NIST Special Publication 2200
NIST SP 2200-05

Certification Approaches for Weigh-In-Motion Systems in Law Enforcement Applications

Jan Konijnenburg
Loren Minnich
Katrice A. Lippa
Tanvi Pandya
James Willis

This publication is available free of charge from:
https://doi.org/10.6028/NIST.SP.2200-05

Credit: Adobe Stock, NYC DOT, NIST OWM

NIST NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY
U.S. DEPARTMENT OF COMMERCE

NIST Special Publication 2200
NIST SP 2200-05

Certification Approaches for Weigh-In-Motion Systems in Law Enforcement Applications

Jan Konijnenburg
Loren Minnich
Katrice A. Lippa
NIST Office of Weights and Measures
Physical Measurement Laboratory

Tanvi Pandya
New York City
Department of Transportation

James Willis
New York State
Department of Agriculture and Markets

This publication is available free of charge from:
https://doi.org/10.6028/NIST.SP.2200-05

March 2024

U.S. Department of Commerce
Gina M. Raimondo, Secretary

National Institute of Standards and Technology
Laurie E. Locascio, NIST Director and Under Secretary of Commerce for Standards and Technology

NIST SP 2200-05
March 2024

Publication History
Approved by the NIST Editorial Review Board on 2024-03-22

How to Cite this NIST Technical Series Publication
Konijnenburg J, Minnich L, Lippa KA, Pandya T, Willis J (2024) Certification Approaches for Weigh-In-Motion Systems in Law Enforcement Applications. (National Institute of Standards and Technology, Gaithersburg, MD), NIST Special Publication (SP) NIST SP 2200-05. https://doi.org/10.6028/NIST.SP.2200-05

NIST Author ORCID iDs
J Konijnenburg: 0000-0003-2592-873X
L Minnich: 0009-0006-8082-2726
KA Lippa: 0000-0001-8651-8326

Contact Information
owm@nist.gov

Abstract

Every day, overweight and excessively heavy vehicles cause damage to roads, bridges, and other vehicle-based infrastructure. To protect the vital transportation infrastructure for the U.S., states have imposed weight limits for commercial and fleet transport vehicles. A common way for enforcing these weight limits is to guide trucks off the road to weigh stations where the vehicles can be weighed using static truck scales. A disadvantage of these dedicated weigh stations is that they take up a substantial amount of space (which is not always available) and time to conduct weighments, as well as cause delays to traffic flow that may impede commerce based on truck transport. A solution to these problems is the use of high-speed weigh-in-motion (WIM) systems that are installed in the road and weigh vehicles as they pass by while maintaining their speed.

For jurisdictions to effectively use a WIM system for direct enforcement of weight limits, the system must be evaluated against a recognized standard to establish suitability for its intended application. The vast majority of weighing instruments used for legal metrology purposes (including law enforcement) need to comply with the requirements in NIST Handbook 44 *Specifications, Tolerances, and Other Technical Requirements for Weighing and Measuring Devices*. However, the NIST Handbook 44 does not (yet) cover WIM systems for direct enforcement.

Although state and local jurisdictions use NIST Handbook 44 to certify legal metrological instruments, it does not exclude jurisdictions from using additional technical standards to certify certain instruments. New York City recently certified a WIM system to protect a critical section of the Brooklyn-Queens Expressway (BQE) by designating it as a pilot project while efforts were made to amend NIST Handbook 44 to include WIM systems for direct enforcement.

This publication discusses the main characteristics of WIM systems and how they can be used for direct enforcement. An overview of several alternative documentary standards that can be applied for certification of WIM systems is also provided, with further explanation regarding how the New York City Department of Transportation (NYCDOT) implemented the certification of the WIM system to begin issuing citations to overweight vehicles in an effort to protect the BQE.

Keywords

ASTM E1318, axle load, BQE, Brooklyn-Queens Expressway, certification, COST 323, direct enforcement, gross vehicle weight, infrastructure, New York, NIST Handbook 44, NMi international WIM standard, OIML R 134, road protection, weigh-in-motion, weight enforcement, WIM.

Table of Contents

List of Tables

List of Figures

Acknowledgments

The authors appreciate the technical support and implementation efforts provided by Prof. Hani Nassif, Dr. Chaekuk Na, Dr. Patrick Lou, and Jihao Ding at Rutgers University. Additionally, they would like to acknowledge with thanks the financial support received from C2SMARTER (Connected Communities for Smart Mobility towards Accessible and Resilient Transportation for Equitably Reducing Congestion), a Tier 1 University Transportation Center at New York University with Prof. Kaan Ozbay as Director and Shri Iyer as Managing Director at NYU. The organizations cited are not responsible for the accuracy of facts and views expressed by the authors.

Author Contributions

JK: Conceptualization, Investigation, Project administration, Writing – original draft, Writing – review & editing; **LM**: Investigation, Writing – review & editing; **KAL**: Supervision, Writing – review & editing; **TP**: Writing – original draft, Writing – review & editing, Project administration, Methodology, Visualization; **JW**: Writing – review & editing.

1. Introduction

According to *Fact Sheet: The Bipartisan Infrastructure Deal* [1], one in five miles of U.S. highways and major roads and over 45,000 bridges are in poor condition. A major contributor to road damage stems from heavy or excess weight vehicles – or to be more precise – the heavy axle loads of these vehicles onto the road surface and/or pavement. As claimed by an article of Inside Science [2], this damage grows exponentially with the axle load of the vehicle. For comparison, a 40-ton commercial truck with 8 axles causes 625 times more road damage than a 2-ton passenger sedan with 2 axles.

So, what does this damage cost us as a nation? According to the same Inside Science article [2] the annual expenses in 2017 on highways and roads in the U.S. was $ 181 billion. Besides the costs of the material damage, there is also the economic loss due to traffic jams and road closures, and even more serious, the possibility of injuries or loss of life due to collapsing structures. In 2019, 7.5% of the highway bridges were designated structurally deficient or poor [3]. A dissertation from the Utah State University [4] shows that in 2014, the expected bridge failure rate is 1 out of 4,700 annually, with a failure being a partial or total collapse. Of these, 12% were attributable to overload.

The Brooklyn-Queens Expressway (BQE) is a heavily used highway that comprises a critical link of I-278 – the sole Interstate highway in Brooklyn that connects Manhattan, Staten Island, and Queens in New York. Regionally, it is also the only freight route into the New York City (NYC) area from New Jersey to the south through Staten Island and a vital freight route for Nassau and Suffolk Counties. This portion of BQE was completed in 1954; parts of the expressway are at the end of their design life and in a deteriorating state.

A weigh-in-motion (WIM) system installed on the BQE in October 2019 revealed the presence of significantly overweight vehicles, i.e., greatly exceeding Federal Highway Administration (FHWA) legal load limits, with gross vehicle weights that range from just over 80,000 lb (36,287 kg) to as high as 200,000 lb (90,718 kg). Of the approximately 25,000 trucks a day on this section of the BQE, over 10% were found to be overweight. The NYC Department of Transportation (NYCDOT) conducted structural assessments that considered not only the material degradation but also accounted for the large number of overweight vehicles in the site-specific live load factors. This effort highlighted the impact of overweight vehicles on the remaining service life of the structure. While urgent repairs are underway to protect this critical piece of infrastructure, additional means to slow down further deterioration needed to be identified. The New York State legislature authorized the NYCDOT to conduct overweight vehicle enforcement through a weigh-in-motion system demonstration program on this section of the BQE in 2021.

NIST Handbook 44 *Specifications, Tolerances, and Other Technical Requirements for Weighing and Measuring Devices* [5] defines the requirements for weighing and measuring instruments used in commercial transactions and for law enforcement purposes. NIST Handbook 44 includes Section 2.25 Weigh-In-Motion Systems Used for Vehicle Enforcement Screening-Tentative. As the title of this code already states, the WIM systems covered by this code are only used for screening and not for direct enforcement. Thus, any overweight vehicle violations are issued

based on subsequent static scale measurements. This tentative code for screening equipment was incorporated in the NIST Handbook 44 in 2015. However, high-speed WIM systems for direct enforcement applications are currently not covered by the existing language in NIST Handbook 44. Therefore, certification of high-speed WIM systems for direct enforcement based on NIST Handbook 44 is not yet possible.

As a documentary standard, the language within NIST Handbook 44 is considered "model code" and is adopted by each state in some form. Thus, it is not a law or regulation, but rather language to be used by state legislative bodies as a model for the creation of laws and regulations. Ultimately, weighing and measuring instruments used for commerce and law enforcement must comply with the language that is adopted and serves as the state's official legislation. Compliance with NIST Handbook 44 is a generally accepted method to prove compliance with this legislation, but it is not necessarily the only method.

The relevant weights and measures or law enforcement agency within a state's jurisdiction has the ultimate authority (and responsibility) to impose any necessary requirements for approval, testing, and regulation of highway weight enforcement equipment that will be used to determine violations and ultimately protect the state's critical infrastructure. These administrative entities may utilize the model law language within NIST Handbook 44 (e.g., removing its tentative status and making any other necessary changes) or adopt the specifications (or similar) requirements from other international standards (e.g., OIML R 134, ASTM E1318, or COST 323.)

This special publication describes a similar approach by the New York City Department of Transportation to successfully implement direct enforcement of weight limits for vehicles on the BQE using a high-speed WIM system. This was also conducted in parallel with submission of proposed changes to the WIM system model code in NIST Handbook 44 (and the National Type Evaluation Program (NTEP)) through the National Conference on Weights and Measures (NCWM) standard development process. While not always a viable option for other weights and measures authorities, a similar approach may be considered if a critical need exists to utilize other measurement devices and/or instruments in legal metrology applications that are not presently covered by the model code in NIST Handbook 44.

2. Weigh-in-motion (WIM) Systems

Weigh-In-Motion (WIM) systems are designed specifically to weigh vehicles "in motion", in contrast to the more common static vehicle scales. These WIM systems consist of one or multiple load sensors that are installed in the pavement of the roadway or placed on top of the roadway as a portable system option. WIM systems have existed for several decades and are used in applications such as data collection, tolling and vehicle screening. But these systems are not yet widely used for trade or direct enforcement of weight limits on public roadways.

The International Organization of Legal Metrology (OIML) sets international standards for weighing and measuring instruments used for legal purposes such as trade and law enforcement. OIML certified laboratories perform OIML certifications of instruments according to these

standards. At the time of this publication, only 28 OIML certificates for WIM systems are registered [6] on the OIML site.

WIM systems are loosely categorized as either: 1) low speed systems or 2) high speed systems. While there is not a defined boundary between the two, the low-speed systems generally operate with vehicles speeds up to approximately 50 kilometers per hour (approximately 30 miles per hour), whereas high speed systems are designed for use up to the roadway speed limit. Table 1 shows the typical usage and operational specifications of WIM systems for each category. Trade and other commercial applications require relatively high accuracy of the weighment, thus low speed WIM systems are generally required here. Given their use in trade and commerce, these systems are generally installed at designated locations that are near airports, shipping ports, major traffic hubs, etc. The high-speed WIM systems are mostly used on public highways to detect overloaded vehicles. Initially, high-speed WIM systems were mainly used for screening purposes only. With the performance of WIM systems consistently improving with technological advancements, these systems are now being used in multiple countries for direct enforcement. High-speed WIM systems are not yet being used in regulatory applications for trade and commerce as the accuracy requirements for those applications are stricter.

Table 1. Typical characteristics of low-speed and high-speed WIM systems.

Low-speed WIM	**High-speed WIM**
Used for commercial applications	Used for law enforcement
Installed at designated locations	Installed on public roads
Relatively high accuracy (OIML R 134[a]: 0.2% to 2%)	Relatively low accuracy (OIML R 134[a]: 5% to 10%)
Vehicle weighing and/or axle load weighing	Axle load weighing

[a]OIML R 134 *Automatic Instruments for Weighing Road Vehicles in Motion and Measuring Axle Loads*

High-speed WIM systems are generally installed on public roads and use narrow load sensors that measure the load of individual axles. Because of the limited contact time that a vehicle is positioned directly on the sensor, high-speed WIM systems are not as accurate as low-speed WIM systems or static scales. Other vehicle operation conditions, such as bouncing of a relatively empty vehicle at higher speeds, can also affect the accuracy of the measurement.

Weighments for commercial transactions require relatively high accuracy (generally within 2%) to ensure marketplace equity. Further, only a small deviation is allowed in the weighments that result in either direction (termed *over registration* when the weight determined is more than the actual weight or *under registration* when the weight determined is less than the actual weight). This protects both parties in commercial applications (the seller and the buyer) who have an equal interest in accurate measurements. The buyer does not want to overpay for the quantity of the product being purchased, while the seller does not want to be underpaid for the goods being sold.

When enforcing vehicle weight restrictions, the primary goal is to enforce the law and safeguard both infrastructure and public safety. Therefore, maximizing the number of detections of overweight vehicles (and the consequential increase in violation deterrence) is more important than maximizing the monetary amount of the citations. To prevent drivers from being cited incorrectly (or, worst case, wrongfully losing their license to operate commercial vehicles), the weighing result from the WIM system must be corrected to account for the inaccuracy of the system. If the corrected value exceeds the legal weight limit, then it constitutes a clear violation. For example, if a 10% correction is applied to the measured weight value, then 90% of this weight value stands as the basis for a possible citation.

Given the critical need to reduce the number of highly problematic (i.e., significantly overweight) vehicles, high-speed WIM systems could be deemed suitably accurate for this urgent law enforcement purpose. Jurisdictions must decide if the benefit of more rigorous law enforcement outweighs a possible reduction of issued citations.

3. Certification of WIM systems under NIST Handbook 44

According to NIST Handbook 130 *Uniform Laws and Regulations in the Areas of Legal Metrology and Fuel Quality*, section II, *Uniformity of Laws and Regulations* [7], all U.S. states have, in some form, voluntarily adopted and will implement the model code in NIST Handbook 44 for weighing and measuring instruments used in commercial and law enforcement applications. Adoption of these laws and regulations signifies that these instruments must comply with all specifications, tolerances, and user requirements and that they are to be evaluated according to the test procedures described in NIST Handbook 44.

To validate that the design of an instrument complies with NIST Handbook 44, a type evaluation is performed under the NCWM National Type Evaluation Program (NTEP). The tests performed on the instrument are described in the applicable section of NCWM Publication 14 *Weighing Devices* [8]. After the instrument has passed all applicable tests during the type evaluation process, it receives an NTEP Certificate of Conformance (NTEP CC) as proof of compliance. As described in NIST Handbook 130, section II, *Uniformity of Laws and Regulations* most U.S. states require a type evaluation of an instrument used for legal purposes; however, a few states opt to not require a type evaluation.

When placed into service, the weighing instrument is evaluated for compliance with the specifications, tolerances, and user requirements detailed in NIST Handbook 44. In states that require a device to have an NTEP Certificate of Conformance, the device is evaluated to ensure that it was produced to meet the stipulations on the certificate, e.g., capacity limits, size, the type of materials used, etc. However, testing of the scale to check performance characteristics can only be conducted according to more generalized test procedures described in NIST Handbook 44, limiting the extensiveness of these evaluations. Subsequent verifications should be performed throughout the time the weighing instrument is used for legal applications.

Until 2022, WIM systems were only covered by NIST Handbook 44 (section 2.25, *Weigh-In-Motion Systems – Tentative Code*) for Vehicle Enforcement Screening applications. As the title suggests, WIM systems under this section cannot be automatically used for direct enforcement. Vehicles that are flagged for exceeding the weight limit by these WIM systems are to be reweighed on a certified static scale to determine the final weight value for a possible citation. (In some states, the weight value from the WIM system is used as a basis for the citation after the driver declines the option offered to him to reweigh the vehicle on a certified static scale.)

Provisions for WIM systems used for commercial trade applications, in NIST Handbook 44 referred to as WIM vehicle scales, were added to NIST Handbook 44 in 2022. As these provisions were added to section 2.20 (Scales code), these WIM systems must comply with the same tolerance levels as static scales used for trade. Hence, these systems are in general low-speed WIM systems and not suitable to be installed on public highways.

In 2021, the State of New York (NYS) passed legislation permitting use of WIM systems for direct enforcement of weight limits as a demonstration program. In August 2022, the New York City Department of Transportation (NYCDOT), together with C2SMART (USDOT Tier 1 University Transportation Center) and Kistler (manufacturer of the WIM system utilized by NYCDOT), submitted a proposal to the NCWM to amend NIST Handbook 44 [9] to include regulations for WIM systems used for direct law enforcement. Unlike the existing code for WIM systems in section 2.25, *Weigh-In-Motion Systems – Tentative Code*, weight values obtained from the WIM system could then be directly used for citing overweight vehicles without the need to reweigh these vehicles on a static scale. The submission is part of an attempt by NYCDOT to reduce the number of overweight vehicles passing over the Brooklyn-Queens Expressway.

The proposal to amend NIST Handbook 44 is currently under consideration by the Specifications and Tolerances (S&T) Committee of the National Conference on Weights and Measures (NCWM). If the proposal is adopted by the NCWM, the adopted code for WIM systems for direct enforcement will be added to the NIST Handbook 44, allowing these systems to be regulated in a manner congruous to that of most (if not all) other instruments used in legal metrology applications. The proposal will be voted on during the 109th NCWM Annual meeting in July 2024 and, if adopted, will be added into the NIST Handbook 44 to take effect January 1, 2025.

4. Certification of WIM systems based on other documentary standards

The fact that a certain instrument or instrument type is not specifically covered by the different sections in NIST Handbook 44 does not necessarily mean that the instrument cannot be used for legal metrological purposes. NIST Handbook 44 is a legal metrology documentary standard that contains model code concerning proof of compliance with state laws and enforcement of associated regulations. But if the state's legislation permits, it is possible to prove compliance through other standards for implementation of relevant legal metrology device evaluation methods. For WIM systems, there are existing international standards that can serve as alternative model code for evaluations of this type of weighing instrument.

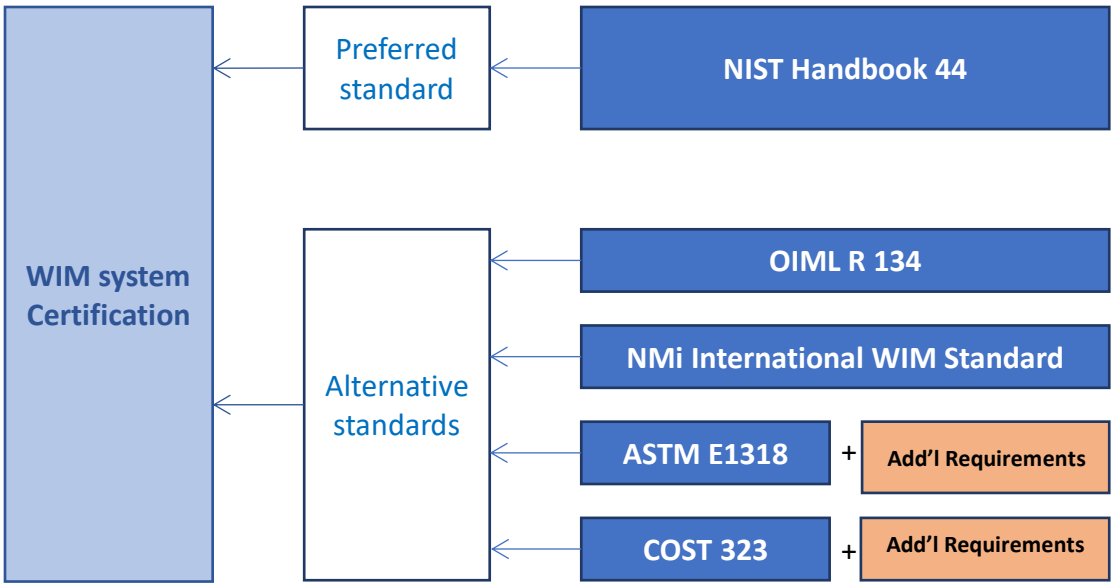

Fig. 1. Preferred and alternative standards to be used for certification of WIM systems. The application of ASTM E1318 and COST 323 may benefit from additional legal metrology requirements (see section 4.5).

Figure 1 shows the preferred and the internationally recognized documentary standards (OIML R 134, ASTM E1318, COST 323, and NMi International; each described in following sections 4.1 through 4.4, respectively) that states may alternatively use for the certification of WIM systems. OIML R 134 and the NMi International WIM Standard are developed from a legal metrology perspective and offer a complete set of requirements for WIM systems used for law enforcement purposes. ASTM E1318 and COST 323 focus on the field testing of WIM systems and lack requirements that are common for instruments used in legal applications. States may consider additional metrologically relevant requirements when applying these two alternative standards; these are described in further detail in section 4.5.

4.1. OIML R 134

One appropriate alternative standard for the evaluation of WIM systems is the OIML R 134 *Automatic Instruments for Weighing Road Vehicles in Motion and Measuring Axle Loads* [10]. Like all OIML Recommendations, OIML R 134 is focused on the technical aspects of the weighing instrument for use in legal metrological applications.

OIML R 134 applies to all WIM systems that are installed in a controlled weighing area (areas with requirements on the aprons, or approaches, on either end of the weighing instrument) and used for determining vehicle mass, single-axle loads and/or axle-group loads. As with all OIML Recommendations, OIML R 134 does not specify a certain application. Therefore, this Recommendation could apply to both commercial and law enforcement applications (and any other application where certification of WIM systems is required). Additionally, the technical specifications and requirements of OIML Recommendations for weighing instruments universally apply to the relevant metrological purpose, regardless of the specific type of technology that is used to fulfill that purpose. Thus, under the OIML R 134 standard, WIM systems may use a

weighing platform that is capable of handling vehicle traffic or road sensors (or any other suitable technology to weigh vehicles).

To accommodate multiple applications, R 134 specifies multiple accuracy classes for both vehicle mass and single-axle loads/axle-group loads. The vehicle mass accuracy classes range from Class 0.2 (0.2% accuracy) to Class 10 (10% accuracy), while the accuracy classes for single-axle loads and axle-group loads range from Class A (0.5% accuracy for two-axle vehicles and 1% for other vehicles) to Class F (8% accuracy for two-axle vehicles and 16% for other vehicles).

The range of accuracy classes as described in the Recommendation offer flexibility in the use of WIM systems for range of applications such as commerce, law enforcement, safety regulations, and monitoring. Furthermore, this may provide regulators more flexibility to choose the appropriate level of accuracy for their current needs and purposes within their jurisdiction.

Although no single application is assigned to the different accuracy classes in OIML R 134, in practice, these classes often serve clearly distinct purposes. WIM systems with a high accuracy class (Class 0.2 to Class 1) are often used for commercial applications. With the current technology, this kind of accuracy can only be achieved by performing the measurements at low speed. Therefore, these installations are generally not installed on public roads, but rather within dedicated weighing areas near trade facilities. WIM systems that are installed on public roads are generally used to measure vehicles at high speed. This tends to make them less accurate and thus not suitable for commercial applications. These types of systems are generally used for law enforcement.

Additionally, OIML R 134 offers technical guidance regarding appropriate testing conditions and procedures for WIM systems, both dynamically and statically as the applied technology permits. For example, large weighing platforms that can hold a complete vehicle (often used in low-speed WIM systems with a relatively high accuracy) can easily be tested statically with test weights. WIM systems using narrow road sensors (often used for high-speed WIM systems with a lower accuracy) cannot be tested statically and require dynamic testing using reference vehicles.

Where NIST Handbook 44 delineates individual sections for WIM systems for commercial application (section 2.20, *Scales*) and WIM systems for law enforcement (section 2.25, *Weigh-In-Motion Systems – Tentative Code*), OIML R 134 covers both applications and types of WIM systems.

4.2. ASTM E1318

Another documentary standard that provides evaluation methods for WIM systems is ASTM E1318 *Standard Specification for Highway Weigh-In-Motion (WIM) Systems with User Requirements and Test Methods* [11]. This standard from the American Society for Testing and Materials (ASTM) defines four types of WIM systems (Type I to IV). Type I and Type II systems are both used for traffic data collection, with Type I having slightly stricter tolerances than Type II. Type III systems are to be used exclusively for screening vehicles at weigh enforcement stations,

and thus cannot be used for direct enforcement (the issuance of citations based on the measured values from WIM). Type IV is defined to be used for direct enforcement but only at low vehicle speeds (up to 10 mph, or 16 km/h). Type IV installations have not yet been certified in the U.S. for use in direct enforcement applications.

While the tolerances for Types I, II and III WIM systems are based on a percentage of the load, the tolerance for Type IV systems used in direct enforcement applications is a fixed value, regardless of the load. However, this tolerance is only valid for loads equal to or exceeding a threshold value. This approach does not correspond with the performance of actual WIM systems, which exhibit an error proportional to the load. Furthermore, the metric tolerances do not correspond to the tolerances in imperial units. For example, the tolerance for the wheel load is set to 300 lb or 100 kg, while 300 lb equals 136 kg; 36% more than stated. All in all, the defined tolerances for Type IV systems are ambiguous and do not reflect the actual error curve of a WIM system. Although not advocated as suitable for direct enforcement, the tolerances of Types I, II and III systems seem to be more suitable since these Types use a percent tolerance.

The ASTM E1318 standard is predominately focused on field testing of WIM systems. Although ASTM E1318 does describe general approaches for type approval testing, it does not prescribe any specific laboratory-based evaluations, such as influence factor tests, electromagnetic compatibility (EMC) disturbance tests, or an examination of software security aspects. This makes the standard minimally applicable for use in legal metrological applications. Additional requirements are necessary to achieve a similar level of security and resilience to disturbances and influence factors as other weighing instruments that are under legal control as described in NIST Handbook 44.

Furthermore, the tolerances provided in ASTM E1318 are applied to only 95% of the measurements. If this standard is applied to WIM installations that are to be used for legal applications, then 100% of the measurements must be within tolerance.

4.3. COST 323

The European Cooperation in Science and Technology (COST) is a funding organization for the creation of interdisciplinary research networks (termed COST Actions) that brings researchers and innovators together to investigate a topic of their choice. The COST 323 Action is comprised of legal metrology and weighing instrument specialists from 16 European countries and is focused on WIM systems. The COST 323 Final Report *Weigh-In-Motion of Road Vehicles* [12] is a pre-standardization document with technical considerations that standardization committees can use as a reference. The specifications within the report provide a complete on-site WIM system performance assessment but exclude any potential laboratory evaluations.

The specification defines six distinct accuracy classes (A to E) that can be applied for different applications such as the generation of robust statistics, preselection of vehicles, and use in legal metrology applications. The accuracies range from 5% (Class A) for legal metrology purposes (e.g., commercial transactions) to 25% (Class D) for gathering viable statistical data and signific

information. An additional Class E has an undefined tolerance and is used specifically to designate systems that cannot meet the accuracies defined for Classes A through D.

Like the ASTM E1318 standard, the specifications provided within the COST 323 report are not sufficient for use as a standard for WIM systems in legal applications. Additional requirements are necessary to achieve levels of metrological security (e.g., protection against manipulation of measuring results) and confidence in accurate and robust operations (e.g., laboratory testing under extreme conditions) that are similar to those of other weighing instruments under legal control and covered by NIST Handbook 44.

Moreover, the COST 323 report also describes a statistical approach for the classification and evaluation of WIM systems. If this standard is applied to WIM installations that are to be used for legal applications, then the tolerances must be applied to 100% of the measurements.

4.4. NMi International WIM Standard

Each of these WIM documentary standards (OIML R 134, ASTM E1318 and COST 323) have their own area of use and each possesses specific advantages and disadvantages. OIML R 134 focuses on the regulation of WIM systems in legal metrological applications. Conversely, the scope of the ASTM E1318 and COST 323 standards cover multiple applications (e.g., legal metrology, data collection, safety), yet focus on field testing only and do not include procedures or requirements for type evaluation. None of these standards exclusively cover the full extent of all the typical operational conditions and potential applications for WIM systems. This has led to a variety of significantly different national requirements. This lack of harmonization leads to an increased cost for manufacturers, vendors, and users of WIM systems.

NMi, (Netherlands Measurement Institute) as a European notified body and OIML certificate issuing authority, has recognized the need for an international standard that can be applied for all types of WIM systems and for both legal and non-legal applications. Together with experts from industry and regulatory bodies, NMi developed an international multi-application standard [13] for WIM systems that has merged and implemented the technical strengths and advantages of the OIML R 134, ASTM E1318 and COST 323 documentary standards. The standard has a set of general requirements for all applications based on OIML D 11, *General requirements for measuring instruments - Environmental conditions*, [14]. A range of environmental aspects are also considered, which includes temperature range, relative humidity, electromagnetic fields (conducted currents, RFI and ESD) and variations and disturbances in the power supply voltage (voltage and frequency fluctuations, voltage dips, bursts, and surges).

In addition to general requirements, there exists a specific set of technical requirements for the suitable application of WIM systems that are to be used for data collection applications. Likewise, a separate set of technical requirements exist for WIM systems used for legal applications. Although the hardware for WIM systems used in both data collection and legal metrology applications may be identical, they do have different tolerance and accuracy requirements for compliance purposes. The main differences are the confidence level (95% for statistical

applications and 100% for legal applications) and the mandatory security measures (sealing and protection against fraud and manipulation) for legal applications.

Considering the legal metrology applications, the NMi standard provides guidance on additional technical and metrological specifications required for direct enforcement, type approval testing, initial verification (placing an installation into service), and in-service verifications. For legal applications, the standard defines four individual accuracy classes with an accuracy on gross vehicle weight ranging from 3% to 10%.

4.5. Additional considerations for certification using ASTM E1318 or COST 323

As described in sections 4.2 and 4.3 herein, the ASTM E1318 and COST 323 standards are not comprehensive and do not provide sufficient assurance of a correct weighing result for legal metrology applications. These two standards mainly focus on the requirements for the physical installation and field testing of WIM systems during routine operations. Requirements regarding device security and environmental influence and disturbance factors are not considered. These aspects are generally evaluated under routine laboratory conditions during type evaluation.

The vast majority of weighing instruments used as legal metrology devices in the U.S. comply with the requirements provided in NIST Handbook 44. These are requirements to provide sufficient assurance for an accurate weighing or measuring result. To achieve the same level of assurance for WIM systems, it is strongly advised to apply relevant specifications from the sections 2.20. Electronic Scales and 1.10. General Code of NIST Handbook 44 for the aspects not covered by the ASTM E1318 or COST 323 standards. Alternatively, requirements from the OIML R 134 or NMi International WIM standard may also be applied.

NIST Office of Weights and Measures has composed a list (Table 2) of possible additional aspects for states to consider when applying ASTM E1318 or COST 323 for the certification of a WIM system. Please note that this list is not exhaustive. States may consider additional aspects.

Table 2. Additional legal metrological aspects to be considered beyond requirements described in ASTM E1318 and COST 323.

Additional legal metrological aspect	Remarks
Acceptance tolerance	In general, the acceptance tolerance is set to 50% of the maintenance tolerance for weighing devices used for legal applications.
Fraudulent use	General requirement that the instrument does not facilitate fraud.
Security	Requirements on sealing of the instrument.
Software	Requirements on software identification.
Markings	Requirements on metrological markings on the instrument.

Additional legal metrological aspect	Remarks
Metrological specifications	Number of divisions, minimum scale division, etc.
Suitability	General requirement that the WIM installation is suitable for its purpose.
Proper indication	Requirements for the proper indication of measurement results (e.g., correct use of unit, number of digits, etc.).
Units of measure	Prescribing certain units.
Zero setting and zero-tracking	Requirements on zero-setting functionality.
Obtained data for direct enforcement	A list of data to be generated by the instrument that is required in case of citation (e.g., pictures of the license plate and vehicle position on the road).
Interlocks	List all aspects that shall be considered by the instrument when validating a measurement (e.g., maximum speed, acceleration, and deceleration, changing lanes, etc.). Requirements for preventing or marking measurements that are obtained under these interlock conditions.
Drift due to temperature	Requirements on maximum temperature effect on zero-load
Voltage variation	Requirements on the effect of variation of the supply voltage.
EMC disturbances	Requirements on the resilience to EMC disturbances such as ESD, RFI and surges.
Permanence	Requirements to add a level of confidence that the instrument will function properly over a longer period (e.g., an automatic detection of faults and malfunctions).
Additional test vehicles	Requirement that the instrument is suitable for all types of vehicles that can be expected on the location of installation (e.g., tanker trucks).

Furthermore, NIST Handbook 44 provides clear guidance for weights and measures officials on system performance of weighing and measuring instruments as well as device testing procedures. Hence, it is commonly used by inspection bodies as a field manual. This additional guidance regarding field inspections is currently lacking in international standards, such as ASTM E1318.

5. Certification of the WIM system on the NYS Brooklyn-Queens Expressway

In October 2019, NYCDOT joined C2SMART's research efforts and WIM sensors were installed in both directions of the BQE. This installation was completed without repaving or other significant efforts to create a smooth riding surface. As initial data was obtained, two major findings were apparent: 1) a high volume of overweight vehicles was detected and 2) sensors were performing well within the tolerance for WIM systems proposed to the NCWM for inclusion in the NIST

Handbook 44 [9], even with minimal site preparation. The NYPD stepped up enforcement using portable scales; however, the operational constraints of the site severely limited the number of violations issued by traditional enforcement methods (i.e., direct ticketing). Far fewer vehicles could be cited by this method than the number of overweight vehicles determined using the WIM systems. This led to a campaign to obtain legal authority for the direct enforcement of overweight vehicle limits using WIM system technology.

5.1. Legislative basis for direct enforcement

Legislation to authorize the use of WIM systems for direct enforcement of the road weight limits in the state of New York was introduced in January 2021 and signed into law on December 22, 2021 [15]. During the development of the legislation, the question of which suitable technical standards are appropriate for the certification of WIM systems arose because there were no existing legal metrology standard technical requirements that could be referenced for this purpose. Those specified in ASTM 1318 were deemed the most appropriate for inclusion in the legislation. As noted in preceding sections of this publication, ASTM 1318 does not provide adequate detail about testing procedures for certification purposes. The certification of weighing instruments (i.e., legal metrology devices) used in enforcement is conducted by the NYS Department of Agriculture. After the legislative authority to use WIM systems for direct enforcement was obtained and a system was installed on the BQE, NYCDOT began coordination efforts with NYS Department of Agriculture to initiate the related certification process. Upon discussion with NYS Department of Agriculture, it was determined that NIST Handbook 44 was a more suitable legal metrology code reference document since all other weighing instruments used for law enforcement are regulated through NIST Handbook 44. However, it required an update to specifically address certification for direct enforcement using WIM technology.

As the proposal to update NIST Handbook 44 progressed via the normal NCWM standards development procedure [16], it was realized that establishing a uniform national standard could take two years or longer. However, NYCDOT had a pressing need to begin enforcement given the condition of the BQE structure and the significant percentage of overweight trucks on the roadway. Based on previous experience with the Alternative Technology Pilot program [17] for evaluation of software-based taximeters in 2015, NYCDOT pursued a memorandum of agreement with NYS Department of Agriculture and Markets (NYSDAM) concerning the testing and certification of equipment outside of the NIST Handbook 44 guidelines. This resulted in an agreement allowing NYSDAM to test and certify the WIM system for the BQE using the most recent version of NIST Handbook 44 proposed language, until such time as that proposed standard is adopted.

As a stop-gap measure, section 179(11) of Article 16 of the NYS Agriculture and Markets Law [18] allows for such arrangements while relevant national standards are being formalized. As NYS Department of Agriculture is an active participant in both NCWM and the Northeastern Weights and Measures Association (NEWMA), they can readily solicit input from a broad group of stakeholders and communicate relevant information about proposals to update NIST Handbook 44. They also participated in the demonstration of an operational WIM system at a

screening facility in Madison, Wisconsin that is operated by the Motor Carrier Enforcement Section of the Wisconsin State Patrol. The demonstration provided valuable insight into the operation of the WIM system technology, the logistical challenges with the testing procedure, and the necessary audit trail that will be required for device certification. After completion of the demonstration, the WIM system evaluation procedure was updated to optimize the process for an improved evaluation of systems for enforcement purposes.

With a better understanding of the process to update applicable legal metrology documentary standards, the state of New York passed legislation [19] allowing certification to proceed in accordance with the MOA between NYCDOT and NYSDAM, using the latest version of the proposal [9] to update the model code in NIST Handbook 44, pending its adoption as a permanent code. This act passed in 2023, providing clarity to the certification requirements.

5.2. Implementation of the certification

The newly implemented State of New York law required that warnings be issued to all vehicles on the BQE with an overweight violation status during the ninety-day period immediately preceding the certification of the WIM system for citation issuance. Upon completion of the installation of the WIM system and other necessary equipment to support the automatic violation processing system in August of 2023, NYCDOT began issuing warnings to those vehicles in violation of the legal weight limits.

Within this time, NYCDOT requested the NYS Department of Agriculture to test the WIM system and provide certification if it was found to be satisfactory in performance. The most recent version of the proposal to update NIST Handbook 44 (August 14, 2023) was used as an initial guideline for the certification process. NYCDOT created a site-specific protocol, which listed the appropriate vehicle testing speeds based on site conditions, a list of suitable test vehicles, and appropriate test vehicle weights. This site-specific procedure was further detailed with an identification of a reference scale, timing of certification of the reference scale, and the order of test runs. After review and approval by the NYS Department of Agriculture, the detailed protocol was utilized to conduct certification testing during the overnight hours of October 28 and 29, 2023. With support from C2SMART and Kistler, NYCDOT procured the test trucks and drivers, while NYS personnel witnessed every step of the process and reviewed the data obtained from the sensors in real time. The certification process was completed over a period of two nights (1 AM to 7 AM) using the initial data (currently unpublished) collected from two vehicle traffic lanes. To avoid significantly impacting normal traffic operations, testing during non-peak traffic hours was necessary along this corridor which is heavily congested during daytime hours.

5.3. Preliminary results

In preparation for automatic enforcement and issuing of violations, Figure 2 illustrates how the number of warnings issued weekly changed during the 90-day warning period before certification of the WIM system installation. It should be noted that as the direct enforcement system only

exists at a single location along the BQE in the direction of travel from Queens to Brooklyn, it can be avoided by choosing an alternative route for that portion of the drive. Therefore, the drop in the number of warnings might not be due to a reduction in the number of overweight vehicles traveling on NYC roadways in the area, but it does indicate the reduced incidence of overweight vehicles burdening the aging BQE.

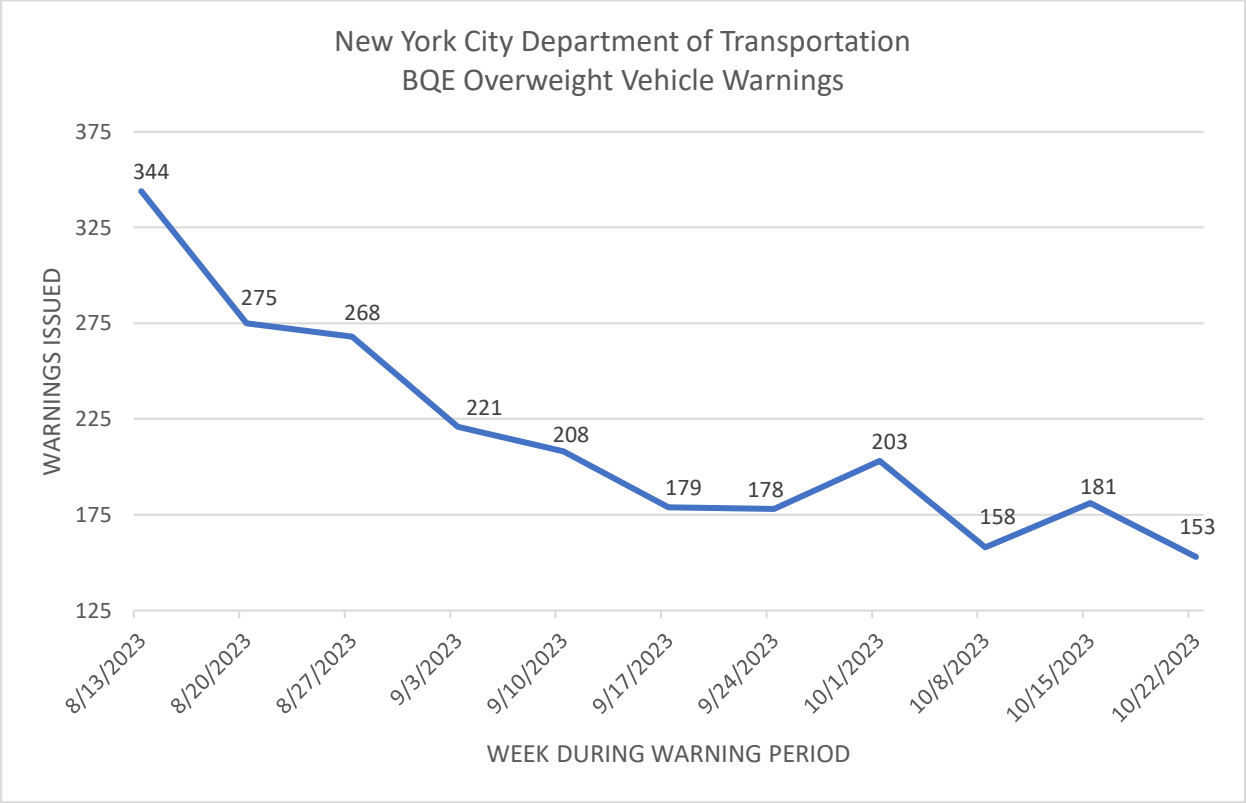

Fig. 2. Brooklyn-Queens Expressway (BQE) overweight vehicle warnings.

The preliminary results from the testing imply that the current tolerance requirements could be achieved and ultimately provide high confidence in the system, especially considering the system was installed nearly a year prior. While the logistics of testing are challenging in dense urban areas such as the BQE, the results demonstrate the capability to correctly identify overweight vehicles with a high degree of confidence.

In addition to testing and certification of the system, the NYCDOT also requires each registered violation to be reviewed by trained personnel to ensure that all procedures of the program are being executed appropriately and that any registered violation not meeting all evidence requirements is not cited. This ensures that the WIM technology and the associated cameras and other programming are identifying violations according to the legislative requirements and best practices of enforcement.

6. Challenges and Considerations for NIST Handbook 44 Adoption

During the open hearing sessions held at the NCWM 2023 and 2024 national and regional weights and measures association conferences, several concerns and questions were raised by several state regulators and industry stakeholders regarding the current proposal to amend NIST Handbook 44 to include WIM systems for direct enforcement. These concerns ranged from the automatic adoption and implementation of the WIM system code to the technical details of the tolerances and scale divisions that will be used in direct enforcement procedures. Each of these concerns is addressed herein through an examination of underlying technical considerations and their overall practical use in legal metrology applications relevant to weights and measures.

6.1. Mandatory acceptance of WIM system code

Most states (36 of 53) [7] automatically adopt the most recent version of NIST Handbook 44 as it is amended and updated each year. A concern exists among states that may not have adequate resources at present to provide inspections of high-speed WIM systems for direct enforcement of weight limit violations if the proposal is adopted by NCWM during the 2024 voting cycle.

It is noteworthy that state and local jurisdictions can, at their discretion, exclude any part of the relevant section in the NIST Handbook 44 from their laws. This is described explicitly within the Section 1.2 Form of Promulgation within NIST Handbook 44 Appendix A. *Fundamental Considerations Associated with the Enforcement of Handbook 44 Codes.* Thus, states and local jurisdictions that are required to initiate a process to adopt more recent versions of NIST Handbook 44 could also exclude this section, if they decide to adopt a version that includes it.

6.2. Large tolerance

One of the more frequent concerns often voiced is the relatively large tolerance applied to gross vehicle weights, the axle loads, and axle-group loads. A static vehicle scale at a weigh station has a tolerance of 0.2% for the gross vehicle weight. The submitted proposal for WIM systems [9] recommends a tolerance of 10%, which is a 50-fold increase to static scales. When comparing these tolerances between devices that appear to have similar applications, this increase may cause concern and thus hesitation to endorse and/or adopt the language by some weights and measures stakeholders.

Some weights and measures stakeholders have expressed views that WIM systems should meet the same tolerances as other weighing instruments for weighing vehicles. Although considered weighing instruments, WIM systems are not scales and thus their technical performance and associated evaluation parameters should not be treated as such. WIM systems are less accurate than static vehicle scales because they operate in distinctly different ways, especially high-speed systems. For example, belt-conveyor scale systems and automatic bulk weighing systems are both designed to weigh bulk products. However, they operate with very distinct physical mechanisms and have different technical performance characteristics. It is impossible to evaluate belt-conveyor scale systems using test procedures developed for automatic bulk weighing

systems and vice versa. As a result, both have their own section in NIST Handbook 44 with individual sets of requirements and tolerances. Furthermore, a tolerance of 10% is considered acceptable in other internationally recognized WIM standards, such as OIML R 134, ASTM E1318, and COST323. The proposed tolerances in the current WIM proposal (WIM-23.1, *2.26 Weigh-in-Motion Systems Used for Vehicle Direct Enforcement*) to amend NIST Handbook 44 are consistent with all commonly used documentary WIM standards.

Another concern raised by the weights and measures community questions whether high-speed WIM installations are metrologically sound enough for enforcement of road weight limits. To ensure proper usage of the WIM system as a legal metrology measurement device, jurisdictions must account for appropriate and consistently applied tolerances when creating parameters and technical justifications to issue violations. Importantly, measuring instruments that are used for law enforcement applications may not meet the same requirements as instruments used in commercial transactions. For example, vehicle scales and portable wheel-load weighers are both used for highway weight enforcement. Yet, vehicle scales are a Class III L instrument and have stricter tolerances than portable wheel-load weighers, which are categorized as Class IIII. The reason is that vehicle scales can also be used for commercial transactions unlike wheel-load weighers which can only be used for law enforcement applications. To ensure validity the WIM system-based measurement must be corrected for the uncertainty of the installation when used for enforcement of vehicle weight limits, (i.e., reduced with the tolerance), this ensures there is a very minimal chance that any weight value determined by the WIM system and used for a citation will exceed the actual weight of the vehicle. In other words, no unjust citations based on erroneous measurements will be issued.

Because of this correction, the weight value used for citations is expected to be on average 5% to 15% lower than the actual vehicle weight. It is for each jurisdiction to decide whether this adjustment (and possible under-registration) is acceptable. If not, a state can simply exclude WIM systems from being used for law enforcement applications in their jurisdiction.

6.3. Large scale divisions

Most static vehicle scales have a scale division of 10 kg (or 20 lb), while the WIM proposal for the amendment of NIST Handbook 44 allows scale divisions up to 200 kg (or 500 lb). Some states have expressed concerns that such a large scale division is not suitable for weighing road vehicles.

This increase of the scale division for WIM systems is justifiable based on the following technical considerations. First, static vehicle scales as covered in section 2.20 *Scales* of NIST Handbook 44 applies to both law enforcement and commercial applications. When used for commercial transactions, the scale must be suitable to weigh not only large, fully loaded vehicles, but also small, unloaded vehicles. That means that these scales must produce an accurate weighment throughout their entire weighing range. The minimum recommended load for a Class III L vehicle scale is set to 50 e, which with a scale division of 10 kg equals 500 kg. The relative error due to the rounding to one scale division could be as much as 0.5 e/50 e = 1%.

A weighing instrument that is used for law enforcement applications is used to cite vehicles exceeding the weight limit. These are large and fully loaded vehicles. Therefore, the scale is only used on the high end (upper 60%) of the weighing range. For example, if the road weight limit is 20,000 kg, then the maximum relative error due to the rounding on a WIM system with a 200 kg scale division equals 100 kg/20,000 kg = 0.5% which is less than the relative error due to rounding at the recommended minimum load on a static vehicle scale.

Second, the tolerance of the WIM system is much higher than for commercial static vehicle scales. For a Class III L static vehicle scale, the relative error due to rounding could be as much as 1% at the lower end (50 scale divisions) while the overall tolerance is 0.2%. In this case, the maximum rounding error could be five times greater than the tolerance. On a WIM system with a 10% tolerance, a 1% rounding error is only a tenth of the tolerance. In other words, the influence of a larger scale division on a WIM system is nullified by its large tolerance.

6.4. Integration in the existing scale code

Another concern expressed by stakeholders is that because of the large tolerances being proposed, WIM systems are held to a different standard than static vehicle scales that fall under section 2.20 Scales in NIST Handbook 44. Some weights and measures stakeholders have contested that WIM systems should be held to the same requirements as static vehicle scales and, therefore, should fall under section 2.20 *Scales* of NIST Handbook 44.

But such a comparison is only applicable to instruments of the same type, which is not what is under consideration by the current WIM proposal. Although a high-speed WIM system is utilized as a weighing instrument, it is not a scale with respect to its underlying physical measuring capability and thus it cannot be evaluated in the same manner. Where static vehicle scales weigh the vehicle in its entirety, WIM systems calculate the gross vehicle weight from weighing the individual axle loads. Furthermore, the load receiving sensors of most high-speed WIM systems are narrow and unable to receive the amount of test weights representing the axle load of a fully loaded truck. These, and other fundamental technical differences in the operation of the WIM measuring device thus necessitates that its associated code remain as a separate section in NIST Handbook 44.

Furthermore, the weighing instruments covered by section 2.20 *Scales* of NIST Handbook 44 can be used for both law enforcement and commercial applications. High-speed WIM systems cannot be used for commercial applications due to their relatively low accuracy. However, they are very well suited for law enforcement applications as described in section 6.2.

Because high-speed WIM systems are not used for commercial applications and use different technology than traditional vehicle scales, they do not fit under section 2.20 *Scales* of NIST Handbook 44 and thus require a separate section in the Handbook.

High-speed WIM systems should be considered a valuable tool in a state's or local jurisdiction's enforcement toolbox to manage compliance with road weight limits. Jurisdictions need to maintain flexibility and consider and potentially use all their tools in the toolbox.

6.5. Automated measurement

Unlike manually operated static scales, WIM systems operate automatically, and the driver is not able to see the weighing result during the weighment. The driver has no opportunity to dispute the outcome of the weighment immediately after the weighment has taken place. This is a different approach from the way overweight vehicles are cited on a traditional static vehicle scale, for which the driver is immediately notified of the violation upon weighment. This different approach can cause some hesitation and cast doubt about the reliability or the transparency of the WIM installation.

But this situation can be compared with another similar fully automatic device operation that is widely accepted within the legal metrology community. Currently, automated speed cameras are allowed in 27 states by state law and/or city ordinance [20]. With these instruments, the driver also has no opportunity to dispute the measurement at the moment of the violation. Yet, there is always a means for legal recourse in case of a dispute. Automated systems do not circumvent due process. This type of direct enforcement is widely accepted throughout the U.S. and measurements produced by these instruments are upheld in court.

It is important that an automated instrument used for law enforcement must provide sufficient supporting evidence, (e.g., pictures, calibration date, date and time stamp, internal check), to refute any challenge to the validity of the citation.

6.6. WIM test procedures

High-speed WIM systems often use narrow road sensors (several inches wide, across each monitored lane), precluding these systems from being tested with a static standard load, as is commonly used for testing a vehicle scale. Field testing of these WIM systems can only be achieved by using test vehicles that replicate typical vehicle load conditions and traffic patterns. This requires tests on multiple types of test vehicles, each with different loads, that are required to drive multiple times over the sensors to collect appropriately representative data. It is recognized that this type of testing requires significant resources for both testing staff and equipment (i.e., vehicles), as well as for coordinating efforts among authorities responsible for normal roadway operations.

Unlike instruments used in commercial applications, state regulators have the ultimate authority to determine which measuring instruments shall be used for law enforcement applications. The availability of resources may be one of the more decisive factors when considering a WIM installation for road weight limit enforcement. Notably, the inclusion of WIM system model code for law enforcement applications in NIST Handbook 44 does provide states an established mechanism to install and operate WIM systems for enforcement. Furthermore, it is the states' prerogative to exclude certain sections of NIST Handbook 44 in their regulations.

7. Summary and Future Considerations

WIM systems embody a modern and sophisticated measurement tool that can help state and local jurisdictions protect their critical (and often deteriorating) infrastructure while also ensuring public safety and trust. As with adoption and effective utilization of any new technology, the initial implementation always requires significant investment in time and resources to integrate it into routine use under uniform, standardized operations.

A recommended first step is for all stakeholders (i.e., industry, state and local regulators, federal agencies, and other law enforcement entities) to work cooperatively towards the development of a suitable (and uniform) model code containing specifications and tolerances for WIM systems to be used in law enforcement applications. Then, this model language can be electively and voluntarily adopted by individual state and local jurisdictions as they see fit.

In several states, weights and measures officials are currently responsible for testing law enforcement weighing devices. To be most effective, these officials need to establish a close working relationship with the regulatory body that is responsible for enforcing vehicle weight limits. Weights and measures programs that do not test vehicle weight limit enforcement devices in their respective state (but may in the future) might consider establishing a relationship with the relevant law enforcement authority in their state. This will facilitate discussions of the advantages and disadvantages of these WIM systems and create awareness of the types of devices that are available and appropriate for their specific needs. It would be beneficial for the regulatory bodies responsible for enforcement to have an up-to-date knowledge and continuous source of information as this emergent weights and measures issue evolves.

Further, some of the state regulatory authorities may already possess some of the resources needed to perform the test of the systems. Notably, the states for which weights and measures programs are separate from authorities involved in testing law enforcement measuring devices may have the greatest challenge; appropriate arrangements between any weights and measures and law enforcement authorities will be required to ensure that any weighing devices are tested and used properly to mitigate liability when issuing citations.

If utilized with appropriate technical considerations as described herein, there is an opportunity for these WIM systems to provide a more efficient method of ensuring compliance with vehicle weight limits. Implementation of this automated technology may afford state and local jurisdictions with more options regarding the allocation of valuable resources (i.e., dedicated personnel, time, and equipment) to other pressing issues.

In closing, implementation of these WIM systems for purposes of enforcement will not only protect critical roadway and bridge infrastructure, but offer greater efficiency and safety for vehicle drivers, enforcement officers, and the general public that share the roadways across the U.S.

References

[1] The White House, *Fact Sheet: The Bipartisan Infrastructure Deal*. The White House, 2021. [Online]. Available: https://www.whitehouse.gov/briefing-room/statements-releases/2021/11/06/fact-sheet-the-bipartisan-infrastructure-deal/

[2] Y. Yiu, "How Much Damage Do Heavy Trucks Do to Our Roads?," *Inside Science*, Oct. 12, 2020. [Online]. Available: https://www.insidescience.org/news/how-much-damage-do-heavy-trucks-do-our-roads

[3] American Society of Civil Engineers (ASCE), "2021 Infrastructure Report Card - Bridges." [Online]. Available: https://infrastructurereportcard.org/cat-item/bridges-infrastructure/

[4] W. Cook, "Bridge Failure Rates, Consequences, and Predictive Trends," Utah State University, 2014. doi: 10.26076/bfec-580b.

[5] Konijnenburg J, Lee GD, Minnich LB, J. Williams, L. Warfield, and Lippa K, "Specifications, Tolerances, and Other Technical Requirements for Weighing and Measuring Devices," 2024. doi: 10.6028/NIST.HB.44-2024.

[6] OIML, "Search registered OIML certificates," OIML. [Online]. Available: https://www.oiml.org/en/oiml-cs/certificat_view

[7] McGuire J, Warfield L, and K. Lippa, "Uniform Laws and Regulations in the Areas of Legal Metrology and Fuel Quality," 2024. doi: 10.6028/NIST.HB.130-2024.

[8] NCWM, "NCWM Publication 14," 2023. [Online]. Available: https://www.ncwm.com/publications

[9] National Conference on Weights and Measures, "Specifications and Tolerances (S&T) Committee 2024 Interim Meeting Agenda - Item WIM-23.1," 2024. [Online]. Available: https://cdn.ncwm.com/userfiles/files/Meetings/Interim/Pub%2015%20Archive/2024/4-ST-Master-.pdf

[10] OIML, "OIML R 134 - Automatic instruments for weighing road vehicles in motion and measuring axle loads," 2006. [Online]. Available: https://www.oiml.org/en/publications/recommendations/publication_view?p_type=1&p_status=1

[11] ASTM International, "ASTM E1318-09(2017) - Standard Specification for Highway Weigh-In-Motion (WIM) Systems with User Requirements and Test Methods," West Conshohocken, PA, 2017. doi: 10.1520/E1318-09R17.

[12] B. Jacob, E. O'Brien, and S. Jehaes, "COST_323 - Weigh-in-Motion of Road Vehicles," 1998. [Online]. Available: https://www.is-wim.org/doc/wim_eu_specs_cost323.pdf

[13] NMi Certin, "NMi International WIM standard," Delft, 2019. [Online]. Available: https://nmi.nl/markets/wim/

[14] OIML, "OIML D 11 - General requirements for measuring instruments - Environmental conditions," 2013. [Online]. Available: https://www.oiml.org/en/publications/documents/publication_view?p_type=2&p_status=1

[15] The New York State Senate, *Senate Bill S2740B*. 2021. [Online]. Available: https://www.nysenate.gov/legislation/bills/2021/S2740

[16] NCWM, "Standards Development." [Online]. Available: https://www.ncwm.com/standards-dev

[17] New York City Taxi and Limousine Commission, “Alternative Technology Pilot Report,” Aug. 2017. [Online]. Available: https://www.nyc.gov/assets/tlc/downloads/pdf/alternative_technology_pilot_report.pdf

[18] The New York State Senate, *SECTION 179 - Powers and duties of the commissioner*. US, 2021. [Online]. Available: https://www.nysenate.gov/legislation/laws/AGM/179

[19] The New York State Senate, *Senate Bill S6246*. US, 2023. [Online]. Available: https://www.nysenate.gov/legislation/bills/2023/S6246

[20] Insurance Institute for Highway Safety (IIHS) and Highway Loss Data Institute (HLDI), “Safety camera laws.” [Online]. Available: https://www.iihs.org/topics/red-light-running/safety-camera-laws

Appendix A. List of Symbols, Abbreviations, and Acronyms

ASTM	American Society for Testing and Materials
BQE	Brooklyn-Queens Expressway
C2SMART	USDOT Tier 1 University Transportation Center
COST	European Cooperation in Science and Technology
EMC	electromagnetic compatibility
ESD	electrostatic discharge
FHWA	Federal Highway Administration
MOA	Memorandum of Agreement
NCWM	National Conference on Weights and Measures
NIST	National Institute of Standards and Technology
NMi	Netherlands Measurement Institute
NTEP	National Type Evaluation Program
NTEP CC	NTEP Certificate of Conformance
NYC	New York City
NYS	New York State
NYSDAM	New York State Department of Agriculture and Markets
NYPD	New York City Police Department
NYCDOT	New York City Department of Transportation
OIML	International Organization of Legal Metrology
RFI	Radio Frequency Interference
USDOT	United States Department of Transportation
WIM	Weigh in Motion
RIME	Rutgers Infrastructure Monitoring and Evaluation