CATALOGING METHOD AND EVALUATION OF PAVEMENT STRUCTURE STABILITY FOR HS-WIM SYSTEM INSTALLATION

A. J. ALMEIDA
Researcher at the Transportation and Logistics Laboratory (LabTrans), Federal University of Santa Catarina (UFSC), Florianópolis, Brazil. Dr. from UFSC.

G.G. OTTO
Researcher at the Transportation and Logistics Laboratory (LabTrans), Federal University of Santa Catarina (UFSC), Florianópolis, Brazil. Dr. from UFSC

S. R. SANTILLAN
CEO of Entrevias Concessionária de Rodovias S.A. Brazil

K.J.C. SHINOHARA
Researcher at the Transportation and Logistics Laboratory (LabTrans), Federal University of Santa Catarina (UFSC), Florianópolis, Brazil. Dra. from UFSC.

A. C Morossino
mastering at Federal University of Santa Catarina (UFSC), Florianópolis, Brazil. Civil engineer from UFSC.

F. DE MORI
Researcher at the Transportation and Logistics Laboratory (LabTrans), Federal University of Santa Catarina (UFSC), Florianópolis, Brazil. Dr. from UFSC.

V. Tani
Researcher at the Transportation and logistics Laboratory (LabTrans), Federal University of Santa Catarina (UFSC), Florianópolis, Brazil. Dr. from UFSC.

A. M. VALENTE
Professor at the Transportation and Logistics Laboratory (LabTrans), Federal University of Santa Catarina (UFSC), Florianopolis, Brazil. Dr. from UFSC.

Abstract

The installation of Weigh-in-Motion (WIM) systems is crucial in the pavement structure, as their performance directly affects the quality of the data obtained. However, determining the right time to install WIM sensors can be challenging, particularly for newly constructed pavements that are in the consolidation phase, which is characterized by a decrease in deflection values. To ensure optimal performance of high-speed WIM systems, it is essential to have well-defined and durable pavement structures that can withstand heavy traffic and support the sensors. Achieving this requires considering economic factors and varying climate conditions across different regions.

This research aims to evaluate the consolidation of asphalt pavement structures by measuring the deflection on the pavement surface over time using the Benkelman Beam before installing WIM systems.

Additionally, this article proposes a simplified catalog method of pavement solutions that offer robust structures capable of supporting the use of high-speed WIM technology under various traffic, climate, and subgrade conditions.

The evaluation of pavement stability was conducted on two lanes of SP-330 in the State of São Paulo, Brazil, close to the General Inspection Post (PGF - Postos Gerais de Fiscalização) A and B. The research was conducted in two stages, with the first stage involving monitoring and evaluating pavement performance in terms of arrows measured on-site and their stability over time. The second stage involved classifying pavement structures according to the COST-323 specification.

The analysis of deformation evolution on the pavement surface over 50 days showed a sharp reduction in deflections, particularly on SP-330 Norte, where deflections fell below half of the initial value, i.e., below 20.10^{-3} mm. Finally, it was found that both PGFs met the "excellent" class I of the COST-323 classification. Finally, a simplified cataloging method of pavement solutions is presented for the installation of HS-WIM systems

Keywords: Asphalt Pavement Structure, WIM System, Deflection, Pavement Catalog.

1. Introduction

The road transportation mode is responsible for a significant portion of cargo transport in Brazil, and with the growth of the economy and trade, there is an increase in traffic, leading to larger and heavier loads. Therefore, it is crucial to have effective monitoring and control systems for road freight transport operations, such as the Weight-In-Motion (WIM) system, to ensure safe operations, control of the competitive environment, and infrastructure maintenance.

To achieve success in direct inspection projects, it is essential to ensure that all components necessary for this purpose are in constant harmony, and the knowledge and use of new technologies aid in this process. The installation of weighing sensors on specific pavement that meets the appropriate standards is necessary for the correct operation of the WIM system. Furthermore, all WIM equipment must collect data properly.

The new weight inspection model of the Transport Agency of the State of São Paulo (ARTESP) for new concession contracts includes the installation of the Weigh-in-Motion System (SISPEMOV) on the pavement in places that precede the General Inspection Posts (PGFs). Therefore, this article discusses two stages of study and analysis conducted by the Transportation and Logistics Laboratory (LabTrans) of the Federal University of Santa Catarina (UFSC) to provide technical support and assistance in implementing two PGFs in São Paulo, Brazil.

To evaluate the pavement, this study presents the geometric characteristics of the section under analysis, such as longitudinal/transverse inclination, the length of the tangent, the structure of the pavement, the characteristic deflection, the sinking of the wheel track, and evaluation of pavement deflection monitoring. Based on the information gathered through on-site surveys and projects, an analysis was carried out to classify the weighing place's class for the WIM system installed in the two pre-defined locations.

The performance of the HS-WIM system depends on the pavement's type and its functional and structural condition, which affects the sensors' useful life, system accuracy, and calibration. Thus, understanding the mechanical behavior of various floor structure solutions that can be used as installation cradles for the HS-WIM system is essential.

Additionally, this article proposes a simplified catalog of pavement solutions for the implementation of the HS-WIM technology with direct inspection and ECP, taking into account various subgrade conditions, traffic, climate, and functional and structural parameters in different regions of Brazil. This catalog will assist DNIT in selecting the appropriate pavement type for installing HS-WIM systems to monitor overweight vehicles while considering the system's performance.

2. Characteristics of Pavement Structure

The characterization of the pavement structures of the PGFs is done through the location of the PGF, containing the length of the lane, width of the lane and shoulder, longitudinal and transverse unevenness and thickness of the coating layer.

PGF A is located on the Anhanguera highway (SP-330), at km 373, north lane, toward the state of Minas Gerais/Brazil. PGF B is located on the Anhanguera highway (SP-330) at km 376, south lane, towards Ribeirão Preto/São Paulo/Brazil.

Therefore, in Table 1, the characteristics of the highways of the two PGFs of the Entrevias, concessionary company, and consortium are presented.

Table 1 - Characteristics of the highways of the PGFs

Characteristics of the track destined for WIM	PGF A	PGF B
Length (m)	100	100
Width (m)	7,20	8,05
Shoulder width (m)	3,50	3,20
Longitudinal slope (%)	0,69	0,35
Transversal slope (%)	2,00	2,00
Thickness of the asphalt concrete layer (cm)	20	20

It should be noted that the pavement structure and the road geometry of the PGFs have similar characteristics, as shown in Table 1.

3. Deflection Evolution during the Consolidation Phase of the Pavement Structure

The action of traffic loads on asphalt pavements causes permanent and recoverable deformations. According to Brasil (2006), permanent deformations are those that remain even after the effect of the load has ceased, that is, they have a residual character. On the other hand, recoverable deformations or deflections represent an indication of the viscoelastic behavior of the structure, ceasing to exist a few moments after the load is removed, these deformations cause the paving layers to bend and their repetition is responsible for the phenomenon of fatigue of the asphalt layers.

The deflection of a pavement, according to Pérez (2016), represents the response of the structural layers and the subgrade to the application of the load. As Gonçalves (1999) puts it, when a load is applied to an area of the pavement surface, all layers flex due to the stresses and deformations generated by the load, the value of this deflection in each layer depends on the modulus of elasticity and decreases with depth and distance from the load application point.

The deflection values measured on the flexible pavement depend on many factors, according to Ramos-García and Castro (2011) the deflection is influenced by the pavement structure, applied load, pavement conditions and environmental factors, such as the temperature of the asphalt concrete and the content moisture content of granular materials. Asphalt concrete properties change with changing temperature, so this is a determining factor in its performance, as its response to traffic loads will be different at different pavement temperatures. According to Medina and Motta (2005), the structurally sounder pavements slope less than the weaker ones, in addition, pavements with lower deflections support a greater number of traffic requests.

The relationship between deflection and traffic load repetitions can be seen in Figure 1, which deals with the life stages of an asphalt pavement. According to Brasil (2006), the pavement goes through three phases: the consolidation phase where the deflection decreases due to traffic action; the elastic phase in which the deflection remains almost constant; and the fatigue phase in which there is an accelerated increase in the deflection value due to the loss of structural capacity of the pavement.

Thus, newly constructed pavements must be in the consolidation phase which, according to DNER (1979) is characterized by a decrease in the deflection value, due to the additional consolidation provided by the traffic in the different layers of the pavement. The deflection value tends to stabilize at the end of this first phase.

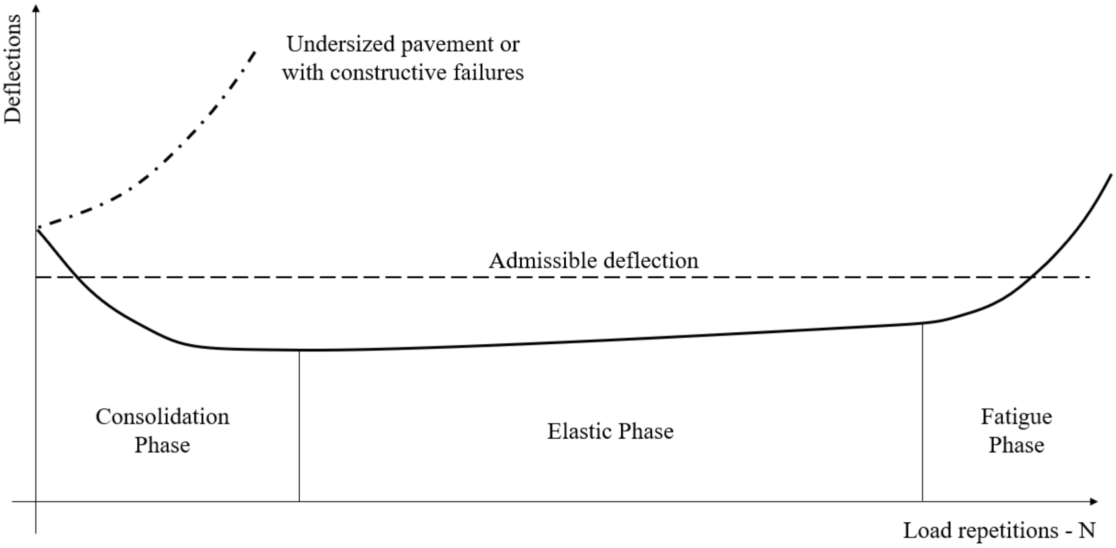


Figure 1 - Life stages of a pavement. Source: Adapted from Brazil (2006)

In order to know the structural condition of the pavement, it is necessary to carry out a structural assessment which, as Balbo (2007) puts it, encompasses the complete characterization of structural elements and variables of the pavement through the objective description of its behavior through traffic loads and factors environmental factors, according to Bernucci et al. (2008), for large extensions of track, the most appropriate evaluation is that which uses non-destructive methods, due to the possibility of numerous repetitions at the same point in order to monitor the load capacity over time. According to Shahin (1994) non-destructive tests are the most reliable methods to determine the structural condition of a pavement in service.

One of the most used non-destructive methods for structural evaluation of pavement in Brazil is the Benkelman Beam Test. It is the type of test that consists of using a standardized truck with double rear wheels with tires calibrated to a pressure of 0.55 Mpa and a load of 80 kN (8.2 tf).

With each wheel passage, the pavement undergoes a total displacement that, according to Bernucci et al. (2008), can be divided into two components: permanent deformation, which results in sinking of the wheel tracks; and the elastic deformation that results in the alternating bending of the casing, called deflection. According to National Cooperative Highway Research Program (NCHRP) (2004) the measured deflection is used to determine the structural adequacy of the pavement, related to the number of repetitions of admissible loads.

3.1. Analysis of Deflections

As an integral part of the first stage of analysis, data were collected on pavement deflections using the Benkelman Beam test, with the aim of establishing a comparison between the evolution of pavement deflection over time and the performance of installed weighing systems. In order to avoid the effects caused by the temperature variation of the asphalt concrete on the pavement deflection during the performance evaluation, Ramos-García and Castro (2001) observe that all deflection tests should be carried out at the same temperature. However, considering the impossibility of maintaining the same temperature in all tests, different authors have established factors that allow adjusting the deflection by the pavement temperature measured in tests, making it possible to calculate the equivalent deflection of the asphalt pavement at a given reference temperature.

According to Pérez (2016), the interference of temperature in the deflection is due to the viscoelastic behavior and sensitive to thermal variations of asphalt concrete, thus, it is necessary to correct the deflection measurements carried out with temperatures different from the reference temperature which, according to the Department of Roads in São Paulo DER/SP (2006), can be adopted at 25°C, which was used for the present research. Figure 2 presents the correction factor as a function of the measurement temperature for different asphalt coating thicknesses, according to DER/SP (2006).

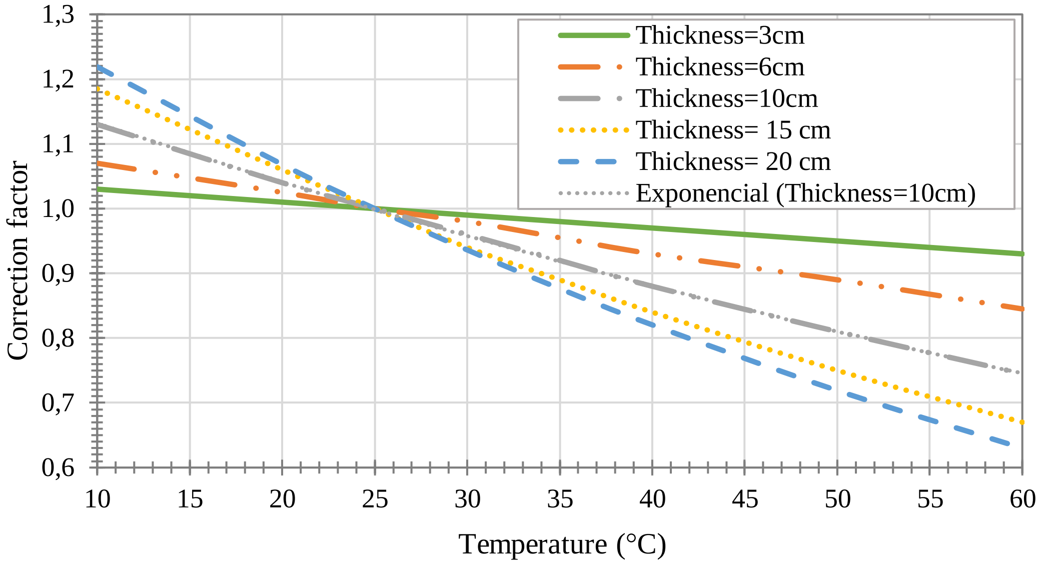


Figure 2 - Deflection correction factor as a function of temperature and thickness of the pavement covering layer. Source: LabTrans/UFSC (2019) adapted from DER/SP (2006)

As the pavements of the PGFs have a thickness of 20 cm of asphalt concrete coating, use the correction factor referring to a thickness of 20 cm and given by D_ref=D×(1.391e^(-0.013·T)). Where:

D_ref is the deflection corrected for the reference temperature (25°C);

D is the deflection measured in the structural evaluation test;

T is the pavement surface temperature at the point of the deflection measurement at the time of the test.

After correcting the temperature deflections, it is necessary to carry out a statistical analysis to detect spurious values. During deflectometric control with a Benkelman Beam, random errors may occur caused, for example, by vehicle traffic vibration, strong winds and involuntary movements of the test truck, in addition to systematic errors due to miscalibration of the Benkelman Beam, lack of test truck tire pressure control, changes in loading time between measurements, inconsistent observations and the perception of operating the beam when performing the test. Thus, it is necessary to carry out a statistical analysis to remove extreme values, called outliers which, according to Grubbs (1969) are observations that seem to deviate significantly from the rest of the sample in which they occur.

When the sample size is small (N<30) and the population is approximately normal, Equation 1, referring to Student's t distribution, can be used to calculate the confidence intervals for the population mean.

$$IC = \overline{x} \pm t_\alpha \frac{s}{\sqrt{N}} \tag{1}$$

Where:

IC is the confidence interval of the data set for the established confidence level;

$\overline{x}$ is the mean of the set;

t_α is the critical t-value for the degree of confidence α;

s is the standard deviation of the set;

N is the size of the sample.

Data that remain within the confidence interval are kept, with such certainty that they represent the true population value, and the rest are rejected. By adopting a confidence level of 90% and calculating the confidence interval using the student's t distribution, it was possible to improve the data statistically and thus define the behavior trends of the pavement of each checkpoint, as shown in the Figure 3.

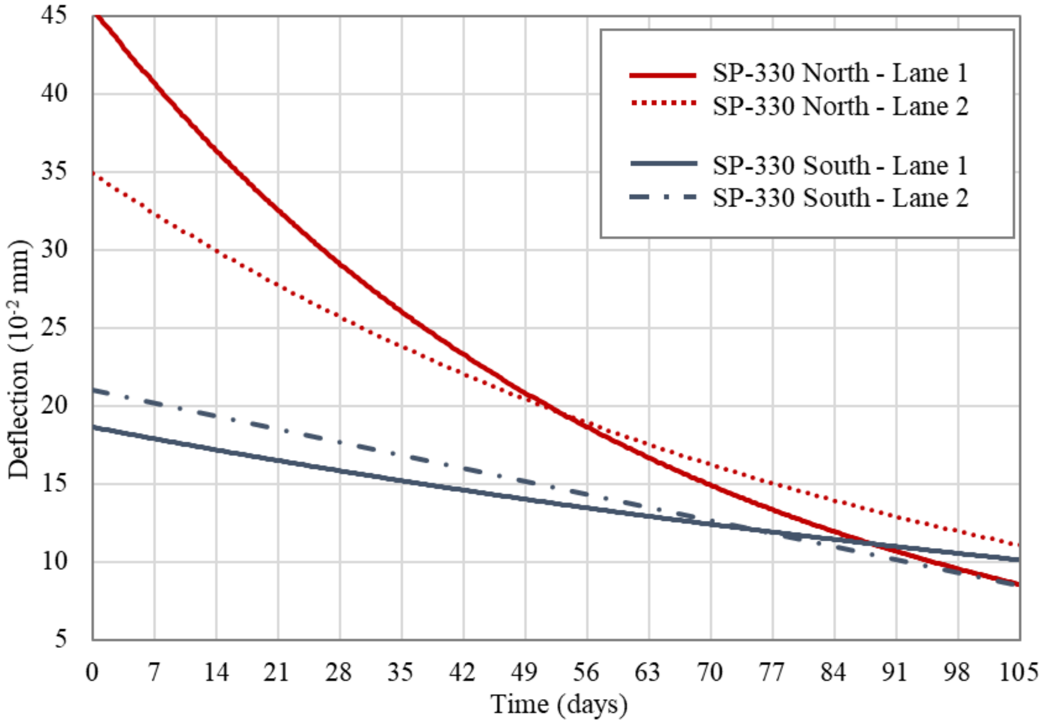


Figure 3 - Evolution of deflections in the pavement consolidation phase in PGFs A e B

It is observed that both trends, in general, converge to a decrease in permanent deformation followed by stabilization close to a deflection of 10.10^{-2} mm, characterizing what is expected for the consolidation phase of the pavement, that is, between 95 days and 100 days.

4. Evaluation of the Pavement Structure Regarding the Cost-323 Classes

Weigh-in-Motion sensors are installed directly on the pavement, enabling the collection of weighing data and the classification and identification of heavy vehicles, without the need for these vehicles to enter a weighing station. The nature of weighing sensors varies between different technologies, e.g. ceramic, polymer, quartz, optical, etc. The installation of these sensors requires special care on the pavement before installation.

Thus, the specification COST 323 (2002) classifies the weighing sites according to the values of deformation by wheel track, by deflection and by irregularities in the pavement. The classification is divided into three levels (I, II and III) “excellent”, “good” and “acceptable”, respectively. Thus, each class has a specific level on the conditions of the pavement, according to what is exposed in Table 2.

Table 2 - Parameters for implementing WIM systems from the European Standard COST 323 divided by class. Source: COST (2002)

Pavement characteristics		**Class I**	**Class II**	**Class III**
Longitudinal inclination		< 1,0%	< 2,0%	< 2,0%
Transversal inclination		< 3,0%	< 3,0 %	< 3,0 %
Maximum Deflection 13,0t (10^{-2} mm)	semi-rigid pavement	15,0 ± 3,0	20,0 ± 5,0	30,0 ± 10,0
	thick asphalt pavement	20,0 ± 4,0	35,0 ± 8,0	50,0 ± 12,0
	flexible pavement	30,0 ± 7,0	50,0 ± 10,0	75,0 ± 15,0
Maximum Deflection 8,2t (10^{-2} mm)	semi-rigid pavement	9,0 ± 2,0	13,0 ± 3,0	19,0 ± 6,0
	thick asphalt pavement	13,0 ± 3,0	22,0 ± 5,0	32,0 ± 8,0
	flexible pavement	19,0 ± 4,0	32,0 ± 6,0	47,0 ± 9,0
Curvature radius		> 1000 m		
epth of the wheel track		≤ 4,0 mm	≤ 7,0 mm	≤ 10,0 mm

Furthermore, Table 3 presents the analysis of the characteristics of the PGFs, as well as the evaluation of these characteristics for inclusion in the specific classes for WIM of COST 323. Thus, it was possible to classify each PGF after the follow-up period of the consolidation phase.

Table 3 - Classification of pavement for installation of the WIM system according to COST 323 COST (2002)

PGF	**Pavement**	**Evaluation base**	**Classe COST 323**	**Observation**
PGF 01	Lane1	Long. Inclin.	Class I	In general, it falls into Class I.
		Transv. Inclin.	Class I	
		Deflection	Class I	
	Lane 2	Long. Inclin.	Class I	
		Transv. Inclin.	Class I	
		Deflection	Class I	
PGF 02	Lane 1	Long. Inclin.	Class I	In general, it falls into Class I.
		Transv. Inclin.	Class I	
		Deflection	Class I	
	Lane 2	Long. Inclin.	Class I	
		Transv. Inclin.	Class I	
		Deflection	Class I	

Finally, both PGFs were classified in Class I “excellent” of COST 323. However, it should be noted that the pavement was only established in Class I after the consolidation period, accompanied by means of deflection tests for more than 70 days after opening to traffic. At the beginning of the tests, both PGFs presented deflections above the stipulated as “excellent”, and would be placed in lower classes without adequate monitoring of pavement consolidation.

5. Methodology applied to the construction of a flowchart of flooring solutions for the WIM system

The pavement structure solutions catalog provides a range of options, such as flexible, thick, semi-rigid, and rigid pavement structures. The flowchart in the catalog not only proposes potential construction interventions and offers designers with final pavement structures suitable for use in the Pavement Control Station (ECP) for the WIM system, but also aims to present a comprehensive set of solutions. This is accomplished by establishing minimum and maximum values based on extensive data and bibliographic research, enabling users to choose from various paths in the flowchart. The flowchart defines and presents all parameters utilized in determining pavement structure solutions, together with their respective class and subclass limit values. These limits provide designers with the flexibility to select different options based on their specific requirements and desired outcomes.

5.1. Support ground

For asphalt concrete pavement, a limit of 60 MPa for elastic modulus was defined based on the subgrade CBR classification, which varies with deflections on the pavement surface. Silty and expandable soils have lower CBR values at 6%, while fine soils, including sandy soils, have CBR values between 8% and 20%. Based on this, a dimensioning analysis was carried out by varying the subgrade value (between 2% and 20%). Subgrades with CBR greater than 6% did not result in significant thickness variations in the layers.

For rigid pavement, dimensioning was done for each N by varying the subgrade's CBR value (%) and setting the same sub-base layer thickness. Two types of sub-base were defined: granular sub-base (BG) and gravel sub-base treated with cement (BT). Values between 2% and 8% were found since road institutions allow subgrades with CBR greater than or equal to 2%. These values correspond to elastic moduli ranging from 20 MPa to 80 MPa. The thicknesses of the plates were obtained through trials until they met the criteria of fatigue and erosion failure, using the Portland Cement Association (PCA) method in the 1984 version (Brasil (a), 2005). Based on this analysis, the following elastic moduli were defined for Simple Rigid Pavements without Shoulders (PRSS): $20 \text{ MPa} \leq E < 30$ Mpa; $30 \text{ MPa} \leq E < 40$ Mpa e $E \geq 40$ MPa.

For Simple Rigid Pavements with Shoulders (PRSC), the elastic moduli were defined in the following ranges: $20 \text{ MPa} \leq E < 30$ Mpa; $30 \text{ MPa} \leq E < 60$ MPa e $E \geq 60$ MPa.

For Structurally Reinforced Rigid Pavement without Shoulders (PREAS) and Continuously Reinforced Rigid Pavement without Shoulders (PRCAS), the elastic modulus limit was established at 40MPa, that is, $40 \text{ MPa} < E$ and $E \geq 40$ MPa. For Structurally Reinforced Rigid Pavement with Shoulder (PREAC) and Continuously Reinforced Rigid Pavement with Shoulder (PRCAC), the elastic modulus limit was determined at 60 MPa, that is, $60 \text{ MPa} < E$ and $E \geq 60$ MPa.

5.2. Defect level

The classification will be based on the Flexible Pavement Condition Index (ICPF), which represents the estimated rate of defects based on the functional evaluation of the pavement, classifying the surface of the pavement section according to the concepts shown in Table 1.

Table 1 - ICPF Concepts

Concepts	**Description**	**ICPF**
Excellent	It just needs routine maintenance.	5 – 4
Good	Asphaltic mud application – superficial wear, not very severe cracks in not very extensive areas.	4 – 3
Regular	Correction of localized points or resurfacing – cracked pavement, with "pots" and infrequent patches and with longitudinal or transversal irregularities.	3 – 2
Bad	Resurfacing with previous corrections – generalized defects with previous corrections in localized areas – superficial or deep patches.	2 – 1
Terrible	Reconstruction - generalized defects with previous corrections fully. Degradation of the coating and other layers – water infiltration and decompression of the base.	1 - 0

Source: Brazil [(b)] (2003)

Additionally, the stretch will also be classified using the International Irregularity Index (IRI), which indicates a reference plane that can directly affect different factors related to the passage of users through the stretch, such as vehicle dynamics and load distribution. Thus, the pavement defect levels – low, medium and high – are defined in relation to these two parameters, as shown in Table 2**Erro! Fonte de referência não encontrada.**.

Table 2 - Classification of defect levels

Classification	Minimum requirements	
	ICPF	IRI
Low	ICPF > 4	IRI ≤ 2.0
Average	3 < ICPF ≤ 4	2.0 < IRI ≤ 3.0
High	ICPF ≤ 3	IRI > 3.0

Source: Brazil [(b)] (2003)

5.3. Surface layer deflection

The deflection on the pavement surface is a structural parameter and varies with the magnitude of the load, that is, the displacement speed, with the characteristics of the pavement and with the types of coating. Therefore, the life of the pavement that houses the WIM sensors depends on the deflection on its surface, since the electromechanical response of the sensors varies with the deflection on the pavement according to Otto (2018). In this sense, considering the COST 323 classification for WIM sites and the results of research carried out in this area, an acceptable value of $60x10^{-2}$ mm is suggested, considering that for higher values the pavement enters the plastic state, that is, fatigue occurs of the pavement.

5.4. Number N

The number "N" refers to the number of repetitions (or operations) of the vehicle axles, equivalent to the requests of a standard road axle during a useful life period considered for the pavement. The limit values and ranges of the Number "N" adopted for the definitions in the catalog are specified for each type of pavement, due to the influence of this parameter in the dimensioning. For asphalt concrete pavements, the "N" number intervals were defined as: N ≤ 5x106; 5x106 < N ≤ 1x107; 1x107 < N ≤ 5x 107 and N > 5x107. In turn, for simple rigid floors, intervals of N ≤ 5x106 were adopted; 5x106 < N ≤ 1x107; 1x107 < N ≤ 5x107; 5x107< N ≤ 1x108; 1x108 < N ≤ 5x108 and 5x 108 < N ≤ 9x108. For reinforced rigid pavements, N ≤ 1x107 and N > 1x107 with granular sub-base layer and N ≤ 1x107, 1x107 < N ≤ 5x108 and N > 5x108 with cement-treated gravel sub-base layer were considered.

5.5. Application of the solutions catalog flowchart

Figure 4 shows the flowchart of the solutions catalog for asphalt concrete pavement structures with the variables and their respective limits that must be met to choose a solution.

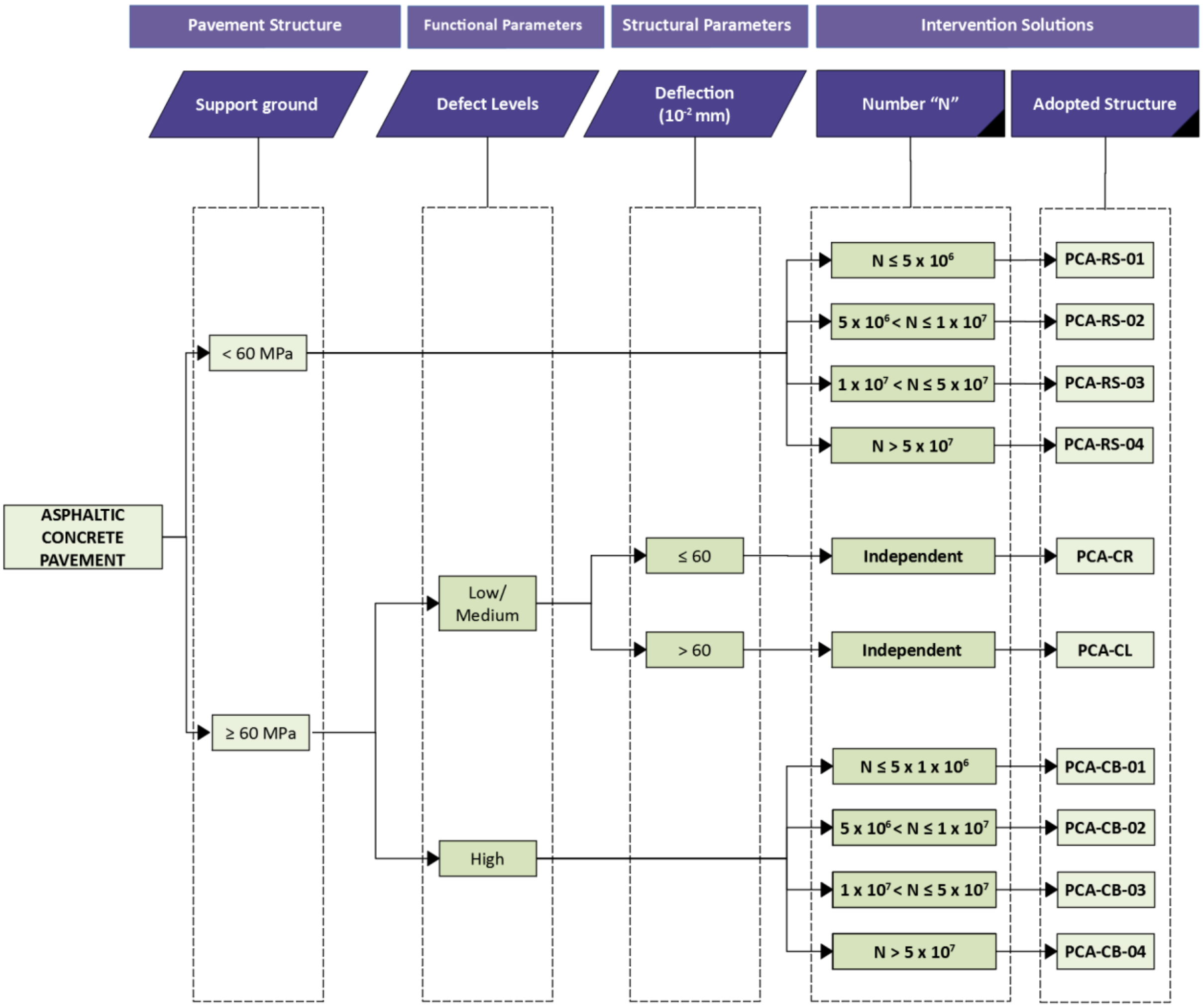
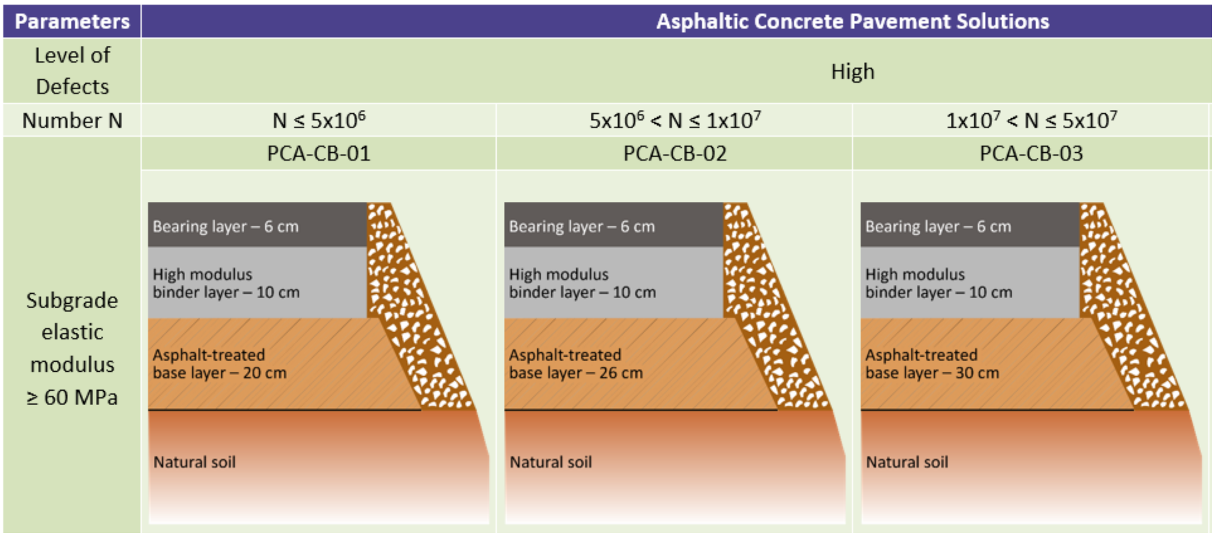


Figure 3 – Example of asphalt pavement structure flowchart

Once the most appropriate structure has been chosen, a sheet containing the specifications of the structure adopted, an example shown in Figure 5, accompanies the catalog.



Parameters	Asphaltic Concrete Pavement Solutions		
Level of Defects	High		
Number N	$N \leq 5x10^6$	$5x10^6 < N \leq 1x10^7$	$1x10^7 < N \leq 5x10^7$
Subgrade elastic modulus $\geq$ 60 MPa	PCA-CB-01	PCA-CB-02	PCA-CB-03

Figure 5 – Example of a catalog sheet

6. Final Considerations

In this study, we received data on pavement structure characteristics, traffic, and deflections, which were measured on different days in two PGFs. Based on the data, we identified that both PGFs have a 20 cm thickness of high modulus asphalt concrete layer. Deflection data were analyzed by correcting for temperature and eliminating outliers using confidence intervals based on the student’s t distribution. The graphs showed inclined lines of deflections that decreased over time, indicating stability of the pavement structures after 95 days of construction or restoration.

To create a comprehensive catalog of pavement solutions for HS-WIM systems, it is crucial to consider various indicators such as VMDa and N number, to categorize highways based on logistical corridors, past infractions on highway sections, and impact of overloading heavy vehicles on pavement lifespan. It is also essential to evaluate the structural and functional conditions of the pavements when selecting solutions for the installation of the HS-WIM system. Therefore, we defined main functional (Flexible Pavement Condition Index - ICPF, International Irregularity Index - IRI) and structural (deflections) parameters for using the flowchart.

To ensure the flowchart methodology is easy to use and produces high-quality results, we designed entry parameters that meet the minimum requirements for good pavement and WIM system performance. We also defined limits for functional and structural variables so that a wide range of pavement structures with different thicknesses, subgrade support, and surface layer characteristics could be included in the proposed solutions. The flowchart is designed to be used in an intuitive and simplified way, with a logical sequence of paths that reflect the characteristics of the pavement structure.

We proposed standard structures for asphaltic or rigid concrete pavement that meet the technical requirements for implementing the WIM system. By analyzing the effect of varying foundation support soil, we developed a catalog of standard structures for rigid pavement, sub-base of granular material, and sub-base of crushed stone treated with cement. Additionally, we included alternative reinforced rigid concrete structure solutions for both types of sub-base.

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