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Method for Setting Weight Tolerance Limits in High-Speed Weigh-in-Motion Systems: A Case Study in Brazil

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Abstract: High-speed weighing systems are considered a potential tool to restrain overloaded vehicles traffic, since this practice promotes threats to the infrastructure's durability and to citizens' safety. In view of the discussion on the certification of such systems, a method to define the weight tolerance limits of heavy goods vehicles was proposed in this work, using statistical experimentation methods. The method was applied to a case study in Brazil, which considered a high-speed weighing system and three known vehicles (3C, 2S3, and 3S3). The vehicles were loaded with gravel and the bending plate scale was used to set the weight. The test was conducted by checking the weight of the vehicles in the HS-WIM system and composed by the observance of three mandatory speeds (60, 70, and 80 km/h), in three different lateral positions in relation to the lane (center, left, and right), and at various times during the collection days. As result, maximum weights accuracy limits were obtained for gross vehicle weight (GVW) and for axes groups (G1, G2, and G3) as 13% (GVW), 20% (G1), 20% (G2), and 17% (G3).

Keywords: weigh-in-motion systems; tolerance limits; overweighting

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1. Introduction

The road sector assumes an important role for a country's economy, making clear the duty of public initiative to interfere through the provision of policies that stimulate and strengthen its dynamics. One of the ways to stimulate the national economy is to make a competitive infrastructure through the construction, maintenance, and adequacy of roads [1]. However, overloaded vehicles create serious threats to the operation of road transportation, with increasing risks to citizens, compromising road safety, severe impacts on infrastructure durability (pavements and bridges), and unfair competition between modes of transportation and operators [2,3].

According to ref. [4], weighing stations are the first checkpoint of vehicle compliance, and in recent decades weighing technologies known as Weigh-in-Motion (WIM) have been developed to reduce travel delays and to increase the enforcement of overweight violations. WIM can be divided into two types: Low-Speed Weigh-in-Motion (LS-WIM) and High-Speed Weigh-in-Motion (HS-WIM) [2].

Additionally, according to ref. [2], HS-WIM systems have the advantage of being fully automated, from which it becomes possible to register all vehicles that pass through the highway. Such systems still do not require the use of additional infrastructures, such as administrative buildings and parking yards, and can be installed in the infrastructure itself (pavements and bridges) and in any section of it if they meet the specifications related to WIM systems. Additionally, ref. [5] considered that, as heavy goods vehicles traffic is increasing each year, more vehicles should be controlled. In this sense, the direct overweight enforcement from HS-WIM systems is understood by the authors as a more dissuasive solution to the inhibition of the practice of overloaded vehicles when compared with the static weighing or LS-WIM.

In addition, the use of HS-WIM systems would allow the agencies and entities responsible for managing the road infrastructure to obtain greater coverage regarding the enforcement of overweighting and information related to traffic. Because of this increase in enforcement, the reduction of overloaded vehicles would allow the improvement of the service levels of highways, either in relation to the reduction of accidents, or to the preservation of useful life of road infrastructures, in addition to the decrease related to unfair competitiveness corresponding to the freight value [6].

From the related above, the development and improvement of technologies related to HS-WIM, together with the improvement of technologies and communication systems and data integration, allow the transmission of information in near real-time and, therefore, allow the development of technologies and systems aimed at direct enforcement of overloaded vehicles. However, the issues related to the certification of such systems by competent metrological entities are still some of the main obstacles to their implementation. In Brazil, for example, there are still no certified HS-WIM systems for direct overweight enforcement, and the commercial systems available are not able to meet the metrological specifications established by the Brazilian Institute of Metrology, Quality and Technology (INMETRO) [6].

In this way, considering the potentialities of development and use of the HS-WIM system, mainly for the purposes of enforcing and controlling the weight of heavy goods vehicles, as well as considering the discussion about the certifications of such systems, this paper aimed to propose a method for setting weight tolerance limits of heavy goods vehicles, based on statistical methods of experimentation. Therefore, the main contribution of the manuscript is helping in the metrological specifications for setting weight tolerance limits in HS-WIM systems, and showing that these limits could depend on several aspects, such as speed, lateral positions in relation to the lane, and pavement temperatures. In addition, after certification of the HS-WIM system, it is possible to enable the implementation of direct supervision of overweight, not causing harm to those who travel in accordance with the legislation. Section 2 presents a brief introduction to the weigh-in-motion system and the materials and method used is shown in Section 3. A case study for validation of the method is presented in Section 4 and conclusions are in Section 5.

2. Weigh-in-Motion of Heavy Goods Vehicles

Dynamic weighing, worldwide called WIM, was first used in the 1950s in the United States as a tool, mainly, for the collection of vehicle load samples by axle and Gross Vehicle Weight (GVW) for the purpose of pavements design. From the 1970s, new WIM technologies were developed in Europe, and between the 1970s and 1980s, data from WIM were used for traffic surveillance and statistical collection of road freight transportation. In the 1990s, in North America and Europe, the first international specifications emerged contemplating tests relating to WIM systems. Since 2000, the accuracy and suitability of WIM systems have been improved, which has enabled them to be used more frequently for pre-selection overloaded vehicles purposes [2,7].

The WIM, therefore, began to be developed to improve the efficiency of the control of overloaded vehicles, alternatively to static weighing, which gained popularity due to the possibility of collecting traffic data, in an automated and continuous way, without the need for human intervention [2,8,9]. HS-WIM systems consist of a set of sensors, which is complemented with electronic devices and software for control of the system itself and data collection, control, analysis, data storage, and with communication hardware for data transmission [10]. For better illustration, a generic HS-WIM system is shown in Figure 1.

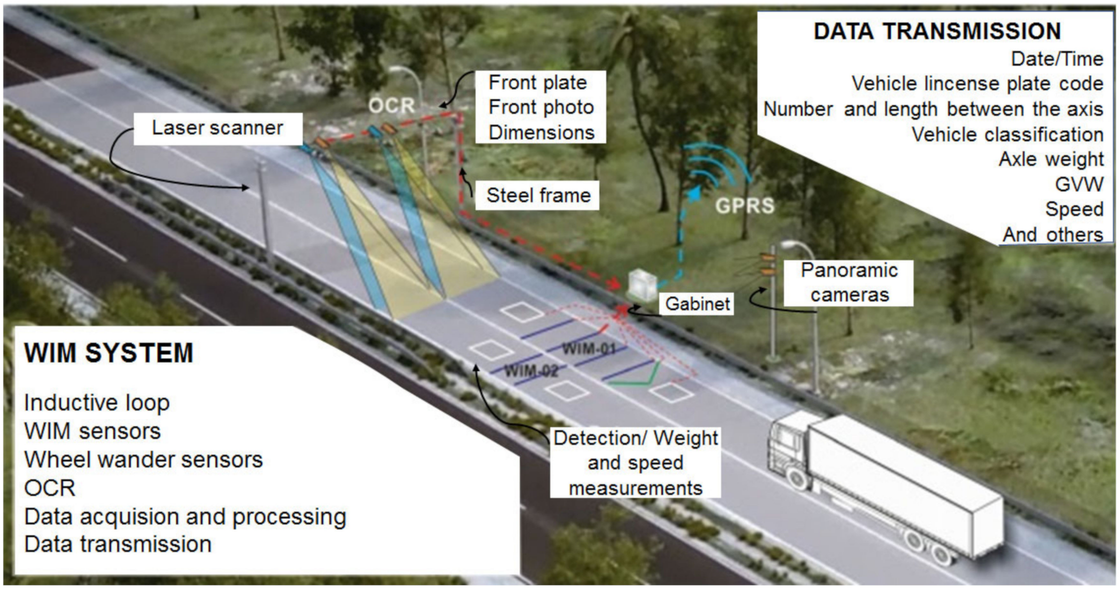

Figure 1. General structure of an HS-WIM system. Source: adapted from ref. [6].

Based on Figure 1, the technologies related to the weighing sensors (WIM sensors) that make up the HS-WIM systems are installed in the structures of pavements, either on their surface or within them, in one or more highway lanes. From these sensors, measurements of axle loads are obtained, automatically, under normal traffic conditions, at the free-flow speed or at the speed of enforcement, from 30 km/h [2,7,11].

2.1. Weight Estimation

The WIM technique consists of the process of estimating the Gross Vehicle Weight (GVW) of a vehicle and the part of that weight that is distributed between the axles, wheels, and tires, in comparison to the weight of the parked vehicle (static weight), from the measurement and analysis of the vertical component of the dynamic force (impact force) of the tire of each wheel of the vehicle, weight being due only to the gravitational force acting on the mass, composed of all the components of the vehicle and the goods transported [7,11]. Regarding weighing technologies, ref. [12] stated that when installed on the pavement, it becomes part of the weighing system. Ref. [13] also stated that the electrical–mechanical responses of sensors used for weighing in motion can be represented by the combination between the moving load and the pavement reactions.

The development of WIM on highways presents a challenge; therefore, the static weight, with certain precision and reliability, from the spatial distribution of the impact force, which varies around the weight, and the time, along the trajectory traveled by the wheels of the vehicle on the pavement and sensors, is estimated. For the estimation of static weight, the measurements of the impact forces are associated with other parameters, such as speed and position of the vehicle on the lanes of the highway, and the distribution above is influenced by the dynamics of the vehicle, as well as by the individual movement of each axle, which are a function of the interaction of the tires with the pavement. In this sense, the more disturbances, the greater the dynamic variation and, consequently, the greater the difficulty in estimating static weight from WIM instruments [7,14,15].

However, regarding factors related to the uncertainties of weight measurements estimated from WIM sensors, it is emphasized that, according to ref. [16], any weighing instrument presents a total error, which consists of the difference between the measured weight and the actual static weight under ideal conditions. Additionally, according to ref. [16], the difference between the sensor response in relation to the application of a load and the load applied is defined as an intrinsic error. The difference between the applied force and the actual static load equivalent to be estimated is characterized as an error due to external factors.

The accuracy of a sensor (intrinsic error) can be tested under laboratory conditions and, depending on technology, can be influenced by factors such as temperature, positioning of the load on the sensor (eccentric load), inclination of the sensor in relation to the applied load, bending, lateral forces or sensitivity to non-vertical forces, repeatability, strain, humidity, electromagnetic susceptibility, among others [16]. On the other hand, errors due to external factors are characterized by the combination of influences resulting from traffic characteristics, the pavement on which the weighing system is installed and the respective sensor or set of sensors, and the sensor or sensors itself. Among various external influences, the oscillatory movement of vehicles is considered as the one with the greatest factor of influence, being divided by the oscillatory movement of the chassis, which depends on the type of load and its distribution along the vehicle, and by the oscillatory movement of the axles. The magnitude, in turn, depends on the speed, the type of suspension and the flatness of the pavement, and, as a minor factor, of its roughness [16].

2.2. Performance and Evaluation Requirements of WIM Systems

According to ref. [7], among the questions related to the definition of performance requirements of the WIM system, it is highlighted the specifications related to the minimum accuracy (tolerances) and reliability for each of the required items of the system are established according to the desired application. According to the authors, the adoption of extremely strict specifications regarding accuracy and reliability can result in the non-existence, in the market, of technologies that can achieve such specifications, or only the existence of those whose prices make their acquisition unfeasible. In this sense, the authors understand that it is necessary to have a balance between what is needed for the desired application and what can be expected of the available sensors and technologies under ordinary conditions of use.

About the definition of the accuracy and reliability of measures resulting from WIM systems, the main international documents are the European Specification COST 323 of 2002, the International Recommendation OIML R-134-1 of 2006, the American Standard Specification ASTM-E1318-09 of 2009, and the document produced by the Independent Metrological Institute of the Netherlands of 2016, which is termed as NMi International Standard WIM. However, all these documents present different criteria and standards regarding the definition and consideration of the precisions or tolerance intervals of errors, with no consensus and uniformity regarding their application, including with regard to HS-WIM, since some of them do not even predict the use of HS-WIM systems, focusing on direct vehicle enforcement. Moreover, each country can adopt its specific metrological legislation [7,11,17–20]. In Brazil, for example, the Metrological Technical Regulation (RTM), in which the maximum permissible errors are established for WIM systems, considers the International Recommendation OIML R-134-1, but with some differences [21].

Considering the installation of WIM systems on highways, following ref. [20], some geometric criteria and requirements are established to be met in relation to the pavement on which the WIM system will be installed, for a segment between 200 m before the system and 50 m after its installation site. Furthermore, the site should be free of constructive interference that causes vehicle bumps, due to sudden changes in inclinations, or that allows constant alternation between bearing lanes, and changes in speed (acceleration, deceleration). In addition, ref. [22] showed how Weigh-in-Motion System can be used in Freight Traffic Management in Urban Areas, and results suggest that emissions can be reduced and traffic flows can be improved, since, following ref. [23], traffic loading has a considerable effect on pavements performance.

With regard to the use of WIM systems, for legal purposes (inspection), ref. [20] established metrological performance requirements for four classes of accuracy. The minimum weight range for GVW measurements should exceed 3500 kg, while for axle load measurements the minimum weight range should be between 2000 kg and 15,000 kg.

3. Materials and Methods

The proposed method (Figure 2) aims to enable the definition of weight tolerance limits of heavy goods vehicles for the HS-WIM system, based on the use of statistical methods of experimentation. In this sense, it is expected to contribute to the development and use of HS-WIM technologies and systems, mainly for the purpose of overweight enforcement and control. The method is composed of a methodological sequencing that includes three steps: definition and characterization of the test site; field testing and data collection; and data analysis.

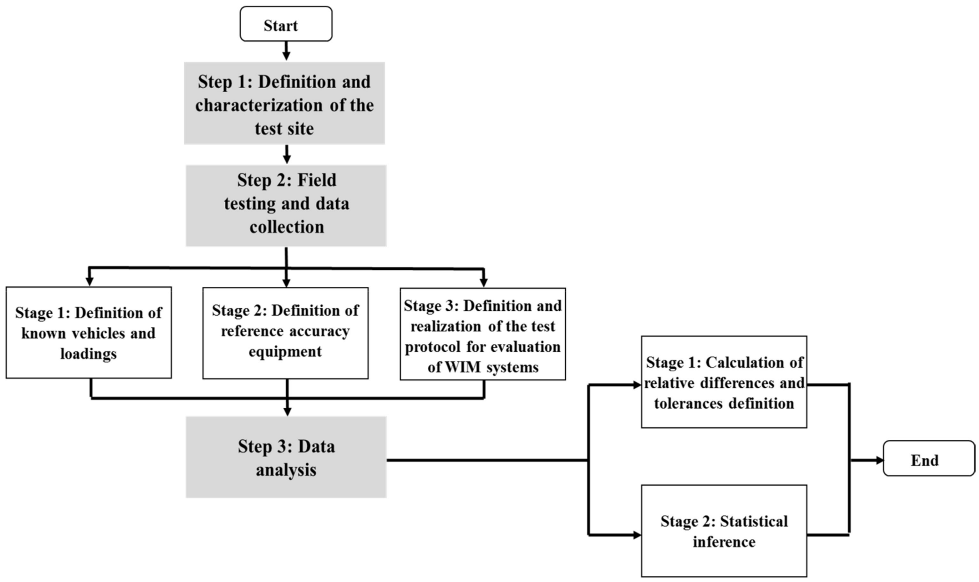

Figure 2. Proposed method for definition of tolerance limits in HS-WIM system.

3.1. Step 1: Definition and Characterization of the Test Site

The sites to be defined for field testing shall be indicated by the competent authorities for the enforcement of heavy goods vehicles and for the maintenance of the highways under their constituency, once such departments have knowledge of the places that need to be enforced in relation to overweight. Furthermore, the definition of the sites should occur so that they are representative, especially in relation to traffic and regarding the climate and environmental conditions of the sites or regions that are characterized as required for the development of enforcement acts using HS-WIM instruments.

Additionally, due to the traffic–pavement–sensor interaction, the test site must meet the geometric criteria previously established for different pavement structures, which supposes the need to adopt specifications and/or domestic or international standards that establish minimum conditions to be achieved by these structures, in compatibility with the use of HS-WIM instruments. Furthermore, it is required that the site presents the maximum possible variability, not only in relation to pavement structures, but also to technologies related to WIM sensors available on the market.

3.2. Step 2: Field Testing and Data Collection

This step is composed of three stages, which are divided into the definition of the known vehicles (reference) and their loading, the definition of the accuracy weighing equipment or instrument, which will be used to obtain the reference weight measurements, and in the definition and realization of the test protocol for evaluation of HS-WIW systems.

3.2.1. Definition of Known Vehicles and Loadings

At least two known vehicles shall be provided. The definition of vehicles should prioritize the maximum possible kind of vehicles and their representativeness in relation to the total volume of heavy goods vehicles existing at the installation site of the HS-WIM system. On the other hand, the loading should be compatible with the applicability provided for the system, taking into the choice of loads that present stability, regarding the maintenance of the center of gravity of the total loading, and low moisture absorption, so that there is no additional loading due to adsorption and/or accumulation of water, when performing the tests.

3.2.2. Definition of Reference Accuracy Equipment

The precision equipment can be static weighing or LS-WIM, and must have a certification report issued by the competent authority, which serves as validation that it is able to be used commercially and/or legally, considering the purposes determined when approving the model, as well as considering the tolerances of allowed measures. Once the equipment is defined, which can be located previously or after the installation of the HS-WIM system at the site, enough weighing repetitions should be carried out using the known vehicles, recording the weight measurements (GVW, axle weight and/or axle group). Such measures should be assessed to obtain the reference measures.

3.2.3. Definition and Realization of the Test Protocol for Evaluation of WIM Systems

For the test protocol, control and test parameters should be provided to include as much as possible or the main factors of influence for which a given HS-WIM system is to be evaluated, as well as enough weighing repetitions provided for each of the known vehicles and for each of the defined parameters, with the hourly markings corresponding to each weighing. The variations in weight measurements (GVW, axle weight and/or axle group), resulting from variations related to vehicle types and axles, speed, and temperature, end up configuring such parameters as mandatory for the evaluation of weight sensors and WIM systems. Furthermore, the tests should be developed at various times during the days defined for data collection to obtain different readings for the temperature of the pavement at the time of weighing, which can be obtained from temperature sensors installed in the structure of the pavement.

3.3. Step 3: Data Analysis

This step is composed of two stages, which are divided into the calculation of the relative differences of weight measures and definition of tolerances, and the realization of statistical inference, having the application of statistical tests, and data analysis.

3.3.1. Calculation of Relative Differences and Tolerances Definition

Based on the weight measurements obtained from the HS-WIM system under evaluation, as well as considering the reference weight measurements obtained from some precision equipment, the relative differences for GVW measurements, weight per axis and/or by a group of axes are calculated, according to Equation (1).

$$d_i = \frac{P_i - P_r}{P_r} \tag{1}$$

where d_i is the relative difference between the weight measurements obtained from the HS-WIM system (P_i) and the corresponding reference measures (P_r), obtained from the precision equipment, for $i = 1, 2, 3 \ldots, n$ relative weight measurements, axle weight and/or axle group. Subsequently, the process of defining tolerances begins, and as required procedures to obtain the maximum and minimum values of weight tolerances, box-plots are created.

3.3.2. Statistical Inference

In this stage, the accuracy of the HS-WIM system (WIM sensors) is evaluated for the effects of the variety of differences related to the weight measurements obtained in relation to the parameters defined in the test protocol. In relation to the accuracy of the HS-WIM system, the student's *t*-test can be used to verify whether the mean weights in several measurements are equal to the actual weight. The null hypothesis (H_0) is that the mean of the observed values is equal to the actual weight (or that the difference between them is equal to zero). The alternative hypothesis (H_1) is that the mean of the values is different from the actual weight measured (or that the difference between the two is nonzero). The test statistic is given by:

$$(H_0)\ \overline{x} = \mu\ (H_1)\ \overline{x} \neq \mu t = \frac{\overline{x} - \mu}{S/\sqrt{n}} \tag{2}$$

where n is the sample size; $\overline{x}$ is the mean weights; and S is the standard deviation of the weights,

$$S = \sqrt{\frac{\Sigma x_i^2 - n\overline{x}^2}{n-1}} \tag{3}$$

For the comparison of mean weights (or relative differences) between different vehicles, temperatures, or between any other parameters, the analysis of variance (ANOVA) can be used when the assumptions of normality and homoscedasticity of variances are satisfied, or the Kruskal–Wallis nonparametric test when the assumptions of the ANOVA are not satisfied. In both tests, the null hypothesis (H_0) is that the means of the populations are all the same, against the alternative hypothesis (H_1) that at least two means of the populations differ from each other. The Kruskal–Wallis test statistic is given by [24]:

$$H = \left[\frac{12}{N(N+1)} \sum_{i=1}^{k} \frac{R_i^2}{n_i} \right] - 3(N+1) \tag{4}$$

where $N = n_i + n_2 + \cdots + n_k$, and n_i is the sample size for each population "k".

4. Results of a Case Study

The data used in this study were from the partnership between the Brazilian Department of Transportation Infrastructure (DNIT) and the Federal University of Santa Catarina (UFSC), through its Transportation and Logistics Laboratory (LABTRANS) located at Florianópolis, Brazil. SAS 9.4 software was used for all data analysis. The application of the previous method is below.

4.1. Step 1: Definition and Characterization of the Test Site

This work used the infrastructure for the Vehicle Weighing Station (PPV 16.08), located in the municipality of Araranguá/SC, more specifically at km 418.5 of the highway BR-101/SC. About the climate, this locality presents a short and warm summer, with a maximum temperature of about 29 °C (on average), a short and comfortable winter with a minimum temperature of about 8 °C (on average), and average precipitation of about 1300 mm/year, these averages referring to the period from September 2008 to May 2020 [25]. For this work, the pavement structure relative to section A02 of segment II (Experimental Track) was used, as shown in Figure 3, which refers to a thick bituminous concrete pavement. This pavement has geometry equal to 120 m long, a total width of 7.2 m (3.6 m in each lane), and it was constructed to meet the parameters established for Class I of the European Specification COST 323, as ref. [11]. This structure is located about 750 m from the weighting precision equipment (segment III), and it has an HS-WIM system composed of piezo-ceramic and piezo-polymer sensors. In general, the results for sections A01 and A03 were the same for section A02, and because of that, they are not shown here.

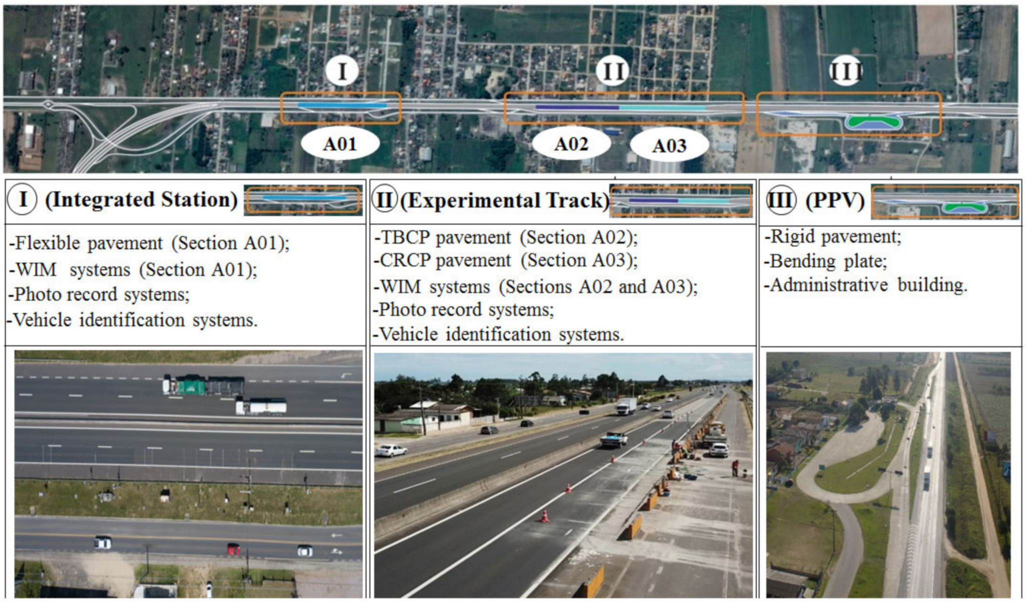

Figure 3. WIM weighing site located in Araranguá/SC. Source: Adapted from refs. [6,26].

4.2. Step 2: Field Testing and Data Collection

The following is a description of the application of the three stages of Step 2 of the proposed method.

4.2.1. Definition of Known Vehicles and Loadings

For this study, three known vehicles were considered (three-axle unarticulated truck, five-axle articulated truck, and six-axle articulated truck), according to the description in Figure 4, in view of their representativeness in relation to local traffic. Each of them was loaded with gravel, due to its stability and low possibility of water absorption, and the vehicles were loaded close to the maximum weight limits (total loading).

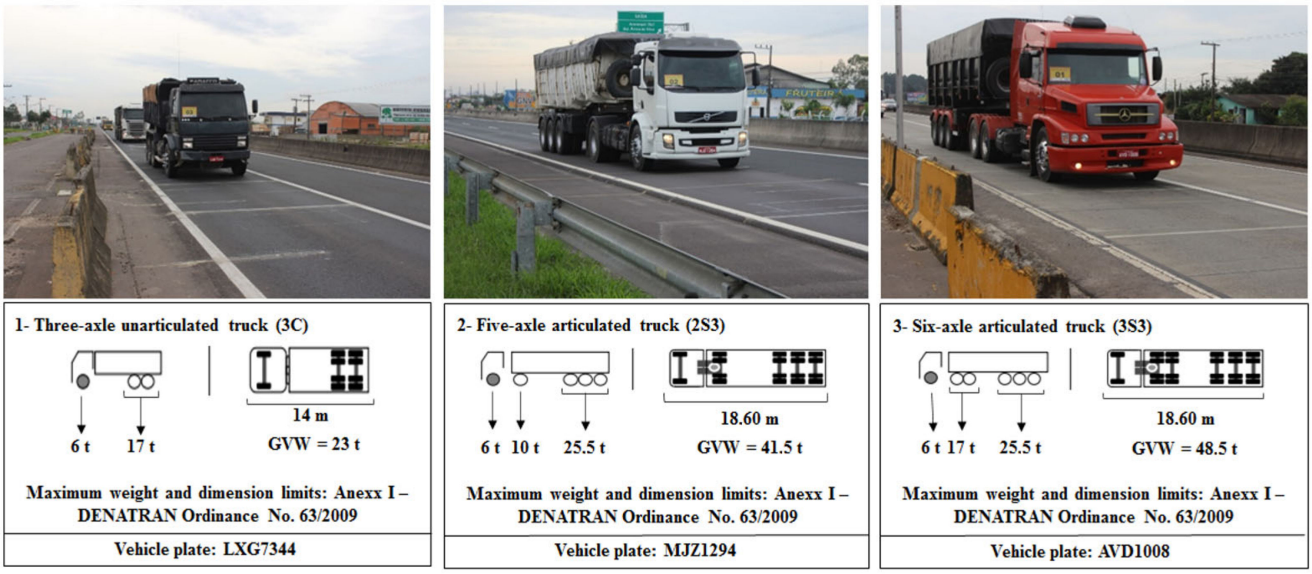

Figure 4. Vehicles used in the case study.

4.2.2. Definition of Reference Accuracy Equipment

The precision equipment considered was the bending plate scale, located in segment III (PPV 16.08), and which was verified by INMETRO on 20 December 2018, having been approved with one-year verification validity, for the accuracy class of GVW measurements (±2.5%) and axle weight (±4.0%), considering speeds up to 6 km/h. In this sense, for each of the known vehicles, 20 weighing repetitions were performed on the scale, and after evaluation of the recorded measures, the following reference weight measurements were obtained: (i) 3-axle truck (3C), with GVW equal to 23,216 kg, weight of axle group 1 (G1) equal to 5475 kg, and weight of axle group 2 (G2) equal to 17,741 kg; (ii) 5-axle articulated truck (2S3), with GVW equal to 41,075 kg, axle group weight 1 (G1) equal to 5787 kg, axle group weight 2 (G2) equal to 10,487 kg, and weight of axle group 3 (G3) equal to 24,801 kg; (iii) 6-axle articulated truck (3S3), with GVW equal to 44,287 kg, axle group weight 1 (G1) equal to 5245 kg, axle group weight 2 (G2) equal to 16,208 kg, and weight of axle group 3 (G3) equal to 22,834 kg.

4.2.3. Definition and Realization of the Test Protocol for Evaluation of WIM Systems

The test for each known vehicle was composed by the observance of three mandatory speeds (60, 70, and 80 km/h) and, when possible, by a fourth speed (90 km/h) once these speeds were regularly used in that locality. It was also considered that each vehicle goes in three different lateral positions in relation to the lane (center, left, and right), in which the HS-WIM system was installed. Furthermore, the performance of the vehicles by the HS-WIM system was considered at various times during the collection days, as well as the recording of pavement temperatures from the temperature sensors installed on the pavement. The test was performed from 5 May 2019 to 9 May 2019, and at least 30 weighs were performed for each known vehicle, including the variation of speed and lateral position. From the vehicles plates, as well as from OCR equipment and photo registration, weight measurements were identified and obtained from the data collection system developed by LabTrans/UFSC.

4.3. Step 3: Data Analysis

The application of the two stages of Step 3 of the proposed method is presented below.

4.3.1. Calculation of Relative Differences and Tolerances Definition

The absolute frequencies of the sets of relative differences in weight measurements (GVW, weight per axle, and weight per axle group), for each known reference vehicle, including the conditions of speed and lateral position on the lane and two sets of temperatures are in Table 1. In total there are 177 observations.

Table 1. Absolute frequencies for Section A02.

Absolute Frequencies—Section A02									
Speed	**Lateral Position on the Lane**	**Vehicles**						**Total**	
		3C with 2 Groups of Axles (3C)		**2S3 with 3 Groups of Axles (2S3)**		**3S3 with 3 Groups of Axles (3S3)**			
		Pavement Temperatures		**Pavement Temperatures**		**Pavement Temperatures**			
		<37.0 °C	**≥37.0 °C**	**<37.0 °C**	**≥37.0 °C**	**<37.0 °C**	**≥37.0 °C**		
60 km/h	center	8	0	7	0	7	0	22	56
	left	7	0	6	0	7	0	20	
	right	2	5	2	5	0	0	14	
70 km/h	center	0	5	0	7	0	3	15	51
	left	2	5	2	5	1	3	18	
	right	6	0	7	0	5	0	18	
80 km/h	center	0	6	0	7	0	1	14	48
	left	0	9	0	10	0	1	20	
	right	1	6	1	6	0	0	14	
90 km/h	center	0	3	1	5	0	1	10	22
	left	0	4	0	6	0	2	12	
	right	0	0	0	0	0	0	0	
Totals		26	43	26	51	20	11	177	
		69		77		31			

The relative differences in weight measurements (GVW and axes groups) were obtained based on Equation (1). In this study, for the construction of the box-plots, the data sets, which include the variations in speed and lateral position of the vehicles on the lane, were separated for each known vehicle and for two sets of pavement temperatures, formed by temperatures below and above 37 °C. Figures 5–7 show the results for each type of vehicle used.

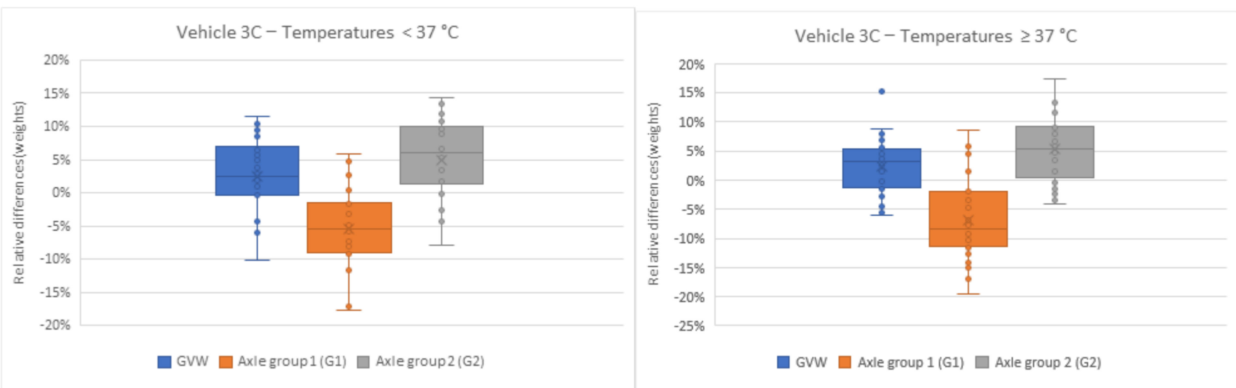

Figure 5. Box-plots of the relative differences of weight measurements by GVW and axle groups—non-articulated truck (3C), 3-axles and 2 groups of axles—Section A02.

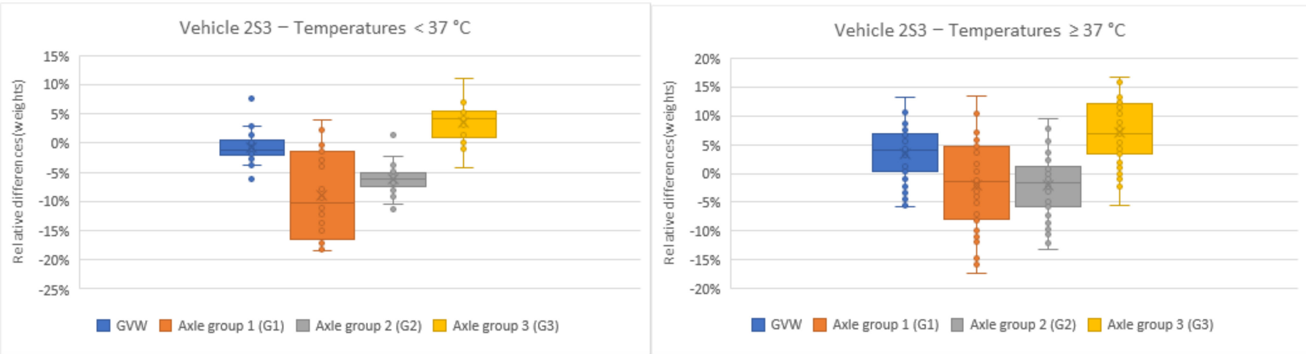

Figure 6. Box-plots of the relative differences of weight measurements by GVW and axles groups—articulated truck (2S3), five axles and three groups of axles—Section A02.

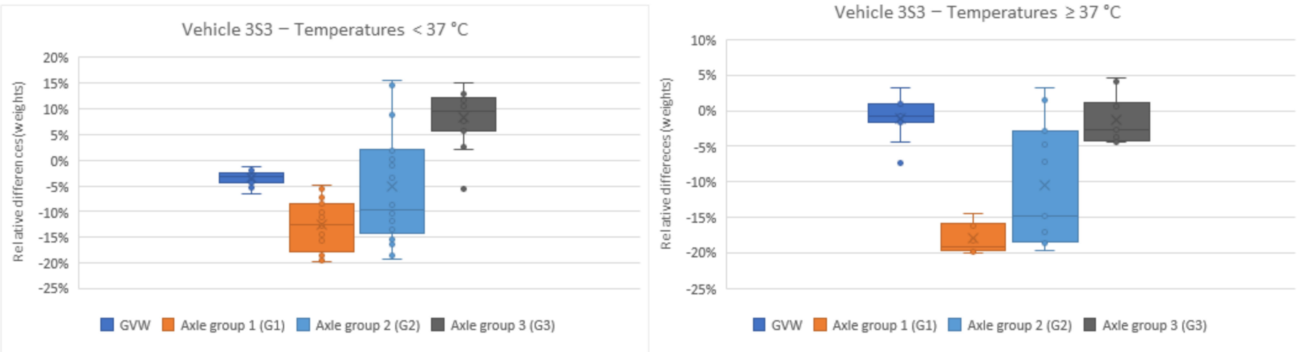

Figure 7. Box-plots of the relative differences of weight measurements by GVW and axles groups—articulated truck (3S3), six axles and three groups of axles—Section A02.

Based on Figure 5, it is verified that the highest degree of dispersion between the differences related to GVW measurements and weighting by axes groups were in axis group 1 in both temperature sets. The absolute maximum relative differences of weight measurements, considering the two sets of temperatures were equal to 12% (GVW), 20% (G1), and 17% (G2).

Based on Figure 6, it is verified that the highest dispersion of differences related to GVW measurements and weight by axle groups occurred in axle group 1, for both temperature sets, although specifically for temperatures above 37 °C the dispersion was higher. The absolute maximum relative differences in weight measurements, considering the two sets of temperatures were equal to 13% (GVW), 19% (G1), 13% (G2), and 17% (G3).

Based on Figure 7, it is verified that the highest dispersion of differences related to GVW measurements and weight by axle groups occurred in axle group 2, for both temperature sets, although specifically for temperatures below 37 °C the dispersion was higher. The absolute maximum relative differences in weight measurements, considering the two sets of temperatures were equal to 7% (GVW), 20% (G1), 20% (G2), and 15% (G3).

In general, from Sections A01, A02, and A03, the maximum percentages obtained, in module, considering all reference vehicles, were equal to 13% (GVW), 20% (G1), 20% (G2), and 17% (G3), and in most cases, the distribution related to the weight measures corresponding to the groups of axes 1 were those with the highest degrees of dispersion, while GVW distribution, on the other hand, showed the lowest dispersion.

However, obtaining adequate maximum and minimum percentages for the purpose of defining tolerances to the HS-WIM system required that this system be calibrated, minimizing total errors (intrinsic and due to external factors) and enabling more adequate accuracy in relation to the weight measurements to be estimated. Similarly, considering the various factors that can influence the achievement of weight measurements, which are often inherent to the reality of each country, the definition of tolerances requires that several parameters be compared in order to identify the existence of equality between them, as well as which of the parameters may be predominant and, also, what considerations should be made in terms of defining tolerances. In this sense, the following section presents the statistical analysis first including the verification of the accuracy of the evaluated system and, finally, the comparison between some of the established parameters.

4.3.2. Statistical Inference

For this work, it was intended to compare if there was a difference between the pavement temperature, speed, and lateral position for each type of vehicle and weight measurements (Table 2) and if there was a difference between the vehicles regarding the differences related to GVW measurements and the weight of axle groups for each temperature set (Table 3). The *p*-values of the tests (ANOVA or Kruskal–Wallis, depending on the satisfied assumptions) are presented in Tables 2 and 3.

Table 2. Comparison between temperatures, speed, lateral position by vehicle type, and types of weight measurements.

Weight Measurements	Speed	Lateral Position	Vehicles					
			3C		2S3		3S3	
			Pavement Temperatures		Pavement Temperatures		Pavement Temperatures	
			<37.0 °C	≥37.0 °C	<37.0 °C	≥37.0 °C	<37.0 °C	≥37.0 °C
GVW	60 km/h	Center	0.0002 *	-	0.0328 *	-	0.0001 *	-
		Left	**0.3141** ^{NS}	-	0.0130 *	**-**	0.0026 *	-
		Right	**0.1056** ^{NS5}	0.0287 *	0.0036 *	0.0006 *	-	-
	70 km/h	Center		**0.3750** ^{NS5}		0.0038 *	-	**0.4532** ^{NS5}
		Left	**0.5215** ^{NS5}	**0.2314** ^{NS5}	**0.2730** ^{NS5}	0.0152 *	-	**0.0554** ^{NS5}
		Right	0.0009 *		**0.8105** ^{NS}		0.0003 *	-
	80 km/h	Center	-	0.0157 *	-	0.0001 *	-	-
		Left	-	**0.1129** ^{NS}	-	0.0001 *	-	-
		Right	-	**0.6554** ^{NS}	-	**0.8351** ^{NS}		-
	90 km/h	Center	-	**0.7506** ^{NS5}	-	**0.1172** ^{NS5}	-	-
		Left	-	**0.1250** ^{NS5}	-	0.0435 *	-	**0.2211** ^{NS5}
		Right	-		-		-	-
Axle group (G1)	60 km/h	Center	**0.4226** ^{NS}	-	0.0003 *	-	0.0001 *	-
		Left	0.0285 *	-	0.0001 *	-	0.0001 *	-
		Right	0.0018 *	0.0151 *	**0.0797** ^{NS5}	0.0009 *	-	-
	70 km/h	Center	-	0.0148 *		**0.3878** ^{NS}	-	0.0001 *
		Left	**0.8335** ^{NS5}	**0.2705** ^{NS5}	**0.6780** ^{NS5}	**0.2494** ^{NS5}	-	0.0030 *
		Right	0.0004 *	-	**0.1046** ^{NS}		**0.0625** ^{NS5}	-
	80 km/h	Center	-	**0.2188** ^{NS}	-	**0.7409** ^{NS}	-	-
		Left	-	**0.2985** ^{NS}	-	**0.0544** ^{NS}	-	-
		Right	-	0.0008 *	-	**0.1250** ^{NS}	-	-
	90 km/h	Center	-	**0.0992** ^{NS5}	-	0.0292 *	-	-
		Left	-	**0.3092** ^{NS5}	-	**0.5932** ^{NS}	-	0.0288 *
		Right	-		-	-	-	-

Table 2. *Cont.*

Weight Measurements	Speed	Lateral Position	Vehicles					
			3C		2S3		3S3	
			Pavement Temperatures		Pavement Temperatures		Pavement Temperatures	
			<37.0 °C	**≥37.0 °C**	**<37.0 °C**	**≥37.0 °C**	**<37.0 °C**	**≥37.0 °C**
Axle group (G2)	60 km/h	Center	0.0001 *	-	0.0001 *	-	0.0003 *	-
		Left	**0.8692** NS	-	0.0001 *	-	0.0118 *	-
		Right	**0.1932** NS5	**0.1363** NS5	0.0244 *	0.0001 *	-	-
	70 km/h	Center	-	**0.0831** NS5		**0.0478** NS	-	**0.7749** NS5
		Left	**0.3627** NS5	**0.0456** NS5	**0.8444** NS5	**0.0864** NS5	-	**0.0922** NS5
		Right	0.0004 *	-	0.0001 *		0.0125 *	-
	80 km/h	Center	-	0.0003 *	-	0.0203 *	-	-
		Left	-	0.0186 *	-	**0.6201** NS	-	-
		Right	-	**0.0892** NS	-	**0.1167** NS	-	-
	90 km/h	Center	-	**0.3227** NS5	-	0.0080 *	-	-
		Left	-	0.0130 *	-	**0.5615** NS	-	**0.2460** NS5
		Right	-	-	-	-	-	-
Axle group (G3)	60 km/h	Center	-	-	0.0009 *	-	0.0001 *	-
		Left	-	-	**0.3233** NS	-	0.0001 *	-
		Right	-	-	**0.1265** NS5	**0.5827** NS5	-	-
	70 km/h	Center	-	-	-	0.0051	-	**0.7371** NS5
		Left	-	-	**0.1904** NS5	0.0079 *	-	0.0039 *
		Right	-	-	0.0154 *	-	**0.3693** NS5	-
	80 km/h	Center	-	-	-	0.0001 *	-	-
		Left	-	-	-	0.0001 *	-	-
		Right	-	-	-	**0.1691** NS	-	-
	90 km/h	Center	-	-	-	**0.0553** NS5	-	-
		Left	-	-	-	0.0202 *	-	**0.9767** NS5
		Right	-	-	-	-	-	-

* (Significant at 5%)/**NS** (Non-significant at 5%)/**NS5** (Non-significant at 5% for frequencies ≤ 5).

Table 3. (*p*-Values) and multiple comparisons for Section A02.

Sector A02—(*p*-Values) and Multiple Comparisons													
Items	**Tests**	**Relative Differences in Weight Measurements (Variables)—ANOVA and Kruskal-Wallis**						**Relative Differences in Weight Measurements (Variables)—Tukey**					
		Description of Distributions		**GVW**	**G1**	**G2**	**G3**	**Description of Distributions**		**GVW**	**G1**	**G2**	**G3**
1	Comparison between vehicles	3C						3C/2S3 (vice versa)		**NS**	**NS**	*	
		2S3		0.0001 *	0.0001 *	0.0001 *	**0.5893** ^{NS}	2S3/3S3 (vice versa)		*	*	*	-
		3S3						3S3/3C (vice versa)		*	*	*	
2	Comparison between temperatures	<37.0 °C		0.0001 *	0.0257 *	**0.1211** ^{NS}	**0.9752** ^{NS}	<37.0 °C and ≥37.0 °C		*	*	-	-
		≥37.0 °C											
3	Comparison between speeds	60 km/h						60 and 70 km/h (vice versa)		*	**NS**	*	**NS**
								60 and 80 km/h (vice versa)		*	*	*	**NS**
		70 km/h		0.0001 *	0.0009 *	0.0004 *	0.0367 *	60 and 90 km/h (vice versa)		*	**NS**	**NS**	**NS**
		80 km/h						70 and 80 km/h (vice versa)		*	**NS**	**NS**	*
		90 km/h						70 and 90 km/h (vice versa)		**NS**	**NS**	**NS**	**NS**
								80 and 90 km/h (vice versa)		**NS**	**NS**	**NS**	**NS**
4	Comparison between temperatures by vehicle types	3C	<37.0 °C	**0.9789** ^{NS}	**0.1935** ^{NS}	**0.7705** ^{NS}	-	3C	<37.0 °C and ≥37.0 °C	-	-	-	-
			≥37.0 °C										
		2S3	<37.0 °C	0.0001 *	0.0007 *	0.0003 *	0.0038 *	2S3	<37.0 °C and ≥37.0 °C	*	*	*	*
			≥37.0 °C										
		3S3	<37.0 °C	0.0022 *	0.0022 *	0.0002 *	0.0001 *	3S3	<37.0 °C and ≥37.0 °C	*	*	*	*
			≥37.0 °C										

Table 3. *Cont.*

Sector A02—(*p*-Values) and Multiple Comparisons													
Items	Tests	Relative Differences in Weight Measurements (Variables)—ANOVA and Kruskal-Wallis						Relative Differences in Weight Measurements (Variables)—Tukey					
		Description of Distributions		GVW	G1	G2	G3	Description of Distributions		GVW	G1	G2	G3
5	Comparison between speeds by vehicle types	3C	60 km/h					3C	60 and 70 km/h (vice versa)				
									60 and 80 km/h (vice versa)				
			70 km/h	**0.4716** ^{NS}	**0.9622** ^{NS}	**0.2154** ^{NS}	-		60 and 90 km/h (vice versa)	-	-	-	-
									70 and 80 km/h (vice versa)				
			80 km/h						70 and 90 km/h (vice versa)				
			90 km/h						80 and 90 km/h (vice versa)				
		2S3	60 km/h					2S3	60 and 70 km/h (vice versa)	*	*	*	*
									60 and 80 km/h (vice versa)	*	*	*	*
			70 km/h	0.0001 *	0.0001 *	0.0001 *	0.0002 *		60 and 90 km/h (vice versa)	*	*	*	**NS**
									70 and 80 km/h (vice versa)	**NS**	**NS**	**NS**	**NS**
			80 km/h						70 and 90 km/h (vice versa)	**NS**	**NS**	**NS**	**NS**
			90 km/h						80 and 90 km/h (vice versa)	**NS**	**NS**	**NS**	**NS**
		3S3	60 km/h					3S3	60 and 70 km/h (vice versa)		*	*	*
									60 and 80 km/h (vice versa)		**NS**	**NS**	*
			70 km/h	**0.1978** ^{NS}	0.0028 *	0.0056 *	0.0001 *		60 and 90 km/h (vice versa)	-	**NS**	**NS**	*
									70 and 80 km/h (vice versa)		**NS**	*	**NS**
			80 km/h						70 and 90 km/h (vice versa)		**NS**	*	**NS**
			90 km/h						80 and 90 km/h (vice versa)		**NS**	**NS**	**NS**

Table 3. *Cont.*

Sector A02—(*p*-Values) and Multiple Comparisons													
Items	**Tests**	**Relative Differences in Weight Measurements (Variables)—ANOVA and Kruskal-Wallis**						**Relative Differences in Weight Measurements (Variables)—Tukey**					
		Description of Distributions		**GVW**	**G1**	**G2**	**G3**	**Description of Distributions**		**GVW**	**G1**	**G2**	**G3**
6	Comparison between vehicles by speed range	60 km/h	3C	**0.0562** ^{NS}	0.0001 *	0.0001 *	0.0001 *	60 km/h	3C/2S3 (vice versa)	-	*	*	-
			2S3						2S3/3S3 (vice versa)		**NS**	**NS**	*
			3S3						3S3/3C (vice versa)		*	*	-
		70 km/h	3C	0.0001 *	0.0001 *	0.0001 *	0.0009 *	70 km/h	3C/2S3 (vice versa)	**NS**	*	*	-
			2S3						2S3/3S3 (vice versa)	*	*	*	*
			3S3						3S3/3C (vice versa)	*	*	**NS**	-
		80 km/h	3C	**0.0508** ^{NS}	0.0016 *	0.0001 *	0.0343 *	80 km/h	3C/2S3 (vice versa)	-	*	*	-
			2S3						2S3/3S3 (vice versa)		*	*	*
			3S3						3S3/3C (vice versa)		**NS**	*	-
		90 km/h	3C	**0.4783** ^{NS}	**0.0797** ^{NS}	0.0009 *	**0.2482** ^{NS}	90 km/h	3C/2S3 (vice versa)	-	-	*	-
			2S3						2S3/3S3 (vice versa)			*	
			3S3						3S3/3C (vice versa)			*	

G: Group of axles/(*) Significant at 5%/(NS): Non-significant at 5%.

Table 2 shows that the HS-WIM system evaluated was not properly accurate in relation to the weight measurements (GVW and weight per axle groups) estimated for all variations of vehicle, speed, lateral position on the lane, and pavement temperatures, since there was a large number of p-values that indicated a significant difference at 5% significance level. Such inaccuracies show some problems of the HS-WIM system in relation to intrinsic errors and/or due to external factors. In this sense, the maximum and minimum limits identified from the box-plots could not be considered valid, in general, to the definition of tolerances. For all possible combinations between GVW and weights by groups of axes, speed, lateral position on the lane, pavement temperatures, and vehicle configuration please check Table S1 in the Supplementary Materials; taking as a specific reference the observations related to GVW and weights by groups of axes, it was observed that, for vehicle configuration and speed variations, lateral position on the lane, and pavement temperatures, the measurements or differences related to the groups of axes 1 (G1) were those that presented a higher number of significant differences at 5% significance level. This finding may be related to the fact that the distribution corresponding to the weight measurements of axel group 1 were those with a higher degree of dispersion.

Next, regardless of the situation of accuracy identified for the HS-WIM system, differences were made between the mean weights (or relative differences) of different parameters to verify the equality between them and, therefore, determine if there was an influence of a given parameter on the weight measurements to be obtained by the system under evaluation. Having been previously evaluated by the sample means for their goodness-of-fit to the normal distribution, by using the Kolmogorov–Smirnov test, as well as the previous assessment of the equality of variances, by means of the Levene homoscedasticity test, the p-values were obtained from the application of the ANOVA test or the Kruskal–Wallis test (when the ANOVA assumptions of normality and/or homogeneity of variances were not satisfied) and they are shown in Table 3.

Table 3, therefore, includes the p-values corresponding to six comparative tests of different parameters, namely: (i) comparison between vehicles; (ii) comparison between temperatures; (iii) comparison between speeds; (iv) comparison between temperatures by vehicle types; (v) comparison between speeds by vehicle types; and (vi) comparison between vehicles by speed range. In case of significant difference at a 5% significance level (p-value < 0.05) in ANOVA or Kruskal–Wallis tests, the Tukey multiple comparison test was applied for those distributions of relative differences in weight measurements (GVW and weight by axle groups).

Regarding the comparison between the vehicles, it is possible to observe that, with the exception of the measures related to axle group 3 (G3), there were significant differences between at least two of the population means of the vehicles considered, which was confirmed according to the multiple comparison test. This result shows that the configuration of vehicles seems to influence section A02 in relation to the weight measurements.

Considering the comparison between the temperature sets, it was observed that, with the exception of the measurements related to GVW and the groups of axes 1, for the weight measurements corresponding to the groups of axes 2 (G2) and 3 (G3), not significant differences were identified between the two temperature sets. This result shows that temperature variations seemed to influence the weight measurements related to GVW and axis groups 1 and, therefore, seemed to influence section A02 in relation to the weight measurements.

From the comparison between the speeds, it was observed that significant differences were identified between at least two of them, for all weight measurements, as also verified from the multiple comparison test. This result shows that, in relation to section A02, speed seemed to influence the weight measurements (GVW and axle groups), especially when comparing the speeds of 60 km/h and 80 km/h.

Regarding the comparison between temperatures by types of vehicles, it was observed that, with the exception of the 3C vehicle, significant differences were present between the temperature sets for all weight measurements, considering the other vehicles (2S3 and 3S3). This result, confirmed by the multiple comparison test, shows that, depending on the vehicle configuration, temperature variations seemed to influence section A02 in relation to the weight measurements.

From the comparison between the speed ranges by types of vehicles, it was observed that, with the exception of the 3C vehicle and GVW of the 3S3 vehicle, significant differences were identified for all other weight measurements, which was confirmed according to the multiple comparison test. The result of this comparison shows that, depending on the configuration of the vehicles, the speed variations, especially comparing the speed of 60 km/h with the others, seemed to influence the weight measurements in section A02.

Finally, from the results of the comparison between the types of vehicles by speed range, it was observed that significant differences were identified between at least two of the vehicles, for each speed range, considering the different weight measurements, which was confirmed by the multiple comparison test. These results show that, depending on the speed range, vehicle settings seemed to influence weight measurements.

In general, considering the *p*-values for the section A02, given the comparative tests performed and the accuracy situation of the HS-WIM system, and also from the tests of multiple comparisons, it was possible to verify that all of them seemed to be influenced by vehicle configurations, including the respective characteristics of traffic (load and its distribution, dimensions, types of axles, wheel spacing, type of wheel, tire filling pressure and their distribution on the pavement, etc.), by the variations in speed and also by the association or relationship between the types of vehicles and the speeds, when interacting with the pavement and their respective geometric characteristics and responses to the applied loads. This result is consistent with the considerations pointed out by ref. [27] regarding vehicle–road interaction and also about dynamic load.

Similarly to that pointed out by ref. [27], as well as considering what was pointed out by ref. [12], when pavement is part of the weighing system, the effects resulting from dynamic loads, i.e., vehicle oscillations/vibrations (associated with speed variations), when interacting with the pavement surface and also from weighing sensors, end up determining how weight measurements (GVW and axle weights or axle groups) can be understood by HS-WIM systems. However, considering the aspects above pointed out by ref. [16] on the effects resulting from the error due to vehicle oscillations, based on the results identified in this research, tolerances should be defined based on compliance with vehicle configurations, in compliance with speed variations, and respecting the necessary suitability for geometric conformation of pavement structures, especially regarding the levels of longitudinal roughness.

Still, considering the *p*-values obtained for the sections A01, A02, and A03, given the comparative tests performed and the accuracy situation of the HS-WIM system, it was possible to verify that the effects of temperature variations, in relation to obtaining weight measurements, seemed to influence the HS-WIM systems whose pavement structures were composed of an asphalt concrete coating layer, not influencing the rigid pavements, then structured in Portland cement concrete. In this sense, based on the results found, depending on the type of pavement structure to be used for the composition of the HS-WIM system, in association with the place where a particular HS-WIM system is to be installed, the effects resulting from the temperature variation of the pavement should be considered for the purpose of defining tolerances.

5. Conclusions

This work aimed to identify the weight tolerance limits for HS-WIM systems through a controlled experiment. It was found that the maximum weight tolerance limits for GVW varied between 7% and 12%, and for axle groups, these limits varied between 15% and 20%. Furthermore, it was found that such weight tolerance limits varied according to the vehicle configuration and the pavement temperature, with the adoption of different limits.

Finally, the use of statistical methods of experimentation proved to be a mechanism capable of presenting relevant results including the improvement of algorithms for calibration of HS-WIM systems, improving the levels of accuracy, and control of data quality. It is recommended for future work to use other types of vehicles more used in other regions of Brazil, such as in the North and Northeast regions, which have quite different pavement and temperature characteristics from the South region.

This research has some limitations, the first being the use of a limited number of heavy commercial vehicles, which were restricted to those representatives of the place of installation of the HS-WIM system. Additionally, the method was applied only in one region of Brazil, not covering other locations and/or regions of the country with different weather conditions. However, a greater scope of the factors mentioned may involve high costs, either related to the construction of sections of pavements, or to the acquisition of systems and rental of vehicles. For this research, for example, considering exclusively the rental of the vehicles used, the total cost was approximately US$ 4000.00, which is approximately R$ 20,000.00.

This research also did not include the variation and verification of parameters related to vehicle characteristics or configurations, such as wheel types, tire types, tire filling pressure, and types of suspensions, which could influence the estimation of weight measurements by HS-WIM systems. With regard to pavement structures, there were no checks on constructive and/or geometric and performance conditions of the pavement, mainly in terms of longitudinal irregularity.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su14127039/s1, Table S1: Comparison between temperatures, speed, lateral position by vehicle type and, types of weight measurements.

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