Guide for Users of Weigh-In-Motion

AN INTRODUCTION TO WEIGH-IN-MOTION

ISWIM
International Society for Weigh in Motion

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Foreword and Acknowledgement

The broad Weigh-in-Motion (WIM) community comprises three distinct stakeholder groups:

- Users of WIM and the information it collects
- Academics and researchers in WIM technology and its associated data
- Vendors that provide WIM products and/or services.

For these groups to work harmoniously necessitates at least one application or use; common understanding, language and expectations of what WIM can deliver and under what circumstances.

A responsibility of the International Society for Weigh-In-Motion (ISWIM) is to better inform stakeholders to the use, myriad applications and appreciation of the information that is collected by WIM.

It had become evident to ISWIM that a ‘user guide’ would benefit all stakeholders. Becoming an informed purchaser and user ensures that the delivered system and associated service meets the expected needs be that of a public or private organisation. Additionally, the provider or vendor of this system or service is able to develop and deliver a fit-for-purpose solution that explicitly meets the needs of their customer. I also invite academics and researchers to familiarise themselves with this user guide, in doing so to permit them to see WIM and its applications from the ‘lens’ of a user.

This will mean better engagement for all and a much richer outcome.

I would like to acknowledge and thank Hans van Loo (ISWIM Contractor) for producing the user guide herewith, well supported by Aleš Žnidarič (ISWIM Information Officer) and Andy Lees (ISWIM Vice-President End-users), all of which are members of the ISWIM Promotions Group. I would like to acknowledge the Board of ISWIM for recognising the importance of this initiative and approving the work program and vendors for making significant contributions to the user guide.

Chris Koniditsiotis BEng(GeolEng), CertProjMg, MEng(CivEng)
President, International Society for Weigh–in-Motion

May 2019

1 Executive Summary

1.1 Background

Weigh-in-motion (WIM) is a technology that can be used for various private and public purposes (i.e. applications) related to the weights and axle loads of road and rail vehicles. WIM systems are installed on the road or rail track or on a vehicle and measure, store and provide data from the traffic flow and/ or the specific vehicle. For WIM systems certain specific conditions apply. These conditions have an impact on the quality and reliability of the data measured by the WIM system and of the durability of the sensors and WIM system itself.

WIM systems measure the dynamic axle loads of the vehicles and try to calculate the best possible estimate of the related static values. The WIM systems have to perform unattended, under harsh traffic and environmental conditions, often without any control over the way the vehicle is moving, or the driver is behaving. As a result of these specific measurement conditions, a successful implementation of a WIM system requires specific knowledge and experience.

Over the past decades, a vast amount of scientific and practical experience has been gathered on the development, installation and operation of WIM systems. However, these experiences often come in the form of technical scientific reports, which are typically not accessible or understandable to a novice user of WIM systems or data. They often lack the answers that a WIM user is looking for. Consequently, the International Society for Weigh-In-Motion has decided to develop a document providing basic, yet a comprehensive introduction to WIM.

This document covers different aspects related to the working, specification, purchase, installation, testing, operation and maintenance of WIM systems, and the application of the data they produce. To enhance accessibility for users starting with WIM, these topics are described in an easy-to-understand language. This means that sometimes a simplified description is given that may not be completely in line with the latest scientific results. For those interested in more detailed and scientific explanations, references to these detailed reports are included.

1.2 Importance of vehicle weight information

Knowing that the proper installation, operation, calibration and maintenance of WIM systems are difficult, the question arises:

”Why use WIM systems in the first place?”

The answer is simple:

”Only a WIM will provide detailed vehicle weight information!”

The weight information consists of the gross vehicle weight and axle (group) loads combined with other parameters like: date and time, location, speed and vehicle class. For on-board WIM systems this pertains to the specific vehicle only. For in-road WIM systems this applies to the entire vehicle traffic flow.

This weight information provides the user with detailed knowledge of the loading of heavy goods vehicles. This knowledge will replace the assumptions and estimates that had previously been used; as a result, margins of uncertainty are reduced. This means, for example, that the match between the heavy goods vehicles and the road/rail infrastructure can be optimised. This leads to more efficient goods transportation and better economic infrastructure management and productivity.

1.3 Introduction to Weigh-In-Motion

Weighing-in-motion is generally defined as the process of measuring the dynamic tyre forces of a moving road vehicle (dynamic wheel loads) and estimating the gross vehicle weight (GVW) and the portion of that weight carried by each wheel, axle, and axle group of a corresponding static vehicle (static wheel and axle loads).

Besides measuring the gross vehicle weight, axle group loads, axle loads and often wheel loads of the passing vehicles, a WIM system will also determine other parameters related to the vehicle and its passage over the WIM system. This is combined in what is often referred to as the 'Vehicle Record', consisting of:

- Unique record number;
- Location of WIM system including the lane and direction of travel;
- Date and Time of passage;
- Vehicle speed;
- Axle distances;
- Wheel base and/or Vehicle length;
- Vehicle classification.

Depending on the policy need and hence application, a WIM system may be combined with other sensors or devices, in such cases the vehicle record may be extended, for example with images of the vehicle. Independent of the sensing technology used there are several different ways to measure the gross vehicle weight, axle group loads and axle loads of a vehicle:

- **Static weighing**, even though by definition not weighing in motion, the static weighing of road vehicles has an important relationship to WIM. The static weighing results are, in most cases, used as the reference values when testing and calibrating a WIM system. Static weighing systems are in many countries around the world legally approved for direct enforcement or trade applications, with a type approval certification according to the international OIML standards.
- **Low speed WIM (LS-WIM)**, where the weighing takes place in a dedicated controlled area, mostly outside the main traffic lane, on a flat and smooth platform (generally made of concrete) that is longer than 30 m. In the weighing area the velocity and transverse movement of the passing vehicles are controlled in order to eliminate the dynamic effects of the vehicle. This ensures that the tyre impact forces are as close as possible to the static wheel loads. In many countries LS-WIM is legally approved for direct enforcement and trade, with a type approval issued according to the international OIML or similar national standards.

- **High speed WIM (HS-WIM)**; here the weighing is carried out in the open traffic lanes at normal speed and under free flow conditions. The measurements are affected by the vehicle dynamics that depend on a combination of the geometry of the road, the driving behaviour of the driver and the reaction of the vehicle suspension on the influences mentioned previously. In general, good high speed WIM systems on smooth roads have an inaccuracy of between ±5 to ± 10 % for GVW measurements. More and less accurate systems are also available.
- **Bridge WIM (B-WIM)** is a special type of dynamic weighing system where the sensors are attached to the soffit (bottom side of beams or deck) of a bridge, viaduct or culvert. The sensors typically measure strains due to the bending of the bridge caused by the passing vehicles. In addition to the same vehicle information as provided by the pavement WIM systems, the B-WIM systems can also collect valuable data about bridge behaviour that can be used for safety assessment of the bridge.
- **Dynamic On-Board WIM (OBW)** systems are fitted to vehicles, rather than to the infrastructure. An OBW system will constantly measure the GVW, axle and wheel loads of the vehicle while it is moving. The typical measurement inaccuracy is between ±1 and ±3 %, depending on the sensing technology. The measured weight data of the moving vehicle may be combined with location (GPS) data and stored during the entire travel. Such combined OBW systems can be used to manage heavy vehicle operation and to monitor compliance to access to certain parts of the road network.
- **Stress-In-Motion (SIM)** systems are installed in the road pavement and are capable of measuring the individual multi-dimensional tyre-road contact stresses (the tyre profile). SIM measurement is a relatively new development in WIM that offers applications in advanced pavement design, detailed vehicle classification, tyre management and road safety.
- **Rail WIM** systems are installed on a railway track in order to measure the dynamic wheel forces and other characteristics of passing trains. Compared to Road-WIM, a Rail-WIM system will generally have better measurement accuracy, typically ±2 % for GVW. This is due to the more controlled weighing conditions and improved calibration possibilities.

In general, a complete WIM system includes a set of weighing sensors, either mounted in the pavement or attached to a bridge, and a road side unit containing all the electronics including data processing unit, data storage and communication devices. Depending on the application, various additional sensors may be added and linked to a WIM system, such as temperature and deflection sensors to compensate for the variation in the sensor response, or cameras for overview photos and licence plate recognition for weight enforcement.

WIM sensors come in a number of different forms such as strip, bar, scale or plate. All strip sensors are narrower than the tyre imprint, and will acquire a measurement signal at least over the time the wheel or axle has a presence over them. Therefore, it is necessary to know the vehicle speed and to integrate the signal with time to get the wheel/axle force. The width of the scale/plate sensors in the traffic direction is greater than a wheel imprint and therefore it is capable of measuring the wheel impact force immediately. For both strip and scale WIM sensors, many different measurement technologies can be used.

1.4 Applications of WIM

There are many applications for WIM systems and WIM data. Often the same WIM systems can be used for more than one application. Noting, the vartied local, regional and national policy needs, the broad uses are:

- **Information on vehicle and traffic loading**: this information provides an important input for transportation studies that help to optimise the planning and design of the future road network. The detailed and accurate loading information is an important input both for the design codes of the road infrastructure (new roads and bridges) and for the planning of the maintenance of the existing infrastructure. Additionally, the information from WIM systems can be used for detailed analysis of transport flows over the road network and its development over time. This information can also be used in providing evidence for Government policy. There are a myriad of specific applications within this group driven by policy needs. Infrastructure design, maintenance and use; transport analysis and planning; freght studies; economic and productivity studies; improved and more safe access arrangements.
- **Weight enforcement**: the objective of weight enforcement is to achieve a better compliance with loading regulations and, as a consequence, a reduction of overloading and its negative effects; increased wear and tear of the road infrastructure, unfair competition and reduced safety. Low speed and high speed WIM systems offer a range of applications that will assist in a more efficient and effective weight enforcement. The applications described in this document are: road side controls, statistics and planning, pre-selection, company profiling and direct enforcement.
- **Tolling and Payment by weight**: the road users pay a toll fee based on the actual weight and/or axle loads of their vehicles. This is in line with the 'polluter pays' principle, since the height of the fee for using a toll road is proportional to the wear caused by the vehicle. The WIM systems not only ensure fair toll prices but may also generate additional revenue to finance maintenance of the infrastructure. This application includes the use of low speed WIM systems at the toll plazas and of high speed WIM under the free flow conditions.
- **Industrial applications**: at ports, industrial and logistic centres. WIM systems can be used to check the weights and axle loads of trucks leaving the site, to prevent overloading before the trucks enter the road network. In case the WIM systems are certified for trade applications they can also be used for the invoicing of industrial (bulk) goods by weight.
- **Railway WIM**: WIM systems installed in railway tracks may be used for one or a combination of the following applications:
  - Rail track design and maintenance; by recording the total track loading a more efficient planning of rail track design and maintenance can be made;
  - Train maintenance; in combination with a train identification system, the WIM can record the dynamic wheel loads of each train car. An early detection of high dynamics (e.g. because of flat spots) allows quick intervention for maintenance avoiding additional wear and tear of the train and track.
  - Rail track access pricing; WIM can be used to monitor the access of trains to a railway track. This can be used for track access pricing related to the number and weights of the trains, the distance travelled on the rail network.

1.5 Select the right WIM

A five step selection procedure is described below on how to buy and use a WIM system that is a best fit for the purpose and operating conditions. These steps are:

- Determine the application, including a description of the purpose, the way the WIM data will be used and what will be the requirements for the WIM data. The application determines the performance criteria for the system and possible criteria for the surroundings of the site;
- In case of on-board WIM identify if a specific vehicle mass is needed or in case of in-road WIM select the locations for the systems, based on the application, the traffic and pavement conditions and available facilities. In the case of low speed WIM, the WIM location is often at the premises of the customer, in a dedicated weighing area or driveway close to the road network. In the selection of the actual location for the installation of a high speed WIM system, three consecutive steps should be taken:

  a. A first, rough, selection of the road section to be measured based on the purpose of the WIM system and the general traffic conditions;
  b. In the case of use as pre-selection tool, the selection of a suitable location for the static – or low speed – measurement needed for legal prosecution of overloaded vehicles, the static weighing area;
  c. Selection of the final location, the detailed location for the WIM system will be determined based on the pavement, road geometry and traffic conditions and facilities available on site.

- Define the performance requirements for the systems and describe the procedures for testing and calibration of the systems. Typical and realistic accuracy requirements for high speed WIM systems are:

  – For statistics: gross vehicle weight: ±15 % and axle loads: ±20 % (for 95 % of all measurements);
  – For pre-selection: gross vehicle weight: ±10 % and axle loads: ±15 % (for 95 % of all measurements);
  – For direct enforcement and tolling by weight: gross vehicle weight: ±5 % and axle loads: ±10 % (for 100 % of all measurements).

For low speed WIM systems the typical measurement inaccuracy is roughly less than half of the values for high speed systems. Other performance requirements are the accuracy for the measurement of the axle distances and/or vehicle length, the number of axles, vehicle classification, the time stamp and the speed of passage.

- Installation, calibration and testing of the systems, after selection of the best offer, to monitor the installation. When finished and after calibration, execute the test procedure and, based on the test results, decide to accept the systems or not;
- Use of the systems, including the collection, storage, quality monitoring and application of the WIM data. Due to the nature of WIM-systems and the 'hostile' environment in which they have to operate, damage, wear and tear on the system's hardware and the surrounding pavement are part of normal operation. This means that the performance of all WIM systems will reduce over time, normally slowly because of wear and tear but sometimes quickly in case of damage to – parts of – the system. During the operation of a WIM system, different processes are required to ensure the WIM system is working correctly and data quality checks will ensure the minimum quality of the data generated by the system is of the required standard.

2 Introduction

2.1 Background

Weigh-In-Motion (WIM) is a technology that has been in use for several decades by many different users around the world for various applications related to the weights and axle loads of road or rail vehicles. Like other Intelligent Transportation Systems (ITS), WIM systems are installed on the road or rail track and measure, store and provide data from the traffic flow. However, for WIM systems, certain specific conditions apply that cannot be seen with other ITS systems. These conditions have an impact on the quality and reliability of the data measured by the WIM system and of the durability of the sensors and WIM system itself.

Weighing-in-motion is a challenge; sensors installed on, in, or under the pavement (or under a bridge) measure the dynamic wheel or axle loads of the passing vehicles and try to calculate the best possible estimate of the related static values. Thus, the WIM has to perform unattended, under harsh traffic and environmental conditions without any control over the way the vehicle is moving or the driver is behaving. As a result of these specific measurement conditions, a successful implementation of a WIM system requires specific knowledge and experience.

Over the past decades, vast amounts of scientific and practical experience have been gathered on the development, installation and operation of WIM systems. A series of International Conferences on WIM (ICWIM 1 to 7) have played an important role in the dissemination of the research results and experiences related to development and implementation of WIM. However, this information often comes in the form of scientific papers or research reports containing many technical details that the WIM user may have difficulty understanding. These papers and reports are also often lacking the answers a beginner is seeking.

2.2 Objective

WIM beginners often have difficulty finding documents providing a basic, yet comprehensive introduction to WIM. The International Society for Weigh-In-Motion has developed this document in order to fill this gap.

2.3 Content

This document covers different aspects related to the specification, purchase, installation, testing, operation, maintenance and use of WIM systems and of the data that these systems generate. To enhance accessibility for WIM users, these topics are described in an easy-to-understand language. This means that sometimes simplified descriptions are given that may not be completely in line with the latest scientific results. For those interested in more details explanations references to other reports are included.

This document will try to answer questions like:

- What is weighing-in-motion?
- What does a WIM system measure?
- What is the importance of weight information?
- What technologies are available?
- What factors influence WIM measurements?
- What performance may be expected from a WIM system?
- What are realistic requirements for a WIM system?
- What are the possible applications of WIM data?
- How to select a suitable location to install a WIM system?
- How to test if a new WIM system meets its specifications?
- What is involved in the maintenance of a WIM system?
- What is needed for the good operation of a WIM system?

This document will not answer questions like:

- What is the best WIM system available?
- What is the best WIM technology?
- What manufacturer sells which specific WIM technology?
- How much does a WIM system cost?

These questions depend on the intended application and specific local conditions to be answered in a general document like this. Hopefully this document will guide the reader to find the answers to these questions and to select the correct WIM system for their specific need.

2.4 International Society for WIM

The International Society for Weigh-In-Motion (ISWIM) is an international non-profit organisation, legally established in Switzerland in 2007. ISWIM is an international network of, and for, people and organisations active in the field of Weigh-In-Motion.

The society brings together users, researchers, contractors, consultants and vendors of WIM systems. This includes systems installed in or under the road pavements, bridges, rail tracks and those on board vehicles. ISWIM organises periodically the International Conferences on WIM (ICWIM), regional seminars and workshops as part of other international conferences and exhibitions, and appoints the International Scientific Committee (ISC) for WIM.

Figure 2.1: Logo of the International Society for Weigh-In-Motion *Source: ISWIM*

The aims of ISWIM are to support the advances and standardisation of weigh-in-motion technologies and the more widespread application of WIM systems and data. ISWIM performs these activities through:

1. Organisation of international conferences, regional seminars and workshops, on WIM technology and applications.
2. Support of international research and development projects on WIM.
3. Support of developing standards relating to WIM and its applications.
4. Publication of papers and articles in international magazines.
5. Promotion of the application and use of WIM systems and data at exhibitions and trade fairs.
6. Providing a discussion forum on many aspects of WIM.

For more information on ISWIM contact:

- Website: www.is-wim.org
- e-mail: iswim@free.fr
- LinkedIn: www.linkedin.com/groups/13400438

3 Introduction to Weigh-In-Motion

This chapter provides an overview of WIM and the myriad of technologies and sensors.

3.1 Definitions

Axle: An axle comprises of two, or more wheel assemblies with centres lying approximately on a common axis orientated transversely to the nominal direction of motion of the vehicle.

Axle Distance: The distance between the centres of two axles.

Axle Group: A set of axles on the same vehicle, defined by the total number of axles included in the group where the centres of the axles are spaced less than a specified value.

Axle Group Load [kg]: The total load of all wheels included in an axle group.

Axle Load [kg]: The sum of all the wheel loads of an axle of a vehicle.

Axle Spacing: See Axle Distance.

Bridge WIM (B-WIM): A WIM-system using an instrumented bridge to measure the response of the bridge to passing vehicles. From the measurements, the axle loads and gross weight of the passing vehicles are calculated.

Dynamic Tyre Force [kN]: The component of the time-varying force applied perpendicularly to the road surface by the tyre(s) on a wheel of a moving vehicle.

Dynamic Wheel Load [kg]: The dynamic tyre forces on a wheel of a moving vehicle represented in the unit of mass, hence divided by the local acceleration of free fall.

Equivalent Single Axle Load (ESAL): A method, originally developed in North America, to transform all axle loads of vehicles into their equivalent values, to represent the effect that they have on the pavement.

Gross Vehicle Weight (GVW) [kg]: The external force of gravity acting vertically downwards on a vehicle, including all connected components, with a magnitude equal to the mass of the vehicle represented in the unit of mass, hence not multiplied by the local acceleration of free fall.

High Speed WIM (HS-WIM): The weighing of a vehicle in motion in the normal traffic flow, using a system installed directly on/in/under a normal road.

In-Road WIM: A WIM-system where the measurement sensors are installed on, in or under the road pavement.

Legal Applications: Applications of WIM systems with a direct connection to a legal or financial transaction, e.g. trade, tolling by weight, direct weight enforcement. Such WIM systems require a legal approval by a notified body that certifies the requirements for each individual measurement.

Low Speed WIM (LS-WIM): The weighing of a vehicle in motion in a controlled weighing area and under controlled traffic conditions, such as limited vehicle speeds in order to minimise the dynamic effects.

Load Equivalency Factor (LEF): A method developed in Europe to transform all axle loads of vehicles into their equivalent values, to represent the effect that they have on the pavement.

Load Receptor: A sensor installed in or under the road pavement measuring the dynamic force exerted by the wheel or axle of a vehicle on the road.

On-Board WIM (OBW): A WIM-system installed on a vehicle that will constantly measure the dynamic wheel/axle forces during travel.

Pavement-WIM: see In-Road WIM.

Rail-WIM: A WIM-system installed on a railway track to measure the dynamic wheel forces and characteristics of passing trains.

Sensor: Part of a measuring instrument that is directly affected by the parameter to be measured and produces a related signal.

Sensor Array: Physical arrangement of the sensors, including the number of the different types of sensors and their mutual position and distances.

Static Weighing: Weighing of gross vehicle weights or axle loads of vehicles that are stationary.

Static Wheel Load [kg]: The portion of the gross weight imposed upon a weighing instrument by the tyre(s) of a stationary wheel at the time of weighing, due only to the vertical downward force of gravity acting on the mass of the vehicle.

Statistic Applications: Applications of WIM systems without a direct connection to a legal or financial transaction, e.g. traffic monitoring, pavement loading, pre-selection for weight enforcement. Such WIM systems do not require legal approval by a notified body.

Stress-In-Motion (SIM): WIM systems capable of measuring the individual multi-dimensional (3D) tyre-road contact stresses (the tyre profile) under moving tyres.

Vehicle Class: Group of vehicles with the same characteristics such as the number of axles, number of axle groups, vehicle length, etc.

Vehicle Length: Distance between the front and the back of a vehicle.

Vehicle Signature: Measured electromagnetic or optical characteristics of a passing vehicle providing a unique identification of the vehicle.

Weigh Bridge: A weighing instrument which measures the complete stationary vehicle weight at once. Weigh bridges are generally used to measure the gross vehicle weight reference value for the testing or calibration of WIM systems.

Weigh-In-Motion (WIM): The process of estimating the wheel and/or axle loads and gross weight of a moving vehicle, by measurement and analysis of the dynamic vehicle tyre forces.

Weigh-In-Motion System (Instrument): A set of mounted sensors and electronics with software which measures dynamic tyre forces and vehicle presence of a moving vehicle with respect to time and calculates wheel and/or axle loads and gross weights estimates, as well as other vehicle parameters such as speed, axle spacing, vehicle class, etc.

Wheel Base: Distance between the first and last axle of a vehicle.

3.2 What is weighing-in-motion?

Road based weighing-in-motion is generally defined as the process of measuring the dynamic tyre forces of a moving road vehicle (dynamic wheel loads) and estimating the gross vehicle weight (GVW) and the portion of that weight carried by each wheel, axle, and axle group of a corresponding static vehicle (the static wheel/axle loads). There are a number of things that are important to realise from this definition:

1. A WIM system will measure one physical quantity (dynamic wheel loads) and will calculate an estimate of something else (static wheel loads, axle loads and GVW) as output;
2. The GVW is directly related to the total mass of the vehicle and static axle loads are related to the distribution of the mass over the axles. Like the total mass of the vehicle, the GVW and static axle loads are constant and can only be measured directly when the vehicle is standing still – and the brakes are released;
3. When driving, the dynamic wheel/axle loads of a vehicle vary in time because of the movement of the complete vehicle (bouncing, rolling and pitching) and that of the individual axles (hopping). These movements are caused by the reaction of the vehicle to the pavement surface and external disturbances like braking, acceleration, steering and wind;
4. The magnitude of the dynamic variation of a dynamic axle load depends on the quality of the road, especially the evenness of the pavement surface and the deflection of the road construction, the characteristics of the vehicle, and primarily the type and condition of the suspension system and the distribution of the load;
5. The magnitude of the dynamic variation around the static loads is unknown to the WIM system. In general, the more disturbances, the higher the dynamic variations and the more difficulties the WIM system will have to calculate the static loads accurately;

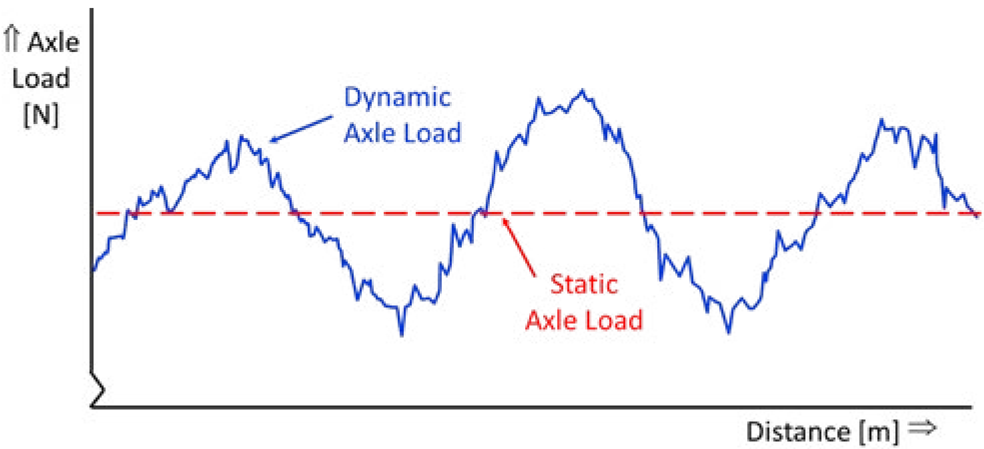

Figure 3.1: Dynamic and static axle loads *Source: VAN LOO*

1st Law of WIM:

A WIM system installed on a good road may give good results; a WIM installed on a poor road will always give poor results.

More information on dynamic weighing and vehicle dynamics and vehicle-road interaction can be found in (Cebon, 1999) and (Green & Cebon, 1995).

3.3 What does a WIM system measure?

Besides measuring the gross vehicle weight, axle group loads, axle loads and often wheel loads of the passing vehicles, a WIM system will also determine other parameters related to the vehicle and its passage over the WIM system.

This is combined in what is often referred to as the 'Vehicle Record', consisting of:

- Unique record number;
- Location of WIM system including the lane and direction of travel;
- Date and Time of passage;
- Vehicle speed;
- Axle distances;
- Wheel base and/or Vehicle length;
- Vehicle classification.

Figure 3.2: Example of data measured by an extended WIM system. *Source: RIJKSWATERSTAAT*

Depending on the application, a WIM system may be combined with other sensors or ITS systems. In such cases the vehicle record may be extended with:

- Temperature of the pavement or bridge, at one or several locations;
- Deflection of the pavement;
- Height and/or width of the vehicle;
- Single/double tyre detection;
- Tyre pressure distribution;
- Lateral position of the vehicle in a lane;
- Identification number (tag) of the vehicle;
- Overview picture of the vehicle;
- Picture of the licence plate or registration number;
- Licence plate or registration number;
- Picture of dangerous goods identification shield;
- Code of dangerous goods shield;
- Vehicle signature;
- Bridge dynamic amplification factor.

3.4 A very brief history of WIM

WIM was first utilised in the United States in the 1950s by Professor Clyde Lee and used in the AASHTO road test (AASHO, 1961) that began in 1958. Originally it was used mainly to collect large sample of dynamic axle and vehicle loads for pavement design purposes. Bending plates were the first type of sensors used for dynamic weighing. From the 1970s', new technologies of WIM sensors were developed in Europe, such as wire, strip and bar sensors based on capacitive, piezo-electric (ceramic, then polymer and then quartz), and finally fibre optics sensing. Bridge WIM was also introduced in the US in the late 1970s and then further developed in Australia and Europe in the 1990s.

In the 70s and 80s, WIM data was primarily used:

- as input for road pavement design and maintenance and for bridge design code calibration (e.g. Canadian code, Eurocode),
- for bridge assessment, for calculation of remaining fatigue lifetime and of extreme loads and load effects, and
- for traffic monitoring and collection of statistics on road freight transport.

In the 1990s, the first WIM standard (ASTM-E1318-09, 2009) was published in North America, and the COST 323 action provided draft European specifications of WIM as well as reports on Pan-European tests of WIM system (COST 323, 2002). The European research project WAVE (2002) and other initiatives delivered improved technologies and new methodologies of WIM. These first tests were done with the combination of WIM systems with video as a tool to assist overloading enforcement controls (WIM-NL, 2002).

In the early 2000s, the accuracy and reliability of WIM systems were significantly improved, and they were used more frequently for overload screening and pre-selection for road side weight enforcement controls (virtual weigh stations). The OIML R134 (2009) was published as an international standard of low speed WIM systems for legal applications like tolling by weight and direct weight enforcement. Most recently, the NMi WIM standard (2016) offers a basis for the introduction of high speed WIM systems for direct automatic enforcement and free flow tolling by weight.

Furthermore, on-board WIM systems are now being used for government in addition to commercial applications. More information on the history of WIM can be found in the listed WAVE and COST 323 reports.

3.5 Different types of vehicle weighing

Independent of the sensing technology used, there are several different ways to measure the gross vehicle weight, axle group loads and axle loads of a vehicle (Figure 3.3).

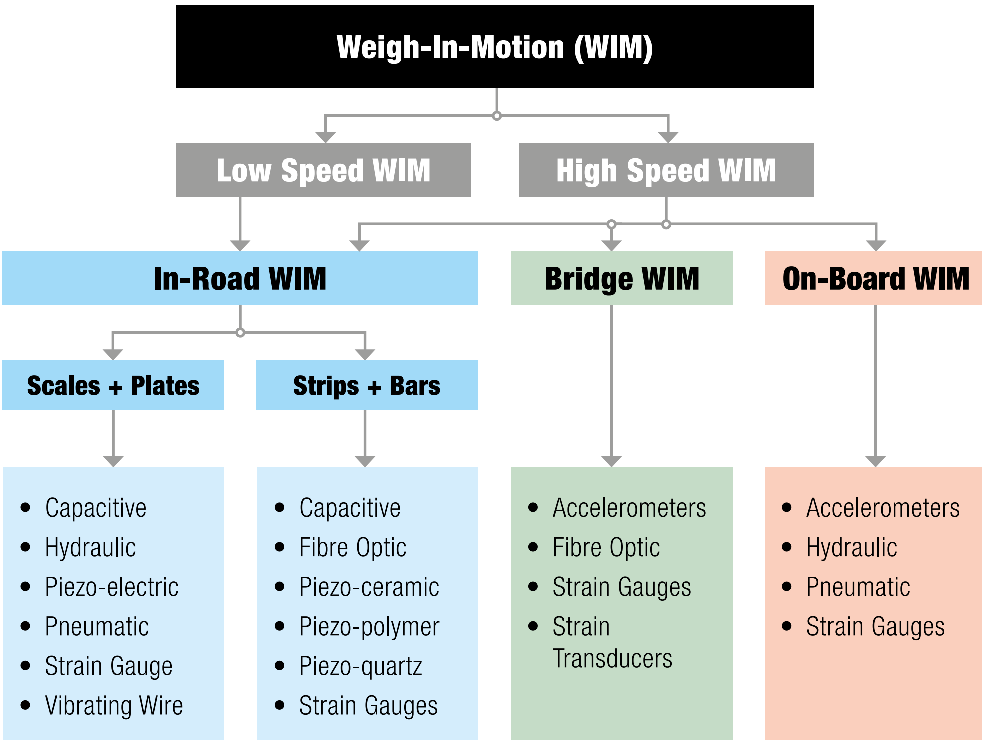

Figure 3.3: Different technologies used in WIM systems

Source: ISWIM

3.5.1 Static weighing

Even though by definition this is not weighing in motion, the static weighing of the gross vehicle weight and axle loads of vehicles has an important relationship to WIM. This is because static measurements are, in most cases, used as reference values when testing and calibrating a WIM system. As explained, the GVW and static axle loads are the values that any WIM-system is designed to estimate/calculate.

The most accurate way to measure the GVW of a vehicle is to use a full draught static weigh bridge that is capable of measuring the full weight of the entire vehicle at once. The measurement inaccuracy of such weigh bridges is typically below ±1 %. To measure the individual static axle or wheel loads, often fixed or portable weighing scales or plates are used, with a typical measurement inaccuracy of less than ±2 %. This can be achieved only if a correct weighing procedure is followed.

With one set of axle scales for static weighing the weighing procedure requires that the vehicle has to be moved several times and stopped for each axle load measurement with the wheels of each selected axle supported on the scale. Moving the vehicle may redistribute the gross vehicle weight among axles, wheels or tyres, thus it is important to minimise this variation throughout the measurement procedure.

This requires:

- keeping all wheels (including those not being weighed at the time) in a horizontal plane, and
- moving the vehicle forward smoothly, and
- releasing the brakes during every measurement.

Static weighing systems are legally approved for direct enforcement or trade in many countries around the world with a type approval according to international standards OIML R76 (2006) in case all the vehicle's axles are weighed simultaneously and OIML R134 (2009) where the vehicle's axles are weighed sequentially.

3.5.2 Dynamic In-Road weighing

With an In-Road WIM system (for either low or high speed) the measurement sensors are installed on, in, or under the road pavement. The sensors measure the dynamic vertical component of the tyre force from each wheel of the vehicle as the vehicle passes over the sensors of the system. The measured tyre forces — along with other measured or calculated parameters, such as speed and longitudinal position of the vehicle in the traffic lane — are then used to estimate the GVW and loads carried by each wheel, axle, and axle group of a corresponding static vehicle.

3.5.3 Low speed weighing

With low speed WIM (LS-WIM) the weighing is performed within a dedicated controlled area, mostly outside the traffic lane, on a flat and smooth platform (generally in concrete), longer than 30 m. In the weighing area the velocity and transverse movement of the passing vehicles are controlled, in order to eliminate the dynamic effects of the vehicle and thus to ensure that the tyre impact forces are equal to the static wheel loads. LS-WIM systems are mostly load cell scales based on different measurement technologies. The typical measurement inaccuracy is around ±2 %, depending on the speed range. The measurement accuracy depends on the quality of the installation, the geometry, and smoothness of the weighing platform, the approaches and exits. The measurement performance also depends on the methods used to capture measurements, the algorithms to analyse the raw weight data and the ways to deal with disturbances caused by the movement of the vehicle.

In many countries LS-WIM is legally approved for direct enforcement and trade with a type approval according to the international OIML R 134 (2009) or similar national standards.

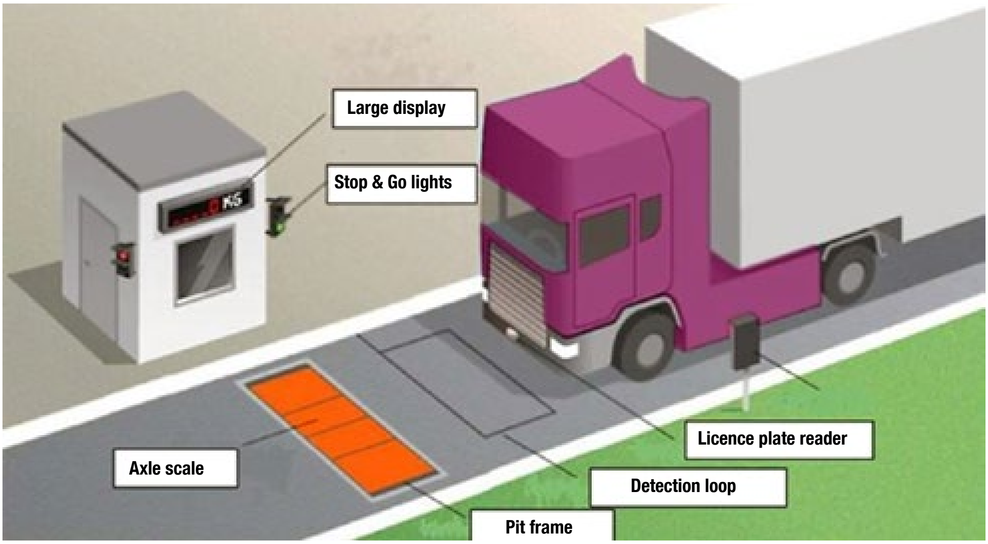

Figure 3.4: Typical low speed WIM system design *Source: STERELA*

3.5.4 High speed weighing

With high speed WIM (HS-WIM) the weighing is carried out in the open traffic lanes at normal speed (i.e. 30 km/h or above) and under free flow conditions. The measurements are affected by the vehicle dynamics (vertical accelerations) that depends on (Cebon, 1999):

- the geometry of the road pavement before the WIM site; this includes smoothness of the pavement surface, rutting, bumps, settlements, potholes and slopes of the road;
- disturbances to the movement of the vehicle caused by driving behaviour, accelerating, braking, steering and environmental conditions like wind, rain, snow, ice;
- the reaction of the vehicle suspension on the influences mentioned above; this depends on the vehicle mass, the type of load, the axle load distribution and the suspension system of the vehicle.

In addition to the impact of these disturbances the measurement performance of a high speed WIM system also depends on the type, number and configuration of sensors and the quality of the data processing algorithms. In general, high speed WIM systems have an inaccuracy of between ±5 to ±10 % for GVW measurements, although more and less accurate systems are available.

3.5.5 Bridge WIM

Bridge WIM (B-WIM) is a special type of dynamic weighing system where the sensors are attached to the soffit (bottom side of the slab and/or beams) of a bridge, viaduct or culvert. The sensors typically measure strains due to the bending of the bridge caused by the passing vehicles. Knowing the key characteristics about bridge behaviour under loading, the so-called influence lines, the system calculates the GVW and axle loads of the passing vehicle. Basically, a bridge performs as a large dynamic weighing scale. As a result, the measurement inaccuracy depends on the type and condition of the bridge, in particular its length and smoothens of its surface. Instrumentation of an appropriate bridge with levelled pavement will likely provide results with GVW inaccuracy of ±5 to ±10 %. In addition to the same vehicle information as provided by the pavement WIM systems, the B-WIM systems also collect valuable data about bridge behaviour that can be used for safety assessment of the instrumented or similar bridges (OBrien et al., 2008).

3.5.6 Dynamic On-Board weighing

On-Board Weighing (OBW) systems are fitted to vehicles, rather than to the infrastructure. An OBW system will constantly measure the GVW, axle and wheel loads of the vehicle while it is moving or stationary. Many different measurement techniques and technologies are available depending on the type of vehicle and the type of suspension system. Examples of primary weighing sensors are load cells, strain gauges and air or hydraulic pressure transducers. The typical measurement inaccuracy is between ±1 and ±3 % depending on the sensing technology. The measured weight data of the moving vehicle may be combined with location (GPS) data and stored during the entire travel. Such combined OBW systems can be used to manage heavy vehicle operation and to monitor compliance to access to certain parts of the road network (Koniditsiotis et al., 2012).

3.5.7 Railway Weighing

A Rail-WIM system is installed on a railway track or a bridge in order to measure the dynamic wheel forces and other characteristics of passing trains. Different sensing methods are used for weighing trains in motion; this can be done by measuring:

- The strains directly from the rail. This allows trains to be weighed while travelling at all operating speeds (including high speed); however, it is less accurate than the second method. In addition, on electrified tracks, the electric current may cause problems and insulated sensors are required.
- The vertical axle forces transmitted through the rail to the sleepers and the embankment. This method requires the installation of a solid foundation under the track and also requires that trains to travel at low speeds during measurement to ensure accuracy.
- The response of a railway bridge. This method is similar to a road B-WIM system.

Compared to Road-WIM, a Rail-WIM system will generally have better measurement accuracy, typically ±2 % for GVW. This is due to the more controlled weighing conditions (no lateral variation, the trains always drive over the same track) and improved calibration possibilities (locomotives often have a standardised weight that can be used to calibrate each measurement).

3.6 Different WIM technologies

In general, a complete WIM system includes:

1. A set of weighing sensors, either mounted in the pavement (In-road sensors), or attached to a bridge (B-WIM). For on-board WIM, the sensors are installed on the vehicle. Additional sensors are mostly used to measure vehicle speed, length, wheel transverse location, etc. Road sensors can be scales, plates, strips or bars mounted inside the pavement, and sometimes mats attached to the pavement surface. Strain transducers or strain gauges are most commonly used for Bridge WIM installations. Strain gauges, load cells, pressure transducers, etc. are used for on-board weighing.
2. A road side unit – or central vehicle unit - containing all the electronics including a data acquisition tool, data processing unit with software for weight calculation, (self-) calibration tool, user interface, a data storage, power source and communication devices. For on-board weighing the control module is in the vehicle proper.
3. Other sensors or measuring systems: depending on the WIM technology and application, various additional sensors may be added and linked to a WIM system, such as temperature and deflection sensors to compensate variation in the sensor response, or cameras for overview pictures and licence plate recognition for enforcement.

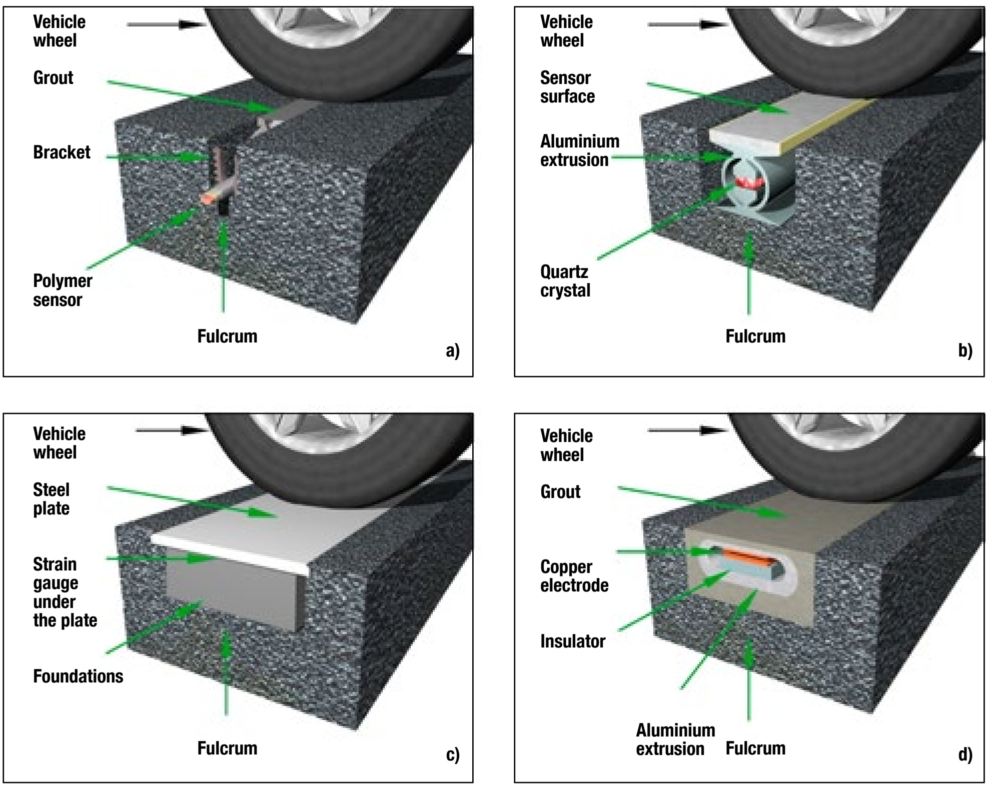

Figure 3.5: Pavement WIM sensor technologies: (a) piezo-electric or piezo-polymer bar, (b) piezo-quartz, (c) bending plate, (d) capacitive sensor

Source: BURNOS & RYS, 2017

The information provided in this chapter on the accuracy and broad economics of the various technologies should be interpreted as an indication only. Actual accuracy and cost will vary considerably depending on the specifics of the application, the local traffic, road and environmental conditions and the vendor of the systems. A similar overview of WIM technology and considerations on procurement are presented in Part I of the Federal Highway Administration Weigh-In-Motion Pocket Guide (FHWA-1, 2018). Some of the most popular WIM sensor technologies are presented in Figure 3 .5.

3.6.1 Strip and bar sensors

Strips and bar WIM sensors were first introduced in the 1970s to provide low cost and less intrusive solutions as an alternative to plate sensors. These sensors are installed into the slots cut in the upper pavement layer and are fixed with epoxy grouting. The sensors are either installed below the surface of the pavement or are ground flush with the pavement surface. As a result, the manufacturing, installation and maintenance cost are reduced and it only takes a few hours to install them.

A strip sensor is flat (below 2 cm in height), 1 to 5 cm wide, up to 5.50 m long and may be flexible. The typical dimensions of a cross-section of a bar sensor are 3 to 7 cm (width and height, the length vary between 1 to 2 m and is always rigid. In daily practice the bar sensors are often referred to as strip sensors.

Through the combination of different sensors, their total length can be adapted for a half lane (wheel weighing) or for a whole lane (axle weighing). They are mounted in slots of 4 to 8 cm in depth and width. Both, strips and bars contain material with specific characteristics (piezoelectric properties) and measure a physical quantity that is proportional to the applied pressure, such as capacitance (capacitive sensors), strain (strain gauges) or light variation (fibre optic sensors). Strips and bars are used for LS- and HS-WIM installations.

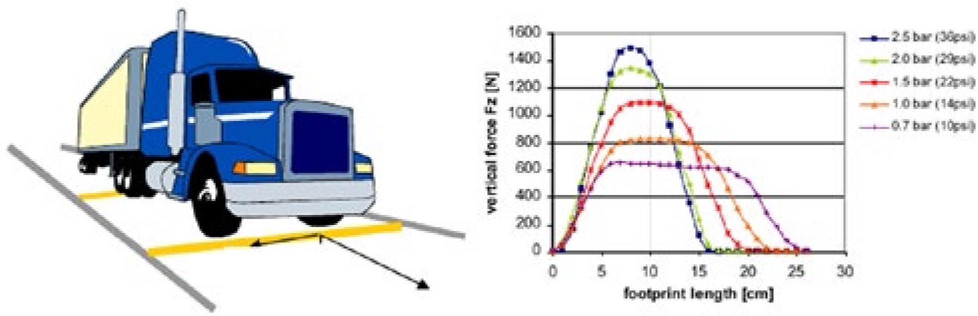

Figure 3.6: Working principle of a strip or bar WIM sensor *Source: KISTLER*

All strip sensors are narrower than the tyre imprint, and will measure the response signal as long as a wheel is working on it. Therefore, the vehicle speed is required to integrate the signal with time to get the wheel/axle force. Compared to scales in general, the strip sensors are more sensitive to vehicle dynamics and the pavement stiffness, and, consequently, to the temperature variations. Some strip sensor systems use a self-calibration procedure to compensate the effects of these external factors especially temperature variations. The prices of these sensors vary depending on the technology, but in general they are cheaper than scales. The most common sensor technologies available on the market are:

- **Capacitive strips** consisting of 2 or more conducting plates separated by layers of di-electric material creating an electrical capacitor. A force applied to the bar will compress the di-electric material, decrease the distance between the plates and increase its capacitance;
- **Piezo-polymer strips** consist of a flat coaxial cable with a thick brass outer sheet, with a piezo-electric film spiral-wrapped around a silver plated copper wire. A force applied to the strip will result in a signal between the core and sheath of the sensor. These sensors are relatively thin and flexible and are less expensive technology, but are also less accurate and more sensitive to the temperature variations;
- **Piezo-ceramic bars** consist of a coaxial cable with the sheath made of a copper tube, which contains a polarised piezo-electric ceramic powder with a copper wire running through the centre. A force applied to the cable will result in a signal between the core and sheath of the sensor. The sensors offer an intermediate solution, both in accuracy and in cost;
- **Piezo-quartz bars** consist of a row of quartz discs mounted in an aluminium profile. When a load is submitted to the sensor, a charge is generated that is proportional to the load. Piezo-quartz strip sensors have a low sensitivity to temperature variations. The sensors have good accuracy at an above average cost. Subsurface piezo-quartz bars are installed below the road surface but are less accurate although they have a longer life span;

- **Strain-gauge bars** sensors consist of several strain gauges that measure the deformation (strains) of the bars as a result of the load on the sensor. The resistance of a strain gauge will change when it is deformed in a certain direction. Strain gauges have temperature compensation performed as part of the sensor. These sensors have good accuracy and average cost;
- **Fibre optic cables** or strips measure the force acting on the cable by measuring the changes in the characteristics of the light beam. This may be based on different principles:
  - phase shift of the outgoing beam with respect to the incoming beam;
  - change in the polarisation of light when the geometry of the light conductor changes under the load;
  - changes in the spectral characteristics of the optical path under a load;
  - changes in the optical path intensity (amplitude), which changes with the load on the light conductor along its points.

Over the years many different types of fibre optic sensors were developed and tested but are not yet marketed on a large scale, often due to problems with durability and temperature compensation.

More information on strip and bar sensors can be found on the websites of several of the ISWIM vendors listed in section 7.2.

3.6.2 Scales and plates

WIM scales are instrumented plates mounted in a rigid frame fixed in the pavement structure, and measure the wheel/tyre vertical forces of the running vehicles. The scale length in the traffic direction is more than a wheel/tyre imprint (≈ 0.30 m), but less than the minimum axle spacing (0.80 m). The scale width is either below 1 m (wheel scale) or above 3 m (axle scale). Therefore, it is capable of measuring either the wheel or axle impact force. The main technologies of WIM scales are:

- **Load cell scales**: a load cell is a transducer unit that converts a load or force acting on it into an electronic signal. The measurement principle may be based on different technologies: capacitive, hydraulic, piezo-electric, pneumatic, strain gauge or vibrating wire. In a WIM scale, one or more load cells are mounted between a rigid steel plate (on top) and the support frame (at the bottom). The load cell(s) measure the vertical forces transferred from the wheel/axle to the plate and then to the frame. The load cells are factory calibrated and may be certified by the legal metrology institutes. In general, these sensors have good accuracy at above average cost. They are used both for low speed (LS-)WIM and high speed (HS-)WIM conditions, mainly for enforcement and industrial purposes.
- **Bending plates**: the plate is simply supported by the frame at its edges, and instrumented with stain gauges, which measure the bend of the plate while a wheel or axle is crossing it. The bending strains are proportional to the vertical force if applied at the same location. Combining several strain gauges, the wheel transverse location may be estimated and the measured vertical force becomes almost independent on it. In general, these sensors have good accuracy, and an average cost. They are mainly used for HS-WIM and as axle weighing scales.
- **Capacitive mats** consisting of two or more conducting plates separated by layers of di-electric material creating an electrical capacitor. A force applied to the mat will compress the di-electric material, decreasing the distance between the plates and increase its capacitance. This is the least expensive technology, but also the least accurate. It is used both in fixed and portable installations and is mainly used for enforcement purposes.


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- **Hydraulic plates** consisting of two steel plates with regularly-spaced elastically deformable tubular spring elements placed between the plates. The elements are filled with a hydraulic liquid and connected to a gauge measuring the changes in volume resulting from a deformation of the elements. A force applied to the plate will cause a deformation in the tubular spring elements that is linear to the weight on the plate. They are used for static and low speed WIM conditions, mainly for enforcement and industrial purposes.

More information on scale and plate sensors can be found on the websites of several of the ISWIM vendors listed in paragraph 7.2.

3.6.3 Bridge WIM

Bridge WIM (B-WIM) was introduced in the US in the late 1970s (Moses, 1979). An existing bridge is used as a weighing scale to find the axle loads of the passing vehicles. This is done by monitoring strains in a bridge superstructure (girders or slab) that are induced by vehicles crossing overhead. The most common sensors employed are strain gauges and strain transducers.

Modern B-WIM systems provide identical vehicle-by-vehicle data as the more common pavement WIM systems, plus some additional information that can help with the structural assessment of bridges: strain measurements, influence lines (how the bridge behaves under loading), girder distribution factors (how the load is transferred throughout the structure) and dynamic amplification of loading (Žnidarič et al., 2002). While calibration and connectivity to other types of traffic monitoring equipment are identical to those for pavement WIM systems, the instrumentation and maintenance are simpler and less intrusive. In most cases, sensors are not needed on the pavement surface and, consequently, traffic is not disrupted during installation and maintenance. Their disadvantages are that appropriate bridges are not available on all road sections and that specific bridge knowledge is required if uncommon bridges are instrumented.

The types of structures instrumented with B-WIM system range from short culverts, widely used in Australia (Peters, 1986), to the most common beam-and-slab and slab bridges, and long-span orthotropic deck bridges, such as the Millau viaduct in France, the second tallest bridge in the world. In a few cases even masonry arch bridges have been used. In the daily practice, the bridges for B-WIM are selected based on the required level of accuracy. As the weighing platform consists of the entire bridge or at least one bridge span, the results (gross weight and axle loads) are very accurate, providing that the road surface is smooth and is without potholes or ruts that may induce excessive vibration of the bridge. Although B-WIM systems are used for permanent installations, their main benefits are associated with their portability, i.e. when:

- WIM data from several different road sections are required,
- only a few days or weeks of data are needed from each site,
- locations for pre-selection of potentially overloaded vehicles are varied on a regular basis or
- bridge assessment requires realistic information about traffic loads and the true bridge behaviour of the structure under the traffic loading.

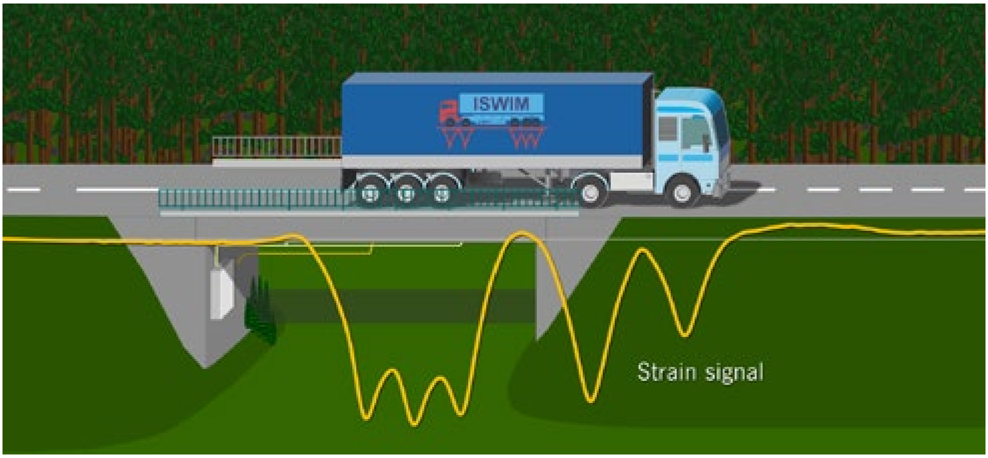

Figure 3.7: Working principle of a Bridge WIM system. *Source: CESTEL*

More information on Bridge WIM can be found for example in (O'Brien et al., 2008), (Richardson et al., 2014), (Kalin et al., 2015) and (Žnidarič et al., 2017).

3.6.4 On-board weighing

On-Board-Weighing (OBW) systems have been used in the trucking industry for many years. They weigh the vehicle when it is stationary, e.g. at parking lots, rest areas or red traffic lights. Their main application is to optimise truck fleet management and routing with respect to their capacity and load limits. OBW is currently the most reliable system, data readings provided by OBW systems are required to provide an accuracy of 2% within 95% of readings, or an error of ±500 kg. To ensure accuracy of these readings, OBW systems are periodically (at least twice a year) calibrated at weigh stations, where a calibration certificate is completed (Koniditsiotis et al., 2012).

Figure 3.8: Display of On-Board Weighing measurements *Source: AXTEC*

The technology has improved and currently dynamic OBW systems, that weigh the vehicle when it is in motion, are available on the market. In a dynamic OBW system, the weight values are monitored continuously with a certain sampling frequency. As with In-Road WIM, the “real” static weight values are estimated using complex algorithms. In principle, a dynamic system could be built out of any sensor type such as load cells, strain gauges, and air or hydraulic pressure transducers, but also other sensors, such as accelerometers and displacement sensors may be used.

The typical measurement inaccuracy is between ±1-3 %, depending on the sensing technology. A successful example of the use of OBW systems to manage heavy vehicle access and compliance to the road network, is the implementation into Australia’s Intelligent Access Program (IAP) that has resulted in improved productivity, efficiency and safety outcomes. More information on On-Board weighing and IAP can be found at (Koniditsiotis et al., 2012).

3.6.5 Stress-In-Motion

Systems capable of measuring the individual multi-dimensional (3D) tyre-road contact stresses (the tyre profile) under moving tyres are generally called Stress-In-Motion (SIM) systems. Stress in motion measurement is a relatively new development that offers applications in advanced pavement design, detailed vehicle classification, tyre management and road safety (de Beer, 2008).

The first SIM sensors were developed in South Africa (de Beer et al., 2004) and were mainly used in research projects to study the multi-dimensional tyre-road contact stresses and their effect on pavements. The system consists of a matrix of sensors, each sensor measuring the vertical forces from the tyre when the wheel passes slowly over the system. This type of SIM technology provides a detailed insight into the multi-dimensional contact stresses between tyres and the road surface. This may be used in the protection of road infrastructure through the advanced mechanistic design of road pavements.

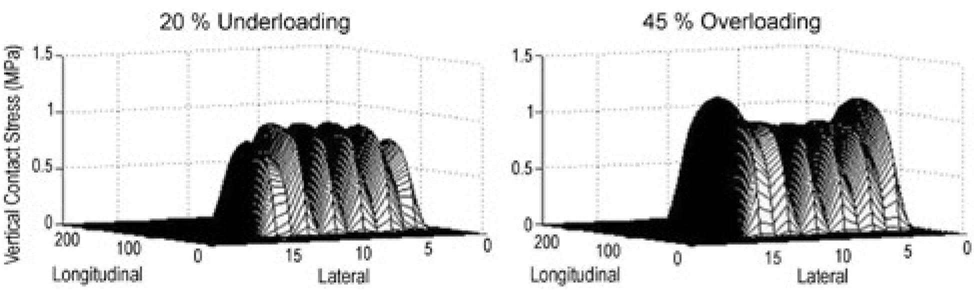

Figure 3.9: Example of Stress-in-Motion measurements *Source: DE BEER*

Recently other SIM-systems have become commercially available, using fibre optic or piezo electric strip sensors. These new SIM systems provide tyre footprint data that is less detailed than the previous research systems. However, they are more robust and suited for day to day operation under normal traffic conditions.

Besides the pavement design applications, these systems are also used for tyre management, commercial vehicle safety and toll road applications. Here the systems will detect abnormalities in the tyre thread, the tyre pressure (under or over inflated tyres) of all tyres on a vehicle and the load distribution over the different wheels on one axle. More information on Stress-In-Motion sensors can be found on (de Beer et al., 2004) and the websites of some of the ISWIM vendors listed in paragraph 7.2.

3.6.6 Rail WIM

In general, a Rail WIM system will measure the deflection of the rail – or a part of the rail bridge - during the passage of a train. From the sensor signals the dynamic and static axle loads, bogie load (axle group) and GVW of each of the cars of the train are determined. Different sensing techniques are being used, like strain gauges, piezo-quartz or fibre optic devices. In most cases the sensors are attached directly to the rail, except for Bridge WIM, where they are attached to the structure itself (Žnidarič et al., 2016).

Compared to the road WIM systems, the rail variations generate results with higher accuracy and reliability, with typical inaccuracies of ±2 % for GVW and ±5 % for axle load measurements (de Graaf & van de Hoek, 2005; Wood et al., 2016). This is caused by two things:

- As the wheels of the train strictly follow the rails there is no variation in the lateral position of the train when it passes over the sensors. This reduces the disturbances caused by lateral movements (by steering) and makes the measurements more repeatable.
- Locomotives, especially the electric ones, have a fixed and known weight. This can be used for automatic calibration, monitoring and improvement of the measurement accuracy. The locomotives can be detected based on the combination of axle configuration and weights or through electronic or optical identification of individual locomotives.

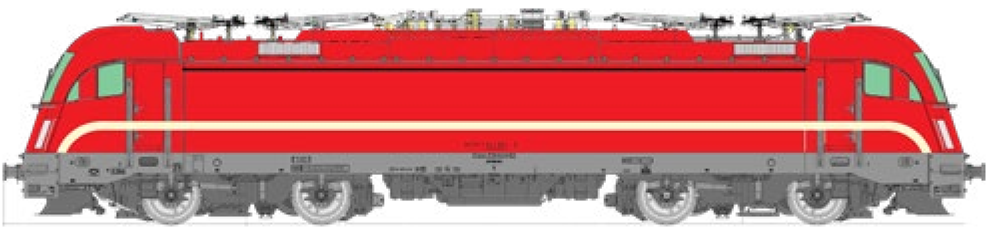

Figure 3.10: Example of locomotive with fixed weight and dimensions *Source: ZAG*

4 Use of Weigh-In-Motion data

This chapter provides a short description of the possible applications for WIM systems and their data.

4.1 Statistics on traffic loading

Real time monitoring of the actual traffic flow on a road network helps to optimise traffic movement. WIM systems are able to deliver detailed real time traffic information without disrupting the traffic flow. Depending on the technology, they can be installed in one location permanently, to monitor the development of the traffic flow over time at that specific site, or in the case of B-WIM, they can be moved over different locations to capture shorter, yet still significant traffic samples over a complete road network.

> **2st Law of WIM:**
>
> Only a WIM system will provide a complete picture of the actual traffic loading at a particular location.

Detailed information on the traffic flow also provides an important input for transportation studies that help to optimise the planning and design of the future road network. Organisations responsible for the construction and maintenance of roads and bridges need realistic information on the actual traffic loading on their net. This loading information is an important input, both for the design codes of the road infrastructure (new roads and bridges) and for the planning of the maintenance of the existing infrastructure (La Torre, 2008; Moffatt, 2017).

Additionally, the information from WIM systems can be used for detailed analysis of transport flows over the road network and over time. The WIM systems will deliver detailed and reliable data on traffic volume, speed, classification, and loading (axle loads and gross vehicle weight) for all vehicles passing the WIM site. Using the trends from years of historic WIM data, forecasts can be made for the future development of road traffic and transport (Morrison et al., 2013) and also assist as evidence in formulating government policy.

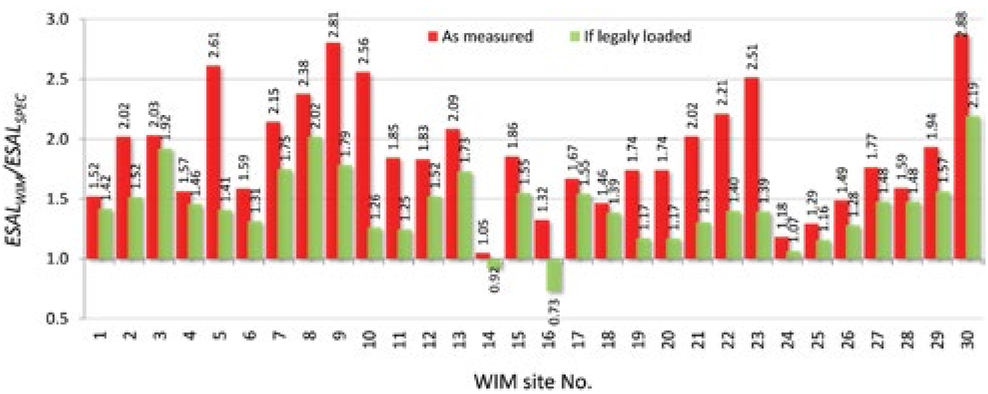

Figure 4.1: Difference between calculated pavement loading if based on traffic counting and on WIM data *Source: CESTEL*

Basic traffic counters will provide information on the number, speed and length of the passing vehicles. Count data is often used to estimate the vehicle weights axle loads and vehicle classification, however this may result in significant errors in the estimated values and consequently in the results of the studies. An example is given in Figure 4.1, which compares results of ESAL calculations (see the following section) for 30 different locations.

Results based on WIM data ($ESAL_{WIM}$) are compared to those calculated from the results of counting and the vehicle factors specified in the Slovene specifications for determining load effects on pavements ($ESAL_{SPEC}$). Value 1.0 means that the specifications would correctly account for traffic loading. In reality, the true load effects on pavements are up to 2.88 times higher (the darker red bars). Even if all trucks were legally loaded, i.e. the measured axle loads would be reduced to their legal limits, the results based on traffic counting would be vastly underestimated (the lighter green bars).

4.1.1 Pavement design and management

Heavy trucks increase pavement wear, contribute to premature pavement failure and increased maintenance costs. The moving traffic loading induces tensile stresses in the bound asphalt or concrete layer which, over time, causes irreversible deformations in the underlying layers. The repeated loading causes fatigue damage in the bound layers which eventually deform and crack, leading to permanent deformation of the road surface. The pavement reaches the end of its life when the severity of cracking and/or permanent surface deformation exceeds acceptance levels for safety, comfort and transport economics.

In general pavements are built for specific numbers (a few 100-thousands to a few million) of passing standard axles. With the exception of under-designed structures, these should not fail under heavier axles, passage but will deteriorate faster.

The pavement wear due to traffic is related to the axle loads and configurations and the tyre pressure. Although other approaches exist (Rys et al., 2015), most countries use the Equivalent Standard Axle Loads or ESALs. This concept, developed by the American Association of State Highway Officials (AASHO, 1961) in the 1960s, transforms all axle loads into their equivalent values, to represent the effect that they have on the pavement. The empirical formula for to calculate ESAL for an axle was derived from curve fitting to experimental data:

$$ESAL = \sum_i f_A \left(\frac{P_i}{P_{ref}}\right)^n$$

where P_i is the load of the axle of a vehicle P_{ref}, is the reference axle load, taken as 18 kips or 80 kN in North America and Australasia, 130 kN in France and 10 tons or 100 kN in most other countries, f_A are the adjustment factors explained below, and n depends on the pavement structure. A number of researchers have investigated this power law model and have found exponent values ranging from less than 2 to more than 12 (DIVINE, 1998; Cebon, 1999). In practice, four has remained the most commonly used value for n.

The pavement wear associated with different tyre or axle group configurations varies. This is considered either by the adjustment factors in the above formula or by specifying different reference weights for various axle configurations. In Europe, ESAL is sometimes called Load Equivalency Factor (LEF). In COST 334 study (Hjort et al., 2008), LEF is multiplied by the *Tyre Configuration Factor* (TCF)

to obtain the *Axle Wear Factor* (AWF). TCF depends on size and configuration of the axle, tyre type, road type and wear mode. For the main roads, the primary pavement wear mechanism considered is rutting, with the second power relationship to calculate the LEF.

The pavement wear contribution also varies substantially for different axles of a vehicle. For a typical loaded 5-axle semi-trailer:

- the steer axle has high contribution as it is fitted with single tyres and carries relatively little payload;
- the drive axle, fitted with dual tyres, generates far smaller pavement wear per unit payload, even though it is 65 % heavier than the steer axle;
- the trailer axle group can generate even less pavement wear per unit payload, but the effect strongly depends on the type of tyre that the trailer is equipped with.

The fourth or even higher power means that the wear increases exponentially with overloading and is consequently often greatly underestimated. For example, 5 % overloading adds 21 %, 10 % overloading 46 % and 20 % overloading over 107 % to the pavement wear. Therefore, realistic estimate of influence of traffic loading on pavement cannot be calculated without measurement of the axle loads, either with weigh-in-motion or on-board-weighing systems.

Figure 4.2 gives an example of ESAL wear calculation caused by three different vehicles: a 1.3 tonne car, a 5-axle semi-trailer and an extreme 108 tonne road crane. In this example, the wear due to a 5-axle vehicle is 50.000 times higher and that of the extreme road crane is 370.000 times higher than that of a car.

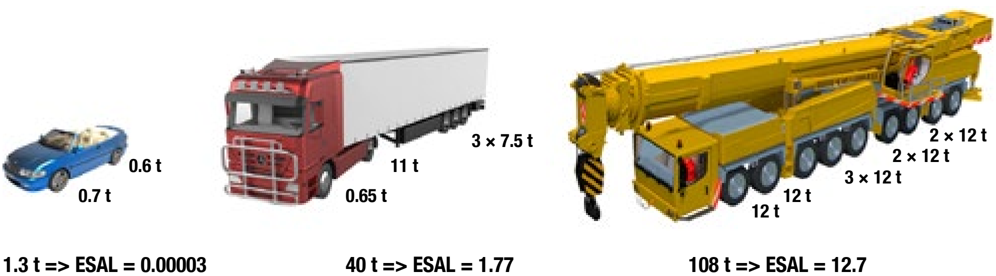

Figure 4.2: Examples of ESAL calculations for different vehicles *Source: ZAG*

4.1.2 Bridge design and management

Bridges are critical components of any road transportation network. It is, therefore, of the utmost importance that they are kept in operation without major disturbance, such as closures due to repairs. During their lifetime, bridges deteriorate while the loading increases. Both factors affect their safety. Unlike pavement failure, which primarily reduces driving comfort, bridge failures are not acceptable as they can cost lives and, consequently, undermine confidence in the entire transportation infrastructure.

Historically, the design loads in the bridge design codes were governed by their self-weight (dead loads), with lower influence of traffic loads. Since the mid-20th century lighter bridge structures are

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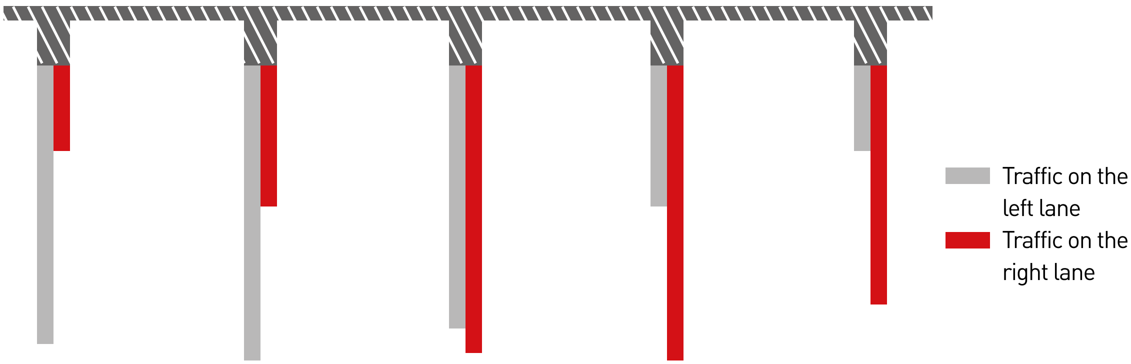
WIM and much more

SiWIM® collects real traffic data and identifies the true behaviour of a bridge through its actual influence line and load distributions, which are crucial for properly converting traffic loads into load effects (axle loads into moments and shear forces).

What is the real **traffic loading**?
What is **loading distribution** of the bridge?
What is **dynamic behaviour** of the bridge under traffic loading?

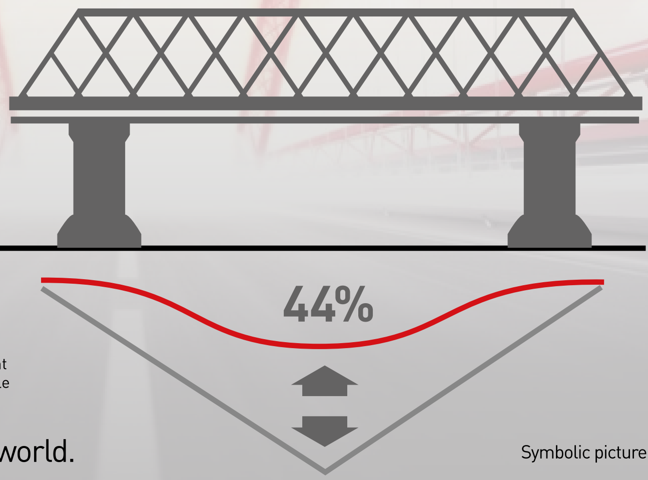
SiWIM®

Load distribution



Influence line*

M THEORETICAL > M MEASURED



measured influence line
theoretical influence line

* Influence line is defined as the bending moment at the point of measurement (strain transducer location) due to a unit axle load moving along the bridge.

Measured by the best WIM in the world.

designed, lately using advanced computer programs, and the truck weights increased. Therefore, accurate traffic loading information started to gain importance. The modern bridge loading codes, using load and resistance factors or safety factors, are designed and calibrated using measured gross weights and axle load distributions.

Typical applications of WIM data for bridges are:

- Calibration of bridge design codes. All modern codes, such as Eurocode 1 (EN 1991 - Eurocode 1, 2009), were calibrated using large sets of WIM data collected on the most trafficked roads.
- Long span bridges: Bridges with spans longer than 200 metres, or other exceptional structures, require more accurate and detailed design, for both economical and safety reasons. Using WIM data collected on different routes, and during long time periods, allows the derivation of reliable probabilistic distributions, which provides for making an optimal design or in-service verification of these structures (Figure 4.3).
- Assessment of existing bridges: Over time bridges deteriorate, which reduces their capacity. At the same time the traffic loading increases. Consequently, their level of safety decreases, which is acceptable only to a certain degree. Assessing realistic safety of a bridge requires the true traffic load effects which can only be obtained by WIM systems (Žnidarič et al., 2012).
- Fatigue of steel bridges: Details of steel bridges are prone to fatigue. To assess the remaining lifetime of these structures it is essential to know the true traffic loading and what levels and frequencies of stress the traffic induces.

Figure 4.3: Example of a WIM system installed on a bridge in China *Source: IRD*

WIM data collected on different routes and during long time periods allows reliable probabilistic distributions to be calculated, which also makes it possible to make an optimal design or in-service verification (OBrien et al., 2015).

4.1.3 Bridge protection

Historic bridges are generally designed and built in a time where heavy good vehicles were much lighter or did not exist at all. These bridges often still serve as part of the modern road transport network, at the same time they may have an important historic and cultural value to society. A WIM system can detect an overloaded vehicle before it crosses such bridges or enters the historic centre of a city. This avoids unnecessary damage, reduces maintenance cost and helps to protect cultural heritage sites.

4.1.4 Tyre management

Underinflated or overinflated tyres have an increased risk of a blowout and potential accidents, have a negative effect on fuel consumption and will increase tyre wear. Incorrectly inflated tyres are not easy to detect by visual inspection particularly as inner tyres aren't easily visible. Low speed WIM or SIM measurements can be used to check the tyre pressure, wheel loads, axle loads and vehicle weight. In case a potential problem is detected, the driver or fleet manager of the truck can be notified. This results in lower running costs, increased traffic safety and an extended tyre life.

Figure 4.4: WIM system used for tyre management *Source: WHEELRIGHT*

4.1.5 Special transports

Certain truck combinations are, through the addition of extra axles, specially adapted to carry excessively heavy and/or long and wide loads. Under the conditions stated in their permit, these special transports are allowed to carry excessive loads on specific routes.

Figure 4.5: Special transport crossing a bridge *Source: ZAG*

Data from WIM systems can be used to determine and plan possible routes for special transports and to verify compliance with their permits. This will avoid unnecessary damage to bridges and pavements, reduce maintenance costs, increase road safety and at the same time maximise use of the road network and increase transport efficiency.

4.1.6 Traffic Safety

Tyre anomalies, such as flat, underinflated, missing or mismatched diameter tyres result in vehicle imbalance, improper load distribution and potential safety issues. Overloaded or overinflated tyres not only experience increased wear and tear, they also have an increased risk of a blowout. These tyre anomalies are a major factor in traffic accidents and are a safety concern for inspection agencies and road tunnel operators.

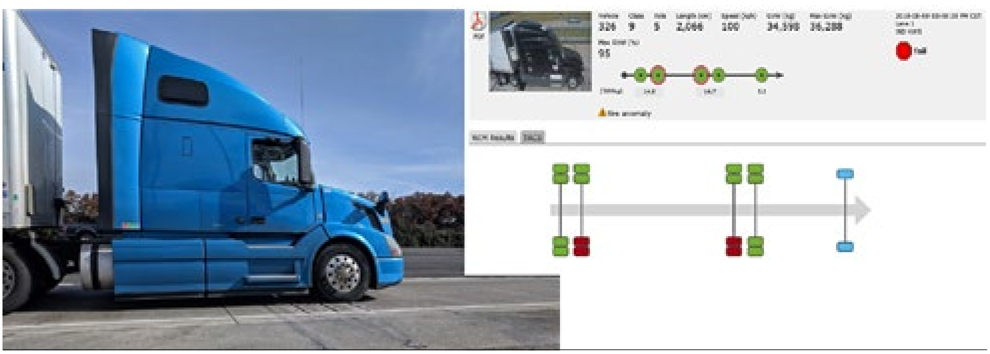


Figure 4.6: Array of tyre sensors producing WIM and tyre information *Source: IRD*

Tyre anomaly detection systems are special WIM systems using either SIM-sensors or an array of in-road WIM sensors capable of measuring the tyre-to-road contact area for every tyre that comes in contact with the sensors. The sensors produce a stream of data containing time, distance and pressure information from numerous points along the length of the sensors installed in the surface of the road. The measurement data from the tyres is processed by roadside electronics, and system software evaluates whether a tyre should be flagged. These 'flagged' vehicles may be selected for inspection by vehicle or transport inspectors or be refused access to a certain road section, e.g. a tunnel. Such tyre anomaly detection systems are independent of the speed of the vehicle and provide measurement data at low speeds as well as highway speeds.

4.1.7 Traffic and transportation management

Real time monitoring of the actual traffic flow on a road network helps to optimise traffic management. WIM systems are able to deliver automatic and detailed real time traffic management information 24/7 without disrupting the traffic flow.

Detailed information on the traffic flow road also provides an important input for transportation studies that help transport authorities to optimise the planning and design of the future road network.

WIM systems will also detect not only overloading but also under loading, hence vehicles driving unloaded or partially loaded. Data from WIM systems may help governments to develop policies that improve the efficiency of the freight transport as a whole. On-board WIM systems may be used by transportation companies to maximise the loading of each individual vehicle and the efficiency of their logistic process as a whole.

4.1.8 Freight studies

Reliable data from WIM systems is an important input for detailed studies of freight transportation, both road and rail. WIM data provides detailed information of the distribution of loading over different types of vehicles, over the road network and over time (hour of the day, day of the week, etc.).

The studies of transportation trends are often the basis for long term decisions for freight policy, regulations for weight and dimension for commercial vehicles, and necessary investments required for road and rail infrastructure.

For example, longer and heavier vehicles, particularly on long distance corridors, could possibly contribute to the reliable and efficient movement of freight. By carrying greater payloads with fewer vehicles, they would be more competitive and fuel efficient. They would reduce congestion, which is a factor in fuel consumption, and would consume considerably less energy per unit of freight compared to the present fleet of vehicles (Morrison et al., 2013). On the other hand, depending on the increase of weight and dimensions, there would be some negative effects on the infrastructure, particularly bridges, which may have to be upgraded. WIM data is an important input for the monitoring and assessment of the effects of these larger vehicles.

Figure 4.7: Use of WIM measurements for transport studies in South Africa *Source: MIKROS*

4.1.9 In-road and on-board WIM

In-road (pavement and bridge) and on-board WIM systems monitor vehicle mass information for different purposes and policy uses. Both need to be operated, maintained and calibrated to ensure the quality of data they generate. This makes them operationally compatible and even co-dependant. Both in-road and on-board WIM systems require calibration, to ensure that each system is weighing properly. The traditional practice is to calibrate every three months, every six months or annually. However, in practice, some WIM systems tend to be better than others and some operating environments and their weighing systems tend to last longer than others. The co-dependency and the combination of the specific characteristics of these two technologies offer possibilities to improve the calibration process and, consequently, the quality of data generated by both types of WIM systems.

4.1.10 Railway WIM

A railway WIM system will record wheel, axle, and bogey loads, the gross weight of each rail car and the total train weight. Furthermore, the load imbalance of each car (front/back and left/right) can be calculated and wheel damage (e.g. flat spots) can be detected. The system also counts the number of axles of each car, the total number of cars and axles of the train, and determines the total length, driving direction, and speed of the train. Rail-WIM systems may be used for one or a combination of applications (de Graaf & van de Hoek, 2005):

- Track maintenance; a design, by recording the total track loading more efficient planning can be made for the maintenance of the different parts of the railway track. The same data can be used as input for an optimised design of new railway tracks and bridges;
- Train maintenance; in combination with a train identification system the WIM can record the dynamic wheel loads of each train car. An early detection of high dynamics (e.g. because of flat spots) allows quick intervention for maintenance avoiding additional wear and tear of the train and track. At the same time, it allows the reduction in unnecessary maintenance of well performing wheels and train cars;

- Track access pricing; again, in combination with a train identification system the WIM can be used to monitor train access to a railway track. This information can also be used as a basis for track access pricing related to the number and weight of the trains, the distance travelled on the rail network and the calculated damage caused to the track.

4.2 Weight enforcement

In general, restrictions on vehicle weights are based on safety considerations and a desire to limit the wear that Heavy Goods Vehicles (HGVs) cause to the road infrastructure. Limits are set for the maximum permissible vehicle mass and maximum axle land axle group loads. The limits are often separately specified for single axles, tandem axle groups and tridem axle groups. This is dependent on the axle distances for the type of axle, e.g. driven or non-driven axles, and axles with single or double tyres. Loading limitations are often determined by a combination of international, national or regional regulations. The main reasons for overloading by road transport are economic pressure and incorrect loading:

1. Carrying 10 % more load is roughly the same as a 10 % saving which gives an overloading transport company a considerable unfair commercial advantage over a company transporting within legal limits.
2. A lot of axle overloading can be blamed on unstructured or incorrect vehicle loading, particularly in the case of multi-delivery transport. This can occur when a portion of a payload is unloaded from the vehicle causing redistribution of the load over the axles.

The objective of weight enforcement is a better compliance with loading regulations and, as a consequence, a reduction of overloading (REMOVE, 2006). The effectiveness of weight enforcement is determined by a balance between the height of the fine and the chance of being caught. For example, when the fine for overloading is relatively high, but the likelihood of being apprehended is low, the cost of the penalty for the operator may be spread over the additional overloaded runs that were not detected. WIM systems may be used in different ways to improve the efficiency and effectiveness of overloading enforcement (Jacob & van Loo, 2008).

4.2.1 Road side controls

In this application, the potentially overloaded vehicles are directed to a dedicated weighing area to be weighed using a weighing instrument that is legally approved for enforcement, a static weighing scale or low speed WIM. The weighing area is located right next to the main road or in close proximity to an exit from the main road. This area may be a permanent weigh station with fixed weighing scales or a temporary weighing area with portable scales.

The advantage of a permanent weigh station is that it is normally well equipped with all the facilities needed to measure and process large numbers of trucks. The advantage of using portable scales is the flexibility to move quickly from one location to the next. In this way, violators with overloaded vehicles are less likely to escape control.

Figure 4.8: Road side weight enforcement using static scales in Switzerland *Source: HEANNI*

4.2.2 Statistics and planning

In this application, the data measured by a high speed WIM system or a network of HS-WIM systems is used to generate statistical overviews on the loading situation on a specific road or road network. Enforcement agencies can use these overviews in the planning of enforcement activities, such as when and where their control units are deployed (van Saan & van Loo, 2002).

The statistics may also be used for the evaluation of the effects of enforcement activities. The main advantage of using WIM this way is that it allows enforcement agencies to focus their limited resources at the peaks in the overloading, both in time and place.

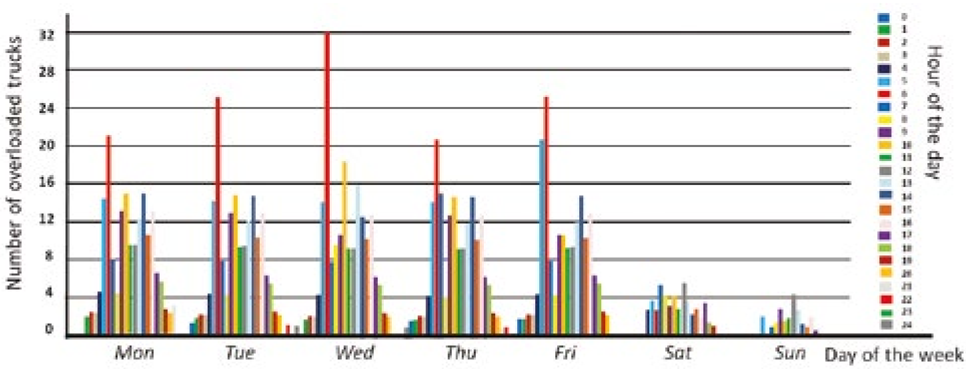


Figure 4.9: Using WIM data for planning of weight enforcement controls *Source: RIJKSWATERSTAAT*

4.2.3 Pre-selection

The high speed WIM system weighs all passing vehicles. When it detects an overloaded vehicle, an image of the vehicle is taken and the target vehicle is guided to the dedicated weighing area. There the selected trucks are weighed using a weighing instrument that is legally accepted for enforcement, generally a static weighing scale or low speed WIM (Jones, 2008). In the USA this application is referred to as a 'Virtual Weigh Station' or even 'Virtual WIM'.

Figure 4.10: Example of a 'Virtual' WIM system used for pre-selection in USA *Source: INTERCOMP*

The main advantage of this application is that the hit-rate (the percentage of controlled trucks that are actually overloaded) increases to more than 95 %. This result in more efficient controls because only overloaded trucks are checked and also gives an advantage to the 'good' transport companies by keeping their correctly loaded vehicles rolling. Finally, the information from the WIM can also be used for statistics and planning (Stanczyk et al., 2008; Bosso et al., 2016).

4.2.4 Company profiling

All data measured by a network of WIM systems, including the pictures of the suspiciously overloaded vehicles, are stored in a database. Based on this information, the offending transport companies are selected for further action by the enforcement agency. This action may vary from sending a warning letter, to a visit of the company for an inspection or further legal action.

The advantages of this way of enforcement are that the enforcement activities are directly aimed at compliance with loading regulations, i.e. preventive or incentive activities instead of writing the tickets. Since the focus is only on problematic transport companies, a relatively low number of enforcement personnel are required. Finally, the effect of the enforcement efforts is nationwide and not limited to the roads directly around the WIM systems (Jacob & van Loo, 2008).

Figure 4.11: Example of WIM system capable of company profiling in Europe *Source: STERELA*

4.2.5 Direct enforcement

In this application of WIM, the evidence for the prosecution of an overloaded vehicle is directly based on the measurement by the WIM system. The procedure from the WIM measurement to prosecution is completely automated and is similar to that of automatic speed enforcement. This type of enforcement system can be operational 24/7 without the need for any enforcement personnel and is specifically suitable for highways with a high volume of trucks. The advantage is that all passing vehicles are controlled and most overloaded trucks are detected. Experiences with the use of WIM for direct weight enforcement from the Czech Republic are described in papers of Doupal et al. (Doupal & Fucik, 2016) and Kriz et al. (2016).

The implementation of WIM systems for direct enforcement does require the most advanced of WIM systems and an organisational structure which will guarantee the minimum quality (accuracy and reliability) of each individual WIM measurement that is used for enforcement. This structure consists of three elements: legal acceptance, system certification and data quality control (Oosterman & van Loo, 2017).

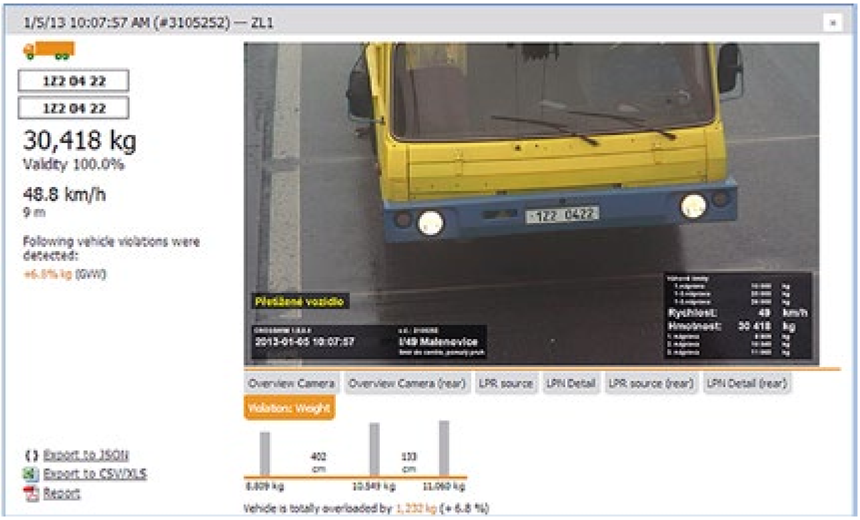


Figure 4.12: WIM registration used for direct weight enforcement in Czech Republic *Source: CROSS*

4.3 Tolling and payment by weight

The traditional approach to determine an access fee for a toll road is based on the type of vehicle, mainly based on the number of axles. In reality, the key damaging factors for the road infrastructure, particularly the pavements, are the vehicles gross weight and their individual axle loads. Thus, the traditional tolling only vaguely incorporates the true vehicle interactions on the infrastructure.

In line with the 'polluter pays' principle, the fee for using a toll road should be proportional to the wear caused by the vehicle. At weight-based toll roads, the users pay according to the actual weight of their vehicles. The WIM systems not only ensure fair toll prices but may also generate additional revenue to finance maintenance of the infrastructure.

A WIM system can be integrated into both types of existing toll collection systems: with manual toll collection at toll plazas and as a part of fully automatic electronic toll collection under free traffic flow. In both cases the toll fees can be collected with greater efficiency (Geroudet & Delmas, 2016).

In addition, the WIM system can be used to detect overloaded vehicles. Depending on the local conditions, these overloaded vehicles may be denied access to the toll road to protect the infrastructure or pay an extra fee to cover the costs for the additional damages.

4.3.1 Low speed tolling at toll plaza

At a toll plaza, the traffic is divided over, often, a large number of lanes separated by barriers that also include a booth for toll fee payment. As each of the lanes are constructed in this manner, the velocity and transverse movement of the passing vehicles is limited. Special care is taken to detect drivers that try to manipulate the WIM measurement by braking in front of the sensors or trying to 'jump' over the sensors.

Figure 4.13: Example of WIM system used for low speed tolling in Vietnam *Source: CROSS*

In order to further eliminate the dynamic effects of the vehicle when passing the weighing area, the WIM system should be installed in a flat and smooth platform (generally made of concrete), with a total length of more than 30 m. This way it can be assumed that the measured tyre forces are equal to the static wheel loads. In many countries, low speed tolling by weight is legally approved according to the international OIML R134 standard or a similar national standard.

Figure 4.14: Example of WIM for HGV tolling in Switzerland *Source: KISTLER*

4.3.2 High speed tolling, free flow

In this case, the HS-WIM systems are installed in the traffic lanes of a highway where there is no restriction on the speed and lateral movement of the vehicles. The weight measurement by the WIM is linked to the correct vehicle by means of an electronic tag or Automatic Number Plate Recognition (ANPR-cameras). The NMi (2016) or OIML R134 (2009) WIM standards may be used as a basis for the legal approval of high speed WIM systems for tolling by weight (Daxberger & Santillian, 2016).

4.4 Industrial applications

For these applications low speed WIM systems are generally used. They are more efficient than the static scales as they significantly reduce the measurement time and provide higher throughput of measured vehicles per hour.

4.4.1 At (sea) ports

At sea ports, LS-WIM systems are used in controlling the entries and exits of terminals. The WIM system can check the weight of all the cargo (containers) being loaded onto a ship to optimise the load distribution over the ship or controlling the loading of heavy vehicles on the ferries. At the same time, the correct loading of the trucks that transport cargo from the port can be checked.

4.4.2 At industrial or logistic plants

Likewise, the WIM systems can be used to check the weights and axle loads of trucks leaving the plant and prevent overloading before the trucks enter the road network.

If the WIM systems are certified for trade applications, they can also be used for the invoicing of industrial (bulk) goods by weight.

Figure 4.15: Example of WIM system for industrial weighing in Middle East region *Source: CAPTELS*

5 Select the right WIM

The selection of a WIM system is linked to the application needs, information requirements and specific location sought.

5.1 Overview of the 5-step selection process

This process describes five steps that need to be considered when buying a WIM system, to fit the specific purpose and conditions. These five steps are:

1. Determine the application, including a description of the purpose, the way the WIM data will be used and what the data requirements are.
2. Select the locations for the systems, based on the application, the traffic and pavement conditions, safety of the operation staff and the available facilities.
3. Define the performance requirements for the systems and describe the procedures for calibration and testing of the systems.
4. After selection of the best offer, monitor the installation. After installation aqnd calibration, execute the test procedure and, based on its results, decide to accept the systems or not.
5. Describe the use of the systems, including the collection, storage, quality monitoring and application of the WIM data.

3rd Law of WIM:

There is no such thing as the best WIM system. It all depends on how and where you want to use the system(s).

5.2 Determine the application

Prior to the selection of a suitable location is to determine the intended application of the system. This includes the requirements for the system, such as possible criteria for the surroundings of the site. For example, a pre-selection system needs to be up-stream and close to the control station for legal weighing.

5.2.1 Purpose of application

Why do you want/need a WIM system? Reflecting on section 4, what is its policy need and what problem is it dealing with? For example, more efficient weight enforcement will result in less overloading which will subsequently cause less damage to the road infrastructure and, lower maintenance costs, with fewer road works and traffic jams etc. At the same time, a reduction in overloading will increase road safety and improve fair competition between transport companies. A more accurate knowledge of the actual traffic loading distribution may allow an increase of the loading limits for bridges without additional maintenance or strengthening.

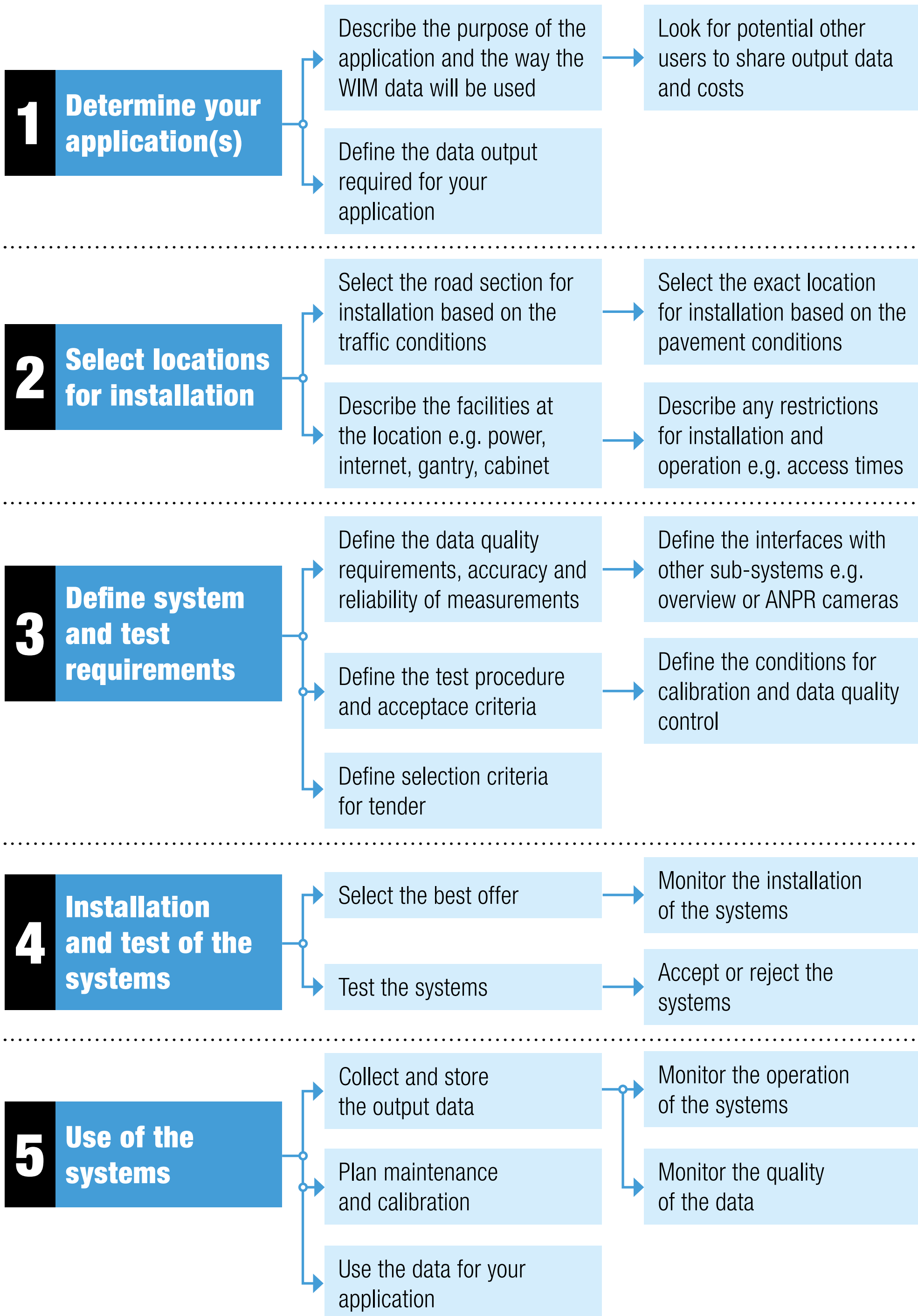


Figure 5.1: 5-step selection process of a WIM system

Source: ISWIM

At the same time, a similar calculation of the overall costs of using WIM needs to be made. This is more than just the price of the WIM sensors, it includes:

- preparation works that involve the business case, site selection, specifications, tender documents;
- system components like WIM and other sensors, cameras, poles or gantry, road side cabinet, data processing and storage, data communication, etc.;
- installation of the system including road closures, work permits and acceptance tests;
- operation of the systems including regular monitoring of the operation, data quality controls, periodical maintenance and calibration of the system and, finally, use of the data provided by the WIM system;
- the length of operational period of a WIM system (life time), especially in case of the sensors installed in the pavement.

Be aware that WIM systems can be used for more than one application at the same time. For example, a pre-selection site will also collect information on the traffic flow and pavement loading. Try to pool resources by finding potential other users of the data collected by the WIM, this way a part of the costs may be shared by different organisations.

5.2.2 Description of the application

Make a detailed description of the way the data from the WIM systems will be used by each of the intended users. The better this description, the easier it will be to determine the performance requirements for the system. This description will also help future providers of the system to better understand your requirements, resulting in more relevant offers and possibly cost reductions through innovative solutions. Next, prepare a detailed description of the exact data per vehicle the WIM system should provide. This includes all items in the vehicle record:

- Unique identification (registration) number,
- Date and time stamp (yy-mm-dd + hh:mn:ss:cc),
- Location: road, direction, traffic lane,
- Type of vehicle or class according to a given classification scheme,
- Speed of the vehicle when passing the system,
- Total vehicle length and/or wheel base,
- Number of axles,
- Gross vehicle weight and axle loads,
- Distances between axles.

And in some cases:

- Wheel loads,
- Imbalance (left /right),
- Weights per sensor (if more than one sensor per lane),
- Vehicle width or wheel spacing on an axle,
- Wheel lateral location,
- Wheel type (single / dual tyre),
- Calibration coefficient (of the WIM sensors),
- License plate number,
- Vehicle signature
- Error code (to validate or eliminate measurements).

Note, for example, many bridge applications require the time stamp to at least 1/100 of a second which many WIM systems do not provide by default.

5.3 Select the right location for a WIM site

In the case of high speed WIM, the WIM site location is defined as the point in a road – mostly a highway or national road – where the system is or will be installed. In the case of low speed WIM, the WIM location is often at the premises of the customer, in a dedicated weighing area or driveway close to the road network. The WIM site selection is the second step in the procedure to find the best WIM system. Some vendors actively support customers during selecting and qualifying the location of potential WIM sites. This allows their dedicated technology to avoid performance issues after installation. In the selection of the actual location for the installation of a HS-WIM system, the following steps should be taken:

I. **Choice of the road section** to be measured, this is a first rough selection of the location based on the purpose of the WIM system and the general traffic conditions (selection of sections of 10-30 km);

II. **For a pre-selection application**, the next step is to find of a suitable location for the static – or low speed – measurements needed for legal prosecution of overloaded vehicles, the static weighing area (reduction of section size to 1-3 km);

III. **Selection of the final location**, the detailed location for the WIM system is determined based on the characteristics of the road, the pavement and the direct surroundings (resolution of selected section 10 – 30m). This step consists of two parts:

a. Road/bridge and traffic conditions
b. Pavement conditions
c. Available facilities and operational safety

Often several different organisations are involved in the installation, maintenance and use of the WIM system. It is strongly advised to contact all organisations involved in the early stages of the selection procedure. A similar WIM site selection procedure is described in Part II of the Federal Highway Administration Weigh-In-Motion Pocket Guide (FHWA-2, 2018).

5.3.1 Selecting the road section

This concerns the first selection of approximately 10 to 30 km long section of the road network where the WIM system should be installed. The criteria for selection are:

- Determine if there are other users that may be interested in using WIM data, perhaps for a different application, and are willing to share the costs for the installation and operation of the WIM systems. Different applications may result in different criteria and thus could affect the choice of the WIM location. At this early stage it is still easy to change the location of a WIM system to facilitate an additional user. When the system is already installed, it is a different story.
- When the WIM system should be a part of a regional or national network then the locations of the systems should be distributed over the whole road network. The number of WIM systems should be optimised in relation to the purpose of the network. At all times, WIM locations on the same transport route or too close together should be avoided.
- What is the scope of the (network of) WIM systems, e.g., is it only for measurement on the main (inter-) national transport routes? These are normally routes with a high density of heavy goods vehicles. This way the network of WIM systems does not have to be particularly dense but is still measuring a major part of the truck traffic. To be able to measure the local and short distance transport, the network must be denser, hence it will require (many) more WIM systems.
- Within the road network, select a road section with a high number of passing trucks and/or with a (suspected) high number of overloaded trucks. If no information on overloading is available, either the overloading may be assumed constant over the whole road network or it may be differentiated based on geographical characteristics, major ports or industrial centres. These assumptions may be verified through short term measurements (1-2 weeks) prior to the installation of a permanent WIM system;
- What are the predictions for possible developments in the future in relation to the road network and transport flows? E.g., is there a future construction of a new highway section planned or the development of a new transport terminal (harbour)? These should be accounted for.
- Particularly when used for enforcement (pre-selection), the section should be checked for possible evasion routes. These are easy and/or economically feasible ways for trucks to evade the section, typically by using the secondary roads. Generally, the overloaded trucks will tend to try to avoid being recorded by a WIM system, making the controls less effective. Also, these evading overloaded trucks will cause a bias in the overall measurement data. Finally, the secondary road network is less suited for large numbers of (overloaded) heavy trucks, for reasons of road and design capacity and traffic safety.

5.3.2 Road and traffic condition

Use the 1st Law of WIM as the general rule for the selection of WIM sites. This paragraph describes the steps needed in the procedure of a proper selection, the criteria for the road and traffic conditions described below by values may be replaced by criteria specified in various international specifications (ASTM-E1318-09, 2009; COST 323, 2002; NMi, 2016).

> **1st Law of WIM:**
>
> A WIM system installed on a good road may give good results; a WIM installed on a poor road will always give poor results.

The WIM system should be installed away from any area with frequent lane changes, acceleration or deceleration, (e.g., close to traffic lights, toll station, slip roads, railway crossings), in order to weigh vehicles travelling at a uniform speed. More specifically:

- Within 500 m prior to the WIM site there should not be any entrance ramps to the main road. An entrance may result in disturbance of the traffic flow, accelerating and/or manoeuvring trucks, again resulting in less accurate measurement.
- Within 200 m after the WIM there should not be any exit ramps from the main road. An exit may also result in disturbance to the traffic flow, from braking and/or manoeuvring trucks, this will again result in less accurate measurements.
- Within 200 m prior to the WIM array there should not be a bridge or viaduct in the road with a bump at the joint between a bridge and the (fixed) pavement. This can result in extra vehicle dynamics and less accurate WIM-measurements. These bumps tend to enlarge over the years that the WIM system is intended to be operational for reducing the measurement accuracy over time.
- In the case of no bump and/or short term measurements, bridges do not pose any limitation to the site selection. In these cases, the WIM system can be located close to the bridge or even on/ under the bridge (B-WIM systems).
- Within 200 m before or after the WIM there should not be a change in the number of lanes, junction or intersection.
- The radius of the curvature at the WIM should be larger than 2000 m. Trucks tend to ‘cut the corners’ in curves, causing some of the wheels to (partially) miss the WIM sensors. This will result in less reliable WIM measurements.
- There are no plans for resurfacing the pavement in this section within the next 5 years. With pavement resurfacing, the WIM sensors will either be destroyed or have to be de-installed and re-installed after resurfacing.
- In the case of pre-selection for overload enforcement, the section will require one or more gantries for installation of cameras for vehicle identifications.
- At the WIM site there should be access to a fixed or mobile data network for the transportation of the measurements to a central processing and/or data base.

5.3.3 Road pavement conditions

The performance of any WIM system is dependent on the site characteristics: road geometry and road evenness. The road section between 200 m upstream and 50 m downstream of the system should meet the recommended minimum criteria for the geometrical characteristics given in the Table 5 .1.

Pavement			Criteria
Rutting (3 m – beam)		Rut depth max. (mm)	≤ 4
Deflection	Semi-rigid	Deflection (10^{-2}mm)	≤ 15
(quasi-static)	All bitumen	Deflection (10^{-2}mm)	≤ 20
(13t – axle)	Flexible	Deflection (10^{-2}mm)	≤ 30
Deflection	Semi-rigid	Deflection (10^{-2}mm)	≤ 10
(dynamic)	All bitumen	Deflection (10^{-2}mm)	≤ 15
(5t – load)	Flexible	Deflection (10^{-2}mm)	≤ 20
Evenness	IRI index	Index (m/km)	< 1.3
	APL	Rating (SW, MW, LW)	9 – 10
Longitudinal slope		(average)	< 1 %
Transversal slope		(average)	< 3 %

Table 5.1: Minimum criteria for road conditions

In general, the location should have a continuous pavement without any visible cracks, bumps or holes or other types of sudden local change in slope. The longitudinal slope should always be less than 2%. In addition, the characteristics of the pavement should be consistent with the WIM technology deployed and recommended by the vendor of the WIM sensors. To avoid performance issues after installation, it is recommended to consult with the vendor in the evaluation phase to assess road conditions. More information on requirements for site selection can be found in (COST 323, 2002; ASTM-E1318-09, 2009; FHWA-2, 2018).

5.3.4 Location for LS-WIM systems

Many LS-WIM systems are installed:

I. In customers' premises, to detect overload issues prior to the vehicle going on the road, or for commercial (trade) applications. The exact position of the WIM system is generally determined by the application and local constraints. What is important for the installation are the dimensions, level and flatness of the aprons before and after the WIM system.

II. In dedicated weighing areas close to the traffic network, for weight enforcement purposes. To maximise performance for weight enforcement, a good LS-WIM site should:

- be in the proximity of the high speed pre-selection system with easy access to the road network;
- have the ability to control the speed and limit the lateral movement of vehicles during measurement;
- have the ability to park the overloaded vehicles, so that they can have their loads re-distributed or re-allocated to another vehicle, before they resume their journey;

– have aprons with sufficient level, flatness and dimensions. Typically, a length of at least 1 vehicle length in both directions, or a total length of 30 to 40 m;
– often LS-WIM systems are located alongside other inspection facilities that check roadworthiness, permits, drivers hours etc. Thus, consideration needs to be given to the demands of other agencies / authorities.

5.4 System requirements

Knowing what the WIM system should do, what data it should provide and where it should operate prescribes which (measurement) performance is required and knowing how the performance of these systems will be tested after they are installed.

5.4.1 Performance requirements

The first issue with the performance requirements is to define the output format for the WIM system, in other words what data items should be included in the vehicle record generated by the system. Second, how many days of data should the system be able to store in between downloads, or is data being continuously being disseminated? Then, what are the minimum accuracy - and reliability – specifications for each of these items required for your application? Here it is important to understand the relationship between the intended application, performance specifications, operational conditions and ultimately price.

A common mistake is to go for the highest possible specification just to be on the 'safe side'. This can result in a position where you will not receive any offers, or only offers that are far more expensive than the available budget or, offers that simply cannot deliver. Try to find a balance between what is really needed for your application and what is realistic to expect under the operational conditions at the site. One of the important requirements – but definitely not the only one – is the specified weighing accuracy of the system. Typical and realistic accuracy requirements for high-speed WIM systems are:

1. For statistics: gross vehicle weight: ±15 % and axle loads: ±20 % (for 95 % of all measurements);
2. For pre-selection: gross vehicle weight: ±10 % and axle loads: ±15 % (for 95 % of all measurements);
3. For direct enforcement and tolling by weight: gross vehicle weight: ±5 % and axle loads: ±10 % (for 100 % of all measurements).

For low-speed WIM systems the typical measurement inaccuracy is roughly less than half of the values for high-speed systems. Other performance requirements are the accuracy for the measurement of the axle distances and/or vehicle length, the number of axles, vehicle classification, the time and the speed of the vehicle.

5.4.2 Operational requirements

The rated operating conditions are the ranges of influence quantities for which the performance of the system lies within the specifications. The operating ranges should describe the traffic and environmental conditions that the WIM system is likely to encounter during operation. The

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specifications should contain a description of the operating conditions for the WIM system consisting of at least ranges for:

- traffic, including: weighing, traffic intensity and vehicle speeds;
- environment, including: temperature and humidity, dust and water resistance, electromagnetic conditions, mechanical conditions and electrical power.

Here, only the operating conditions are mentioned that may have an influence on the accuracy and reliability of the measurements. You can also specify additional operating ranges for quantities that may influence the durability of the system. In case a condition during measurement is beyond its operating range, the system must:

- automatically invalidate (block) measurement results from being issued, or;
- automatically delete the measurement results, or;
- indicate or print out the value of the measured value, and at the same time indicate or print out a clear warning that the measurement is outside the system's operating range.

5.4.3 International standards

More information can be found on international standards and specifications for WIM systems (COST 323, 2002; ASTM-E1318-09, 2009; OIML R134, 2009; NMi, 2016). The first two, among others, specify requirements for the road condition at the location of the WIM system, which may be used instead of the values recommended in this document.

5.5 Test procedure and criteria

After a WIM system has been installed, calibrated and pronounced operational by the manufacturer, it is ready to be tested. During the test, a sample of measurements will be compared with pre-set criteria to determine if the system will pass or fail.

5.5.1 Reference vehicles

The first step is to define the reference vehicles that should be used for the acceptance test. This includes:

- The number and types of vehicles that should be used. The greater the variety of vehicles used in the test, the more confident you will be that the WIM system will work correctly for all vehicles. At the same time, the greater the number of vehicles, the more expensive the test. It is recommended to use, primarily, the most common types of vehicles that give the best representation of the traffic flow at the location of the WIM system. If more than one vehicle is used, choose vehicles with different dynamic characteristics, e.g. a 3-axle rigid truck with spring leaf suspension and a 5-axle tractor + semi-trailer combination with air suspension;

- The number of runs that each vehicle should make over the system in combination, including variation of the speed and lateral position; typical options are twice on the left side, 6 times in the middle and twice on the right side of the instrumented lane and twice near the maximum, twice near the minimum and 6 times near the average operating speed range. Again, the higher the number of runs, the higher the confidence in the test results, but also the subsequent costs of the test. In practice, the reference vehicle should make at least 10 runs over each instrumented lane. The exact number of runs also depends on the local road conditions and on how long it takes to make an individual test run;

- The loading of the vehicles, e.g. empty, half loaded or fully loaded to their legal limit. Generally, this is determined by the application in combination with, again, the available test-budget. E.g., in case of weight enforcement applications focussing on overloaded vehicles, often only fully loaded vehicles are used for the test. Furthermore, for testing of the measurement accuracy, only the reference vehicles with a stable centre of gravity when in motion should be used, this excludes carriers of liquids and other moving loads.

5.5.2 Reference scales

The gross vehicle weight and the axle group loads of the reference vehicles should be determined using a static (or low speed) weigh bridge or scales capable of weighing the whole vehicle at once. The load on each individual axle of the reference vehicle is determined subsequently using static (or low speed), fixed or portable axle scales or plates. The error of the reference scales/plates should be less than or equal to one third of the error specified for the WIM system under test.

It is recommended to repeat the static reference measurements at least 3 times and use the mean values as the reference for the test. In case of significant difference in the static measurements, these should be repeated and the outlying measurement(s) should be removed. The mean GVW, axle group loads and axle loads are calculated as the arithmetic average of recorded values.

To eliminate the possible shift in loads between axles when measuring axle per axle, it is recommended to use the corrected mean reference load value per axle $AL_{i,c}$. This is calculated as:

$$AL_{i,C} = \frac{AL_i \cdot VM_{ref}}{VM}$$

where:

AL_i is the mean value of the i^{th} axle load of the vehicle
VM_{ref} is the value of the reference gross vehicle mass determined by full-draught weighing;
WM is the sum of mean axle loads of the individual axles of the vehicle.

5.5.3 Evaluation of weighing results

During the test, the values of all gross vehicle mass measurements and all axle load measurements should be recorded. For each recorded value (total vehicle mass, axle or axle group load), the relative error is calculated in percent:

$$E = \frac{C - R}{R} \cdot 100$$

where:

C is the value measured by the WIM system,
R is the corresponding reference value measured by the reference scales.

The relative number of cases, when the relative error exceeds the relative measurement error, as specified for the WIM for each quantity, is determined. This number is expressed for each quantity as follows:

$$P = \frac{n}{N} \cdot 100$$

where:

n is the number of cases with calculated differences exceeding the specified maximum error;
N is the total number of recorded values for the given quantity.

In order to be accepted, the percentage of relative errors exceeding the specified maximum error shall not be greater than x %. The value for x should be specified by the user and agreed with by the vendor prior to the acceptance test. It should be noted that the outcome of such an acceptance test gives the answer to the question, should the system be accepted or not.

5.5.4 Accuracy assessment

An alternative way is to simulate/calculate an estimation of the actual accuracy performance of the WIM system under test. This includes a statistical assessment of the measurement accuracy based on the following characteristics of the test sample:

- evaluation of GVW or axle load measurements,
- number of samples, average value and standard deviation of the samples;
- required reliability of the measurements, generally the 95th percentile or 2 standard deviations interval of a normal distribution is used;
- minimum confidence level for the outcome of the calculation.

Using these inputs, a statistical simulation will calculate the highest accuracy level that the system can be accepted for the specified confidence level. Such simulations provide more insight in the actual measurement performance of the system under test and the impact the – size of the – test procedure has. At the same time these methods require a more in depth knowledge of the statistics of testing. More information on accuracy assessment of WIM systems based on test results can be found in (COST 323, 2002) and (Slavik, 2008).

5.5.5 Other performance tests

Other non-weighing related performance tests for a WIM system are, for example:

- Completion rate test, e.g. for at least 100 vehicles that have correctly passed the system, verify if the system generates a complete vehicle record.
- Classification rate test, e.g. for at least 100 vehicle records from vehicles that have correctly passed the system, verify that the system makes a correct classification of the vehicle. This may be done by visual inspection from the road side or by using video recording.
- Length measurements test, e.g. the length, wheelbase and axle distances of all test vehicles used for testing the weighing accuracy are measured, using a certified length measurement tool, and are compared with the results of the WIM measurements.

A possible criterion for acceptance of these tests could be that at least 95 % of the measurements shall be within the specified accuracy.

Another aspect of the performance is the ability of the system to detect disturbances in the measurements and process such measurements in the correct way. Possible actions of the system could be to generate:

- a measurement with compensation of the disturbing effect, or
- a warning of possible reduced accuracy, or
- an error message with a description as to why no measurement could be generated.

More information on test procedures can be found in (COST 323, 2002; ASTM-E1318-09, 2009; OIML R134, 2009; NMi, 2016).

5.5.6 System calibration

Generally, a system is calibrated for the first time after installation and before the acceptance tests. The first calibration is performed under the responsibility of the vendor. It is recommended to leave a period of at least two weeks between installation and calibration to make sure the sensors and surrounding pavement have completely settled. A similar period of 2 weeks is recommended between the first calibration and the acceptance test, this to be able to assess the stability of the calibration over time.

The system calibration procedures are described in more detail in the next chapter.

6 Operation of a WIM system

This chapter discusses the issues involved in the operation of a WIM system.

6.1 Use of WIM data

An in-road WIM system will provide detailed data of all passing vehicles; these data can be combined with measurements from other sensors/systems such as:

- vehicle dimensions, height and width,
- images with the overview of the entire vehicle or its specific parts, like the identification number or dangerous goods indication shield or plate,
- license plate or electronic identification number,
- electromagnetic or optical vehicle signature
- on-board WIM data of passing vehicles.

From these individual vehicle records aggregated statistical data per time period can be calculated, with the total, average and extreme values. Results can be presented as histograms of any of the detailed data (type/class of vehicles, speed, vehicle length or axle spacing, GVW or axle load, etc.). Short period aggregated data (e.g. for 5-minute, 1-hour intervals) are used for real time traffic information and management. Long-time aggregated data (1 week to 1 year) are used for statistics, traffic monitoring and road operation or maintenance.

WIM systems will deliver detailed information on the actual traffic loading on a road network without disrupting the traffic flow. In-Road WIM systems will provide data on the complete traffic loading on the locations where the WIM are installed. While On-Board WIM will provide the loading information of the instrumented vehicles over the entire road network.

Organisations responsible for the construction and maintenance of roads and bridges need realistic information on the actual traffic loading on their roads. This loading information is an important input both for the design codes of the road infrastructure (new roads and bridges) and for the planning of the maintenance of the existing infrastructure. Detailed information on the traffic loading is also an important input for traffic and transportation studies that help to optimise the planning and design of the future road network.

2st Law of WIM:

Only a WIM system will provide a complete picture of the actual traffic loading on a road network.

Reliable WIM data will provide the user an accurate and detailed picture of the actual transport flows and loading of the road infrastructure. This increased knowledge of the actual situation allows users to make better founded decisions on the design, maintenance and usage of the road network. For example, better knowledge of the actual traffic loading on a certain bridge may allow engineers to reduce safety margins in the calculation of the structural safety. This can result in the raising of load limitations of certain bridges (Moffatt, 2017), allowing heavier trucks to pass without any restrictions.

6.2 Operation of WIM systems

Due to the nature of WIM systems and the 'hostile' environment in which they have to operate, damage, wear and tear on the system's hardware and the surrounding pavement need to be anticipated and expected. This means that the performance of all WIM systems will degrade over time, normally slowly because of wear and tear but sometimes more quickly in the case of damage to key parts of the system or pavement. In the operation of a WIM system three periodical processes can be identified: visual inspection, sensor maintenance and system calibration (FHWA-3, 2018).

6.2.1 Visual inspection

This includes a quick visual inspection of the sensors and the pavement directly surrounding the sensors, without closing the lane for traffic. The goal is to look for any visible signs of damage to either the sensors or the pavement. Normally, visual inspection is not sufficient to detect internal defects, but it may well be sufficient to observe some serious installation problems. The sooner such a problem is detected, the sooner the issue can be resolved. The frequency for such inspections depends on:

- the type of WIM technology; for example, the sensors of a Bridge WIM have no direct contact with the passing vehicles, will have less wear and tear and, consequently, the inspection frequency can be longer;
- the accessibility of the location of the installation in relation to available budgets; it may not be economical to frequently drive for hours just to have a look at a system;
- the traffic, pavement and environmental conditions at the site;
  - roads with a high intensity of heavy vehicles will see more wear and tear;
  - concrete pavements are generally stronger and more stable than asphalt pavements and need less attention;
  - extremely high and low temperatures may affect the durability of WIM sensors and freeze-thaw-cycles may affect the installation of sensors in the road pavement.

Remote monitoring involves the remote checking on a regular basis of:

- the correct technical operation of the system, this includes the hours the system, the individual sensors and other system components were operational and generating data. In addition also the amount of data generated per hour or per day can be monitored.
- Potential changes in the data it self, this may include the daily averages for GVW, front axle weight, tandem axle weight, tandem axle spacing and changes in the peaks for empty and full trucks, the distribution over vehicle classes, etc.

6.2.2 Sensor maintenance

The frequency and nature of the sensor maintenance strongly depends on the type of WIM sensor technology, the type of pavement, and the traffic and environmental conditions. WIM sensors with moving parts may become filled with dust or mud that will have to be removed after a certain period. The top layer of certain strip and bar sensors installed in asphalt pavements will have to be ground flush to the pavement surface, to compensate for increased rutting (FHWA-3, 2018).

6.2.3 System calibration

The objective of a system calibration is to establish the average measurement error of the system. The measurement error is the difference between the value measured/calculated by the WIM system and a static reference value. Once the average error has been noted this value can be used to make adjustments to the system. Strictly speaking, the term calibration means just the act of comparison, and does not include any subsequent adjustment. In daily WIM practice 'calibration' means both, calibration and justification (Papagiannakis, 2008).

Justification is generally done by changing the 'calibration factor' that is used in the calculation of the measurement results. Each lane of the system will have to be calibrated separately since they should either be considered separate measurement systems or, in the case of a B-WIM, contributions of measured strains under each lane on weighing results have to be determined. The frequency of a system calibration may vary depending on the application, operational conditions and available budgets. Common practice is to perform at least one calibration per year.

For a proper calibration it is recommended to use the most common type of vehicle at the site and, if possible, to use two different types of vehicles (i.e. one 2-axle rigid truck and one 5-axle tractor + semi-trailer combination). The truck(s) should be loaded close to their maximum permissible loads, and each should make at least ten passes over the system at speeds that are typical for the site. For trade or tolling applications, the same number of passes should be made when the trucks are empty or partially loaded.

Figure 6.1: A 4-axle calibration truck passing WIM sensors *Source: KALIBRA*

The frequency and exact procedure for the calibration (the number and type of vehicles, the number of runs and the loading of the vehicles) should be agreed between the vendor and the customer prior to the calibration itself. The ways the results of the calibration are implemented into the WIM system depend on the manufacturer. It may be implemented in the form of one factor for all measurements or divided into separate factors for different measurements (e.g. axle loads and GVW), different types of vehicles (e.g. different factor for shorter than for longer vehicles) and for separate ranges (e.g. for axle loads: 0-5t, 5-10t, 10-15t, 15-20t or for speeds: 0-40km/h, 40-80km/h, 80-120km/h). Examples of calibration procedures can be found in (COST 323, 2002; ASTM-E1318-09, 2009; FHWA-3, 2018).

Another form of calibration is often referred to as 'automatic calibration' which is strictly speaking not calibration since no hard reference values are used. This type of compensation is described in the next paragraph. Sometimes the term 'automatic calibration' is also used for the compensation of drift in the measurements caused by external influences, like temperature variations (Burnos, 2012).

6.3 Quality of WIM Data

The quality (accuracy, reliability and stability) of the measurement data used in any study directly determines the quality of the results and conclusions of the study. For a realistic study on the impact of heavy truck traffic, the quality of the WIM data must be verified. Studies based on WIM data with little, if any idea of the quality of the data may result in erroneous conclusions. The WIM data from different projects have shown variability that could not be explained by mere differences in the national loading regulations alone. The differences in the data may have originated from variations in the local traffic flow, the environmental conditions or from differences in performance of the WIM systems, e.g. the type of WIM technology used or, possibly, structural measurement errors.

A full guarantee of the quality of WIM data can only be given after an extensive evaluation of the performance of the WIM system, the traffic and environmental conditions over a long period of time (e.g. 1 year). In most cases, such an extensive evaluation is too time consuming, too expensive to carry out and also too complicated since it requires an in depth knowledge of WIM systems and sensor behaviour. A limited and simplified evaluation could fill the gap between an extensive and expensive test and no test at all, allowing for a quick assessment of the quality of the WIM data (Lees & van Loo, 2016).

In general, the tests will look at the stability of certain elements or characteristics of the measured data. The characteristics are based on the common practice described in international literature on WIM data quality management. These tests could then be used to compare the relative quality of different WIM sites (the quality of the data from site A is better than that of site B) and, if possible, to give an indication of the absolute quality of the data of a particular site (the data from site C has a quality that is sufficient).

It is important to realise that the quality tests will not be able to distinguish between variations in the measurements by the WIM system and variations in the truck traffic at a certain site. This means that in the case the test results would produce an "insufficient" verdict on the quality of data because of large variations in the WIM data, the reason for this could be explained by the variations in the traffic flow and not because of the WIM system. In this case, the results of the tests should be interpreted as: "Do not use this data without additional checks on the quality of the data."

The challenge is to find the right tests and criteria to assess the quality of the data. In other words, this means to identify certain types of vehicles, which axle composition and loads are stable and are commonly found at the WIM sites. This can either be caused by international regulations for the maximum weights and dimensions for heavy goods vehicles (examples 1 and 2) or by standards in vehicle design (examples 3 and 4). The following examples of such characteristics can be used in the quality checks:

1. The vehicle length of truck + trailer combinations and that of tractor + semi-trailer (articulated) combinations. E.g. for most EU member states the maximum allowable lengths for these combinations are respectively 18.75 m and 16.50 m;
2. The gross vehicle weight (GVW) of 3 axle trucks and that of 5 axle tractor + semi-trailer (articulated) combinations. E.g. for international transports in most EU member states the maximum allowable GVW's for these combinations are 26 tonnes and 40/44 tonne respectively;
3. The axle load of the first (steering) axle of the fully loaded 5 or 6 axle articulated vehicles. International experience has shown that for the fully loaded vehicles the load on this axle lies normally in a relatively narrow bandwidth;
4. The axle distance between the 2nd and 3rd (driven) axles of 6 axle tractor + semi-trailer combinations. International experience has shown that the distance between these axles is very stable at 1.30 to 1.35 m, as this allows the highest axle loads;

Besides the weight and length related tests, other parameters should be checked to provide an indication of the correct operation of the WIM system:

- The variation in the number of registrations per day;
- The number or percentage of unclassified vehicles – or classified as 'Other´ - per day;
- The number or percentage of measurement or system errors per day;
- The number of hours without registration (between 04:00 and 24:00h)

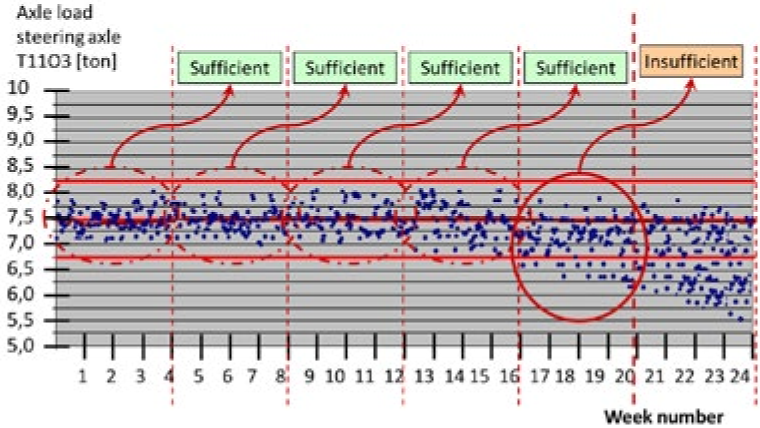

Figure 6.2: Example of data quality check *Source: VAN LOO*

For the first four tests described above, the average values and standard deviation should be calculated. The average value can be compared with a reference value to check for the absolute quality, the standard deviation gives a value for the stability of the measurements.

Examples of data quality control systems can be found all over the world, e.g. in papers of Guerson et al. (2016) from Brazil, de Wet (2010) from South Africa, Lees & van Loo (2016) from the EU and Nichols & Bullock (2004) from the USA.

7 Additional information

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7.2 ISWIM Vendors

www.camea.cz	www.irdinc.com	www.wheelright.co.uk	www.pesage-captels.com
www.kistler.com	www.kapsch.net	www.cestel.eu	www.sterela.fr
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www.traffic-data-systems.com	www.q-free.com	www.te.com/usa-en/home.htm	www.intercompcompany.com
www.axtec.com	www.betamont.sk	www.wanji.net.cn	

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