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IMPLEMENTATION OF WIM SYSTEMS FOR

Direct Weight Enforcement

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The **International Society for Weigh-In-Motion** (ISWIM) is a global organization bringing together all stakeholders with an interest in Weigh-In-Motion (WIM) technology, its application, data it collects and information it generates. Our members are users, researchers and vendors of WIM systems including systems in or under the road pavement, bridges, rail tracks and on-board vehicles.

The **International Society for Weigh-In-Motion** has produced and is disseminating this publication to make the information contained herein available for use by ISWIM members. The information in this publication was reviewed by the ISWIM Editorial Board. This document does not circumvent any available standard Weigh-In-Motion (WIM) specifications, national or international standards, or other official WIM documentation.

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Preface

This document is part of the publication series "ISWIM Practitioners' Guides" produced by the International Society for Weigh-In-Motion (ISWIM). The aim of this publication series is to provide WIM practitioners, technicians, and end-users with a series of guides illustrating "best practices" concerning the various aspects of WIM technology and its applications. This document does not circumvent any available standard WIM specifications.

On behalf of ISWIM, I would like to acknowledge and thank Gustavo Otto for taking the lead in championing the re-development of the ISWIM Practitioners' Guides Series, and the support of the individual Editorial Board members. Specific to this guide, I would like to thank the members of the working group and authors, namely Hans van Loo, Gerhard de Wet, Andy Lees, Chris Koniditsiotis, Christopher Klauser, Eugene O'Brien, Emil Doupal, Gustavo Otto, Martin Hauptman and Tanvi Pandya.

Deborah Walker
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Foreword

This guide, developed by a group of ISWIM volunteers, serves as a valuable resource for contractors, transportation agency personnel, and road owners involved in the implementation and use of high-speed WIM systems for direct weight enforcement. Direct weight enforcement means that the measurements from the high-speed WIM system are used directly for weight enforcement without the need for any legally accepted verification measurements by a low-speed WIM or static weighing system.

The purpose of this document is to offer an overview of the different aspects, advantages and challenges involved in the implementation of WIM for direct enforcement. It also provides recommendations based on experiences and best practices from the global WIM industry, and perspectives of agencies involved in enforcement along with published documentation, aiming to assist in the successful implementation of high-speed WIM systems for direct weight enforcement. It may be used to serve as a basis for the establishment of specific requirements, regulations and procedures for a successful implementation of WIM for direct weight enforcement.

It is important to emphasize that this guide does NOT intend to serve as a standard or to dictate what actions individuals or organizations should take. Rather, it provides an overview of the best practices and experiences taken from the international WIM and enforcement communities in the implementation and use of high-speed WIM systems for direct weight enforcement. This document was designed to be informative, and users can decide if they would like to utilize its recommendations. The details of the actual implementation processes will vary depending on the specific legal, operational and environmental conditions, and financial/organizational constraints of the end user organization.

Any comments or questions for this guide could be provided by email to: *info@is-wim.net*.

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Table of Contents

1 INTRODUCTION 6
Definitions and Scope 6
Status of WIM for Direct Weight Enforcement 7
This Guide 7

2 WHY CONSIDER WIM FOR DIRECT ENFORCEMENT? 8
Why Fight Overloading? 8
Limitations of Conventional Enforcement 8
Benefits of Direct Enforcement 9

3 KEY ELEMENTS FOR IMPLEMENTATION 10

4 LEGAL ACCEPTANCE 12
Metrological Requirements 12
Maximum Permissible Error (MPE) 13
Setting Accuracy Requirements 13
International vs. National WIM Standards 14
Statistical Reliability and Certainty of Fair Sanction 15

5 SYSTEM CERTIFICATION 16
Levels of Testing and System Certification 16
Requirements for WIM performance tests 18

6 DATA QUALITY CONTROL 19
Focus on In-service Accuracy 19
General WIM Performance Stability Tests 20
WIM Weighing Accuracy Tests 21
WIM Measurement Confidence Tests 23

7 CONSIDERATIONS FOR IMPLEMENTATION 24
Using Inaccuracy and Grace Margins 24
Start with Certain Heavy Vehicle Types 24
Effect of Load Transfer between Axles 25

Integration of enforcement approaches 25
Continuation of enforcement activities 26
Dealing with multiple detections 27
Vehicle identification 27

8 EXAMPLES OF ACTUAL IMPLEMENTATIONS 28
Czech Republic 28
South Africa 28
Brazil 29
New York City 29
Hungary 30

9 CONCLUSIONS AND RECOMENDATIONS 31
Conclusions 31
Recommendations 32

11 REFERENCES 34

WIM Vendors Affiliated to ISWIM 36

Consultants Affiliated to ISWIM 36

1 INTRODUCTION

Definitions and Scope

This guide is specifically designed for high-speed Weigh-In-Motion (WIM) systems used for direct weight enforcement. 'Weigh-In-Motion' is defined [ISWIM, 2022] as: the process of determining the wheel and/or axle loads and gross weight of a moving vehicle, by measurement and analysis of the dynamic vehicle tyre forces. More definitions of WIM terms used in this document can be found in the "*ISWIM Glossary of Terms*" published on the ISWIM website and available for download.

Weigh-In-Motion systems come in many different shapes and forms such as strips, scales, plates and bridge WIM that use a variety of sensing technologies (e.g. load cells, bending plates, strain gauges, piezo electric, piezo quartz, fibre optic). This guide refers to WIM systems, WIM measurements and WIM data in general and is strictly independent of the type of WIM system and the sensing technology. This guide will focus on WIM data, its application for direct enforcement of heavy vehicle overloading, data quality requirements and preconditions for successful implementation.

Within this guide, when WIM is mentioned, it refers to high-speed WIM (HS-WIM) unless named explicitly as a low-speed WIM (LS-WIM). HS-WIM is defined as the weighing of a vehicle in motion in normal, free traffic flow conditions, using a system installed directly on/in/under an in-service road, culvert, or bridge. This means that there is no specific control over the behaviour of the vehicle during its passage over the HS-WIM system.

There are several ways in which WIM systems have contributed to weight enforcement, such as pre-selection or virtual weigh stations where heavy vehicles are screened for potential overloading, company profiling and direct weight enforcement. For a broader overview of the different applications of WIM see the "ISWIM Guide for Users of WIM" [ISWIM, 2019].

This guide deals only with WIM systems and data used for direct weight enforcement. WIM systems used for direct enforcement are set apart from those used for other applications by the following key differences:

- For direct weight enforcement, the WIM measurement serves as proof of overloading and will be used directly as the basis for a legal infringement and financial transaction (i.e. fine). This means that the **accuracy of each individual measurement** has to be guaranteed to be within the prescribed tolerance that was accepted by the regulator. The measurement accuracy of such WIM systems is typically specified as the Maximum Permissible Error (MPE).
- For all other enforcement applications, the WIM measurement will give an indication of a possible overload, but some margin of error may be tolerated because identified heavy vehicles are reweighed and charged using a certified static or LS-WIM scale. For these applications, the **average accuracy of all measurements** is used to gauge the performance of the WIM system statistically. The measurement accuracy is typically specified as a 2σ tolerance interval (where σ is standard deviation) that contains 95% of all measurements.

Status of WIM for Direct Weight Enforcement

The use of WIM for direct enforcement is not yet common. It requires the most advanced of WIM systems to meet the accuracy requirements as well as an excellent organisational structure. Several countries, regions and cities have started with the implementation of WIM for direct weight enforcement: the Czech Republic, Hungary, Russia, Brazil, Wallonia in Belgium and New York City in the USA. Many more are investigating the possibilities or are already preparing for implementation, such as France, Germany, Poland, South Africa, other states in the USA, Argentina, Saudi Arabia and the United Arab Emirates, to name just a few. The status of the implementation of WIM for direct weight enforcement around the world includes a combination of the following developments:

- A number of documents are available that serve as specifications for WIM systems for direct weight enforcement. Two of the best-known international specifications for WIM systems are the American ASTM 1318 [ASTM, 2009] and the European COST 323 [COST, 2002]. While both of these are valuable tools, they are not considered to be suited for legal metrology. The OIML R134 Recommendations [OIML, 2009] are considered suitable for legal metrology, but they did not initially include high-speed WIM and has been under revision since 2019. It remains the most used international reference for WIM enforcement. The NMi-WIM Standard [NMi, 2016] is also suitable for legal metrology but is currently not widely used. In the USA, efforts have been underway since 2022 to update the NIST Handbook 44 [NIST, 2024] with certification testing requirements for direct enforcement by WIM.
- In these implementations, the national or regional authorities (governmental agencies) often develop their own specifications for metrological approval intended to satisfy the specific national/regional road, traffic and overloading conditions and specific governing legal requirements. Although they mostly stem from recognised international specifications, these national/regional standards are consequently different from the international documents and lack uniformity.
- This often results in the situation where manufacturers of WIM systems need to go through a full procedure of type approval for their system in each individual country, region or city in order to have access to that specific market. This may lead to significant additional costs for the manufacturers that are ultimately passed on to the clients. At the same time, for the enforcement authorities, there is the risk that only a few or just one manufacturer will obtain approval, resulting in a lack of competition. This ultimately will lead to additional costs for the authorities/agencies as well, which is particularly relevant for relatively small countries/markets.

This Guide

The purpose of this guide is to:

- Provide an overview of the different facets and challenges involved in the implementation of WIM for direct weight enforcement.
- Describe the experiences and best practice solutions from different end-users around the world.
- Provide recommendations for users on the implementation of WIM for direct weight enforcement.

2 WHY CONSIDER WIM FOR DIRECT ENFORCEMENT?

Why Fight Overloading?

Overloaded vehicles have a Gross Vehicle Weight (GVW), axle group loads and/or individual axle loads higher than the legal limits. Besides negative effects on traffic safety and fair competition between transport companies, the main problem caused by overweight vehicles is the additional wear and tear of the road infrastructure. This includes increased damage to road pavements and bridges; these effects are amplified by the increase in the size, weight and number of road vehicles, combined with an aging road infrastructure. In particular, bridges built decades ago were constructed to meet the loading requirements of the time with related safety factors. Legal loads limits have increased over time and when even those are exceeded, e.g. [Rodrigues, 2024], it contributes to a reduced service life and a smaller factor of safety on the structures. Overweight vehicles also reduce safety of other roadway users due to their need for a longer stopping distance.

Limitations of Conventional Enforcement

Most countries still use conventional enforcement of overloading legislation whereby transgressors are weighed and charged based on measurements from fixed, static weighbridges or portable, axle scales. The combination of a controlled measurement environment and the accuracy of static scales provide for reliable weight measurements that can be used with confidence for sanctioning. Legislation is typically structured around this mode of operation. Traffic control centres (weigh stations) may provide a comprehensive overload control solution, typically including intelligent screening using WIM, static or low speed weighing, charging and a load rectification area. They may also include facilities for the payment of fines, vehicle inspection and testing facilities (for example brake testers), a base for traffic police from which to operate and general visible policing. There are however significant limitations and challenges in the use of static weighing facilities.

- Static weighbridges are expensive to construct, maintain and operate, and require a considerable amount of land area for related buildings and facilities, queuing and circulation of large heavy vehicles and a load rectification area. Especially in dense urban environments, the land required is often simply not available.
- Their influence area is limited to a maximum radius of about 100 km, depending on their location, the road network and the availability of diversion routes. Especially in finely branched road networks, fixed control locations are vulnerable to evasion by overloaded vehicles. To counter this effect, additional enforcement controls on diversion routes will be required.
- Static weighbridges are often only operational during a fixed and limited number of hours per day. These operating hours are well known within the transport industry, allowing potential offenders

to adjust their planning to avoid being controlled. Even with flexible 'business hours' the controls are generally only effective for a short period of time (e.g. an hour) before drivers hear what is happening and take measures to avoid it. As a result the overloading will only shift in time or to other roads in the network.

- The capacity of static weighbridges is limited to a maximum of about 60 vehicles per hour because of the slow acceleration and deceleration properties of large heavy vehicles as they pull on and off the scale, and because of the time it takes for the scale measurement to stabilize under load and again at zero after a vehicle has pulled off the scale.
- Depending on the number of enforcement staff available, combined with the duration and complexity of the administrative procedures required per infringement, the capacity of a weigh station may be reduced to only a couple of vehicles per hour and may create a backlog of trucks waiting to be processed. In many countries this is made worse because the enforcement authorities have to do a full (20+ point) inspection of the vehicle, including paperwork that takes up space in the facility and occupies the personnel.
- A static weighbridge requires human resources for operation. Apart from the associated cost, administrative burden and inefficiency, it also creates the opportunity for bribery and corruption. In addition, operation is limited to the working hours of the enforcement staff which are often well known to the offenders.

Benefits of Direct Enforcement

Several countries have started to investigate, and some have already successfully implemented direct WIM enforcement systems to overcome the limitations of conventional static weighbridges. The main advantages of WIM for direct weight enforcement [REMOVE, 2006] are its combination of high efficiency and high effectiveness. Because of its 24/7 operation, all passing vehicles are monitored which makes evasion in time impossible. With a typical hit rate of more than 99%, (almost) all overloaded vehicles are detected and registered without any disturbance to the normal traffic flow. These WIM systems are highly effective, especially for highway sites with high truck volumes.

Perhaps the most significant benefit of direct WIM enforcement stations is that they are less costly than traffic control centres. This allows for the implementation of a more extensive enforcement network with a wider influence area and less opportunity for freight operators to avoid being weighed. For law abiding operators, direct WIM enforcement offers savings in unnecessary delays and the logistical cost associated with it. Finally, measurement data from WIM systems for direct weight enforcement can also be used for other applications such as company profiling, statistics on overloading and traffic loading in general that can serve as an input for the design and maintenance of road pavements and bridges.

While some vehicles identified as overweight may not receive a sanction for reasons such as not meeting legislative or photographic evidence requirements, the higher enforcement level, especially over a larger network, has the ability to create a culture of compliance. For example, within a year after implementing WIM for direct enforcement on the Brooklyn-Queens Expressway in 2024, the New York City Department of Transportation saw a reduction of 60% in overweight vehicles [Rodriguez, 2024].

3 KEY ELEMENTS FOR IMPLEMENTATION

Unlike the use of WIM data for other applications the implementation of WIM systems for direct weight enforcement generally consists of a critical combination of the following three elements: Legal Acceptance, System Certification and Data Quality Control: see Figure 1.

Figure 1. Elements in implementation of WIM for direct enforcement.

1. **Legal Acceptance** involves the adaptation of the relevant national (or state) legislation in order that the WIM measurements may be recognised as legal evidence for overloading and will be accepted in a court of law. This element is explained in more detail in Chapter 5.
2. **System Certification** involves the testing and approval of WIM system based on accepted metrological standard(s). This element consists of different levels of testing (type approval, initial verification and in-service verification) as explained in more detail in Chapter 6.
3. **Data Quality Control** involves all the procedures for the maintenance, calibration and data quality checks to ensure that the systems continue to operate within specification – for more details see Chapter 7.

Practice has shown that implementing WIM for direct weight enforcement can only be successful if all three elements are in place. These elements may be implemented one after the other, but only together form a process capable of achieving the overall objective of ensuring that each WIM measurement used for direct weight enforcement meets quality requirements and is legally acceptable.

Figure 2 shows a high-level overview of the three elements, the order of their phase in the implementation road map, their role in the overall process, the key requirements involved and finally the reference to the chapter in this guide where more details are provided.

Overall objective: Each WIM measurement used for direct enforcement is legally accepted!

Key elements for successful implementation	**Legal Acceptance** (Enforcement Authorities)	**System Certification** (Legal Metrology)	**Data Quality Control** (Operator)
Project Phase	PREPARATION	IMPLEMENTATION	OPERATION
Role in Process	To provide legal basis for application	To provide proof of performance from day 1	To provide proof of every day performance
Key Requirements	• Measurement accuracy and reliability • Operational procedures › Maintenance and calibration of WIM › Determination of sanction	• Standard test procedure with 3 levels of tests › Type approval › Initial verification › In-service verification	• Continuous performance stability tests › Weighing accuracy › Detection of trends › Confidence level of measurements
Guide reference	See chapter 5	See chapter 6	See chapter 7

Figure 2. Overview of key elements in implementation

When setting national[1] standard specifications for WIM systems, it is recommended that the scope and operational ranges for the systems be defined, and that accuracy requirements for weighing and vehicle classification be clearly set. These specifications should ideally refrain from specifying items such as the technology to be used, the requirements for constructing and installing the WIM system, or the requirements for constructing the surrounding pavement. Keep in mind that the impact of these items on the performance of the WIM cannot be ignored, e.g. the smoothness of the pavement surrounding a WIM has a major impact on the measurement accuracy. However these items are too technology and site specific to be included in generic specifications.

A WIM system is often part of a larger Intelligent Transport System scheme that measures and records not just the vehicle weights and axle loads but also other parameters such as vehicle dimensions, speed, images and license plate numbers. The specifications for the WIM should include the accuracy of the vehicle weighing (gross vehicle weights, axle loads, and wheel loads if needed) and, if needed, the vehicle classification (including axle spacing and vehicle length measurement). Requirements for other measurements should be adopted from other existing national standard specifications, where available, e.g. for automatic license plate reading.

1 In this document two levels of standardization are distinguished; International standards with requirements that are the same for all countries supporting the corresponding international organisation publishing the standard, and National standards with requirements specific for the local, national conditions and is included in national legislation. Depending on the size of a country and their governmental organisation there may be an additional third 'State', 'Canton' or 'Regional' level of standardization. Such state specifications may include additional specific requirements to allow for inclusion into state specific legislation and environmental conditions. In this guide, when 'national standard' is mentioned, it should be interpreted as 'national and/or state standard'.

4 LEGAL ACCEPTANCE

Metrological Requirements

For many national metrology institutes the traceability and reproducibility of all measurements is considered essential for legal applications like trade and enforcement. For HS-WIM systems the traceability of the measured wheel and axle loads to the national standard of weight measurement is created through links with static scales used for reference measurement during testing. Most codes typically state that calibration of measuring equipment should be traceable to precise reference masses. Such reference masses would not be directly applicable to WIM system calibration because the moving vehicles used as references are subject to dynamic forces along with environmental factors. It is important to note that these vehicles would have been weighed at a static weighbridge which was in turn calibrated using reference masses. This provides the traceability from the WIM measurements back to the masses through a series of intermediate steps.

It is evident that some adaptation of conventional metrological requirements and practical processes may be required for WIM accuracy to be certified. This reflects the new thinking required to keep up with technology that operates very differently from traditional static scales. Another way to transition into this new approach may be by requiring the following to achieve certification:

- It may be required that the static weighbridge, where reference vehicles are weighed, be calibrated (using precise reference masses) each time the WIM is calibrated or verified.
- It may be required that the WIM calibration and verification be approved only for the total vehicle weights if the reference vehicles are weighed on a weighbridge capable of measuring only the total vehicle weight.
- It may be required that the WIM calibration and verification be approved only for single axle loads because the WIM system weighs single axles directly and, as a secondary process, calculates axle group loads and total vehicle weights through summation.
- There needs to be an understanding that, when an array of strip weighing sensors is used to produce the single axle measurement, it is not a single measurement but the average of several measurements by multiple components that together constitute a WIM system. The testing of the performance of a WIM system is of the complete system, rather than individual measuring devices.

Maximum Permissible Error (MPE)

Generally, for WIM systems, the measurement error (E) is specified as a relative error between the dynamic WIM measurement (Wd) and a static reference value (Ws), as shown mathematically below.

$$E = (W_d - W_s)/W_s$$

Except for direct enforcement applications, most technical specifications for WIM service systems (e.g., ASTM E1318 and COST 323) use statistical interpretation and confidence intervals to assess whether WIM error is within specified tolerances. For example, the COST 323 is generally used in a way that requires that 95% of WIM errors on total vehicle mass must be within ±15% for Class C(15) systems. However, the risk of unfair sanctioning needs to be eliminated for direct WIM enforcement. The use of a 95th percentile confidence interval may therefore be considered insufficient. The entire direct enforcement initiative would fall into disrepute if infringements were successfully challenged in court.

The international trend is to specify the WIM error tolerance for direct enforcement in terms of Maximum Permissible Error (MPE) that is the WIM system may not commit any errors greater than the stated tolerance interval. When a WIM system has been tested and approved, 100% of its measurements have an error less than the specified MPE level.

From a statistical point of view, an infinitely large test sample would be needed to prove such an absolute certainty. In daily practice, the sample size of acceptance tests is always limited due to practical constraints. It is important that the possibilities and limitations of verification methods be understood and agreed as part of the Legal Acceptance process.

Setting Accuracy Requirements

A key challenge of direct weight enforcement is to match the maximum allowable error accuracy that regulators can use as evidence in court with the accuracy that the WIM system can sustainably achieve in practice. While more accurate WIM systems provide increased credibility to direct weight enforcement, they may be an unduly expensive solution to combat overloading in a country.

In general, enforcement sanctions will be applied when the WIM weight exceeds the legal limit by a specified tolerance. For a WIM system to be effective in changing behaviour, its tolerance should not be too high - a good rule of thumb is around half of the average overloading. When the specified tolerance is greater, most cases of overloading will go unsanctioned. At the same time, if the specified tolerance is much lower, the WIM will be unnecessary high, and the system will need to be highly accurate and probably much more expensive. For example if the average overload at a certain site is 30%, a WIM system with a tolerance of 15% can still be very effective. 'Over-specifying' the WIM may result in unnecessary expensive WIM systems or even a situation where none of the available WIM systems will be able to meet the requirements. It should, however, be borne in mind that overloading will reduce as soon as direct enforcement commences, which may result in the WIM being 'under-specified' for further reduction of overloading. The accuracy specification of the WIM should therefore be based not only on the current level of overloading but also on the desired level of overloading once direct enforcement has taken full effect.

It appears from implementations around the world that a reasonable compromise is to use WIM systems that can achieve an MPE of ±5% on total vehicle weight at type approval tests hence ±10% when in service. The corresponding MPE limits for axle group loads and single axle load measurements are greater than those for total vehicle weight, specifically 7% and 10%, respectively. It is important to specify a WIM system that is fit for purpose and to recognise that, ultimately, the reliability of the WIM measurements is just as important as their accuracy.

International vs. National WIM Standards

Legal systems, prosecution guidelines and traffic regulations differ from one country to the next and also within a country, depending on the size. Even if it were possible to achieve international harmonisation of WIM standards, it would likely not be possible to submit such standards, unchanged, for national or state metrological approval. In addition to specific regulatory constraints, it is possible that the actual accuracy of type approved WIM systems needs to be reconsidered because the pavement at the WIM site in the particular country was not tested as part of the type approval process, or the test procedures were not deemed sufficient to confirm compliance with MPE.

National or regional (state) authorities (governmental agencies) often develop their own national standards for metrological approval which are intended for the specific range of national roadway types, traffic conditions, vehicle types, legal loading limits and/or infrastructure codes. This may include adjustment in the frequencies, number, types and loadings of the test vehicles, the number of passes per vehicle and loading combination, the speed(s) of the vehicles, driving behaviour (e.g. braking/accelerating on the system, lane changes or driving partially on the system) and possibly environmental conditions such as temperature. Because of these – justified – specific local adaptations, the national or state requirements may no longer be compatible with internationally available and accepted documents.

As said before, for type approval certification, manufacturers of WIM systems have to go through a full procedure for their system in each individual country which leads to significant additional costs for the manufacturers. At the same time, for the end-users, this raises the risk that only a few or just one manufacturer will obtain national type approval, resulting in a lack of competition. This will again lead to additional costs for the end-user which is especially relevant for smaller countries. This situation could be mitigated by accepting the type approval certificate from existing international standards (OIML, NMi) issued by accredited international metrology institutes. The requirements for initial verification should be adjusted to match national or local conditions and requirements, while those for initial and in-service verification remain unchanged.

Statistical Reliability and Certainty of Fair Sanction

As is typical for any measurement instrument, proving in statistical terms that the specified tolerance will never be exceeded, is challenging if only small samples of test measurements are used. For WIM verification, a limited number of vehicle passes from a small selection of test vehicles will be utilised. Under normal conditions, heavy vehicles on any route typically have a range of axle configurations, loading intensities, operating speeds, types of suspension, etc. While the use of a limited number of test vehicles (as specified in OIML R134 for example) is justified and even preferred in metrological terms, it is understood that the measurements from test vehicles have statistical limitations and may not be representative of the total vehicle fleet. The decision on the types of vehicle to be used in a test needs to balance forming a representative sample with practical constraints regarding time and budget.

For legal acceptance, it is reasonable to consider that some authorities may require adjustments to test methods to ensure that the accuracy of in-service WIM systems (from which overload sanctions are generated) still complies with the agreed MPE. Statistical reliability should therefore be addressed as part of the permanent in-service verification process or the Data Quality Control system.

5 SYSTEM CERTIFICATION

Levels of Testing and System Certification

The system certification is based on a series of performance tests that provide a basis for legal proof of the performance of the WIM systems. Internationally, three general levels of test can be distinguished to provide a guarantee on the performance of the WIM system across different implementation phases. This approach is based on the principle of "one time testing," which provides maximum confidence for the user in the performance of the WIM system while minimising the costs of test procedures for both the end user and the vendor. These three test levels are generally used for measuring instruments for legal purposes as noted by OIML [2006] and NMi [2017]. The three test levels (Figure 3) are Type Approval, Initial Verification and In-service Verification.

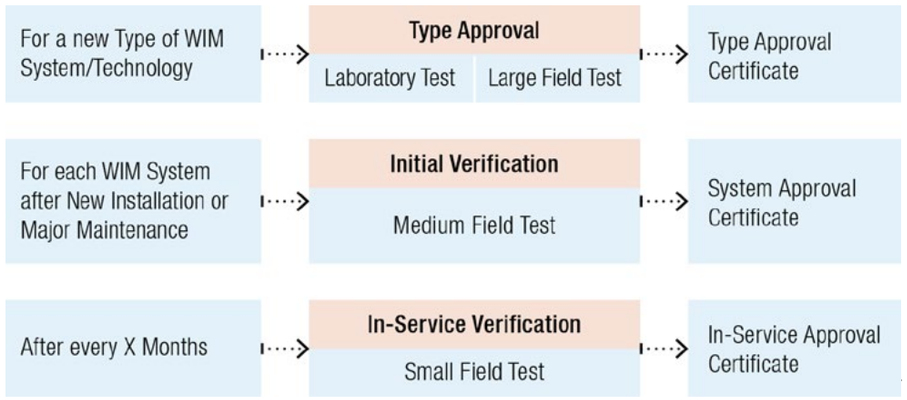

Figure 3. Levels of performance testing

Type Approval Test

This is the first level and most extensive performance test for a new (or significantly modified) type of WIM system where the performance of the system is tested under the full operating ranges. WIM systems of a type comprise all individual systems that are based on the same sensing technology, construction, data processing, storage, etc. A type approval test consists of both laboratory and field tests that should be performed by an internationally accredited metrology institute either on an open road or closed test track. The result of this test is a 'Type Approval' certification stating the minimum performance of all such systems based on the same type of technology. In principle, the certificate for type approval will serve as an international reference base for all following initial verification tests, performed on systems of the same type.

The laboratory tests are performed under controlled conditions to assess the resistance of all components of the WIM system to external environmental influences. These tests include: operating temperature range, relative humidity, immunity to radio frequency electromagnetic fields, AC/DC mains variation and hard- and software security. The field tests are performed at the site where the first WIM system of its type is installed and serve to assess the performance of the system under real life traffic and operational conditions. During the field test a number of different vehicles – sometimes with different loads – make a specified number of passes over the WIM system. In order to pass the test, the difference between the WIM measurement and a static or low speed reference measurement should be within a specified maximum error. The type approval tests and certification are generally initiated by manufacturers of WIM systems.

Initial Verification

The initial verification is the second level and is more limited performance test, made after the installation of a new system or important repair/modification of an existing one. This test is done in order to verify that the performance of the particular WIM system meets the minimum requirements under the specific local (traffic, road and environmental) conditions at the site where it is installed. The initial verification consists of field tests only and generally there are fewer different types of test vehicles and passes over the system than for the type approval tests. The results of this test will be documented in a statement of the system's performance, in the form of an 'Initial Verification Certificate' or 'System Approval Certificate'. This system approval certificate will be issued by the nationally accredited metrology institute recognised by the end user and will serve as a reference base for the in-service verification of this specific WIM system at this location. The initial verification is generally initiated by the enforcement agency in cooperation with the WIM system provider.

In-service Verification

The in-service verification is the third level and is the most limited performance test. It is used to verify that a system is still operating within specifications after a certain period of time, typically once per year. It consists of field tests only, with a lower number of test vehicles and number of passes over the system than the initial verification. The result of this test is a certificate or document stating that this specific system still meets the required specifications. The 'In-service Certificate' must be issued by the same national metrology institute recognised by the end-user as for the initial verification. The in-service verification is generally initiated by the enforcement agency as end-user of the system.

In short:

- The Type Approval certificate serves as a reference of the performance a certain type of WIM system is capable of under ideal circumstances.
- The System Approval certificate is the result of an initial verification and serves as a reference of the minimum performance of a specific WIM system at a specific location.
- The In-service Certificate serves as a reference of the minimum performance of a specific WIM system at a specific location after a certain period of time.

Requirements for WIM performance tests

When determining the specific national requirements for the size of the field test of a WIM system (e.g. number of vehicle runs) there should be a balance between the theoretical, statistical confidence level of the outcome and the practical, operational constraints of the end user and the WIM site under test. From a statistical point of view the test sample should be as high as possible to provide sufficient confidence in the outcome. At the same time, from an operational point of view, the test sample should be realistic under the local operational conditions at the WIM site.

It should be noted that each lane of a WIM system needs to be tested separately. Important questions for the planning of accuracy verifications are: How long does it take to make one full round of a test vehicle over the WIM system? How many runs can one test truck make in a day? How many trucks and load variations are needed? Can all truck+load combinations do their runs at the same time? What are the costs of renting a test truck for a day and what is the budget available to do the tests? All this determines how many days and how much cost is needed for testing. Practical figures for the total number of vehicle runs[2] are between 60 and 100 for type approval, between 30 and 60 for initial verification and between 15 and 30 for in-service verification.

It will be important to set realistic national requirements for the size of initial and in-service verification tests that strike a balance between statistical requirements and practical constraints. Remember that confidence in the results of these acceptance tests is supported by all previous performance tests and the data quality management process, which should run in parallel.

2 This is the sum of all runs made by the different test vehicle+loading combinations.

6 DATA QUALITY CONTROL

Focus on In-service Accuracy

For direct weight enforcement, it is essential that the performance of the WIM system is assured throughout the entire operational period. The weights on which sanctions are based must be accurate to within the legally accepted MPE, every day, for every vehicle. Unlike other types of enforcement equipment such as speed cameras, WIM equipment is installed in a challenging environment and the WIM system's accuracy may therefore deteriorate over time. It cannot be guaranteed that a WIM system that passed the initial verification test will remain sufficiently accurate in the long run unless the installation and surrounding pavement remains in pristine condition. Daily or seasonal changes in temperature may also affect the pavement properties – and in turn WIM performance – on a cyclic basis. While the use of a standard such as OIML R134 is an important step in ensuring that the equipment is correctly installed and operated, additional tests will be required to prove that the accuracy is maintained, and to indicate when corrective measures are required to improve WIM accuracy if/when the need arises from time to time.

Annual in-service WIM system accuracy verifications, such as those stipulated by the governing requirements (e.g., as specified in OIML R134), must be conducted as part of the formal site certification process. However, they are unlikely to suffice as a standalone data quality management process due to the long intervals between tests and the limited sample of vehicles tested. The operation of the WIM system should be part of a quality system defined by the enforcement authority and legally approved, ensuring it is defensible in court. There are three levels of test to consider:

- **General WIM Performance Stability Tests.** The first level of tests includes high-level statistical checks on WIM data to confirm that operation of the WIM system is stable.
- **WIM Weighing Accuracy Tests.** This level of test compares samples of WIM data with known reference (static weighbridge) weights to confirm compliance with specified weighing accuracy.
- **WIM Measurement Confidence Tests.** These tests are integrated into and performed by a WIM system for each measurement to assess its confidence in the quality of the measurement and its suitability for prosecution purposes.

The quality control system must constantly verify the quality of the measurements using a combination of quality checks. The exact implementation of the Data Quality Checks depends on the type of WIM system and the local operational conditions (traffic, road infrastructure and environment). These checks are generally developed by the manufacturer and independent experts, in cooperation with the end user and sometimes also the national or regional metrology authority.

It is recommended to run the data quality management system (DQM) for a couple of months to a year before starting the direct weight enforcement operation to ensure proper functioning. During this time the DQM can be calibrated and fine-tuned and it will show whether the performance of the WIM system is accurate and stable enough to be used for direct enforcement. This will help to develop and adjust the protocols for identifying issues and related responses, and to implement them in the accepted quality system.

General WIM Performance Stability Tests

The first level of quality assurance tests on the WIM data is aimed at monitoring the stability of WIM performance, without directly assessing errors in the data. WIM data performance markers are benchmarked against the recorded performance when the WIM system passed the initial or in-service verification. At these verifications there will be a 'hard' comparison with static or low speed reference measurements.

Additional statistical checks should be done on a number of indicators that are indicative of the stable operation of the WIM system. Weight related indicators could include the mean and standard deviation of the weights of specific types of axles or vehicles, or the relation between different axles and axle groups. For example, the loads on steering axles or drive axles of certain types of vehicle tend to stay within a tight interval.

A popular example of a weight-related indicator for general quality checks is the axle load of the steering (1st) axle of large heavy vehicles. In Europe, the steering axles of fully loaded 5-axle tractor semi-trailer combinations are often used. Experience has shown that the weight of these axles is quite stable and shows little variation (±750kg) around the average value of 7,500kg. On a regular basis the percentage of such axles that falls outside the interval 6,750 – 8,250kg (7,500±0,750kg) is calculated. As long as this percentage is below 5%, the data passes this criterion and is considered 'good data'. The data fails the criterion when this percentage is more than 5%. In this case the data is marked 'insufficient' and will be sent for further problem analysis.

Similar examples are available from around the world, noting that the types of vehicle used may differ based on the prevalent types of large trucks in a country. In South Africa, for example, 6- and 7-axle articulated trucks with single steering and double driving axles are used in the quality management system. Quality parameters include the average and standard deviation of steering axle weight and truck tractor weight, as well as the front-axle to truck-tractor weight ratio [de Wet, 2012] which provides an indication of the extent of load transfer between the steering and driving axles, sensor straddling or driving in between lanes and whether WIM-measured weights are realistically balanced.

The quality of the measurement data in general will also be determined by checking other – non-weight related – indicators, e.g. the number of detected vehicles per hour/day/week, the number of pictures taken, the number of recognised licence plate numbers, the number of full registrations and the distribution of the vehicle types. The stability of electronic outputs (for example loop frequencies), vehicle length and axle spacing may also be gauged against predetermined benchmarks.

A list of data quality criteria may be established for routine assessment and reporting. A characteristic of these checks is that the average quality of the data is constantly determined and compared with the recent past. If one or more of the quality criteria fail to meet their requirements, all data from that WIM system may be labelled as insufficient for direct weight enforcement; see Figure 4. The measurement data remains 'insufficient' until the reason for this failure has been determined and corrected.

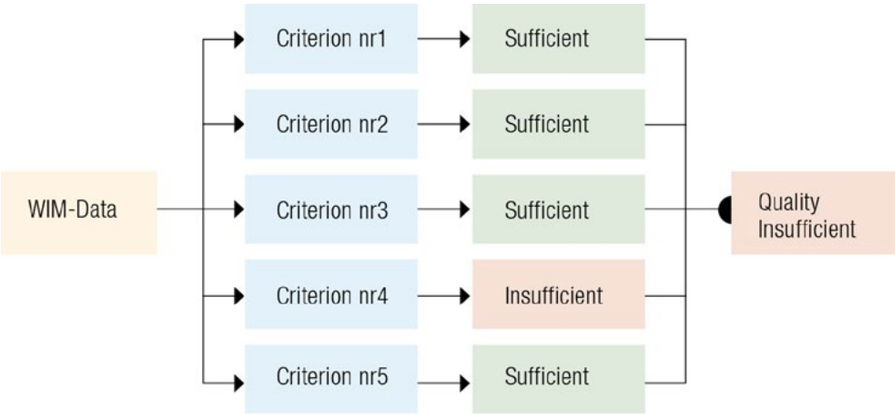

Figure 4. Structure of data quality checks

WIM Weighing Accuracy Tests

Standard initial and in-service WIM accuracy verification tests using test vehicles (such as prescribed in OIML 134) are often considered too cumbersome and expensive to be performed on a monthly basis. While such tests serve the valuable purpose of confirming WIM accuracy to metrological standards using an approved method under controlled conditions, the DQM ideally requires a more cost effective and responsive process. The WIM environment can change; therefore the accuracy of a WIM system for direct enforcement should ideally be assessed continuously. This is done with the checks that are part of the DQM. Keep in mind that these checks do not influence the settings that would influence the measurement performance or calibration of the WIM system in any way since this would invalidate the legal metrology certification.

Direct assessment of the error in the WIM data (by comparing WIM measurements with static weighbridge reference weights) has the advantage of providing the most direct evidence of the stability of the measurement accuracy of the WIM data. Various options can be explored to determine reference weights for WIM-measured vehicles.

- Pre-weighed test vehicles can do repetitive runs over the WIM system, similar to the OIML R134 in-service WIM verification process. This approach can work well when a fleet of test vehicles is permanently available, the number of WIM systems to be verified is low, and nearby safe locations are available for test vehicles to turn around.
- Low-speed WIM can be used to accurately weigh a sample of vehicles that passed over the enforcement WIM system. The key benefits of this approach over the use of test vehicles are that test vehicles and safe locations for U-turns are not necessary. The challenges are that suitable locations for low-speed WIM operation must be available, and a team of technical personnel and traffic police will be required to safely process vehicles. This process also assumes that a sufficient number of heavy, fully loaded or overloaded vehicles are available for weighing.

- In case a network of WIM systems is in operation, the measurements of the same vehicle within a certain time window, made by different WIM systems, can be compared. If the measurements from one particular WIM system significantly differ from the other systems, a warning message can be issued clearly indicating that the measurements from that system require further investigation potentially bringing the use for direct weight enforcement into question.
- Arguably the best option is to link the database of WIM-measured records with the database/s of existing static weighbridges on the road network where heavy vehicles are processed as part of routine operations. Continuous matching of WIM and weighbridge records could produce large samples of WIM verification data on a monthly basis. The benefits of this approach, provided that there are suitable static weighbridge data available, are that large, representative verification samples can be collected at a low cost.

Although the aim of the **WIM accuracy tests** is to confirm compliance with MPE, it would be beneficial to incorporate a statistical approach in the DQM system, where confidence intervals and sample sizes are included in the assessment. The use of a statistical approach will not only indicate if a WIM system passes the MPE criterion, but also how comfortably it passes.

The use of larger samples of measurements to gauge WIM accuracy reduces the risk of erroneous certification. For example, assume that a particular WIM system achieves the specified accuracy 99.9% of the time. Although it technically fails the MPE requirement, this is a very accurate WIM system. The outlying error will only be encountered (on average) once in every 1000 measurements. A small verification sample of 50 measurements would need to be repeated 20 times to observe 1000 errors, giving a realistic chance of detecting excessive error. In this example, there is a 95% probability (19/20) that the verification process will mistakenly pass the WIM system. Furthermore, if only compliance with MPE is tested, the outcome would simply be “Pass” or “Fail,” without providing a meaningful indication of how effective the WIM system is.

A statistical interpretation of the mean and standard deviation of the WIM error allows for a more meaningful calculation of the probability that MPE might be exceeded, even for small test samples. Apart from determining compliance in a particular month, the monthly trend in WIM accuracy can be tracked reliably, and preventative maintenance of the WIM system could be implemented before it actually reaches the point of failing MPE.

The South African TMH3 Specification for traffic and WIM data collection [COTO, 2020] goes a step further and applies a correction to the acceptance threshold to account for the statistical uncertainty brought about by small verification samples and the consequent risk that a substandard WIM system is passed is error (Authority Risk). The smaller the sample, the more comfortably the WIM system must pass the set criteria before TMH3 accepts that it is sufficiently accurate.

WIM Measurement Confidence Tests

Modern, advanced WIM systems calculate a 'Confidence Level' for each of the measured vehicle records. This number (typically expressed as a percentage) reflects the confidence that the WIM system itself has in the quality of each particular measurement and is based on the internal analysis of the signals from all possible sensors in the system. This includes the combination of the weighing (WIM) sensors, the presence sensors (induction loops), and other sensors such as pavement and environment temperature, wind direction and force, pavement deflection, lateral vehicle position, etc. The overall confidence level of a vehicle record is calculated based on a combination of multiple internal checks. Examples of checks are:

- Acceleration or braking of the vehicle during measurement;
- Moving in between lanes or passing partially on a lane during measurement;
- Significant difference in the axle load measurement by different WIM sensors, assuming a multiple strip sensor system design;
- High variations in the axle load measurement during measurement, assuming a scale or scale sensor system design;
- Significant differences between left and right wheel loads, assuming wheel load sensor system design;
- Signals from any of the addition sensors mentioned above outside a pre-defined operational range.

If any of the criteria fail to meet the required level, a warning message is added to the vehicle record, clearly indicating that the quality of this measurement is insufficient for direct weight enforcement.

It is recommended to only use measurements with a sufficiently high confidence level for direct weight enforcement. Always begin the introduction of WIM to introduce direct weight enforcement with conservatively high confidence levels – these margins could be reduced over time and based on practical experience.

7 CONSIDERATIONS FOR IMPLEMENTATION

Using Inaccuracy and Grace Margins

Acceptance of the accuracy limitations of WIM implies that the legal acceptance process must also incorporate safeguards against unfair sanction (a fine, a prosecution or other measure or punishment). The uncertainty in WIM measurement should be offered as a tolerance before a vehicle is sanctioned to ensure that the vehicle was definitely in breach with loading regulations. The tolerance could be applied in two ways. The first approach is to subtract the certified inaccuracy of the WIM system from the measurement result which is then used as the basis for a fine. The second approach is to add the certified accuracy as a grace to the overload limit; sanction is then still based on the unadjusted WIM measurement. Both ways ensure that only actually overloaded vehicles are sanctioned.

For example, a WIM has an MPE of 5%. When it measures a vehicle weight of 50 tonnes, a corrected value of 47.5 tonnes is used to determine if the vehicle was overloaded. This way the enforcement agency always errs on the 'safe side', meaning that the vehicle always had a weight of at least 47.5 tonne. For enforcement agencies it is more important to issue only sanctions that are justified than to 'catch' all possible offenders.

An enforcement agency could also decide to apply an additional 'Enforcement Grace Margin' on top of the corrected WIM measurements. The size of this additional grace margin is a purely operational decision and is not related to the measurement performance of the WIM system used. When starting the implementation of WIM for direct weight enforcement, it is recommended to start with conservatively large grace margins. Over time and based on experience, these margins can be reduced.

Start with Certain Heavy Vehicle Types

In general; WIM systems have more difficulty producing accurate and reliable measurements for vehicles with higher vehicular dynamics. This could be related to the type of vehicle, its construction or its load, e.g. light vehicles, vehicles with old spring leaf suspensions, vehicles with a liquid or moving loads. In the introduction of WIM for direct enforcement, an end-user could start with the enforcement of certain types/classes of vehicle only. For example, in the Walloon region of Belgium the authorities have started their direct weight enforcement only for 5-axle tractor semi-trailer combinations [Antofie, 2019]. This type of vehicle was selected based on experience with the high accuracy and reliability of the WIM measurements and the significant overloading of these vehicles. In New York City the tanker trucks are left out of the direct enforcement operation because of uncertainty with liquid loads [Rodrigues, 2024]. These choices clearly limit the effectiveness of the operation and

may raise questions about the fairness of the enforcement. On the other hand, it may serve as a first step in the implementation in order to build confidence with all organisations involved, while assuring the maximum confidence in the measurements used for enforcement.

Effect of Load Transfer between Axles

Even on a straight, flat road, a moving vehicle needs to apply a horizontal force on the road surface to overcome the rolling resistance and wind resistance that slow the vehicle down. These horizontal forces act at different heights which cause a moment and backward rotation of the vehicle and consequently load transfer from the front axle onto the driving axle/s.

The most significant load transfer occurs on the truck tractors of articulated trucks. For such vehicles, the trailers also exert a significant horizontal pulling force on the kingpin of the truck tractor. Load reduction of between 5% and 8% on the steering axle is typical, which is balanced by an increase in the weight of the driving axle/s. The extent of load transfer increases on uphill sections or when vehicles accelerate. The opposite happens when a vehicle decelerates – the trailer/s push forward onto the kingpin of the track tractor, causing forward rotation and load transfer onto the steering axle. The extent of load transfer for breaking vehicles may be somewhat reduced because of assisted breaking on trailer axles.

With such bias in the data of truck tractors in particular, it is challenging to pass a WIM accuracy verification for the affected axles and axle groups. The extent of a possible shift in load distribution is different for each vehicle depending on its load, driving behaviour and vehicle configuration. It also differs from one WIM location to the next. It follows that the sanctioning of a vehicle on any grounds that are based on the steering axle/s or the driving axle/s measurements carries a higher risk of unfair sanctioning than axle units on trailers or total vehicle mass. It is recommended to implement direct WIM enforcement in a phased approach, with the simpler sanctioning of total vehicle weight and trailer axle units before progressing to steering or driving axle units. An alternative approach is to start with higher tolerances for all measurements and reduce them over time based on practical experience.

Integration of enforcement approaches

Advantages of conventional weight enforcement using static weighbridges include detaining offenders until they have rectified their loads and ensuring that weighing occurs in a controlled environment where registered weights cannot easily be manipulated by vehicle drivers. When direct WIM enforcement is used, an overloaded vehicle is allowed to continue its journey after it has been identified (similar to current speed enforcement practice). The possible traffic safety concern could be addressed by generating additional system alerts for enforcement personnel to intercept vehicles that are significantly overweight or travelling outside of permitted routes. The possibility that deliberate overload transgressors may learn to manipulate their WIM measurements, rendering them unusable in court, is a risk that can be addressed by building a database of vehicles and operators who

habitually manipulate their loads and directly addressing these cases with freight operators. Freight operators generally do not want to spend time appealing sanctions, and experience shows that enforcement by WIM results in massive improvements in levels of compliance.

Direct WIM enforcement can be used in combination with conventional overload control methods. The integration of different overload control approaches can help to strengthen the overall effort as the approaches are complementary [REMOVE, 2006]. For example; data from the network of WIM systems for direct enforcement could be used to audit compliance of freight operators participating in self-regulation initiatives. Potential benefits of adding a static weigh station to a WIM Enforcement system include:

- The accuracy of the enforcement WIM system could be continuously monitored by comparing WIM measurements with their static weight counterparts for the sample of vehicles that were weighed at the static weighbridge.
- WIM data could be used to build a docket of evidence against habitual offenders, described as 'Company Profiling' in [REMOVE, 2006]. Such freight operators could then be targeted at static weighbridges and/or approached separately as part of an indirect enforcement process.

The integration of WIM systems for direct enforcement with other methods of weight enforcement will enhance the effectiveness of the operation and increase compliance with loading regulations. The use of the same WIM data for different applications will make the investment in and use of WIM systems more cost effective.

Continuation of enforcement activities

After a network of WIM systems has been in operation for a certain period of time the overloading on the corresponding road network should stabilise at a reduced level. Consequently in this new situation the number of vehicles that will receive a sanction will be lower than at the start of the implementation. This means that the financial 'revenues' from the sanctions will also be lower, while the costs for operating the WIM network and enforcement activities will remain the same. This often raises the question: "Why is it still needed to invest in these enforcement activities when the problem no longer exists?"

It is important to take a step back and remember what the initial motivation for the investment was. Was it the collection of money from fines or the reduction of the negative effects of overloading (see Chapter 3)? It is recommended to relate the initial investment to the benefits of reducing overloading. Following this line of reasoning, the continuation of enforcement activities and the operation of supporting WIM systems are required for the ongoing prevention of overloading.

To calculate the savings from a reduction in overloading, it is recommended to conduct a baseline zero measurement at the start of the WIM system implementation. This can be done by simply letting the WIM network measure the existing overloading situation prior to using the measurements for weight enforcement.

Dealing with multiple detections

In case a network of WIM systems is being used for direct weight enforcement, it is possible that several WIM systems register the same overloaded vehicle. Unlike speed enforcement, where a driver can quickly adjust the vehicle's speed, it is often impossible for a driver to change the load of their vehicle during an entire journey. In many countries it is legally not allowed to issue multiple sanctions for the same infringement/offence.

There are several possible solutions for this issue:

- Only one of the multiple detections could be used to determine the sanction for overloading. This could be the lowest, the highest or average value depending on what is considered fair and effective.
- Set a maximum limit to the combined fine that can be issued per day per vehicle or per journey, considering that an important part of the objective of enforcement is educative aimed at changing behaviour of the road transport industry in order to reduce the costs of the damage caused by overloading.
- The sanction (value of the fine) could be made depending on the damage done to the road infrastructure. The damage may be calculated based on the amount of overloading and the distance travelled between the WIM stations. The summation of consecutive sanctions along a route would then add up to the cumulative value of road infrastructure damage. The calculation of the damage and the corresponding value of the sanction should be well founded and legally accepted.

Dealing with multiple detections may become more complicated when different authorities are involved. For instance, different parts of a WIM network may be operated by different authorities or different countries/states may be involved.

Vehicle identification

A point that falls outside the scope of this document but is essential for a successful implementation of direct weight enforcement is a positive and correct vehicle identification. The sanction for a detected overload should not only be based on a correct WIM measurements it should also be addressed to the right person or company. Different systems for vehicle identification are available such as: digital cameras with Automatic Number Plate Recognition (ANPR) and electronic RFID-transponders readers.

It is recommended to assess the performance of vehicle identification systems, such as the recognition rate of ANPR systems, and to consider alternative or supplementary methods if needed.

8 EXAMPLES OF ACTUAL IMPLEMENTATIONS

Czech Republic

During the year 2011 different types of WIM systems were certified in accordance with a national regulation designed and elaborated by the Czech Metrology Institute (CMI), taking into account the most important international documents used in this field (OIML R134, COST 323, ASTM E1318 and FIWI [FIWI, 2007]). The regulation is a complex document which specifies the detailed testing procedure for the type approval and verification of WIM systems, the metrological and technical requirements and the functional laboratory tests which have to be carried out when applying for type approval certification.

A unique procedure in the implemented WIM systems is the internal check on the "validity of measurement", which identifies data out of specification due to unusual vehicle and driving behaviour. This allowed the extension of the application of the WIM systems from the standard high-speed traffic data collection to the enforcement application. Based on practical experience from hundreds of WIM sites, some parts of the metrological "Procedure for testing of automatic instruments for weighing road vehicles in motion and measuring axle loads" were changed in conformity with OIML R134. The specified accuracies of measuring are: ± 5% for GVW and ± 11% for measurements of axle loads between 2 and 30 tonne and speeds between 10 and 160 km/h.

South Africa

In South Africa, the implementation of Direct WIM Enforcement (WIMe project) is driven by the South African National Roads Agency (SANRAL) on behalf of National Government. An electronic traffic monitoring network is envisaged that will incorporate approximately 170 WIMe stations. Should the Provincial Governments agree to participate in this strategy, the number of WIMe systems may increase to more than 350. Research into the WIMe concept was concluded in 2023, and the implementation phase of the project started in 2025. The first phase of the project entailed technology trials where competent WIM providers were invited to install test systems to confirm their accuracy under South African traffic and environmental conditions.

The purpose of these trials was to pre-qualify participants for the subsequent WIMe project. Successful bidders would then be required to obtain Type Approval in terms of the national standard developed by the National Regulator for Compulsory Specifications (NRCS) during the probation period of the main WIMe contract. The direct use of an international standard is not possible because the South African judicial system requires that metrological standards for law enforcement must be contained in a South African Standard. The NRCS Requirements are however based on OIML R134 and therefore well aligned with international practice [NRCS, 2024].

WIM for direct weight enforcement may ultimately form part of a holistic national overload control strategy that may include weigh bridges with WIM as pre-selection, a weighbridge bypass system and a self-regulation programme [De Wet & Nordengen, 2025].

Brazil

In Brazil, enforcement of vehicle weight regulations on federal highways is split between the National Department of Transport Infrastructure (DNIT) on non-concession roads and the National Land Transport Agency (ANTT) on concession roads. DNIT operates the Mobile Operational Unit (UMO) program, which couples high-speed WIM screening with mobile enforcement units using static and low speed portable scales, supported by on-site infrastructure such as parking bays for axle rebalancing and unloading. A 2017 national procurement deployed 61 UMO units across the federal network.

In parallel, ANTT has launched WIM for direct enforcement under a controlled, regulatory test environment (Sandbox). In partnership with a concessionaire, four traditional weigh stations were replaced by HS-WIM sites that enable weighing at traffic speed and electronic enforcement. The HS-WIM systems are certified by INMETRO (Brazil's national metrology authority). Brazilian legislation requires the use of INMETRO regulations for legal metrology; therefore, WIM solutions certified under OIML or any other foreign regulations are not legally valid for enforcement in Brazil unless they are certified locally by INMETRO. Together, these initiatives mark Brazil's first large-scale HS-WIM direct enforcement deployments, combining national certification with pilot operations on concession corridors.

New York City

In New York City, the Brooklyn-Queens Expressway (BQE), particularly the New York City Department Of Transportation-owned section between Atlantic Avenue and Sands Street, exemplified the challenge of asset management. As a critical transportation corridor carrying over 130,000 vehicles per day, including a significant volume of freight traffic, the BQE's deteriorating condition became a focal point for asset management innovation resulting in the use of WIM for direct enforcement. The WIM system captures on-site truck load data and enables the issuance of real-time sanctions for vehicles exceeding legal weight limits. This serves both as a data source for ongoing structural analytics and as a behavioural deterrent. After testing different sensor systems and obtaining data over several months, the Department obtained legislative authority to begin a pilot program for direct enforcement of weight limits using WIM on the BQE. It was launched in 2023 and has succeeded in reducing overweight volumes by 60% in this section of the BQE.

Existing standard specifications within the USA do not have codes for type certification or certification for WIM systems for direct weight enforcement. A WIM system that was type certified according to OIML R134 was used for the pilot and a certification test was developed in line with the OIML R134 recommendations but in-line with typical codes in use within the USA. The efforts to update the National Metrology Institute Handbook 44 with technical requirements for measuring devices to include certification testing procedures for WIM systems, are ongoing. However the New York State Department of Agriculture has the authority to certify the system under a pilot program and has done so using the proposal under consideration for inclusion in the handbook. An expansion of the program within New York City with additional locations has been approved by state legislators while additional states within the USA are at varying levels of development of programs within their jurisdictions, see [Rodrigues, 2024].

Hungary

After two years of legislative preparation, the live testing of National Axle Weight Measurement System (TSM), featuring 100+ control sites nationwide on the roads of Hungary, has started in early 2018. Although the size and weight limits for freight traffic control were unchanged, the introduction of TSM into the Hungarian legal system was a major task. A new type of administrative fine for deliberate and repeated manipulation or avoidance of the weight measurements can now be imposed on truck operators. The specifications for the WIM systems and the test and certification procedure are in compliance with the OIML R134 recommendations. The initial verification included the testing and certification of 189 lanes for weighing. This immense logistical task has been carried out between August 2017 and January 2018.

Automatically generated administrative fines for weight limit violations based on WIM data began to be sent out in July 2018. During the introductory period the WIM systems were activated in groups and temporary higher tolerances for weight measurements were applied and separately scheduled. During the first 7 months of operation, 10-15% of certified sites were operational at a given time, in periodic rotation [Ronay-Tobel, 2019]. Fines were applied on 1294 occasions, which is a five-fold increase compared to the average performance of traditional mobile inspections.

9 CONCLUSIONS AND RECOMENDATIONS

The main purpose of this guide is to share and disseminate proven best practice. The following are some of the key takeaways for novice and experienced WIM practitioners.

Conclusions

- Fully automatic direct weight enforcement using Weigh-In-Motion systems, where the WIM measurement is used directly as the basis for legal sanction of overloading, is one of the most efficient ways of weight enforcement.
- WIM systems used for direct weight enforcement are operational 24/7, monitoring 100% of the passing truck traffic.
- Several countries, regions, and cities have started implementing WIM for direct weight enforcement.
- WIM systems for direct weight enforcement can either be implemented on their own or integrated into a holistic overload control programme.
- Several international documents are available that serve as standard specifications for WIM systems for direct weight enforcement.
- National or regional authorities (governmental agencies) often develop their own standards for metrological approval that are intended for the specific national road, traffic and overloading conditions.
- These national standards differ from the international documents. This leads to additional costs for both the governmental agencies as end-user and the providers of WIM systems which is especially relevant for smaller countries.
- The implementation of WIM for direct enforcement requires the most advanced WIM technology and a very careful introduction procedure. It consists of three elements: Legal Acceptance, System Certification and Data Quality Control.
- The first element in a successful implementation is a set of legal regulations and officially verified procedures that will be accepted by a national or state court.
- Next, successive approval tests (Type Approval, Initial Verification and In-service Verification) serve as a reference confirming WIM accuracy to metrological standards.
- Finally, a data quality control system must be in place that constantly verifies the quality of each measurement using a combination of checks.

- WIM weighing accuracy tests comparing samples of WIM data with known reference (static weighbridge) weights are used to confirm weighing accuracy.
- The traceability of the WIM measurements is established through a series of performance tests that connect the WIM measurements via certified static or low-speed reference measurements to the national standard for weight measurements.

Recommendations

- When specifying the performance tests for WIM systems used for direct weight enforcement, the measurement accuracy should preferably be specified in terms of the Maximum Permissible Error (MPE).
- Although the aim of the WIM accuracy tests is to confirm compliance with MPE, it would be beneficial to follow a statistical approach in the DQM system where confidence intervals and sample sizes are incorporated into the assessment.
- Make sure to specify a WIM system that is fit for purpose and be aware that, in the end, the reliability of the WIM measurements is as important as the accuracy.
- Accept the type approval certificate from existing international standards issued by accredited metrology institutes. Only adjust the requirements for the initial verification and in-service verification to specific national or regional conditions.
- Set realistic national or regional requirements for the size of initial and in-service verification tests that strike a balance between statistical reliability and practical constraints.
- If possible, have the full set of legal regulations and operational procedures officially verified and accepted by the adjudicating national or regional authority before the start of the direct enforcement operation.
- Have the data quality management system developed and running for a couple of months to a year before the start of the direct weight enforcement operation to ensure proper functioning.
- The data quality management system should consist of three levels of tests:
  - General WIM performance stability tests with high-level statistical checks on the stability of the WIM data;
  - WIM weighing accuracy tests comparing samples of WIM data with known reference (static weighbridge) weights to confirm weighing accuracy;
  - WIM measurement confidence tests performed by the individual WIM system per measurement to rate the confidence in the quality of the measurement and the suitability for prosecution purposes.
- For weight enforcement applications, subtract the certified measurement inaccuracy (MPE) of the WIM system from the measurements. Alternatively the inaccuracy may be added as a grace margin on top of the legal loading limits before a sanction is applied.

- Only use measurements with a sufficiently high confidence level for direct weight enforcement. Start implementation with conservatively high confidence levels – these margins can be reduced over time and based on practical experience.
- Another way of a step-by-step implementation of WIM for direct enforcement is to start with certain 'easy' types of vehicle only or to exclude certain 'difficult' ones.
- Direct WIM enforcement can be used in combination with conventional overload control methods. The integration of different overload control approaches can help to strengthen the overall effort as the approaches are complementary.
- To be able to calculate the savings from a reduction in overloading resulting from an investment in a network of WIM systems for weight enforcement, it is recommended to do a baseline measurement, i.e., collect overload statistics before implementation of the WIM enforcement process.
- Be aware that positive vehicle identification is essential for a successful implementation of WIM for direct weight enforcement. Assess the performance of different vehicle identification systems.

11 REFERENCES

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