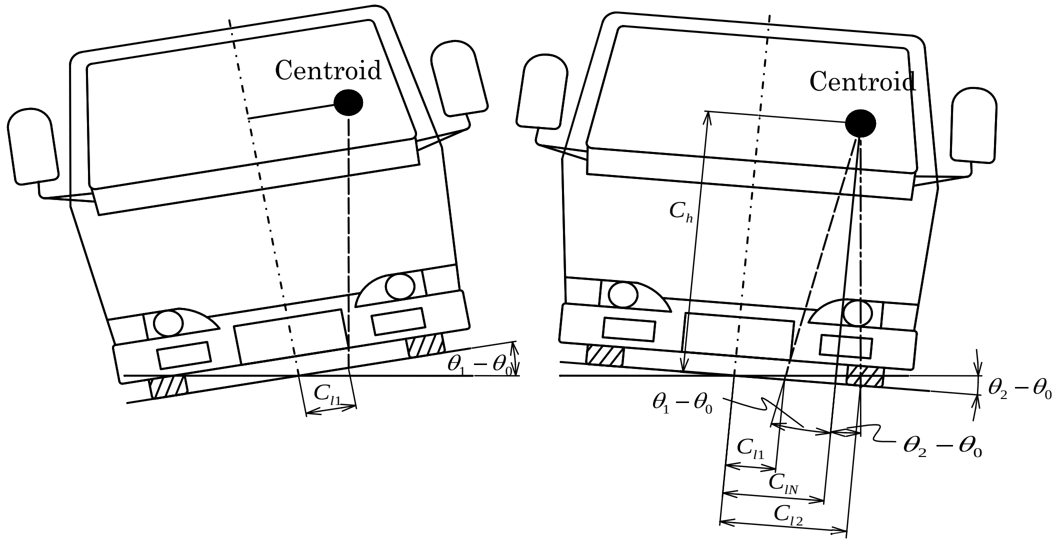


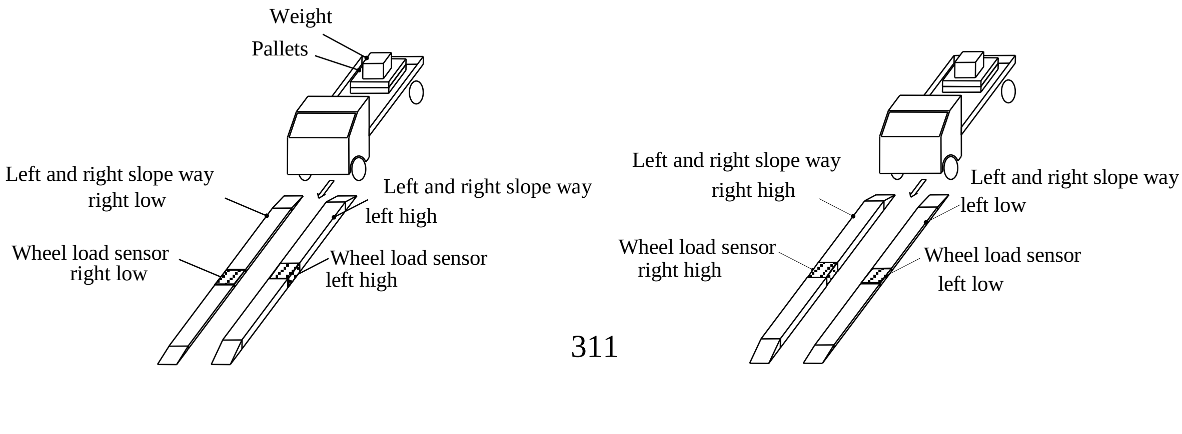
Figure 4 - Lateral and Vertical Centroid Positions

In Figure 4, C_{l1} and C_{l2} are distances between the center of the inclined truck and the point that the vertical line drawn from the centroid position crosses the sloping road surface. C_{lN} is the distance between the center of the uninclined truck and the point the vertical line drawn from the centroid position crosses the flat road surface.

3. Test Method

3.1 Loading Method

As shown in Figure 5, the test system consists of 2 sets of 2 LS-WIM ways. To weigh wheel loads, plate-type sensors are installed one each to the left and right ways which are different in level. The truck runs on the ways while slightly inclining. The reason for 2 types of left-right slope ways in different levels is to obtain a larger difference in the 2 inclination angles. Sensors installed one each on the left and right ways weigh wheel loads to detect the load difference caused by an inclination of the truck and based on the result the centroid positions in lateral, longitudinal and vertical directions are calculated. The vehicle subjected to the test was a 2-axle truck. As shown in Figure 6, the truck was loaded with one or more 150-mm thick pallets and a 1-ton weight at the top to vary the centroid position in the vertical direction.



Test ways of which the left is high in level viewed from the running direction

Test ways of which the right is high in level viewed from the running direction

Figure 5 - 2 Sets of 2 Centroid Measuring Ways with Wheel Load Sensor

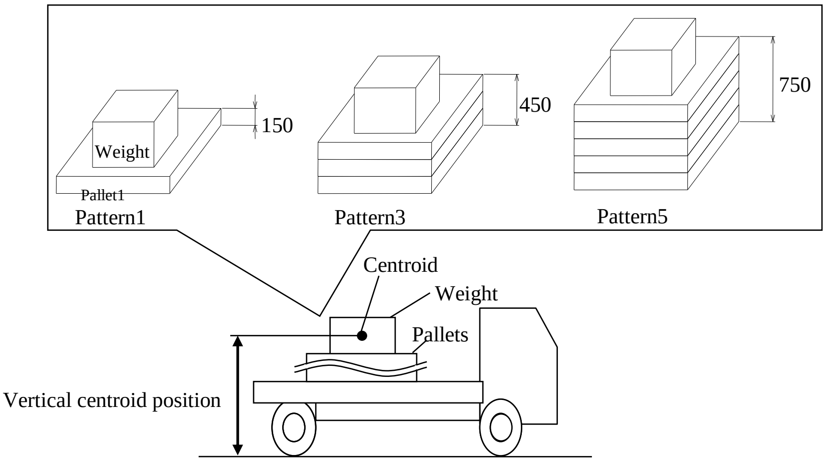


Figure 6 - Loaded Conditions of Test Truck

The number of the loaded pallets and the corresponding centroid positions of the weight are shown in Table 1.

Table 1 - Loaded Conditions and Measured Centroid Positions

	Loaded Condition	Vertical Centroid Position
Pattern 1	1-ton weight+150-mm thick pallet× 1	1154mm
Pattern 3	1-ton weight+150-mm thick pallet× 3	1454mm
Pattern 5	1-ton weight+150-mm thick pallet× 5	1754mm

3.2 Method of Calculating Centroid

Calculating Lateral Centroid Position

Lateral centroid positions, C_{11} and C_{l2}, are calculated by inputting weighed loads to left and right wheels of each axle under the conditions where the truck is inclined by θ_1 and θ_2, and the tread location is found from Equation (5). Lateral centroid position, C_{lN}, is calculated by inputting C_{l1} and C_{l2} and measured inclination angles, θ_1 and θ_2, in Equation (8).

Calculating Longitudinal Centroid Position

The longitudinal centroid position of the truck is calculated by inputting each axle load, W_{ai}, and a wheel-based distance between axles, l_{wi}, in Equation (6).

Calculating Vertical Centroid Position

The vertical centroid position, C_h, is calculated by inputting lateral centroid positions, C_{l1} and C_{l2}, under the conditions the truck is inclined by θ_1 and θ_2, and lateral inclination angles, θ_1 and θ_2, in Equation (10).

3.3 Verification Method

It is difficult to determine a reference centroid position of a truck loaded with complicated freight. Thus, the authors evaluated the propriety of centroid calculation methods described in 3.2 as follows.

The centroid position of the stationary loaded truck was compared with that of the running truck to evaluate accuracy of centroid position measurement in motion.

Practically, the loaded weight compresses the suspension spring of the axle, thereby letting the truck body decline. But to eliminate complication, the effect of such the decline is not included for calculation in this paper.

4. Test Results

Table 2 and Figure 7 show the calculated vertical centroid positions of a loaded truck under stationary and running conditions. With all load patterns of 3 different vertical positions, calculated results with the stationary truck are approximately the same as those with the running truck.

Table 2 and Figure 8 show the calculated vertical and lateral centroid positions with the weight-loaded running truck. With 3 load patterns of different vertical weight positions, the lateral centroid positions vary only by 30 mm or so. Only with pattern No. 3 did changing the loading condition in lateral direction change the calculated centroid position.

The calculated vertical centroid position of the Pattern 3 eccentricity is higher than that of the Pattern 3. The authors think that the loaded weight of the Pattern 3 eccentricity compresses the suspension springs more than Pattern 3 since the weight is not loaded on the center of the truck.

Table 2 and Figure 9 show calculated vertical and longitudinal centroid positions for the running truck. With 3 load patterns of different vertical weight position, the longitudinal centroid positions are virtually identical. The calculated longitudinal centroid position of the Pattern 3 eccentricity is equal to that of the Pattern 3. The authors think the reference positions of the Pattern 3 eccentricity and Pattern 3 are not changed since the loaded weight equally compress the suspension springs of the front and rear axles.

Table 2 - Calculated 3-Dmensional Centroid Positions with Weight-Loaded Running Truck

	Vertical Position		Lateral Position Running Condition	Longitudinal Position Running Condition
	Stationary Condition	Running Condition		
Pattern 1	620mm	484mm to 526mm	-60mm to -58mm	1255mm to 1263mm
Pattern 3	727mm	681mm to 688mm	-76mm to -72mm	1248mm to 1255mm

Pattern 3 Eccentricity	776mm	714mm to 800mm	44mm to 46mm	1254mm to 1264mm
Pattern 5	925mm	781mm to 912mm	-89mm to -87mm	1252mm to 1253mm

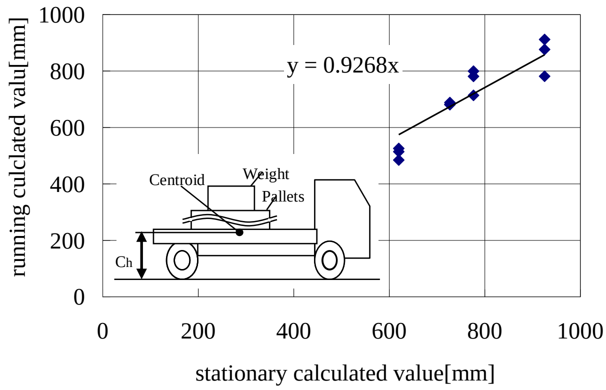


Figure 7 - Calculated Vertical Centroid Positions of Loaded Truck under Stationary and Running Conditions

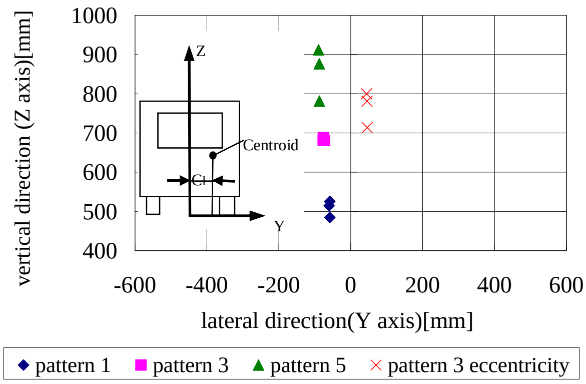


Figure 8 - Calculated Vertical and Lateral Centroid Positions with Weight - Loaded Running Truck

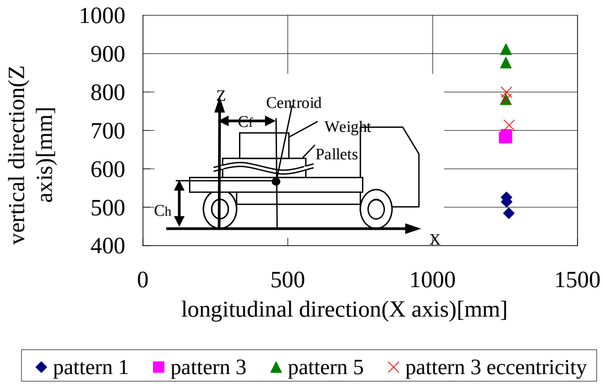


Figure 9 - Calculated Vertical and Longitudinal Centroid Positions with Weight-Loaded Running Truck

Suppose the accuracy of the wheel load sensor is 0.01 tons. In the aforementioned Equation (2) , W_L and W_R were varied from the reference values in a range of ±0.01 tons to vary the lateral centroid position, C_l. Then, the vertical centroid position was calculated using Equation (10). Table 3 shows the resulting errors.

Table 3 - Vertical Centroid Position Errors Caused by Accuracy of the Wheel Load Sensor

	Error Range of Vertical Centroid Position
Pattern 1	-174mm～+174mm
Pattern 3	-168mm～+168mm
Pattern 3 Eccentricity	-168mm～+168mm
Pattern 5	-161mm～+161mm

5. Conclusion and Future Subjects

Calculated centroid positions of the truck changed at a certain ratio according to varied weight loading positions in the vertical or lateral direction. The test results are virtually identical for both stationary and running conditions, indicating that centroid position measurement is possible with running trucks. Future subjects may be as follows:

(1) Automated measurement of the inclination angle of the truck
(2) Accumulation and verification of data through use of heavier trucks for improved accuracy
(3) Tests with multi-axle trucks and container-loaded trailers

The tested presented in this paper revealed that LS-WIM technology enables 3-dimensional measurement of the centroid position of a truck. For the practical use of the measuring method, it is required that the truck safely pass the weighing left and right ways, and the inclination angle of truck can be made as large as possible. To satisfy these requirements, the most suitable inclination angle of truck should be determined and the plate-type sensor installation condition should be decided. A future subject is planned to verify centroid position measurement with heavier trucks based on these requirements.

The authors will conduct further research and development of weigh-in-motion technology, aiming at construction of a freight vehicle monitoring system that can contribute to effective prevention of sideways turning of container transport vehicles based on centroid position and load information.

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SENSORS TEST AT THEIR POSSIBLE FAILURE IN THE ARRAY AND ITS REDUCED TOPOLOGIES FOR THE ACCURATE WIM METHODS

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Abstract

Research and development engineering for the weigh-in-motion (WIM) technology equipment requires that algorithms be implemented in the equipment. The methods by which the equipment is tested in our R&D team is more applicable to accurate enforcement and toll-by-weight functions than to statistical volume data collection for traffic evaluation and its control. The test site used in this paper is described and evaluated according to the COST 323 criteria as an excellent one. The sensor array configuration is important and determines the accuracy level of the equipment. The paper describes a test developed with the goal of considering possible reduction of sensors in the sensor array in case of their failure. It is significant which sensor fails as well as its location in the array. This influence can be seen from the results.

Keywords: Weigh-in-motion, algorithms implemented in the equipment, sensor array configuration, accuracy level, reduction of sensors, sensor failure.

Résumé

La recherche et le développement dans le domaine du pesage en marche (WIM) requiert des algorithmes implantés dans l’équipement. Les méthodes avec lesquelles notre équipe de R&D teste notre équipement sont adaptées pour les applications telles le contrôle des surcharges et les péages proportionnels aux poids total en charge. Le site test utilisé est décrit dans ce papier ; il est évalué comme étant excellent suivant le COST323. La configuration et la répartition des capteurs sont des critères importants et conditionnent la précision du système. Le papier décrit un test considérant une possible diminution du nombre de capteurs, en supposant l’échec de l’un d’entre eux. L’influence est différente si le capteur supprimé est celui qui dysfonctionne, ou un autre. Les tests prouvent cela.

Mots-clés: Pesage en marche, algorithmes implantés dans l’équipement, configuration des capteurs, niveau de précision, diminution des capteurs, dysfonctionnement des capteurs.

1. Introduction

When new equipment is being introduced at the WIM measuring site, there is usually not discussion what the user shall do in case of the failure except having contacting the supplier. However, repair can take long time and it is an interesting question whether the site can provide relevant results despite the failure or reduced operational capability. The answer could be provided if the user is aware of accuracy level in the specific failure situation. The relation of cost and value to the decision of the urgency of the repair might be considered using published information (e.g. WIM Handbook (1997)).

On our WIM test site, in one lane, four piezoelectric Kistler Lineas sensors have been applied in the array and measured in the 2+2 full configuration and the 2+1, 1+2, 1+1a, 1+1b and 0+1 reduced configurations. The failure was simulated by the disconnecting of the corresponding sensor. This paper presents the approaches, results and their discussion from this research. The measuring WIM system can still work with the reconfigurations but the accuracy is reduced. The impact on the results of the specific sensor combinations can be found in this paper. These combinations are described in the paper as reduced sensor array topologies.

The detailed geometric description for the site is given to allow discussion Sensors are distributed to left and right side of the lane and the curvature with slope play a role at the particular configuration.

Our R&D team cooperates closely with the users of the applications and it is anticipated that the improvements described in this paper follow international technology trends with many installations and user experiences at home and in other countries, Urgela, S. and Janotka, R. (2008), Cerovská, A. and Urgela, S. (2010).

2. Test site description

The site corresponds with criteria for the choice of WIM sites according to the literature and the European WIM specification (1999), Chapter 5, and was evaluated as excellent. The important parameters of the site can be seen in Figure 1. There is a slight longitudinal slope on the road. The site was chosen because it was available for the experiment and we can say that it offered very good site conditions despite the mountainous character of this area. The measurements were performed at the end of the summer in good weather. The site has WIM sensors in all lanes and loops which help to measure all other parameters of traffic flow except the weight. Loop signals allow triggering of the weight evaluation process. This sensor configuration is according to the Golden River and Kistler recommendation and it is being widely used. Each sensor row consists of two sensors. Each sensor covers half of the traffic lane. The distance between sensor rows is 4 m. Processing electronics and firmware are two Golden River Marksman 660 with 16 channels in total, 8 in each direction, 4 in each lane. The results were measured with the accurately weighed calibration vehicle Scania possessing four axles with a gross weight of 26,590 kg. The axles are distributed as two front axles and two rear axles. The axle weights are distributed as 6170 kg and 5780 kg on the front axles and 7390 kg and 7250 kg on the rear axles. The vehicle speed varied between 68 and 73 km/h during the measurements. The first two (front) axles possess independent spring suspension and second two (rear) axles possess coupled spring suspension.

This WIM site and all other sites developed by our R&D team have data processing enhancements, telecommunication features related with the WIM, counter and classifier network, cameras, automated number plate recognition, variable information full color panels, and traffic signs to be utilized as the enforcement, pre-selection and hopefully soon also as toll-by-weight equipment under our trademark Measure-in-Motion® vehicle detector.

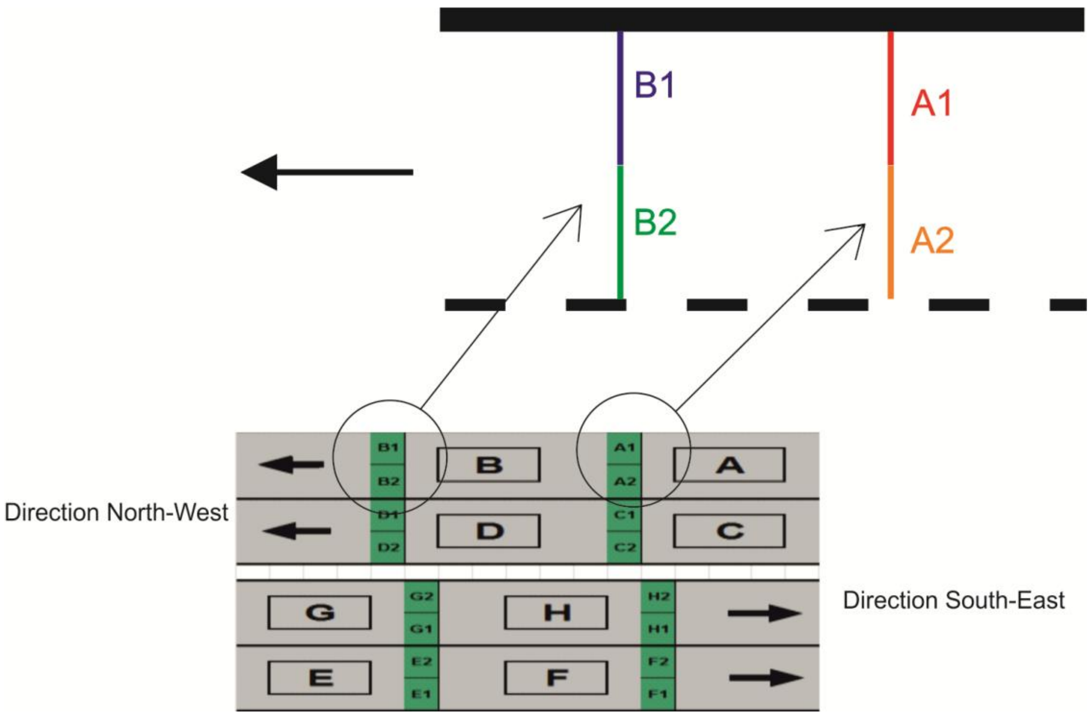


Figure 1 – Test site geometry and the sensor array

3. Experimental results and discussion

The average and absolute errors of the values measured at different configurations are shown in Table 1. Each value e was obtained from 10 runs. A total of 60 runs of the calibration vehicle were performed and n is number of runs. The first table represents mean absolute error (MAE) given by

$$MAE = \frac{1}{n}\sum_{i=1}^{n}|e_i|$$

It is the average of the absolute errors (variation between real static weight r of the vehicle and dynamically measured values m) and second table represents the error dispersion interval (EDI) given by

$$EDI = \frac{(m_{max} - m_{min})}{r} 100$$

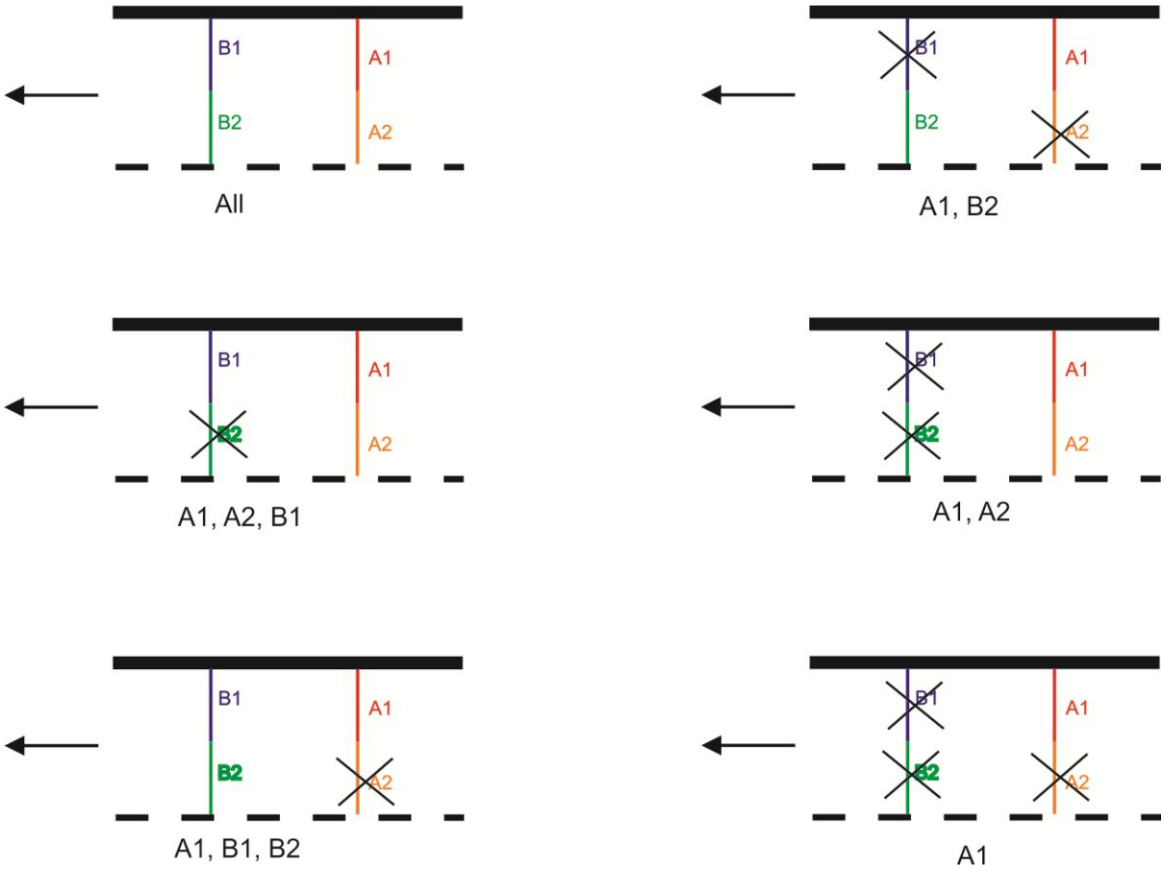
It can be seen from the results that not every axle and every sensor configuration has unique behavior and does not cause the same error. Some axles behave worse than others. It depends on the particular vehicle type and another vehicle type might have more equal errors from axle to axle. However, a good quality vehicle should not have large differences between the axle errors. Some configurations show worse results and some the better ones. Because the site geometry is not straight and flat but possesses curvature and tilt, as a realistic site in the mountain country usually is, the configurations are affected by left and right side sensitivity.

Table 1 - The average and absolute errors of the values measured at the reduced sensor array topologies. At the bottom, the sensor configuration is shown in Figure 1.

Active Sensors	Average Error					
	Gross Weight	Ax1	Ax2	Ax3	Ax4	GoA
All	1,09%	3,29%	5,59%	2,73%	1,99%	1,01%
A1,A2,B1	3,07%	6,56%	3,93%	3,68%	3,27%	2,70%
A1,B1,B2	1,59%	7,03%	4,01%	2,69%	1,90%	1,30%
A1,B2	2,50%	6,21%	6,31%	5,66%	2,59%	2,95%
A1,A2	2,67%	1,93%	9,01%	4,48%	3,53%	2,74%
A1	2,72%	1,49%	8,02%	3,70%	5,15%	3,28%

Active Sensors	Error Dispersion Interval					
	Gross Weight	Ax1	Ax2	Ax3	Ax4	GoA
All	3,87%	3,89%	7,27%	8,39%	6,62%	3,89%
A1,A2,B1	7,63%	3,40%	16,78%	11,77%	10,90%	9,08%
A1,B1,B2	4,29%	3,89%	16,26%	10,96%	6,62%	4,78%
A1,B2	7,00%	4,05%	17,30%	17,32%	7,72%	7,92%
A1,A2	8,95%	10,21%	16,44%	13,80%	12,14%	9,70%
A1	6,24%	4,54%	23,36%	10,83%	17,79%	7,99%

The relations between sensors, schematically drawn on Figure 1 and the names of the full and reduced sensor array topologies as they appear in this paper, are clear from the Figure 2. The results for the individual sensor array topologies are measured and evaluated for each axle of the vehicle (Ax1 is the first front axle, etc., and Ax4 is the last rear axle).


B1
A1
B2
A2
All
A1, B2
A1, A2, B1
A1, A2
A1, B1, B2
A1

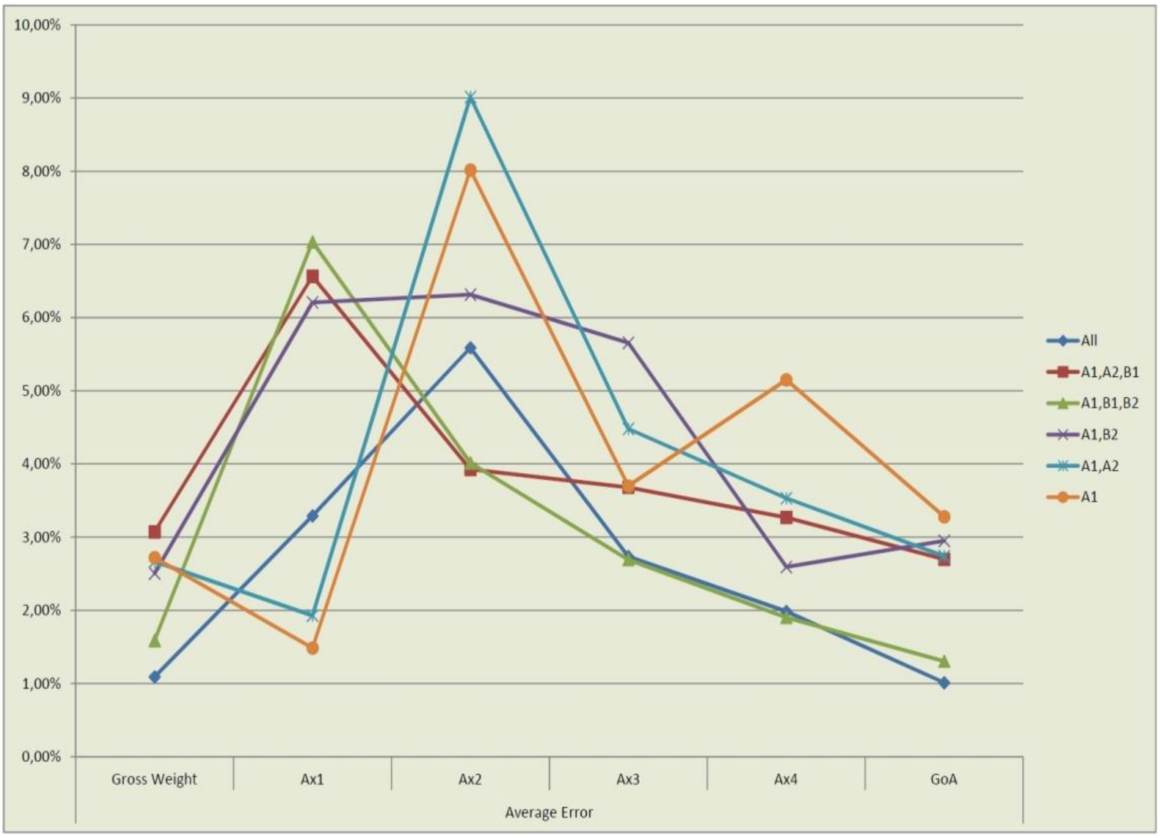

10,00%
9,00%
8,00%
7,00%
6,00%
5,00%
4,00%
3,00%
2,00%
1,00%
0,00%
Gross Weight
Ax1
Ax2
Ax3
Ax4
GoA
Average Error
All
A1,A2,B1
A1,B1,B2
A1,B2
A1,A2
A1

Figure 2 (previous page) – The mean absolute error of the measured values for gross weight, each of four axles and group of axles showing relations with the different configurations of the reduced sensor array topologies.

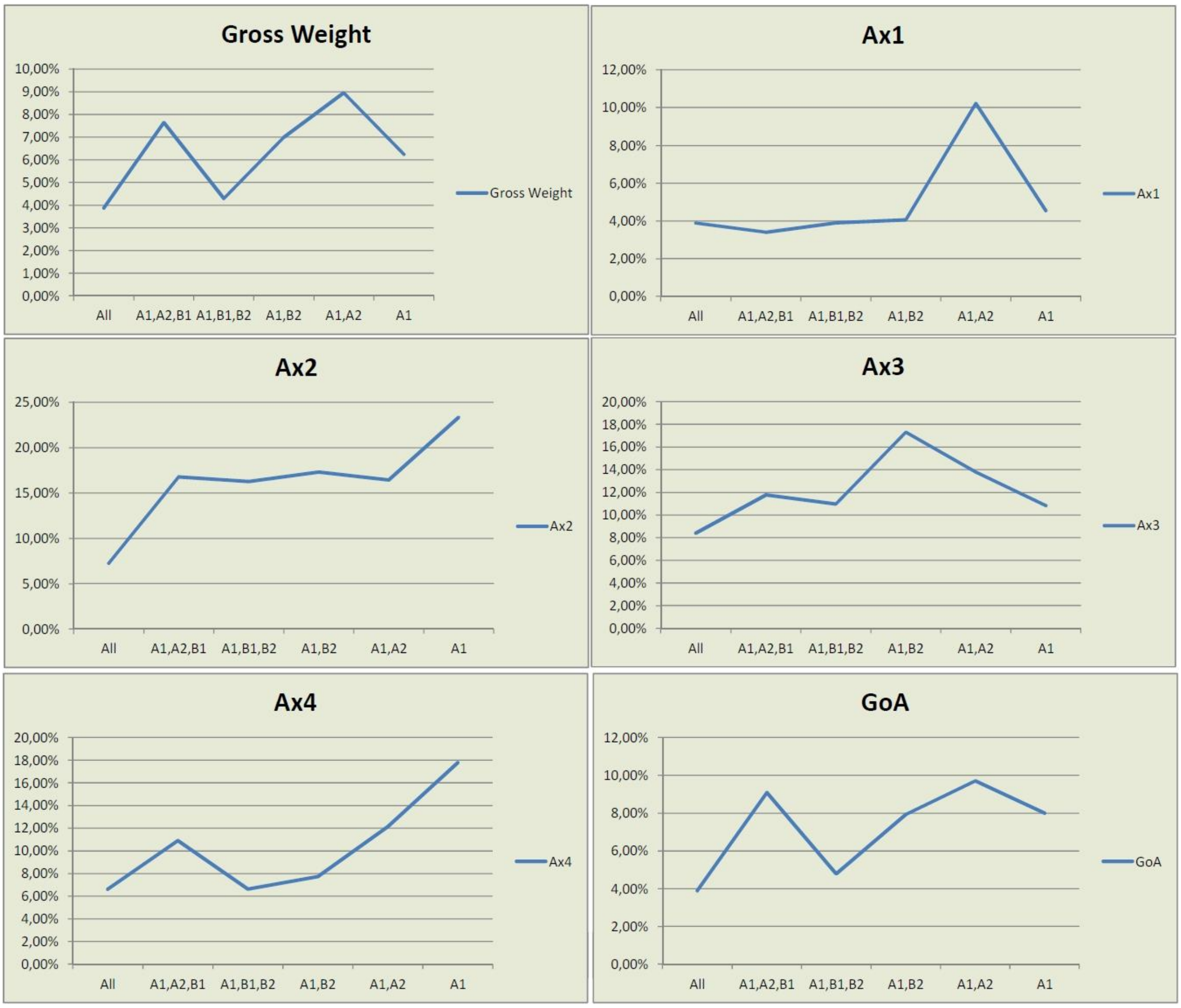


Figure 3 – The mean absolute errors of the measured values showing relations of the different configurations of the reduced sensor array topologies of the experiments with the gross weight, each of four axles and group of axles.

4. Conclusions

The discussion of the results can be explained on basis of the Figures and Tables.

Table 2 – The COST 323 European WIM specification accuracy calculation results for the comparison of the tested reduced sensor array topologies.
(next page)

Sensor Topology : All

Conditions [1]	Test plan		Env[1]		Initial verification (Yes=1, No=0):						1	
	r1		II									
SYSTEM	**Number**	**Identified**	**Mean**	**Std deviat**	π_0	Class	$0.8*\delta$	δ_{min}	δ_c	class	π	Accepted
Entity		(%)	(%)	(%)	(%)		(%)	(%)	(%)		(%)	class
gross weight	10	100	0,34	1,26	93,3	A(5)	4	4,0	5,0	5	96,0	
group of axles	10	100	-0,22	1,31	93,3	A(5)	6	5,0	4,4	5	99,5	B(10)
1st single axle	10	100	-3,29	1,28	93,3	B+(7)	9	7,0	5,5	7	99,7	
2nd single axle	10	100	5,59	2,05	93,3	B(10)	12	9,0	7,2	10	98,0	
1st axle of group	10	100	-2,00	2,32	93,3	A(5)	8	8,0	5,0	5	95,0	
2st axle of group	10	100	1,60	2,19	93,3	A(5)	8	8,0	5,0	5	97,0	

Sensor Topology : A1,A2,B1

Conditions [1]	Test plan		Env[1]		Initial verification (Yes=1, No=0):						1	
	r1		II									
SYSTEM	**Number**	**Identified**	**Mean**	**Std deviat**	π_0	Class	$0.8*\delta$	δ_{min}	δ_c	class	π	Accepted
Entity		(%)	(%)	(%)	(%)		(%)	(%)	(%)		(%)	class
gross weight	10	100	-2,81	2,23	93,3	B(10)	8	6,0	7,5	10	92,8	
group of axles	10	100	-1,95	2,90	93,3	B(10)	10	9,0	7,9	10	96,9	C(15)
1st single axle	10	100	-6,56	1,17	93,3	B(10)	12	9,0	7,2	10	99,8	
2nd single axle	10	100	-0,95	4,82	93,3	C(15)	16	13,0	11,0	15	97,0	
1st axle of group	10	100	-2,68	4,03	93,3	B(10)	16	12,0	7,5	10	98,4	
2st axle of group	10	100	-1,20	3,64	93,3	B+(7)	11	9,0	5,6	7	95,1	

Sensor Topology : A1,B1,B2

Conditions [1]	Test plan		Env[1]		Initial verification (Yes=1, No=0):						1	
	r1		II									
SYSTEM	**Number**	**Identified**	**Mean**	**Std deviat**	π_0	Class	$0.8*\delta$	δ_{min}	δ_c	class	π	Accepted
Entity		(%)	(%)	(%)	(%)		(%)	(%)	(%)		(%)	class
gross weight	10	100	-1,04	1,44	93,3	B+(7)	6	5,0	6,3	7	98,0	
group of axles	10	100	-0,36	1,54	93,3	A(5)	6	4,0	3,5	5	98,4	C(15)
1st single axle	10	100	-7,03	1,25	93,3	B(10)	12	9,0	7,2	10	99,5	
2nd single axle	10	100	3,60	4,38	93,3	C(15)	16	12,1	10,1	15	96,6	
1st axle of group	10	100	-0,47	3,41	93,3	B+(7)	11	9,0	5,6	7	96,9	
2st axle of group	10	100	-0,25	2,28	93,3	A(5)	8	4,0	2,5	5	97,9	

Sensor Topology : A1,B2

Conditions [1]	Test plan		Env[1]		Initial verification (Yes=1, No=0):						1	
	r1		II									
SYSTEM	**Number**	**Identified**	**Mean**	**Std deviat**	π_0	Class	$0.8*\delta$	δ_{min}	δ_c	class	π	Accepted
Entity		(%)	(%)	(%)	(%)		(%)	(%)	(%)		(%)	class
gross weight	10	100	-1,78	2,35	93,3	B(10)	8	6,0	7,5	10	95,3	
group of axles	10	100	-2,55	2,63	93,3	B(10)	10	9,0	7,9	10	97,4	D+(20)
1st single axle	10	100	-6,21	1,25	93,3	B(10)	12	9,0	7,2	10	99,8	
2nd single axle	10	100	4,90	5,87	93,3	D+(20)	20	17,0	16,3	20	94,9	
1st axle of group	10	100	-3,22	5,68	93,3	B(10)	16	12,0	7,5	10	90,7	
2st axle of group	10	100	-1,88	2,55	93,3	A(5)	8	4,0	2,5	5	93,1	

Sensor Topology : A1,A2

Conditions [1]	Test plan		Env[1]		Initial verification (Yes=1, No=0):						1	
	r1		II									
SYSTEM	**Number**	**Identified**	**Mean**	**Std deviat**	π_0	Class	$0.8*\delta$	δ_{min}	δ_c	class	π	Accepted
Entity		(%)	(%)	(%)	(%)		(%)	(%)	(%)		(%)	class
gross weight	10	100	2,01	2,76	93,3	B(10)	8	6,0	7,5	10	90,1	
group of axles	10	100	0,35	3,38	93,3	B(10)	10	9,0	7,9	10	95,7	D+(20)
1st single axle	10	100	-0,96	2,58	93,3	B+(7)	9	7,0	5,5	7	96,9	
2nd single axle	10	100	9,01	4,57	93,3	D+(20)	20	16,1	15,1	20	93,7	
1st axle of group	10	100	-0,07	5,34	93,3	B(10)	16	12,0	7,5	10	95,2	
2st axle of group	10	100	0,77	4,08	93,3	B+(7)	11	8,5	5,3	7	92,4	

Sensor Topology : A1

Conditions [1]	Test plan		Env[1]		Initial verification (Yes=1, No=0):						1	
	r1		II									
SYSTEM	**Number**	**Identified**	**Mean**	**Std deviat**	π_0	Class	$0.8*\delta$	δ_{min}	δ_c	class	π	Accepted
Entity		(%)	(%)	(%)	(%)		(%)	(%)	(%)		(%)	class
gross weight	10	100	2,21	2,58	93,3	B(10)	8	6,0	7,5	10	91,4	
group of axles	10	100	1,16	3,55	93,3	B(10)	10	9,0	7,9	10	93,8	D(25)
1st single axle	10	100	1,11	1,65	93,3	A(5)	6	4,0	3,0	5	98,1	
2nd single axle	10	100	6,06	7,86	93,3	D(25)	24	21,0	21,3	25	91,8	
1st axle of group	10	100	1,98	4,00	93,3	B+(7)	11	11,0	6,9	7	91,2	
2st axle of group	10	100	0,32	6,53	93,3	C(15)	20	17,0	10,6	15	95,6	

From data given in the tables and their graphical interpretations shown in the figures it can be concluded that the more sensors are involved in each reduced sensor array topology the more accurate results can be achieved. This paper describes experiments with the particular vehicle on the particular site. In the case of the geometry and the particular algorithms implemented in the equipment, the COST 323 European WIM specification accuracy calculated results are from B(10) at fully functional array to D(25) on one sensor covering the half of the lane (see Table 2). The higher the number of sensors, the lower mean absolute error is shown in Figure 3.

As can be seen in Figure 2, one of the test vehicle axles, the 2nd single axle, greatly impacts the results. The type of the vehicle suspension was described in Section 2 and its behavior might have caused higher dispersion of the values measured at this axle. For the vehicles used for such a purpose, the air suspension is recommended.

The reduced sensor array topology with the three sensors shows one class lower accuracy when compared to the fully functional array, in our case C(15), and it might be interesting to investigate it in more detailed relation to the site geometry and vehicles of more classes in future research.

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6. Acknowledgements

Authors thank to colleagues Rysula M. and Horák, J. for the data evaluations and Maciak, J. and Remeselník, V. for the helpful discussions.
This work has been supported through the research and development operational program by the European Regional Development Fund and the Ministry of Education of the Slovak

Republic, project ITMS 26220220089 “New methods of measurement of physical dynamic parameters and interactions of motor vehicles, traffic flow and road”.

Session 5

Application of WIM to Bridges

Chair : ALES ZNIDARIC (ZAG, Slovenia)

Co-chair : ANDREW NICHOLS (Marshall University, United States)

A DUAL PURPOSE BRIDGE HEALTH MONITORING AND WEIGH-IN-MOTION SYSTEM FOR A STEEL GIRDER BRIDGE



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Abstract

Bridge weigh-in-motion (BWIM) leveraged with bridge health monitoring (BHM) can help transportation agencies to maintain their bridge infrastructure and meet the ever increasing demand for safe, efficient and cost effective transportation systems. In Connecticut, BHM is being implemented as long-term systems that monitor critical vulnerabilities in bridges using sensor measurements of the bridge response to traffic loading over time. This paper provides an overview of a new BWIM method that provides a nonintrusive approach to WIM using various sensor technologies and data acquisition equipment installed for long-term BHM. The design and implementation of a prototype dual-purpose BHM/BWIM system being deployed on Interstate 91 (I-91) in Connecticut is introduced, preliminary performance of various sensor technologies is evaluated, and results from a pilot study of BWIM to determine the utility of the proposed BWIM method is presented.

Keywords: Weigh-in-Motion, Bridge Health Monitoring, sensors.

Résumé

Le pesage par pont instrumenté (B-WIM) associé à la surveillance de la santé structurelle des ponts peut permettre aux gestionnaires d'infrastructures d'optimiser la maintenance de leur patrimoine et répondre à la demande toujours croissante de moyens de transport sûrs, fiables et peu coûteux. Dans le Connecticut, les systèmes de santé structurelle sont utilisés en tant que systèmes permettant de détecter à long terme les vulnérabilités des ponts, en enregistrant les mesures des réponses du pont aux sollicitations du trafic. Cet article propose une vue d'ensemble sur une nouvelle méthode de pesage par pont instrumenté qui permet un pesage en marche non intrusif et l'acquisition des données de l'équipement pour surveillance structurelle de l'ouvrage. La conception et la fabrication d'un prototype d'un système avec ce double objectif sur la route inter-Etats Interstate 91 dans le Connecticut sont explicitées, des premiers résultats sur les performances des capteurs sont montrés et des données d'une étude pilote sur l'utilité de ce nouveau système sont présentées.

Mots-clés: Pesage en marche, surveillance de la santé structurelle des ponts, capteurs.

1. Introduction

Leveraging long-term bridge monitoring systems with BWIM will enable agencies to collect weight data on a more comprehensive network. Improved load information on the transportation network will lead to better bridge, pavement and highway designs, as well as improved decisions and efficiency; the ability to weigh and screen commercial vehicles in a timely fashion for weight enforcement; the collection of speed, weight and class data for traffic monitoring; and increased safety and timely identification of changes in the structural system for maintenance and operation.

The goal of long-term bridge health monitoring is to identify changes in a bridge's dynamic behavior over multi-year periods as an indicator of the structural health of the bridge. To achieve this goal, highway bridges are instrumented with sensors, data acquisition and processing power. Research is on-going in the area of long-term bridge monitoring, in particular long-term vibration-based monitoring for the purposes of detecting damage, monitoring deterioration and allocating resources (Farrar et al., 1999, Chakraborty et al., 1995, Salawu et al., 1997, Doebling et al., 1996, Caicedo et al., 2000, and Chang, 2000).

Bridge Weigh-In-Motion (BWIM) uses the dynamic response of a bridge to determine gross-vehicle weight, speed, and axle spacing. The advantage of BWIM as implemented in this research is that it does not require installation of sensors in the pavement, nor use any axle detectors in the roadway. Proposed over 30 years ago by Moses (1979), BWIM continues to receive attention with the advancement of sensor and data acquisition technologies and with the extensive research conducted in Europe in the 1990's through the Weighing in motion of Axles and Vehicles for Europe (WAVE) project (Jacob, 2002). A recent study by the Connecticut Academy of Science and Engineering (CASE) recommends that BWIM, as a promising non-intrusive technology, should be considered for WIM in Connecticut (Connecticut Academy of Science and Engineering, 2008). This paper describes a new BWIM method that provides a nonintrusive approach to WIM and presents an enhanced combined BHM/BWIM system using various sensor technologies.

2. Bridge Weigh-in-Motion Methodology

The BWIM methodology presented in this paper uses strain measurements from the steel girder of the slab-on-girder highway and builds on the theory from the work of Ojio and Yamada (2002) and the findings of Cardini and DeWolf (2009) and Wall et al. (2009). The unique aspect of this method is the use of the second time derivative of the measured strain to identify, with large negative spikes or peaks, the time it takes for the first axle of the truck to travel from the start of the bridge to the mid-span, t_1 (sec) (Christenson et al., 2011). Knowing this time, truck speed is determined as

$$v = \frac{L}{2(t_1)}$$

(1)

where v is the speed of the truck (ft/sec) and L is the length of the bridge (ft). The second derivative of the strain also provides the times when each of the remaining axles pass over the mid-span of the bridge; t_2, t_3, t_4 and t_5 for a 5-axle truck. Given these times, the truck's axle spacing, x_n, can be calculated as

$$x_n = v(t_{n+1} - t_n), \qquad n = 1,2,\ldots,N\text{-}1$$

(2)

where x_n is the distance between the n-1 and n^{th} axles, and t_n is the time it takes for the n^{th} axle to reach the mid-span of the bridge after the truck first enters the bridge, and N is the total number of axles of the truck.

Gross vehicle weight (GVW) is determined from the method of Ojio and Yamada (2002). This method relates the known GVW of a test truck to the GVW of any *unknown* as

$$\frac{A_k}{GVW_k} = \frac{A_u}{GVW_u} \tag{3}$$

where A_k and GVW_k are the calculated area and reference gross vehicle weight for a test truck of *known* weight, and A_u and GVW_u are the calculated area and gross vehicle weight for a truck with *unknown* weight. The ratio of GVW_k to A_k is defined as the calibration constant β

$$\beta = \frac{GVW_k}{A_k} \tag{4}$$

Substituting Eq. (4) into Eq. (3) and rearranging provides the GVW of the unknown truck as

$$GVW_u = A_u \beta \tag{5}$$

where A is a function of strain, $\varepsilon(t)$. The displacement can be written in terms of velocity and time, $x = vt$, and lastly the equation can be written in discrete form as

$$A(t) = v\int_{-\infty}^{\infty} \varepsilon(t)dt = \frac{v\Delta t}{M}\sum_{i=1}^{M}\varepsilon(i\Delta t) \tag{6}$$

where Δt is the discrete sample time of the strain measurement, and M is the total number of measurements needed for the truck to cross the bridge.

2.1 Prototype BHW / BWIM system

A prototype system was designed specifically to meet the research objectives of this study, including the evaluation of sensor technologies for BWIM and BHM applications. The system includes five types of sensors, an automatic data acquisition unit and personal computer (PC). The five sensor types include two types of sensors to measure strain (foil-type and piezoelectric), two types of accelerometers (piezoelectric and capacitance) and a temperature sensor (Resistance Temperature Detector (RTD)). The sensor layout design is provided in Figure 1.

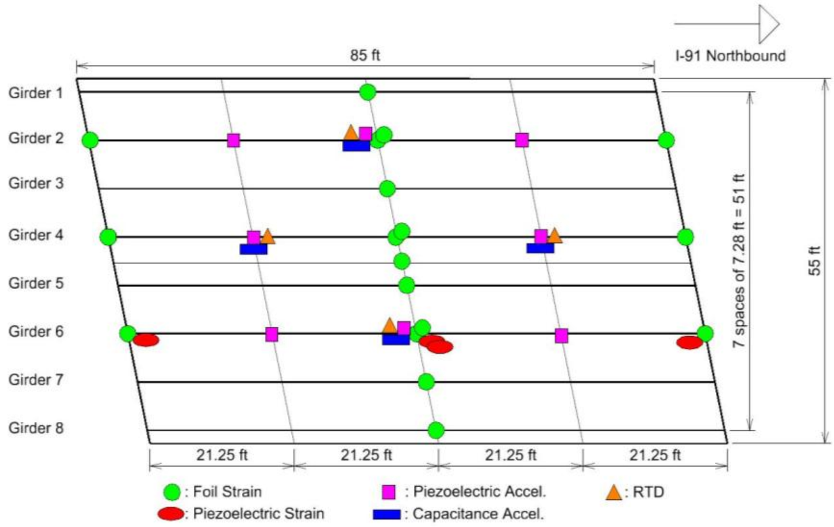


Figure 1 - A Schematic of Sensor Layout and Sensor Type for the Meriden Bridge.

Strain sensors at the bridge bearings are used to detect vehicle presence on the bridge. The mid-span locations have strain sensors located at the top and bottom of the web of the steel girder to determine the neutral axis of the bridge cross-section, assess the composite behavior of the bridge girders with respect to the bridge deck, and detect any changes in the location of the neutral axis indicative of deck damage for BHM. Two types of strain sensor technologies are evaluated to provide dynamic strain measurements: foil-type; and piezoelectric technologies. A magnetic mounting device was developed to enable installation of the piezoelectric strain gage without drilling into the girder. The two types of strain sensors are collocated and will be evaluated and compared in this study.

Accelerometers were installed at the quarter and mid-span of the bridge, to identify natural frequencies and mode shapes for BHM purposes. The ability for the accelerometers to provide similar information as the second derivative of the strain sensors was also evaluated. Two types of accelerometer technologies were considered: piezoelectric and capacitance technologies. As with the strain sensors, the accelerometers are collocated and will be evaluated and compared in this study.

The temperature sensors are Resistance Temperature Detectors (RTDs) that are surface mounted underneath the bridge. Temperature measurements will be used for both BHM and BWIM to assess for environmental variability in the results.

The data acquisition and PC are located in a cabinet mounted at the bridge. The data acquisition unit provides signal conditioning and high sampling rates needed for the output from the various sensors. The PC is programmed to implement the BHM/BWIM methods automatically. The PC is remotely accessible using a cellular modem.

The prototype BHM/BWIM system is installed on a single-span, multi-girder steel-composite highway bridge on Interstate-91 (I-91) Northbound in the town of Meriden, Connecticut. This single-span bridge is 85 feet in length with multiple plate-stringers supported by eight girders. The bridge carries three lanes of northbound traffic at 57,000 annual average daily traffic (AADT) and 9% trucks. The bridge is located just (less than a mile) prior to a weigh station with an operational static scale. This proximity to the weigh station provides the opportunity to validate and compare BWIM results directly with the static scale measurements on a per vehicle basis. Feasibility tests were conducted at this location in 2009 using portable bridge-monitoring equipment. These feasibility tests provided valuable information to design the prototype system (Christenson, 2011).

2.2 Pilot Study

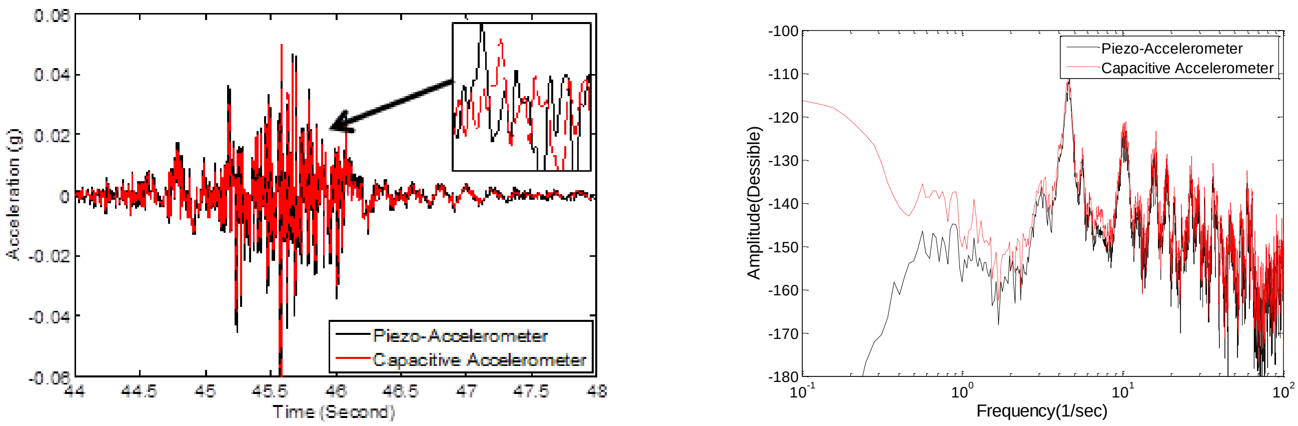
A pilot study, conducted on December 13, 2011, included an initial field test using a loaded 5-axle truck of known weight making multiple passes over the prototype bridge system. The purpose of this initial field test was for initial calibration of the BWIM method. A secondary purpose of the pilot study was to gather information on the various sensor responses, assess the ability to calculate speed data and evaluate the variability in the results from applying the calibration to the initial test vehicle calculations.

The test vehicle was a five-axle semi-trailer with air-ride suspension. The vehicle loaded to 68,600 lbs. The static weight was obtained at the weigh station prior to testing. A total of twelve passes were collected during the field test: five passes in the middle lane and seven passes in the slow lane. The truck driver attempted to vary the speed at 50, 55, 60 miles per hour (mph) according to instructions and based on traffic.

2.3 Pilot Study Test Results

The speed of the truck was recorded from a commercial navigation system installed in the truck. This speed was validated with a second GPS unit provided by the research team. The speed of the truck was also calculated based on bridge strain data and using Equation (1). The speed recorded from the commercial navigation system was used as the “ground-truth” or “actual” truck speed for comparison with the speed calculated from the bridge response. The calculated (bridge) speeds are all within 5 mph of the measured (GPS) speeds. The average difference between the measured and calculated speed is 4.5%.

The performance of the two accelerometer technologies, piezoelectric and capacitive, is examined in the time domain and frequency domain as shown in Figure 2(a) and (b). The data shown are from accelerometers placed on girder 6 at mid-span with the truck traveling in the slow lane at a speed of 62 mph. An eight-pole low-pass filter with a 100 Hz cutoff frequency was used to reduce the effect of noise on the acceleration data. The piezoelectric and capacitive accelerometers have a frequency range of 0.1 to 200 Hz and 0 to 250 Hz, respectively. From the time domain plots the two accelerometers are observed to have similar noise levels and provide comparable measurements. A time lag of 0.019 seconds was observed in the capacitive accelerometers relative to the piezoelectric accelerometers (inset in Figure 2(a)). In the frequency domain the two sensor technologies provide similar performance above 3 Hz, while the piezoelectric accelerometer rolls off at lower frequencies. Neither accelerometer can capture the crossing of truck axles over the midspan. It is expected that accelerometers with larger bandwidth will be able to measure this large negative acceleration when the axles pass over the center of the bridge and can be used as redundant or replacement measurements for the truck speed. Piezoelectric accelerometers with higher frequency range (>1000 Hz) are being considered for this purpose.

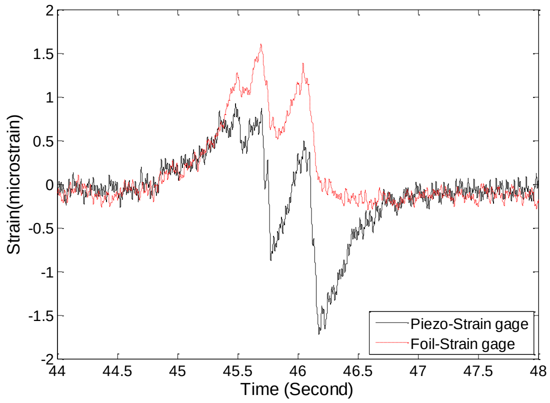


(a) (b)

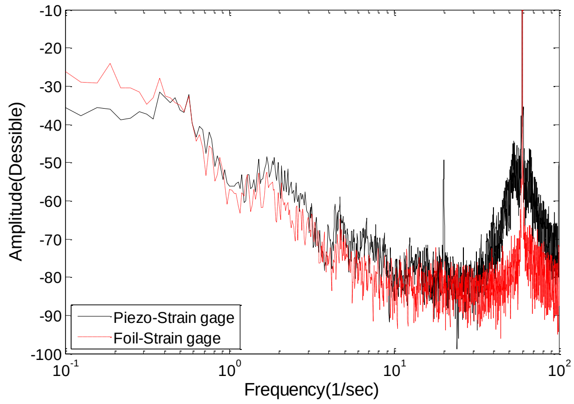
Figure 2- Piezoelectric Accelerometer vs. Capacitive Accelerometer Data: (a) time history for truck crossing; (b) auto power spectral density of acceleration.

The performance of the two types of strain gage technologies, foil strain gage and piezoelectric strain gage, are compared in Figures 3(a) and (b) in the time domain and frequency domain, respectively. These data are measured from the gages on girder 6 at the North bearing. A comparison in time domain shows the time decay observed in the piezoelectric strain gauge signals resulting from the signal conditioner used for this sensor. The attenuation at low frequencies was observed in the frequency domain as well. The data from both sensor technologies are in good agreement from 0.5-10 Hz. A large peak in the autopower spectral density functions of both strain sensors was observed at 60 Hz corresponding to ground loop noise. An eight-pole low-pass filter with a 30 Hz cutoff frequency was applied to reduce the effect of the ground loop noise at 60 Hz. The strain measurements from the foil-type strain sensors are used for BWIM measurements.

The axle spacing of the test truck is calculated using the calculated speed and Equation (2) with time intervals based on the large negative spikes in the second derivative of the strain history, as shown in Figure 4. Table 1 presents the measured and calculated axle spacing for the middle lane and slow lane. The prediction of axle spacing for Run 6 is incomplete. for the last three axles due to the presence of multiple vehicles on the bridge. The axle spacing is slightly overestimated in comparison to actual measurements, due to an overestimation bias in the speed calculation. This overestimation demonstrates both the sensitivity and importance of the speed calculation.



(a)



(b)

Figure 3- Piezoelectric Strain Sensors vs. Foil Strain Gages Data: (a) time history for truck crossing; (b) autopower spectral density of acceleration.

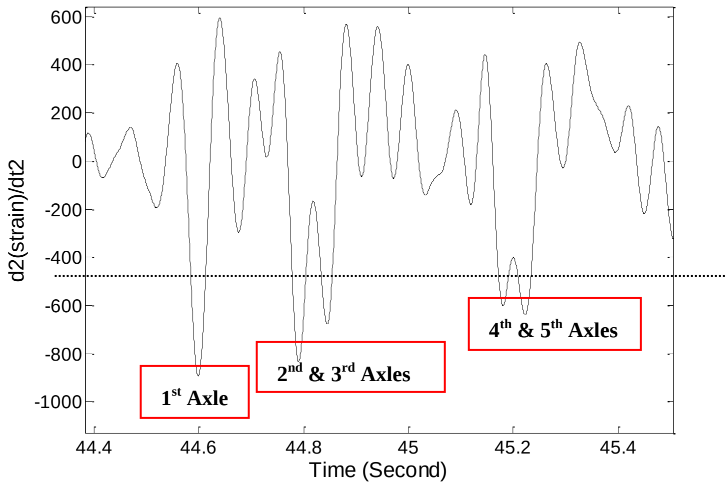


Figure 4- Negative Spikes in Second Derivative of Strain Measurement when the Truck Axles Pass Over the Mid-Span of the Bridge.

For calibration, the ratio of GVW_k to A_k, called β, is calculated from Equation (4) for each pass in the middle lane and each pass in the slow lane, based on the static weight of the truck (68,600 lb) and the measured strain at the midspan of girders 6 and 4, respectively. The calibration constant β was then calculated as the average of these values, 0.032 (lb/ft) for the middle lane and 0.034 (lb/ft) for the slow lane. The standard deviation of β is 0.0036 lb/ft, which demonstrates the repeatability of the method.

Table 1- Comparison of Measured and Calculated Truck Axle Spacing

Axles	Meas. (ft)	Calculated (Middle Lanes) ft					Calculated (Slow Lanes) ft						
		1	2	3	4	5	6	7	8	9	10	11	12
1 to 2	**17**	17.6	17.9	17.7	17.6	17.7	17.1	17.4	17.3	17.3	17.4	17.4	17.5
2 to 3	**4.2**	5.3	5.4	5.3	5.7	6	*	5.5	5.7	5.6	5.4	5.5	5.4
3 to 4	**30.6**	31.7	31	31	30.6	31.7	*	31	30.5	34.4	31.1	31.1	30.6
4 to 5	**4.1**	5.5	5.5	5.3	5.4	5.4	*	5.3	5.5	5.4	12.4	5.5	5.2

"*" issues due to presence of multiple trucks on the bridge.

Based on the selection of β, the weight of the truck of known-weight for different runs is calculated using Equation (5). These results are presented in Table 2. The measured and calculated weight of the truck are in a well agreement in most of the cases and the average difference between the calculated and measured weight was respectively, 8.0% and 7.8 % for the middle and slow lanes. While these weights were calculated using the constant β, calculated from the same data set, the weight data are useful to ascertain the variation when applied to the variation from the test truck. Given the limited set of data, use of a smaller sub-set of data was examined so that the remaining runs could be used as verification. Applying this technique, the outcome was a comparable β. Additional test runs are planned to apply the calibration factor, β, to different vehicles and a larger number of vehicles.

Table 2- Comparison of Measured (68,600 lb) to Calculated Truck Weight

	Middle Lane					Slow Lane						
Runs	1	2	3	4	5	6	7	8	9	10	11	12
Weight (lb)	66551	68780	62120	65157	84206	70008	59488	70538	64001	66805	85386	70488
Difference%	2.99	0.26	9.45	5.02	22.75	2.05	13.28	2.83	6.7	2.62	24.47	2.75

3. Conclusion

This paper describes preliminary results from a pilot study of an in-service highway bridge instrumented with a prototype BHM/ BWIM system. The prototype system is designed to use various sensor technologies for the calculation of weigh-in-motion data and evaluation of different types of sensor technologies for BHM and BWIM applications. A new BWIM method that provides for non-intrusive means of obtaining weigh-in-motion data is presented and an initial field test was conducted as part of pilot study where a truck of known-weight conducted multiple passes over the instrumented bridge. Based on this initial field test, the system was calibrated and weigh-in-motion data (i.e. speed, axle-spacing and weight data) were calculated. Foil-type strain sensors are observed to provide better strain measurements during truck crossings than the piezoelectric strain sensors due to a larger time constant. Both accelerometers provide similar measurements above 3 Hz. The calculated speed, axle spacing and weight data are in reasonable agreement with the measured data. Inaccuracies due to multiple vehicle presence on the bridge can be addressed by considering the response of multiple girders. Truck speed measurements, observed to be critical in the accurate calculation of axle spacing and weight, can be enhanced by using accelerometers with larger bandwidth. The second phase of the project will explore these enhancements and validate the BWIM methodology with vehicles from the traffic stream and variations in temperature.

4. Acknowledgement

The authors gratefully acknowledge the Federal Highway Administration and the Connecticut Department of Transportation for funding of this project through the State Planning and Research (SPR) program, project SPR-2265. This report, prepared in cooperation with the Connecticut Department of Transportation and the Federal Highway Administration, does not constitute a standard, specification, or regulation. The contents of

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WIM BASED SIMULATION MODEL OF SITE SPECIFIC LIVE LOAD EFFECT ON THE BRIDGES

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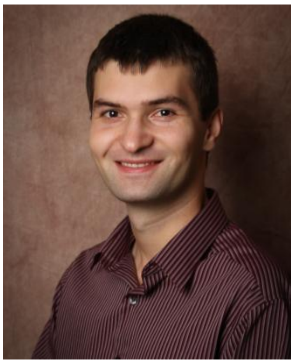

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Abstract

Truck traffic as well as live load effect on the bridges is strongly site-specific. Weigh-in-motion (WIM) measurements provide an important data base. The analysis of gross vehicle weight (GVW) and load effects (moments) indicates that the cumulative distribution functions (CDF) have a complex shape. This paper attempts to develop CDF's for groups of vehicles, depending on category, mostly number of axles. The considered WIM data base includes 35 millions of vehicles. The resulting CDF's are closer to a normal distribution which is important in extrapolation to predict maximum live load for extended periods of time. The paper also presents the development of a simulation procedure for site-specific live load effect on bridges.

Keywords: Weigh-in-motion, live load effect, maximum live load.

Résumé

Le trafic poids lourds, tout comme les charges temporaires sur les ouvrages, dépendent fortement du site considéré. Le pesage en marche (WIM) fournit une importante base de données sur ces caractéristiques. L'analyse du poids total en charge du véhicule (GVW) et des effets de charge (moments) indique que les fonctions de répartition (CDF) ont une forme difficile à appréhender. Ce document tente de déterminer des CDF pour des catégories de véhicules, qui sont, elles, choisies principalement en fonction du nombre d'essieu. La base de données de pesage considérée contient 35 millions de véhicules. La CDF en découlant est proche d'une distribution normale, ce qui est important dans l'extrapolation pour prédire la charge maximale rencontrée par l'ouvrage sur des périodes prolongées. Ce document présente également l'élaboration d'une procédure de simulation de l'effet subi par cet ouvrage spécifiquement.

Mots-clés: Pesage en marche, effet des charges temporaires, effet maximum.

1. Introduction

Truck traffic as well as live load effect on the bridges is strongly site specific. Often, it is important to know what is the actual live load effect for a particular site. Design codes such as AASHTO LRFD or AASHTO Manual of Bridge Evaluation specify live load. However, the codes provisions are very general and do not account for local traffic conditions. Bridge owners often have to know what is the actual live load on their structures. Knowledge of the actual live load is also important in evaluation of existing bridges or in scheduling of maintenance.

WIM stations are an important source of data about the local truck traffic conditions that can be used to develop a site-specific live load model. However, they are expensive to build and maintain. Moreover, WIM stations are mostly located on interstate highways with the traffic conditions that are different than on local roads. Local authorities such as States DOT's as well as private bridge owners are interested in having a procedure for simulation of live effect on bridges based on local truck traffic conditions.

Vehicle Classification

All vehicles recorded by WIM stations are categorized. The FHWA vehicle classification scheme is separated into categories depending on whether the vehicle carries passengers or commodities. Non-passenger vehicles are further subdivided by number of axles and number of units, including both power and trailer units. The addition of a light trailer to a vehicle does not change the classification of the vehicle. The algorithm most commonly used for classification is based on the "Scheme F" developed by Maine DOT in the mid-1980s (FHWA, 2011). Vehicles are categorized into 13 classes:

Class 1 - All two or three-wheeled motorized vehicles. Typical vehicles in this category have saddle type seats and are steered by handlebars rather than steering wheels. This category includes motorcycles, motor scooters, mopeds, motor-powered bicycles, and three-wheel motorcycles.

Class 2 - All sedans, coupes, and station wagons manufactured primarily for the purpose of carrying passengers and including those passenger cars pulling recreational or other light trailers.

Class 3 - All two-axle, four-tire, vehicles, other than passenger cars. Included in this classification are pickups, panels, vans, and other vehicles such as campers, motor homes, ambulances, hearses, carryalls, and minibuses. Other two-axle, four-tire single- unit vehicles pulling recreational or other light trailers are included in this classification .

Class 4 - All vehicles manufactured as traditional passenger-carrying buses with two axles and six tires or three or more axles. This category includes only traditional buses (including school buses) functioning as passenger-carrying vehicles. Modified buses should be considered to be a truck and should be appropriately classified.

Class 5 - All vehicles on a single frame including trucks, camping and recreational vehicles, motor homes, etc., with two axles and dual rear wheels.

Class 6 - All vehicles on a single frame including trucks, camping and recreational vehicles, motor homes, etc., with three axles.
Class 7 - All trucks on a single frame with four or more axles.
Class 8 - All vehicles with four or fewer axles consisting of two units, one of which is a tractor or straight truck power unit.
Class 9 - All five-axle vehicles consisting of two units, one of which is a tractor or straight truck power unit.
Class 10 - All vehicles with six or more axles consisting of two units, one of which is a tractor or straight truck power unit.
Class 11 - All vehicles with five or fewer axles consisting of three or more units, one of which is a tractor or straight truck power unit.
Class 12 - All six-axle vehicles consisting of three or more units, one of which is a tractor or straight truck power unit.
Class 13 - All vehicles with seven or more axles consisting of three or more units, one of which is a tractor or straight truck power unit (Wyman et. al., 1985).

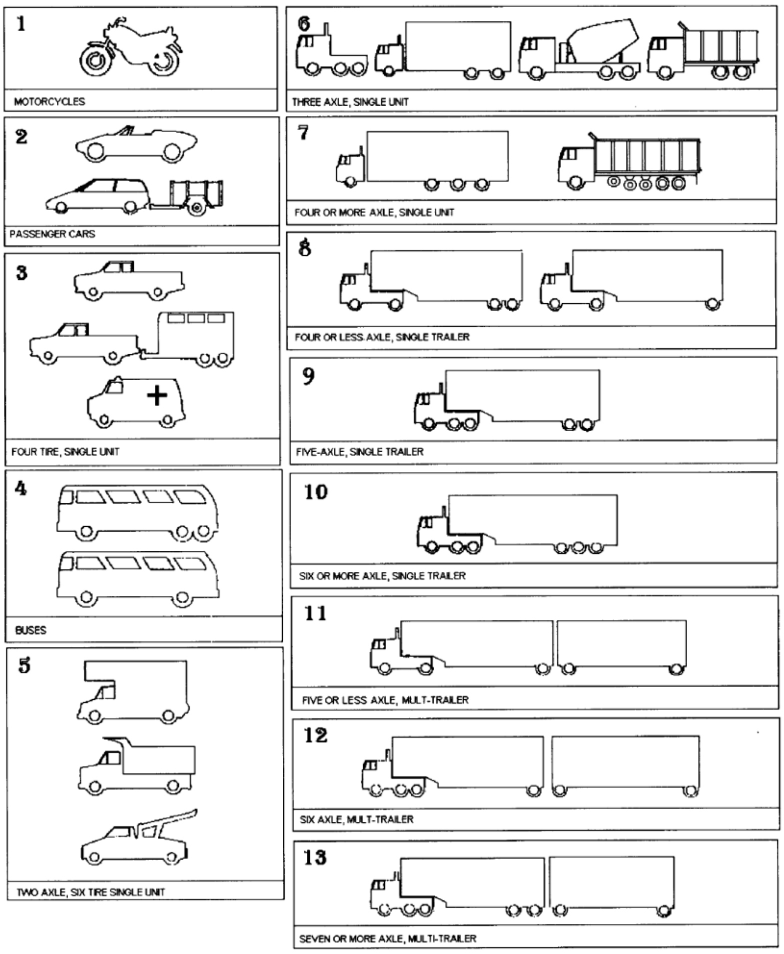


Figure 1 - FHWA vehicle classification scheme F report (Wyman et. al., 1985).

2. Statistical Models for Vehicle Classes

Extensive WIM data used for the development of a simulation model includes 35 million trucks. The vehicles were recorded in 32 different WIM sites in 19 States. All vehicles recorded by WIM station are assigned to one of the vehicle classes. Vehicle classes 4-13 are considered as trucks.

The maximum bending moments due to all 35 million WIM data trucks were calculated for the span of 90 ft divided by moment due to HL93 loading (AASHTO, 2010) and grouped according to the corresponding vehicle class. The HL-93 live load is a superposition of a design truck and a uniformly distributed load of 0. 64 kip/ft (9.3 kN/m). The design truck has three axles with spacing 8 ft (2.4m) and 14 ft (4.3 m), leading axle weight of 8 kips (35 kN) and following axle weights of 32 kips (142 kN). Results for each class are plotted on normal probability paper (Nowak and Collins, 2000). Distribution of vehicle class 13 is shown on Figure 2.

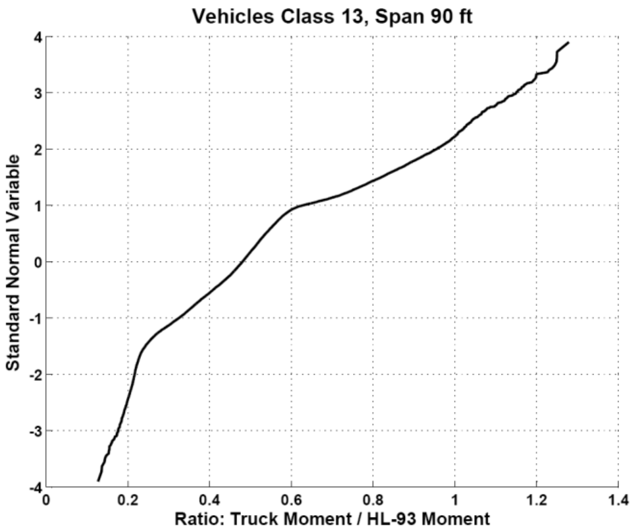


Figure 2 - Distribution of ratio: truck moment / HL-93 moment for vehicles class 13.

Each class has a unique distribution which cannot be fitted by one of common distributions. The best result was obtained by fitting different normal distributions for the original curve on the normal probability paper. Normal distribution on normal probability paper is represented by a straight line.

The cumulative distribution function (CDF) of the moment due to vehicles of class 13 can be replaced by 3 approximately straight-line segments as is shown on Figure 3.

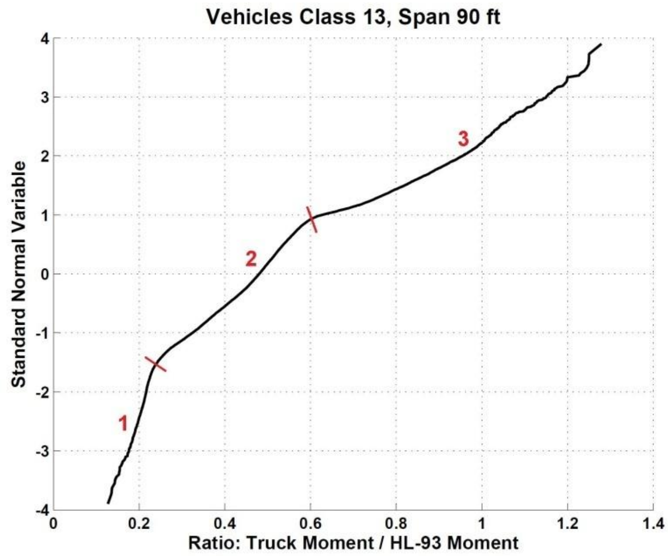


Figure 3 - WIM data for vehicle class 13 divided into 3 sets.

For the vehicles of class 13, the first segment covers the ratios of WIM truck moment and HL-93 moment below 0.22, the second segment covers 0.22-0.6 and third segment covers ratios above 0.6. Each segment was plotted separately on the probability paper, in Figure 4. Scatter plot in Fig. 5.4 indicates that the distribution tails are less populated. About 70% of data population is whithin +/- one standard deviation from the mean, which corresponds to +/-1 on the vertical axis.

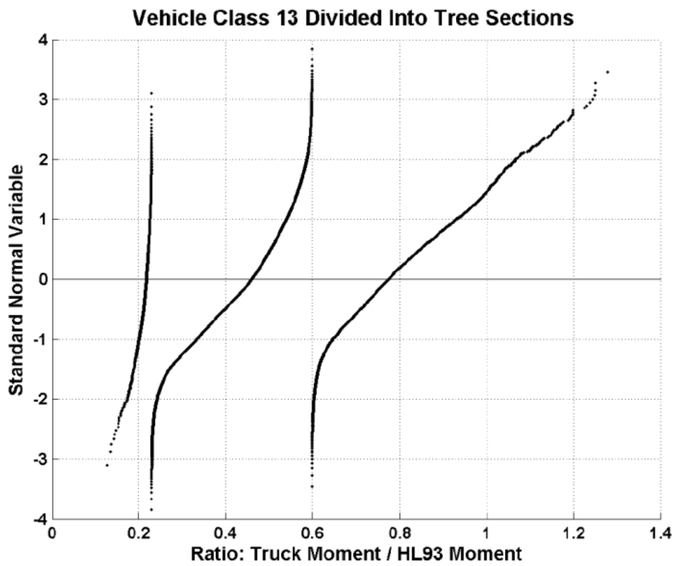


Figure 4 - Distributions of sets of vehicle class 13.

Number of trucks in each set and percentile to the total number of vehicles in class was calculated. Next, a straight line was fitted to each data set with the special attention to the center part of the distribution (+/-1 at the standard normal variable axis), Figure 5. Statistical parameters (mean value and standard deviation) were obtained directly from the graphs.

For vehicle class 13, three data sets were considered. Set 1 with the vehicles that caused moment ratio below 2.2 contains 4.88 % of all vehicles in this class. Mean value, μ, for this set is 0.22 and standard deviation, σ, is 0.03. Set 2 with vehicles which caused moment ratio between 2.2-0.6 contains 77.34 % of all vehicles in this class. Mean value, μ, for this set is 0.45 and standard deviation, σ, is 0.1. Set 3 with vehicles which caused moment ratio above 0.6 contains 17.78 % of all vehicles in this class. Mean value, μ, for this set is 0.79 and standard deviation, σ, is 0.15.

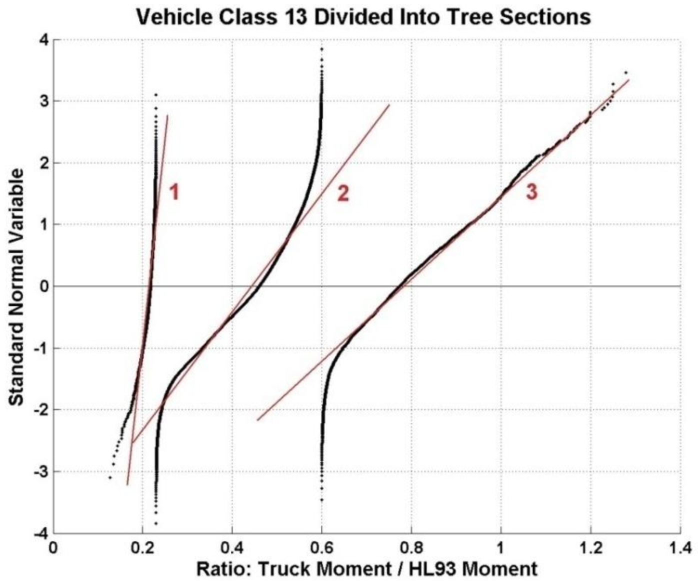


Figure 5 - Normal distributions fitted to WIM data for vehicle class 13.

The best fit to the vehicle class 13 was obtained when the set 1 was simulated within range 0.05 to 0.25, set 2 within range 0.23-0.6 and set 3 above 0.6. Generated moment ratios of vehicles class 13 are shown on Figure 6.

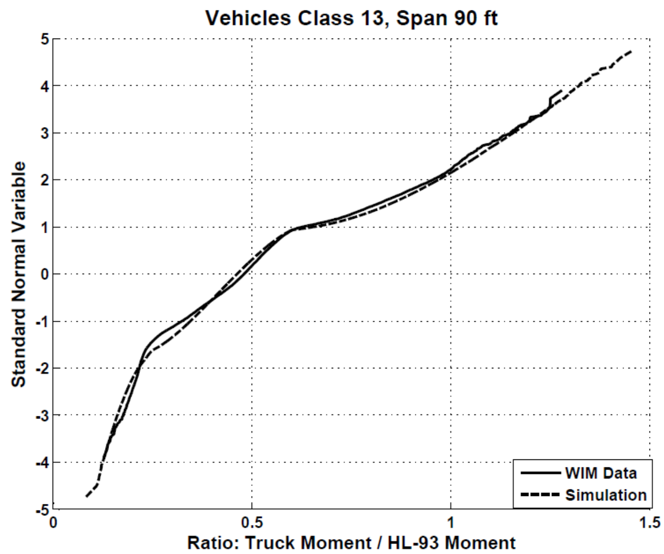


Figure 6 - Live load moment ratios for vehicle class 13.

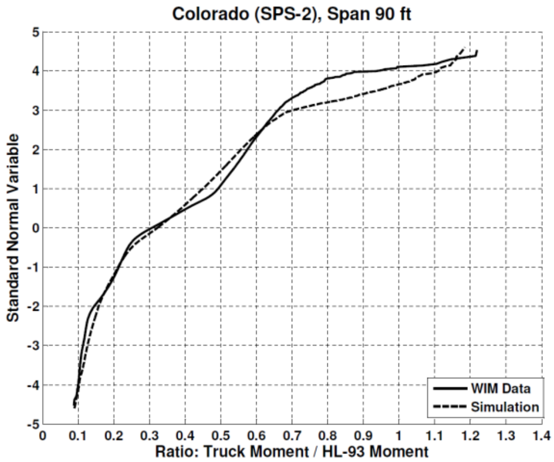
Similar procedure was repeated for vehicle of class 4-12. Statistical parameters for all considered vehicle classes are summarized in Table 1. All considered classes were simulated using two or three normal distributions, trimmed to appropriate ranges to obtain the best fit. Generated moment ratios for each vehicle class show good or very good fit to the actual values from WIM data.

Table 1 - Statistical parameters of simulation model.

Vehicle Class	Set	Trim Range	% of vehicles in class	Mean Value	Standard Deviation
4	1	> 0.08	31.30	0.16	0.02
	2	> 0.20	68.70	0.32	0.08
5	1	> 0.08	21.60	0.15	0.015
	2	> 0.15	78.40	0.17	0.08
6	1	> 0.08	78.58	0.175	0.017
	2	> 0.20	21.42	0.32	0.12
7	1	> 0.08	20.90	0.20	0.02
	2	> 0.20	79.10	0.555	0.07
8	1	0.10-0.30	80.40	0.22	0.03
	2	0.20-0.45	17.50	0.34	0.04
	3	> 0.45	2.10	0.53	0.09
9	1	> 0.08	22.30	0.22	0.03
	2	> 0.20	77.70	0.37	0.10
10	1	0.08-0.30	45.40	0.22	0.03
	2	0.30-0.70	54.50	0.43	0.06
	3	> 0.60	0.50	0.75	0.06
11	1	0.10-0.20	27.50	0.18	0.02
	2	0.20-0.45	47.20	0.30	0.08
	3	> 0.45	25.30	0.49	0.04
12	1	> 0.08	18.10	0.22	0.03
	2	> 0.20	81.90	0.33	0.07
13	1	0.08-0.25	4.88	0.22	0.03
	2	0.23-0.60	77.34	0.45	0.10
	3	> 0.60	17.78	0.79	0.15

3. Results of Simulation

For a few sites with the available WIM data, the simulations were carried out using developed algorithm. Results were plotted on the normal probability paper and compared with the actual distribution from the WIM data in Figures 7-8. In all simulated cases, the WIM data is very close to the actual live load.



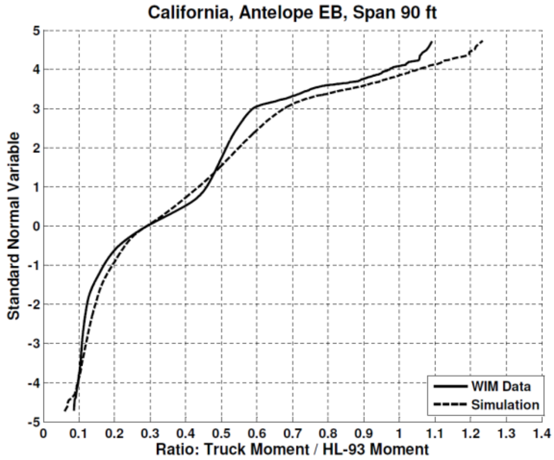
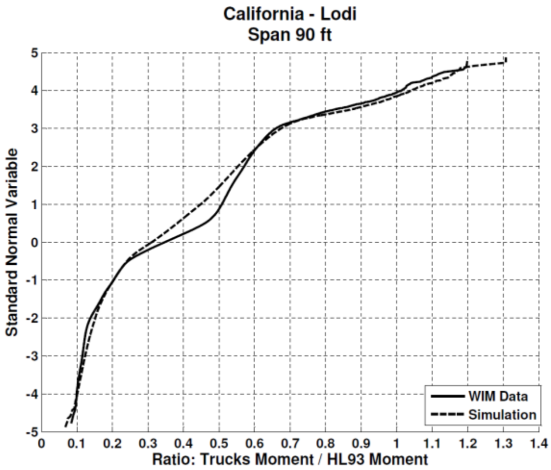


Figure 7 - Comparison of moment ratios based on WIM data and simulation for Colorado SPS-2 and California Antelope EB.



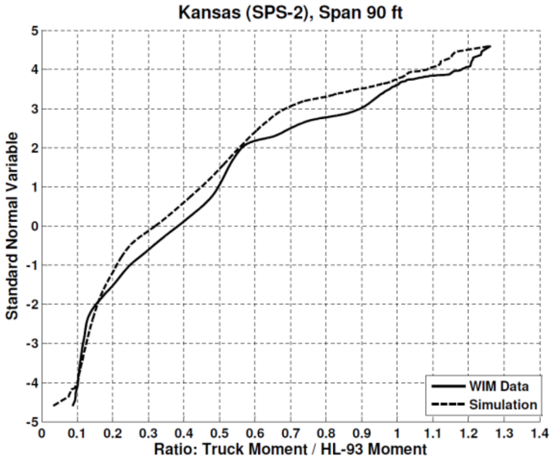


Figure 8 - Comparison of moment ratios based on WIM data and simulation for Lodi and Kansas SPS-2.

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MODELING TRAFFIC LOADS ON BRIDGES – A SIMPLIFIED APPROACH USING BRIDGE WIM MEASUREMENTS




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Abstract
Knowing the realistic loading of heavy traffic on existing road bridges is a key to an optimized structural safety assessment procedure. Within the recent European Commission Framework Programme (FP) research projects on Assessment and Rehabilitation of Central European Highway Structures (ARCHES, 2009), a reasonably simple approach to modeling the expected maximum traffic load effects has been developed. While based on the traditional convolution method, its main evolutions are that the indirect calculation of characteristic load effects through convoluted traffic loads is replaced by a procedure that convolutes directly the load effects, and that modeling of the tail of the distribution is simplified in order to allow fast calculation of expected maximum load effects based on the weigh-in-motion data and the relevant influence lines of a bridge. Efficiency of the method is illustrated with examples.
Keywords: Load modeling, convolution, traffic, bridge loading, Weigh-in-Motion, WIM.

Résumé
Connaitre les charges réalistes de trafic lourd sur les ponts existants est crucial pour optimiser la procédure d'évaluation de la santé structurelle. Dans le cadre du programme européen de recherche, des projets de recherche sur l'évaluation et la réhabilitation des structures des autoroutes européennes (ARCHES, 2009) ont mis en place une méthode pour modéliser les effets maximums de trafic prévus. Bien que basée sur la technique basique de convolution, elle permet de remplacer le calcul d'effets et l'extrapolation de convolution de trafics par une convolution directe d'effets du trafic. La modélisation de la queue de distribution est simplifiée, ce qui permet le calcul rapide des effets maximums à prévoir en se basant sur des données de trafic. L'efficacité de la méthode est démontrée par quelques exemples.
Mots-clés: Modélisation des charges, convolution, trafic, chargement de ponts, pesage en marche, WIM.

1. Introduction

Knowing the realistic loading of heavy traffic on existing road bridges is a key to an optimized structural safety assessment procedure. Codes of practice for the design of bridges such as Eurocode 1: Part 2 (EC1 2003) must be sufficiently general to be applicable to many different bridge types with widely varying traffic loading conditions and for the entire lifespan of the structures. However, bridge maintenance, especially if it includes major rehabilitation and reconstruction measures, is expensive, and bridge owners need to allocate limited resources efficiently. The available assessment codes that support maintenance decisions are also general, but due to having less unknowns (assessment is performed on specific bridges) they are less conservative (Moses, 2001). It is well recognized that site-specific assessment, based on measured traffic, can lead to significant cost reductions for maintenance.

The main challenge of evaluation of traffic loading is how to predict the probable maximum bridge load effects (bending moments, shears) over a selected lifetime. A common approach is to measure traffic data for some weeks, to fit a statistical distribution to the calculated load effects, and to use these distributions to estimate maximum lifetime effects. Several authors have proposed methods based either on fitting statistical, mainly Gumbel, Fréchet or Weibull, distributions to the data samples, or using Monte Carlo (MC) simulation to extrapolate the limited available traffic information. As an example, Sivakumar, Moses and Ghosn (2011) have fit a normal distribution to the upper 5% of the traffic data distribution. In this paper, this method is from here on denoted as the "NCHRP method".

To further investigate this issue, the recent European Commission FP6 project (ARCHES, 2009) proposed two methods for predicting the maximum expected load effects on bridges. Primarily, a detailed MC model was built at University College in Dublin and was calibrated against over a million trucks from WIM sites in two European countries (Enright, OBrien, & Dempsey, 2010). The model extrapolated not only vehicle weights but also types (axle configurations), and is considered to give a more realistic estimate of lifetime loading than other existing methods. Its downside is that it requires comprehensive expert knowledge about bridge traffic modeling and considerable computer power to obtain the results.
Alternatively, a straightforward method to modeling the expected maximum traffic load effects has been proposed. It applies simpler, yet fast, processing of the WIM data measured with the SiWIM bridge WIM system. This paper describes the procedure and demonstrates its efficiency using a test data sample that was used also in the ARCHES analysis.

2. Modified convolution method

The proposed approach is based on the convolution method ((Sivakumar, Ghosn, & Moses, 2011), (Žnidarič & Moses, 1997)) and assumes that the highest load effects are achieved when two vehicles from independent traffic flows in each traffic lane are placed side-by-side on a bridge at the place of the highest reaction. Such an approach can be justified on a majority of bridges with influence lines shorter than approximately 30 m (or even more on the integral, frame-type of structures), where, due to the typical length of heavy vehicles, the critical event occurs when there is one vehicle in each of the two lanes. The traffic loading information is obtained from the bridge-WIM measurements combined with the bridge influence lines. Results are presented as the expected maximum moments and shear forces in a specified time period.

The main advancement compared to the approach proposed by (Moses & Verma, 1987) is that the original indirect calculation of characteristic load effects through the convoluted traffic loads is replaced by calculating first the distributions of load effects and performing the convolution methods afterwards. This reduces the number of assumptions and subjective judgments. The recent NHCRP report (Sivakumar, Ghosn, & Moses, 2011) describes a similar approach. The computational procedure is divided into the following five steps:

1. Collection of weigh-in-motion data.
2. Calculation of load effects using influence lines, and generation of histograms.
3. Performing convolution of load effect histograms.
4. Evaluation of number of expected multiple-presence events on the critical section of the bridge.
5. Determination of convolution curves and, from there, the maximum load effects.

2.1 Collection of weigh-in-motion data

Heavy vehicle loading information can be collected with any reasonably accurate weigh-in-motion (WIM) system, with results in at least class C(15) according to European specifications for WIM (COST 323, 2002). It is beneficial if a bridge WIM system is used as it will provide measured influence lines that can optimise the analytical structural model of the bridge (Žnidarič, Lavrič, & Kalin, 2010). Regardless of the technology used, the WIM data for bridge load modeling should not only provide axle loads and configurations of each vehicle, but also their time stamps to one hundredth of a second, to allow accurate modeling of the extreme loading events.

2.2 Calculation of load effects

Traffic loads of individual vehicles from the data sample are converted into traffic load effects (bending moments, shear) by using influence lines (Žnidarič & Lavrič, 2010). In most cases theoretical influence lines are used but these can be replaced by the modeled influence lines based on bridge WIM measurements that will give more realistic load effects (ARCHES, 2009). To demonstrate the feasibility of the proposed convolution method, a theoretical influence line for a 25-m simply supported span was used in this paper.

The calculated static load effects are transformed into histograms that display the relative frequencies of load effects separately for each traffic lane. Intervals (bins) on the X-axis must be sufficiently small to provide good resolution of the histograms (Figure 1 and Figure 2). To allow for modeling of the tails of the distributions, the abscissa must exceed the maximum calculated load effects by at least 10%.

As can be seen from Figure 1, the values of the extreme load events are scarce, especially in the overtaking lane 2. This impedes the modeling of the tail and leads to a variety of possible results, depending on the method and parameters used (ARCHES, 2009). In order to smooth the distribution curve and to extend it beyond the highest measured values, a modified "moving average" approximation of histograms was considered. Contrary to the definition of the moving average, which averages data following the averaged data value, the approximation here is made by averaging the selected number of values before and after the averaged value. In Figure 1 and Figure 2 these smoothed approximated histograms are plotted as the thick continuous lines over the raw data bars.

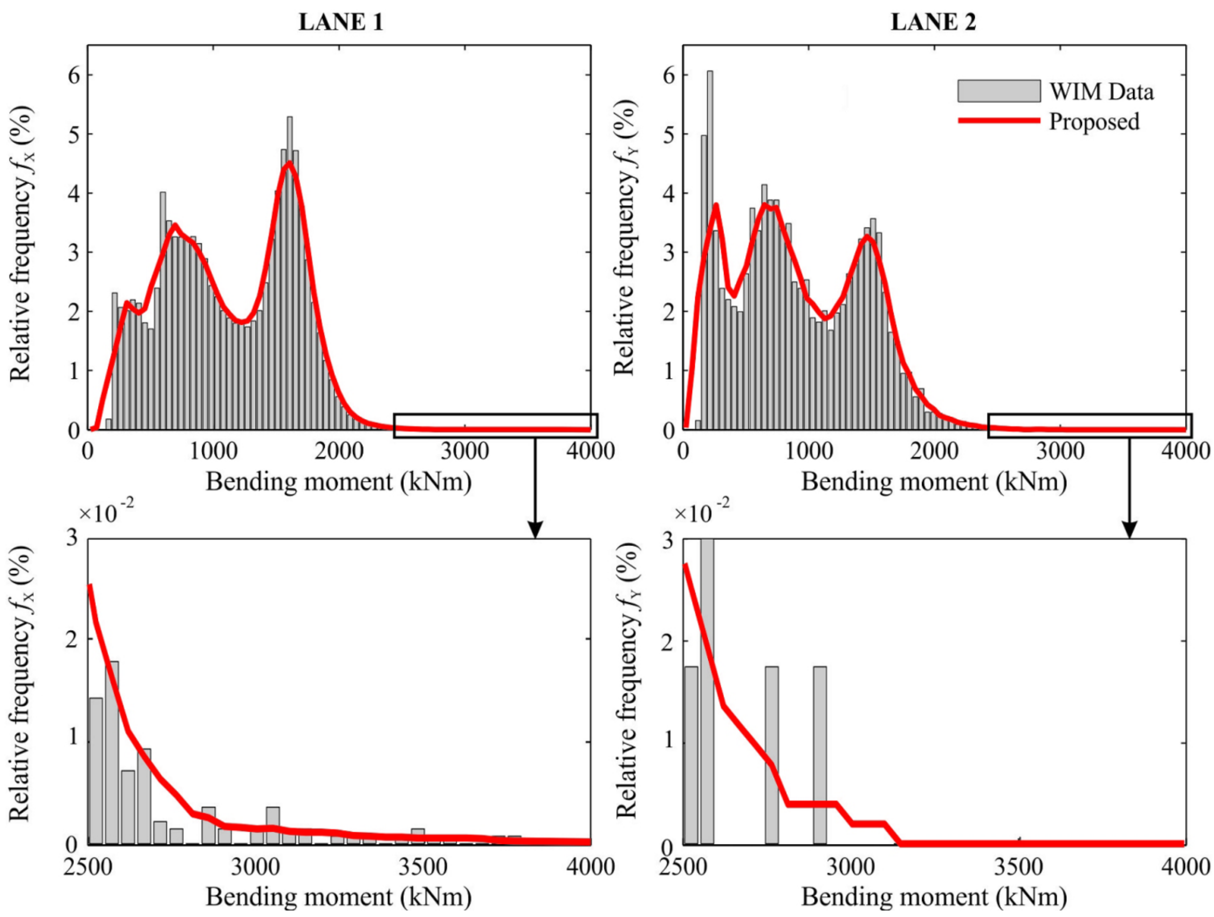


Figure 1 – Relative frequency histograms of bending moments for each lane

The number of points to average currently depends on subjective judgment and accounts for the number of vehicles in the population and the degree of overloading. With more reliable traffic information, fewer data points are averaged. Experience shows that averaging ±2 to ±10 points gives realistic modeling of the tail when comparing the results with more sophisticated methods. ±10 points means more conservative results as it emphasizes the tail much more towards the higher values. With the specific data sample ±2 points were averaged.

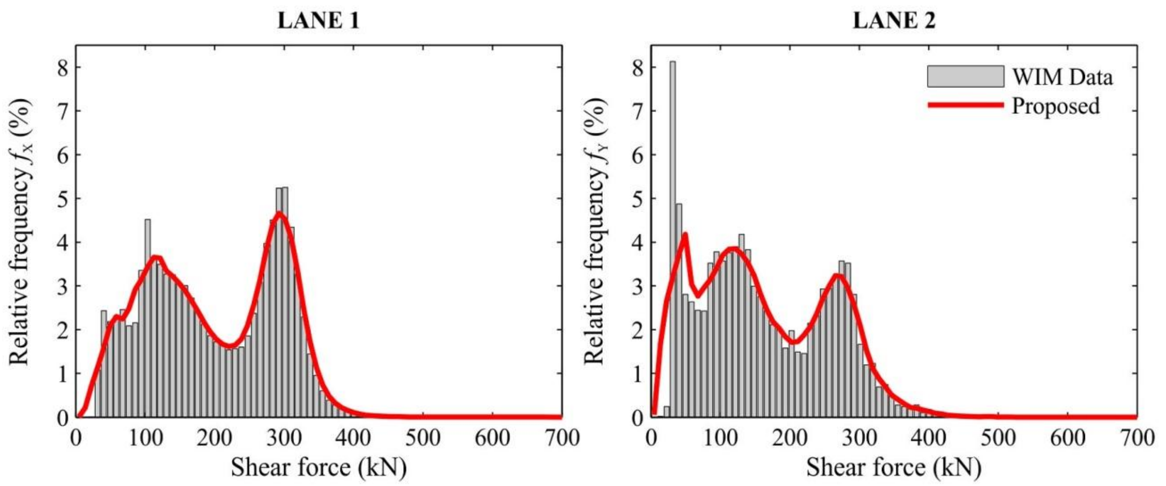


Figure 2 – Relative frequency histograms of shear forces for each lane

2.3 Convoluting the load effect histograms

In the next stage the approximated histograms of load effects are convoluted to determine the probability mass function and the corresponding cumulative distribution function (denoted as "convolution curve" in this paper) for an event composed of vehicles from both lanes. Assuming that the distributions of the load effects for lanes 1 and 2 are independent, the probability mass function for an event is expressed as:

$$\mathrm{f_Z(z)} = \sum_{\mathrm{k=1}}^{\mathrm{m}} \mathrm{f_X(k) \cdot f_Y(z - k)} \tag{1}$$

where f_X and f_Y are the PMF – probability mass functions (approximated histograms) of load effects for lane 1 and lane 2, and f_Z is the PMF of the load effects for an event comprising one vehicle from lanes 1 and 2. X and Y are assumed to be independent, i.e. traffic in lane 1 does not affect traffic in lane 2. Consequently, Z is equal to X + Y. If f_X and f_Y include *m* bins, then the length of f_Z consists of 2.*m*-1 bins.
In the next step, from the probability mass function of an event f_Z, the cumulative probability density function (probability curve F_Z(z)) is calculated.

2.4 Convolution curves and maximum load effects

To determine the convolution curves F_{max} for different time period *z,* the extreme value theory is applied (Ang & Tang, 1975):

$$\mathrm{F_{max}(z) = {F_Z}^N(z)} \tag{2}$$

where *N* is number of multiple-presence events, i.e. when vehicles from both lanes meet on the critical section of the bridge. Evaluation of *N* is described in section **Error! Reference source not found.**. **Error! Reference source not found.** shows the convolution curves for different time periods for bending moments (left) and shear forces (right). Results obtained from the proposed approximated histograms are compared to the results obtained using raw

WIM data and the *NCHRP tail modelling method*. The maximum load effects are defined as the median values of the functions F_{max}.

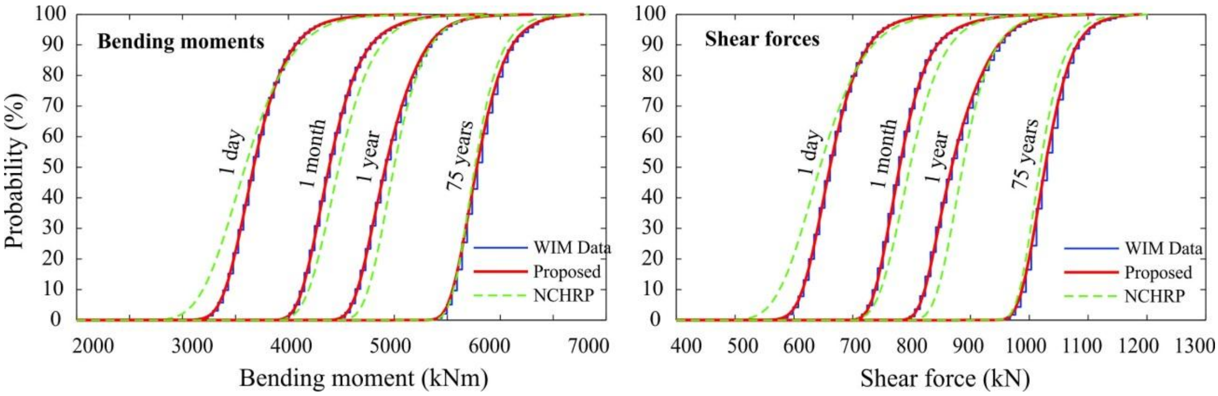


Figure 3 – Convolution curves for different time periods for bending moments and shear forces obtained by different procedures.

The total predicted maximum load effects (moments and shear forces) that are used in the process of structural assessment are adjusted with the *Dynamic Amplification Factor* and the load distribution factor. This topic exceeds the scope of this paper.

2.5 Number of expected events N

The number of expected convoluted events N governs how the maximum traffic loading on the bridge will increase over time. As more multiple-presence events (heavy vehicles meeting) occur on the bridge, the higher the forecasted load effect will be in a specified time period.

The SiWIM bridge-WIM system calculates N directly from the measured WIM database by checking whether individual pairs of vehicles meet within the critical section of the bridge or not. N is based on the assumption that a *multiple-presence event* occurs when the centres of gravity of two vehicles, following each other or meeting, lie within that part of the bridge where the area under the influence line (moments or shear) exceeds 50% of its total area. In other words, if both vehicles in a meeting event do not induce at least 50% of their maximum loading effects, this is not considered as a multiple-presence event. Details about the procedure for calculating *N* are given in (ARCHES, 2009).

3. Analysis of the results

Comparison of the results obtained by the proposed method with the results of the more advanced simulation method was conducted:

- using raw WIM data, i.e. with measured data without modeling of the tail,
- of modeling the tail (upper 5% of the data) with the normal distribution, as recommended in the NCHRP report 683 (Sivakumar, Ghosn, & Moses, 2011), and
- detailed simulation (Enright, OBrien, & Dempsey, 2010).

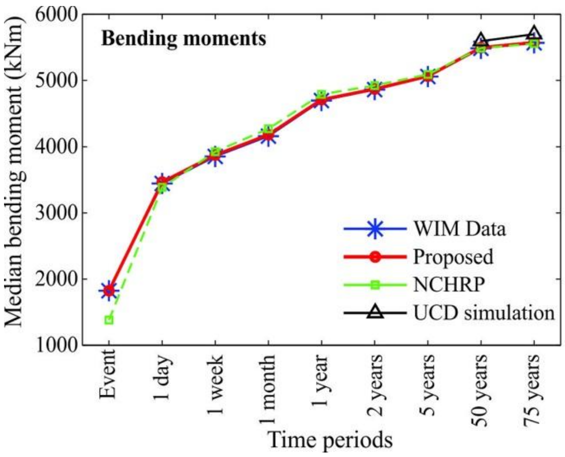
The same sample of WIM data measured on a motorway in Slovenia was applied on a 25-m long bridge with a simply supported influence line. Convolution curves in Figure 3 compare results of the proposed method with the raw WIM data and the NCHRP method. While there are some differences in median values for shorter time periods, these are narrowed down to 0.2% for bending moments (Table 1) and 0.6% for shear forces (Table 2).
In addition, both tables and Figure 4 compare MATLAB generated results of the three procedures with results of the full simulation method developed by UCD in the ARCHES project. Bending moments are very close to each other: the UCD values are 2.7% higher, but they had accounted for a probable increase of heavy vehicles' dimensions in the future. At the same time, only a low ±2 point moving average was applied in the proposed method. The values for shear are more conservative as the UCD method predicts 8% lower values.

Table 1. Comparison of the results – bending moments

Time period	Median				Standard deviation (%)			Proposed / NCHRP	Proposed / UCD
	WIM	Proposed	NCHRP	UCD	WIM	Proposed	NCHRP		
1 month	4 153.9	4 176.9	4 246.5		5.68	5.66	5.87	98,4%	
1 year	4 676.1	4 698.7	4 800.2		5.54	5.36	4.56	97,9%	
5 years	5 053.8	5 062.2	5 117.0		4.44	4.43	3.98	98,9%	
50 years	5 510.5	5 519.3	5 530.1	5 646.5	3.89	3.85	3.39	99,8%	97,7%
75 years	5 586.9	5 594.4	5 598.7	5 750.5	3.75	3.75	3.29	99,9%	97,3%

Table 2. Comparison of the results – shear forces

Time period	Median				Standard deviation (%)			Proposed / NCHRP	Proposed / UCD
	WIM	Proposed	NCHRP	UCD	WIM	Proposed	NCHRP		
1 month	715,9	721,1	732,4		7.29	7.02	5.33	98,5%	
1 year	797,1	802,4	824,9		2.97	3.10	4.25	97,3%	
5 years	865,5	866,6	877,8		3.54	3.38	3.75	98,7%	
50 years	949,7	951,2	946,9	876.0	4.06	3.64	3.22	100,4%	108,6%
75 years	963,2	963,9	958,3	891.0	3.59	3.31	3.14	100,6%	108,2%



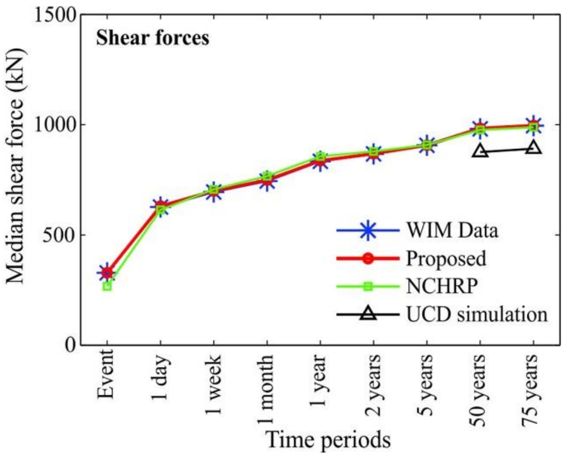


Figure 4 – Median bending moments for different time periods obtained by different procedures.

Using the same data sample, Figure 5 illustrates results of the proposed method generated directly by the SiWIM bridge-WIM system.

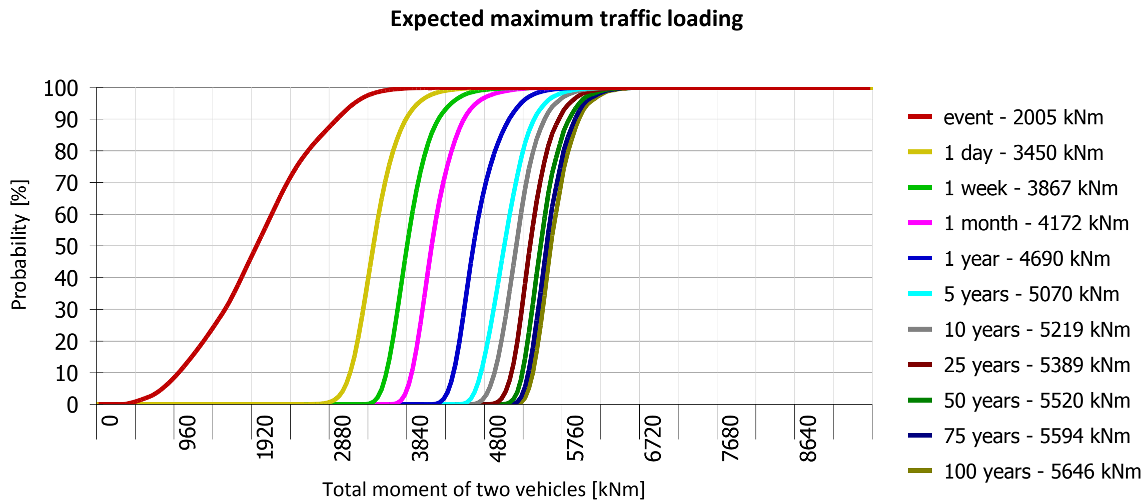


Figure 5 – Convolution results for bending moments as calculated by the SiWIM system

4. Conclusion

Bridge weigh-in-motion systems have experienced considerable development in recent years, not only as measuring devices but also as suppliers of vital data to optimize bridge assessment procedures. In order to apply the measured WIM data more directly in structural analysis (prediction of maximum traffic load effects on bridges), a procedure was developed that uses simple statistical methods to model the tail of load effect distributions and then the traditional extreme value theory approach to extrapolate information to longer time periods. Its main advantages are that is computationally very fast and that is implemented in a bridge-WIM system to employ it directly on measured data. Its disadvantage remains that currently it is only applicable to short to medium-span 2-lane bridges, where a critical loading event is induced by only two vehicles meeting on the bridge. This is mitigated by the fact that such bridges in most countries typically comprise over 90% of entire population of bridges, which greatly increases the potential of the method. Furthermore, additional work is needed to select the number of averaged data points which has a notable effect on the loading predictions.

Nevertheless, comparisons with other available methods show that the results are very close to the results obtained by the method from the NCHRP 683 report (Sivakumar, Ghosn, & Moses, 2011). On the concrete data sample used for this paper, the results for bending moments were also within 3% of the results of the very advanced simulation procedure

(Enright, OBrien, & Dempsey, 2010) that predicts potential increase of physical growth of heavy vehicles. The results for shear were on the conservative side for 8%.

5. Acknowledgments

The authors wish to express their gratitude to the EC for the financial support of the ARCHES 6th Framework project.

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USE OF WEIGH-IN-MOTION (WIM) DATA FOR SITE-SPECIFIC LRFR BRIDGE RATING

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Abstract

In this paper, truck weigh-in-motion (WIM) data are used to develop live load factors for use on Alabama state-owned bridges. The factors are calibrated using the same statistical methods that were used in the original development of AASHTO's Load and Resistance Factor Rating (LRFR) Manual. This paper describes the jurisdictional and enforcement characteristics in the state, the WIM data filtering, sorting, and quality control, as well as the calibration process. Large WIM data sets from five sites were used in the calibration and included different truck volumes, seasonal and directional variations, and WIM data collection windows. Certain MATLAB programs were developed in the live load factor calibration process. The resulting state-specific live load factors are smaller than those of LRFR manual and are recommended to the Alabama Department of Transportation (ALDOT) in rating their bridges more efficiently.

Keywords: Live load factors, Bridge rating, Weight-In-Motion, LRFR

Résumé

Dans ce papier, les données de pesage en marche de poids lourds sont utilisées pour développer des coefficients de calcul des charges temporaires. Ceux-ci sont calibrés en utilisant les mêmes méthodes que celles développés initialement pour le guide de l'association AASHTO sur l'évaluation des facteurs de charge et de résistance (LRFR en anglais). Cet article décrit aussi les caractéristiques juridiques et la verbalisation dans cet Etat, la manière de nettoyer les fichiers de trafic, classer ceux-ci, le contrôle de qualité, le processus de calibration. De grandes quantités de données de trafic de cinq sites de pesage en marche ont été utilisées pour la calibration. Elles contenaient différentes sortes de poids lourds, des variations saisonnières et directionnelles et différentes périodes d'enregistrement. Divers programmes MATLAB ont été développés pour la calibration des coefficients de charges temporaires. Ces derniers, qui sont ainsi spécifiques aux sites étudiés, sont inférieurs à ceux du manuel LRFR. Ils sont recommandés au département des transports de l'Etat d'Alabama (ALDOT en anglais) pour évaluer leurs ouvrages de manière plus efficace.

Mots-clés: Charges temporaires, évaluation des ouvrages d'art, pesage en marche, LRFR.

1. Introduction

As of 2009 over 24% of bridges in the United States are structurally deficient or functionally obsolete and 30% are over 50 years old (U.S. DOT, 2009). Deteriorating bridges can lead to a reduced load rating and the requirement to post a bridge for a live load significantly below the legal limit, resulting in transportation network inefficiencies. One method for load rating bridges is to use the American Association of State Highway and Transportation Official's (AASHTO) Load and Resistance Factor Rating (LRFR) Manual (AASHTO, 2003). For bridge rating and evaluation, LRFR Specifications are the transition from the AASHTO Manual for Condition Evaluation of Bridges (AASHTO, 1994), and the specifications extend the limit states design philosophy from AASHTO load and resistance factor design (LRFD) (AASHTO, 2004) to evaluation of existing bridges. The live load factors presented in the LRFR Manual are, therefore, the result of the live load calibration for the LRFD Specifications and are meant to encompass legal trucks and certain exclusion vehicles across the United States. However, realizing that these load factors may be overly conservative for load rating and posting bridges, the LRFR Manual allows for the determination of site-specific live load factors using a statistical analysis of weigh-in-motion (WIM) data at or near the bridge site. Due to the lack of reliable truck data in the United States at that time, the truck data from the Ontario Ministry of Transportation were used in the calibration of this live load factor. To yield the most accurate bridge ratings, site-to-site variability of live loads should be incorporated in the reliability analyses (Ghosn and Moses, 1986). Following the methodology developed in NCHRP Project No. 12-46 (Moses, 2001) and incorporated in the LRFR specifications, live load factors for strength evaluation were developed for state-owned bridges in Alabama using WIM data from sites across the state. This paper investigates five WIM sites in Alabama to determine live load factors more representative of truck traffic in the state based on the characteristic vehicle population. Significant differences in permitting requirements exist in different States in the United States. Thus, to evaluate the impact of truck weight regulations on site-specific live load factors, the WIM data is sorted in accordance with the truck weight regulations in force in Alabama and Oregon, respectively. The purpose of the comparison analysis concerning the regulations for both Alabama and Oregon is to provide more accurate site-specific live load factors for the evaluation of existing bridges in Alabama and to provide guidelines for the determination of live load factors for other states with different enforcement regulations.

2. Live Load Factor Methodology

It is assumed when determining the live load factors that only the top 20 percent of the truck weight population influences the maximum loading events (Moses, 2001). The maximum loading event for calibration places a legal truck or a permit truck (whichever is the rating vehicle of interest at the time) in one lane and a random truck (referred to as the alongside vehicle) in the adjoining lane (Pelphrey et al, 2008). Therefore, the basic case for load rating in accordance with the LRFR Manual occurs with two-lanes of live load, and live load factor for the rating vehicle is influenced by both the weight of the rating vehicle and that of the random alongside one.

2.1 Selection of WIM Sites in Alabama and Data Collection

Five specific WIM sites on five highways were selected based on the truck volume, and WIM data were collected from ALDOT's website for 2008 at the sites 911, 915, 934, 942, and 960, along each route, respectively. The traffic volume for each site is shown in Table 1. In order to determine the optimum time for data collection, each month was divided into three periods, including: (1) the entire month; (2) the first 2 weeks from 1st to 14th; and (3) the last 2 weeks from 15th to 28th. In addition, each calendar year of data was divided into four seasons: winter, spring, summer, and fall. Each season covered three months, with winter including Dec – Feb, spring including Mar – May, summer including June – Aug, and fall including Sep - Nov.

Table 1 - Total traffic volume and truck traffic volume at each WIM site

Site	Location	ADTT	TADT	Winter	Spring	Summer	Fall
911	Coosa County / US-280	1722	17%	Dec, Jan, Feb	Mar, Apr, May	Jun, Jul, Aug	Sep, Oct, Nov
915	Washington County / US-43	1393	18%	Dec, Jan, Feb	Mar, Apr, May	Jun, Jul, Aug	Sep, Oct, Nov
934	Walker County / US-78	3065	17%	Dec, Jan, Feb	Mar, Apr, May	Jun, Jul, Aug	Sep, Oct, Nov
942	Montgomery County / US-231	3175	22%	Dec, Feb	Mar, Apr, May	Jun, Jul, Aug	Oct, Nov
960	Clarke County / US-84	827	22%	Dec, Jan, Feb	Mar, Apr, May	Jun, Jul	Sep, Oct, Nov

Note: (1) ADTT means Average Daily Truck Traffic and TADT means percentage of Trucks in the Average Daily Traffic.

2.2 Sorting WIM Data by Vehicle Weight

Each state has their own regulations for determining legal weights and different classifications of permit weights. Two approaches were used to classify the site-specific data. One sorting is based on the classifications of vehicle weight used by the Oregon Department of Transportation (ODOT) and presented in five ODOT permit Weight Tables. The other approach is based on the classification used by ALDOT. ALDOT classifies trucks into three broad categories based on weight as: (1) Legal trucks; (2) Annual permits or continuous trip permits (CTP) which can be divided into two subcategories (a) Annual Permit (no routing); (b) Annual Permit (routing); and (3) Single Trip Permits (STP).

The raw WIM records from each collection site were provided in text format for data processing. Several programs were written in MatLab to organize and filter the data to remove records with formatting mistakes, spurious data, and other errors. The data was filtered using the criteria presented by Pelphrey et al. in 2008 (Pelphrey et al., 2008). In addition, NCHRP Report 454 (Moses, 2001) indicates that the live load factors should be calculated based on one direction of data. For the brevity, this paper just lists the filtered vehicles numbers of site 911 as in table 2.

Table 2 - Vehicle number of different directions for each month of site 911

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Total	36063	49400	54435	57739	53040	61510	43344	53617	56699	56912	51813	50402
West	31221	26747	29552	30664	20905	32303	17111	26652	25854	26366	24525	24174
East	4842	22653	24883	27075	32135	29207	26233	26965	30845	30546	27288	26228
% of West	86.6%	54.1%	54.3%	53.1%	39.4%	52.5%	39.5%	49.7%	45.6%	46.3%	47.3%	48.0%
% of East	13.4%	45.9%	45.7%	46.9%	60.6%	47.5%	60.5%	50.3%	54.4%	53.7%	52.7%	52.0%

After filtering the WIM data, the truck records were sorted into proper permit Weight Tables. Two sorting algorithms were used, which are noted as conventional sort and modified sort in this paper. The conventional sort method sorts vehicles based on their GVW, axle group weights, and length (GVW + axle group sort) in accordance with the detailed Weight Tables. The modified sort method sorts vehicles based only on their GVW and rear-to-steer axle length, and it does not account for axle groupings (GVW + truck length sort) (Pelphrey et al., 2008).

2.3 Sorting Results Based on ODOT Regulation

As ODOT has detailed permit Weight Tables, the conventional sort method was used to classify trucks into permit Weight Tables 1, 2, 3, 4, and 5, or Weight Table X in accordance with the ODOT regulations. The column Weight Table X represents the trucks that did not meet the criteria for Weight Tables 1-5 (Pelphrey et al., 2008). For the brevity, herein we just list the sorting results for the whole month to the West direction as table 3; the sorting results for the first two weeks (1st-14th) and the last two weeks (15th-28th) are not listed. Statistical values that were calculated based on the GVW of the top 20% of the 3S2 legal truck and the alongside one, respectively, were listed in table 4.

2.4 Sorting Results Based on ALDOT Regulation

The conventional sort method was used to classify trucks into Weight Table 1 representing legal trucks in accordance with the ALDOT regulations. The modified sort was used to classify permit trucks according to the ALDOT regulations into Weight Table 2, representing CTP's that do not require routing, Weight Table 3, representing CTP's that do require annual routing, and Weight Table 4, STP's. For each sorting routine, a small portion of the WIM data could not be classified according to the weight regulations and these records were placed into Weight Table X. The sorting results of each month of site 911 to the West direction are listed in table 5. Statistical values based on the GVW of the top 20% of the rating and alongside truck are listed in table 6.

Table 3 Number of vehicles of site 911 to the West direction – ODOT sort

Season	Month	Weight Table 1	Weight Table 2	Weight Table 3	Weight Table 4	Weight Table 5	Weight Table X	Total Records	CTP from WT3 to WT2	3S2 truck	Along-side truck	Permit truck	STP per day	Days
Winter	Dec	22293	1	1441	12	3	424	24174	1312	8917	23606	568	18	31
	Jan	29196	23	1838	14	1	149	31221	1283	8885	30502	719	23	31
	Feb	25239	12	1370	14	0	112	26747	723	5951	25974	773	27	29
Spring	Mar	27835	51	1490	33	0	143	29552	1162	9808	29048	504	16	31
	Apr	28876	45	1479	67	5	192	30664	1023	9353	29944	720	24	30
	May	19624	25	1101	25	1	129	20905	841	6816	20490	415	13	31
Summer	Jun	30456	14	1647	32	0	154	32303	1259	1050	31729	574	19	30
	Jul	16206	8	762	22	2	111	17111	624	6197	16838	273	9	31
	Aug	25181	7	1276	9	2	177	26652	1189	1084	26377	275	9	31
Fall	Sep	24246	10	1400	16	1	181	25854	1286	1070	25542	312	10	30
	Oct	24473	5	1479	41	4	364	26366	1345	1025	25823	543	18	31
	Nov	22879	8	1279	8	6	345	24525	1150	9035	24037	488	16	30

Note: The column Days means the effective days in the data recording.

Table 4 Statistics of trucks to the West direction of site 911 - ODOT sort

Statistic Items	Winter				Spring				Summer				Fall			
	Dec	Jan	Feb	Season	Mar	Apr	May	Season	Jun	Jul	Aug	Season	Sep	Oct	Nov	Season
W^*_{3S2}	71.34	72.86	72.91	72.37	72.73	72.15	72.71	72.52	73.36	72.54	72.27	72.77	72.02	71.61	71.52	71.74
σ^*_{3S2}	2.94	2.63	2.37	2.68	2.66	2.51	2.46	2.56	2.33	2.40	2.58	2.44	2.51	2.87	2.89	2.74
W^*_{along}	70.38	67.28	62.32	66.94	69.35	67.67	69.31	68.73	69.20	68.73	70.37	69.55	71.24	70.29	69.63	70.47
σ^*_{along}	8.53	10.58	12.60	10.58	8.56	9.23	8.32	8.75	8.50	8.28	7.22	7.96	6.84	8.08	8.63	7.78

Table 5 Number of vehicles of site 911 to the West direction – ALDOT sort

Season	Month	Weight Table 1	Weight Table 2	Weight Table 3	Weight Table 4	Weight Table X	Total Records	3S2 truck	Number of CTPs	CTP per day	Days	Number of STPs
Winter	Dec	22621	1529	23	0	1	24174	9218	1552	50	31	1
	Jan	29807	1399	11	0	4	31221	9308	1410	45	31	4
	Feb	25709	1028	8	0	2	26747	6202	1036	36	29	2
Spring	Mar	28338	1194	11	0	9	29552	10209	1205	39	31	9
	Apr	29341	1286	32	0	5	30664	9661	1318	44	30	5
	May	20006	877	22	0	0	20905	7108	899	29	31	0
Summer	Jun	31006	1285	9	1	2	32303	10984	1294	43	30	3
	Jul	16460	642	7	0	2	17111	6418	649	21	31	2
	Aug	25528	1117	6	0	1	26652	11173	1123	36	31	1
Fall	Sep	24569	1273	12	0	0	25854	10997	1285	43	30	0
	Oct	24830	1506	28	1	1	26366	10587	1534	49	31	2
	Nov	23145	1359	21	0	0	24525	9284	1380	46	30	0

Note: The number of alongside truck is the vehicle numbers belong to Weight Table 1.

Table 6 Statistics of trucks to the West direction of site 911 - ALDOT sort

Statistic Items	Winter				Spring				Summer				Fall			
	Dec	Jan	Feb	Season	Mar	Apr	May	Season	Jun	Jul	Aug	Season	Sep	Oct	Nov	Season
W^*_{3S2}	72.50	74.27	74.03	73.63	73.96	73.20	73.86	73.67	74.52	73.53	73.16	73.82	72.85	72.70	72.53	72.71
σ^*_{3S2}	2.95	2.58	2.42	2.69	2.68	2.72	2.49	2.66	2.32	2.43	2.52	2.43	2.53	2.86	2.97	2.77
W^*_{along}	64.33	62.52	59.09	62.05	65.46	63.82	65.43	64.85	65.64	65.38	66.33	65.85	66.78	65.03	64.18	65.42
σ^*_{along}	8.56	10.56	11.86	10.48	8.49	8.98	8.40	8.66	8.85	8.43	7.52	8.26	6.80	8.24	8.70	7.87

3. Calculation of Live Load Factors

In order to make a comparison and provide more detailed information in evaluating existing bridges for ALDOT and other states as well, the live load factors for legal vehicles, CTP's and STP's were developed based on the two sorting methods, say, the ODOT sort and ALDOT sort.

3.1 Live Load Factors Based on Oregon Regulation

NCHRP Report 454 gives the equations for the LRFR live load factors based on two-lanes of live load (Moses, 2001). Pelphrey et al. (2008) modifies the equations and calibrate the site-specific live load factors for Oregon based on the WIM data base of the state. In addition, Oregon DOT has a set of 13 rating vehicles (including legal, CTP, and STP) with detailed figures (ODOT, 2011). The first calibration method of live load factor for Alabama is based on Oregon regulation and strictly follows the process applied in Oregon. Similarly, five years is used for the evaluation period and the possibility of side-by-side occurrence is same as that applied in Oregon.

3.2 Live Load Factors Based on ALDOT Regulation

The second calibration method is based on Alabama regulation and strictly follows the process applied in NCHRP Report 454 (Moses, 2001). The report gives the specific equation to calibrate the live load factor for legal truck based on the statistics parameter of legal trucks for two-lane case and one-lane case, respectively. As the calibration process in Oregon are based on two-lane case, herein, in order to make a comparison with the live load factors calculated based on ODOT regulations, the two-lane case was chosen to calibrate the live load factor for legal trucks.

NCHRP Report 454 also mentions that in the case of routine permits, there is random traffic alongside the permit vehicle, while special permits, on the other hand, are assumed to cross the span without another truck alongside. This means for CTPs, the two-lane case will govern the live load calibration; while for STPs, the one-lane case will dominate.

The calibrated live load factors for STP vehicles in terms of ODOT regulation are based on two-lane case. In order to make a comparison of the results based both on ALDOT regulations and ODOT ones, we should estimate the average equivalent two-lane live-load factor by dividing one-lane factor by 1.7 (Moses, 2001). However, for the STPs, if the number of crossings during the total during evaluation period is less than one, the live load factor for the rating vehicles will be a constant equaling to 1.08 (the equivalent two-lane live load factor is taken as 0.64).
ALDOT does not have specific rating vehicles in the state, so the ODOT vehicles were used to determine live load factors for comparison when sorting the WIM data in accordance with ALDOT regulations. Due to the differences in permit weight classifications, several permit rating vehicles of ODOT were reclassified as following: OR-CTP-2A and OR-CTP-2B are treated as STP vehicles according to ALDOT classifications; OR-STP-3 is classified as an annual permit with routing and OR-STP-4A as an annual permit without routing. The proposed rating vehicles (including 13 rating vehicles of ODOT) are referred to table 7.

4. Results of Site-specific Live Load Factor

Site-specific live load factors were calculated for five WIM sites in Alabama using both the ODOT and ALDOT regulations. Herein we just illustrate the results for site 911. The effect of different time windows and directions on the calculated live load factors for each rating vehicle based on ODOT regulation and ALDOT one are illustrated in figures 1 and 2, respectively.

By comparing the plots for the three collection windows, it can be determined that a continuous two weeks of WIM data is generally sufficient to accurately determine the live load factors for legal trucks and CTP trucks, but may not be sufficient to determine the live load factor for STP trucks. To determine the live load factor for STP trucks using a two week interval of data, that interval should be selected carefully to ensure that the average number of STP trucks crossing the site per day during the interval exceeds one. Figure 3 shows the comparison of live load factor of different sites among the LRFR Manual, the

Oregon site-specific live load factor with similar ADTT, and the Alabama site-specific live load factor based on different sorting method. The live load factors from different sources are listed in table 7.

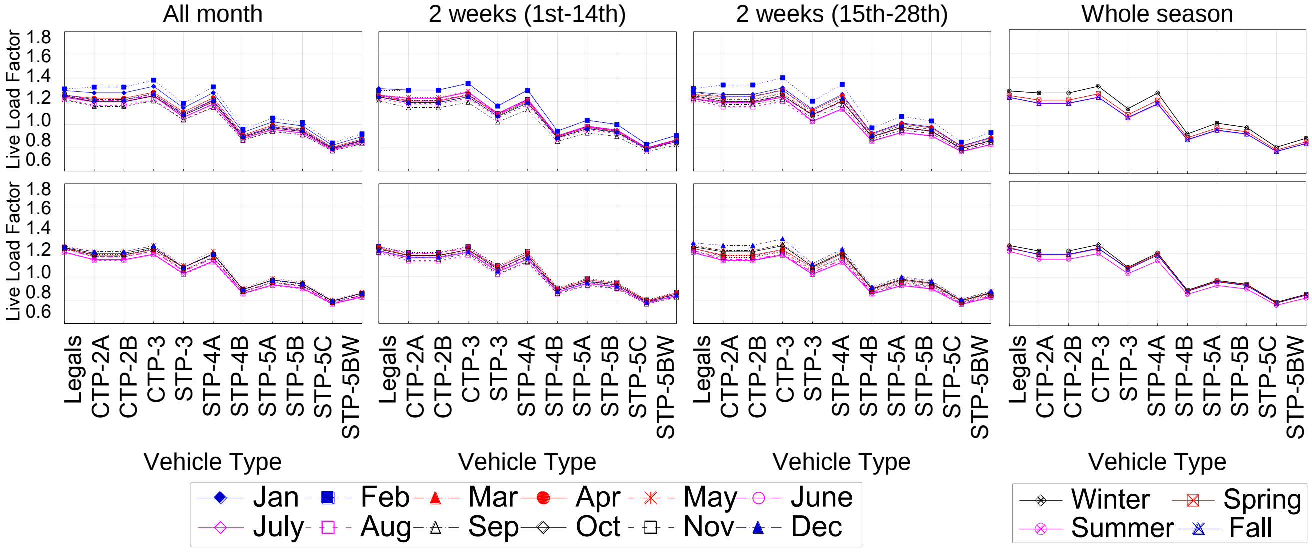


Figure 1 - Live load factors for WIM site 911 at different time windows– ODOT sort

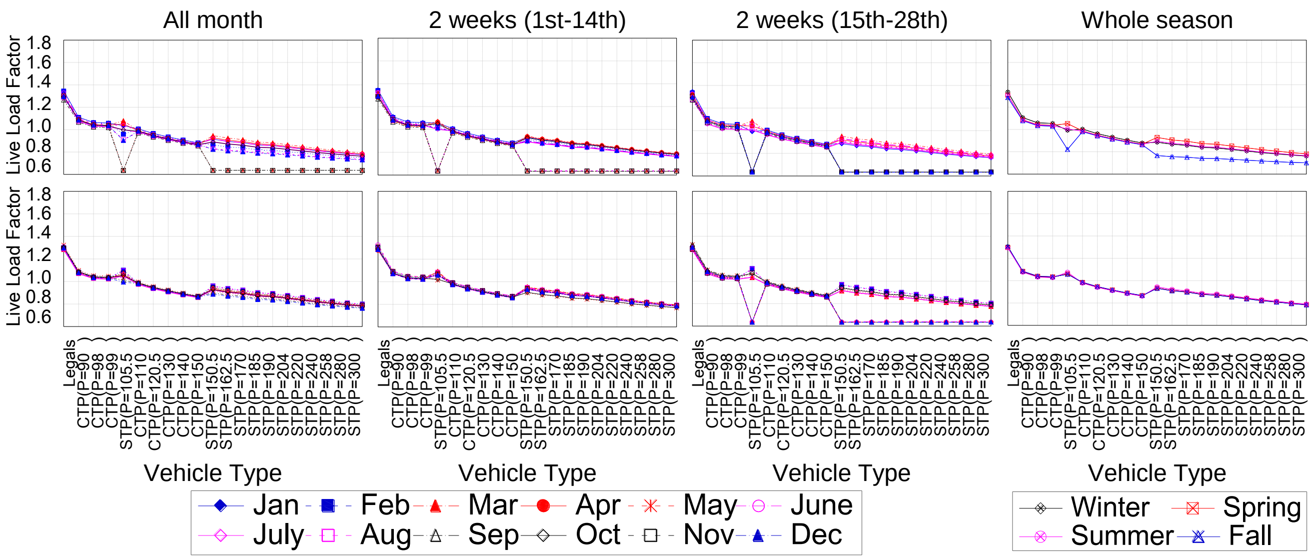
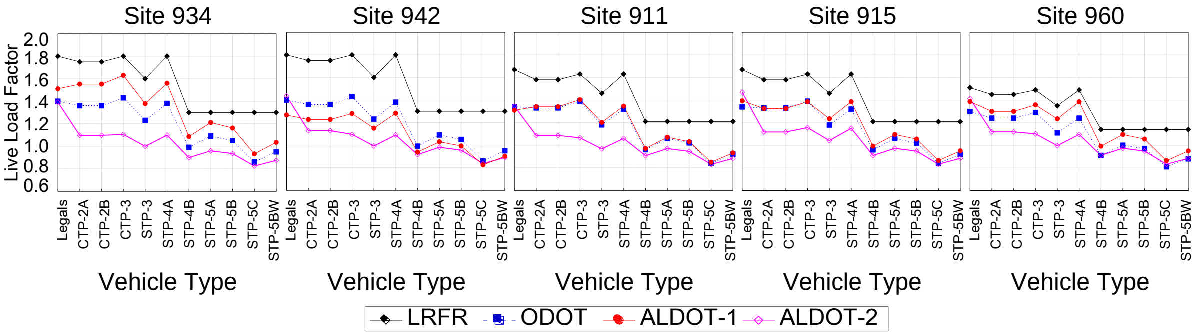


Figure 2 - Live load factors for WIM site 911 at different time windows– ALDOT sort



Note: (1) "ODOT" means the live load factor based on the Oregon data base with ODOT sort; (2) "ALDOT-1, ALDOT-2" means the live load factor based on the Alabama data base with the application of the ODOT sort and ALDOT sore, respectively.

Figure 3 - Comparison of live load factor of different sites

Table 7 Comparison of live load factors at different sites

ODOT	ALDOT	Live load Factor by ADTT											
		ADTT≈5000				ADTT≈1500				ADTT≈500			
		①	②	③	④	①	②	③	④	①	②	③	④
Legals	Legals	1.80	1.40	1.27	1.44	1.67	1.34	1.39	1.47	1.51	1.30	1.39	1.41
	CTP (P=90)				1.16				1.21				1.15
CTP-3 (98)	CTP (P=98)	1.80	1.43	1.28	1.11	1.63	1.39	1.40	1.16	1.49	1.29	1.36	1.10
STP-4A (99)	CTP (P=99)	1.80	1.38	1.28	1.10	1.63	1.32	1.39	1.15	1.49	1.24	1.39	1.10
CTP-2A/2B (105.5)	STP (P=105.5)	1.75	1.36	1.23	1.13	1.58	1.33	1.34	1.12	1.45	1.24	1.30	1.12
	CTP (P=110)				1.04				1.09				1.04
STP-3 (120.5)	CTP (P=120.5)	1.60	1.23	1.15	1.00	1.46	1.18	1.24	1.04	1.35	1.11	1.23	1.00
	CTP (P=130)				0.97				1.01				0.96
	CTP (P=140)				0.94				0.97				0.93
	CTP (P=150)				0.91				0.94				0.91
STP-5A (150.5)	STP (P=150.5)	1.30	1.09	1.03	0.98	1.21	1.06	1.10	0.97	1.14	1.00	1.10	0.97
STP-5B (162.5)	STP (P=162.5)	1.30	1.05	0.99	0.96	1.21	1.02	1.06	0.95	1.14	0.97	1.06	0.95
	STP (P=170)				0.94				0.94				0.94
STP-4B (185)	STP (P=185)	1.30	0.99	0.94	0.92	1.21	0.96	0.99	0.91	1.14	0.91	0.99	0.91
	STP (P=190)				0.91				0.90				0.90
STP-5BW (204)	STP (P=204)	1.30	0.95	0.90	0.89	1.21	0.92	0.95	0.89	1.14	0.88	0.95	0.89
	STP (P=220)				0.87				0.87				0.87
	STP (P=240)				0.85				0.85				0.85
STP-5C (258)	STP (P=258)	1.30	0.86	0.83	0.84	1.21	0.84	0.87	0.83	1.14	0.81	0.86	0.83
	STP (P=280)				0.82				0.82				0.82
	STP (P=300)				0.81				0.81				0.81

Note: (1) Column ① means the live load factors from LRFR; Column ② means the live load factors are computed based on Oregon WIM data and Oregon regulations; Columns ③ and ④ mean the live load factors are computed based on Alabama WIM data with Oregon regulation and Alabama regulation, respectively; (2) The live load factor for columns ③ and ④ are the selected maximum value considering: two different directions, four different time windows, and sites with similar ADTT, after leaving out the data of those months which have missing data record over four days and significantly large standard deviation.

5. Conclusions and Recommendations

(1) A statewide calibration of live load factors is investigated for LRFR bridge load rating by ALDOT. Lower factors compared to those presented in the LRFR Manual are developed utilizing large sets of WIM data from five highways within Alabama.

(2) In accordance with the original LRFR calibration process, the WIM data were filtered and organized so that high quality data were used to yield reliable statistical values. The live load factors were calculated based on ODOT and ALDOT permit weight

classifications, and both classification systems resulted in live load factors less than those of the LRFR Manual.

(3) The live load factors calculated from traffic traveling in different directions does not demonstrate obvious differences if the volume of traffic does not differ significantly between the two directions. Seasonal variations in the calculated live load factors are also not large.

(4) The live load factors for STPs for the ODOT regulation are not as reliable as for the ODOT classification. It this case, it is recommended to use a longer data collection window until sufficient STP crossings are encountered. Two weeks of data collection is acceptable for the live load factor calibration for legal vehicles and CTP vehicles.

(5) The live load factors in LRFR Manual are overly conservative for efficiently and economically evaluating bridges. It is recommended that ALDOT consider using site specific live load factors when load rating bridges to improve network efficiency, especially when the prescribed live load factors result in a bridge needing to be posted.

6. Acknowledgements

The project is supported by the National Science Foundation (1100742) and National Natural Science Foundation of China (51178178).

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A COMBINED WEIGH-IN-MOTION AND STRUCTURAL HEALTH MONITORING SYSTEM ON A WISCONSIN-MICHIGAN BORDER BRIDGE

Earned B.S. (computer engineering) and M.S. (civil engineering) degrees from Northwestern University. Registered professional engineer. Currently a research engineer and Ph.D. candidate at Northwestern University Infrastructure Technology Institute, Evanston, Illinois.

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Abstract

This paper describes work in progress on integration of a commercial weigh-in-motion system with a research-oriented bridge structural health monitoring system on the border between the states of Wisconsin and Michigan in the north-central USA. The installation, initially motivated by concerns of overload damage to the bridge from logging trucks, is providing high-quality, long-term data streams for use in local traffic planning, bridge structural management, and research in structural health monitoring and bridge mechanics. The system has been collecting data for each truck crossing the bridge since November 2009; data acquisition will to continue at least through the summer of 2012.

Keywords: Bridges, Structural Health Monitoring, Weigh-in-Motion, WIM, B-WIM

Résumé

Cet article décrit le travail sur l'intégration d'un système commercial de pesage en marche avec un système de surveillance structurel pour un pont sur la frontière entre les Etats de Wisconsin et Michigan dans la partie Centre-Nord des Etats-Unis. Initialement, l'installation était en réponse au risque de dommages structurels par les camions lourds transportant des produits d'une scierie située dans le secteur. Actuellement, le système combiné enregistre en continu des données de qualité qui peuvent être utilisées pour la planification de la circulation locale, la gestion de l'état structural du pont, et d'enquêter sur les propriétés mécaniques du pont. Le système combiné a enregistré des données pour chaque camion qui a traversé le pont depuis Novembre 2009, et l'enregistrement se poursuivra jusqu'à l'été 2012.

Mots-clés: Ponts, surveillance structurale, pesage en marche, WIM, B-WIM

1. Introduction

Concern over possible overload damage to a rural highway bridge due to heavy logging trucks has led to an opportunity for deployment of an integrated weigh-in-motion (WIM) and bridge structural health monitoring (SHM) system. This integrated system, composed of a commercial in-pavement WIM installation and research-oriented SHM instrumentation, provides high quality long-term data streams for both the traffic loads imposed on the bridge and the structural response at critical points on the bridge. The system has recorded data for every truck crossing the bridge since November 2009, and data acquisition will continue at least through the summer of 2012. Data from the integrated WIM-SHM system will serve several purposes, including (1) providing actual truck loads and measured bridge response data to help structural engineers ensure the serviceability of the subject bridge and similar structures, and (2) establishing a data set of truck parameters and measured bridge responses for several years' worth of truck crossings – over 122,000 truck crossings have been recorded to date – that can be used to develop and validate bridge weigh-in-motion algorithms.

1.1 The Bridge

Wisconsin Bridge B-26-7 carries the westbound lanes of US Highway 2 over the Montreal River, between Ironwood, Michigan, and Hurley, Wisconsin. US-2 is the primary east-west route across northern Wisconsin and Michigan's Upper Peninsula, along the southern shore of Lake Superior. The bridge is a 120 foot (37 m) long five-girder steel structure which is continuous over two piers. The average daily traffic is 5200 vehicles, 13% of which are trucks. This otherwise unremarkable bridge represents a special opportunity for research because the Wisconsin Department of Transportation (WisDOT) selected the approach to the bridge for a weigh-in-motion site. Logging is an important economic activity in northern Wisconsin and Michigan's Upper Peninsula, and a large portion of timber cut in the Hurley-Ironwood area is transported to a sawmill in Ashland, Wisconsin, approximately 40 miles (64 km) west on US Highway 2. The volume of truck traffic and weight of log trucks are of interest to highway engineers due to the extra stress placed on bridges and pavements both as legal weight limits for log trucks increase and as increasing numbers of trucks are suspected to run overweight. In this sense, and in terms of its age and design, the Hurley bridge is representative of many similar structures in the region.

1.2 Motivation

The purpose of this project is to build a database of trucks crossing the Hurley bridge and the response of critical areas of the bridge to trucks of various weights and axle configurations. The combined data stream will be useful for bridge engineering studies (e.g., estimating changes in fatigue life of certain bridge details under increased truck weights), traffic engineering, and research into and validation of bridge weigh-in-motion systems. Finally, the Web-based data display system developed for Hurley will provide a useful framework for managing large bridge SHM and WIM data sets. The structural engineering applications of the combined SHM and WIM data will be focused upon maintaining the serviceability of the Hurley bridge and similar bridges in a cost-effective manner by informing maintenance activities and any future preservation or rehabilitation efforts, and upon providing insight into actual bridge behavior that may be useful for determination of load factors and other structural design considerations.

1.3 Bridge Weigh-in-Motion (B-WIM)

Bridge weigh-in-motion (B-WIM) is a method to obtain vehicle weights as vehicles cross an instrumented bridge. B-WIM was developed in the late 1970s (Moses, 1979), and was subsequently deployed in several studies in the United States, including in Ohio (e.g., Moses and Ghosn, 1983), Maine (Wyman, 1986), and South Dakota (Huft, 1986), as well as in Canada and Australia. In Japan, Matsui and El-Hakim (1989) investigated B-WIM using crack opening in reinforced concrete slab bridges. A renewed interest in B-WIM began in Europe – particularly in Ireland and Slovenia – in the mid-1990s, leading to the Weigh-in-Motion of Axles and Vehicles for Europe (WAVE) project (Jacob, 2002), which included data from bridges in France and elsewhere. Recent work in Europe includes sites in Slovenia (e.g. Kalin et al., 2006) and Sweden (e.g., McNulty and O'Brien, 2003; Winnerholt and Persson, 2010), to name just a few examples. A brief history of B-WIM work worldwide, and a synopsis of some recent developments in Europe and Asia, is given by O'Brien et al. (2008).

B-WIM is an attractive option for weight data collection because, with little or no equipment visible on the roadway, drivers are less likely to know their vehicles are being weighed and possibly modify their behavior in response. This is especially true for "nothing-on-road" B-WIM installations such as those described by Kalin et al. (2006). Development and validation of B-WIM algorithms to calculate vehicle weights from bridge response measurements require databases of bridge response to known vehicle weights and configurations. While the Hurley project remains a work in progress, it is expected that the bridge response data from the SHM system and vehicle data from the in-pavement WIM system at Hurley will provide a useful calibration database for B-WIM research, particularly due to the sheer size of the database and the fact that it spans several years, enabling investigation of seasonal effects on bridge response.

2. In-Pavement WIM System and Cameras

The weigh-in-motion system is a commercial in-pavement installation. In each lane, there are two load plates (each with multiple load cells), two loop detectors, and two piezo sensors per lane. US-2 has two lanes in either direction; the east- and westbound lanes cross the Montreal River on separate but identical bridges. Only the westbound traffic information is used for this project, since only the westbound bridge is instrumented. The locations of the scales and the bridges are shown in Figure 1. The WIM system records axle configuration, axle weights, gross vehicle weight, speed, and other parameters for each vehicle approaching the bridge. When the WIM system detects a truck of US Federal

Highway Administration (FHWA) Class 7 or higher, it signals the bridge SHM system to record dynamic data as the truck crosses the bridge.

Cameras focused on each lane photograph each passing vehicle. The photographic record of vehicles crossing the bridge helps to clarify special situations on the bridge: two or more vehicles on the bridge at once, snowplows (which tend to drive near the shoulder, missing one of the load cells), and unusual vehicle configurations (e.g., custom log trailers), to name a few. Law enforcement officers have access to real-time WIM data and photographs from their patrol cars and are able to use WIM data as a basis to pull over suspected overweight trucks and weigh them on static scales. Citations may then be issued based upon static scale readings.

3. Bridge SHM System

The structural health monitoring installation is a research-grade system composed almost entirely from off-the-shelf components. SHM sensors measure strains, accelerations, temperatures, and displacements at critical locations on the bridge. The primary sensors are strain gauges on the bottom flange of each of the five girders at midspan, with additional sensors on Girder 4, directly beneath the right traffic lane: one gauge on the top flange in the negative moment region over one of the piers, and sets of closely-aligned gauges to measure high localized strains at the ends of a cover plate, a common fatigue-prone detail. Locations of sensors on the bridge are shown in Figure 2.

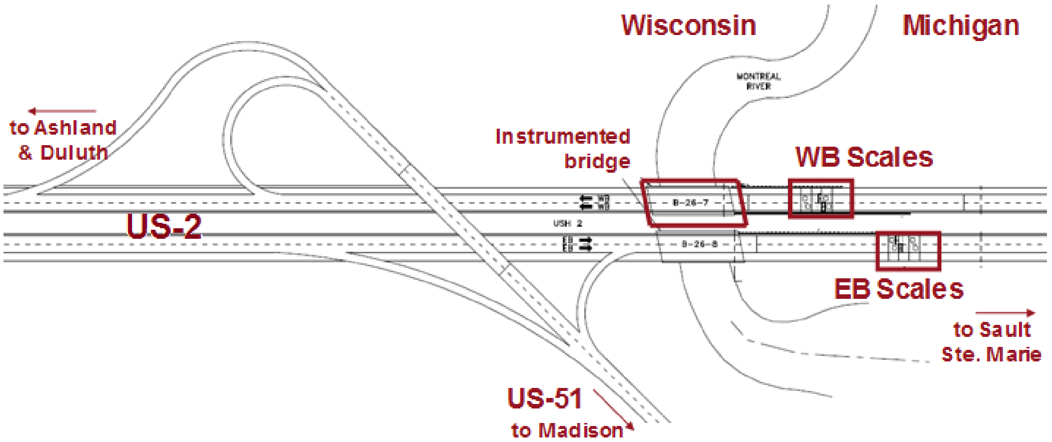

Figure 1 - Plan of US Highway 2 at Wisconsin-Michigan border, showing location of in-pavement WIM and instrumented bridge.

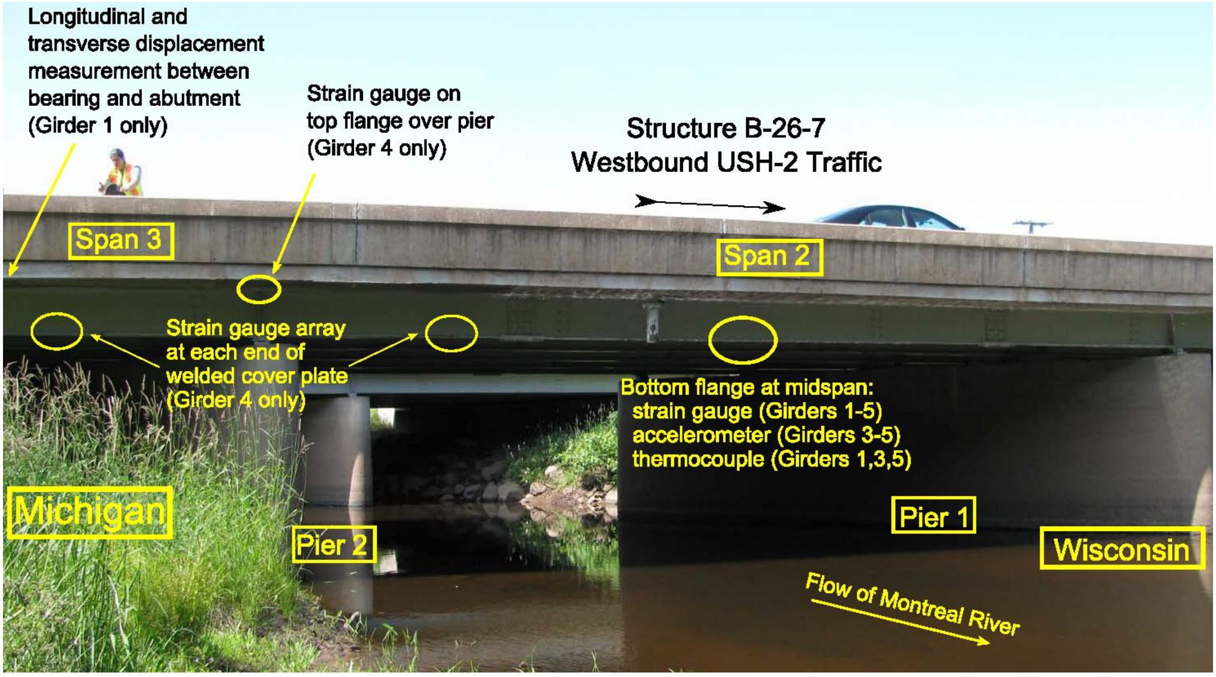

Figure 2 - Locations of SHM sensors on the bridge.

4. Combined Data Acquisition and Data Reduction

When triggered by the WIM system, the SHM system records data at high frequency (100 Hz) for five seconds, enough time for a vehicle to cross the bridge and for the bridge's free vibration response to decay. The complete sensor waveforms are saved permanently. Selected parameters are computed and stored for faster analysis of large numbers of vehicle crossings. Currently, the most important parameter is the maximum absolute zero-to-peak departure (ZTP) for each sensor during a vehicle crossing. ZTP is calculated as the maximum absolute value departure, during the vehicle crossing, from the sensor reading just before the vehicle arrived on the bridge. Because the basis for ZTP calculation is the reading just before the vehicle arrived on the bridge, and not an arbitrary "zero" point from earlier in the project, the ZTP calculation is not affected by changes in thermal strain – only the dynamic effect of the vehicle crossing is recorded. For the strain gauges at midspan, ZTP is a reasonable approximation to the cyclic strain used in rainflow-type fatigue analysis (e.g., Downing and Socie, 1982). Other parameters – especially the area on the strain-vs-time curve for the strain gauges at midspan – may be calculated for comparison with bridge load test and B-WIM data from the literature, such as the Moses algorithm (1979), the South Dakota B-WIM study (Huft, 1986), and others (e.g., Leming & Stalford, 2003).

4.1 Preliminary Results

Histograms of vehicle weight data from the in-pavement WIM and peak strain data from midspan of Girder 3 collected thus far are shown in Figure 3 below. Since Girder 3 is located along the centerline of the bridge, it is influenced by traffic in both lanes.

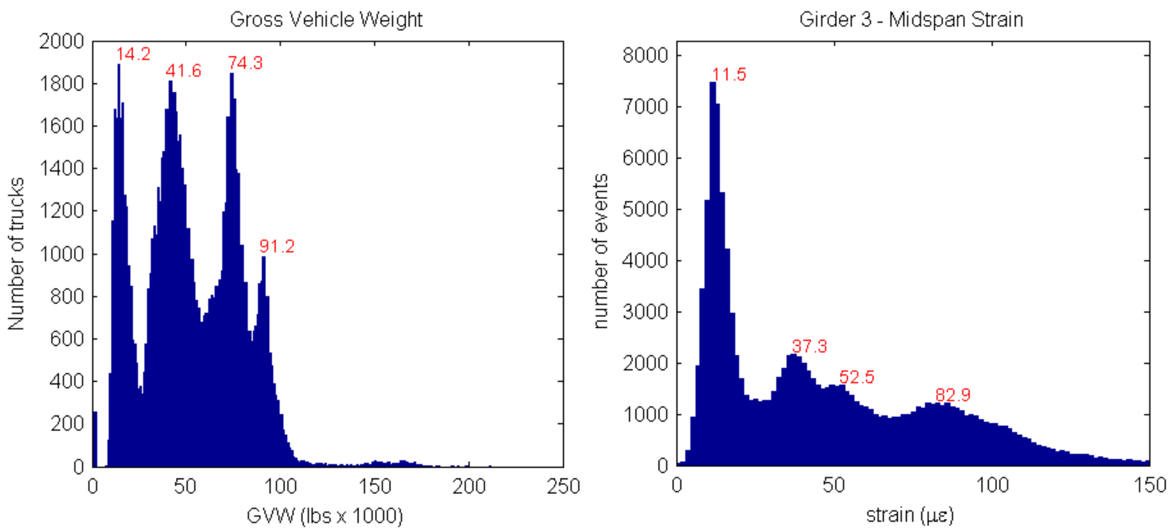

Figure 3 – Histograms of gross vehicle weight (left) and peak strain at midspan on Girder 3 (right) for truck crossings recorded thus far.

5. Internet-Enabled Data Management

Integration of WIM and SHM data collected continuously for a span of several years presents additional challenges. The WIM and SHM systems each record data in their own proprietary file formats. To link the SHM sensor record with the WIM data, custom software was developed to import both data sets into a relational database. The database serves as a searchable, comprehensive repository for all project data, eliminating the need to traverse multiple data files to find data of interest. Finally, the project database is connected to a password-protected Web site, allowing state officials and researchers alike easy access to the data without having to install additional software. The latest data from the bridge are automatically uploaded to the Web site nightly, enabling near-real time updates without human intervention. Once the data are transmitted from the bridge to the laboratory and entered into the database, they are automatically plotted and made available on the password-protected Web site. The site serves as a searchable clearinghouse for all SHM and WIM data collected from the bridge. The Web site includes a button to download the data used to generate long-term data pages, truck summary pages, and truck detail pages in tabular format (either as tab-delimited text or as an HTML table) for use with external software. This functionality allows the user to find data of interest through the graphical Web interface rather than by searching through large data tables manually while retaining the ability to use external software for analysis.

5.1 Long-Term Data

Hourly readings from the SHM sensors as well as air temperature and steel temperature from three points on the bridge provide a record of changes in strain and displacement driven by long-term phenomena such as daily and seasonal temperature cycles. These quasi-static data will be particularly important when using autoregressive statistical methods to identify long-term trends among daily and seasonal variations. This is an area of ongoing research.

5.2 Dynamic (Truck) Data

During each truck crossing, the SHM system records signals from all sensors at 100 Hz for five seconds, including a one-second pre-trigger buffer. This recording window allows capture of the bridge's dynamic response before, during, and after truck crossing – since a vehicle traveling at the posted speed limit of 55 mph (88 km/h) will cross the bridge in 1.5 seconds, there is sufficient time to record the free vibration response of the bridge after the truck passes. Authorized users may browse the Web-accessible database by date and time, by WIM violation code (overweight by axle, overweight by gross vehicle weight, or speeding), or by vehicle type. The dynamic event summary page, shown in Figure 4, shows the vehicle's FHWA classification, lane, gross weight, and speed. Records for overweight vehicles are highlighted. Clicking on a truck record from the dynamic event summary page leads to the detailed data page for that event. The detail page, the top portion of which is shown in Figure 5, displays additional WIM data for the truck as well as complete traces from each SHM sensor. For most truck crossings, the influence of each axle is plainly visible on the strain gauge traces.

6. Conclusions and Future Work

A combined WIM and SHM system has been deployed on a rural highway bridge subject to heavy logging trucks. The commercial WIM system records weight, speed, and other data for each vehicle approaching the bridge and sends a trigger signal to the bridge SHM system when vehicles of interest approach the bridge. When triggered, the SHM system records dynamic data from strain, displacement, and acceleration sensors on the bridge, capturing the bridge's dynamic response as the truck arrives at, crosses, and leaves the bridge. Both the complete sensor waveforms and parameterized data are recorded and uploaded to a database, which is accessible to researchers and the bridge owner via a password-protected Web site.

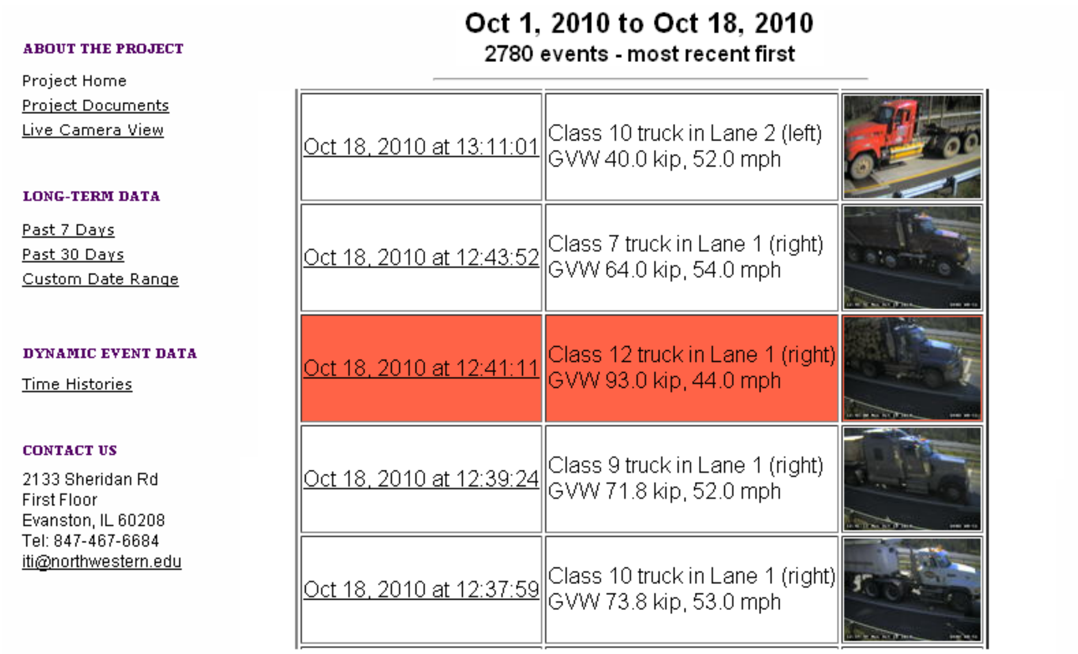

Figure 4 - Screen capture of results of a truck query as shown on the project Web site. Overweight trucks are highlighted. Clicking on an individual truck record displays the detail page for that record (e.g., Figure).

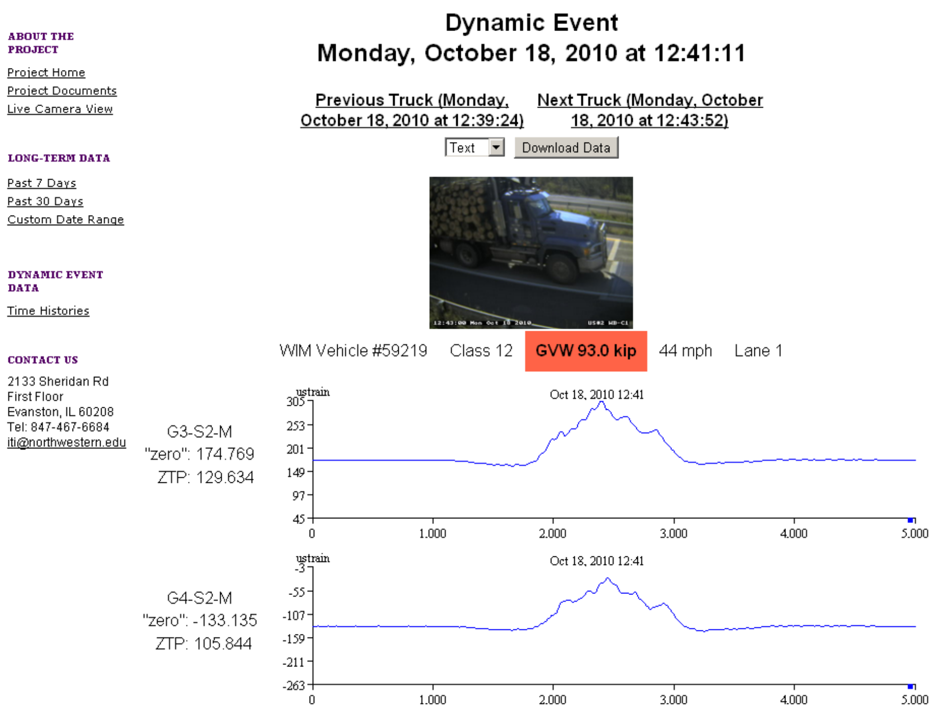

Figure 5 - Screen capture of the detail page for the overweight truck highlighted in Figure , showing WIM data and traces from two strain gauges

The Hurley bridge project remains a work in progress. Data acquisition is expected to continue at least through the summer of 2012. Now that a substantial number of truck crossings have been captured, researchers and practicing engineers will use the data to evaluate the structural condition of the Hurley bridge and, by extension, similar bridges on regional logging routes. The data will also be used to evaluate and refine weigh-in-motion techniques based upon instrumented bridges (B-WIM), starting with methods currently found in the literature.

7. Acknowledgements

This ongoing work is funded by the Northwestern University Infrastructure Technology Institute, a National University Transportation Center supported by the US Department of Transportation Research and Innovative Technology Administration. The kind assistance of the Wisconsin Department of Transportation is gratefully acknowledged.

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WIM INSTALLATION KÖHLBRAND BRIDGE

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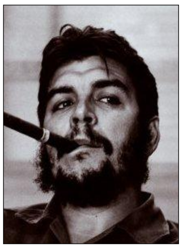

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Abstract

The Hamburg Port Authority (HPA) and Traffic Data Systems GmbH (TDS) installed a weigh in motion (WIM) system on the Köhlbrand bridge. The Köhlbrand bridge is a 3,618m long cable-stayed bridge located in Hamburg and connects the port of Hamburg with the highway A7. Vehicles up to 40 tons may cross the bridge at a maximum speed of 50 km/h. Heavier vehicles require a special permit. Due to the inconsistency in the number of permits HPA decided to monitor the traffic by means of a WIM system. This paper presents the pre-installation analysis, the installation and results of ongoing permanent measurement.

Keywords: Truck, WIM, special permits.

Résumé

L'autorité du port autonome de Hambourg et la société « Traffic Data Systems » ont installé un système de pesage en marche sur le pont Köhlbrand de Hambourg. Le pont Köhlbrand est long de 3618m et c'est un pont à haubans situé à Hambourg qui relie le port de Hambourg à l'autoroute A7. Les véhicules pesant moins de 40t peuvent le franchir à une vitesse de 50km/h. Des véhicules plus lourds nécessitent des autorisations spéciales. Suite au nombre de telles autorisations accordées, l'autorité du port de Hambourg a décidé de surveiller le trafic à l'aide d'un système de pesage en marche. Ce papier présente l'analyse pré-installation, l'installation elle-même et quelques résultats des mesures actuelles.

Mots-clés: Poids lourds, pesage en marche, autorisations spéciales.

1. Introduction

The Köhlbrand bridge (Figure 1) connects the port of Hamburg with the autobahn A7, the major north-south transversal in Germany. It has been in operation since 1974. A total length of 3,618m makes it the second largest bridge in Germany.
Vehicles with a total weight of more than the allowed 40 tons may use the bridge with a special permit which has to be individually granted for every single route. As the monthly requests for these permits seemed to be much too low, HPA decided to install a WIM system directly on the bridge.

Fig. 1 Köhlbrand bridge (Source: TDS)

2. Implementation

The goal was to install a standard TDS WIM configuration (Figure 2) without too much tweaking caused by the special restrictions on site. In general this could be achieved to a great extent. However, a few modifications were still necessary as outlined in chapter 3.2.

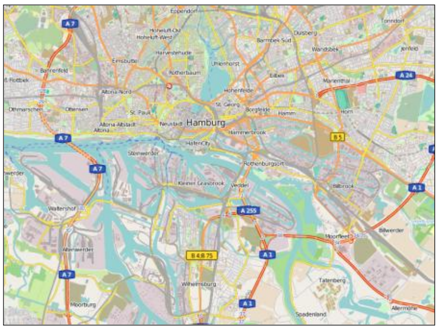

Fig. 2 Location of Köhlbrand bridge (Source: Open Street Map)

2.1 TDS WIM System

The basic TDS WIM System consists of several function groups as shown in Figure 3. The components are briefly listed in order to allow further discussion of modifications needed for this particular installation.

Force Sensor

The most important functional unit is the piezo electric force sensor. The force sensor consists of two twin bars spanning the full width of the lanes. The force sensors are connected to individual charge amplifiers and associated ADC[8] via coax cables. Note that each sensor bar allows separate measurement of single wheels. All post processing maintains strict access to individual wheel data.

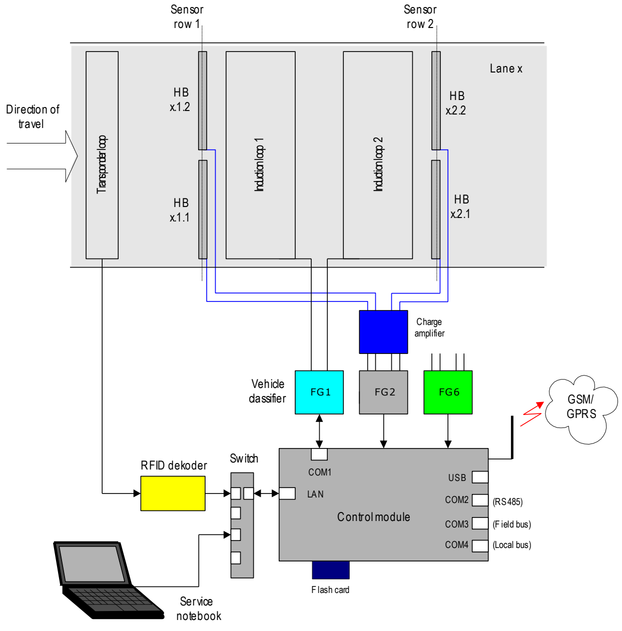

Fig. 3 TDS Weigh-In-Motion Setup (Source: TDS)

Inductive Loop Detector

As the force sensors can only detect single wheels or axles, an overall vehicle detection system (VDS) is necessary to provide the information on how to group wheel and axle data. The VDS consists of two inductive loops (loop 1+2) and the evaluation unit FG1[9]. The VDS not only detects vehicles but classifies them according to TLS2002 8+1 predefined classes. This is required to carry out proper discrimination between various vehicle configurations like trucks, trucks with trailers and tractors with trailers.

RFID Detector

The RFID[10] detection system is very important for maintaining overall system integrity. Individual reference vehicles can be precisely identified during calibration and later verification of the WIM system. By means of the RFID system all calibration and verification procedures can be done during regular operation without blocking traffic[11].

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8 ADC: Analog to Digital converter

9 FG1 According to german TLS Funktionsgruppe 1 (functional unit 1), consists of a TDS VDK900 or TMCS

10 RFID Radio-Frequency Identification

11 It turned out that RFID could not be used for this particular setup as the customer did not allow the installation of the extra detector loop outside the WIM area.

FG6 Subsystem
The FG6[12] subsystem is optional. It is mainly used to monitor power supply and maintain security by intrusion detection and the like.

Computation and Communication
All subsystems are controlled by an integrated controller equipped with non volatile storage and wide and local area communication devices.

Modifications for the Köhlbrand bridge Installation
The customer requested full WIM coverage for the four lane road passing the Köhlbrand bridge. Due to the fact that TDS WIM systems are designed for operation on a plane and horizontal surface with solid grounding, several factors and objections have to be considered first. We will divide these restrictions into primary and secondary categories.

2.2 Primary Restrictions

This category covers the restrictions on the principal weight measurement method caused by the dedicated environment on the Köhlbrand bridge. All these issues are discussed in detail in chapter 3.

Force Measurement
The basic principle of weight measurement with TDS WIM systems is the continuous registration of forces imposed by (vehicle-)wheels on a fixed surface. In general for most traditional WIM systems stiffness of the supporting ground is considered infinite. In other words, no one really cares. However, previous installations of TDS WIM systems showed that even weak groundings can be handled to a reasonable extent.

Vibrations
Due to the nature of the measuring procedure vibrations have much more impact on the results than quasi static deviations. Typical time constants observed during dynamic vehicle weighing are in the range of several milliseconds to about one second. The first time constant is important for wheel measurement whereas the second one covers the total time required to weigh a vehicle.

Uniformity
Last but not least it is very important that traffic passing the WIM system is in uniform motion. It is also mandatory that traffic passes in a straight line. To allow constant velocity, a leading and trailing path of about ten vehicle lengths is needed. Of course the surface should be plane in all directions within 1 to 2 degrees. Especially in the longitudinal direction the path, including leading and trailing tracks, should be flat and uniform to eliminate unwanted acceleration or braking. Downhill and related forces can be neglected.

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12 FG6 According to german TLS Funktionsgruppe 6 (functional unit 6), integrated with VDK900

2.3 Secondary Restrictions

Whereas the restrictions of the first category have direct impact on the weighing result, others exist with this type of installation that might influence usability as well.

Inductive Loop Subsystem

As mentioned before, vehicle detection is effected by means of two inductive loops. This vehicle detection and classification system is generally very reliable and well approved. Even under difficult environmental conditions. There is only one major drawback. Steel reinforced concrete is usually not the best support for an inductive loop. There is too much magnetic active material that results in parasitic inductance which reduces sensitivity of the detection and classification system. In order to provide usable results, evaluation electronics had to be tuned carefully.

Fig. 4 Damaged Inductive Loop (Source: TDS)

Fig. 5 Sensor Fixation (Source: TDS)

Another problem resulted from the relatively thin pavement that had been used to cover the inductive loops. Of course any damage to the bridge body is strictly forbidden. Figure 4 shows one of the inductive loops after several months of operation[13]. To reduce this problem integration of the inductive loops with the armament of the supporting concrete is recommended.

13 Note that the piezo sensor shows no defects at all.

Sensor Fixation

It is mandatory to mount the piezo sensors according to the specifications of the manufacturer ([1], [2]). Figure 5 shows the sensor in its slot perpendicular to the lane before sealing. As seen in the illustration, the sensor is "glued" to the supporting concrete after sealing.

Wiring

It was impossible to mount necessary equipment (amplifiers, power supplies, computer etc.) next to the sensors. The only space available was inside the box girder. This presents no problem at all except for two details.
The sensors (both piezo and inductive loop) have to be wired to the controlling equipment. Once again, there is no chance to simply drill holes and find the shortest path. This would not be worth mentioning, but the piezo sensors require a very sensitive charge amplifier that makes it difficult to bridge long distances. In the future we will use charge amplifiers directly integrated into the piezo sensors so low impedance interfaces can be used and wiring can be much more robust.

Telecommunication

As with many "aged" buildings the Köhlbrand bridge has no telecommunication infrastructure that could be used to retrieve online data from the WIM system. The standard TDS WIM system is equipped with a GSM/EDGE modem that provides sufficient bandwidth for data download. Unfortunately additional bandwidth is needed for the Neurosoft surveillance camera data and the box girder makes a next to perfect galvanic cage for the GSM RF. The problem was solved by using a remote UMTS interface. The antenna of the UMTS interface was simply plugged through an already existing hole in the box girder.

3. Site Analysis

The building consists of three parts, the eastern ramp bridge with a length of 2,050m, a 520m cable-stayed bridge over the river Elbe and the western ramp bridge with a length of 1,048m. Clear height is 53m above high tide (Figure 8).
To find a location on the bridge with minimal longitudinal and lateral gradient was clearly the main issue. Due to the design of the bridge the WIM system could only be located on the eastern ramp. Extensive vibration measurements were carried out prior to the final decision of the exact location. As the building is constructed in reinforced concrete the stiffness is generally very high. Of course the WIM sensors would be located directly above a pier. To give reasonable results, the oscillations were measured in the middle between two piers (Figure 6).

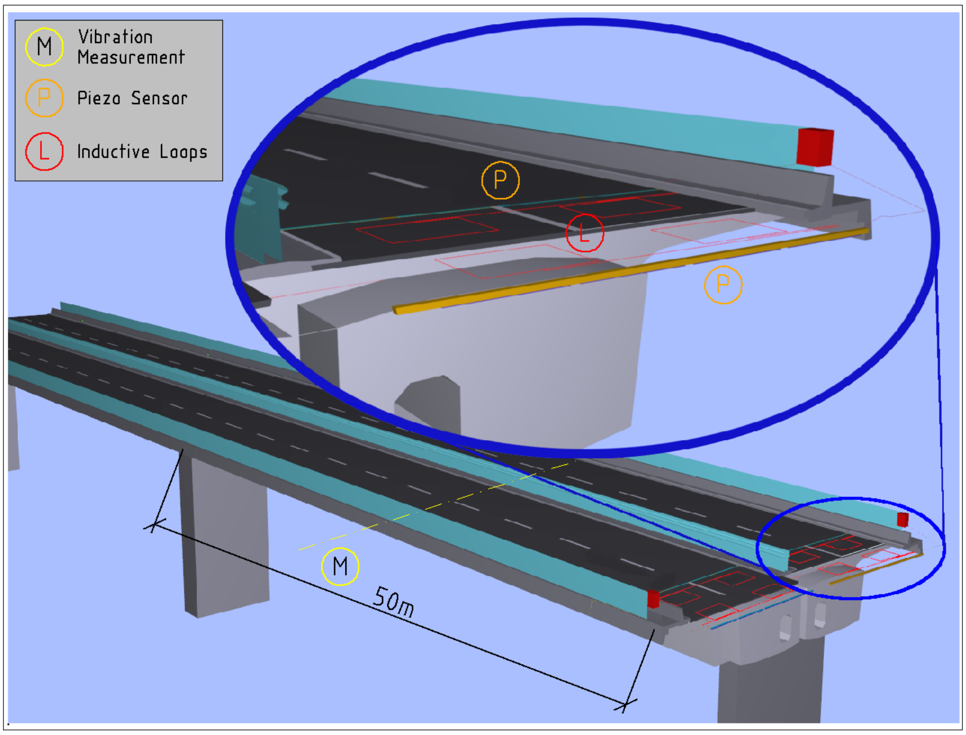

Fig. 6 Vibration Analysis and Sensor Placement (Source: HPA)

It turned out that oscillation differences between top and bottom of the box girder were in the range of measuring accuracy. This means the superstruction profile only moves in vertical direction as a whole entity.

Maximum measured vertical movement due to traffic is 0.3 mm at 50m span (6*10-6). As expected, stiffness of the profile is extremely high. This results in very little (if not zero) strain on the force sensor as it is mounted in transversal direction because the torsion stiffness of the profile is even higher than in longitudinal direction ([3], Figure 7).

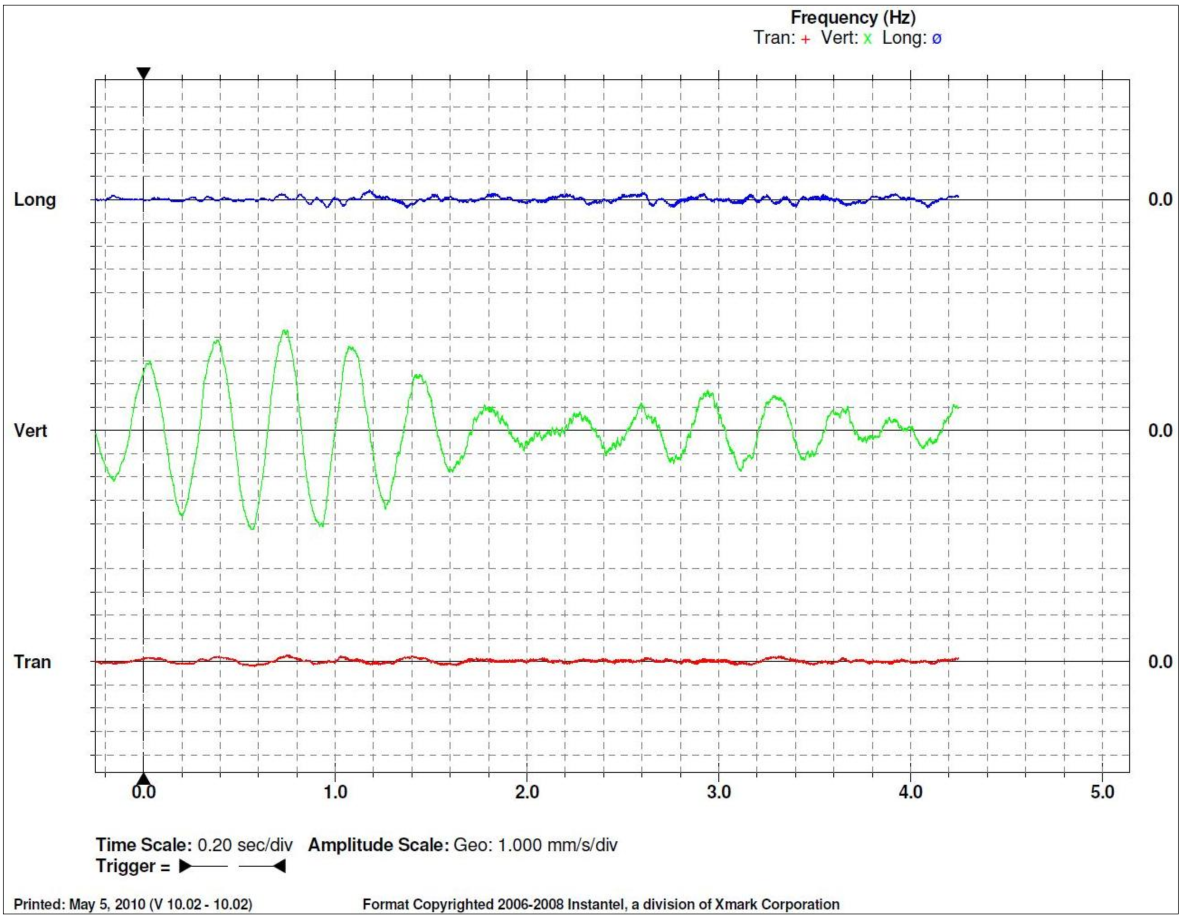

Fig. 7: Vibration Analysis Report (Source: HPA)

Directly above the piers the profile is strengthened by solid concrete bulkheads, each with a total mass of about 135 tons.

So in total the installation of the force sensors caused no problems at all. In fact the environment on this particular bridge seems to be even better than in "regular" WIM locations with often unknown foundation.

However, difficulties were caused by the inductive loop system. The inductive loop system is used to detect a vehicle in the range of the force sensors. It is mandatory for reliable separation of individual vehicles and even trailers. Without this kind of information it is almost impossible to assign the measured wheel weights to vehicles. The major impact on inductive loop performance is of course the extensive usage of steel inside the construction. This results in very small deviations of the inductance caused by vehicles passing the inductive loop. The quality of vehicle detection is in general very poor. Thorough optimization of the well approved TDS VDK detector solved this problem. Another problem arose from the fact that pavement thickness is very thin, which resulted in poor fixation of the inductive loops.

Last but not least there was no reasonable communication infrastructure available to transfer the data (including digitized video) to the appropriate destinations. Only after a valid routing path for a UMTS antenna was found was it possible to fulfil the communication requirements.

4. Results

4.1 Calibration

The WIM System was calibrated on (12./13. March 2011) using four different vehicles with total weights of 12 to 40 tons and TDS standard procedures. The only difficulties observed resulted from the reduced sensitivity of the inductive loops due to the distortions caused by the reinforcement (see chapter 3.1.2). The necessity of tuning the inductive loop classifier caused some delay and the total number of measurements was reduced to about 110[14]. The WIM calibration itself presented no problems. The required accuracy of 5 % for gross vehicle weight (GVW) could be achieved.

4.2 Operation

The WIM system on the Köhlbrand bridge went into preliminary operation at the end of 2010, about nine months after first customer contacts. Final acceptance was in March 2011. The data presented was acquired from April to August 2011. Due to reconstruction work from September to October 2011 the system was only temporarily in use. Extensive stop & go traffic on the bridge damaged the asphalt pavement causing deep groves. The inductive loops of one lane were damaged and had to be replaced. The piezo sensors survived without damage. Since November 2011 the WIM system has been operating normally.

4.3 Results

The principle results after five months of operation are:

- The bridge is used by significantly more vehicles than expected. Indeed traffic was highly underestimated.
- The number of vehicles with total weights of 40 to 60 tons is much higher than expected.
- There are many more heavy weight vehicles on the bridge than special permits issued. (Figure 9).
- Average speed of heavy vehicles is much higher than the max. allowed speed of 50 km/h. Additional burden was not covered by current maintenance budget.

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14 During the measurements of the first lane it turned out that all weighing results matched calibrated GVW within 10% without any adjustments to the factory settings of calibration parameters. This was well within customers requirements. Therefore customer accepted no further calibration and verification efforts.

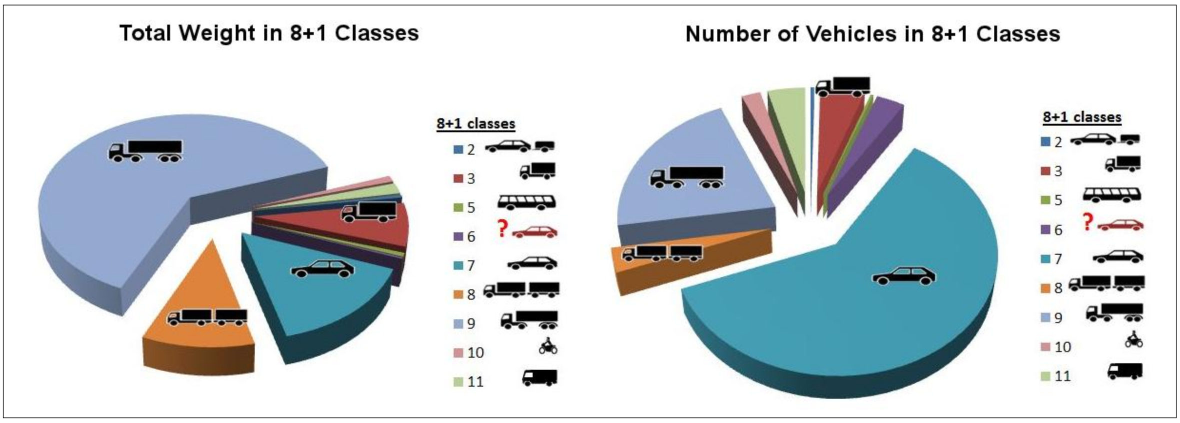

Fig. 8 Vehicle Statistics by Weight and Count

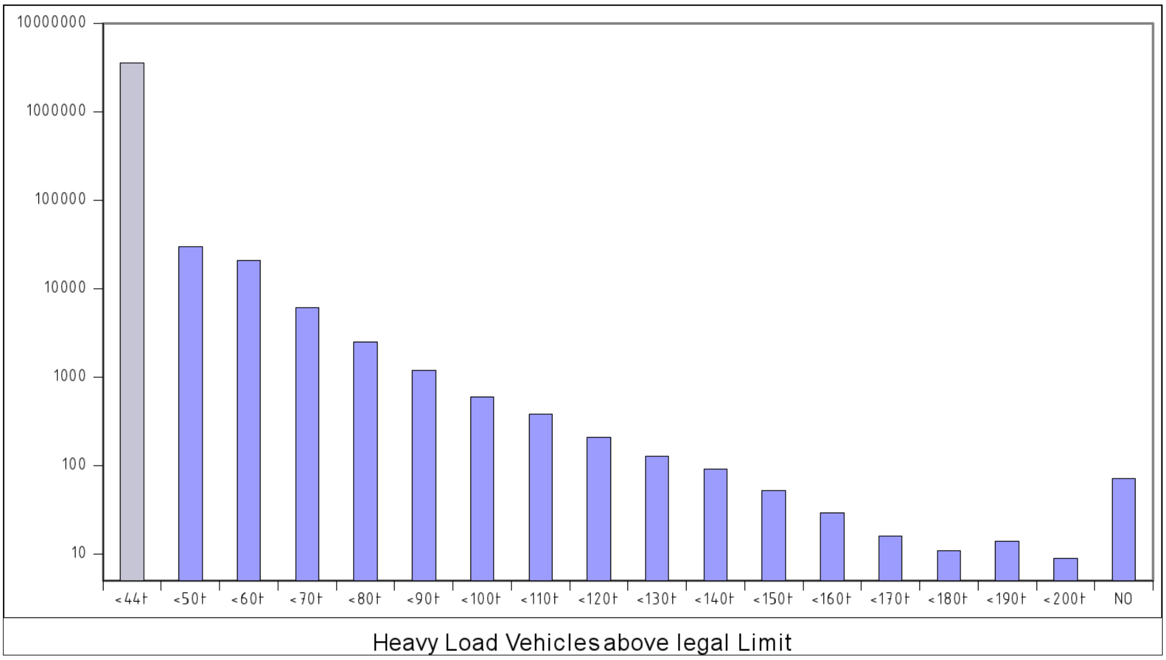

Fig. 9 Vehicles requiring Special Permit (above 44 t) (Source: HPA)

5. Summary

It could be demonstrated that it is possible to install a piezo sensor based WIM system on a particular bridge. The design and installation of the system took little to no extra effort compared to a traditional TDS WIM system. Of course the site inspection has to be performed with more care. It is necessary that structural engineers familiar with the building are involved prior to any layout decision.

The WIM system described in this paper can reliably and accurately monitor vehicle count, weight and speed 24 hours per day without any operator intervention.

The WIM system met the expectations of the customer, the owner and operator of the bridge, to the full. But there is still room for improvement. Monitoring of the accuracy is very difficult. Although two automated methods exist to identify calibration vehicles, neither methods cannot be used in this particular installation. The preferred RFID method cannot be used because of the lack of permission to install an extra inductive loop outside the WIM area. The second method, automated number plate recognition, is prohibited by law. The only alternative would be to fully shut down traffic on the bridge. Future systems shall be equipped with the additional inductive loop for RFID monitoring.

6. Literature

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Kistler AG, Lineas Installation Hints, 2006
Hamburg Port Authority, Messbericht Schwingungsmessung an der Köhlbrandbrücke, 2010
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ASSESSING CONFIDENCE INTERVALS OF EXTREME TRAFFIC LOADS FOR BRIDGES



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Abstract

For short- to medium-span bridges, truck gross vehicle weights (GVW) and axle loads are of great importance to assess extreme load effects, as extreme load events are obtained by combining the extremes of GVWs or axle loads. In this paper, three known prediction methods are applied, a normal distribution fitting to the sample distribution upper tail, the block maxima method and the peaks-over-threshold method, to extrapolate extreme traffic loads. Moreover, two methods, the delta method and the profile likelihood method, are introduced to assess the confidence in these extrapolations. Results show that the generalized Pareto distribution based peaks-over-threshold method is the best among these three methods to assess the extreme traffic loads.

Keywords: WIM data, gross vehicle weight, return period, return level, confidence interval, delta method, profile likelihood method, generalized extreme value distribution, generalized Pareto distribution.

Résumé

Pour les ponts de courte ou moyenne portée, le poids total et le poids par essieu des camions sont cruciaux pour déterminer les sollicitations extrêmes induites dans la structure. En effet, les cas de charges extrêmes sont obtenus en combinant les maxima de ces deux types de charges. Trois méthodes classiques, un ajustement de gaussienne sur la queue de la distribution d’échantillon, la méthode des maxima de blocs et celles les pics au-dessus d’un seuil, sont appliquées pour extrapoler les charges extrêmes. En outre deux méthodes, la méthode Delta et la méthode de vraisemblance de profil, sont introduites pour déterminer le niveau de confiance de l’extrapolation. Les résultats montrent que la distribution de Pareto généralisée issue de la méthode des pics au-dessus d’un seuil est la mieux adaptée pour extrapoler les charges du trafic.

Mots-clés: Données de pesage en marche, poids total, période de retour, intervalle de confiance, méthode Delta, méthode de vraisemblance de profil, la distribution des valeurs extrêmes généralisées, distribution de Pareto généralisée.

1. Introduction

Bridges need to provide safe crossing for all vehicles, with respect to ultimate and serviceability limit states. Thus accurately assessing traffic loads on existing bridges during their lifetime is important. However, using the load models of the current design standards, like Eurocode 1991-2 (CEN, 2003) in Europe, which are made for designing new structures, may often lead to the conclusion that the bridge will fail. Indeed, these load models include a safety margin, which has been designed to take into account any possible future modification in the traffic (weights and dimensions of the trucks for example). Therefore, site-specific traffic loads and corresponding load effects are required to assess an existing bridge (O'Connor et al., 2002). There is considerable potential for reducing the assessed traffic actions by considering actual traffic loads which can be obtained by weigh-in-motion (WIM) or bridge weigh-in-motion (B-WIM) systems.

The yearly maximum or lifetime maximum distribution function is a major component to build the limit state function in reliability assessment, which is provided by extreme value theory (EVT). However, it is usually more convenient to interpret extreme value models in terms of quantiles or return levels relative to individual parameter values. The standard statistical method adopted to assess traffic load or traffic load effect return levels assumes that the distribution of yearly maximum traffic load effects can be approximated by a Gumbel distribution (O'Connor et al. 2002; Caprani, 2005), a Weibull distribution (Bailey, 1996) or a generalized extreme value distribution (GEVD) (Caprani, 2005). The R-year return level estimation is then a certain quantile of the underlying distribution corresponding to this R-year return period, commonly referred as 1000-year return level in Eurocode 1991-2 (CEN, 2003), which is the quantile corresponding to a 10% probability of exceedance during 100 years.

Since the observations are drawn from random variables, repetitions of the measurements would generate different observations, e.g. different traffic load effects, and hence different estimates of the R-year return level. Thus, the sampling process induces randomness in the estimator. Quantifying estimate accuracy can usually be made more explicit by calculating a confidence interval (CI) in statistics.

This paper focuses on applying the fitting distribution method to the upper tail, block maxima, and peaks-over-threshold (POT) approaches to obtain maximum-likelihood (ML) estimates for GVW return levels. Their variability is investigated by the delta method and the profile likelihood method to build confidence intervals.

Section 2 introduces the two sets of WIM data used in the analysis. Section 3 describes the theory of the three extrapolation methods and of the two methods used for building confidence intervals, giving their advantages and drawbacks. Section 4 provides comparison and comments based on the 1000-year return level of GVW for two sets of WIM data.

2. WIM Data

Traffic load data were collected from January to May 2010 by a piezo-ceramic WIM system on the A9 motorway at Saint-Jean-de-Védas, near Montpellier in Southeast France (Figure 1). The motorway has 4 traffic lanes (2 in each direction) but only the north bound traffic lanes were recorded. A total of 846,019 trucks (GVW>3.5 t) were recorded, which gives an average daily truck traffic (ADTT) of 6,130 trucks. Some suspicious data (outliers) were eliminated according to accepted criteria (Sivakumar, 2010) such as axle spacing greater than 20 m. Finally 835,468 trucks were kept for the analysis. Another set of WIM data was recorded from April to May 2010 on the A31 motorway near Loisy, in the East of France, for comparison. This sample contains 374,119 trucks after filtering the outliers.

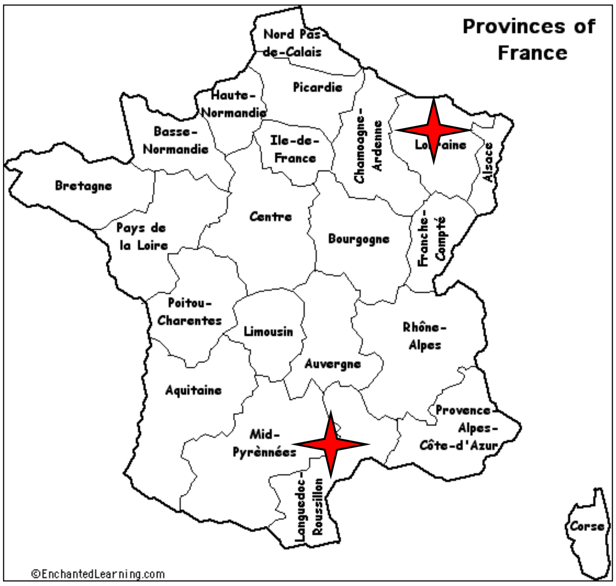


Figure 1 - The measurement locations

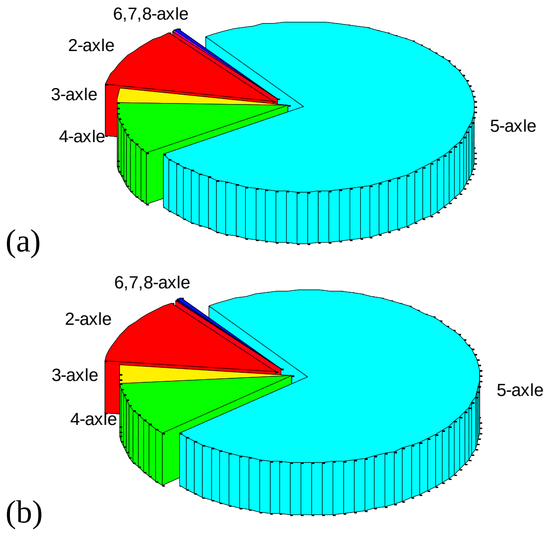
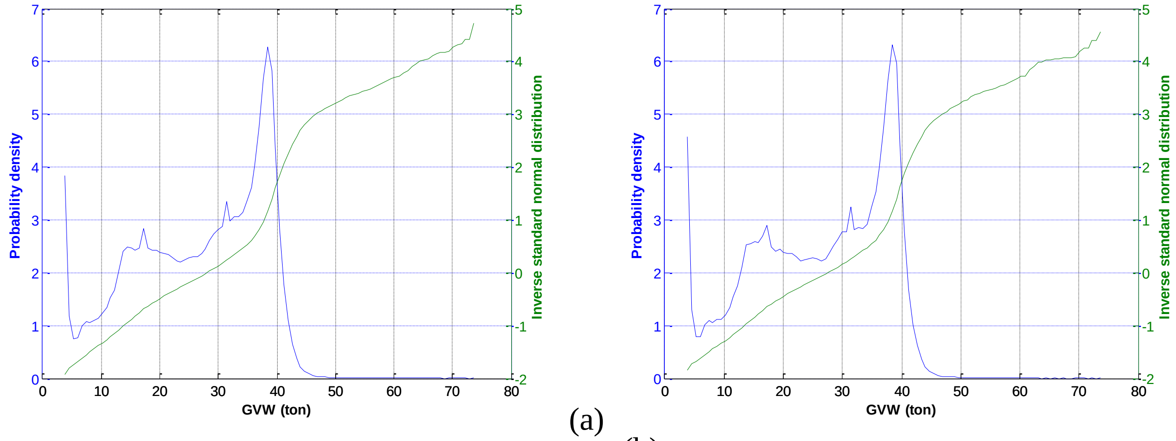


Figure 2 - Proportion of vehicle types (a) Saint-Jean-de-Vedas, (b)Loisy

Table 1 - Gross vehicle weight statistics

Statistics	Location of WIM station			
	Saint-Jean-de-Vedas		Loisy	
	All	Weekdays	All	Weekdays
Number of surveyed days	138	98	61	43
Total number of trucks	835,468	656,974	374,119	323,470
Maximum of GVWs (tons)	74	74	74	74
Mean of daily maxima (tons)	57.5	58.5	57.5	60.9
COV of daily maxima (%)	12.7	12.2	13.4	10.5
Mean of top 1% trucks (tons)	44.9	44.8	44.9	45.0
COV of top 1% trucks (%)	7.8	8.0	7.7	8.1
Mean of top 0.5% trucks (tons)	46.7	46.7	46.7	47.0
COV of top 0.5% trucks (%)	9.0	9.2	8.8	9.2

Nearly 75% of the trucks were 5-axle articulated trucks at both sites (Figure 2). Both samples have similar statistics on GVW: maximum, mean value, and coefficient of variation (COV) (see Table 1 and Figure 2), although the sample sizes are quite different. The statistics of the whole samples or of the week day only are different, above all for small sample size.



(a) (b)

Figure 3 - Single vehicle GVW relative frequencies (a) St. Jean de Vedas, (b) Loisy (the x-axis is the GVW and the y-axis is the probability of appearance)

3. Theory of Extrapolation

3.1 Methods for extrapolating R-year Level

In bridge engineering, the GVW of heavy trucks is particularly important to assess load effects on structures, as single-heavy-truck combined with common trucks governs the traffic loading scenarios for short- to medium-span bridges. The R-year return period level of GVW based upon a set of samples can be extrapolated with the maximum distribution of the sample. Let X be a random variable and F its cumulated distribution function. Let's denote $x_1, \cdots, x_n$ an identically and independent distributed sample of F. The maximum value over the "n-observation" period is $M_n = \max\{x_1, \cdots, x_n\}$, and the distribution of M_n is $\Pr\{M_n\} = \{F(z)\}^n$.

The distribution of M_n can be exactly derived according to the parent distribution function F of the sample (Coles, 2001). However, only the upper tail of parent distribution function really contributes to the distribution function of the maximum, obtained by raising F to the power *n*. Thus, (Nowak, 1994) fits the Normal distribution to the upper tail of the ratio of load effect to the effect of the American load model HS20 to extrapolate average 75-year maximum load effect. (Jacob and Maillard, 1991) adopts the half-Normal distribution and the Gumbel distribution, which were used in the background study of the Eurocode 1991-2 (Flint and Jacob, 1996).

It is noticed that very small discrepancies in the estimate of F can lead to substantial discrepancies for F^n. Statisticians have found that F^n asymptotically approximates the three extreme value distributions (EVD): Gumbel, Frechet and Weibull, which makes it possible to avoid raising the power of the parent distribution function. But a decision needs to be made on selecting the distribution type of EVD. A unification of the three families of EVD into a single family known as GEVD, as been widely used in recent years to avoid choosing which of the three families is the most appropriate for the data (Coles, 2001). Periodic maxima consisting of the largest values drawn from blocks which are defined by measurement periods, day or month, are recorded, and this block maximum method is very practical to fit GEVD, if the block length is sufficient, and if enough blocks can be obtained.

In recent years, especially in hydrology, finance and wind engineering, it was agreed that the discard of some of the largest observations in the block, given that only the block maximum is considered, represents a loss of information if the maximum values of other blocks are lower than these rejected values. The peaks-over-threshold method is an approach that avoids having to decide the distribution type and efficiently using upper tail data. Indeed the excess over the threshold conforms to generalized Pareto distribution (GPD). (Crespo-Minguillon and Casas, 1997) uses the POT approach to study weekly maximal traffic load effects.

Therefore these three methods of fitting the distribution to upper tail data, i.e. block maxima method for daily maxima, peaks-over-threshold method for excesses over high threshold, and extrapolating extreme values, have been applied to the WIM data observed to calculate the extreme traffic loads.

3.2 Confidence Intervals for Return Period Levels

Practically, a finite number of samples are used to estimate the distribution parameters. The question is to know how close the estimates are to the real values. Quantifying the accuracy of an estimator can usually be done by calculating a confidence interval. For theory purposes (Shao 2003) wrote:

$$P\left(\theta \in C(\mathrm{X}) = \left[\underline{\theta}(\mathrm{X}), \bar{\theta}(\mathrm{X})\right]\right) = 1-\alpha \qquad (1)$$

where $\left[\underline{\theta}(\mathrm{X}), \bar{\theta}(\mathrm{X})\right]$ is the confidence interval, for the $(1-\alpha)$ confidence level. The lower and upper bounds of this confidence interval must be determined. All parameters of the above considered prediction methods are estimated by maximum likelihood estimation (MLE) methods, while delta method and profile likelihood function based method are commonly used for building confidence intervals of ML estimates (Coles, 2001).

The delta method is a common technique to determine confidence intervals for functions of ML estimates, when direct evaluation of that function variance is not feasible. Generally, the ML estimate, denoted by $\hat{\theta}$, follows an asymptotic Normal distribution:

$$\sqrt{n}(\hat{\theta}-\theta) \hookrightarrow N\left[0, Var(\hat{\theta})\right]$$

The principle of the profile likelihood method is to invert a likelihood-ratio test to obtain a CI for the considered parameter. Let a statistical model with parameter θ that can be partitioned into two component, $\left(\theta^{(1)}, \theta^{(2)}\right)$, of which $\theta^{(1)}$ is the k-dimensional vector of interest and $\theta^{(2)}$ is the remaining parameters in the model. Maximizing the log-likelihood function $l\left(\theta^{(1)}, \theta^{(2)}\right)$ with respect to $\theta^{(2)}$ for fixed $\theta^{(1)}$ leads to the profile log-likelihood $l_p\left(\theta^{(1)}\right) = \max_{\theta^{(2)}}\left\{l\left(\theta^{(1)}, \theta^{(2)}\right)\right\}$, and $D_p\left(\theta^{(1)}\right) = 2\left\{l\left(\hat{\theta}_0\right) - l_p\left(\theta^{(1)}\right)\right\}$, where $l\left(\hat{\theta}_0\right)$ denotes the maximized log-likelihood, conforms to Chi-square distribution with k-degree of freedom according to the statistical theory (Coles 2001). For the concerned variable, $z = G(\theta) = G\left(\theta^{(1)}, \theta^{(2)}\right)$, a function of θ, the re-parameterization of the parameters of interest $\theta^{(1)} = G^{-1}\left(z, \theta^{(2)}\right)$ is obtained. The profile likelihood, $l_p(\mathrm{z})$, for z is then obtained by maximizing the $l\left(G^{-1}\left(z, \theta^{(2)}\right), \theta^{(2)}\right)$ with respect to the remaining $\theta^{(2)}$, and the CI for z is constructed with the asymptotic χ_1^2 distribution.

4. Comments and Comparison

In this section, the results of the calculations are presented: in Table 2, may be found the 1000-year return period level of the GVW of the WIM data for the two locations presented earlier. For each location, the three methods are applied and the last column shows results for the return period level. Table 3 contains the corresponding confidence intervals for this 1000-year return period level, assessed for each location and with the two methods explained in the previous section. Indeed, the following general comments can be made:

- The results for the two WIM sites show that a larger sample size ensures more reliable estimates (narrower CI); moreover, using only the weekday data leads to narrower CI.
- A simple fitting of a normal distribution to the data upper tail provides much higher estimates than the other two extreme value theory based methods. This is surely due to the selected normal distribution: the shape parameters (Table 2) of the two EVT based methods are negative, which means that the underlying parent distribution has a bounded tail, while the normal shape has an exponential infinite bound.
- The slightly larger mean and COV causes larger estimates. Using data excluding weekend days induce smaller estimates of return levels (Table 2 and Table 3). The same phenomenon occurs with the confidence interval length.
- Among the three prediction methods, the block maxima method (GPD) mostly has much larger length of confidence intervals than the other methods. It must be caused by the larger COV of the daily maxima than of initial data, and less data are involved in estimation.
- The estimated confidence interval from delta method is greater than the one obtained by the profile likelihood method; this demonstrates the statement by Coles (2001) that profile likelihood method usually gives more accurate estimates than delta method.

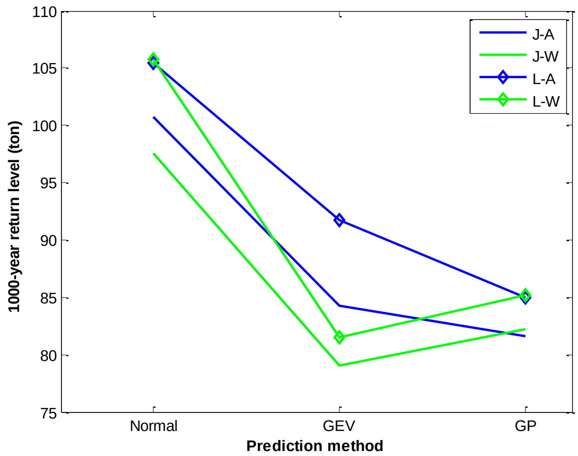
Table 2 - 1000-year return period level of GVW (in tons)

Site	Method	Distribution parameter			Return level
		Shape, ξ	Scale, σ	Location, μ	
Saint-Jean-de-Vedas	Normal		8.72 (7.56)	47.29 (51.61)	100.70 (97.60)
	GEVD	-0.22 (-0.27)	6.90 (6.96)	54.76 (55.97)	84.24 (79.09)
	GPD	-0.20 (-0.19)	5.57 (5.33)		81.63 (82.25)
Loisy	Normal		10.53 (10.88)	40.99 (39.41)	105.49 (105.79)
	GEVD	-0.16 (-0.26)	6.91 (6.15)	54.40 (58.64)	91.70 (81.50)
	GPD	-0.17 (-0.17)	6.37 (6.39)		84.99 (85.16)

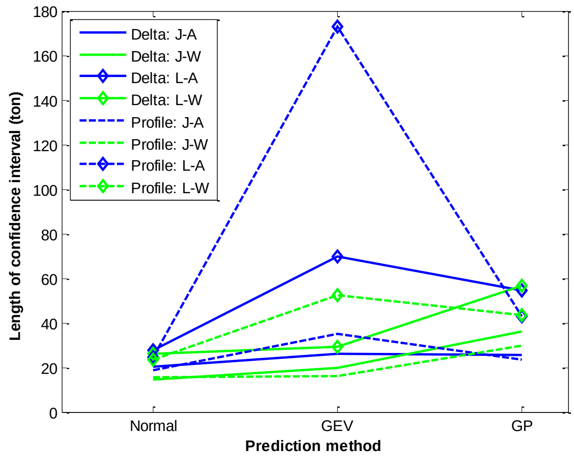
Note: numbers in brackets denote the result based on weekdays' data, as in the table below.

Table 3 - 95% confidence interval for 1000-year return level of GVW (in tons)

Site	CI	Normal		GEVD		GPD	
		Delta	Profile	Delta	Profile	Delta	Profile
Saint-Jean-de-Vedas	Lower	90.62 (90.28)	92.69 (91.53)	71.27 (71.25)	76.51 (75.06)	68.93 (64.18)	76.08 (76.05)
	Length	20.15 (14.65)	18.75 (15.36)	25.94 (19.92)	35.22 (15.92)	25.40 (36.14)	23.37 (29.76)
Loisy	Lower	91.79 (92.73)	94.89 (95.48)	56.79 (66.84)	75.73 (74.40)	57.70 (56.83)	76.38 (76.45)
	Length	27.39 (26.12)	24.64 (23.52)	69.83 (29.31)	172.83 (52.30)	54.58 (56.66)	42.80 (43.26)



(a) Return level



(b) Length of confidence interval

Figure 4 - Comparison (J-A: Saint-Jean-de-Vedas all days, J-W: Saint-Jean-de-Vedas weekdays; L-A: Loisy all days, L-W: Loisy weekdays)

5. Conclusion

Various prediction methods are applied to extrapolate GVW 1000-year return levels, for two sets of WIM data measured on two different motorway sites, and different period lengths. Comparison of these methods requires a careful choice of the distribution type to extrapolate the remote future value, and the two EVT based methods should be the better approach to extrapolation as they give quite similar findings. However, the difference between the two EVT based methods has been revealed through building confidence intervals. Small discrepancies between the block maxima, excluding weekends, generate noticeable changes, while the POT method adopting a more realistic technique to drawing data from the sample leads to more stable results. Thus, the threshold model is the better extrapolation approach among the studied methods, and the profile likelihood approach provides a narrower confidence interval length than the delta method.

6. Acknowledgement

The authors greatly acknowledge the financial support provided by the Marie Curie Initial Training Network's TEAM (Training in European Asset Management) project.

We also would like to thank the Centre Technique de l'Equipement de l'Est, which their help with the WIM data. Finally, we also acknowledge François Toutlemonde, the deputy chief of the Structures department of IFSTTAR.

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PORTABLE BRIDGE WIM DATA COLLECTION STRATEGY FOR SECONDARY ROADS




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Abstract
A common method of collecting traffic loading data across a large road network is to use a network of permanent pavement-based WIM systems. An alternative is to use one or more portable Bridge Weigh-In-Motion systems which are moved periodically between bridges on the network. To make optimum use of such a system, a suitable data collection strategy is needed to choose locations for the system. This paper describes a number of possible strategies which the authors have investigated for the National Roads Authority in Ireland. The different strategies are examined and their advantages and disadvantages compared. Their effectiveness at detecting a heavy loading event is also investigated and the preferred approach is identified.
Keywords: Bridge, Weigh-In-Motion, WIM, B-WIM, BWIM, Data, Strategy, Secondary Roads, Traffic, Loading.

Résumé
Une méthode usuelle pour recueillir des données de trafic sur un réseau routier étendu est d’utiliser un réseau de stations de pesage en marche intégrées dans la chaussée. Une alternative est d’utiliser le système de pesage par pont instrumenté qui est portable car il peut être transporté à intervalles réguliers d’un pont à l’autre. Pour optimiser l’utilisation d’un tel système, une stratégie d’utilisation doit être établie. Ce papier décrit un certain nombre de stratégies que les auteurs ont étudiées en s’intéressant au réseau routier Irlandais. Pour chacune d’entre elles, les avantages et les inconvénients sont présentés. Leur efficacité à détecter des surcharges est également étudiée et la meilleure démarche est identifiée.
Mots-clés: Pont, pesage en marche, WIM, B-WIM, données, stratégie, routes secondaires, trafic, charges.

1. Introduction

Traditionally, to collect loading information on an extensive road network, it has been necessary to install multiple permanent Weigh-In-Motion (WIM) systems. This is an expensive investment and causes disruption to traffic during installation and maintenance. With the recent advances in Bridge WIM (B-WIM) technology, a feasible alternative is to use one or more portable B-WIM systems which can be moved between bridges throughout the road network. These systems can be easily moved and the predominance of nothing-on-road axle detection techniques (OBrien et al, 2008) means that they can be installed with little or no disruption to traffic. By moving a B-WIM system at regular intervals, a picture of the distribution of traffic loading throughout a road network can be obtained.

The value of the data obtained from a portable B-WIM system depends on the locations where it is installed. A data collection strategy is therefore needed to put the B-WIM system to best use. This strategy should allow an accurate estimation of the general traffic loading throughout the network to be obtained but can also be altered to target "problem" areas.

The idea of using a data collection strategy to locate weighing operations is not a new one. In Montana, USA (Stephens et al, 2003) data gathered from an extensive WIM network was used to choose locations for enforcement operations for the following year. Strategies were developed for processing the WIM information and the areas to be targeted by enforcement were determined on a monthly basis. It is estimated that $500,000 of pavement damage per year was saved. However, the strategy used in Montana is not directly comparable as it was used for locating enforcement operations rather than sites for WIM data collection.

This paper is based on work which was carried out for the National Roads Authority (NRA) in Ireland. The road network in Ireland includes 1,187 km of motorways and serves a total area of approximately 70,000 km^2 divided into 26 counties (administrative regions). The NRA plans to install permanent pavement-based WIM systems to gather traffic loading data on Ireland's major inter-urban routes. This study investigates the additional use of a portable B-WIM system to gather data on 15,000 km of other roads which will not be covered by the permanent WIM systems. These include secondary, regional and legacy national primary roads (i.e., former national primary roads which, although still in use, have been superseded, typically by motorways). This B-WIM system would be moved around the country regularly and a method of choosing locations for the installations is needed. Various data collection strategies are examined in order to identify the optimal strategy.

2. Review of Irish Road Network

Representative samples of road in one county – Co. Kildare, which has an area of 1,693 km^2– were examined in order to get an idea of the number of bridges which would be suitable for B-WIM on legacy national primary, national secondary and regional roads. An NRA database was used to examine bridges on a legacy national primary road and on two selected national secondary roads. Site visits were made to a number of regional roads and their bridges surveyed - see Figure 1.

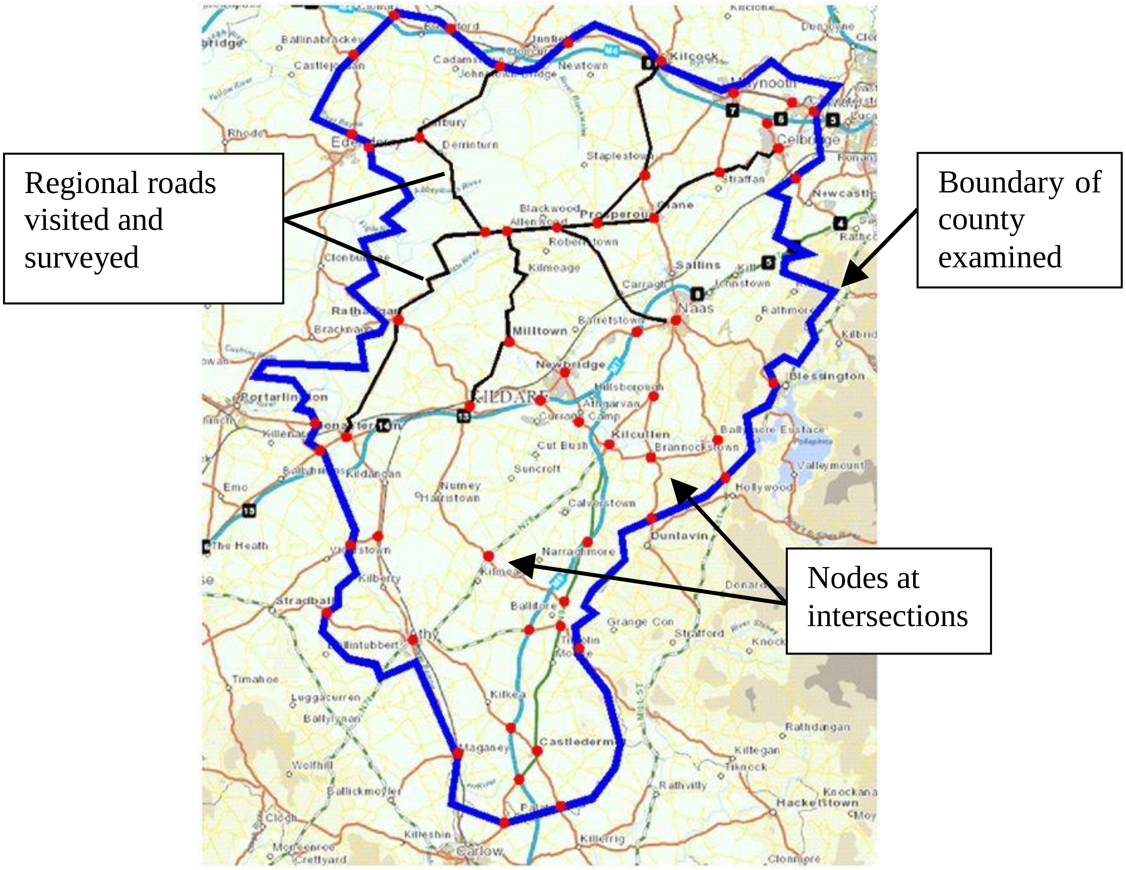

Figure 1 – Regional Roads Visited and Surveyed and Nodes at Intersections of Relevant Roads

2.1 Suitability for B-WIM

The suitability of a bridge for B-WIM (Hitchcock et al, 2011; Žnidarič et al, 1999) is assessed using four criteria:

1. **Construction material:** Steel is best but reinforced concrete bridges can also be used. Masonry and other arched bridges were deemed unsuitable.
2. **Access:** Soffit of the bridge must be accessible. Bridges located over fast flowing rivers or busy roads/railways were deemed unsuitable.
3. **Span:** Short, simply supported, spans are preferred but continuous bridges can also be used.
4. **Skew:** Ideally the bridges should not be skewed although some skew can be allowed for in the B-WIM software.

Using the four criteria listed above, the suitability of bridges for a B-WIM system, was assessed and bridges divided into the following categories:

Category 0: Not Feasible – Bridge not suitable for B-WIM installation
Category 1: Feasible – Possible to install system, but with some complications
Category 2: Ideal – System could easily be installed on this bridge

2.2 Suitability of Irish Bridges

Tables 1 and 2 give summary information on the bridges examined and their suitability for B-WIM. Ireland has a relatively high proportion of masonry arch bridges (Gibbons and Fanning, 2011), which are unsuitable for B-WIM. The proportion of B-WIM suitable bridges in countries with fewer masonry arch bridges may to be higher than in Ireland. Photographs of bridges in each of the three categories are provided in Figure 2.

Table 1 - Summary of Bridges on each Road Type Examined and Suitability for B-WIM

Road Type	Length Examined (km)	No. of Bridges	Cat. 0	Cat. 1	Cat.2
Legacy Primary	116	41	34	5	2
Secondary	62	47	39	6	2
Regional	122	44	36	7	1

Table 2 - Suitability of Bridges Examined for B-WIM System

Road Type	% Suitable for B-WIM (Cat. 1 or 2)	Average Distance Between Suitable Bridges (km)
Legacy Primary	17	17
Secondary	17	8
Regional	18	15

(a) Category 0 (a) Category 1 (a) Category 2

Figure 2 – Samples of the Bridges Examined

3. Data Collection Methods

Different methods for choosing the roads on which the B-WIM system would be installed were investigated. An ideal method would cover as much of the network as possible while also capturing significant loading events.

3.1 Length Method

This method identifies the individual roads being examined according to their road number. Each road is then divided into sections about 15 km in length. A section of road is picked randomly – with equal probability of all such sections being selected – and the B-WIM system installed on a suitable bridge on this section of road. If a suitable bridge is not available on that section, then the nearest suitable bridge on the same road is used. The B-WIM system is left at each site for a week before being moved to another randomly chosen section of road. An installation period of a week was chosen so the system could measure vehicle weights on many different roads and a general picture of the loading on the network of roads could be obtained. The average distances between suitable bridges shown in Table 2 suggest that a majority of the sections selected should either contain a suitable bridge or be reasonably close to one.

Once a section of road has been chosen it is either excluded from future selections or included. If it is excluded:

- Every section of road in the country will be covered in a fixed time.
- Existing sources of heavy loads that repeatedly use the same roads will be caught in that fixed time.
- If a new source of heavy loading emerges on a route that has already been picked, it will not be detected until the cycle of all roads is complete.

If selected road sections are included as candidates for future selection:

- It will not be possible to guarantee that every road section in the country will be selected in a fixed time period.
- New and emerging sources of heavy loads are just as likely to be selected as existing sources.

Given the extremely long cycle to cover all sections (20 years based on an estimated 15,000 km of roads), the latter approach is recommended. It is also recommended that the selection of road sections should take account of their relative Average Daily Truck Traffic (ADTT), with busier roads being selected more often.

3.2 Node Method

This method involves using nodes to divide up all the roads being examined into segments. A node is located at any intersection of these roads. The network is then divided up into sections, with each section beginning at one node and finishing at the next node encountered. Sections are then randomly chosen and the B-WIM system installed on a suitable bridge on this section of road. If no suitable bridge is found then another section is randomly chosen. Sections with higher truck volumes can be weighted, as for the length method, to increase their probabilities of selection in proportion to their ADTT's. This method was applied to County Kildare and 56 nodes were found – see Figure 1 – which resulted in 75 sections of road. Assuming each of the 26 counties contains the same number of road sections, we get an approximation of 1,950 road sections for the whole country of Ireland.

Large loads will travel the full length of the section of road between each pair of nodes, with the exception of the sections at the beginning and end of their journey. The aim of this method then is to divide the network into stretches of road which experience near uniform loading. The disadvantage of this method is that it results in more road sections than the length method and would take nearly twice as long to examine every section in the country. These sections of road also tend to be short, with lengths varying between about 2.5 km and 15 km, based on the data collected for the county examined. Therefore when a short section is chosen it is unlikely to contain a suitable bridge, which leads to some inconsistencies.

3.3 Targeted Data Collection

This method involves using the portable B-WIM system to solely target known or perceived sources of heavy loads. The system is moved around the country on a weekly basis or as required, between areas that were identified as likely to experience overloaded vehicles. If overloaded vehicles are detected on a road, the police could then be asked to target this route and set up checkpoints or to visit repeat offenders. There is some anecdotal evidence that this kind of approach is working well elsewhere in Europe. Sources of overloading may include:

- Precast Concrete Manufacturers
- Steel Suppliers/Manufacturers
- Logging areas and Sawmills
- Ports
- Crane Suppliers/Manufacturers

A targeted data collection approach could also be used to examine sections of road:

- Where abnormal road surface deterioration is experienced. Such roads maybe identified using local knowledge or by comparing yearly road roughness data.
- With high ADTT.
- Which are alternatives to tolled motorways.
- Where there is concern about the condition of a particular bridge.
- Which are close to a source of, or destination for, heavy vehicles.

The advantage of this method is that it is much more likely to capture extreme events than the length and node methods. The disadvantage is that the data collected is biased and does not give an indication the underlying general trend on the road network.

3.4 Case Study

To get an indication of the ability of these methods to capture extreme loading events or trends, a hypothetical scenario was created and examined using each approach. The scenario considered that a major heavy vehicle destination exists at a chosen location (Cavan in Figure 3) and that once a week, heavy trucks travel from Athlone to Cavan. These weekly trips are assumed to continue for one year. The route was chosen as it does not contain any inter-urban roads and uses only roads which are relevant to this report. The route covers 81 km of regional and national secondary roads – see Figure 3. It is assumed that a single portable B-WIM system is employed to cover all 26 counties.

Length method

As the route covers 81 km of road, it will contain 5.4 (81/15) road sections according to the length method. Based on an estimated total length of 15,000 km, there are 1,000 segments of road in the country. The probability of successfully capturing the event at least once in one year (50 working weeks) is calculated from basic probability concepts (Ang and Tang, 2007) using Equation (1):

$$P(Capturing\ Event) = p + qp + q^2p + q^3p + \dots\dots\dots\dots q^{49}p \qquad (1)$$

where: p = the probability of any of the 5.4 sections being measured in a given week
q = the probability of one of the sections not being measured in a given week

Using Equation (1), the probability of this Athlone/Cavan event being captured by the length method is 23.7%.

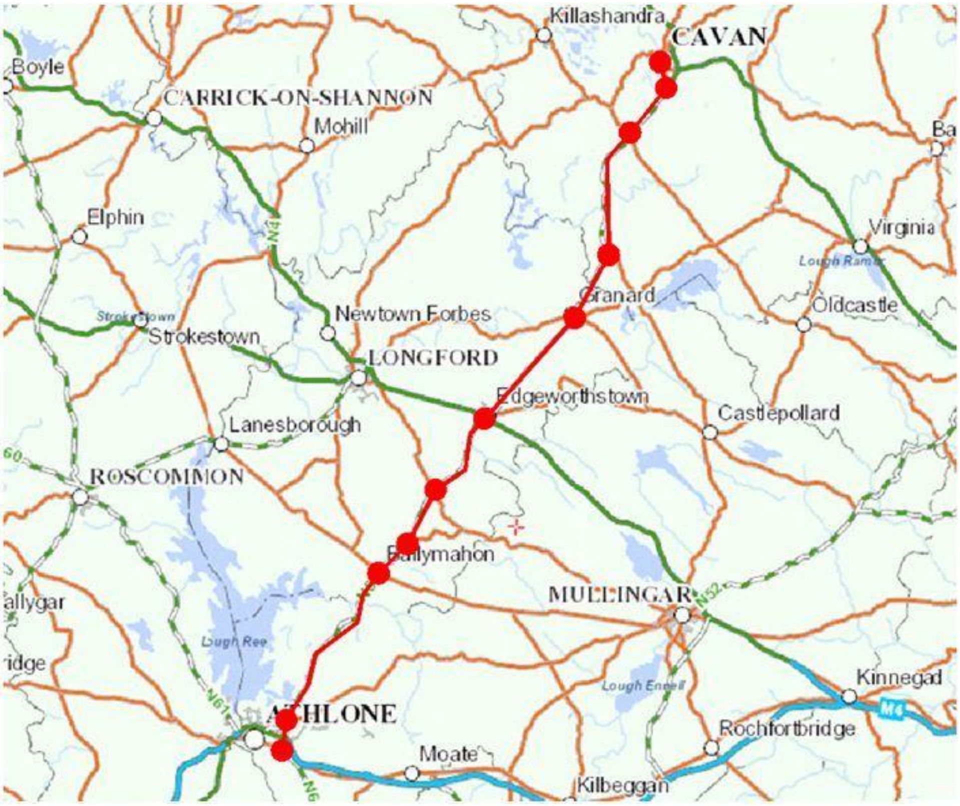

Figure 3 – Hypothetical Route Examined - Route Highlighted and Nodes Shown

Node method

The route in question was found to contain 10 road segments – see Figure 3. For the purposes of this study, the crude assumption is made that each of these road segments contains a suitable bridge. In reality it is unlikely that this would be the case. It is also estimated, by extrapolating from the county examined, that there are 1950 road sections in the country. The probability of this event being captured by the node method is calculated as 22.7%.

Mixed Targeted and Random Approach

The random (length and node) methods give better statistical information on the complete distribution of loading in the target networks. Targeting likely locations of overload on the other hand is statistically biased – the data collected tends to represent the upper end of the true loading distribution and its use could result in excessive conservatism in pavement design or bridge assessment. However, targeting has the advantage that it may result in a reduction in the extent of overloading which saves costs in the pavement maintenance budget in particular. A compromise between these two approaches is to divide the B-WIM system equally between random and targeted approaches. Assuming that the hypothetical event is not among the routes targeted, the probability of it being detected is reduced to 12.7% for the length method or 12.1% for the node method. Doubling the number of B-WIM systems would result in nearly double the probability of success while also allowing one sensor to be permanently used for the targeted approach.

4. Conclusions and Recommendations

The length and node methods perform similarly in the case study, i.e., each gives a similar probability of detecting the repeated overloading scenario. As the length method is easier to understand and to implement, it is recommended in preference to the node method. To avoid problems associated with the long cycle, it is recommended that repeat selections be allowed.

It is recommended that the length method be operated for half the operating time of the B-WIM system and targeted data collection for the other half of the time. This addresses the shortfalls of the methods discussed in Section 3, as it targets problem areas while also examining the loading conditions on typical legacy national primary, national secondary and regional roads.

The initial capital cost of a portable B-WIM system is similar to that of a permanent WIM installation. This portable B-WIM proposal requires weekly reinstallations and recalibrations and would have relatively high operational costs compared with a single permanent system. Despite the cost of these weekly reinstallations, if the aim is to cover an entire secondary road network, the portable B-WIM proposal is hugely less expensive than a network of permanent systems.

5. Acknowledgements

The authors gratefully acknowledge the financial support and assistance of the Irish National Roads Authority.

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Session 6

Application of WIM to Pavements

Chair : MORRIS DE BEER (CSIR, South Africa)

Co-chair : DEBORAH WALKER (FHWA, United States)

APPLICATIONS OF WEIGH-IN-MOTION IN PAVEMENT ENGINEERING

Received her bachelor of science (B.S.) in 1981 from the University Colorado, Boulder, USA, in Architectural Engineering. After working for seven years in the private sector, she obtained her master's degree (M.S.) in civil engineering from the University of Illinois in 1995. From 1998 to 2001, she has worked as a research engineer at ETH in Zurich and where she received her Dr. sc. in 2011 focusing on multi scale characterization of porous asphalt. Since 2001 she has been working as a research engineer at Empa. Her research focus is on the one hand on monitoring the environmental footprint of heavy vehicles and on the other on mechanical behavior of asphalt pavements.

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Abstract

WIM data is an indispensable tool in meeting modern challenges in pavement design. Although the mechanistic empirical design method (MEPDG) has improved pavement design, this review paper shows that it is important to be aware of the advantages and disadvantages of data and methods being used. A state-of-the-art MEPDG software demonstrates how a pre-established data base on traffic loading, climate conditions and materials specifications can simplify the input in an MEPDG. A second example demonstrates the importance of data accuracy and the use of site specific traffic data for pavement design. The third example demonstrates the importance and difference in design methods in pavement design. Whereas, a fourth example demonstrates the importance of data accuracy and proper calibration of WIM systems in pavement design.

Keywords: Weigh-in-Motion, WIM, Pavement Design

Résumé

Les données de trafic sont un outil important pour concevoir correctement les chaussées. Même si la méthode de conception empirique a amélioré la conception des chaussées (MEPDG), ce papier bibliographique montre qu'il est important d'être conscient des avantages et des inconvénients des données et des méthodes utilisées. Un logiciel d'état de l'art MEPDG montre comment des données préétablies de charges de trafic, de climat et de matériaux peut simplifier les entrées du MEPDG. Un deuxième exemple montre l'importance de la précision des données et de l'utilisation de données de trafic spécifiques pour la conception des chaussées. Le troisième exemple démontre l'importance et la différence entre méthodes de conception de chaussées. Finalement, un quatrième exemple montre l'importance de la précision et la calibration des stations de pesage pour la conception de chaussées.

Mots-clés: Pesage en marche, WIM, conception de chaussée.

1. Introduction

The road network in every country is one of its greatest investments. However, it has a limited performance period and needs periodic maintenance. The maintenance schedule and replacement cycle depend to a large degree on the mechanical wear caused by heavily loaded vehicles. It is well known and documented that some overloaded axles can cause unexpectedly severe and premature damage to the road structure. Pavement distress modes such as cracking, rutting, raveling, polishing and loss of strength are a result of damage caused by vehicles.

COST 334 (2000) has identified the following four main challenges to pavement designers:

1. The trend to increase allowable weights for heavy goods vehicle weights and dimensions
2. The trend toward increased use of wide single tires instead of dual tires
3. More "canalizing" of goods vehicles, have raised the stresses to which pavement surfacings have been subjected
4. Overloading of a small proportion of heavy goods vehicles

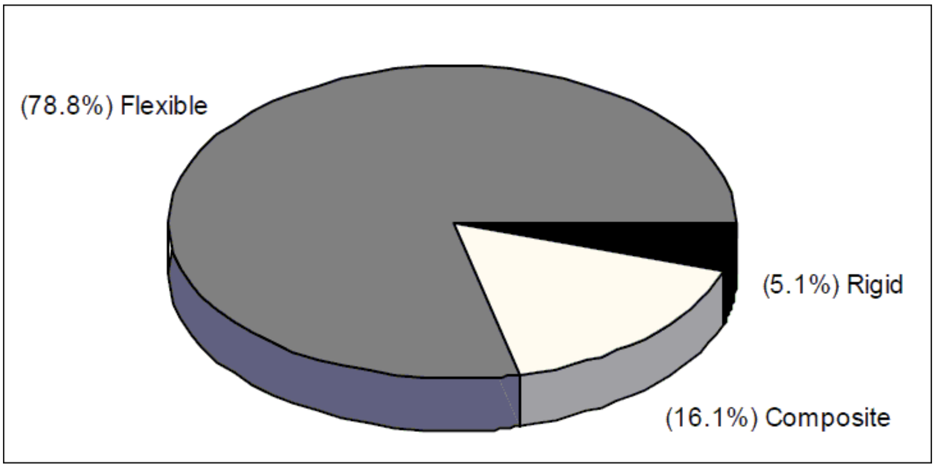

Figure 1 - Pavement types in Europe (COST 334)

Also reported in COST 334 (2000); flexible pavements are the most commonly used type of pavements as shown in the representative pie chart from Europe. Pavement design requires information on material characteristics obtained through laboratory tests, traffic information that should ideally come from weigh in motion (WIM) and environmental information such as temperature and moisture.

To address the modern challenges in pavement design listed above, the best strategy is to use the best locally available heavy vehicle information such as that provided by WIM sensors. WIM systems have been in operation since the 1980’s and they are currently widely used around the world.

Changes in traffic trends can have a significant impact on design life of the infrastructures. The best locally available traffic data used for pavement design allows incorporation of data that is site specific as this data changes over time. WIM sensors can deliver the following data that is relevant for pavement design:

- Monitoring of trends in traffic

- Significant changes in heavy vehicle allowable limits within particular weight categories
- Increase intensity of use on certain routes
- Development of appropriate lane and distributional factors for multilane facilities

Most systems weighing road vehicles in motion provide all the necessary data to calculate equivalent traffic, Neq. An algorithm can be easily developed to calculate the equivalent number of axles corresponding to the passage of any vehicle. Depending on the type of pavement failure modes used in design, different types of WIM data can be used. Axle loads are important for traditional empirical design methods. However vehicle configuration data can be used in mechanistic empirical methods.

The state-of-the-art pavement design methods such as the mechanistic empirical design guide (MEPDG) requires various input parameters and related traffic data that can only be delivered using WIM sites. The data required by MEPDG are axle load distributions by load range for different types of axles and vehicle classes. Such data are collected for example through the Long Term Pavement Performance (LTPP) sited in the US (Ahn et al., 2011). The goal of this review paper is to present and discuss some modern challenges in pavement design by presenting four recent papers as example.

2. Example 1: MEPDG from California

The first example is from University of California at Davis, where using the Mechanistic Empirical Pavement Design Guide (MEPDG), a computer program namely CalME, was developed for the California department of transportation (Caltrans) for Analysis and design of new flexible pavements as well as rehabilitation of existing pavements (Ullidtz et. al. 2010). The inputs are traffic data, climate and materials.

In case of overlay design, an additional program (CalBack) delivers the moduli from Falling Weight Deflectometer (FWD) data. For traffic data axle load spectrum from a WIM station is used where the operator has access to all WIM data collected in California. The climate input is from defined climate zones. The CalME database includes surface temperature each hour for a period of 30 years that has been pre-calculated for a range of pavement structures. The traffic and climate information is chosen by the user from a list. The design life (default 20 years), number of axle loadings in the design lane in the first year as well as annual growth rate in percent can be imported from the traffic data base or input by the user. The CalME materials library provides the material information. The output is stresses, strains and deflection within the pavement using theoretical models.

This first example demonstrates how a pre-established data base on traffic loading from relevant WIM sites, climate conditions and materials specifications can deliver the relevant input in an MEPDG.

3. Example 2: Impact of traffic data on pavement design in the absence of WIM

The second example presented is the results of research from Arizona State U. This example discusses the impact of using traffic data and national default values in the absence of WIM on Pavement Design (Ahn et al., 2011). To this end, a study was done where pavement design was compared using site specific information from WIM from 14 sites and in the absence of WIM where national default values for load distribution factors (ADOT(Arizona department of transportation)/default) are used. The WIM sites are part of the LTPP program. The study had two goals: on the one hand the input data was compared; on the other the pavement distress predictions by the MEPDG were compared. Available data was average daily truck traffic (ADTT) and vehicle classification percentages (VCP) and the missing data was monthly adjustment factors (MAF) and the number of axles per truck and axle load distribution factors. ADTT and VCP are available through the ADOT, however the other data are missing in the absence of WIM. The goal was to see how the MEPDG performs with limited traffic information; an important input parameter is the ADTT.

Figure , a sample of the results, shows the truck volumes per day from the ADOT database in comparison to the LTPP database for all sections in the investigation. It is apparent that for most sections the ADOT data lies above the 45-degree line. Showing that the ADOT data over estimated the truck volumes. The authors show that the ADOT design lane truck volume was approximately 1.43 times higher on average than the LTPP values. The two data bases reported similar VCPs. Other discrepancies were the national average axle load distribution factors which differed from site specific values whereas number of axles per truck was fairly close to the site specific ones. The output of the MEPDG showed large prediction errors especially for longitudinal cracking; in some cases more than 40% in absolute percent error on average. The main source of error is reported to be the difference in design lane truck volume.

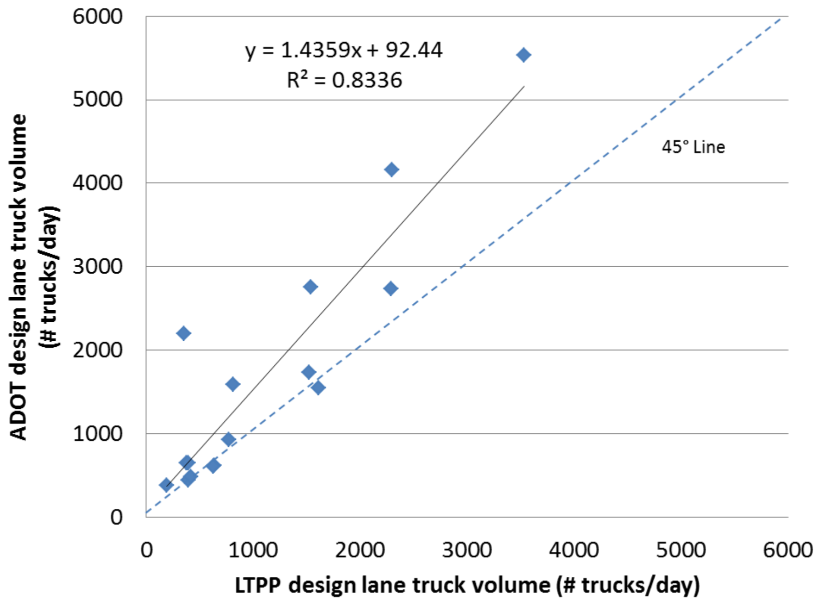

Figure 2 - ADOT data is greater than the LTPP data indicating that truck volumes are over estimated (after Ahn et al. 2011)

4. Example 3: Comparison of pavement design methods

The third example discussed is a Canadian study comparing methods for pavement design (Perraton et al., 2011). The authors are comparing results of four design methods: AASHTO, French method (FPD), MEPDG and the Asphalt Institute (AI) method. This comparison was based on EB, a classical hot mix asphalt (HMA) vs. Stone Mastix asphalt (SMA), a high performance asphalt. The two materials differ in term of stiffness modulus. Specifically, EB14 has a much higher complex modulus whereas SMA has a much better fatigue performance in terms of fatigue life. This is demonstrated from the Wöhler curves in Figure 3.

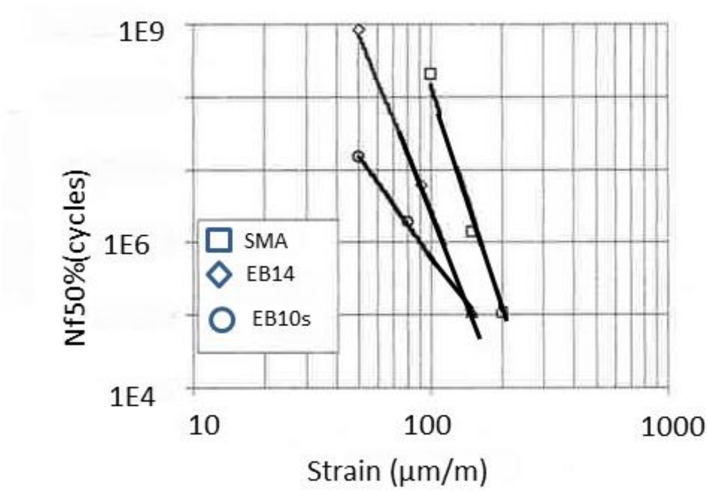

Figure 3 - Wöhler curves showing fatigue behavior of SMA vs EB 14 at 10°C and 10Hz (after Perraton (2010))

The criteria was based on required minimal thickness of the SMA under the same design conditions and reaching an equivalent load capacity as the reference section EB based on fatigue aspects of pavement design (reflective cracking). Their results shown in Table 8 indicate that the tendency is the opposite between AASHTO and FPD. This is expected as SMA has a lower stiffness in comparison to EB14 and considering that resilient modulus is the main criteria used in the AASHTO design. This fact leads to the conclusion by the authors that the 1993 AASHTO design guide is inadequate in reflecting high performance materials in the design. In contrast the FDP shows a difference in the base course thickness when using the two mixes as a result reflecting the benefit of the fatigue performance in pavement design. Furthermore, the AI method was found the most conservative, i.e. yielding the largest thickness and inappropriate for pavement design with special mixes as quality of materials is not considered. The MEPDG method was deemed promising but according to the authors it required significant local work to define damage models and transfer functions.
This paper demonstrates the differences of an empirical pavement design method (AASHTO) compared to mechanistic-empirical methods (FPD, AI, MEPDG). The traffic data used for all methods were standard traffic data and not site specific data from WIM stations.

Table 8 - Comparison of methods for highway conditions (EB: A classical HMA SMA: Stone Mastix asphalt)

Design Method	**FPD**		**AASHTO**		**AI**		**MEPDG**	
Pavement Layer	EB14	SMA	EB14	SMA	EB14	SMA	EB14	SMA
Asphalt surface course (mm)	50	50	50	50	50	50	50	50
Asphalt Base (mm)	137	91	137	158	224	224	229	216
Granular Base (mm)	150	150	150	150	400	400	150	150
Granular subbase (mm)	250	250	250	250			250	250

5. Example 4: Effect of accuracy of WIM data on pavement design

The fourth example is from the University of Texas, Austin that demonstrates the importance of data accuracy and proper calibration of WIM systems (Prozzi & Hong, 2007). The authors indicate that as a result of WIM system instability resulting from sensor technology, environmental effects, pavement condition as well as other factors, measurement inaccuracies occur. Therefore, the need for periodic calibration and maintenance of WIM systems. The percent error is defined as the percent difference between the WIM weight and static weight divided by the static weight. Two types of errors in WIM data are considered: first, random error resulting from the WIM sensor intrinsic properties and second systematic error resulting from improper calibration. Both types of errors and their effect on measurement error distribution are graphically represented in Figure 4.

It was found that both types of errors led to an over estimation of load-pavement impact. However, WIM systematic error resulting from calibration contributed more significantly in comparison to random error to load-pavement impact estimation. Specifically, it was shown that a 10% over-calibration (+10% biased) resulted in a 51% overestimation of the load-pavement impact whereas a 10% under-calibration (-10% biased) resulted in a 31% under estimation of the load-pavement impact.

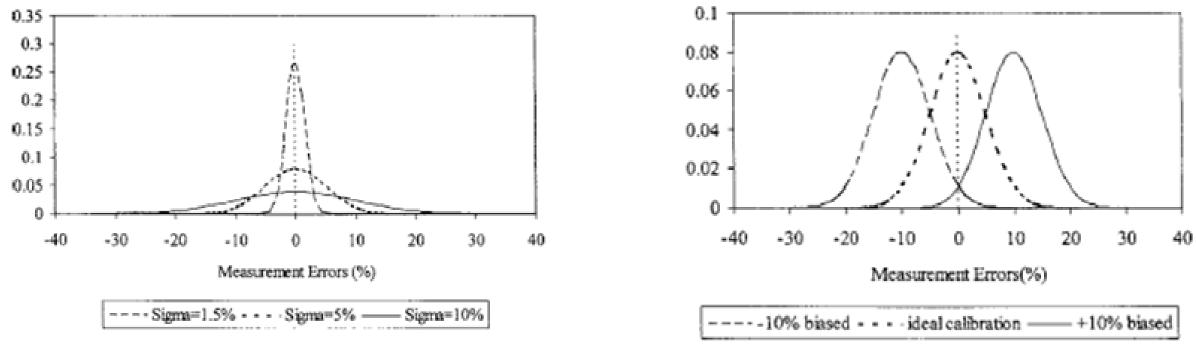

Figure 4 – Effect of WIM system accuracy (random error), left and effect of WIM system biases (systematic error) on measurement error distribution, right (Prozzi & Hong, 2007)

6. Conclusions

WIM data is an indispensable tool in meeting modern challenges in pavement design. Although the mechanistic empirical design method has improved pavement design, this review paper shows that it is important to be aware of the advantages and disadvantages of data and methods being used.

The first example demonstrates how a pre-established data base on traffic loading, climate conditions and materials specifications can simplify the input in an MEPDG.

The second example demonstrates the importance of data accuracy and the use of site specific traffic data for pavement design. The study has shown that some distress predictions are not affected significantly however the longitudinal crack predictions using MEPDG can be significantly over or under estimated in the absence of WIM data.

The third example demonstrates the importance of the difference in design methods in pavement design.

The fourth example demonstrates the importance of data accuracy and proper calibration of WIM systems in pavement design.

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PAVEMENT DAMAGE DUE TO DYNAMIC LOAD - BRAZILIAN ROAD DETERIORATION TEST WITH MS/WIM

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Abstract
In Brazil, pavement damage is aggravated by the constant use of overloaded heavy vehicles. The overloading practice increases as the control of heavy vehicles decreases. The purpose of this study is to do a continuous road assessment concerning strains, stress, moisture and temperature of pavement as well as recording dynamic loads. Mainly, this study deals with monitoring the pavement mechanical reaction in adverse conditions of humidity and temperature. Since pavement deterioration is related to the dynamic impact generated by heavy vehicles, the work is divided into two activities. The first activity considers pavement instrumentation, with sensors installed in each pavement layer. It also deals with the data acquisition obtained from the pavement signal response in specific periods of times, related to one vehicle axle. The second activity consists in doing the fatigue test and the complex modulus determination.
Keywords: Pavement, Deterioration, Assessment, Fatigue, Temperature.

Résumé
Les dommages aux chaussées sont aggravés par les surcharges fréquentes des véhicules lourds au Brésil. L’occurrence de ces surcharges augmente si la fréquence des contrôles des véhicules lourds diminue. Le but de cette étude est de faire une évaluation continue des routes en considérant des déformations, des tensions, l'humidité et la température de la chaussée, ainsi que l'enregistrement continu des efforts des charges dynamiques. Cette étude traite principalement de la surveillance de la réaction mécanique des chaussées dans des conditions défavorables d'humidité et de température. Le travail est organisé en deux activités car la détérioration de la chaussée est liée à l'impact dynamique générée par les véhicules lourds. La première activité considère l'instrumentation des chaussées avec des capteurs installés dans toutes les couches de la chaussée. Elle traite également de l'acquisition des données obtenues à partir du signal de réponse des chaussées à un essieu durant certaines périodes. La deuxième activité consiste à réaliser un essai de fatigue et déterminer le module complexe.
Mots-clés: Chaussées, détérioration, évaluation, fatigue, température.

1. Introduction

This project is inserted in a broader study called the High-speed Multiple Sensors Weigh in Motion Systems Specification, Operation and Assessment, as well as Pavement Mechanical Analysis. This project was born due to DNIT (National Department of Infrastructure and Transportation) needs to perform weight control. Then, one agreement between DNIT and UFSC (Federal University of Santa Catarina) was done to elaborate and define MS/WIM procedures. In Brazil, these new technologies have the potential to be applied to statistics collection, pre-selection and, in the future, weight enforcement.

This work aims to study pavement deterioration in real conditions by doing pavement assessment. Information from pavement instrumentation and multiple sensor weigh in motion equipment are used to define a pavement deterioration model.

The road mechanical behavior study provides a better understanding of the physical phenomena involved in the axle force in motion. The pavement structural response, as vehicles ride on the pavement surface, is defined by stress and strain efforts in given temperature and moisture conditions. The necessary activities to build the mechanical behavior concept are performed either in field or in laboratory.

In the field, two independent data acquisition systems provide strain and stress information. The data can be found in the pavement structural layers as well as the dynamic load from the free flow traffic. In the laboratory, material control tests allow determination of the mechanical characteristics of the material, mainly by fatigue and complex modulus testing, both performed in the Pavement Laboratory at Federal University of Santa Catarina, UFSC.

The sensors address both average wheel tracks shown on the road segment chosen. Sensors are positioned at these two data acquisition points in different depths corresponding to the layer interfaces. The first group consists of pairs of strain gauges in longitudinal and transversal directions. The second group is constituted by pressure cells, placed on each pavement layer. The third set, a group of moisture sensors, are installed at three different depths. It uses dielectric permittivity which corresponds to the water volume content inside the granular layers. One weigh in motion sensor, made with optical technology, is used to collect axle weight information, for better understanding of the pavement mechanical behavior. Finally, a group of three temperature sensors are installed inside the asphalt concrete.

High-speed multiple-sensor-weigh-in-motion has been under research by several international organisms and countries (FHWA, 2007). For Brazil, as for most nations, weigh in motion systems are an important tool to perform weight enforcement directly on the highway. The installation cost of this new technology is lower than weigh station installation, maintenance and operation. In this study the WIM systems aid in performing a complete analysis of the fleet

2. Field Analysis

The deterioration study is part of a DNIT and UFSC experimental project about modern weigh in motion technologies. In the field, the main objective is to analyze a pavement structure in real conditions of load and climate. The results will provide a better understanding of the complexity of field conditions. For this project a 700-meter-long experimental track was built, located in BR-101 highway, km 418, near Araranguá city, Santa Catarina state, Brazil. It was designed to be the Weigh Station main entrance, presented in Figure 1.

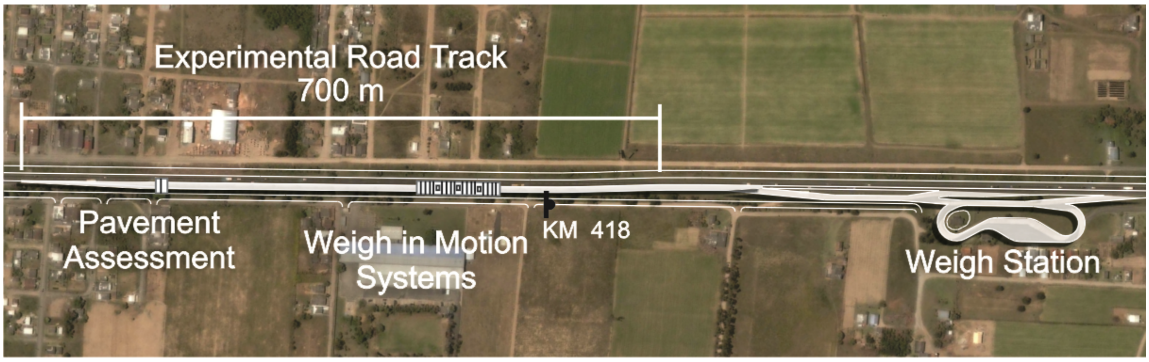

Figure 1 – Site of DNIT experimental road track

The road track was instrumented with sensors located in two different places. The first group of sensors is related to pavement assessment and was installed in February, 2011. The second group corresponds to the weigh in motion sensors, installed in April, 2009. The information from the two systems complement each other, thus creating a deterioration profile. It allows correlating the axle dynamic force with pavement structure response.

2.1 Pavement Response Measurements

The pavement structure fatigue process has its origin in the repeated interactions between the tire and the pavement. The pavement strain and stress assessment shows the intensity of the forces applied. It can be used to evaluate the pavement support parameters. "Perret (2003)" stated that pavement response is related to the force level and the load conditions. Pavement design aims to obtain an appropriate behavior during lifetime, besides ensuring safety and comfort to the road users. This process considers the load applied over time, the deformation found in the bottom of surface course and the stress found in the top of subgrade.

The Figure 2 show the deformation effect observed on the asphalt course lower layer, which is monitoring by sensors in longitudinal and transversal alignment.

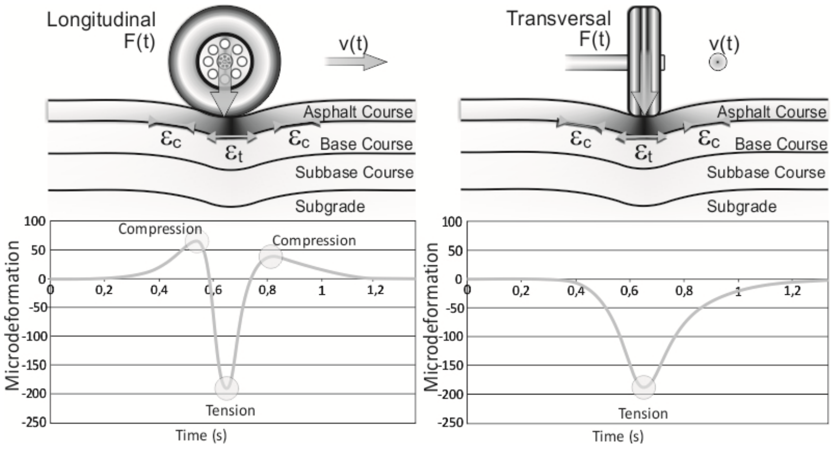

Figure 2 – Deformation signals at the bottom of the asphalt layer

This curve represents the deformation characteristic curve of "Perret (2003)" study. The signal presents the effects of dynamic load. As the tire approaches the longitudinal deformation sensors, the signal recorded presents a compression force. When the tire is over the sensor, the signal recorded presents a tensile force; ultimately, when tire moves away, the sensors records again compression force. As the transversal sensor, the signal recorded is only tensile forces.

Figure 3 illustrates a basic scheme explaining the location of the sensors. The pavement structure is composed of one asphalt course and two granular base and subbase courses (not treated), both over a compacted subgrade made of sand type material. The sensors are organized in groups of deformation, stress, temperature, humidity and weight. The deformation group records deformation in two directions and in each layer. The stress group records stress in the top of each pavement layer. The temperature group records asphalt layer temperature at three different depths. The humidity group records moisture in all granular layers. The weigh in motion sensor uses optical technology. When a load is applied to the sensor, it experiences a decrease of optical transmittance. An interface detects these changes and transforms them into signals for traffic data processing.

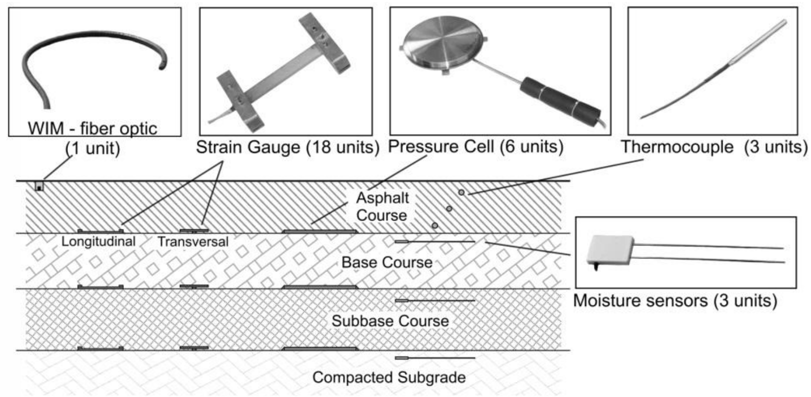

Figure 3 – Pavement assessment installation basic schematic

The Figure 4 presents the spatial arrangement with groups of sensors positioned on the pavement surface.

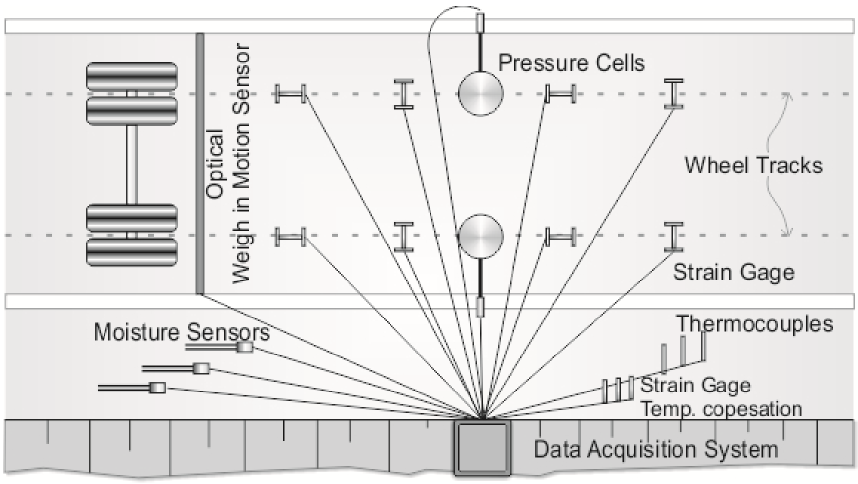

Figure 4 – Installation sensor lay-out

The data acquisition shelter is considered as the reference origin to the sensor installation. Sensors that measure pavement deformation and stress are positioned allying with both wheel tracks. Weighing sensors are installed in the transverse direction relative to the vehicle road track. There is one strain gauge, in the non-interference region, for each layer and it is programmed to indicate the electrical resistance variation due to temperature variation. In this study, the others sensors do not need a specific location relative to the horizontal distribution but do need specific depth.

Recording the deformation at the bottom of the asphalt layer can help to predict when the pavement structure loses the capability to resist the load applied. A load produced by a rolling wheel creates a deformation zone, known as deflection bowl, which changes the pavement structural shape. The deformation generated follows an alternated bending, changing from compression to tension and back to compression, as the vehicle wheel moves away. This alternated bending has a specific frequency which is proportional to the velocity of the vehicle. Knowing these frequencies provides a better understanding of how a flexible pavement works and what parameter can be used in laboratory tests. The asphalt concrete behavior depends directly on temperature and load application time, since it is a viscoelastic material.

3. Intermediate Results

The results achieved thus far show the complexity of real condition studies. Multiple tasks are necessary to achieve the study objective, which must be well planned and thorough. The activities recently completed can be categorized as: equipment specification and installation; data acquisition and transmission; and fatigue and complex modulus laboratory determination.

3.1 Sensor Installation

The installation of the sensors and the infrastructure for data acquisition and information transmission are completed. The Figure 5 is a photograph of the sensor installation on top of base course, in the pavement structure. This set of sensors is responsible for giving information on asphalt deformation and pressure, which are transmitted to the lower layers.

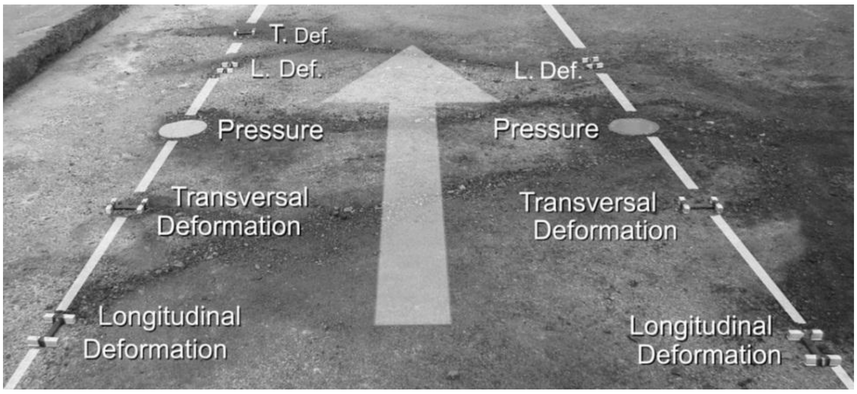

Figure 5 – Sensors on top of base course

3.2 Asphalt Mechanical Characteristics

The laboratory analysis complements the field analysis, because it gives information on the mechanical behavior of each material. The asphalt material samples was collected in two stages, allowing assessment of the natural aging process. The first stage was at the beginning of the study which is considered as time zero (t_0), when it is still a new layer. The second time was at end of the study when the natural aging effects and amount of energy received can be added to the deterioration model.

Asphalt mechanical characteristics were determined using an alternating bending machine. This equipment allows computation of the complex modulus and the fatigue characteristics in different conditions of temperature and load frequency. The results of complex modulus determination give the linear viscoelastic characteristics of the asphalt material, because they are measured in the context of small deformations. All viscoelastic materials have a response delay related to the tension applied. For small deformations, the small sinusoidal force produces a sinusoidal response. The modulus of the complex |E*| can be express by Equation (1):

$$|E^*| = \sqrt{E_1^2 + E_2^2} \qquad (1)$$

The different components of the complex modulus vary with temperature and frequency. The experimental results |E*|, φ, E1 and E2 are expressed by graphical representation called: Isotherme, equivalent frequency, Isochrone, Cole-Cole and Black space. The Figure 6 shows the complex modulus representation of the asphalt mixture from the experimental road track. E1 represents the real component (elastic) and E2 the imaginary part (viscoelastic). The specimen is a block with dimensions h_{layer}(17cm) x 60cm x 40cm removed from the asphalt course. From it, trapezoidal specimens are made to perform complex modulus and fatigue tests in the two point bending machine.

The Cole-Cole representation provides the parameters for the Huet-Sayegh model (Huet, 1963), which provides parameters for pavement design, shown in Table 1, calculated with the aid of Viscoanalyse (LCPC-software). The model is obtained by a spring of stiffness E_0, which represents the elastic modulus. The model is given by Equation (2).

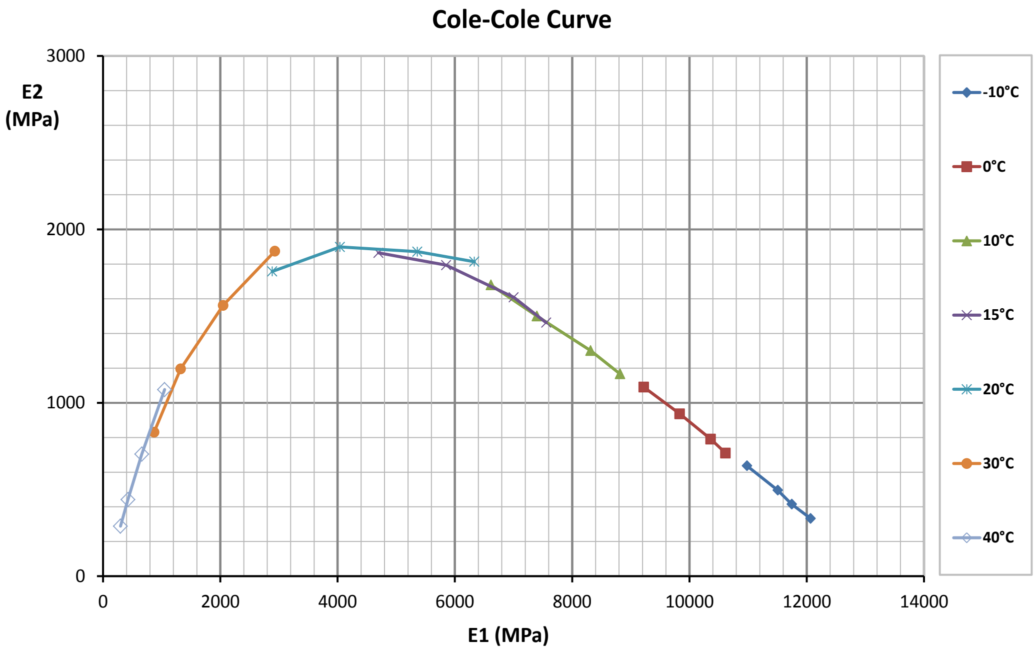

Figure 6 – Cole-Cole complex modulus representation

$$E^*(i\omega\tau) = E_o + \frac{E_\infty - E_o}{1+\delta(i\omega\tau)^{-k}+(i\omega\tau)^{-h}} \quad (2)$$

Table 1 – Hute-Sayegh parameters

Eo	Einf	Delta	k	h	τ	C1	C2	T ref.	A0	A1	A2
1.254	13139	0.573	0.132	0.518	0.065	21.433	195.397	15	1.405	-0.295	0.0013

The fatigue test is performed in continuous mode with controlled deformation; thus the stiffness of the specimen decreases as the number of deformations applied increases. The results require approximately 10^6 alternating deformations in the two point bending test. The test aims to find the deformation corresponding to one million cycles applied, called ε_6. The criteria adopted are the same as recommended by French fatigue test method, so the test was executed at 10ºC and 25 Hz.

The fatigue curve is presented in the Figure 7. The curve represents the susceptibility of asphalt mixture to deformation and is represented in the log-log scale. The abscissa is the deformation, in 10^{-6} m, and the ordinate is the accumulate number of deformation cycles. The curve is a line represented by an exponential equation, where the slope of the curve is the exponent. The fatigue equation found is:

$$N = 1.22 * 10^{16} * Def^{-5.10} \quad (3)$$

The deformation specific result of fatigue test result is the deformation at 10^6 cycles. When the number of cycle N is substituted in the equation (3), it yields a deformation ε_6 of 95.024 µm. N represents the number of axles accumulated on the pavement over the years; in other words, the sum of loads which will pass over the road section during the pavement lifetime. Therefore, the equation enables comparison of the deformation found in field with the fatigue curve to establish the degree of deterioration.

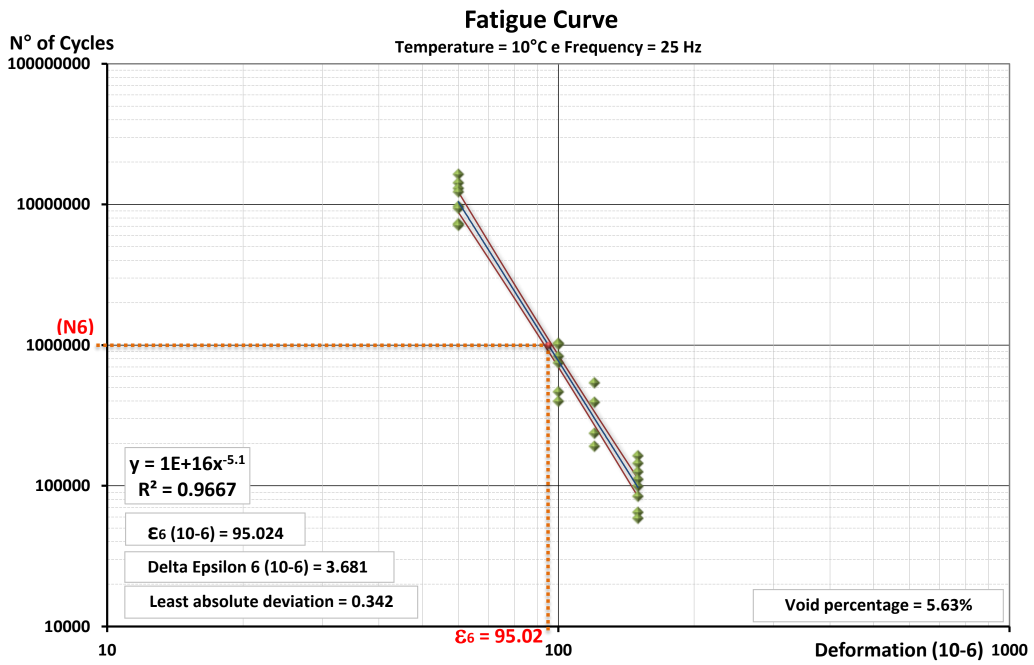

Figure 7 – Asphalt mixture fatigue curve

The next steps include data collection from field and comparison with a finite element model. The model will be built using the software Viscoroute (LCPC), which considers materials as viscoelastic and an axle with a certain velocity. Calibration will be applied using data collected from field. Ultimately, simulations will provide information on pavement behavior under real conditions.

4. Conclusions

The conditions around this study are unique due to the parameters found in field, such as: vehicle fleet, type of pavement structure, climate conditions, an exclusive experimental road, complete set of pavement sensors, 48 weigh in motion sensors of three different technologies, and nearby a weigh station. Monitoring the deformations and stress in the pavement structure combined with weigh in motion data acquisition will permit identification of the types of vehicles and loads transported. The information collected will combine data from WIM systems with pavement assessment data. That information will allow verification of damage progression due to load characteristics found in the experimental track. The deterioration study identifies and quantifies the damage caused by overloaded vehicles. Thus, the investigation can provide elements which permit a pavement deterioration model. The study is not yet completed and more analysis will be performed.

The Brazilian WIM tests so far are promising, but the great number of sensors and systems demands much attention and care. Thus far, controlled tests and calibration of the piezoquartz data acquisition system have been performed. Now, the technical staff is working to build an integrated data acquisition system that includes all sensors. The evaluation of data collected to this point are not conclusive and do not allow comparisons between systems. Technical staff is working to achieve this analysis.

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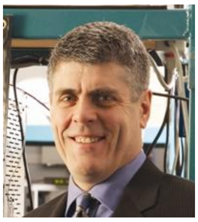
EVALUATING THE ROLE OF WEIGH-IN-MOTION IN MECHANISTIC PAVEMENT ANALYSIS





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Abstract

Mechanistic road modeling requires accurate traffic load spectra data in order to achieve realistic pavement response prediction under diverse traffic loading. As a result, Weigh-in-Motion systems are increasingly being employed in data collection applications to provide actual traffic load spectra in real field conditions.

This paper employs a 3D orthotropic road structural primary response model, *PSIPave3D™*, to calculate pavement primary strain response and illustrate the importance of accurate traffic data when predicting strains across specific road classes. Based on conventional truck loadings on typical in-service roads, this research showed that there can be a significant difference in predicting the fatigue or rutting life of pavements using conventional performance transfer functions. This research demonstrates that it is now possible to accurately calculate the shear strain behavior in all structural layers of typical road structures across diverse traffic load spectra as determined from weigh-in-motion. When coupled with accurate material constitutive theory and road structural modeling, this ability will lead to improved performance prediction of road structures based on actual accumulation of visco-plastic shear strains under repeated load spectra.

Keywords: Mechanistic Pavement Design, Traffic Data Collection, WIM System, *PSIPave3D™*

Résumé

Les modélisations mécanistiques de chaussées de route nécessitent des données de trafic exactes afin de réaliser une prédiction correcte de la réponse de la chaussée aux différents chargements de trafic. Par conséquent, les systèmes de pesage en marche sont de plus en plus employés pour la collecte de données permettant d'obtenir une image correcte du trafic réel.

Cet article utilise un modèle 3D orthotrope de la réponse de la structure d'une route *PSIPave3D™*. Ce modèle est utilisé pour calculer les réponses en termes de tensions primaires et pour illustrer l'importance de données de trafic précises pour prédire les tensions induites dans différentes classes de routes spécifiques. Cette recherche a montré qu'il y a une différence importante avec les prédictions de fatigue et d'orniérage de chaussés basées sur les charges de camions conventionnels. De plus, il a été montré qu'il est possible de calculer exactement l'évolution des tensions dans toutes les couches structurelles de la chaussée, qui peuvent conduire à la prédiction des performances améliorées des structures routières sur la base de l'accumulation des déformations visco-plastiques sous charges répétées.

Mots-Clés : Conception mécanistique de la chaussé, collecte de données de trafic, pesage en marche, *PSIPave3D™*.

1. Background

Historically, empirical approaches have been standard practice for flexible pavement design in North America. Equivalent Single Axle Loads (ESALs) have been used as the standard measure of traffic loadings in pavement design engineering and management practice for decades (AASHTO 1993). However, conventional load equivalencies may not accurately represent the actual primary response of pavements (Podborochynski et al 2011, Berthelot et al 2011a.). Without considering the true mechanistic behavior of pavements under the vehicle load spectra to which they are subjected, damage prediction experienced by road structures using conventional load equivalencies is limited. Accurate damage prediction and therefore traffic load spectra, is essential to optimize life cycle pavement performance from an asset management perspective.

In recent years, pavement engineering has utilized computational mechanics to conduct numerical structural modeling of roads. Mechanistic road models require accurate load spectra, road structural geometry, and material constitutive properties in order to precisely predict pavement primary response. The complexities of pavement design are directly related to different traffic trends, vehicle weights and configurations, vehicle speed, and the interaction of traffic loading with pavement materials, and climatic effects. These factors can all be encoded in computational mechanistic road models.

As stated above, one of the major inputs in any road design is traffic load data. Information such as loads axle, and axle groups, as well as vehicle configuration in a certain section of a roadway is needed to accurately assess the impact of commercial trucks on various road segments. The combination of accurate traffic loading and a computational mechanistic model will assist engineers in road structural design, pavement management, and load management or weight restriction decisions. Consequently, with the use of Weigh-in-Motion (WIM), pavement damage can be predicted and monitored in real time. Based on accurate traffic data analysis, the spatial distribution of fundamental state variables such as deflection, tensile, compressive, and shear strain within each pavement layer can be calculated accurately with a non-linear orthotropic 3D road model then compared to visco-plastic flow and fracture properties of the road materials.

Intelligent Transportation Systems (ITS) are increasingly being employed to characterize traffic data, and provide valuable information on vehicle load spectra for inputs for road structural analysis. This research examined the utilization of Weigh-In-Motion load spectra data for the computation of primary mechanistic pavement response as a function of vehicle loadings as determined by Weigh-in-Motion.

2. Role of Weigh-In-Motion Data Collection

Weigh-In-Motion (WIM) systems play a significant role in many road transportation systems including commercial vehicle weight and dimensions monitoring and enforcement. WIM is also an essential traffic data collection tool for providing accurate load spectra information for asset management purposes.

Several WIM sensors are commonly deployed and are currently used in traffic data collection applications such as piezoelectric sensors, piezoquartz sensors, bending plate scales, and single load cell scales (PIARC 2004). As vehicles travel over a set of WIM sensors, data such as gross vehicle weight (GVW), vehicle speed, axle group load, and vehicle classification are stored in data base files and can be used in many pavement design application and pavement management performance prediction models (PIARC 1999). For example, in recognizing the need for accurate traffic data, the Strategic Highway Research Program's Long-Term Pavement Performance (SHRP-LTPP) has employed WIM systems to provide field data collection and quantify traffic loading on LTPP pavement test sections throughout North America (German et al 1994).

3. Traditional Load-Related Damage Formulations of Pavement Life

It has been documented that overweight trucks inflict exponential rates of increasing damage to roads as a function of increasing load (Thomas, 2008, Berthelot et al 2008, Bergan et al 1998). The 1993 *AASHTO Guide for the Design of Pavement Structures* (Design Guide) modeled the effect of increasing load as a fourth power law damage relationship (AASHTO 1993). In North America, commercial vehicles have grown in number and weight load spectra over the past few decades (PIARC 2004). However, many jurisdictions have also increased allowable truck weights and dimensions to improve haul efficiency. As a result, roadways are often subjected to load spectra significantly greater than those originally used in road tests from which conventional pavement design equations were developed (Podborochynski et al 2011). Increased traffic loading on pavements has a significant impact on the life cycle performance of pavements and hence the life cycle costs of building and maintaining road networks.

Weigh-In-Motion systems have the ability to provide traffic load spectra data necessary to calculate the strain state occurring within a road structure. Critical strains can then be used within a performance transfer function to quantify road damage as outlined in the Asphalt Institute Structural Thickness Manual (MS-1), the AASHTO Design Guide based on the AASHTO Road Test, or the more modern Mechanistic–Empirical Pavement Design Guide (MEPDG), developed under NCHRP Project 1-37A (Kweon and Cottrell 2011).

4. Mechanistic Primary Response Road Modeling

A non-linear orthotropic road structural model, *PSIPave3D™*, was used to calculate the primary pavement structural responses for a typical Saskatchewan rural primary pavement structures at primary legal load limits. The highway structure examined was a flexible pavement structure consisting of a hot mix asphalt concrete (HMAC) layer (150 mm thickness) and granular base layer (400 mm thickness) constructed on subgrade. The response of the highway structure was compared across dry highway conditions and across wet highway conditions. Normal and shear strains, as well as peak surface deflections, were calculated. The results of the orthotropic modeling are presented in Table 1.

Peak surface deflections, depicted in Figure 1, were calculated to validate the primary response results of the model, as the model peak surface deflection results could be compared to the results measured in the field using heavy weight deflectometer (HWD) testing equipment. In comparing the field-observed deflections to the model-predicted deflections, the model was validated as being representative of typical Saskatchewan pavements (Prang and Berthelot 2009, Berthelot et al. 2008, Berthelot et al. 2008a).

Although the results are presented here are only at primary legal load limits for brevity, an important application of load spectra information, determined from WIM-collected data, is the calculation of fundamental strain responses and peak surface deflections of pavement structures in response to vehicle loads. Traditionally, pavement performance transfer functions are used to correlate fatigue failure to the tensile strain at the bottom of the hot mix asphalt concrete (HMAC) layer (ε_T) and the elastic modulus of the HMAC, and to correlate rutting to the vertical compressive strain at the top of the subgrade (Huang 2004), as shown in Figure 2.

Table 1 – Primary Model Responses for Dry and Wet-Aged Primary Highway

	Dry Primary Highway			Wet-Aged Primary Highway		
	Single Axle	Tandem Axle	Tridem Axle	Single Axle	Tandem Axle	Tridem Axle
Peak Surface Deflection (mm)	0.19	0.25	0.32	1.77	1.95	2.27
Vertical Compressive Micro Strain	91	95	107	1417	1191	1078
Horizontal Tensile Micro Strain	58	57	51	789	681	619
Shear Micro Strain in HMAC Layer	357	381	374	837	827	729
Shear Micro Strain in Granular Base	120	120	108	1630	1419	1205
Shear Micro Strain in Subgrade	81	101	113	1907	1793	1815
Rutting (Loads to Failure)	1.68E+09	1.38E+09	8.13E+08	7.71E+03	1.68E+04	2.62E+04
Fatigue Cracking (Loads to Failure)	1.51E+08	1.60E+08	2.30E+08	2.80E+04	4.55E+04	6.23E+04

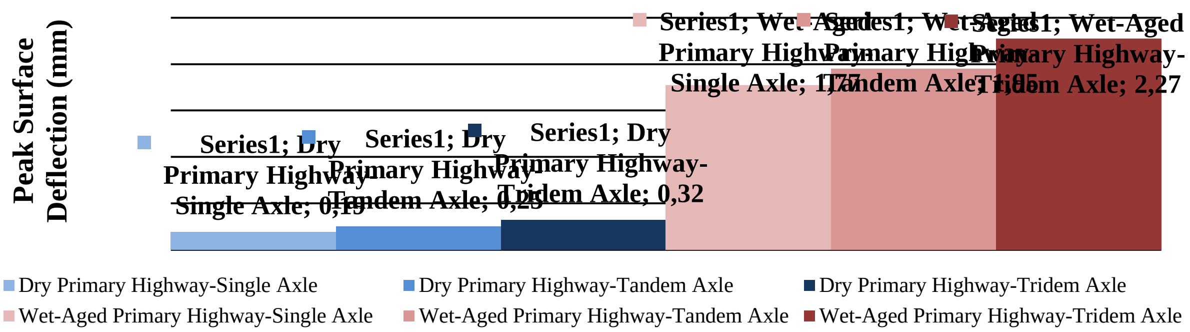


Figure 1 – Peak Surface Deflections across Dry and Wet-Aged Primary Highway

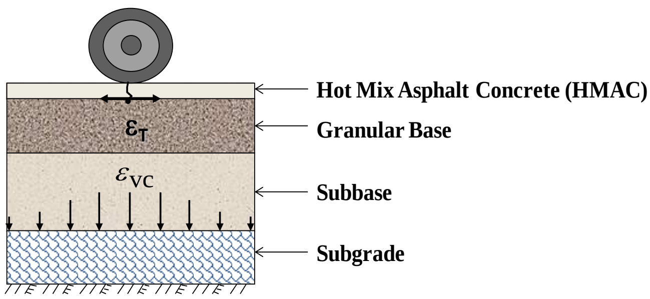
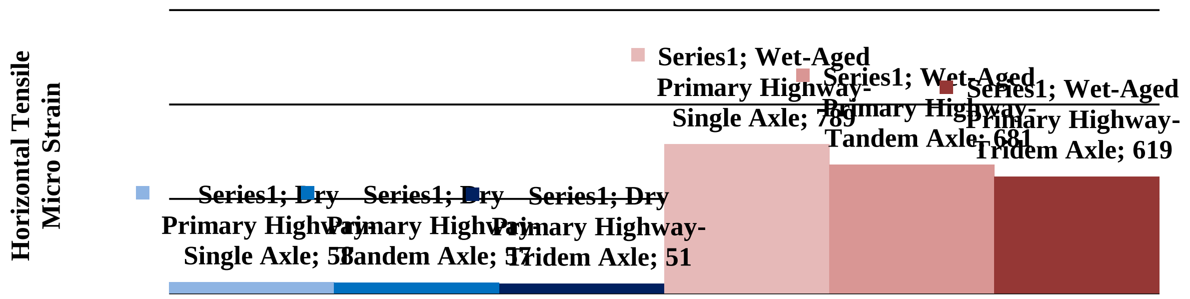
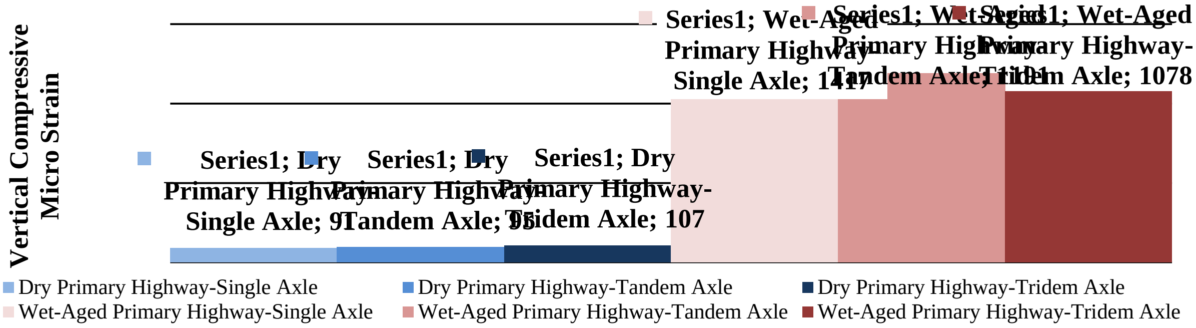


Figure 2 – Critical Orthonormal Pavement Strains used in Conventional Pavement Life Cycle Predictions

The orthonormal strains across axle group types (single, tandem, and tridem) and across dry and wet-aged pavement structural conditions are shown in Figure 3. As seen in Figure 3, the vertical compressive strain at the top of the subgrade and the horizontal tensile strain at the bottom of the HMAC layer are much greater for a wet and aged primary highway structure relative to a dry primary highway structure. As well, the strain state was observed to be significantly different across various axle group configurations.



a) Horizontal Tensile Micro Strain at Bottom of HMAC



b) Vertical Compressive Micro Strain at Top of Subgrade

Figure 3 – Orthonormal Strains across Dry and Wet-Aged Primary Highway for Various Axle Groups

5. Pavement Fatigue and Rutting Life Prediction Calculations

In conventional flexible pavement design, the calculated orthonormal strains have been traditionally used to predict the number of loads to failure in fatigue and permanent deformation (rutting) for flexible pavement structures.

5.1 Asphalt Institute Models

The Asphalt Institute (AI) developed equations for predicting the number of loads to failure in fatigue cracking and permanent deformation through empirical correlations to orthogonal strains and HMAC layer stiffness (for fatigue cracking) (AI 1982). Equation 1 presents the AI equation for predicting the number of loads to failure in fatigue cracking, N_f,

$$N_f = 0.0796\varepsilon_t^{-3.291}E_1^{-0.854} \tag{1}$$

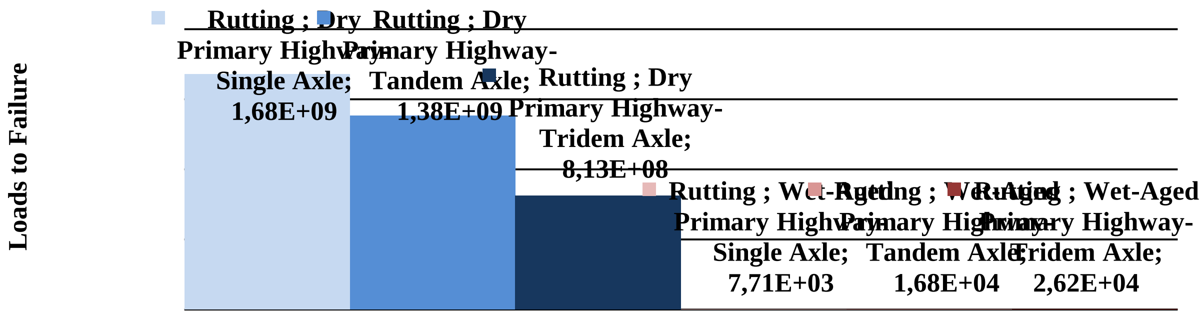
Where ε_t is the horizontal tensile strain induced by the load at the bottom of the asphalt layer, and E_1 is the elastic modulus of the HMAC layer in psi (AI, 1982).

Equation 2 presents the AI equation for predicting the number of loads to failure in rutting, N_d,

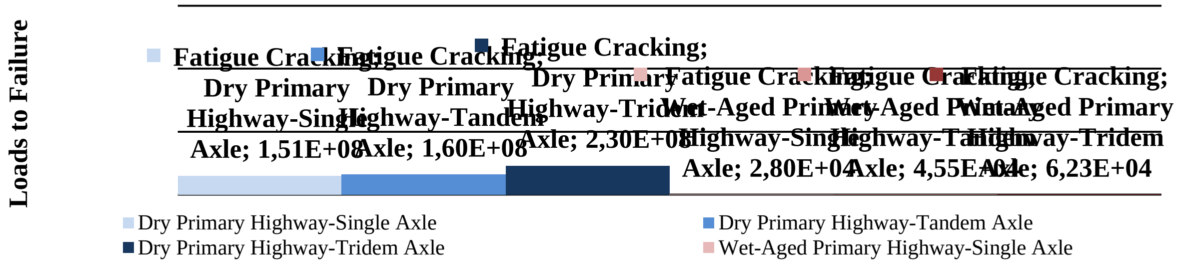
$$N_d = (1.36 \times 10^{-9})\varepsilon_v^{-4.477} \tag{2}$$

Where ε_v is the vertical compressive strain at the top of the subgrade (AI, 1982).

Based on the AI equations, the calculated number of loads to failure in (a) rutting and (b) fatigue cracking are shown in Figure 4. As shown in Figure 4, for both the dry and wet-aged highway structures, increasing the axle group from single to tridem decreases the number of load repetitions to failure.



a) Rutting



b) Fatigue Cracking

Figure 4 – Loads to Failure across Dry and Wet-Aged Highways for Various Axle Group

5.2 MEPDG Fatigue and Rutting Models

Based on the limitations of the 1993 AASHTO Design Guide and the AI method for predicting pavement life, the National Cooperative Highway Research Program (NCHRP) undertook Project 1-37A to develop a pavement design methodology using estimated stresses and strains within the pavement structure and empirical equations to relate these stresses and strains to expected in-field performance (NCHRP, 2007). The fatigue and rutting models developed for the MEPDG still use the same orthonormal strains as AI to determine the number of loads to failure in each mode; however they are used in conjunction with calibration factors (NCHRP, 2007). Equation 3 presents the number of loads to failure in fatigue cracking, N_f, based on horizontal tensile strain (ε_T) and HMAC elastic modulus (E_1):

$$N_f = 0.007566 C C_H \beta_{f1} \varepsilon_t{}^{-3.9492\beta_{f2}} E_1{}^{-1.281\beta_{f3}} \tag{3}$$

where β_{f1}, β_{f2}, β_{f3} are the local or HMAC mixture specific field calibration parameters, C is the factor for mixture properties based on effective asphalt content and air voids, and C_H is the thickness correction factor for bottom-up fatigue cracking (NCHRP, 2007).

Equation 4 presents the equation for the number of loads to failure in rutting, N_d, as

$$\varepsilon_p = \beta_{s1} k_{s1} \varepsilon_v \left(\frac{\varepsilon_0}{\varepsilon_r}\right) e^{-\left(\frac{\rho}{N_d}\right)^{\beta}} \tag{4}$$

where ε_p is the permanent plastic strain (permanent deformation, Δ_{soil} (in), divided by the thickness of the soil layer, h_{soil} (in), k_{s1}, k_{s2}, and k_{s3} are the global calibration coefficients based on soil type, β_{s1} is the rutting local calibration constant, ε_v is the vertical elastic strain in the soil layer, ε_o is the lab permanent strain at number of load cycles, ε_r is the lab resilient strain at number of load cycles, β is the local volumetric soil moisture content constant, and ρ is the local soil resilient modulus and moisture content constant (NCHRP, 2007).

6. Shear Strain Based Road Performance Modeling

It has been well documented that most road structural failures are induced by shear strain. Shear strains generate initial fatigue cracking and tensile strains and dictate permanent plastic deformation in all layers of the pavement structure rather than just the subgrade. However, for computational convenience, the road industry has traditionally assumed orthonormal strains are generally linearly proportional to shear strains. Since the 3D orthotropic road model used in this research is capable of determining shear strains accurately in all layers of a pavement structure, the use of the computational primary response model in conjunction with WIM load spectra data allows for the direct assessment of actual shear failure mechanisms for all road materials. The shear strains across dry and wet-aged highway and across axle groups are shown in Figure 5. As seen in Figure 5, road condition has an impact on level of shear strain experienced within the road. Furthermore, the axle groups and road condition are coupled in terms of their affect on shear strain within the pavement layers.

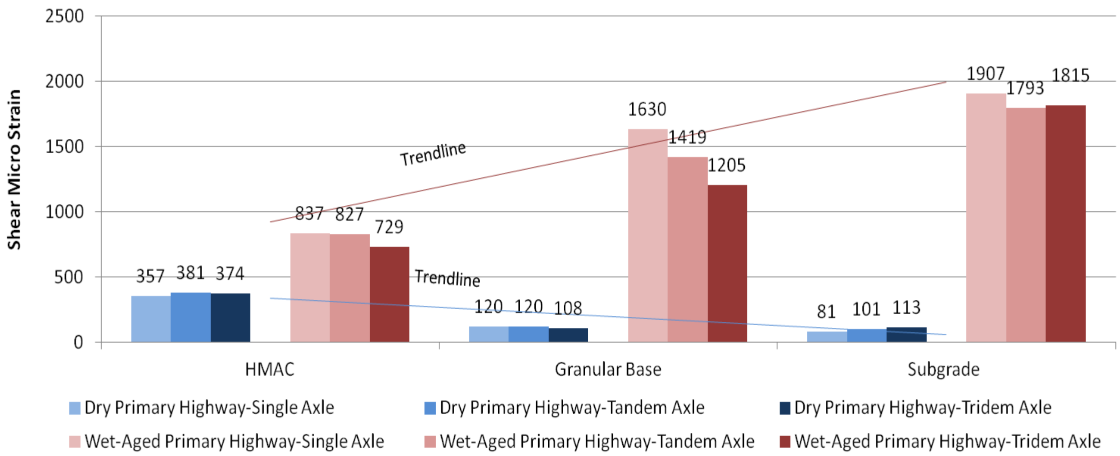


Figure 5 – Shear Micro Strain across Dry and Wet-Aged Primary Highway for Various Axle Groups

Based on these findings, it is clear that Weigh-in-Motion traffic load spectra information can be highly valuable in accurately determing actual shear strains occurring in a road structure, and therefore improve accuracy of pavement performance predictions.

7. Conclusion

Computational mechanics and numerical road structural modeling are being increasingly used in many areas of pavement engineering. However, to be effective, mechanistic road models require accurate traffic load spectra data in order to achieve precise pavement primary response calculations. Weigh-in-Motion systems can be employed to determine actual traffic load spectra in the field; a traffic load spectrum is a significant determinant for the damage prediction and the life cycle performance of pavement structures. This research showed that traffic load spectra data as well as road structural condition have the major impact on pavement fatigue cracking and rutting damage performance predictions. As well, this research showed traffic load spectra data is critical for more advanced, fundamental damage mechanics based road performance prediction models, which are currently being developed. Therefore Weigh-in-Motion is an essential tool lead to improved performance prediction of road structures based on actual accumulation of visco-plastic strains under repeated loads.

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Session Posters

CHECKING WIM AXLE-SPACING MEASUREMENTS

Graduated from the Military University in Brno in 1958. He obtained his Masters Degree in Transportation from the University of California, Berkeley, in 1976, and his Doctor of Science Degree in Engineering from the University of Pretoria in 1978. After working at the National Institute for Transportation and Road Research for 14 years, he joined BKS Consulting Engineers where he is currently a Specialist Transportation Engineer.

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Abstract
The evaluation and rating of error in the measurement of axle-spacing between the tandem driving axles of certain large trucks have recently been added to WIM data quality checks in South Africa. For technological reasons, the axle spacing between the 2nd and 3rd axle is on average 1.35 m with little variation from truck to truck. Since the axle distance is derived from a speed measurement done by inductive loops, and a time measurement done by the weighing sensor, the magnitude of error reflects the soundness of the WIM's operating condition in general. A characteristic called *Error Rating*, *ERas23,* quantifies the above soundness. Excessive values of *ERas23* suggest possible instrumentation faults and need for WIM repair. Graphs of trends demonstrate practical application and experience with *ERas23* in South Africa so far.
Keywords: Weigh-In-Motion, accuracy, data quality, axle-spacing, fault finding.

Resumé
En Afrique du Sud, l'évaluation et la classification des erreurs dans la mesure de la distance entre les essieux constitutifs des tandems moteurs ont été rajoutées récemment dans les verifications de qualité du pesage en marche. En effet, pour des raisons techniques, cette distance entre deuxième et troisième essieu est toujours d'environ 1.35m, avec très peu de variations autour de cette valeur moyenne. Comme la distance entre essieux est calculée grâce à la vitesse estimée avec les mesures des boucles et celle du temps réalisée par le capteur de pesée, l'amplitude de cette erreur reflète la qualité générale de la valeur donnée par la station de pesage. Ainsi une caractéristique, nommée Eras23, quantifie cette qualité. Des valeurs trop importantes de Eras23 suggèrent de potentiels problèmes d'instrumentation et des besoins de réparations de la station. Des graphes qui montrent l'actuelle application de Eras23 en Afrique du Sud sont présentés.
Mots-clefs: Pesage en marche, précision, qualité des données, distance inter-essieux, détection d'erreurs.

1. Periodic WIM data quality analysis

Weigh-In-Motion (WIM) measurements are mainly used for pavement design and loading-law enforcement purposes. The information most sought after includes

- distribution of axle loads,
- equivalent standard axle loads (*ESAL*, also called *E80*),
- classification of heavy vehicles,
- percentage of overloaded heavy vehicles and
- the percentage excess of load above permitted limit.

Although the individual measurements of axle loads and equivalent standard axle loads are not very accurate, the *averages* of thousands of measurements are, provided the WIM is well calibrated and in a good operating condition (Slavik, 2011).

A practical way of achieving good calibration is based on a periodic WIM data analysis. When the WIM operates as a screening scale, weighbridge-measured axle-loads are compared with those recorded by WIM. Based on the comparison, a factor is applied to the WIM-measured loads, to obtain the weighbridge-recorded total. For WIMs that are not used in conjunction with a static weighbridge, the Truck Tractor (TT) Method is used (De Wet, 2010). The TT Method is a retrospective calibration method that uses the truck-tractor mass of a stable population of large loaded trucks as a calibration reference. A series of data quality checks were developed as part of the TT Method, all of which focus on the credibility of axle loading measurements.

In addition to axle loads, the axle spacing obtained from a WIM installation is also very important. The obvious reason is that axle spacing is used in vehicle classification algorithms and checking the compliance with the so-called bridge formula. Secondly, it plays a role in the calibration of loading data since axle spacing is used as a criterion for the selection of trucks that are used in the TT Method. The accuracy of axle spacing measurements is thus one of the prerequisites for the acquisition of accurate and stable loading information.

2. Measuring axle-spacing

The two main components of WIM instrumentation – weighing sensor(s) and inductive loops – must work in harmony to produce accurate axle spacing information. To confirm this, the authors recently developed a testing method that is based on monitoring the spacing between tandem driving axles of certain trucks. Such trucks have six or seven axles and their truck tractors have one steering and two driving axles. The distances between the first and second, second and third, and third and fourth axles are: 2.9 m - 3.9 m, 0.7 – 2.0 m and 4.5 – 9.0 m, respectively. For mechanical reason related to the length of the second prop shaft, the spacing between the second and third axles, i.e. between the driving axles, is about 1.35 m with very little variation from truck to truck. The loop part of WIM supplies speeds, the weighing-sensor part supplies the inter-arrival time of the driving axles. If a WIM is in good operating condition the product of those two – the so called *as23* - should be close to 1.35 m, with a reasonably small variation.

Two factors contribute to the above variation: the actual spread of distances between tandem driving axles and the WIM-measuring error. From a review of truck manufacturers' specifications and a study of thousands of WIM-measured *as23* the authors concluded that the true spread around 1.35 m is as small as ±3 %. This true spread must first be subtracted before evaluating the axle spacing measurement error committed by WIM. The error rating of a WIM for axle spacing measurements, *ERas23,* is defined as the zero-centered interval, ±δ, containing 95 % of the percentage errors committed by WIM when measuring the as23. A large-scale study revealed that at WIMs that operated well the *ERas23* did not exceed ±7 %.

3. The evaluation of Error Rating

The calculation of *ERas23* is based on the assumption that both the true axle spacing and the axle spacing measurement error committed by WIM are normally distributed. To simplify further analysis, it was assumed that the mean of the true distribution is 1.35 m and that the true standard deviation is 3 % of the mean.

When truck tractors travel over a WIM site, the WIM system measures the axle-spacing *as23* with a mean M, and standard deviation S, measured in meters. The mean *percentage* error *m* – errors in this context are the deviations from 1.35 m – is given by Eq.1

$$m = \left(\frac{M - 1.35}{1.35}\right) * 100 \qquad (1)$$

It can be proved that the standard deviation of the percentage error, *s*, is 100/1.35 times larger than S, thus:

$$s = \left(\frac{100}{1.35}\right) * S \qquad (2)$$

Both the true spread of axle-spacings and the measurement error contribute to the above standard deviation. The standard deviation of measurement error alone can be isolated by subtracting the variance of the true spread from the variance of the sample and taking the square root of the result. The following equation should be used:

$$s' = \sqrt{s^2 - x_{as}{}^2} \qquad (3)$$

where:

s’	=	% standard deviation of measurement error on 2nd axle spacing,
s	=	% standard deviation of 2^{nd} axle spacing measured by WIM,
x_{as}	=	% standard deviation of true 2^{nd} axle spacing (assume 3 %).

The calculation of error rating *ERas23* from the values of *m, s’* and sample size *n* is not trivial. A numeric method called Yona (Slavik, 2007), (Slavik, 2008) based on computer simulation was introduced earlier to perform this task. However, for large sample sizes (say, n > 1 000), a simpler procedure based on a nomogram can be used in practice. This alternative method is outlined below.

It is assumed that axle spacing measurement errors are normally distributed. It follows that, for a large sample of say, more than 1000 axle-spacing measurements, the following statements can be made about of a zero-centered interval δ called *Error Rating* (also refer to Figure 1):

- For a mean error of zero, δ = 1.960 * s’. An equal percentage of measurement errors are left of – δ and right of + δ respectively.
- For a large mean error, δ ≈ m + 1.645 * s’. Almost all of the excessive errors are on one side of error distribution.
- In general, an iterative process is required to determine the value δ of a zero-centered interval since unequal proportions of the distribution extend beyond δ on the left and right side of the error distribution.

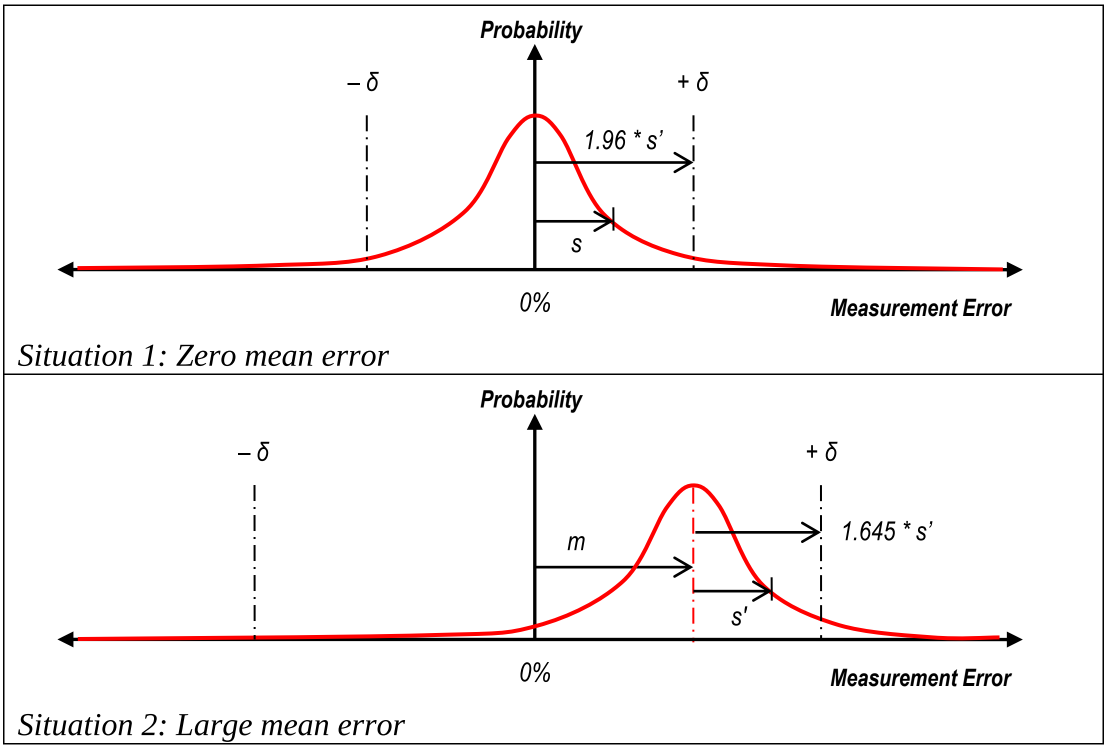

Figure 1: Confidence Intervals for Measurement Error

An iterative procedure was followed to calculate Error Ratings for a range of means and standard deviations of measurement errors, and the results are shown on the contour graph in Figure 2.The graph illustrates that:

- The Error Rating intercept on the vertical axis (i.e. for m = 0) is equal to 1.960 * s’ as illustrated in Figure 1 (Situation 1).
- For m > s’, the Error Rating contours are almost straight lines. The Error Rating can be approximated by m + 1.645 * s’ as illustrated in Figure 1 (Situation 2).

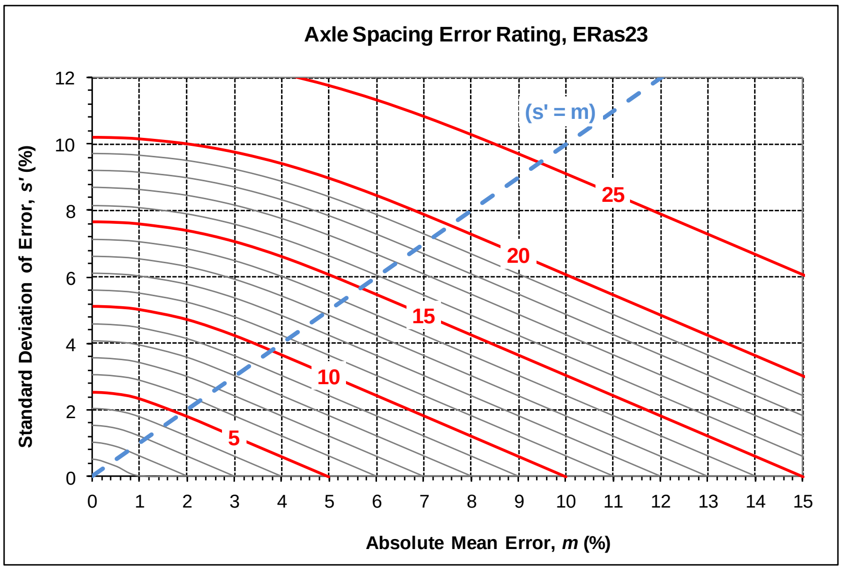

Figure 2: Measurement Error Rating Contours, Using m and s’

The mathematical relationship between *ERas23*, *m* and *s* was established through multiple linear regression analysis. This simplifies the computation of *ERas23* to the extent that it can be calculated easily and accurately on a routine basis.

If s < 3, then

$$ERas23 = |m| \tag{4}$$

If s ≥ 3, calculate the standard deviation s' of measurement error:

$$s' = \sqrt{s^2 - 3^2} \tag{5}$$

For s' < m

$$ERas23 = |m| + (1.645 * s') \tag{6}$$

For s' ≥ m

$$ERas23 = (|m| + 1.645s') * (0.387\alpha^3 - 0.928\alpha^2 + 0.759\alpha + 0.789) \tag{7}$$

where:

$$\alpha = ATAN\left(\frac{s'}{|m|}\right) \tag{8}$$

With the known relationship between m, s and s', it was possible to develop an Error Rating nomogram for large samples using m and s as input, shown in Figure 3. Based on the analysis of data from various WIMs on the N3 and other Toll Concessions, a maximum acceptable Error Rating of 7 was selected as a threshold. The graph below can be used as a quick guide to evaluate the accuracy of axle spacing measurements at a WIM.

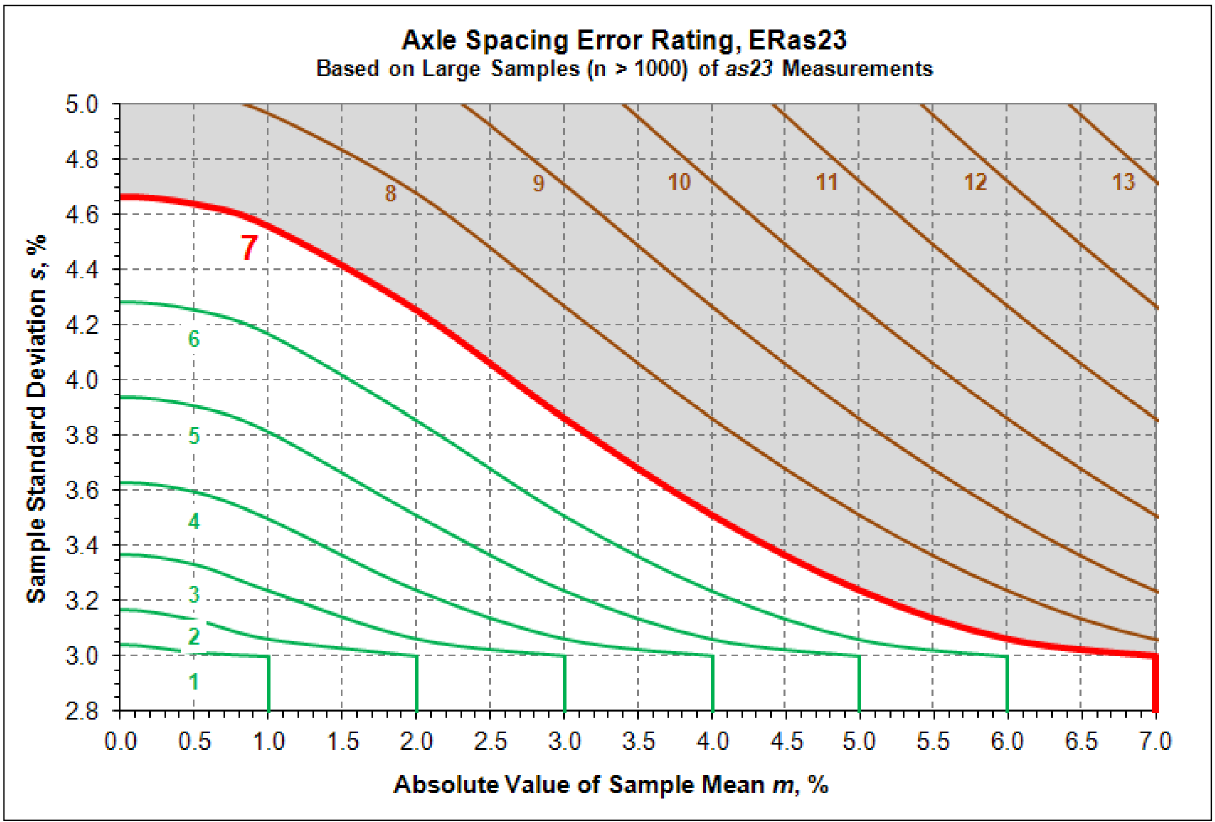

Figure 3: Nomogram for Axle Spacing Measurement Error Rating

At present in South Africa checking on the compliance with the above standard is a periodic WIM-data quality task that is performed, together with the loading data quality checks associated with the TT Method, on a monthly basis.

4. Practical results

An example of *ERas23* values achieved at twelve WIM installations on the N3 National Road, between Johennesburg and Durban, in April 2011, is shown in the Table 1 below.

Table 1: Example of ERas23 at Twelve WIM Installations

WIM	Direction of travel	
	Northbound	Southbound
Wilge	3.67 %	4.67 %
Harrismith	5.48 %	4.38 %
Van Reenen	9.10 %	4.54 %
Roosboom	6.13 %	1.88 %
Hidcote	2.79 %	4.56 %
Cedara	4.34 %	7.14 %

Based on the above evidence, the WIM service provider – Mikros Traffic Monitoring – acknowledged and corrected the failure of the loops at Van Reenen, and deferred decision on the marginal failure at Cedara. The trends in ERas23 at most of the WIM stations that are under monthly scrutiny are stable. An example is shown in Figure 4. The ERas23 trends are mostly flat and below 7 %.

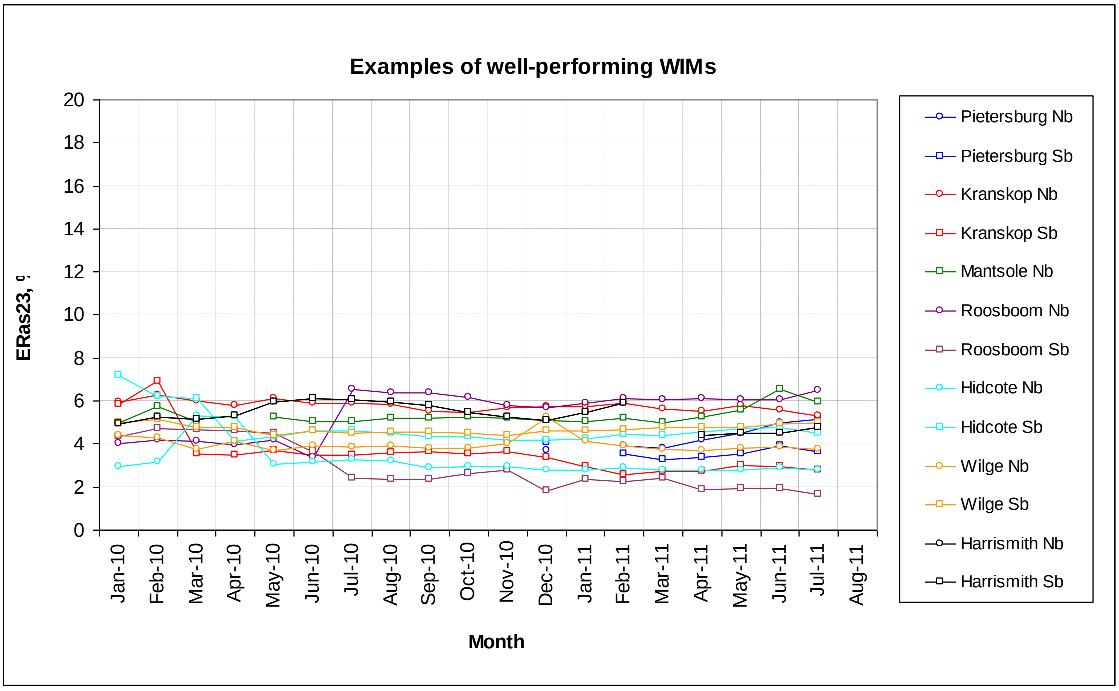

Figure 4: Examples of Stable Long-Term Axle Spacing Measurement Error Ratings

Figure 5 shows how ERas23 responded to a repair after abnormal pattern had been detected and brought to Service Provider’s attention.

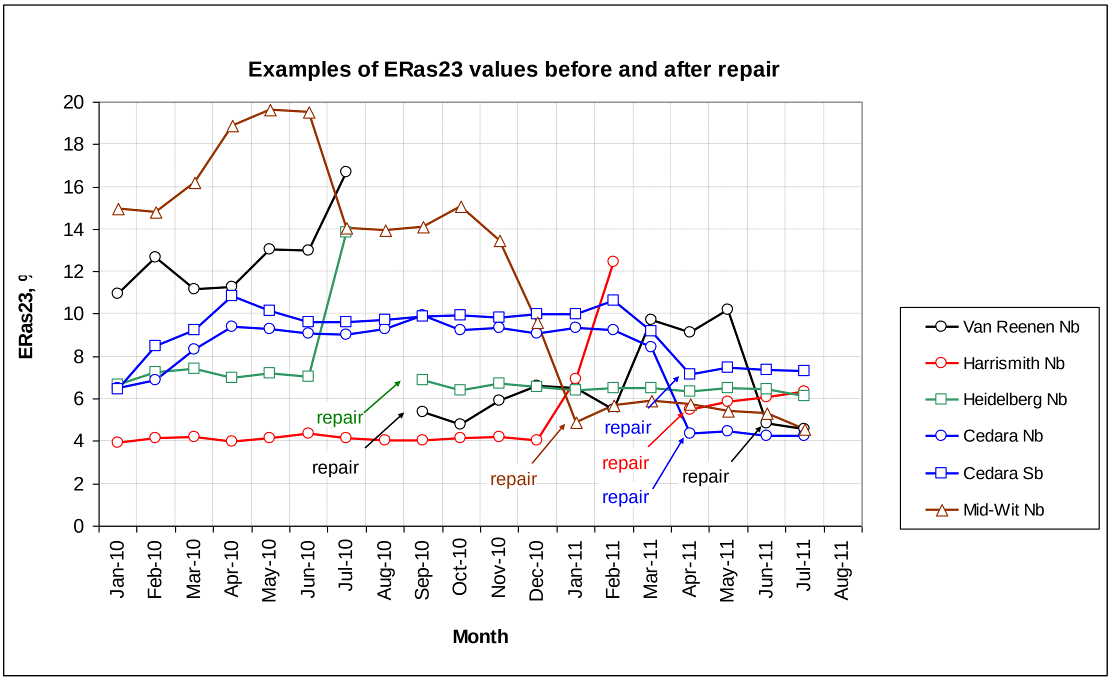

Figure 5: Examples of ERas23 Values Before and After WIM Repair

Although still under development, a new South African WIM instrumentation (nick-named Bosvark) has already been operating at eight locations for several months. The influence of the design refinements and algorithms fine-tuning is apparent from Figure 6.

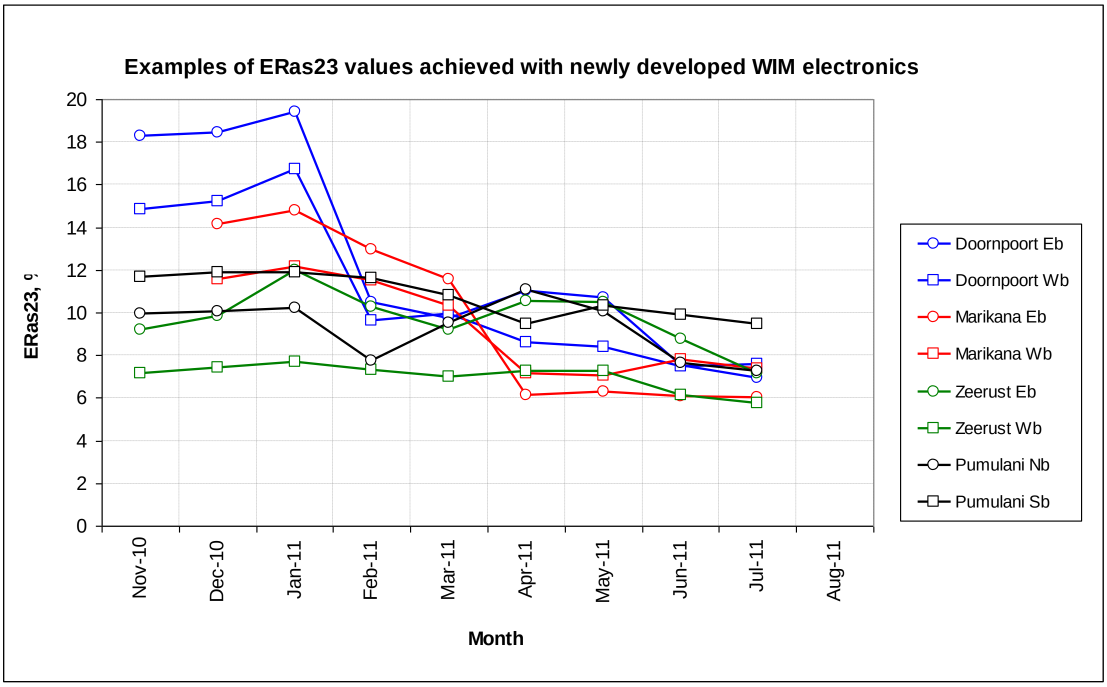

Figure 6: Examples of ERas23 Values Achieved with Newly Developed WIM Electronics

5. Conclusion

The axle-spacing check is a useful tool in the quest for WIM data integrity and quality. It performs three important tasks:

- identifies possible equipment and/or pavement problems; this allows the operator to rectify the situation before large amounts of measurements are lost,
- allows to flag as suspect WIM-collected data whose quality is likely to be compromised,
- aids the development and fine-tuning of the new WIM technology.

6. Acknowledgement

The authors wish to express their gratitude to South African Roads Agency, Bakwena Platinum Corridor Concession, Northern Toll Road Venture, N3 Toll Concession and Trans African Concessions for the permission to use their WIM data and information.

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TRAFFIC-1, USER TAILORED MEASURING SYSTEM OF ROAD TRAFFIC PARAMETERS

    

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Abstract

A new prototype system of road traffic parameters measurement, Traffic-1, is presented in this paper. Innovativeness of the solution is manifested in the structure of the system that can be tailored by the user adequately to current measurement needs and in the implemented sophisticated algorithms of signal processing. The paper contains a brief description of constructed system with particular focus on the used innovations that are the result of many years of research work by the authors.

Keywords: Road traffic parameters measurement, weigh in motion systems, vehicle classification.

Résumé

Ce document présente un prototype de système de mesure des paramètres de trafic, appelé Trafic-1. Le côté innovant de ce système réside dans sa structure qui peut être modifiée par l'utilisateur en fonction des besoins de mesure et des algorithmes de traitement du signal. Le document contient une brève description du système et met l'accent sur ces innovations qui sont le fruit du travail des concepteurs du système durant plusieurs années.

Mots-clés: Mesure des paramètres de trafic, pesage en marche des véhicules, classification des véhicules.

1. Traffic-1 System Structure

The Traffic-1 system (see Figure 1) has been designed for a wide range of users with varied expectations concerning the applied sensors and measured traffic parameters (Ezell, 2010). The system is portable, and its structure as well as the set of used sensors may be easy tailored by the user according to current needs. It allows application of this system on different measurement sites equipped with different kinds of measuring sensors. The Traffic-1 system is openly available from AGH – University of Science and Technology in Cracow, Poland.

The structure of the system is open and consists of the central unit and interchangeable signal conditioning modules. The system is equipped with nine modules, what means that it can fulfil the functions of nine different measuring systems. Each module is purposed to work with a different configuration of road traffic sensors. The system recognises its configuration automatically and activates an applicable data processing algorithm.

Figure 1 - Traffic-1 system with interchangeable signals conditioning modules

The following configurations of measuring sensors (Klein, 2001) are acceptable by system: A - single inductive loop, B – dual-loop detector (speed trap), C- dual-loop detector and single axle detector, D - dual-loop detector and single polymer load sensor, E - dual-loop detector and single quartz load sensor, F – three inductive loop array (it contains 2 narrow loops as wheel detectors), G – single inductive loop and 2 strip axle detectors, H – single inductive loop and 2 polymer load sensors, I – single inductive loop and 2 quartz load sensors.

Depending on the configuration (A – I), the system enables measuring the following vehicle parameters: T - time of arrival in the measurement zone, V - vehicle velocity, L - vehicle length, N_{axle} - number of axles, L_{axle} - distance between successive axles, Trailer - trailer presence, Axle load - loads of individual axles, Total mass - total mass of a vehicle moving with speed between 30km/h up to 80km/h (19 mph up to 50 mph), Cl. magnet - vehicle class based on magnetic profile, Cl. ALT - vehicle class based on the number of axles and the distance between them (different classification schemes are possible, e.g. FHWA F or ALT) (Gajda, et al., 2011). Furthermore, the system enables estimation of the following road traffic characteristics (Maerivoet, 2005): k - traffic density, q - flow of vehicles, ρ – traffic lane occupancy, V_{mean} – mean speed.

Change of the type, number and configuration of the sensors not only affects the number of measured parameters, but also in many cases it influences measurement uncertainty (see Table 1). The presented uncertainties were obtained during field experiments performed in real traffic conditions, by referring the measurement results produced by Trafic-1 system to chosen parameters of the reference vehicles (length and axles distance), pre-weighed vehicles on static load cells (axle load and total mass) or obtained from a reference measurement system (speed measurement system with axle detectors or radar system).

Table 1 - Uncertainty of measurement of road traffic parameters in Traffic-1 system

	T [s]	V [km/h]	L [m]	N_{axle}	L_{axle} [m]	Trailer	Axle # load [N]	Total # m. [kg]	Cl. mag.	Cl. ALT	k, q, r V_{mean}
A	0.01 s	6-23%	20%	–	–	x	–	–	x	–	x
B	0.01 s	1.5% *	2% *	–	–	x	–	–	x	–	x
C	0.01 s	1.5% *	2% *	–	2%	x	–	–	–	x	x
D	0.01 s	1.5% *	2% *	x	2%	x	20-30%	15-20%	–	x	x
E	0.01 s	1.5% *	2% *	x	2%	x	15-25%	15-20%	–	x	x
F	0.01 s	7.5%	8%	8%	10%	x	–	–	–	x	x
G	0.01 s	<1km/h	2% *	x	±2.5 cm	x	–	–	–	x	x
H	0.01 s	<1km/h	2% *	x	±2.5 cm	x	15-20 %	10-15%	–	x	x
I	0.01 s	<1km/h	2% *	x	±2.5 cm	x	10-15%	7-10%	–	x	x

NOTE: "*" - in the sense of standard deviation, "– "- not available, "x" – available, # - results obtained on the pavement of A class according to (ISO8608, 1995).

The Traffic-1 system has been equipped with internal memory able to store 150 thousand vehicles records. The touchscreen LCD enables control of system performance and real time visualisation of measurement results. Interface RS232 and a GSM modem have been chosen for communication. Both interfaces enable transmission of data to an external computer or ftp server. The device has the capability of automatic detection of specific sensor faulty operation.

2. Discussion

The system utilises a range of innovative hardware and software solutions, described below, that increase the functionality and reliability of the device.

2.1 Algorithm for Speed Estimation in a System Equipped with a Single Inductive Loop

In classic Intelligent Transportation Systems (ITS) installations using axle detectors, vehicle speed measurement requires installing two sensors in the pavement in a specific configuration (e.g. dual-loop detector, two polymer axle detectors or load sensors). The Traffic-1 system enables estimation of speed on the basis of a vehicle magnetic profile signal obtained from a single inductive loop, which significantly reduce the cost of the whole system. The method was proposed in 1997 in a study (Gajda, et al., 1997), and also developed by other authors, e.g. (Ritchie et al., 1999). In (Wang et al., 2003), the authors present an algorithm of speed estimation and vehicle-classification which is based on signals from a single inductive loop. The algorithm used in Traffic-1 system is illustrated by equation (1) and in Figure 2.

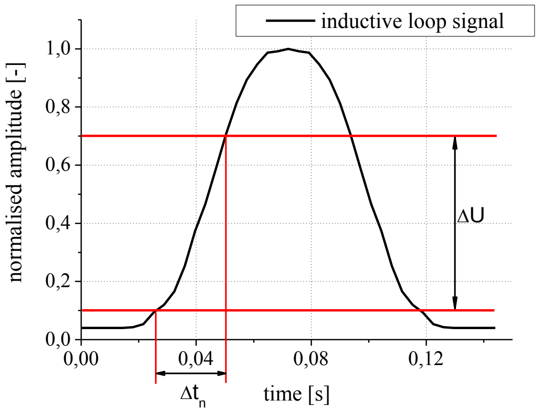

Figure 2 - Example of signal from inductive loop and estimation of the rise time with the method of two levels

$$V = a_1 \frac{\Delta U}{\Delta t_n} + b_1 \tag{1}$$

where:

V - vehicle speed estimation,

Δt_n - rise time,

ΔU - difference between predefined levels,

a_1, b_1 - constant coefficients, specified during calibration of the algorithm.

Example results of speed measurement in a system with a single inductive loop compared to a double sensor reference system have been presented in Figure 3.

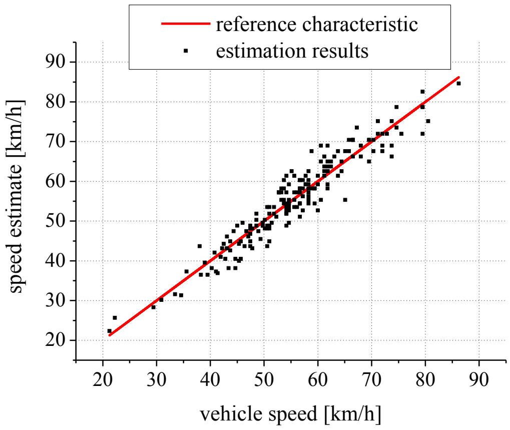

Figure 3 - Speed estimate for passenger vehicles specified according to algorithm (1) as a function of vehicle speed

2.2 Axle Detection on the Basis of the Magnetic Profile

The common method used to measure the number of axles and the distances between them uses a system that includes piezoelectric, resistance, fibre optic, or other axle detectors/sensors (Klein, 2001). Systems that incorporate inductive loops for this purpose are rarely used (Sun 2000), (Gajda et al., 2011), (Oh et al., 2007), (Diamond, 2010). An important advantage of using loop sensors is significantly lower cost in comparison with other axle sensors. The Traffic-1 system uses two narrow (10 cm) and one wide loop sensor with standard dimensions. The narrow loop sensors are used as axle detectors. Example signals from a narrow loop sensor are presented in Figure 4.

Some lorries are able to lift one or two axles. In such cases systems equipped with typical detectors give incorrect axle counts. Systems equipped with inductive loop sensors do not have this disadvantage and count correctly even those axles that are not in contact with the road pavement. The method developed for this capability is a subject in patent proceedings and is presented in detail in (Gajda et al., 2011).

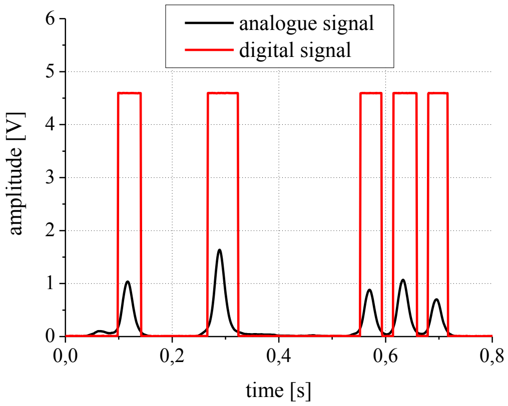

Figure 4 - Example of analog and digital signals from a conditioning system that includes a narrow inductive loop

2.3 Autocalibration and Temperature Correction of Weighing Results

One of the major reasons for the high uncertainty of weighing results in Weigh in Motion (WIM) systems equipped with polymer (piezoelectric) sensors installed in the road pavement is the nonstationarity of the system. This phenomenon is caused by changes of pavement properties under the influence of temperature changes and has special significance in case of polymer load sensors (LTPP, 2010). It has been verified experimentally that changes of weighing results caused by the daily temperature cycle can reach 40% (Burnos, 2008). The authors have developed two methods that enable limitation of the influence of this phenomenon on the accuracy of the results (i.e. autocalibration and temperature correction of weighing results).

The concept of autocalibration consists of continuoust estimation of the calibration coefficient C of the WIM system and modification of weighing results according to the current estimation result:

$$y_s(i)=\frac{1}{C}\cdot y(i) \tag{2}$$

where:

$y_s(i)$ – calibrated result of weighing the i-th vehicle i.e. estimation of total mass of the vehicle or static load of a selected axle,

$y(i)$ – non-calibrated result of weighing the i-th vehicle i.e. result of processing of the load signal from the WIM system sensors.

A necessary condition that enables WIM system autocalibration is the occurrence of so-called reference vehicles in the stream of vehicles moving through the calibrated WIM site. These vehicles are regular road traffic participants and are distinguished by arrangement of three semi-trailer axles in mutual distances of 131 cm, which significantly facilitates their identification, as well as small relative random variability of the first axle load (std=10%), with mean value μ_0=61677 N. It means that the load of this axle is practically independent of the carried load, and therefore can be used as a reference value during autocalibration of the system. For the calibration coefficient calculation, a recursive least squares algorithm with modified exponential forgetting factor has been used (Burnos, 2008). It has been verified experimentally that the use of the autocalibration method in a nonstationary system reduces uncertainty of weighing results by five times.

The temperature correction method requires a model of the temperature characteristics of the WIM site and asphalt temperature measurement. Such model can be specified using the results of weighing the first axle of reference vehicles over a long time period. Figure 5 presents experimentally specified temperature characteristics within the range from -10 to 30 °C. The data were registered from November 2005 until January 2008 at WIM site in Gardawice, in southern Poland (Burnos et al., 2007). In this time (with short pauses for system maintenance) over 100 thousand weighing results of reference vehicles were recorded. Each point in Figure 5 (measurement data) is a mean value of weighing the first axle of thousands of reference vehicles at a selected temperature.

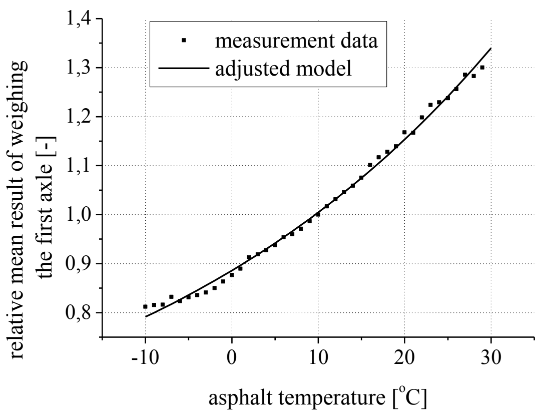

Figure 5 - Temperature characteristics of WIM system within the range from -10 to 30 °C

Experiments have proved that the correction method makes possible even 4-fold reduction of uncertainty of weighing results in nonstationary systems (Burnos 2008).

2.4 Alternative Automatic Vehicle Classification Method

With the Traffic-1 system, it is possible to select either of the implemented algorithms for automatic vehicle classification: FHWA or ALT (Burnos, 2010). In comparison with other methods, the ALT classification algorithm is distinguished by universality resulting from the open structure of vehicle classification scheme as well as the use of fuzzy sets and data fusion in the identification algorithm. The classification is based on an elementary group of components (motorbike, car, delivery vehicle, lorry, tractor, trailer, semi-trailer, bus) out of which the user can build any number of vehicle categories. Since the method is characterised by high selectivity and flexibility, the number and types of vehicle categories can be adjusted to suit the nature of traffic in a given area. For example, the 20 categories of vehicles most frequently occurring on Polish roads were created using the elementary group of components

(8 categories of single vehicles, 6 categories of vehicles combination, 6 categories of articulated vehicles).

The functional basis of the identification algorithm is the measurement of parameters characterising the vehicle, such as: number of axles, axle spacing and vehicle length that constitute a vector of characteristic parameters. The decision on classification of a vehicle into the proper category is made by means of comparison of the characteristic vector value with the vector that is the model of the category. The vehicle category models in ALT classification (unlike classic solutions) have been built on the basis of fuzzy sets.

Experimental verification of the algorithm implemented in Traffic-1 system was conducted on the basis of 1097 recorded vehicles. The results of the automatic classification were compared with the results of the visual specification of vehicle types, and the ratio of correctly classified vehicles to the total number of test vehicles in a given category was computed as a measure of effectiveness.

Effectiveness of the classification of all vehicles was 95%, while in the case of lorries it was 100%. The overall effectiveness of ALT classification was 10% higher than that of FHWA. Furthermore, there were no unclassified vehicles. Simplicity of the method (measuring the distance between axles and vehicle length), its universality, and high effectiveness are definitely its advantages.

3. Conclusion

The presented measurement system Traffic-1 is a universal tool for both long-term measurements of road traffic parameters and short-term measurements realised within the scope of research work. It can be easily moved between different measurement stations. The developed algorithms enable measuring a wide selection of vehicle parameters as well as traffic stream characteristics, at the same time minimising the costs related to the measurement sensors used. More information about Traffic-1 system may be found on www.traffic-1.pl

4. Aknowledgement

The authors would like to thank: Piotr Piwowar and Zbigniew Marszałek – members of “Traffic-1” team - for involvement in the project.

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APPLICATIONS FROM A CENTRALIZED SYSTEM OF WIM

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Abstract

Conventional WIM systems usually measure the length, the speed and the axle weight for each vehicle, and determine infractions using the total weight. According to their degree of accuracy, they answer more or less the needs expressed by highway managers. Today, advanced methods of electronic sensing and data processing allow weighing of vehicles at high speed with sufficient accuracy in the long-term to envisage enforcement in normal traffic flow. This document also shows that the networking of such equipment offers WIM, beyond the standard application of enforcement of weight limits, a whole new set of applications for traffic flow control such as the detection of convoys.

Keywords: Weigh-in-Motion, WIM, HS-WIM, Section speed radar, Convoy detection, Cabotage.

Résumé

Les systèmes conventionnels WIM mesurent couramment pour chaque véhicule la longueur, la vitesse, le poids des essieux et calculent les infractions sur le poids total. Selon leur degré de précision, ils répondent plus ou moins aux besoins exprimés par les exploitants de la route. Aujourd'hui, des méthodes avancées de traitement électronique permettent de peser les véhicules à haute vitesse avec une précision suffisante dans le temps pour envisager le contrôle sanction en trafic courant. Ce document montre de plus que la mise en réseau de tels équipements offre pour le pesage en marche, au-delà des applications standard de contrôle du poids, tout un ensemble d'applications nouvelles de contrôle des flux routiers telles que la détection de convoi.

Mots-clés: Pesée dynamique, Pesage en marche à haute vitesse, Radar tronçon, Détection de convois, Cabotage.

1. Introduction

This paper aims to demonstrate that there now exists a solution to improve road safety by resolving the problems connected to Heavy Goods Vehicles (HGVs). The approach used is:

- Identify safety issues which countries face involving HGVs on their road networks;
- Propose an easy to implement solution suited to these issues for all of these networks, while meeting the required limits of the different road types, vehicle fleets, traffic density and other local specifics. This solution works every day of the year, regardless of weather conditions, and for all vehicles traveling at speeds of 30kph to 250 kph;
- Demonstrate that this solution has been validated, that it is suitable for enforcement, that it is implementation ready, and that it offers new applications not previously available.

2. System deployment

2.1 Context

Problems faced by all road network managers are as follows:

- Road safety, with the higher rate of fatal accidents involving HGVs (13.7% of deaths for 3.3% of vehicles in France) (Marchadour and Jacob, 2008);
- Enforcement of rules to guarantee fair competition among all road transport players (26,500€/year/vehicle of additional benefit for a 5-axle articulated truck if it travels with a 20% gross weight overload all year long) (Marchadour and Jacob, 2008);
- The protection of infrastructure and management of maintenance budgets (a 10% overload on a 13 ton axle results in approximately 60% damage increase for a flexible pavement and about 100% for a rigid pavement) (Marchadour and Jacob, 2008).

The main identified causes are:

- Speeding, which influences road safety due to increased stopping distances, particularly for HGVs, which may have a significant impact on accident fatality;
- Noncompliance with the rules on driving times, which impacts road safety due to drivers' fatigue and the distortion of competition because of shorter trip times;
- Overloading of HGVs, which plays on all these three issues:
  - ✓ It has a strong impact on accident fatality;
  - ✓ It causes significant competition distortion;
  - ✓ It causes damage to the entire road network, leading to reduced quality of service (road work, traffic jams, etc.) and to a significant increase in maintenance budgets.

Today the struggle against the exceeding of speed limits (general use of radars) and excessive driving times (chronotachygraph) are having tangible results. Only the implementation of a systematic solution to the issue of over loads is left to be realized.

The driving codes generally contain all of the legal provisions necessary to effectively fight against overloading. One can note, however, that the implementation of these measures with the currently deployed means (material and human) fails to achieve the desired effects. Static weighing operations, which require stopping the trucks, is time consuming, and significantly limits the number of HGVs weighed. Furthermore it requires expensive weighing areas and a significant number of staff. Consequently, it is not economically feasible to use conventional static weighing, in a systematic way, dissuasive enough to enforce these laws.

Due to the progress in marketed WIM systems over the last 20 years, LCPC (now IFSTTAR) proposed in 2005 to the French Ministry of Transport to develop a national WIM network, to assist in the enforcement of overloading.

The goals defined by the French Ministry of Transport for HS-WIM systems were as follows:

- Identify offending vehicles;
- Select companies for the inspections;
- Achieve better traffic analysis and protect the infrastructure.

2.2 Technical Description

High-speed weighing (HS-WIM) is defined as measuring axle loads of vehicles travelling at speeds in excess of 30 kph. Amongst the WIM sensors used over the past 40 years, such as fiber optic, strain gauge (bending-plate), capacitive sensors and piezoelectric sensors, this paper has selected to focus on piezoelectric sensors, as this technology has been used on highways since the end of the 80's for traffic statistics and infrastructure protection and is also an easy solution to implement for very high speeds (greater than 90 kph).

Over the past 30 years, the accuracy of HS-WIM systems has improved from D(25) or E(30) to B(10) in the best cases, and even B+(7) for some multiple sensor systems, according to the European Specifications on WIM (Jacob et al., 2002). A system's accuracy is determined by the site, the weighing sensors used, the composition and design of the sensor array, the electronics (load amplifiers amongst others), the measurement algorithms (weight, calculation with respect to wheel position, speed, vehicle category …) and the calibration.

A WIM network (Figure 1) includes field equipment (1) fitted at each check point. This equipment, including the sensors and algorithms, forms the core of the network. The data can then be viewed directly (2) for immediate vehicle control, or remotely (4) via an Internet access (5). All of the gathered data is automatically stored on a central server (3), thus enabling subsequent control or other actions.

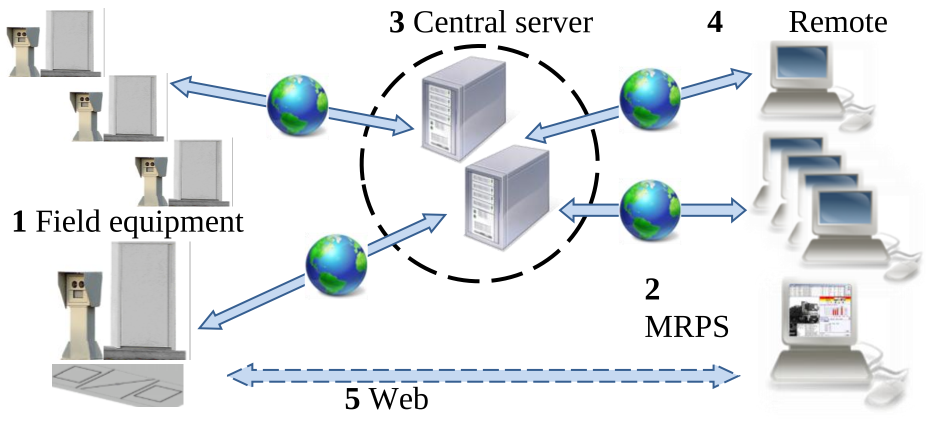

Figure 1 – WIM Network Architecture

To date, France has implemented a network of WIM stations over the motorway and national road network, the earliest of which have been operational since 2006. The WIM systems of this network meet the specifications of the Ministry of Transport, and exceeded the levels anticipated in the call for tender for the following categories: system availability, registration plate recognition rate, number of vehicle categories detected, and measurement precision of speed and length.

The WIM network is now operational at more than 30 sites and covers over 40 lanes. It is to soon be connected to the national registration plate database and is regularly used by Ministry of Transport staff. It is designed to simultaneously handle 50 server connections and more than 500 users.

3. Performance

At the request of the French and Spanish Ministries of Transport, LCPC and CEDEX have carried out trials of existing weighing systems to study the influence of sensors in overall system precision. They were performed between 2007-2010 for the LCPC study (Jacob and Ieng, 2010) and in 2009 for the CEDEX study (Leal and Isidoro, 2010).

3.1 Influence of sensor

Currently, three piezoelectric sensor technologies are in use for WIM: polymer sensors (Fig. 2), ceramic sensors (Fig. 3) and quartz sensors (Fig. 4).

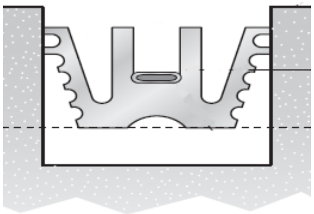

Figure 2 - Polymer Sensor

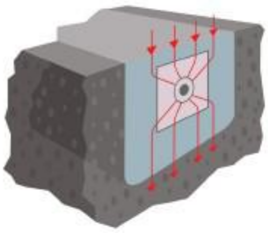

Figure 3 - Ceramic Sensor

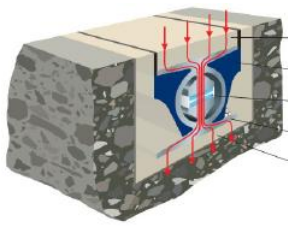

Figure 4 - Quartz Sensor

The LCPC study was conducted over a 3-year period on a highly travelled highway, a Class I WIM site according to the European Specifications, using the same electronics, providing results about the accuracy achieved with polymer, ceramic and quartz sensors.

Sensor array design is a key factor for the accuracy. As the road profile is not perfectly even, an axle dynamic load does oscillate around the static weight at various frequencies. Therefore, a multiple sensor (MS-) WIM system, equipped with several lines of WIM sensors, is more accurate than a single or two line WIM array. Current WIM systems are mainly comprised of 1 or 2 sensor lines for statistical, infrastructure and pre-selection applications. For enforcement applications, an MS-WIM array with more sensors is required to achieve at least an accuracy of class B(10) and possibly B+(7).

3.2 Influence of algorithm and calibration

The study conducted by the CEDEX in Spain showed that the weight results using the piezopolymer systems showed a significant drift more than 5 months after calibration, while those provided by the piezoceramic system did not show any drift after the same time period, under a wide range of temperatures. The reason for these differences in performance might be the self-calibration algorithm provided with the piezoceramic system.

Table 9 - System Comparison by Leal J. (2010)

RESULTS AFTER CALIBRATION												
Measure	Polymer 1				Polymer 2				Piezo-ceramic			
	Lane 1	Lane 2	Lane 3	Lane 4	Lane1	Lane 2	Lane 3	Lane 4	Lane 1	Lane 2	Lane 3	Lane 4
Total weight	D20	C15	C15	C15	-	D20	-	D20	C15	B10	B10	B10
Single axle weights	D25	C15	C15	C15	D20	D20	-	C15	D20	B10	B10	B7
Multiple axle weights	B10	C15	B10	C15	-	-	-	-	-	B7	B10	B10
Group of axles weights	C15	B10	B10	C15	-	-	-	-	-	C15	B10	B10
RESULTS AFTER 5 MONTHS FUNCTIONNING WITHOUT MANUAL INTERVENTION												
Measure	Polymer 1				Polymer 2				Piezo-ceramic			
	Lane 1	Lane 2	Lane 3	Lane 4	Lane1	Lane 2	Lane 3	Lane 4	Lane 1	Lane 2	Lane 3	Lane 4
Total weight	-	-	-	-	D25	-	-	-	-	C15	B10	B10
Single axle weights	-	-	-	-	D20	-	-	-	-	B10	B10	B10
Multiple axle weights	-	-	-	-	-	-	-	-	-	C15	B10	B7
Group of axles weights	-	-	-	-	-	D25	-	-	-	B10	B7	B10

The required accuracy that the WIM systems had to meet in the call for offers was the Class C(15). As can be seen in Table 1, the piezoceramic system obtained one higher than required, Class (B10), in two out of the four lanes and the Class C15 in other lane, both just after calibration and again after 5 months of operation without manual intervention (recalibration).

3.3 Synthesis

WIM accuracy is governed by the combination of:

- Site characteristics: to reduce dynamic effects associated with vehicle speed, the system should be located in a flat and straight section of road, where vehicle speed is almost constant. Moreover, the road profile must be as flat and smooth as possible;
- Sensors: several types of sensors are currently used for HS-WIM. The aforementioned studies suggested that quartz sensors may be more accurate over time. Moreover the layout of the sensors must be adapted to the site and the traffic conditions.
- Calibration method: the accuracy is as improved as the calibration is frequent. A system with self-calibration thus presents a significant advantage for the end-user.

In conclusion, the site quality and the sensor performances are essential, but the studies have also shown the importance of each system component, in particular the self-calibration algorithm used for weight calculation.

4. Applications

4.1 WIM applications

The standard WIM applications are:

- Roadway maintenance: integration of detailed traffic data for scheduling roadway maintenance and defining future road dimensioning;
- In-depth traffic knowledge: integration of detailed traffic data when planning law enforcement campaigns;
- On-road detection: filtering of overloaded or speeding HGVs, which can then be intercepted and directed to an inspection area;
- Company profiling: creation of a file of alleged offending vehicles and transmission of elements to the administration for consideration when making company inspection plans;

For use in infraction detection, WIM stations should have a good vehicle classification, in order to correctly determine the load limits that apply to each vehicle, and if possible a real-time registration plate recognition.

Table 2 has been developed considering the results obtained in the tests carried out by LCPC and CEDEX, and taking into account the user requirements given in the Chapter 4 of the European WIM Specifications of the COST 323, regarding the WIM applications as a function of the accuracy classes:

Table 10 - Systems for WIM applications

		WIM site class (European Specifications COST323)		
		Class I	Class II	Class III
Application	Direct enforcement	Self-calibrated system + 2 quartz sensors	To be investigated with MS-WIM array quartz sensors	NO
	Pre-selection	Self-calibrated system + 1 quartz or 2 coated ceramic sensors	Self-calibrated system + 2 quartz sensors	To be investigated with MS-WIM array quartz sensors
	Infrastructure	Self-calibrated system + 1 quartz or 2 coated ceramic sensor	Self-calibrated system + 2 quartz sensors	To be investigated with MS-WIM array quartz sensors
	Statistics	Self-calibrated system + 1 coated ceramic sensor	Self-calibrated system + 2 coated ceramic sensor	Self-calibrated system + 2 quartz sensors
	Classification	Self-calibrated system + 1 coated ceramic sensor or 2 piezopolymers sensors	Self-calibrated system + 1 coated ceramic sensor or 2 piezopolymers sensors	Self-calibrated system + 1 coated ceramic sensor or 2 piezopolymers sensors

4.2 Additional Applications Reached

WIM stations designed for enforcement, i.e. coupled with video camera and OCR, have revealed a new application:

- Category-based speed: the speed limits are not the same for cars and for HGVs, which has been the major shortcoming of the radar deployed on the road networks over the past years.

The use of a network of these WIM stations offers a broad range of additional potential applications, made possible by the accuracy and the quantity of the collected data:

- Enforcement of corporate regulations concerning travel times and compliance with resting times, thanks to national monitoring of vehicles identified by their registration plates;
- "Cabotage" control: a countrywide mesh enables identification of trucks registered abroad and tracing their routes and their weights on each route. The vehicle can be punished for any illegal loading/unloading operation detected by the system;
- Section speed : the average speed of a given vehicle over several kilometers, taking into account its category;
- Search for stolen vehicles or fight against drug trafficking. Indeed, as all vehicles are identified by the system, it is easy to find a wanted car from a search database.

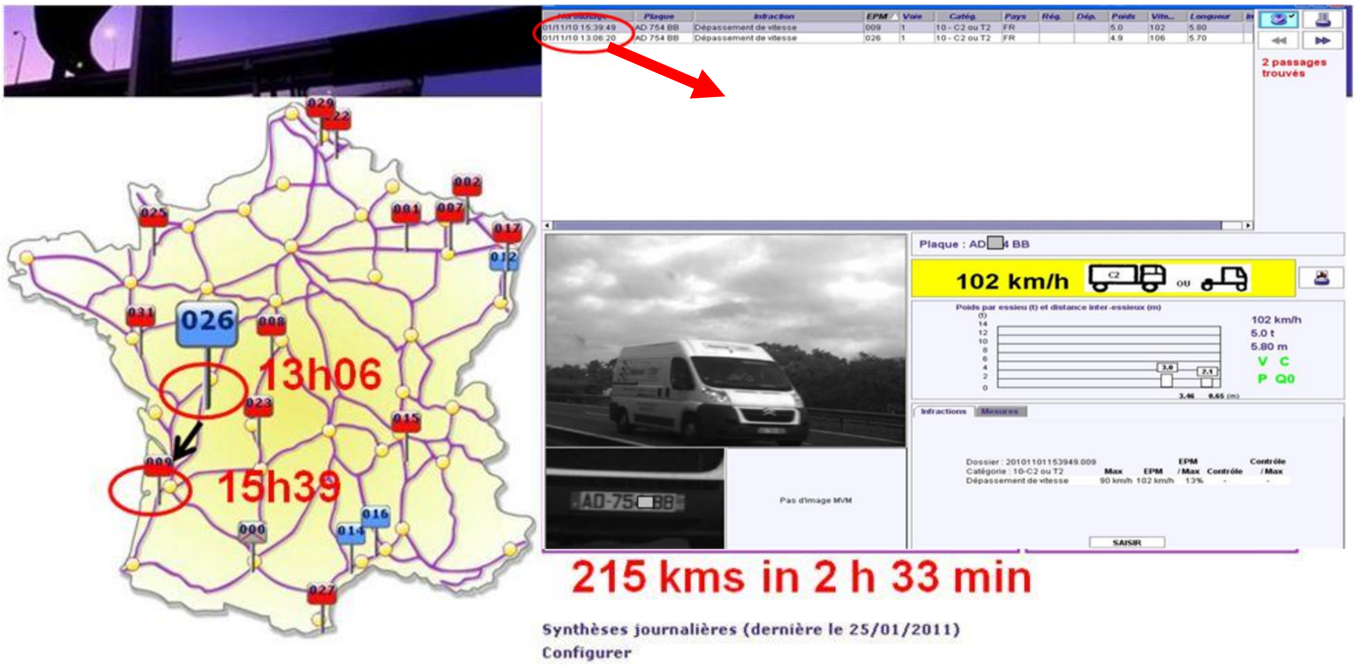

Figure 5 - Section speed radar

Until now, some of these applications were performed by dedicated hardware. High accuracy HS-WIM systems can now include all of these applications in a single tool, used in addition to existing tools. The following uses have been developed for the French authorities:

- Monitoring of HGVs for cabotage control purposes: in France, cabotage control was formerly performed during company inspections. In this manner, inspection was limited to French companies, thus preventing enforcement of the laws governing, in particular, the number of commercial transactions performed by a foreign vehicle between entering and leaving the country. The HS-WIM system installed on the French network enables the vehicle to be monitored by its registration plate. Between each station, the controller knows the vehicle's weight and the time taken to cover the distance;
- Category-based section radar: France has deployed a network of fixed threshold instantaneous speed stations. Thanks to the accuracy of the measurements achieved with the HS-WIM system installed in France, its use has now been extended to the enforcement of speed regulations per vehicle category.
- Convoy detection: the British (NAI) have developed a convoy detection method ("Go Fast" or illicit goods transport) based on a network of plate reader systems. This method consists of comparing the passage of a suspicious vehicle at three points within the country and identifying any accompanying cars (located within a 10-vehicle radius). Thanks to a simple filter on passage date or vehicle type, the HS-WIM system can collect the same data, plus the weight of the suspected vehicle. The roads used by drug traffickers for example, when fitted with HS-WIM hardware, can be monitored remotely and investigations conducted over a period of several days.

It must be noted that global coverage of the road infrastructure network and data centralization are both required to correctly interpret the traffic flows.

5. Conclusion

The HS-WIM system, developed to control excess loads on the road and motorway network, has now reached an accuracy in Class B(10) on excellent (Class I) WIM sites, and sometimes Class B+(7) has even been attained. The network developed in France by the Ministry of Transport has led to new applications. Though existing tools are available for monitoring certain infractions (instantaneous speed, registration plates), the HS-WIM system presented herein is the only one capable of combining all of these applications in a single tool.

6. References

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AN APPRAISAL OF MASS DIFFERENCES BETWEEN INDIVIDUAL TYRES, AXLES AND AXLE GROUPS OF A SELECTION OF HEAVY VEHICLES IN SOUTH AFRICA

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Abstract

For road design accurate quantification of traffic loading remains a challenge. Since the mid 1990s research in South Africa with the Stress-In-Motion (SIM) system concentrated on the interaction forces between slow moving tyres and the textured road surface. A field study of 2 666 Heavy Vehicles (HVs) with Gross Combination Mass, (GCM) > 3 500 kg was conducted, where the mass (or weight) of each tyre (approximately 47 242) was measured. The measurements were done at slow speed over a flat-bed textured SIM device on a specially constructed flat, smooth and rigid concrete platform. Valuable data sets in terms of inter wheel and axle unit mass variation were collected. The overall finding is that assumptions in road design of equal load (or mass or weight) sharing between all tyres, axles and axles groups for HVs are therefore challenged, since unequal tyre, axle and axle group load (or mass or weight) sharing were identified and statistically quantified in this study. It's recommended for inclusion road pavement design optimisation.

Keywords: Stress-In-Motion, SIM, tyre, axle, axle group, left, right, loading, mass, heavy vehicles, mass differences, load differences, weight differences, cumulative frequency, statistical appraisal.

Résumé

Modéliser correctement les charges réelles de trafic sur route reste un problème. Depuis le milieu des années 1990, la recherche Sud-africaine s'est intéressée aux contraintes entre le pneu en mouvement et la surface de la chaussée. Une étude expérimentale a traité le cas de 2666 véhicules de plus de 3.5t, pour lesquels le poids de chaque essieu (au nombre d'environ 47 242) a été mesuré. Ces mesures ont été réalisées à basse vitesse, avec un capteur de contraintes sur une plateforme en béton, rigide, lisse, mince construite spécialement pour cette expérimentation. De précieuses données, sous forme de distances inter-essieux et charges sur essieu, ont été obtenues. La conclusion générale est que des hypothèses, généralement faites en conception de chaussée et admettant un partage équitable de masse entre les pneus, les essieux ou les groupes d'essieux sont remises en cause. En effet, des partages non équitables entre pneus, essieux ou groupe d'essieux ont été identifiés et qualifiés statistiquement dans cette étude. Cette étude pourrait être capitalisée dans le domaine de la conception optimale de chaussée.

Mots-clés: Contraintes, pneu, essieu, groupe d'essieux, gauche, droite, chargement, masse, poids lourds, différences de poids, différences de charges, fréquence cumulée, approbation statistique.

1. Introduction

Accurate quantification of traffic loading (or mass) remains a challenge for the purposes of road pavement design. Generally, it is assumed that vehicle loading (or mass) is equally distributed over the heavy vehicle, and therefore left right tyres, or tyre in dual pairs carry the same load (or mass). Note that in this paper the terms "wheel" and "tyre" are used interchangeably, and also "load", "mass" and "weight", as well as "truck" or "Heavy Vehicle" (HV). Since the mid 1990s research in South Africa with the Stress-In-Motion (SIM) system concentrated on the interaction forces between slow moving tyres and the textured road surface. During the previous ICWIM5 Conference the Stress-In-Motion (SIM) technology used in this study was introduced (De Beer, 2008). During 2003 a study was done on a sample of almost 2 666 Heavy Vehicles (HVs) with Gross Combination Mass, (GCM) > 3 500 kg (3.5t). The mass (or weight) of each tyre (approximately 47 242 tyres) was measured during slow moving vehicle action over the flat-bed textured SIM device on a specially constructed flat, smooth and rigid concrete platform next to the National Route 3 (N3). The study of the data recorded by the Stress-In-Motion (SIM) pads of heavy vehicles (HVs) passing over them at the Heidelberg weighbridge on the N3 during the period August to October 2003 provided valuable data in terms of wheel and axle unit mass (or weight) variation. All the vehicles were classified according to type and axle configuration. Although this paper does not deal with road pavement design issues, the content was prompted on the question of "mass (or load or weight) differences" between *individual* tyres of a dual set of truck tyres, and its associated effect(s) on pavement structural behaviour. This question was further extended to try and find the extent (and impact) of mass differences not only between dual tyre pairs, but also between left vs. right tyres on an axle, or axle groups (or units), as well as between the various axles within an axle groups (or units). This outcome of this paper is based on a study by (De Beer *et al.*, 2011) for the South African National Roads Agency Limited (SANRAL), informed by Theyse (2008).

2. Scope of study and summary of results

The scope of this paper includes the statistical definition and appraisal of the mass (or weight) differences of dual tyre pairs, as well as between left vs. right tyres on an axle, or axle groups (or units), as well as between the various axles within an axle groups (or units) of HVs with 2 axle to 9 axle trucks. The measurements of individual tyre weights (or mass) were made with the SIM technology, illustrated in Figure 1. The selection of trucks analysed is given in Figure 2. In this sample it is clear that the majority of trucks (71 per cent) had 6 or more axles, and represents typical freeway freight traffic in South Africa. The numbers in Figure 2, e.g. "1:2:2:2", represents a typical 7 axle truck, with a single axle (steering) and three sets of tandem axle groups, and a "1:2:3" represents a 6 axle truck with a single axle (steering), tandem group and a tridem axle group. Both dual pairs and single tyres were available in this study, although single tyres on non-steering axles were in total less than 10 per cent of the test sample. The statistical analyses were made on all 11 cases summarized in Table 1, where the masses were compared to the "average mass" of a dual pair tyres, an axle, or axle group. The statistical approach was used to enable the definition of cumulative distributions of the found differences, which can typically be applied in a simulation and probabilistic environment for pavement design. This is proposed for the South African Pavement Design Methodology (SAPDM) (see: http://www.sapdm.co.za), informed by Theyse (2008). The impact, however, of the found tyre/axle mass differences on structural pavement performance still needs to be properly quantified and falls outside the scope of this paper.

Figure 1 - Four pad Stress-In-Motion (SIM) Mk IV system used for data collection used in this study on N3, near Heidelberg Traffic Control Centre (N3-TCC).

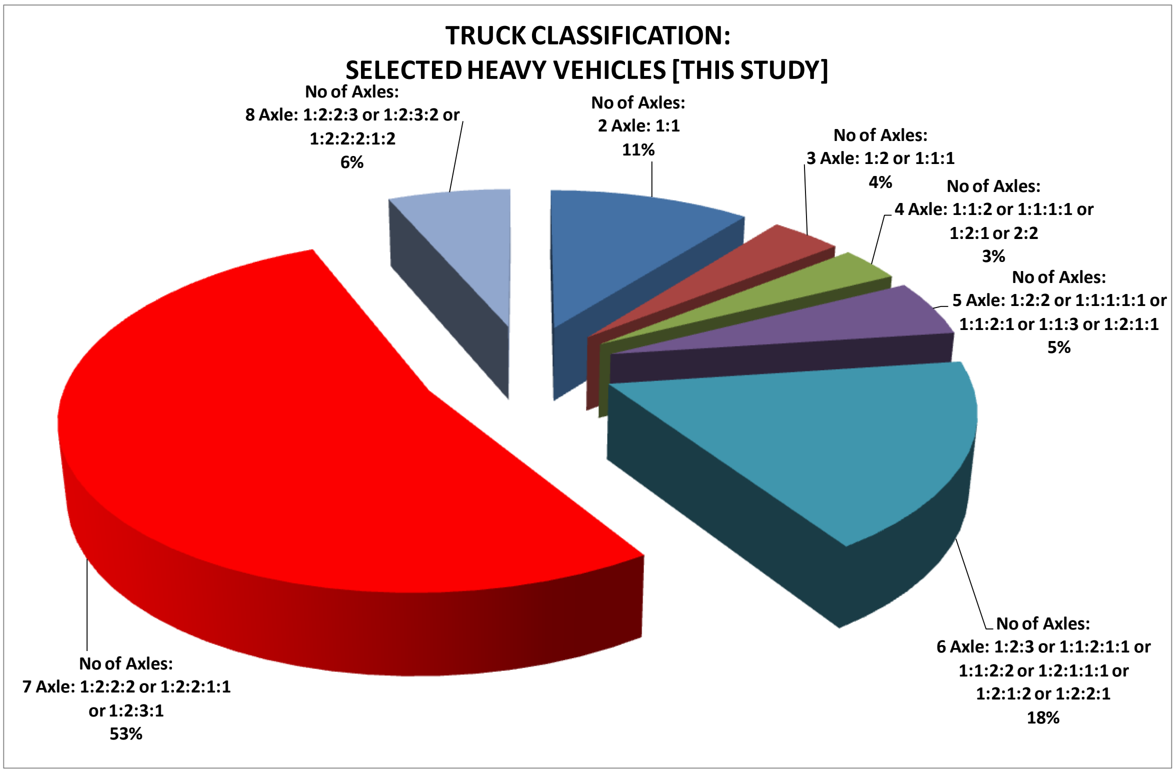


Figure 2 - Classification of measured trucks on the N3-TCC according used in this study (after De Beer *et al.*, 2011).

Table 1: Eleven (11) cases of wheel/axle mass variations analyzed and the found percentage results in brackets (summarized from De Beer *et al.*, 2011).

<table>
<tr><td>Generic Case</td><td>Specific Analyses Cases (11): Wheel/Axles & (n = Number of Records)</td><td>Description and results in percentages</td></tr>
<tr><td>Wheel (or tyre)</td><td>(1) Dual Wheel pairs (n = 23 622):</td><td>Outer (Mass1) and Inner wheel (Mass2) of dual pairs compared with average mass on pair. [68.4 %/31.5 %]*- See Figures 5 and 6 later.[Data range -/+50 %]**</td></tr>
<tr><td>Axle</td><td>(2) Wheels on all Axles (n = 16 005):</td><td>Left wheels (Mass1) and Right wheels (Mass2) (single and dual) compared with average mass on specific axle. [51.1 %/48.8 %], [Data range -/+50 %]</td></tr>
<tr><td rowspan="4">Specific Axles</td><td>(3) Wheels on Steering Axle (n = 2 666):</td><td>Left wheels (Mass1) and Right wheels (Mass2) on steering axle compared with average mass on steering axle. [70.9 %/28.9 %], [Data range -/+10 %]</td></tr>
<tr><td>(4) Wheels on Tandem Drive Axle (n = 1 964):</td><td>Left wheels (Mass1) and Right wheels (Mass2) (single and dual) of tandem drive axles compared with average mass on tandem axle group. [33.0 %/66.9 %], [Data range -/+22 %]</td></tr>
<tr><td>(5) Wheels on Tandem Non Drive axle (n = 1 479):</td><td>Left wheels (Mass1) and Right wheels (Mass2) (single and dual) of tandem non drive axles compared with average mass on tandem axle group. [46.3 %/53.6 %], [Data range -/+20 %]</td></tr>
<tr><td>(6) Wheels on Tridem Axle (n = 400):</td><td>Left wheels (Mass1) and Right wheels (Mass2) (single and dual) of tridem axles compared with average mass on tridem axle group.[68.5 %/31.5 %], .[Data range -/+30 %]</td></tr>
<tr><td rowspan="5">Axle Groups</td><td>(7) Axles on Tandem Drive Axle Groups (n = 2 212):</td><td>Front axle (Mass1) and Rear axle (Mass2) of tandem drive axles compared with average mass on tandem axle group. [38.1 %/61.8 %], [Data range -/+40 %]</td></tr>
<tr><td>(8) Axles on Tandem Non Drive Axle Groups (n = 3 327):</td><td>Front axle (Mass1) and Rear axle (Mass2) of tandem non drive axles
compared with average mass on tandem axle group.[28.5 %/71.5 %], [Data range -/+35 %]</td></tr>
<tr><td>(9) Axles on Tridem Front/Middle Axle Groups (n = 630):</td><td>Front axle (Mass1) and Middle axle (Mass2) of tridem axles compared with average mass on tridem axle group. [31.1 %/68.7 %], [Data range -/+50 %]</td></tr>
<tr><td>(10) Axles on Tridem Front/Rear Axle Groups (n = 630):</td><td>Front axle (Mass1) and Rear axle (Mass2) of tridem axles compared with average mass on tridem axle group. [26.7 %/73.0 %], [Data range -/+70 %]</td></tr>
<tr><td>(11) Axles on Tridem Middle/Rear Axle Groups (n = 630):</td><td>Middle axle (Mass1) and Rear axle (Mass2) of tridem axles compared with average mass on tridem axle group. [30.8 %/69.0 %], [Data range -/+70 %]</td></tr>
</table>

*: Percentage of Mass1 < Average mass/ Percentage of Mass2 < Average mass, or Percentage of Mass2 > Mass1/Percentage of Mass1 > Mass2. ** Data Range indicate "-/+ span of data" around the average mass (in percentage), as measured. See Figure 5 and 6 later.

3. Typical example of statistical analyses: Dual tyre pairs

The statistical analysis of n = 23 622 records (left and right dual tyre pairs) in this study was mainly designed to 1) to quantify mass differences between Inner and Outer tyres relative to the average mass of the pair (if any), and 2) to define statistical best fit curves of continuous cumulative distributions for probabilistic simulation type pavement analyses (mainly for application in the new envisaged SAPDM of SANRAL (SAPDM, 2011). The mass differences were based on comparison of the individual masses of the various tyres (i.e. Inner)/Outer) of the measured trucks with the average mass (kg) on a dual pair of wheels (or tyres) as a "Ton Difference" (TDiff), or "Percentage Difference" (PDiff). For the axles and axle groups, the individual axle masses were compared to the average mass on an axle or axle group (or unit) also as a TDiff or PDiff. In this paper PDiff was used and is explained in the next section.

3.1 Dual Wheel pairs: Outer Tyre vs. Average Mass and Inner Tyre vs. Average Mass

Analysis Case 1: Wheel (Inter-Tyre) comparison: Dual tyre pairs: In this analysis, the Outer wheel mass (Mass1) and Inner wheel mass (Mass2) were compared to the average mass on the measured dual pairs. A total of 23 621 records were measured and used in this analysis. Figure 3 (Category (1) in Table 1) illustrates the definitions of Inner and Outer tyres on the dual tyre pairs.

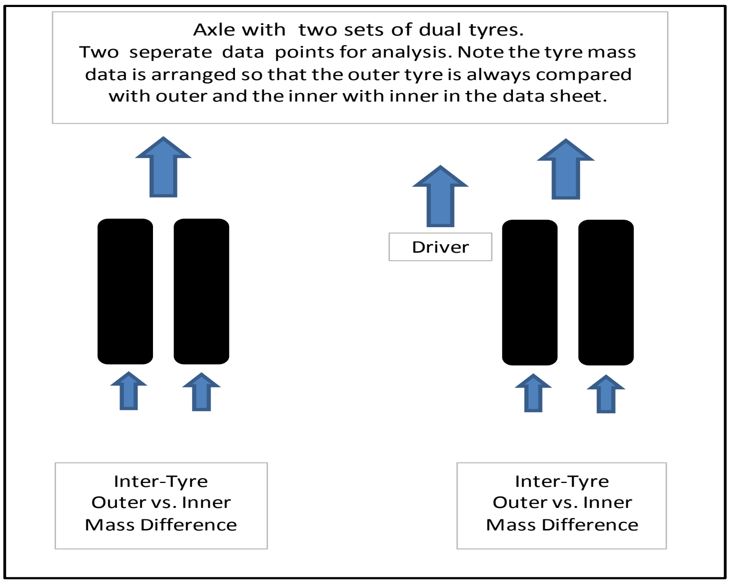
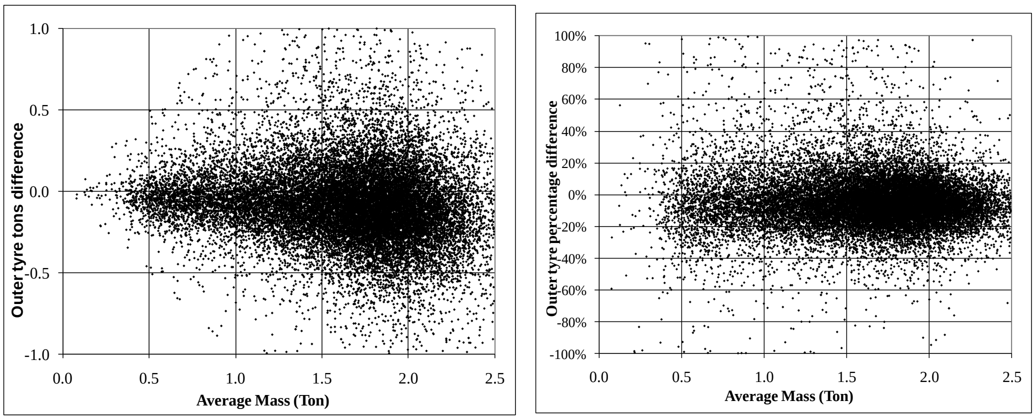


Figure 3 – Inter-Tyre sudy: Outer tyre and Inner tyre (or wheel) of dual pairs as defined for this study-replace with complete figure – text missing at the bottom.

In the study by (De Beer *et al.* 2011), it was shown that scatter plots of the data based on "TDiff" for both tyres (Outer and Inner) appeared to be *less random* and with *no trend* compared to those based on "PDiff". See Figures 4 (a) and (b). It was therefore decided to use the "PDiff" as a basis for further statistical data analysis for the best fit statistical distribution(s), see Figure 5. The results of the raw data of both the Outer and Inner tyre vs. the Cumulative PDiff on all the dual wheel pair data (n = 23 622 records) are shown in Figure 6. Note that the "0 %" on the x-axis reflects the case where Inner Tyre Mass (Mass2) equals the Outer Tyre Mass (Mass1). Figure 7 illustrates five statistical distributions investigated, with its associated parameters given in Table 2.



(a) Mass difference (TDiff) (b) Percentage Difference (PDiff)

Figure 4 - Scatter plot of the mass difference (a) and (b) Percentage Mass difference of the Outer tyres of all 23 622 records compared with its average mass.

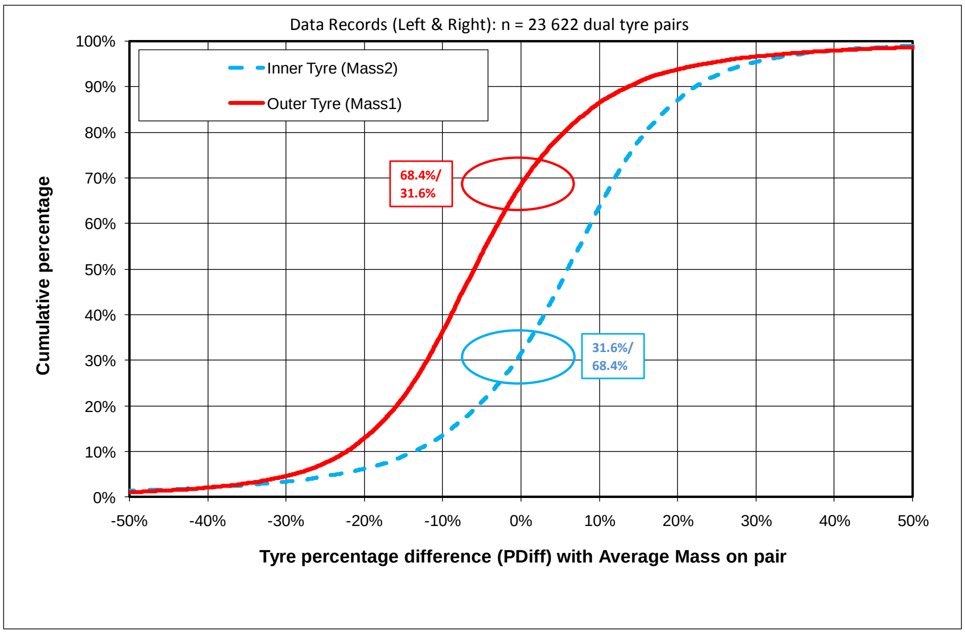


Figure 5 - Cumulative percentage distribution of the raw Pdiff data for both the Inner tyre mass (Mass2) and Outer tyre mass (Mass1).

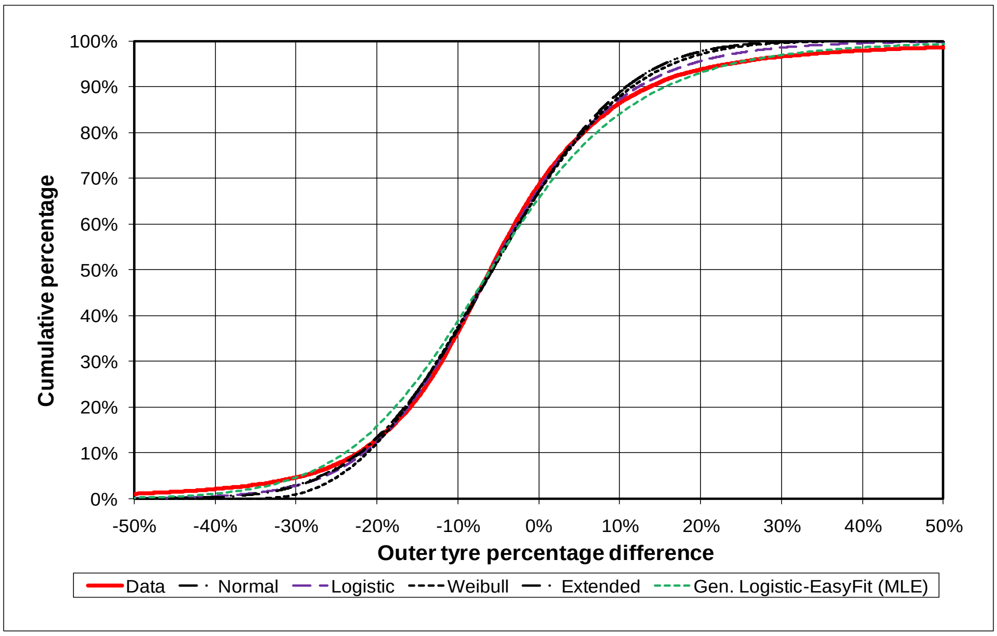


Figure 6 - Example of the cumulative distributions (5 x Statistical fits) for the percentage difference data of the Outer tyre mass. [for EasyFit, see (EasyFit, 2011).]

4. Discussion of results

For the raw data (PDiff) of the Outer tyre (Mass1) given in Figures 5 (upper curve) spanning over a range of +/- 50 %, Figure 6 illustrates the cumulative distribution of the raw PDiff data as well as 5 different statistical distributions investigated. The distributions are all optimised around the raw data in order to identify the “best” distribution (and its associated parameters). The least square method was used in which the square of the differences (least sq. error) between the cumulative observed distribution and the fitted distribution was minimised. This minimisation was undertaken by means of the “solver” algorithm available in Excel. The least square error provided fits better near to the centre of the raw data distribution. As a first step this method was therefore used in fitting the different distributions to the data. Secondly, statistical analyses were also performed using alternative methods provided by the EasyFit (EasyFit, 2011, De Beer *et al.*, 2011). This process was completed for all 11 cases summarised in Table 1. In all cases, the 3 parameter *General Logistic* fit from EasyFit (EasyFit, 2011) was shown to fit the raw PDiff data including the tail ends the best, based on least square error optimization, as well as Kolmogorov Smirnov goodness of fit statistic. See example of cumulative distributions in Figure 6 (Analysis Case 1). The found statistical distribution parameters are summarised in Table 2.

Table 2: Cumulative Distributions and its associated parameters for Outer tyre percentage difference (intended for use in probabilistic road pavement design)

Raw Data		Cumulative Distributions and associated parameters for the Outer-Ton Difference tyre data in Figure 6 – [for definition of the distribution functions and associated symbols, see De Beer *et al.* 2011]									
		Normal		Logistic (3-Parameter)		General Logistic (EasyFit, 2011) (3-Parameter)		Weibull (3-Parameter)		Extended (Kumaraswamy)	
Data Records (n)	23 622		(%)	α =	-0.112	k =	0.083	a =	-0.357	α =	2.191
Average (μ) (%)	-0.048	μ =	-0.057	β =	0.088	σ =	0.090	α =	0.343	β =	15.910
Std. Dev (σ) (%)	0.178	σ =	0.129	λ =	1.585	μ =	-0.060	β =	2.612	η =	20.047
Least Sq. Error (Good at centre of raw data but poor fit at tails ends).		5.895		1.924		--		6.046		4.084	
Kolmogorov Smirnov *: Goodness of fit.		0.087		0.041				0.130		0.129	

* Kolmogorov Smirnov: Goodness of fit statistic from EasyFit, 2011. The lowest found numerical value between different statistical models indicates the better fit for the sample data, similar in application and use as the well known "least sq. error" e.g. Solver in Excel used here.

Figures 5 and 6 indicate that 68.4 % of the Outer tyre (Mass1) is *lighter* than the average mass of the pair, or that 31.5 % of the Inner tyre (Mass2) is lighter than the average of the dual pair. This also translates to the ratio, i.e. 68.4 %/31.5 %, indicating that 68.4 % of the Inner tyres have a mass *higher* than the Outer tyres, and visa versa. This interpretation is true for the data summarised in Table 1 for all 11 cases studied. The data surprisingly show (albeit limited to this data set only), that individual tyres on dual pairs, left/right tyres, left/right tyres on axle groups and front/rear axles on tandem axle groups and front/middle/rear axles on tridem axle groups all do indicate a fair to high degree of unequal load/mass/weight sharing.

5. Use of Data Distributions

As stated earlier, the cumulative distributions of the found mass differences are planned to be applied in a simulation and probabilistic environment for structural road pavement design, proposed for the South African Pavement Design Methodology (SAPDM), currently under development in South Africa. The practical application (and impact assessment) of these wheel/axle mass differences defined by the statistical distributions on structural pavement response is outside the scope of this paper. For more detail on practical application, see Theyse, (2008) and SAPDM, 2011: http://www.sapdm.co.za. It is envisaged that the work in this paper will potentially highlight the impact and structural effect(s) of these found load/mass differences of dual pair tyres (and axle load/mass variations). It should be noted that wheel/axle masses usually assumed to be equally distributed in classic pavement analyses modeling methodologies. The foregoing could be done in a probabilistic simulation framework for future pavement analysis, as suggested by Theyse (2008) and SAPDM (2011).

6. Summary and Conclusions

The statistical appraisal of load (or mass or weight) of individual tyres in dual pairs, left/right tyres on axles, left/right on axle groups (or units), as well as for inter-axles indicated some significant *unequal* load sharing. The overall finding of this study is that the common general assumptions in road pavement design of equal load sharing (or weight or mass) between all tyres, axles and axles groups for heavy vehicles are challenged. It is therefore recommended that the found *unequal mass/weight/load sharing (or differences)* to be incorporated for the further optimization of structural road pavement design methodologies. The impact, however, of these wheel/axle mass differences needs to be further quantified on structural road behaviour. It is envisaged and recommended that this can be facilitated by using the statistical cumulative distribution functions evaluated in this study, and in particular the 3 parameter general logistic cumulative distribution function.

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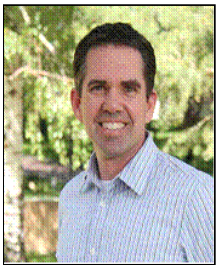
ASSESSMENT OF WEIGH-IN-MOTION (WIM) SYSTEMS: A NATIONWIDE SURVEY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Abstract
Currently, State highway agencies (SHAs) collect traffic data from various sources such as static weigh stations, automatic vehicles classifiers (AVC), and Weigh-In-Motion (WIM) sensors. WIM are advanced traffic data collection systems used to count, classify and weigh vehicles in motion. Periodic assessment of WIM systems is crucial to early identification of problems in the WIM equipment and the pavement structures. To support future maintenance and renewal decisions, a nationwide survey was conducted on WIM systems maintained by SHAs. This paper presents a summary of the survey data collected in relation to WIM equipment type, WIM installation and calibration methods, initial WIM equipment cost, maintenance cost, type of maintenance contracts, warranties, and vendor's support services. . The findings presented in this paper can assist highway agencies in optimizing resources for their WIM programs.

Keywords: Weigh-in-Motion, Survey, Performance Evaluation.

Résumé
Actuellement, les agences des autoroutes américaines (SHA) enregistrent des données de diverses sources, comme les stations de pesage statiques, les classificateurs automatiques de véhicules (AVC) et des stations de pesage en marche. Le pesage en marche est une technologie de collecte de données qui permet de compter, classifier, peser des véhicules en mouvement. Des évaluations périodiques des stations de pesage en marche sont nécessaires pour identifier rapidement les problèmes d'équipement ou de chaussée. Pour prendre les décisions futures de maintenance ou de renouvellement, une enquête nationale sur toutes les stations de pesage administrées par les SHA a été réalisée. Ce papier présente un résumé des données collectées lors de cette enquête, données qui sont en relation avec le type d'équipement, l'installation des stations, les méthodes de calibration, le coût initial d'implantation d'une station, le coût de maintenance, le type de contrats de maintenance, les garanties, les services après-vente du vendeur. Les conclusions présentées dans ce papier peuvent aider les compagnies autoroutières à optimiser leurs ressources pour les programmes de pesage en marche.

Mots-clés: Pesage en marche, enquête, évaluation de la performance.

1. Introduction-Objective

Currently, State highway agencies (SHAs) collect traffic data from various sources such as static weigh stations, automatic vehicles classifiers (AVC), and Weigh-In-Motion (WIM) sensors. WIM are advanced traffic data collection systems used to count, classify and weigh vehicles in motion. WIM data has a multitude of applications including transportation planning bridge design and pavement design. Recent developments in pavement design have necessitated the acquisition of axle load spectra, which can realistically be done only with WIM systems of sufficient time coverage. Hence, accurate WIM data of sufficient coverage have increasingly become a necessity.

Periodic assessment of WIM systems is crucial in identifying early problems in WIM equipment and the supporting pavements. The Federal Highway Administration (FHWA) sponsored a study for assessing existing WIM equipment, performing annual field validations on newly installed and existing WIM equipment, and documenting the reliability of the data being collected (Ostrom, 2008). This study also addressed the installation, maintenance and repair of WIM systems.

Papagiannakis et al. (2008) assembled state-of-the-practice information on the methodologies used by SHAs in evaluating, calibrating, and monitoring high-speed WIM systems. Zhi et al. (1999) evaluated the historic performance of WIM systems in the Province of Manitoba and found large quantities of questionable data produced from WIM systems due to calibration drift. This study emphasized the importance of WIM data quality control prior to their use in research and design. A European study also assessed the load measuring and classification accuracy of WIM systems (Bernard, 2000; Bernard et al. 2000). This study presented a comprehensive review of calibration methods used in WIM systems. Work by Hallenbeck and Weinblatt (2001) briefly reviewed the strengths and weaknesses of selected WIM technologies and described the steps required in selecting WIM equipment types.

The primary objective of the paper at hand is to present a summary of the results of a nationwide survey undertaken on behalf of the Arizona DOT. This survey covered WIM equipment type, WIM installation and calibration methods, initial WIM equipment cost, maintenance cost, type of maintenance contracts used, warranty types, and WIM maintenance activities undertaken. Findings from this study can assist SHAs in optimizing traffic data collection resources.

2. WIM Survey

To support future maintenance and renewal decisions of the Arizona DOT, a nationwide survey was conducted in March of 2009 on traffic data collection WIM. The WIM survey questionnaire covered WIM equipment type, initial WIM equipment cost, maintenance cost, WIM installation and calibration procedures, type of maintenance contracts used, and warranties and vendor’s support services. Prior to sending the WIM survey questionnaire, the researchers contacted SHA representatives via phone to briefly explain the objectives of the survey. Then, an electronic questionnaire was emailed to the State agency traffic coordinators within the United States and Canada. Twenty-nine States and two Canadian Provinces returned the completed WIM survey questionnaire. Maps showing the location of responding organizations (shaded) are presented in Figure 1. A detailed report on assessment of WIM systems including this national WIM survey is provided elsewhere (Zelelew and Senn, 2009).

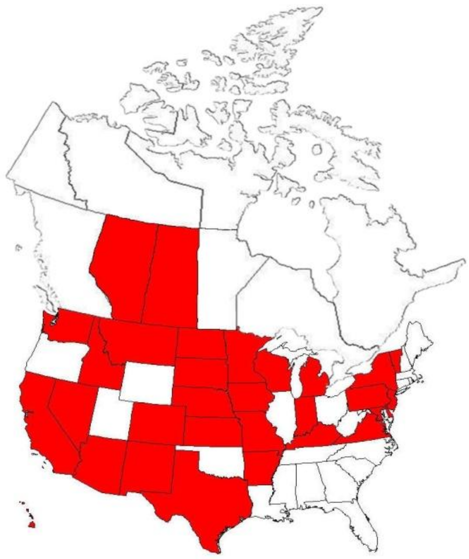

Figure 1 – State and Canadian provinces that responded to the questionnaire (shaded)

3. WIM Survey Results

WIM Equipment Type

The type of WIM sensors used defines the WIM system type. These include bending plate, piezoelectric, piezoquartz, and load cell sensors. Table 1 shows the results of the survey as to the type and number of WIM systems used by the SHAs that responded. This table suggests that piezoelectric sensors are the dominant WIM equipment followed by bending plates. Only a few of the responding States used piezoquartz and load cell WIM technologies at the time the survey was conducted. The survey indicated that only a few SHA utilize portable WIM equipment to support their traffic data collection efforts.

WIM Equipment and Maintenance Costs

The initial WIM equipment costs, installation costs, and maintenance costs can affect WIM equipment selection. Balancing these factors is a challenging process for SHAs, especially when two alternative types of WIM equipment have similar operating characteristics. State agencies reported estimates of the initial cost per lane (including equipment and installation costs, but not construction costs for the pavements housing the equipment and the associated traffic control costs). The equipment costs include operating system software costs. Estimates of the annual maintenance and repair costs (pavement maintenance and repairs, sensor replacement, electronics replacement, calibration costs, and others) were also provided. Table 2 presents the cost comparison among different WIM systems. It is worth mentioning that the cost estimates for the same WIM technology varies from agency to agency, especially so for the installation and maintenance costs. Some SHAs use in-house installation and develop their own operating software, which reduces the initial costs. Piezoelectric sensors are found to be the least expensive WIM sensors, on average, followed by bending plates, piezoquartz sensors and load cells.

Table 1 – Number of WIM system

State/Province	WIM System				Total Number of WIM System
	Bending Plate Scale	Piezoelectric Sensors	Piezoquartz Sensors	Load Cell	
Arizona	0	9	0	0	9
Arkansas	0	51	0	0	51
California	135	0	0	0	135
Colorado	0	14	0	0	14
Delaware	0	27	0	0	27
Hawaii	3	5	0	0	8
Idaho	0	25	0	0	25
Indiana	5	23	1	22	53
Iowa	0	41	0	0	41
Kansas	1	4	0	0	5
Kentucky	0	1	0	1	2
Maryland	1	0	0	0	1
Michigan	2	5	29	0	36
Minnesota	0	10	0	0	10
Missouri	0	13	0	0	13
Montana	3	31	0	0	34
Nebraska	0	30	0	0	30
Nevada	0	8	0	0	8
New Jersey	0	82	0	0	82
New Mexico	3	12	0	0	15
New York	0	24	0	0	24
North Dakota	0	0	12	0	12
Pennsylvania	0	12	0	0	12
South Dakota	14	0	1	0	15
Texas	15	4	5	0	24
Vermont	0	17	0	0	17
Virginia	1	0	10	0	11
Washington	0	37	2	0	39
Wisconsin	0	26	0	0	26
Alberta	0	6	0	0	6
Saskatchewan	0	12	0	0	12

Table 2 – Cost Comparisons

WIM System	Initial Cost Per Lane (Equipment and Installation)	Annual Maintenance Cost Per WIM Station
Piezoelectric Sensors	$25,000 to $35,000	$5,000 to $8,000
Bending Plate Scale	$35,000 to $45,000	$6,000 to $9,000
Piezoquartz Sensors	$45,000 to $60,000	$8,000 to $12,000
Single Load Cells	$75,000*	$10,000*

* Cost estimated by one State only

WIM Installation and Calibration

To obtain quality data, providing and maintaining an adequate operating environment for the WIM equipment is critical. Proper installation of sensors and system electronics is a key for accurate WIM performance. The best WIM technology from the best vendor will not work satisfactorily, if the WIM is poorly installed (McCall and Vodrazka, 1997; Hallenbeck, 1996). The ASTM standard recommends the WIM equipment be installed and maintained in accordance with the recommendations of the WIM vendors (ASTM E 1318, 2009). It also specifies accuracy thresholds that could be met only if the roughness levels at the approach of the WIM sensors are below a certain level.

A WIM system is calibrated to compensate for the prevailing traffic composition, prevailing vehicle speed, environmental conditions and pavement roughens at a particular site. This aims for obtaining WIM measurements sufficiently close to the static loads being applied. Pavement temperature plays a big role in the performance of WIM systems, by altering the response of the sensors to the load and also by affecting the stiffness of the pavement layers. Some WIM equipments (e.g., those with Piezoelectric sensors) are susceptible to variations in temperature. Several vendors use temperature adjustment factors to address this issue.

WIM calibration procedures and intervals affect the accuracy of WIM systems and the overall quality of the traffic data being generated. The FHWA provides descriptions of the current state-of-the-practice in WIM system calibration procedures (FHWA, 2001). SHAs in their majority follow the general calibration provisions of the ASTM standard (ASTM E 1318, 2009) and some of the additional recommendations developed as part of the LTPP program for initial (post-installation) and periodic in-service calibration.

Figure 2 shows data on the frequency of routine calibration performed by the responding SHAs. It is found that a typical WIM calibration interval for most SHAs is one year (61%). Few SHAs perform calibrations on a monthly (9%) or quarterly (3%) basis, while about 27% of them calibrate their WIM equipment as needed. Other SHAs reported that portable WIM equipments are scheduled for calibration at the time of installation only.

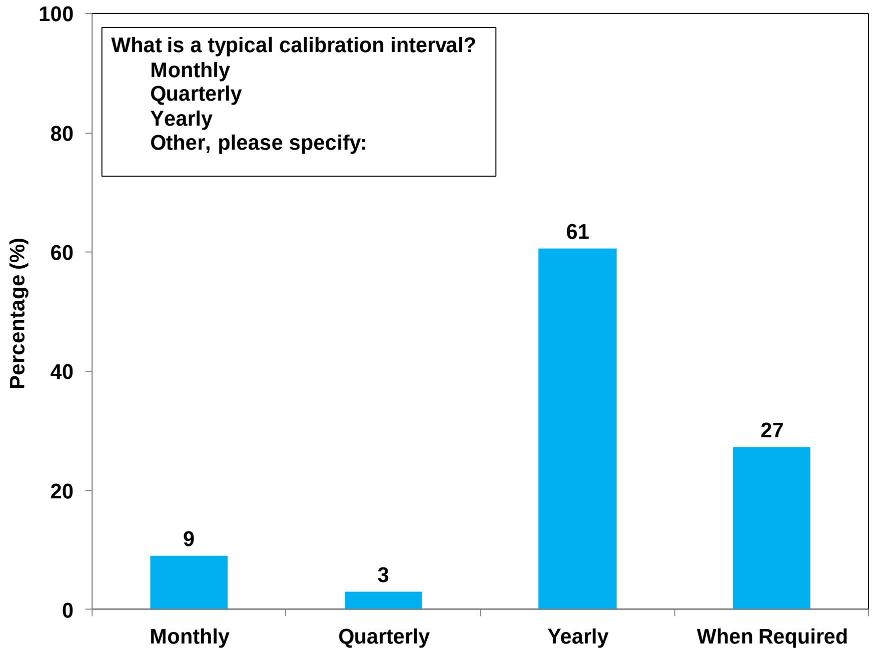

Figure 2 – WIM caliberation interval

Maintenance Contracts

WIM sensor performance is reduced when the pavement structure deteriorates. In most cases, WIM sensor failure is caused not by the failure of the sensor itself but by the failure of the pavement structure around the sensor (McCall and Vodrazka, 1997; Hallenbeck and Weinblatt, 2001). The pavement that contains WIM sensors must be maintained on a regular basis, or replacement of the WIM sensors may be required. In this WIM survey, two types of equipment maintenance contract were identified:

Type A: Charges submitted through invoice as incurred based on agreed rate for labor, materials, parts, and miscellaneous expenses.

Type B: Agreed lump sum contract payment per service period.

The equipment maintenance contracts that the State agencies normally award are presented in Figure 3. Most of the SHAs preferred the Type A equipment maintenance contract (74%). According to the survey, some SHAs implemented neither of the above equipment maintenance contract options. Instead, the WIM maintenance operations are performed by their in-house personnel (37%).

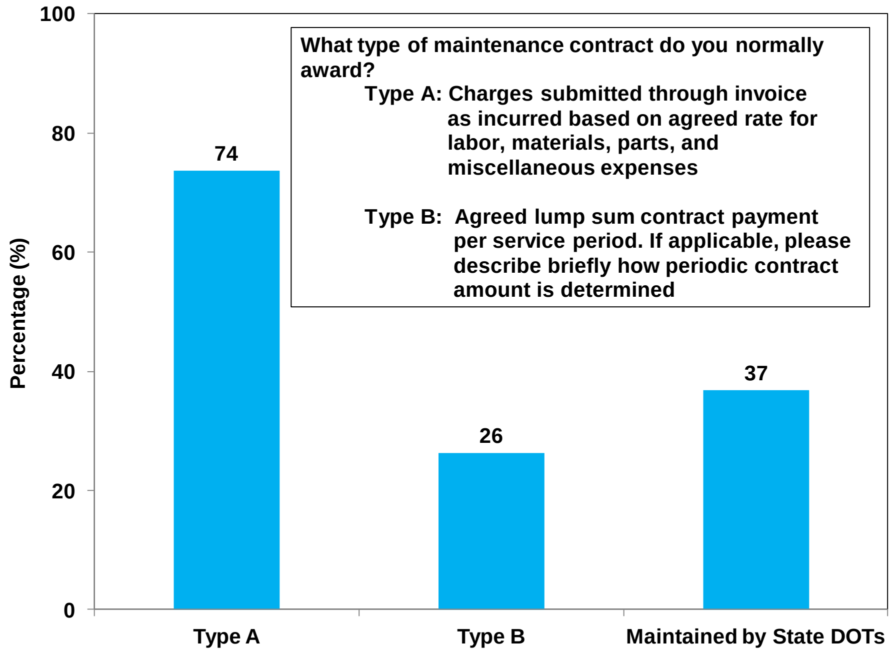

Figure 3 – WIM maintenance contracts

WIM Equipment Warranty

Assurance offered by the vendors, including warranties, affect selection decisions of WIM systems. Warranties provide SHAs insurance against manufacturing defects and also provide incentives for vendors and manufacturers to improve the quality of their products (McCall and Vodrazka, 1997; Hallenbeck and Weinblatt, 2001). When purchasing WIM equipment, it is a good practice to obtain a warranty. The warranty should specify the expected life of the WIM sensors. The survey also included a question on the availability of WIM equipment warranties by State agencies. It is found that 84% of the State agencies successfully used equipment warranties.

Support Services

An additional deciding factor in equipment selection is the level of technical support from vendors. SHAs have benefited from various additional support services from WIM and software vendors including training, equipment repair, calibration, software and hardware troubleshooting, and updates on products and services.

4. Summary and Conclusion

In this paper, the results of a nationwide survey on WIM systems are presented. A summary of the overall practice on WIM systems equipment type, initial equipment cost, maintenance cost, WIM installation and calibration methods, type of maintenance contracts, warranties, and vendor's support services as provided by the SHAs is presented. Based on the WIM survey results, SHAs should consider the following key points on WIM equipment usage:

- Develop WIM system implementation plans.
- Consider WIM system practices by other SHAs.
- Select cost effective WIM systems.
- Develop and maintain a thorough quality assurance and performance measurement program including routine equipment calibration.

- Purchase warranties with WIM systems.
- Consider additional support services from vendors or developing similar in-house capabilities.
- Perform in-house WIM equipment installation.
- Budget sustainable resources for maintenance contracts and other support services, and
- Perform preventive and corrective maintenance at the equipment sites.

In conclusion, utilizing the information contained herein will allow SHAs to make informed decisions regarding the future of their WIM programs.

Acknowledgments
Sincere thanks are expressed to Arizona Transportation Research Center (ATRC) for the continued support throughout the study. The authors would like to acknowledge ADOT and extends special thanks Dr. Estomih 'Tom' Kombe and to all of the SHA traffic coordinators for their participation, contributions, and sharing their experience with WIM systems.

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DESIGNING WIM DATA AGGREGATING SYSTEMS





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Abstract
WIM systems are used in many countries around the world. They provide huge amounts of data for various purposes, but until now the availability of these data were not pervasive. Many users and decision makers want to have better access to these data. This paper introduces two initiatives to make WIM data more accessible and better implemented. The European FiWi database, which is an update of the former COST323 database, is now being completed and will be hosted by the International Society for WIM (ISWIM). Its structure and management is described in this paper. The SITL information and WIM data processing system, mostly based on open-source software, was developed for the French Ministry of Transport. It has short term operational goals, and also is a demonstration of a formal WIM data model. These two projects aim at serving and strengthening the WIM user community by encouraging mutual understanding and promotion of common tools.

Keywords: Weigh-in-motion (WIM), WIM data, database, heavy vehicles, loads, traffic.

Résumé
Les systèmes de pesage en marche sont utilisés dans de nombreux pays de par le monde. Ils produisent de grandes quantités de données pour des applications diverses mais jusqu'à présent, l'accès cette donnée n'était évident. Cet article présente deux initiatives visant à rendre les données WIM plus accessibles et mieux mises en œuvre. La base européenne FiWi, issue de l'ancienne base COST323, est en cours de complétion et sera hébergée par la société internationale pour le pesage en marche (ISWIM). Sa structure et son mode de gestion sont décrits. Le SITL, système d'information et de traitement des données WIM, basé sur des outils open-source, a été développé par le Ministère en charge des Transports français. Il a des objectifs opérationnels à court terme, mais est aussi un démonstrateur pour une modélisation formalisée des données. Ces deux outils visent à renforcer la communauté WIM par une meilleure compréhension réciproque et la promotion d'outils communs.

Mots-clés: Pesage en marche (WIM), données de pesage, base de données, poids lourds, charges, trafic.

1. Introduction

WIM systems are now implemented in many countries and on various road networks for several purposes, such as traffic monitoring, infrastructure (pavement and bridge) design and assessment, and overloaded vehicle screening and enforcement. Gigabytes of data are collected by these WIM systems and stored, either as aggregated data (histograms) or detailed data (per vehicle). However, these data are not always available, even if there is no legal or ownership restriction, because of the many formats and storage systems used and because the data are spread among a very large number of scattered owners.

Moreover, because of a lack of standardization and harmonization, the types of data and measured quantities may differ from one system to another, or by country or region, depending on the WIM technology and on the client requirements and specifications.

Finally, there is a lack of data processing tools and software to fully exploit the richness of the huge amount of WIM data collected, either at the national or the international level, even though some proposals have been made by Folwell and Stephens (1997) and in bridge engineering by Sivakumar et al. (2008).

The former limitations in data transmission and storage capacity have been overcome by the rapid progress of communication networks (fiber optic network, ADSL, 3G) and by the huge increase in computer and memory capacities.

The next challenge in making WIM data available and useful for more users, researchers, engineers, infrastructure and traffic managers, and public authorities, consists of developing WIM databases with easy access, mainly using the Internet, as has been done in the US (CA DOT, MnDOT, NJDOT) and initiated in Europe in the late 90's by the COST323 action (Jacob et al., 2002). Besides the database design, implementation, data collection, management and maintenance, there are issues to be solved for data quality assurance (Henny, 1999; Nichols and Bullock, 2004) and control of access which depends on each user's rights. This paper reports the resultsof two projects aiming to contribute to this challenge in Europe and in France:

- FiWi (FEHRL institutes WIM initiative) was a cooperative project shared among seven members of the Forum of European Highway Research Laboratories in 2007-9 to develop a European standard on WIM (Jacob, 2011) and a renewed European WIM database, updated from the former COST323 database (Jacob et al., 2002).
- SITL (Système d'Information Trafic Lourd/Heavy Traffic Information System) is a more technically oriented French project which aims to aggregate data from two well described fragmented sources into an accessible and useful entity.

2. The FiWi European WIM Database

The FiWi database has the same structure as the former COST323 database, and contains a section for the European WIM sites, a section for the aggregated data and a section for the detailed data. It is planned that this database will be hosted in the ISWIM (International Society for WIM) web site and that priority access will be given to the ISWIM members.

The database is developed in a PHP-MySQL architecture web interface for accessing and managing the data.

2.1 Part I: WIM Sites

Part I of the database (a table) contains one record per identified WIM site/system, as shown in Figure 1. The information gathered for each WIM site is organized into the following fields: (1) Id number, (2) Country, (3) Department, (4) District, (5) Road Number, (6) LocalIdentifier, (7) Number of lanes, (8) Number of equipped lanes (with WIM sensors), (9) Use of the data (main purpose of the site), (10) Type of Data, (11) Site Manager, (12) Road Type, (13) Type of sensors, (14) System vendor, (15) WIM sensor manufacturer, (16) Traffic flow (in veh/day), (17) Heavy Vehicle flow (HGV/day), (18) Calibration method, (19) Number of directions (one or two), (20) Portable/fixed system, (21) Number of sensors per lane, (22) Permanent/temporary measurements, (23) Power supply, (24) Communication tools, (25) Comments, (26) Date of first installation, (27) Date of last installation, (28) Data provider, (29) Last update.

If more than one system is installed at the same site, each system generates one record. Field (11) contains the site manager, i.e. the data owner, while field (28) contains the person who provided the information and the data for this site. Field (9) is a multiple selection list: statistics and traffic management/monitoring, pavement or bridge engineering, overload screening/enforcement, research, test, other.

The record shall be updated when: (i) some WIM sensors or the system itself are replaced, (ii) additional lanes are instrumented for WIM, or more WIM sensors are installed in one lane, or WIM sensors are removed, or instrumented lanes are not anymore used for WIM, (iii) the main use of the data or site purpose is modified, (iv) the type of gathered data is changed. If a site is fully dismantled or not used any more, the record shall not be deleted while some data are still available in the database (see §2.2 and 2.3).

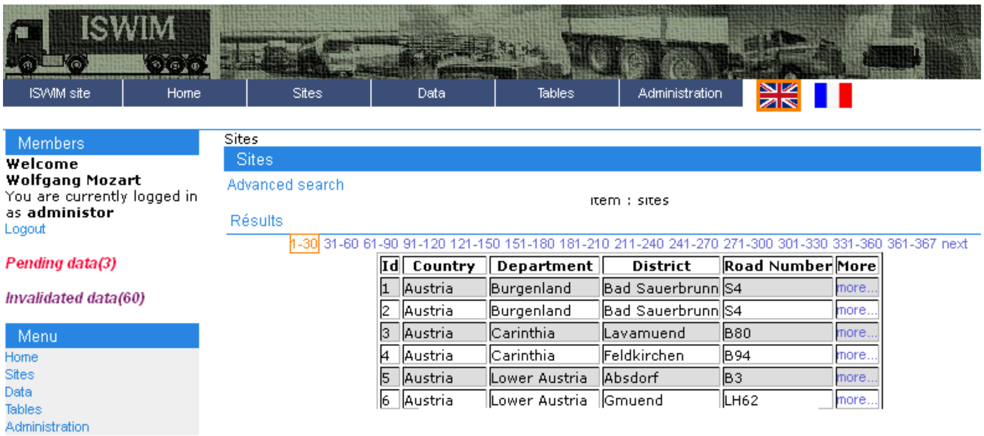

Figure 1 – FiWi European WIM database: part I, WIM sites

2.2 Part II: Aggregated Data

For each site and traffic lane, if available, a table in Part II stores aggregated data, i.e. statistics of the (heavy) traffic. By default and if the WIM system is working 24 hours a day and 7 days a week all through the year, there is one record per year with the statistics of the whole year sample. If the system is working temporarily or if some statistics are available by sub-periods, each continuous measurement period may generate a record; these records are numbered as YYYY-n, the year and the sequential number of the record, sorted by initial date. Only available and reliable data are required, but for a few mandatory fields. All units are converted into the SI system.

The full recorded information is: (1) (Unique) Id number, (2) Site (name and Id number), (3) Period number, (4) Period start, (5) Period end, (6) Period duration, (7) Traffic lane, (8) Flow (all vehicles), (9) Flow (trucks), (10) % of trucks, (11) Speed (all vehicles), (12) Speed (trucks), (13) Vehicle Spacing (all vehicles), (14) Vehicle Spacing (trucks), (15) Truck length, (16) Number of axles per truck, (17) to (24) % of vehicles per Category, (25) to (29) Axle loads (all axles, axles of tandem, axles of tridem, tandem, tridem), (30) Gross vehicle weight, (31) Equivalent single axle load (for loading assessment), (32) Loading assessment method, (33) to (37) Loading effects (per single axle, per tandem, per tridem, per axle - all axles, per truck), (38) Data provider, (39) Last update.

2.3 Part III: Detailed Data

Part III (table) of the database contains identification sheets of detailed (vehicle by vehicle) records, which are stored in the database in separate and downloadable files. The aim of this database is not to store exhaustive and huge amount of detailed data, as that may be expensive and would be in conflict with data IPRs; but rather to store some data samples for users' applications and needs, such as research work, infrastructure assessment, etc.

Each data sample is roughly described by its identification sheet which describes the main data features and measured parameters. A link to the detailed data file is given. The available information is: (1) Id number, (2) Site, (3) Period number, (4) Period duration, (5) Continuous measurement (yes/no), (6) Recorded vehicles (all/trucks), (7) Traffic lane, (8) Comments, (9) Direction, (10) Date of passage (yes/no), (11) Time of passage (yes/no), (12) Speed (yes/no), (13) Vehicle length (yes/no), (14) Statistics on axles (yes/no), (15) Categories (yes/no), (16) Gross Vehicle Weight (yes/no), (17) Axle Loads (yes/no), (18) Code of Error (yes/no), (19) Data provider, (20) Last update, (21) File name.

2.4 Access and Management Rights

The general rules of management and access of this database are based on voluntary-based data provisions by data owners or their representatives, with different access levels and possible limitations by request of the data provider/owner. The database management is also based on a voluntary involvement of data providers, supervisors and managers (see below), at least to initiate the system. However, for a long term period some financial support could be necessary to maintain this database. The society ISWIM will look with its members and sponsors for such support.

User and Manager Types and Access Levels

There are 4 access levels and 3 types of data providers and database managers:

- Simple guest not registered in the ISWIM member database.
- Registered ISWIM members (thus far the individual registration is free).
- Priority ISWIM members, i.e. those who are paying fees (vendors) or other members having granted general rights.
- Users with specific rights, e.g. access rights granted through the data owners/providers.
- Data providers (owners or managers) provide data and upload them into the database. They have the management rights for a list of sites. The uploaded data are not directly displayed, but must be first approved by a supervisor (quality control).
- Supervisors, acting generally for a country or a set of countries (region), or for a set of data providers, appoint the data providers, check and approve the uploaded data.
- Database administrator(s) appoint and grant rights to the supervisors and perform the general maintenance of the database.

Data Access Rights

All of the rights and access management are done through cross link tables (user – data Id). The main rules, as defined at this stage and which may evolve with the development of the database, are:

(1) Simple guests may access the WIM site list, and for each site only the country and site name. A limited sample of aggregated data will also be available for free and general access.

(2) Registered ISWIM members will get, in addition, all of the information of the WIM sites, a larger sample of aggregated data, and a limited sample of detailed data.

(3) Priority ISWIM members/users with specific access rights will get, in addition, all of the unrestricted/authorized aggregated data and detailed data.

The protocol allows any data owner to restrict the data display to a defined type or list of users. A subscription system could be developed in the future if relevant.

3. SITL

The SITL (Système d'Information Trafic Lourd/Heavyweight Traffic Information System) is a full information architecture developed for the French Ministry of Transport. The SITL system is aimed at replacing and expanding a variety of data processing and analysis systems built upon the National HS-WIM network (Marchadour and Jacob, 2008) over the years.

3.1 Principles

Objectives

The French HS-WIM system has produced a large body of data over the years. Various teams created many data treatment tools during particular studies. This rich heritage, because of limited common guidelines, whether technical or conceptual, proved difficult to manage. The idea was for the SITL to create a framework that would allow translating those various assets into a common system of reference that a newcomer could grasp and access quickly.

Design choices

In order to achieve initial objectives of the SITL, widely accepted and documented concepts were used. Major conceptual frameworks were selected from the classic information science and business intelligence (BI) fields of application, namely the Relational Online Analytical Processing (ROLAP) using the Star Schema structure.

From the technical point of view, systems were selected that would be widely available: free (libre) or open source software, namely Postgresql, Apache Tomcat and Talend Open studio.

Data source

The SITL system was initially built around the French HS-WIM data output; but it also aims at aggregating data from various sources, so provisions are made to accommodate those other sources. General conceptual structures are preferred over specific technical ones as often as possible.

The main data source consists of a one-recording-per-vehicle format (heavy-weight vehicles only). This source is later aggregated so it can be merged with less detailed sources.

See Figures 2 and 3.

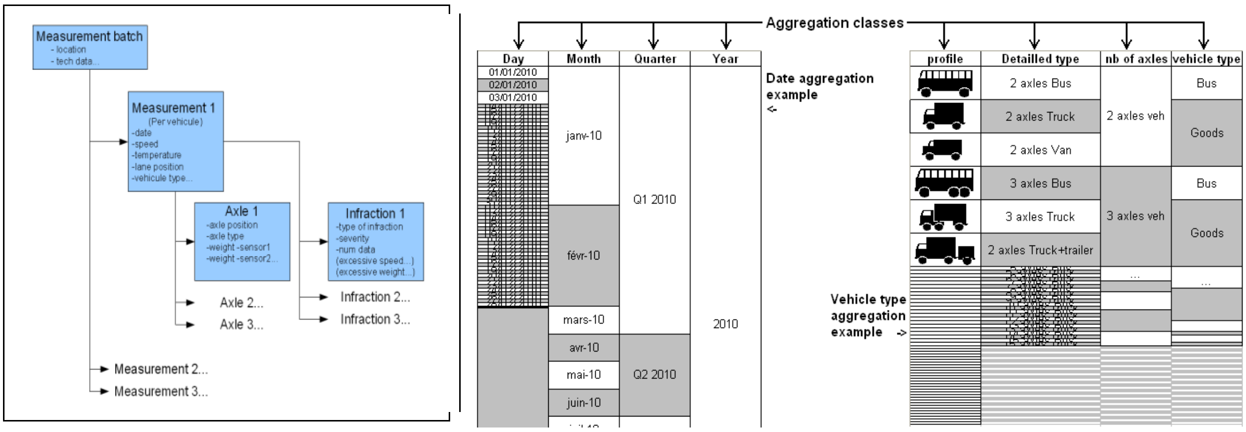

Figure 2 - Source Data Model - XML markup (left), examples of tables for aggregation classes – star schema (right)

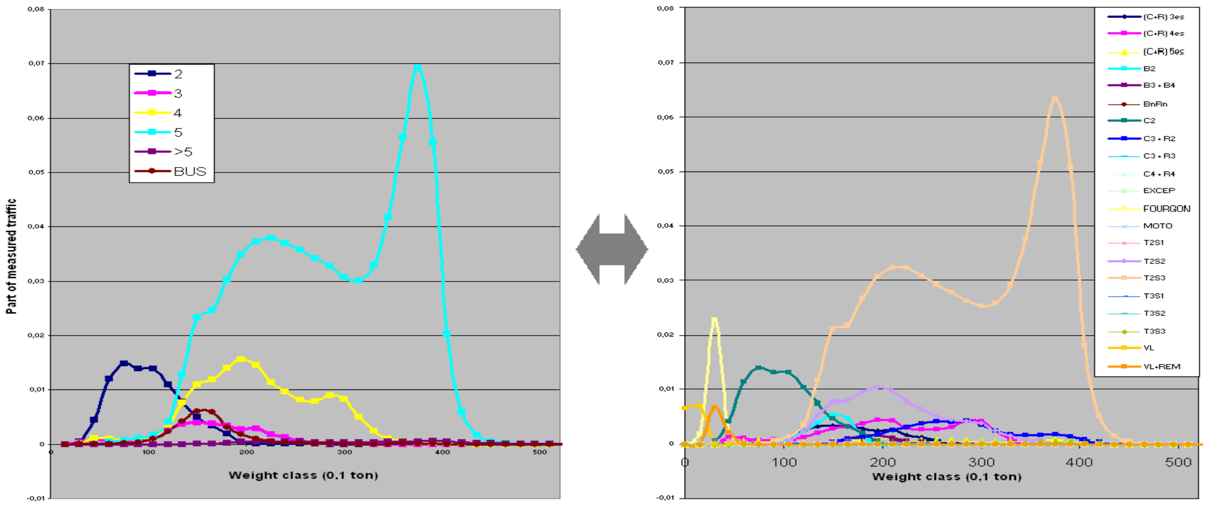

Figure 3 - Example of aggregation classes shift for same result type (detailed classes/ axle number)

Audience

The system is aimed at catering to two distinct audiences:

- a technically expert audience that is capable of directly consulting the database and that generally prefers to access raw data and use its own analysis tools,
- a 'general audience' that has less knowledge of the subject and/or technical tools and will rely on pre-defined results.

The technical audience would access the system with generic tools (ODBC) while the general audience would use a graphic user interface system (web interface) or a BI system such as SpagoBI (to be determined).

3.2 Added Value

SITL is based on the same fundamental data and collection architecture that was used in previous systems. Differences and added value lie in improved storage and analysis, with more robustness and better functionality.

Large disaggregated samples
WIM equipment produces a large volume of data. Because of limited system capacities and performance issues, many systems have used aggregated data: data per classes instead of true values. This reduces data to a smaller volume, allowing easier storage and treatment; but it is done at the expense of precision. Selection of the appropriate data aggregation degree requires a careful planning phase, as those early choices cannot be undone later. Experience shows that, despite best practices, new needs and regulations continually emerge and even the best studies fall short.

Using much disaggregated data requires high-load components capable of handling larger data volumes.High-load components used to be expensive and very specialized tools, such as Oracle, but with the advent of open-source/libre databases such as Postgresql they have become available to even small or medium size projects.Those systems are robust, have high integrity levels and are fast enough given the right computing infrastructure.

Normative environment
Another problem plaguing the previous system was fragmentation. Lacking development guidelines, it was composed of several systems with their own logic and technical implementations.

The new SITL system tries to avoid those short-comings by setting effective general principles. Those principles try to be the most open and least specific. Instead of trying to define specific rules, SITL ressearchers tried instead to identify the most industry and academically accepted rules and to implement them for the given problem.

While those generic rules may not be as powerful as a “tailor-made” architecture, it would make it easier for new users to use, maintain and expand, as any newcomer with knowledge of those widespread conceptual models could easily get started. It was considered that performance issues could be treated by general context evolution, so portability was emphasized.

3.3 Application examples

Being a general purpose WIM data platform, the SITL system can be of use for most common WIM applications. The following is a discussion of possible added value for some of the most common applications of WIM data.

Road maintenance planning
In pavement engineering, aggregated data are used to assess the impacts of heavy traffic, i.e. to calculate the loading effects of a given traffic pattern. That is of particular interest when weight and dimension regulations change and to improve pavement deterioration models. Traffic data are converted into loading effects by applying a power law to axle loads whose factors depend on type of structure and axle. The data also help to improve the pavement design method by characterizing accurately the traffic loading effects.

Low data granularity allows for details in loading assessment, notably:
- Loading effect per axle,
- per axle groups,
- accounting for in-axle-group axle-spacing,
- Accounting for axle lateral position.
-

Bridge maintenance planning
For bridges, detailed data are necessary to assess the damage on any bridge using the concepts of influence lines and surfaces. Fatigue and extreme load effects are the key parameters for bridge durability and safety assessment.

In France, the consequences of weight and dimension changes (generalization of a legal GVW limit at 44 t) on the residual capacity of bridges were recently assessed. Studies showed that distress behavior largely depends on type of bridge considered, for example:

- Fatigue is critical for steel and composite bridges,
- Extreme loads are of importance for reinforced and pre-stressed concrete bridges.

A wide range of diversified data is necessary in order to address multiple existing damage models.

Overweight vehicle policing
Because of the cost of damage to roads, and because of road safety concerns, authorities are actively chasing and prosecuting overloaded vehicles. Existing WIM system accuracy is not high enough for automated fining, so most controls still require roadside intervention. Those operations are expensive to implement because they require both police forces and vehicle weighing specialized technicians.

Overweight vehicle statistics allow optimizing those operations by determining areas and time periods with higher infraction rates.

Socioeconomic studies
Volume of goods deduced from truck weights can be used as an indicator of transport economics and economic activity in general. Country and region data extracted from OCR video systems also give indications regarding freight flows.

Weigh-in-motion systems R&D
Collected data are used for WIM system improvement. R&D may often require data resolution higher than data used for common tasks.

By recording almost all available information, disaggregated data allow for sophisticated and original approaches.

3.4 Developing the system

There are several general directions for expanding the SITL system.

The platform is meant to receive new applications and treatments as they are transferred from the former system. Newly developed expansions will be added as new needs emerge. Norms and guidelines should allow gathering developments from various sources.

Integration tools allow manipulating and processing complex and diverse data sets. The two most common formats available in French WIM architecture are being integrated, and there is a potential for addressing more data sources, for comparisons or cross studies between different systems at a national or an international level, and at reasonable cost.

3.5 Community

The current work was performed for the French administration for standalone needs and per se doesn't require further distribution for establishing its value, yet there are several reasons for spreading the word and publishing tools:

3. first is that there is no motivation for hoarding information. Work has been done and will continue to be done on behalf of the French administration, and its publication is beneficial for the whole WIM community. It helps to stimulate activity and helps all participants by giving them tools, which ends by being beneficial to all.
4. as already pointed out, further study done on behalf of the French administration will be required following the same guidelines so that they can be reused, maintained and expanded. While this is still hypothetical, having other entities (public, commercial) adopting the same or compatible norms would widen common ground.

In short, information is shared with partners with the consideration that it will trigger other information in return. The hope is for creating a snowball effect. One may note that the aim is not to impose a particular model on others but rather to start an interactive data community. Standardization is seldom a one-way road, but more a cooperative effort between WIM vendors and WIM system and data users. A balanced community is probably the best and most durable option, but it requires enough political will. ISWIM may play a leading rule.

4. Conclusion

This paper presents the output of two database and WIM information projects recently completed or still under development.

The FiWi database, which will soon be on the Internet, is a pan-European database of WIM sites with aggregated and detailed data. It is hoped that soon it will present a panorama of existing data diversity.

The SITL project is a French national initiative to transfer and manage WIM data from different sources presented as a WIM data management architecture showcase. It is hoped that it may be put to further use and that it will help to promote convergence amog WIM community participants.

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After Zurich (1995), Lisbon (1998), Orlando (2002), Taipei (2005) and Paris (2008), the International Conference on Weigh-In-Motion (ICWIM6) returns to North America to join with the North American Travel Monitoring Exhibition and Conference (NATMEC 2012). International WIM conferences are organized by the International Society for Weigh-In-Motion (ISWIM).

The conference addresses the broad range of technical issues related to weighing sensors and systems, weight data management and quality assurance, enforcement, road operation and infrastructure related issues. It provides access to current research and best practices, in an international forum for WIM technology, standards, research, policy and applications.

Heavy vehicle mass monitoring, assessment and enforcement are key actions to ensure road safety and fair competition in freight transport, facilitating the inter-modality, and to design and maintain reliable and durable road infrastructures, with a better compliance of weights and dimensions. WIM is becoming part of a global ITS for heavy traffic management, contributing to reduce the environmental impact of freight transport and to a better use of the existing road networks.