STUDY OF THE DYNAMIC EFFECTS OF LOADS AND ACTIONS TO REDUCE THE UNCERTAINTIES

  

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Abstract
This paper presents the results of the study of the dynamic effect of the load and actions to reduce the uncertainties caused. For this, the review of the studies that consider the dynamic oscillation of loads in the accuracy of WIM systems will be presented. At first, the analysis of the experiments performed at the experimental site Brazil will be presented, comparing the results obtained from the instrumentation of the load vehicles with the data obtained with the WIM sensors. In a second part, the analysis of the results of the experiments performed on the IFSTTAR fatigue carousel in Nantes, France, will be compared. Finally, it will be discussed the need to correct the effect of vehicle dynamics and possible methods to decrease uncertainties and increase the accuracy of WIM systems.

Keywords: weigh-in-motion, WIM accuracy, vehicle dynamics, road profile, pavement and sensor interaction.

Résumé
Cet article présente les résultats de l'étude de l'effet dynamique de la charge et les actions visant à réduire les incertitudes causées. Pour cela, nous présentons la synthèse des études prenant en compte l'oscillation dynamique des charges dans la précision des systèmes WIM. Dans un premier temps, l'analyse des expériences effectuées sur le site expérimental du Brésil sera présentée, comparant les résultats obtenus de l'instrumentation des véhicules de charge aux données obtenues avec les capteurs WIM. Dans une seconde partie, l'analyse des résultats des expériences réalisées sur le carrousel de fatigue de l'IFSTTAR à Nantes, en France, sera comparée. Enfin, il sera discuté de la nécessité de corriger l'effet de la dynamique du véhicule et des méthodes possibles pour réduire les incertitudes et augmenter la précision des systèmes WIM.

Mots-clés: pesage en marche, précision WIM, véhicule dynamique, l'uni longitudinal, chaussée et capteurs WIM.

1. Introduction

The Araranguá test site in Santa Catarina is located at km 419 of route BR-101, south of Brazil. It is supported by the National Department of Terrestrial Infrastructure (DNIT), which is part of the Ministry of Transport since 2007. The experimental site consists of three locations with specific applications of WIM technologies. In the first site, called Integrated Station, studies are carried out with market available commercial systems and with WIM applications where a metrological certification is not necessary and that allow integration to other systems. Applications for these systems include classificatory counting of vehicles with weighing, pre-selection of vehicles for the inspection of excess loads and for applications in toll plazas. In the second location, called the traffic control station, studies are carried out with sensors and systems for the design of a technological model with application for Direct Surveillance. The third site is the weighing station, where studies are carried out to define the operational model of the Integrated Automated Enforcement Station (initials in Portuguese are PIAF), the current weighing model adopted on federal highways.

During the test period, soon after the installation of the WIM systems, tests were carried out with instrumented trucks. Four classes of heavy vehicles were chosen, representing 80% of the fleet's cargo vehicles. The classes of load vehicles used in the tests are: heavy truck with 2 axles, heavy truck with 3 axles, semi-trailer truck with 5 axles and semi-trailer truck with 6 axles. The vehicles were instrumented with strain-gages glued on the axles, left and right side, and accelerometers glued to the body. A data acquisition system collected data in real time. The collected signals were processed and crossed with information from a coupled GPS system; both devices working synchronously determined the position of the vehicle with respect to the track and with respect to the WIM system.

This paper presents the results of the study of the dynamic effect of the load and actions to reduce the uncertainties caused. For this, the review of the studies that consider the dynamic oscillation of loads in the accuracy of WIM systems will be presented. At first, the analysis of the experiments performed at the experimental site Brazil will be presented, comparing the results obtained from the instrumentation of the load vehicles with the data obtained with the WIM sensors. In a second part, the analysis of the results of the experiments performed on the IFSTTAR fatigue carousel in Nantes, France, will be compared. Finally, it will be discussed the need to correct the effect of vehicle dynamics and possible methods to decrease uncertainties and increase the accuracy of WIM systems.

2. Road profile and vehicle dynamics

Roadway pavement surfaces usually present longitudinal variations, due to imperfections during construction or to permanent deflection during its service life. Such defects on the road profile cause dynamic perturbations on passing vehicles, causing movements that affect the comfort and safety of passengers, depending on the excitation frequency. They are also the cause of the dynamic overload that accelerate pavement degradation (LCPC, 2009). The variations of the height z of the surface along a longitudinal curve x are defined as the longitudinal profile.

Approaching the WIM sensor, the forces transmitted to the pavement vary according to the dynamic acceleration in each instant t. The weighing sensors detect the stresses exerted on its surface on the instant of the load passage. The resulting vertical force $F(t)$ on the sensor is proportional to the equivalent static force $F_s = m \cdot g$ (mass under the effect of constant gravity acceleration) combined with the dynamic force in a given instant $F_d(t) = m \cdot a(t)$ (mass under the effect of the resulting dynamic acceleration at instant t). Hence,

$$F(t) = F_s + F_d(t) \tag{1}$$

Where: $F(t)$ is the vertical resulting force for each instant t; F_s is the equivalent static force, here considered unaltered; $F_d(t)$ is the dynamic force, which is a function of the roadway profile for instant t in time.

A schematic of the vehicle dynamics is presented in Figure 1. The force $F(t)$ travels at velocity V in the direction of the weighing sensor at a distance determined by Vt. The weighing sensor is at the center of the $[-l; l]$ interval, precisely at $t = 0$. The sensor measures with precision the force $F(0)$. The acceleration $a(t)$ acts on the vehicle mass over the proximity of the WIM sensor. The acceleration $a(0)$ acts at the moment when the load is over the sensor surface. The force action on the sensor corresponds to $F(0) = m \cdot g + m \cdot a(0)$. Negative values of acceleration represent a resulting force inferior to F_s.

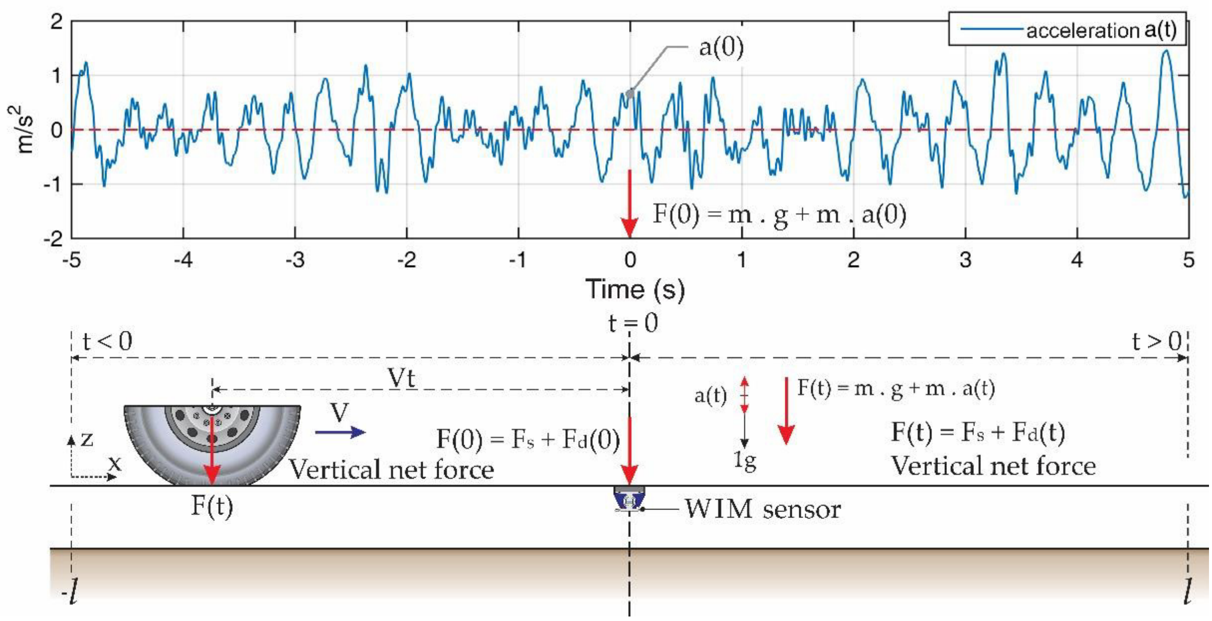

Figure 1 - Effect of the dynamic load over the WIM site, dynamic variation of the applied force and reading of the weighing sensor at instant $t = 0$

The correction of the dynamic effect of the load over the WIM sensor can be considered from the identification of the relation r between the resulting vertical force $F(0)$ and the value of the equivalent static force $F_s \approx \overline{F}$.

$$r = \frac{F(0)}{\overline{F}} \tag{2}$$

Where: r is the correction coefficient for the dynamic force measured at instant $t = 0$; $F(0)$ is the resulting vertical force at instant $t = 0$; $\overline{F}$ is the equivalent static force approximated by the average value of the force $F(t)$. The parameter r considers the fact that using the force's average value over sufficiently large periods reduces the effect of dynamic variation.

2.1 International roughness index - IRI

The International Roughness Index (IRI) adopts as input the defects of the longitudinal profile with wavelength L between 1 and 30 meters and attenuates the defects that are not in this interval. The displacement velocity of the Golden Car is fixated at 80 km/h, and the IRI is approximately sensitive to the frequency band between 0,7 Hz and 22 Hz. The index is calculated as the sum of the differences between the vertical position of the suspended and unsprung mass at the stretch comprehended in L, corrected by the velocity. It can be expressed as follows:

$$IRI = \frac{1}{L}\int_0^{L/V} |\dot{z}_s(t) - \dot{z}_u(t)| dt \quad (2)$$

Where V is the velocity, z_s is the vertical displacement of the suspended mass and z_u the vertical displacement of the unsprung mass. The calculated value for the IRI has the form of a decimal number between 0 (perfect irregularity) and the dimension of an inclination in m/m or m/km.

2.2 Note par Bande de Onde - NBO

In France, another measure used to characterize the irregularities of the transversal profile is the waveband notation (NBO). This method decomposes the profile in three spectral wavebands and analyzes each of them. The energy values (expressed in cm^3) are determined by the product of the sum of the squares of the amplitudes and the interval between two points (MENANT, 2014).

$$E = \Delta x \cdot \sum_{i=1}^{N} A_i^2 \quad (3)$$

Where Δx is the sampling step of the signal, N the number of points measured corresponding to the length of the segment and A_i the amplitude of the signal in cm. The calculation of the DSP consists of determining the power allocation of one signal due to a frequency scale. Here it can be defined as the square of the module of the Fourier transform of the signal $F\{x(t)\}$, divided by the frequency step df.

$$F\{x(t)\} = \int_{-\infty}^{\infty} x(t)e^{-j2\pi ft}\, dt \quad (4)$$

$$DSP = \frac{|F\{x(t)\}|^2}{df} = |F\{x(t)\}| * np * dx \quad (5)$$

Where: $x(t)$ is the number of sampled points and dx the discrete displacement step. The section being analyzed must have length greater than 1000m, to ensure statistical accuracy. This application of the method with DSP only shows the defects with periodical characteristics (IDRRIM-CEREMA, 2014).

The average IRI value over the length of the experimental track is 2,2m/km to the left and 2,2 m/km to the right, with standard deviation of ±0,8 m/km (variation coefficient of 36%). The average value over a stretch of 200 m (between positions 280 and 480 m), centered at the region of the sensors, is of 2,2 m/km (left) and 2,0 m/km (right), with $\sigma = \pm$ 0,4 m/km (variation coefficient of 19%). The maximum values (average of left and right) at the experimental track and over the sensors are respectively 4,1 and 2,7 m/km, and the minimum values 1,1 and 1,7 m/km.

The site's classification, according to COST 323, with regard to the irregularities of the pavement over the region over the sensors, considering a characteristic value of 2,6 m/km (for a confidence interval of 98%, considering the values as a normal distribution), classifies the WIM site as Class II (good). Considering the values obtained by the NBO method, the experimental site was rated as Class III (acceptable), considering all the wave lengths.

3. Vehicle dynamics models

Studies as those of Menant (2014) and Cebon (1991; 1993), amongst others, simulate, using mathematical models, the dynamic forces of the vehicles for analysis of user comfort and/or the amplitudes of the dynamic forces transmitted to the pavement. In both studies, a numerical simulation allowed the determination of the mechanical behavior of the vehicles as a response to the effect generated by the longitudinal profile of the pavements.

The dynamic behavior of a vehicle can be mathematically represented with elements that represent physical properties, as in Figure 2. Elements such as the tire and the suspension are symbolized by a damped spring with constant stiffness. Two simplified models can be used for analysis of the dynamic behavior (CEBON, 1991; 1993; MENANT, 2014).

- The first is a simple axle with two degrees of freedom, known as 'quarter-car'.
- The second, two axles (anterior and posterior, in tandem) with three degrees of freedom, known as a longitudinal 'half-car' (by some authors known as 'walking-beam tandem').

The 'quarter-car' model, shown in Figure 2, has two degrees of freedom at the vertical displacements z_s and z_u. The elements that compose it are (CEBON, 1993): an unsprung mass m_u, that represents the mass of the tire, wheel, bearing and suspension arm, a suspended mass m_s, that represents the mass of the chassis supported by the wheel in question, a spring with constant stiffness k_t, placed between the unsprung mass and the surface of the pavement, that represents the tire (damping c_t in the tire can be considered negligible in relation to the spring stiffness), the parallel association of a spring with constant stiffness k_s and a damping coefficient c_s.

The 'walking-beam tandem' model (also known as 'half-car' model), is also represented in Figure 2, and consists of a suspended mass m_s, which is restricted to the vertical displacement z_s. A rigid beam connects the two axles, and is connected to the suspension spring by a connecting pin in its center. It allows a soft damped rotation vibration (pitch of the tandem axle) of the set beam/axle with frequency between 8 and 14 Hz, unless hydraulic dampers are placed between the axles and the vehicle frame. The beam/axle set has a mass of m_u and a pitching moment of inertia I_u. It moves with a vertical displacement z_u and pitch rotation θ_u. The input longitudinal displacement profile of the system for both wheels are z_{r1} and z_{r2}. This model represents the minority of suspensions that generate great dynamic variation of the tire/pavement contact forces due to the pitching movement of the unsprung mass, as well as the low frequency movement of the suspended mass (CEBON, 1991; CEBON, 1993).

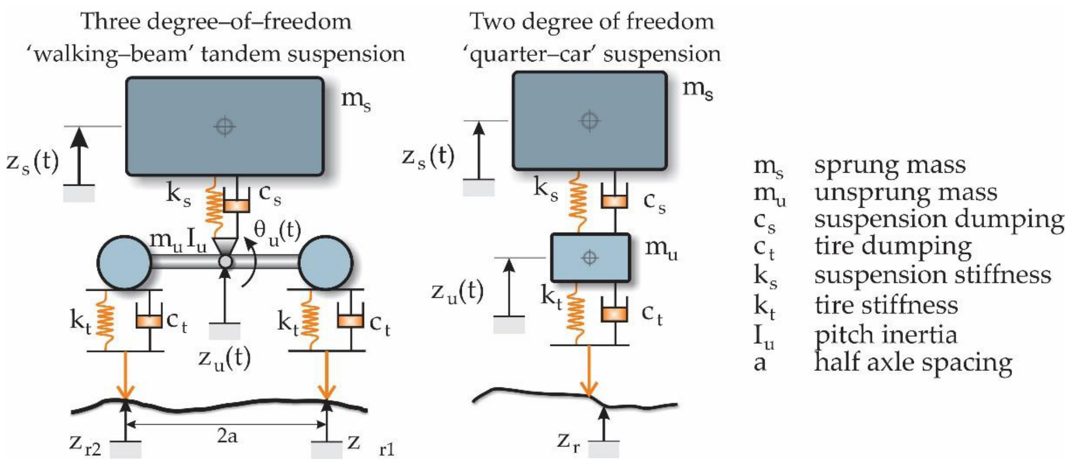

Figure 2 – Vehicle rigid body model

4. Instrumented vehicle test

The test conditions are: four trucks, near-average speed of traffic in the 60 km / h section, three empty loading conditions (tare), ½ load and full load (maximum limit for Total Gross Weight - PBT), number of the expected errors of dynamic force measurement.

The tests with instrumented trucks allow to access the different aspects of the dynamic behavior of the vehicles of load that travel by the highway. Determine the natural frequencies found in the body suspension assembly of the most representative vehicles of the fleet. For the WIM systems, one of the most important factors to consider is the natural frequency of the suspension and body assembly. The instrumentation procedure uses strain gauges attached to the bars of the axes (left and right side) that measure the strain and which are transformed (calibrated) into vertical force (the calibration of the system is performed with the vehicle stationary). Tri-axial accelerometers are glued to the body and measure the acceleration of the unsprung mass, in addition to data acquisition systems that collect and store the signals from these sensors.

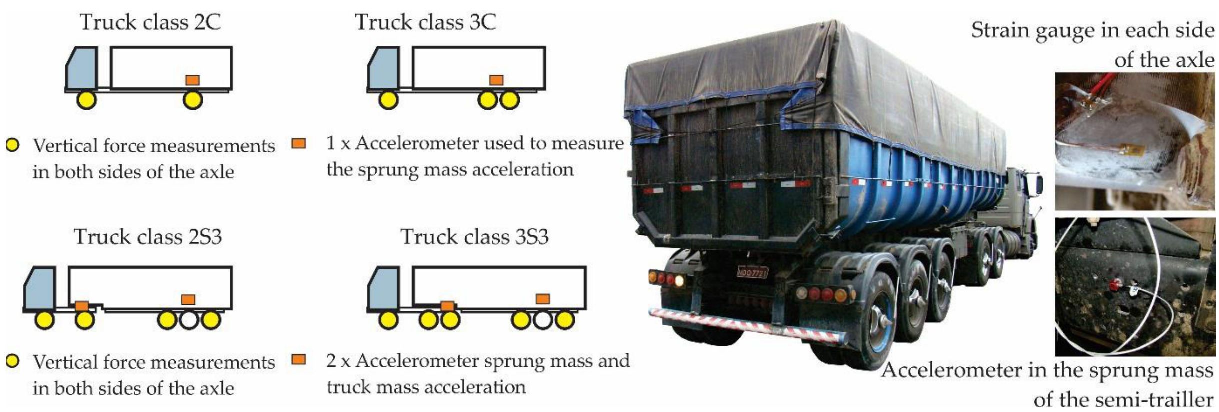

Figure 3 – Instrumented vehicle to measure sprung and unsprung mass accelerations

The recorded data include the forces by axle of the 3S3 class vehicle, loaded with Total Gross Weight (PBT), during a passage at velocity of 44 km/h (Figure 4). This vehicle is composed by a simple axle and a double tandem with drive axle (tractor) and a triple tandem (trailer).

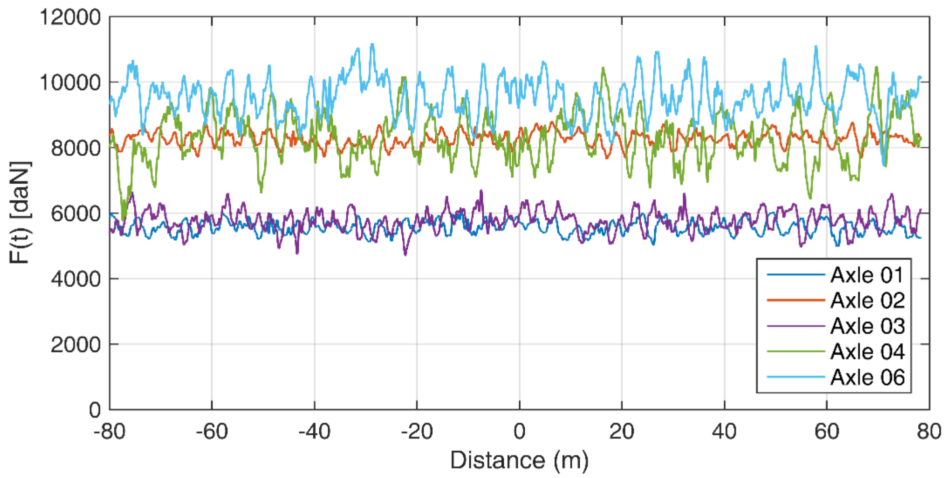

Figure 4 – Axle load forces F(t) of the Vehicle 3S3 travelling at speed of 44 km/h

Figure 5 shows the spectral power density (DSP) of the dynamic force of the 3S3 vehicle. The blue line represents the response for the E1 axle, in red the E2 axle, in yellow the E3 axle, in purple the E4 axle, and in green the E6 axle. The found characteristic frequency is 2,20 Hz for axles E1, E2 and E3 and 1,90 Hz for the remaining E4 and E5 axles. The frequencies found in (2) and (3), representing the effect caused by the wheel bearing over the pavement and the effect of the unsprung mass are, respectively, 7,92 Hz and 11,90 Hz.

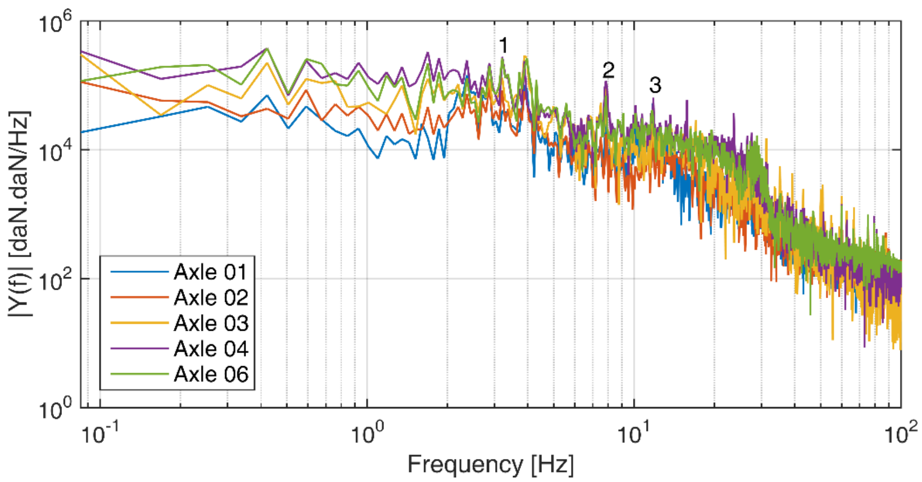

Figure 5 – Densidade espectral de potência (DSP) dos eixos dianteiro e traseiro (média de ambos os lados) do veículo 3S3

The characteristic frequency, to be considered for determining the spacing between the sensors in order to minimize load dispersion errors due to dynamic variations of the axles, for the WIM site, is 2,56 Hz.

5. WIM measurements

Figure 6 shows a superposition of W_d values over 10 passagens of the first axle (E1) of the truck 3C over the 16 WIM sensors, at a speed of 50 km/h. The abscissa axis represent the longitudinal distance over the WIM site, and the ordinate axis represent the weigh measured by each quartz sensor over the experimental track. In blue, the measurement of the strain gauges glued to the same axle, transformed into forces $F(t)$ in kgf. The superposition of the curves show similarities of the recorded dynamic behavior between the vehicle passing over the WIM sensors and the behavior registered by the instrumented vehicle, even if the measurements don't correspond to the same passing moment. The value of the reference static weight is W_s (E1 = 6522 kg).

Table 1 – Natural frequencies (Hz) for the axis of the characteristic vehicles of the experimental track

Vehicle fully loaded	Truck 2C	Truck 3C	Truck 2S3	Truck 3S3	Mean
Min	2,39	2,27	2,76	1,90	2,33
Max	2,90	2,77	3,22	2,30	2,80
Mean	2,64	2,48	3,02	2,11	2,56
-	-	-	-	-	2,56

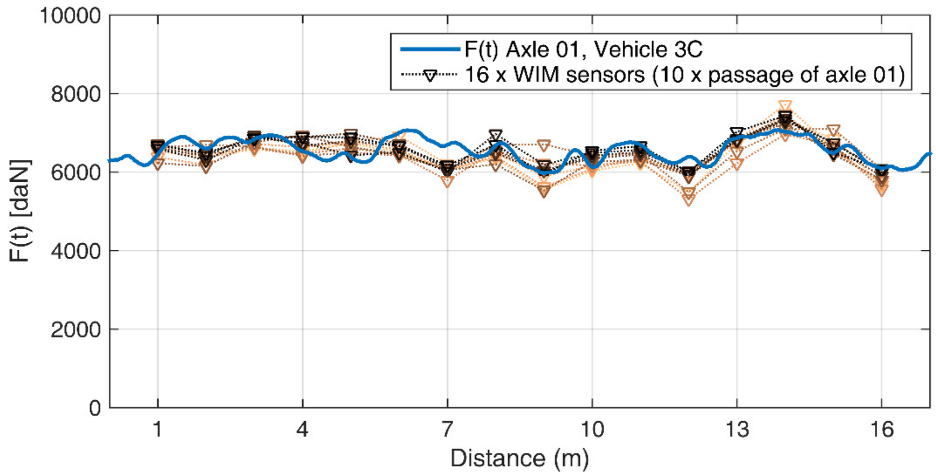

Figure 6 – Superposition between $F(t)$ of axle E1, from truck 3C, and W_d form WIM sensors

Let's consider that exist a way of measure the force F(t) of the axles do any truck passing over the WIM site. To correct the WIM measurement, is necessarily know the minimum length l needed to satisfy the least a certain error between the mean force $\overline{F}$ and the static weight W_s.

The minimum length l, in meters, needed to satisfy the error less than 3%, considering all trucks from the test site of Ararangua, is larger than 100 m, $l \geq 105$ m for an $error < 2\%$, and $l \geq 145$ m for an $error < 1\%$ (Figura 7).

Using the longitudinal profile from the pavement of the circular test track at IFSTTAR in Nantes and the Prosper-Callas numeric vehicle model simulation, for 5 axle truck traveling at speed of 32, 50 and 72 km/h. The minimum length l, in meters, needed to satisfy the error less than 3% is larger than 40 m, $l \geq 87$ m for an $error < 2\%$, and $l \geq 215$ m for an $error < 1\%$ (Figura 8).

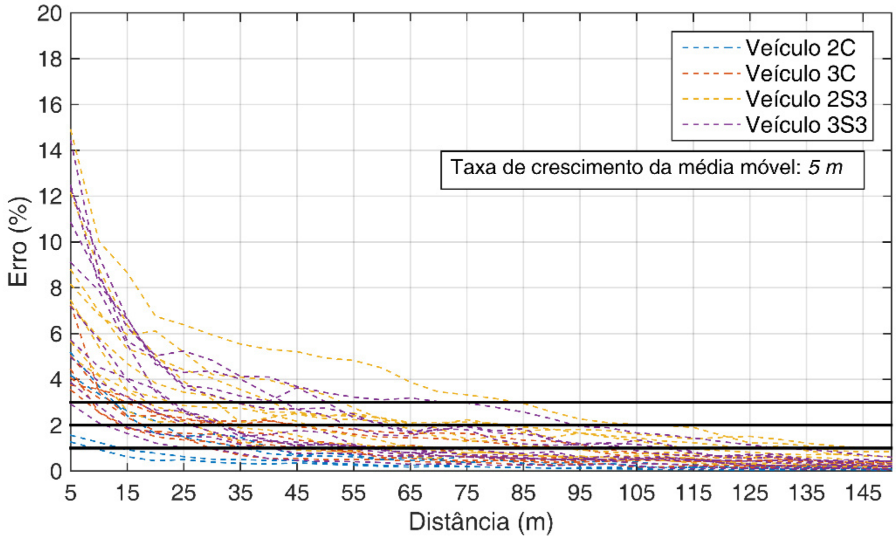

Figure 7 – The error and the minimum length *l*, in steps of 5 m, with the trucks classes 2C, 3C, 2S3 and 3S3

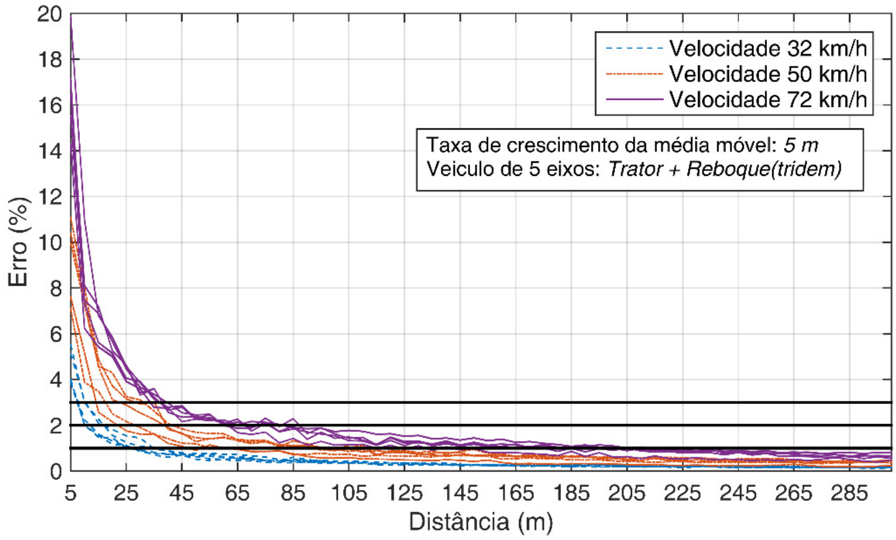

Figure 8 – The error and the minimum length *l*, in steps of 5 m, with the 5 axle form Prosper-Callas

6. Conclusions

The road profile of the roads and highways affect the vehicles dynamic, hence, the axle forces transmitted to the pavement varies accordingly. Those variations generate uncertainties for the high-speed WIM measurements, since calibration don't consider the vehicle dynamic. These uncertainties are the main reason why WIM systems are not able to measure with more accuracy. The instrumentation of all road vehicles is practically impossible. However, another method must be observed.

If we propose measure F(t) along the WIM site $[-l, l]$, even if those measurement are far less accurate than the WIM measurement. The approach presented here could be used to correct the

WIM measurements, obtained with an accurate WIM sensor, to reduce the uncertainties due to vehicle dynamics. Longer the WIM site, better the reduction the WIM uncertainties.

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