Technology Convergence 2023
Setting the Wheels In Motion: Reimagining the future of heavy vehicles, roads and freight

ADDRESSING THE RELIABILITY CHALLENGES OF HIGH-SPEED WIM (HS-WIM) FOR DIRECT ENFORCEMENT

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Abstract

This paper covers the development of a high-speed WIM (HS-WIM) solution designed specifically for direct enforcement applications. The development of the solution focuses on fulfilling needs related to reliability of HS-WIM output. In this context, reliability means the ability to detect vehicle overloading while identifying potential false positives, for a defined period and environment. The key results of this project includes the deployment of a combination of hardware and software solutions designed to guarantee that no overloading penalties are applied to compliant vehicles.

Keywords: WIM, HS-WIM, Direct Enforcement, Reliability.

Resumen

Este documento cubre el desarrollo de una solución WIM de alta velocidad (HS-WIM) diseñada específicamente para aplicaciones de cumplimiento directo. El desarrollo de la solución se enfoca en satisfacer las necesidades relacionadas con la confiabilidad de la salida HS-WIM. En este contexto, la confiabilidad significa la capacidad de detectar la sobrecarga del vehículo al tiempo que identifica posibles falsos positivos, durante un período y entorno definidos. Los resultados clave de este proyecto incluyen el despliegue de una combinación de soluciones de hardware y software diseñadas para garantizar que no se apliquen multas por sobrecarga a los vehículos que cumplen con las normas.

Palabras clave: WIM, HS-WIM, Ejecución Directa, Confiabilidad.

1. Introduction

The use of WIM in weigh station strategies is an ongoing topic study and evaluation in different countries due to the relevance of road transportation and the importance of overload control. While several countries have adopted the use of high-speed WIM (HS-WIM) as a means for selecting or screening potentially overloaded vehicles, a few have achieved significant progress for the use of this type of system for direct enforcement of weight limits. In 2011, the Czech Republic became the first country to establish specific legal and metrological requirements for the certification and use of HS-WIM for direct enforcement (Doupal et al., 2012). Currently, countries such as Brazil (Shinohara et al., 2016), France (Jacob and Cottineau, 2016) and Poland (Gajda et al., 2016) (Konior et al., 2022) are developing comprehensive studies aiming at the assessment of the feasibility of direct enforcement by HS-WIM systems. This paper shares the part of the experience of the Intelligent Weigh-in-Motion (iWIM) research project which aims the development of a HS-WIM system for direct enforcement.

In the context of the iWIM research project, reliability is claimed to be the root of the main challenges for the effectiveness of HS-WIM for direct enforcement. This is because HS-WIM for direct enforcement requires systems to be highly accurate after commissioning and calibration, and also to provide predictable outputs over a known period of time and over different external conditions. This research project is built upon the assumption that a HS-WIM system to be used for direct enforcement should provide outputs at a known level of performance if it’s being used as proof for issuing overloading penalties.

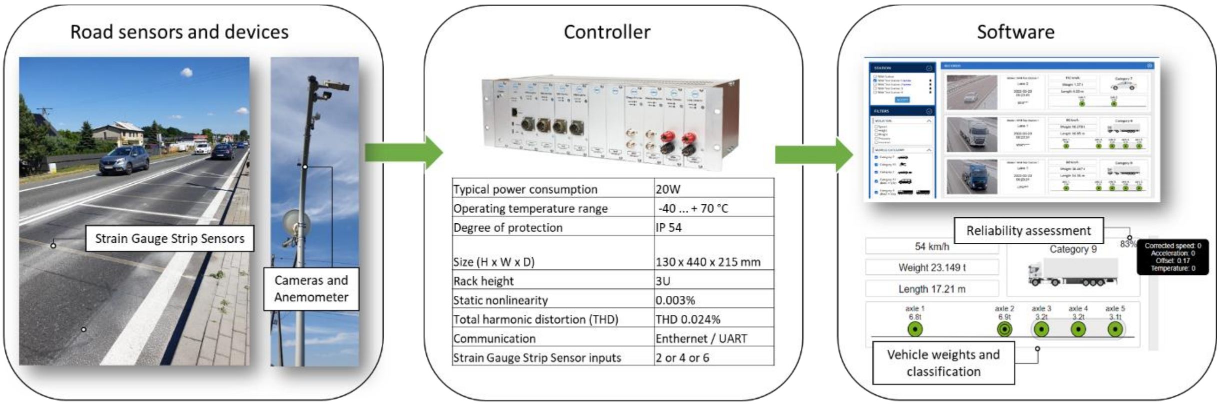
The use of HS-WIM for direct enforcement of vehicle weight limits is the ultimate goal of several government bodies and road agencies around the globe, as it requires minimal physical infrastructure investments, and it tends to bring improved levels of control. The technical efforts described in this paper focus on the development of procedures guaranteeing that all valid HS-WIM measurements will fall within the specified tolerances, while reliability strategies are put into practice to ensure a fair and effective HS-WIM for enforcement operation.

2. HS-WIM system setup

An important part of the project involved the design and development of a hardware and software setup that would be capable of achieving the desired level of automation and reliability in HS-WIM for direct enforcement applications. This part of the project involved the selection of the most appropriate measurement technologies, and the development of processing units that facilitate sensor performance. For this purpose, the iWIM controller was developed with state-the-art processing capabilities and the ability to integrate with all major WIM sensor manufacturers in the market.

The need for reliability derives from the degree of automation required from HS-WIM systems. A high degree of automation is the root of several potential benefits of HS-WIM for direct enforcement, such as lower operation cost, noninterference with traffic flows and the ability to perform enforcement inspections uninterruptedly. However, it can also be seen as the source of the major challenges of HS-WIM for direct enforcement. A fully automated vehicle weighing system requires methods and technologies that are stable and reliable, but this is not an easy task when the installations are done in uncontrolled environments like roadways.

Figure 1 shows an infographic with key elements of the system setup developed in this project:



Typical power consumption	20W
Operating temperature range	-40 ... + 70 °C
Degree of protection	IP 54
Size (H x W x D)	130 x 440 x 215 mm
Rack height	3U
Static nonlinearity	0.003%
Total harmonic distortion (THD)	THD 0.024%
Communication	Enthernet / UART
Strain Gauge Strip Sensor inputs	2 or 4 or 6

Figure 1 – HS-WIM system setup

2.1. Road sensors and devices

As a result of this specific stage of the project, the HS-WIM solution was designed based of strain gauges sensors for wheel load measurement, piezo-polymer sensors installed diagonally at 45° for tire positioning and footprint, induction loops, weather station, ANPR and overview camera (Figure 2). The sensors and cameras are attached to the iWIM controller, which uses advanced field-programmable gate array (FPGA) processors that enable real-time signal processing from all sensors. This device was designed to meet the requirements of automatic fining systems and the WELMEC standard.

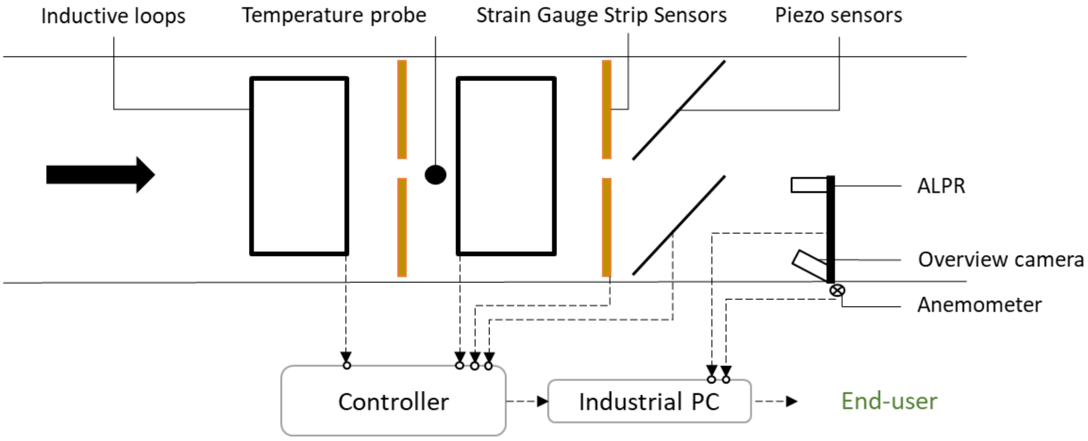


Figure 2 – Road sensors and devices

The sensors and cameras are attached to the iWIM controller, which uses advanced field-programmable gate array (FPGA) processors that enable real-time signal processing from all sensors. This device was designed to meet the requirements of automatic fining systems and the WELMEC standard. The WIM controller communicates with an industrial PC, which runs the software solution and provides the interface with the end-user.

2.1.1. Strain Gauge Strip Sensors

The selection of the WIM sensors in the solution aimed at choosing a technology with high levels of stability during operation throughout the year, regardless of temperature or other external conditions. Previous research on the stability of different sensor technologies in various installations have shown that, while maintaining certain external standards, from investment planning through construction to calibration and commissioning, it is possible to obtain repeatable, stable WIM measurements in high-speed road environments.

Figure 2 shows the results of a study on long-term stability of WIM systems using a Strain Gauge strip sensor layout, which is reported by Konior et al. (2018).

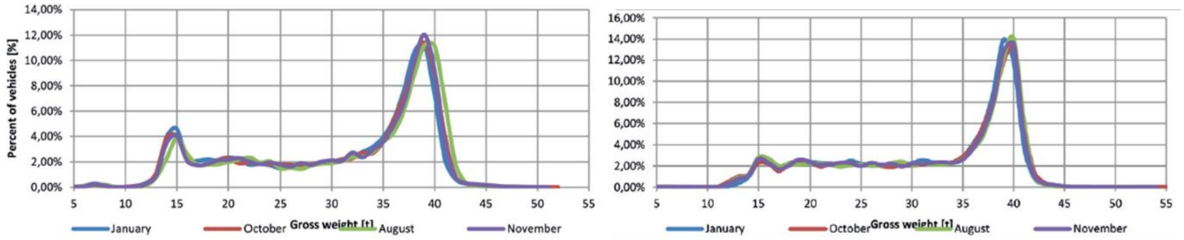


Figure 2 – Gross weight of tractors with semi-trailers in Strzelno (left) and Markowice (right).

The study included the evaluation of long-term stability of different HS-WIM sites and technologies. HS-WIM site with Strain Gauge sensors showed the desired levels of stability, which could be analyzed through the “two peak GVW histogram”, a well-used technique of monitoring the gross weights of 5-axle vehicles over time as a means for WIM data quality management (Quinley, 2010). Each line represents a different month of the year, and when the lines are aligned together it indicates the system maintained performance over the different months.

The results demonstrated in Konior et al. (2018) were later confirmed by Thompson et al., (2019), indicating a high ability of Strain Gauge Strip Sensors to sustain calibration over time and temperature variations.

2.2. WIM Controller

The sensors and cameras are attached to the iWIM controller, which uses advanced field-programmable gate array (FPGA) processors that enable real-time signal processing from all sensors. This device was designed to meet the requirements of automatic fining systems and the WELMEC standard. The controller provides processing and integration of signals from strain gauge load sensors, inductive loops, and additional piezoelectric polymer sensors within a single device and low-level processing capabilities for analog signals. This piece of hardware enables the integration of signals from sensors and image devices. The sampling rate used is 31250 Hz for signals from Strain Gauge strip sensors and Piezo-Polymer sensors, and 3125 Hz for signals from inductive loops. Finally, the use of an additional industrial computer as a dedicated unit also enables the integration of WIM measurements with meteorological sensors and digital cameras.

3. Software

The software solution is a Linux-based application that displays vehicle records with weight information and images in real time. Data from multiple HS-WIM stations can be presented in one module. A set of filters allows searching and visualizing vehicles that meet a given set of criteria, such as weight, class, and speed. The solution enables generation of traffic statistics and the export of data reports in .csv or .xls formats.

3.1. Data Reliability Algorithm

A key challenge of the project was the development of a WIM-data processing algorithm that can perform real-time assessments over the reliability of vehicle records to be used for enforcement purposes. In this context, besides deploying hardware and measurement technologies that are stable over time, the research project included the development of an advanced algorithm that processes vehicle records and assigns a reliability rate for every WIM record. The reliability rate is calculated based on fuzzy logic, and it makes an assessment of multiple variables related to vehicle movement trajectory, surface condition, and weather conditions.

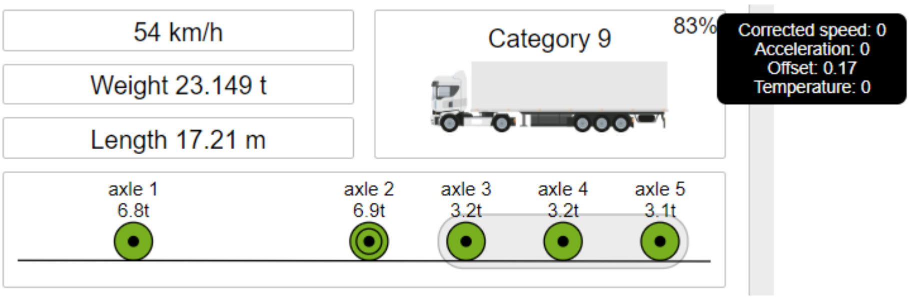
3.1.1. Reliability assessment

As part of the measurement process at the HS-WIM solution, every individual vehicle run goes through a reliability assessment procedure. The reliability assessment algorithm is based on four groups of variables that may affect the reliability of the dynamic load measurement:

- corrected speed (vehicle speed corrected for wind speed value and direction).
- Vehicle acceleration.
- wheel-sensor contact point (offset).
- Road surface temperature.

The system indicates if the measurements in each vehicle record might not be accurate and what specific elements might have affected how accurate they are. It gives a percentage score for how confident one can be about the whole measurement, and also provides a score for each variable that could have affected it, which can range from 0 to 1.

Figure 3 shows how the reliability assessment process is displayed to the end-user, through the use of the software solution developed for the application.



54 km/h
Weight 23.149 t
Length 17.21 m
Category 9
83%
Corrected speed: 0
Acceleration: 0
Offset: 0.17
Temperature: 0

Figure 3 – Reliability assessment process display

3.1.2. Use of Fuzzy Sets

The automated algorithm for reliability assessment uses Fuzzy Sets, based on defined membership functions. Fuzzy Sets are a good option in this case because it deals with complex or ambiguous concepts that are difficult to define precisely using traditional sets or crisp boundaries. Fuzzy Sets allow us to represent these concepts using degrees of membership, where an element can belong to a set to a certain degree between 0 and 1.

For each factor that may affect the reliability of the measurements, the system describes how well it fits into specific membership functions. Instead of having strict rules, it allows for some overlap between these descriptions by using three different groups. This approach helps to capture the complexity of the factors that are considered and allows for more nuanced and flexible analysis.

The three membership functions considered for each factor are:

- how well a parameter value fits into the range of values considered normal for a particular location and type of vehicle.
- how well a parameter value fits into a range of values lower than what is considered normal.
- how well a parameter value fits into a range of values higher than what is considered normal.

The algorithm first converts the recorded values into a form that can be processed by the system, by assigning a degree of membership to each of the three sets previously defined. In the next step, the system uses inference rules to calculate a level of confidence (low, medium, or high) in the accuracy of the measurement for the analyzed parameter.

The system processes the inference rules to determine a fuzzy set that represents the aggregation of data from specific confidence measures for each factor. The defuzzification process is then used to determine a single numerical value that represents the resulting sets. Based on this resulting confidence value, the system provides a final assessment of the possible accuracy of the measurement.

3.1.3. Determining the influence of each factor in measurement accuracy

A experimental study was conducted where test vehicles of known weights were used, and they were driven through the HS-WIM site under varying conditions such as different environmental parameters, traffic dynamics, and driving trajectories. The test vehicles used in the study were 2-axle, 3-axle, and 5-axle vehicles loaded with known standard weights. The total mass of the vehicles used in the study ranged from 18 to 38 tons and over 360 records were collected.

Based on the assessment, ranges of gross mass and axle load errors were identified for individual isolated parameters such as corrected speed, acceleration, offset, and temperature. Analysis of the collected data indicated that the isolated effects of parameters related to vehicle trajectory and motion dynamics, in that specific site, had the most significant impact on overall measurement uncertainty.

Using the data collected, a range of normative values was defined, and membership functions for individual fuzzy sets were proposed for the specific HS-WIM site under analysis. In a full implementation, a similar kind of process should be developed for every different site to be used for direct enforcement purposes.

4. Pilot Implementation

This section presents the results of the application of the reliability algorithm's operation at a HS-WIM site installed on the National Road Network in Poland. Testing of the system was carried out at the measuring site located on the DK44 road in Mikołów – Śmiłowice (Figure 4). Over 150,000 heavy vehicles (i.e., over 3.5 tons) were registered during the time frame between 29/09/2021 and 28/02/2022. The results from this site confirmed the feasibility and readiness of the proposed system for direct enforcement applications.

Figure 3 – Pilot site implementation

Before installing the WIM equipment, the condition of the site was evaluated, which concluded that the pavement in the station area was suitable for Class I conditions, according to COST323 specifications. Once the Strain Gauge Strip Sensors were installed, calibration tests were conducted to assess the system's accuracy, and the results showed that it operating with accuracy class A(5), with a mean relative error of Gross Vehicle Weight measurements not exceeding 2%.

4.1. Data analysis

The first step in the data analysis process was to understand what vehicle categories were more relevant in terms of potential vehicle overloads. By obtaining this information, it would be possible to analyze how the reliability algorithm would behave with these frequently overloaded vehicle categories.   Figure 4 shows how the overload violations were distributed among the different vehicle categories observed at the site.

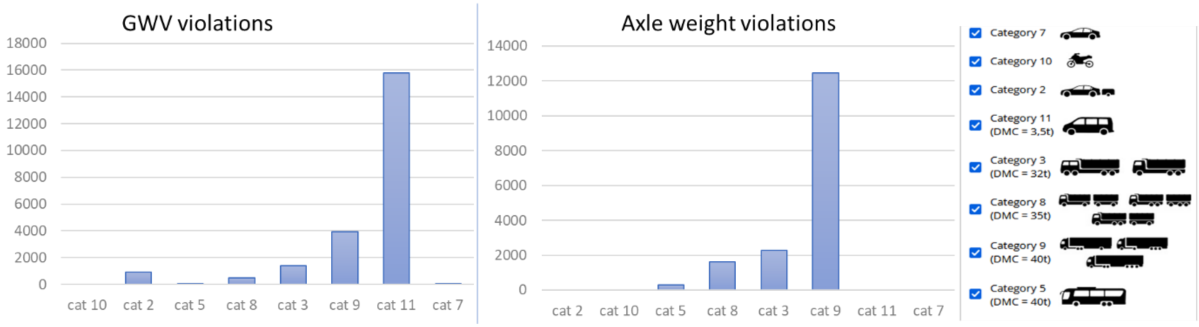


Figure 4 – Overload violations per vehicle class

At this specific site, the most relevant vehicle categories in terms of overload violations are Category 11 (commercial vans) and Category 9 (articulated trucks with 4 to 6 axles). When applying the Reliability Algorithm over these specific vehicle classes, the average reliability rate was 85.63% and 78.69%, which indicates that these vehicles tend to present adequate characteristics for high-accuracy dynamic measurements. Overall, the reliability algorithm appeared to be adequate and feasible for all vehicle categories susceptible to being overloaded.

Upon further examination of the pilot implementation data, it was revealed that the position (offset) of the vehicle run had the highest likelihood of causing an abnormal value for a single parameter, exceeding 40% of the vehicle runs. The second parameter that was most often recorded to have values that were not normal was the corrected speed - more than 20% of the vehicle runs had a corrected speed value that exceeded what the system understood to be optimum (normative) range for higher-performance measurements.

Based on interpretation of data from experimental studies and observations of real traffic, an inference system was developed. The system then considers a reliability level of less than 50% as a significant probability of measurement error. In this context, roughly 22% of the measurements recorded at the site had a chance of presenting lower accuracy performance and therefore could be likely discarded for the application of penalties in a HS-WIM direct enforcement application.

4.1.1. Analyzing the influence of single and multiple parameters over reliability rate

SHAP (SHapley Additive exPlanations) is a popular model-agnostic approach for explaining the output of any machine learning model. SHAP values provide an explanation for the contribution of each feature to the final prediction. By using SHAP graphs, it is possible analyze how often certain measurements with abnormal values happened together, and how they affected the reliability of the overall measurement. This helps understand which parameters are most important in reducing the accuracy of the measurement (Figure 5).

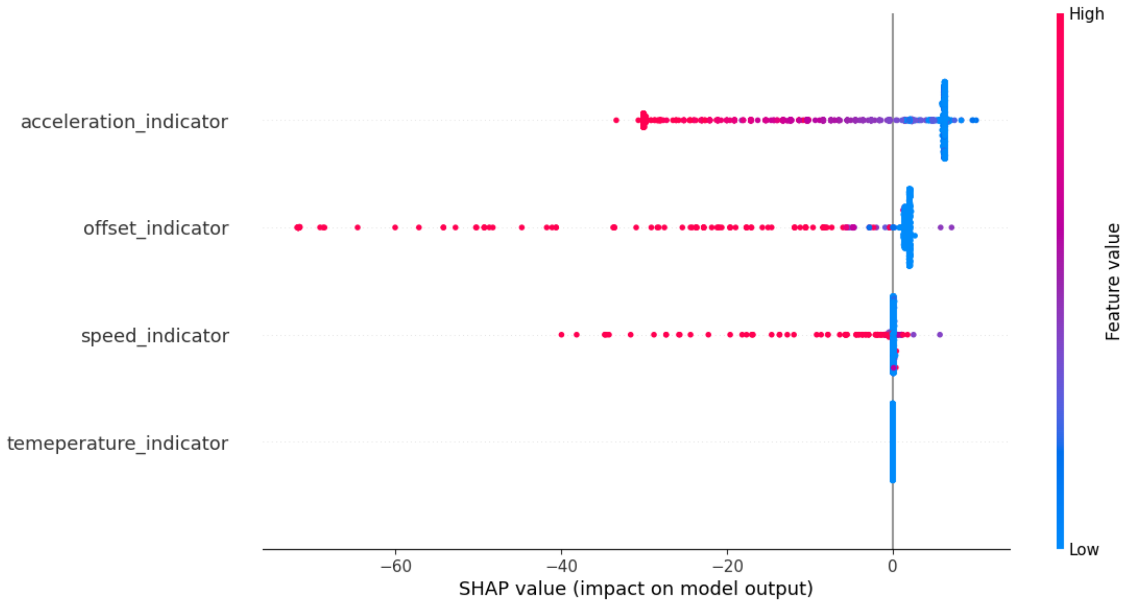


Figure 5 – SHAP analysis of influence of each parameter group on model output

Each feature in a SHAP graph is represented by a horizontal bar, and the length and color of the bar represent the impact of that feature on the final prediction. A blue bar means that the feature is pushing the prediction lower (toward the negative end of the prediction scale), while a red bar means it's pushing the prediction higher (toward the positive end of the prediction scale). The length of the bar represents the strength of the feature's impact on the prediction.

Based on the interpretation of the SHAP graph, it is possible to observe that in that specific site offset can play a more important role in reducing the reliability of the dynamic measurements, while temperature shows an insignificant impact. It is understood that the choice of measurement equipment and the adequacy of the WIM site has contributed to the maintenance of high-quality recorded signals over a wide temperature range.

5. Conclusions

- The biggest challenge in deploying a HS-WIM for direct enforcement system is to guarantee that no vehicle/driver will be penalized while being compliant.
- When deploying a weight measurement system, selecting the right sensors and hardware is important, but it's not enough to guarantee accurate measurements in 100% of the vehicle runs and avoid false positives.
- HS-WIM systems collect data continuously, but the reliability of the data can vary due to factors outside of the measurement technology's control.
- Calibration ensures accurate measurements under standard conditions, but uncertainty can increase if factors deviate from those conditions.
- Two groups of parameters can impact the measurement's reliability: external conditions (like wind and temperature) and vehicle dynamics (like speed and tire-sensor contact location).

- The reliability is assessed using fuzzy processing, which uses fuzzy functions to determine how individual parameters affect the measurement uncertainty. The parameters and membership functions must be adjusted for each specific location.
- Field tests can help determine critical values that, if exceeded, increase the measurement uncertainty. In one specific study described in this paper, for example, the normative speed range was 40-65 km/h.
- Over 40% of recorded vehicle runs had factors that could increase the measurement uncertainty, and around 20% of the measurements analyzed were found to be potentially unreliable.
- A single parameter or a combination of parameters can reduce the overall reliability index below 50%. Offset was the most common isolated parameter leading to potentially unreliable measurements, while speed and acceleration were most commonly affected by multiple non-normative parameters.
- The algorithm developed to assess the reliability of weight measurements is suitable for use at HS-WIM for direct enforcement applications, and it doesn't require significant investments in existing infrastructure.

6. References

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