USE OF WIM SENSORS AND GEOPHONES TO INCREASE THE ACCURACY OF WEIGHING SYSTEMS

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Abstract
The Brazilian road network is characterized by thin and highly flexible pavement structures, which have a negative impact on the pavement's lifespan and the performance of WIM systems. This study presents a general analysis of the response of a WIM system and geophones sensors installed on a test site in Brazil during the passage of three known vehicles at varying speeds, lateral positions, and pavement temperatures. The system comprised 2 piezoelectric WIM polymer sensors, 2 ceramic sensors, 33 geophones, and 6 loop detectors, which are low-cost sensors installed on the pavement surface. The first part of the study provides details about the site instrumentation, the known vehicle testing protocol, and the pavement parameter for a viscoelastic mechanical model. The second part discusses the output of the sensors and the results obtained from the tests. The study concludes by highlighting the need to correct for vehicle dynamics and suggesting possible methods to decrease uncertainties due to dynamic effects and improve the accuracy of WIM systems. The findings of this study have significant implications for the use of WIM technologies on similar road networks worldwide.

Keywords: WIM Accuracy, Vehicle Dynamic, Geophones, Pavement, WIM Sensor, WIM, Highway.

1 Introduction

The effectiveness and durability of WIM technology on pavement depend on the pavement structure. However, the pavement structures within the Brazilian road network are often thin and highly flexible, exacerbated by variations in climate and overloading. This network comprises 200,000 km of highways, of which only 50,000 km are paved. Studies conducted by the National Department of Transport Infrastructure (DNIT) in 2017, 2021, and 2023 have shown that pavement must be adequately prepared before receiving WIM systems and sensors.

When combined with pavement instrumentation, WIM technology enables the correlation of pavement stresses and strains, predicting the lifespan of road infrastructure. This paper presents the instrumentation design and results of the first test with known vehicles, providing a general analysis of instrument response to three vehicles tested under different conditions of speed, lateral positioning, and pavement temperature.

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Approaching the WIM sensor, the forces transmitted to the pavement vary according to dynamic acceleration at each instant t (Otto, 2019). Weighing sensors detect the stresses exerted on their surface during 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). Therefore, the force transmitted to the pavement is proportional to $F(t) = F_s + F_d\ (t)$.

Works such as those by Bahrani et al. (2023), Mannan et al. (2021) and Zhang et al. (2019) delve into the benefits and drawbacks of utilizing geophone sensors, their uses in pavement engineering, and the variables that impact the precision of the data obtained by geophone sensors.

2 Experimental site and instrumentation

To achieve the objectives of the study, a 120-meter test track was constructed using a thick asphalt pavement composed of multiple layers treated with asphalt placed on a solid foundation. The test site is situated at km 418 of the federal highway BR-101, near the municipality of Ararangua in southern Brazil (Lat. 28°58'36.84"S; Long. 49°32'0.72"W). The road has two lanes, and the instruments under evaluation are located in the right-hand lane, which experiences the highest flow of heavy vehicles.

Following the pavement construction, a total of 33 geophones, 6 temperature sensors, 2 piezoelectric polymer technology WIM sensors, and 2 ceramic technology WIM sensors (Figure 1) were installed. The WIM sensors are placed on the pavement surface, transversely aligned to the vehicle lane, with a distance of 2 meters between centers. The geophones are located close to the pavement surface, with a depth of $z = -3$ cm, in the central, left, and right positions.

To ensure accuracy and durability, the pavement structure for this section of the highway is designed to allow the highest possible performance for the installed sensors. The chosen structure comprises three base layers treated with asphalt, a binder layer with dense asphalt, and a surface layer to accommodate the WIM sensors. The reference for the selection of this structure is the French structure catalog (SETRA-LCPC, 1998), type GB3 for T7 traffic. Since the original subgrade had a modulus of less than 120 MPa, a reinforced subgrade (soil + lime) was adopted, as recommended by the catalog. The final dimensions of the structure consist of a 1-meter reinforced subgrade layer with a soil and lime mixture of 5%, three 10 cm courses of asphalt mix BG3 (*Gravel-Bitume*), a 10 cm high module mixture EME (*Enrobé à Module Élevé*) as a binder course, and a 6 cm thin asphalt mixture BBM (*Béton Bitumineux Mince*) as a surface layer.

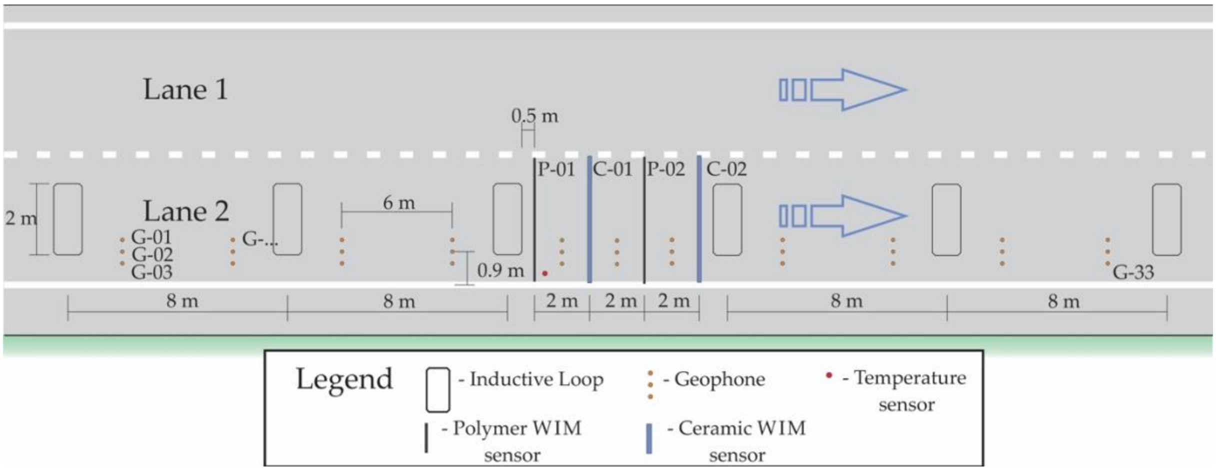

Figure 1 – Experimental site instrumentation design with WIM system and the groups of geophones

To analyze and interpret the signals, it is necessary to establish a fixed reference system for the pavement and other equipment (sensor P-01 in $x = 0$), while the axis of the vehicles is on a moving reference system in space (x, y, z). Assuming that the force applied by the tires to the fixed reference system varies with time $f_0\ (t)$, a transformation from fixed to mobile reference is made by changing the space variables $(X - Vt, Y, Z) \rightarrow (x, y, z)$, which achieves a steady state for comparative analysis between different sensors.

The test campaign consisted of three reference vehicles with different configurations and classes, including a six-axle articulated vehicle (class 3S3), a five-axle articulated vehicle (class 2S3), and a three-axle non-articulated vehicle (class 3C). The testing protocol included multiple runs under various speed and lateral position conditions. The load for each truck was constant and close to the legal limit (Table 1).

Table 1 – Axle weight of each axle of the three known vehicles

Vehicle type	Axle 1 (N)	Axle 2 (N)	Axle 3 (N)	Axle 4 (N)	Axle 5 (N)	Axle 6 (N)
3 axles (rigid)	53.710	97.048	76.995	-	-	-
5 axles (artic.)	56.774	102.881	95.054	81.008	67.235	-
6 axles (artic.)	51.456	90.810	68.190	78.408	81.309	64.286

Seven trials were scheduled for each vehicle, at varying speeds and lateral positions. The selected speeds were 60, 70, and 80 km/h, and the vehicles were tested at the left, center, and right positions. The experiments were conducted over three consecutive days, from May 7 to May 9, 2019.

3 Pavement viscoelastic model

The pavement response under field conditions, such as moving loads and thermo-sensitive viscoelastic behavior of asphalt materials, will be modeled using ViscoRoute (Sohm et al., 2016; Chupin et al., 2010; Chabot et al., 2009; Duhamel et al., 2005; Nguyen, 2002). The pavement is considered as a multiple horizontal layer with thickness e_i and density ρ_i for every layer i (where $i \in \{1, n\}$). The pavement structure is subjected to one or several moving loads in the x direction at a constant speed, V. The load pressure is applied in all three directions on the free surface ($z = 0$).

The mechanical behavior of the materials in each layer can be described as linear elastic or linear viscoelastic-thermally sensitive (refer to Table 2). In the case of linear elasticity, E_i and ν_i represent the modulus and Poisson's ratio, respectively. For viscoelastic materials such as asphalt-treated materials, the mechanical behavior is represented by five viscoelastic coefficients (E_0^i, E_∞^i, k_i, h_i, and δ_i) and three thermal coefficients (A_0^i, A_1^i, and A_2^i) for each layer i (Huet, 1963; Sayegh, 1965).

Table 2 – Pavement structure and mechanical parameter for the elastic and viscoelastic materials

	Thickness (m)	Module (MPa)	Type of material	Condition
Surface course	0.06	11000	AC-BBM	-
Binder course	0.10	14000	AC-EME	Bounded
Base course	0.30	10000	AC-GB3	Bounded
Subbase course	1.00	320	PF2 (Soil+Lime)	Bounded
Compacted sugbrade	Inf.	160		Bounded

For each layer, a fixed Poisson's ratio of 0.35 and a uniform density of 2100 kg/m³ are assumed. In the ViscoRoute model, the first three layers are considered viscoelastic, and the Huet-Sayegh viscoelasticity parameters are determined for the BBSG and GB materials, as listed in Table 3.

Table 3 – Huet-Sayegh viscoelasticity parameters

	BBM	EME	GB
E_0 (MPa)	111	111	125,4
δ	0.190	0.190	0.513
k	0.155	0.155	0.270
$A0$	0.560	0.560	1.453
$A1$	-0.232	-0.232	-0.229
$A2$	0.000718	0.000718	0.000505

The ViscoRoute model offers a prediction of the pavement's mechanical response to various vehicle configurations. Figure 2 displays the deflection velocity of the pavement under the specific test conditions of loads per wheel, speed, and pavement temperatures for these vehicles during the test campaign.

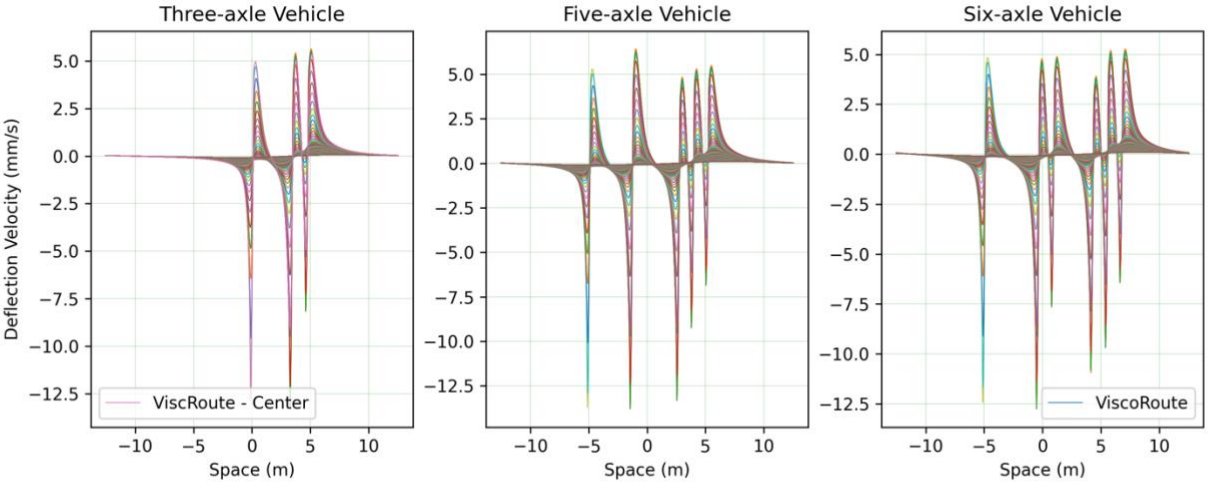

Figure 2 – Prediction of pavement deflection velocity using the viscoroute mathematical model

4 Experimental results

The sensors used in this study aim to collect data on the condition of pavement when heavy vehicles pass over it. The data acquisition system allows the analog data to be transformed into digitized data and stored for each vehicle event. The system is controlled by inductive loops, which trigger data acquisition and terminate it. The sensor sensitivity is the ratio of the electrical response to the stimulus it receives, and the stimuli in the pavement are proportional to the applied load, deflection speed, and temperature conditions. Two types of sensors were used in the study, piezoelectric and geophone sensors. Piezoelectric sensors measure the dynamic load exerted by the axle weight of a vehicle. Geophone sensors, on the other hand, detect and convert pavement vibrations into electrical signals. These sensors can be used to measure the deflection caused by traffic and identify areas of the pavement that may be experiencing excessive stress or strain.

Temperature sensors measure the temperature at different depths (3, 6, 16, 26, 36, and 46 cm) of the asphalt layers. Figure 2 displays the temperature gradient values recorded during a three-day period, from 19/02/2019 to 22/02/2019. Temperature fluctuates due to the effect of solar radiation on the pavement surface and its propagation through the asphalt layers. Temperature variations are less significant in the deeper pavement layers than on the surface, owing to the low heat transfer properties of the asphalt mixture.

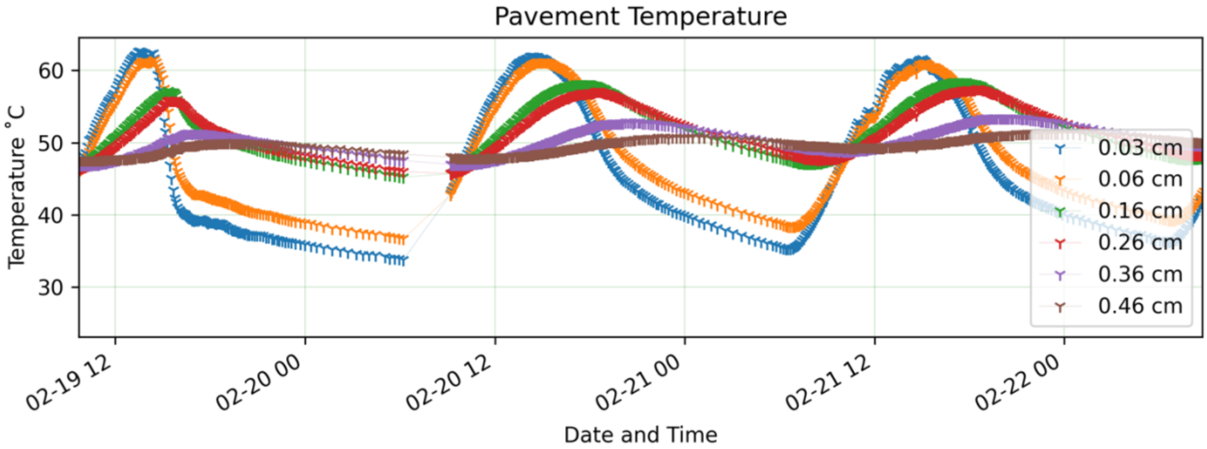

Figure 2 – Temperature variation on the pavement structure during a period of three days

4.1 WIM sensor response

The multiple WIM system provided accurate and reliable data on the traffic flow characteristics, such as vehicle weights, axle loads, and speeds. The four WIM sensor lines, two with polymer (P-01 and P-02) and two with ceramic (C-01 and C-02) technologies, recorded the interactions of the axles as they passed over the installation site. Each technology had its characteristic behavior, as shown in Figure 3a and b. The axle weight was translated by the tension acting on the sensors, and both technologies accurately showed the axle passage. By knowing the distances between the sensors and the time of each peak of the raw signal, it was possible to determine the vehicles' characteristics, such as the number of axles, distances between axles, and speed of passage.

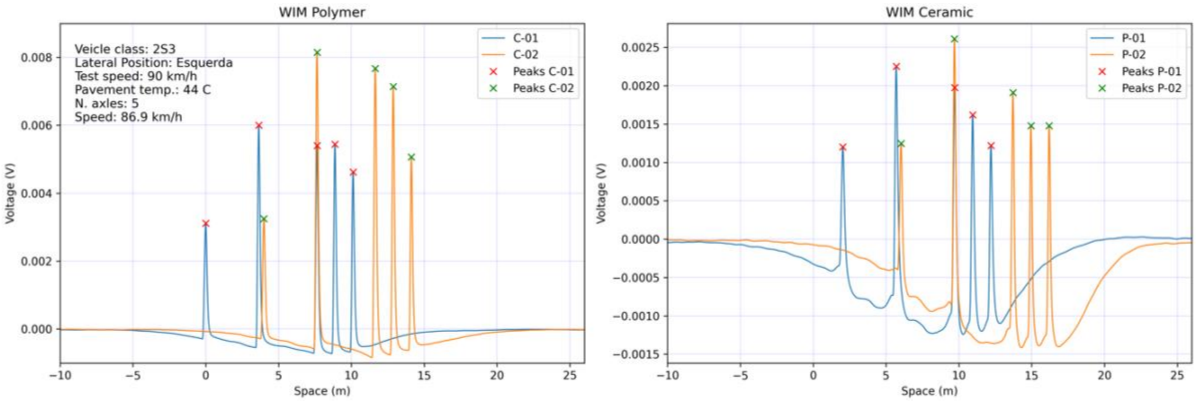

Figure 3 – WIM sensor electrical response of the 5 axles vehicle, at a position Center, Right and Left a) Polymer (P-01, P02) sensors and b) Ceramic (C-01, C-02)

Applying an algorithm that calculated the area under the peak formed, the raw signal was transformed into the axle load equivalent axle weight. Figure 4 shows the weights of each axle, the distance between axles of the five-axle vehicle obtained using a WIM system with all sensors, and a comparison with the reference values. The multiple WIM system proved to be effective in accurately measuring the traffic flow characteristics, providing valuable data for the evaluation of pavement performance and design.

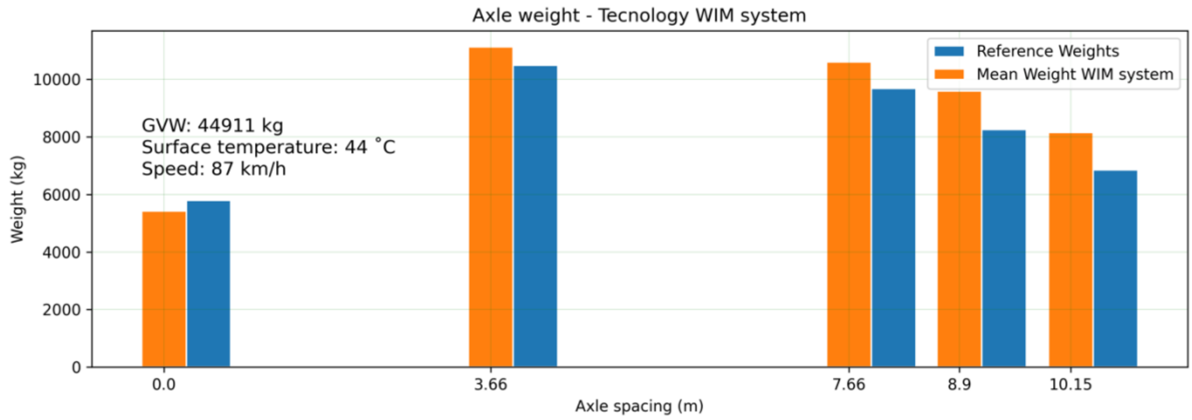

Figure 4 – Results form the mutiple WIM system

4.2 Geophone sensor response

The signals produced by the geophone sensors are directly proportional to the applied load, the speed of the moving load, the lateral position of the load, and the pavement's behavior. The data collected by the geophone sensors provides valuable information about the dynamic weights of the moving loads and their effect on the pavement's structural integrity. By measuring the deflection caused by the moving load, the geophone sensors provide signals that represent the dynamic weights of each axle (Figure 5).

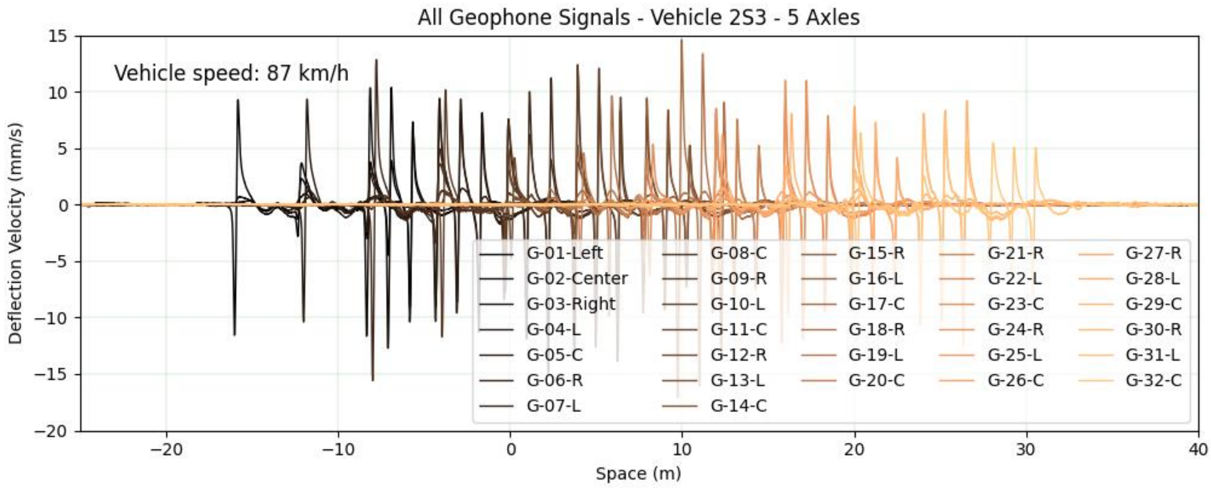

Figure 5 –Singnals from all geophone sensors of the five-axles

If we take into more detailed analisys, Figure 6, we observe that for each line of three-geophones (left, center and right) the vehicle axles are still notable. As the vehicle drives over the sensors, it ocilates the lateral position compare to the road axis. This changes in the lateral positions, shifts the tires of the axle from the geophone sensors. As the tire passes away from the geophones, signals vaires proportionaly. With the line of three geophones it is possible to locate the pick of maximal deflection velocity, porportional to the axle load.

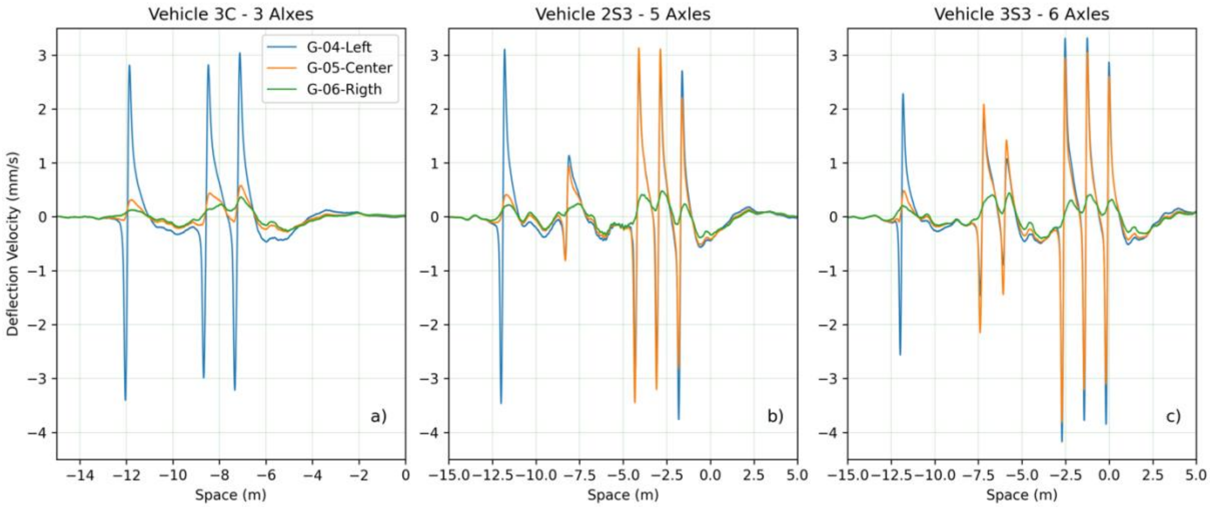

Figure 5 – Geophone signals (G-04, G-05 and G-06) a) trhee-axles vehicle, b) five-axles vehicle and c) six-axles vehicle

The comparison of geophone signals with the corresponding deflection velocity predicted by the ViscoRoute model reveals a striking similarity between the two signals. Additionally, the variation in the lateral position of the tires can also be predicted using the same model. However, the differences observed in the shape of the deflection velocity signal between the real data and the model can be attributed to the characteristics of the geophone itself. Geophones have certain limitations in accurately capturing the full complexity of the pavement response to the moving load.

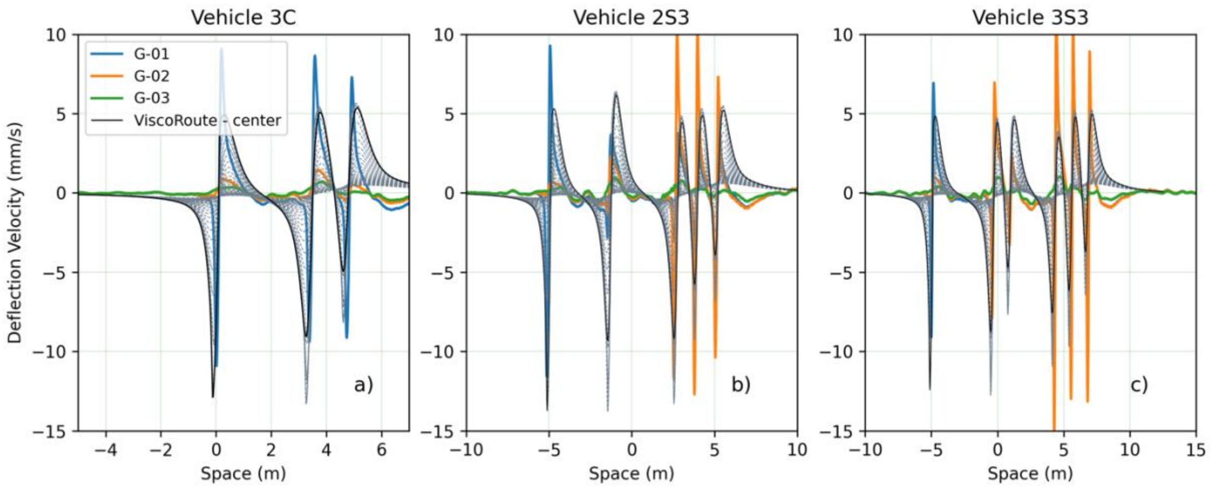

Figure 7 – Geofone singlas and ViscoRoute model

When comparing the signals obtained from the geophone sensors with the signals predicted by the ViscoRoute model, there may be differences in the shape of the signals. This is because the geophone sensors have some inherent limitations, such as their sensitivity to the lateral position of the tires and the unevenness of the pavement surface, which may not be fully captured by the ViscoRoute model.

Therefore, while the ViscoRoute model can provide valuable predictions for pavement response to moving loads, the signals obtained from geophone sensors should be analyzed and interpreted carefully, along with other data and models, to obtain a comprehensive understanding of pavement behavior.

By applying the principles of backcalculation, the displacement velocity signals obtained from geophone sensors can be transformed into corresponding dynamic load values. With dynamic load capture along the geophone sensor grid, it is possible to predict dynamic forces along the installation site, and therefore correct dynamic loads when vehicle axles pass over WIM sensors.

5 Conclusions

The installation of WIM sensors together with pavement instrumentation such as temperature, strain gauge, and geophone is an important tool for assessing pavement behavior. It allows assessing the relationship between strain and stresses of the structure regarding the load of vehicles. Geophones are easily installed on the pavement. As shown, they allow a good correlation of pavement behavior as a function of a moving load. Transforming the deflection velocity response into deflection is possible, but errors that accumulate can be inconvenient when data processing.

Geophone sensors are highly sensitive devices that are used to detect and convert pavement vibration waves into electrical signals. The signals produced by the geophone sensors are directly proportional to the applied load, the speed of the moving load, the lateral position of the load, and the pavement's behavior. The data collected by the geophone sensors provide valuable information about the dynamic weights of the moving loads and their effect on the pavement's structural integrity. Overall, geophone sensors are an essential tool in pavement engineering and are widely used in road construction and maintenance projects. The data collected by geophone sensors can help engineers and transportation officials make informed decisions about pavement design, maintenance, and repair.

WIM sensors are also installed on the pavement surface. The polymer and ceramic technologies tested presented temperature dependence. To increase the accuracy of these instruments, calibration considering temperature is required. Other factors also influence weighing accuracy and are not addressed here, such as vehicle speed and lateral position.

As a general result, it is possible to state that pavement instrumentation allows establishing the relationships between the transported load and the pavement life. A complete set of instrumentation becomes costly and difficult to deploy on an extensive road network. However, a better understanding of sensor behavior will allow the design of more rational and low-cost systems. By applying the principles of backcalculation, the displacement velocity signals obtained from geophone sensors can be transformed into corresponding dynamic load values.

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