Pavement serviceability evaluation using whole body vibration techniques: a case study for urban roads

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Abstract

The quantification of the pavement serviceability, as measured in terms of the present serviceability index (PSI), is most often based on the international roughness index (IRI), a mathematical model developed by the World Bank. The IRI adopts a constant modeling speed of 80 km/h. However, on low-speed urban roads, particularly in developing countries and/or congested roads, this may present a challenge - as vehicle operating speeds could be much lower than 80 km/h, among other limitations associated with the use of IRI as an indicator of ride quality in the urban context. Using the Colombia's City of Barranquilla's urban rigid (concrete) pavements as the datum source, this study was conducted to formulate some alternative pavement serviceability criteria for low-speed roads (30 – 60 km/h) in an urban setting. Deterministic and probabilistic modeling of PSI in the SPSS statistical software were executed based on the whole-body vibration (WBV) concepts, and thereafter, the results were compared with the ISO 2631 standard that addresses human exposure to multiple mechanical shocks. In the study, a modified WBV-based frequency-weighted root-mean-square acceleration parameter (a_{wz}), offering a more realistic representation for modeling the serviceability and ride quality of low-speed urban roads, was formulated. Based on the estimated models, an a_{wz} criterion of 0.98 m/s^2 at a probability acceptance of 85%, for a vehicle operating speed of 50 km/h, was proposed for urban roads. Overall, the study has demonstrated that for accurate estimation of ride quality and comfort (i.e., PSI) of low-speed urban roads, the evaluation criteria should be based on low vehicle speeds that are more representative of urban field conditions. For road agencies such as the City of Barranquilla, the proposed a_{wz} criteria and thresholds can potentially serve as cost-effective supplements for efficient

Pavement Management System (PMS) decision making and optimize maintenance and rehabilitation (*M&R)* timing with respect to urban roads.

Key words: Pavement serviceability, Ride quality, Urban roads, Thresholds, Comfort, PSI, IRI, WBV.

1. Introduction

In general, the decision-making process of a road agency should be supported by a robust Pavement Management System (PMS). A PMS is an objective process to evaluate, design, and program timely maintenance and rehabilitation (*M&R*) activities to prolong the service life of the road network. Performance indicators such as pavement surface roughness, cracking, rutting, etc., represent a key element to a PMS. Based on these indicators, a road agency can prioritize decisions and optimize the limited resources, while guaranteeing an acceptable level of service of the road network. Generally, road authorities try to define and maintain the performance indicators at acceptable levels to sustain/improve the ride quality (among others) on their road infrastructure.

By definition, pavement serviceability is a concept developed in the American Association of State Highway Officials (AASHO) Road Test to assess the ability of a given pavement section to serve the traffic in its current condition (AASHO 1962a). In other words, it is a measure of the comfort and safety experienced by motorists/users when traveling on a road (Carey and Irick 1960). For this reason, the present serviceability index (PSI) is one of the most common indicators used worldwide to design pavement structures, as in the case of the AASHTO 93 design method (AASHTO 1993). Despite the great advances made in the field of pavement design, such as the mechanistic-empirical (M-E) methods, the AASHTO 93 is still the widely used method today, literally in most developing countries including Colombia (ABC 2011, ICPA 2014, INVIAS 2015).

In the AASHO Road Test, it was shown that the roughness of the longitudinal pavement profile is the variable that best describes users' ratings, and therefore, the serviceability of a pavement. Since then, several attempts have been made to relate the pavement roughness to the serviceability concept in different contexts, mainly on rural and interstates roads. The International Roughness Index (IRI) is one such popular index used widely in the PMS's around the world (Múčka 2017).

In a study carried out by Fuentes *et al.* (2019), the authors presented a summary of the pavement serviceability models available in the literature along with their relevant details. One of the main findings of their study is the widespread usage of the IRI for the serviceability estimations in different contexts, purposes, and interpretations. In their study, Fuentes *et al.* (2019) also formulated deterministic and probabilistic serviceability models for urban roads, and proposed some IRI and pavement condition index (PCI) thresholds for the users' acceptance of the pavement condition for developing countries.

However, since the IRI development in 1986 by the World Bank (*Sayers et al.* 1986), different studies have described many limitations about the application of the IRI in urban roads. One of the most reported limitations is the difference between the simulation speed of the quarter car model (80 km/h) and the typical operating vehicle speeds on urban roads (30 to 60 km/h) (Abudinen *et al.* 2017). This discrepancy can undesirably lead to an overestimation of the discomforts perceived by the users under real-time travel conditions.

In consideration of the above challenges/limitations, the current approaches consist of complementing the evaluation of the users' perception using parameters that adequately describe the users' experience when traveling on the roads. The ISO 2631 standard proposes a methodology to quantify the body vibrations with an index called -frequency weighted root mean square (RMS) acceleration (a_w)- (ISO 1997). The a_w index allows for the evaluation of the vibrational effects induced by the pavement profile (surface) irregularities on human comfort at operational vehicle speeds. This flexibility of the a_w index inherently addresses the main limitations of the IRI when making estimations of serviceability on low-speed roads, with operating vehicle speeds less than 80 km/h. The use of representative indicators, such as the a_w index, for real-time travel conditions, is a fundamental component of the PMS and is very critical for rational decision-making processes by the road authorities.

2. Objectives and scope of study

Based on the above background and as a supplement to the IRI criteria, this study was conducted to address the following two objectives, namely to:

(1) Analyze the relationship between the user's subjective perception regarding the level of service provided by a road and the vertical accelerations induced by the road profile using the ISO 2631 whole-body vibration index concept. To accomplish this objective, deterministic and

probabilistic models were formulated and utilized for pavement serviceability estimations on urban roads.

(2) Propose tentative thresholds for pavement serviceability assessment of urban roads using the a_w parameter as a more representative characterization with respect to travel quality; and lastly, compare the proposed a_w thresholds to the ISO 2631 standard.

For the data source, the urban roads in the City of Barranquilla (Colombia) were used as the case study to accomplish the above objectives. In the subsequent section, the literature review is presented followed by the study methodology. Formulation and development of the deterministic and probabilistic models are then presented including statistical analysis and proposition of the acceptance thresholds/criteria. A synthesis and discussion of the results are then presented followed by a summary of conclusions and recommendations to wrap up the paper.

3. Review of literature and technical standards

A literature review including the associated technical standards is presented and discussed under this section. Aspects covered include the pavement serviceability, ride quality, pavement roughness, IRI, whole-body vibration concepts, and ride quality related studies on urban roads.

3.1 Pavement serviceability

During a period of two years (1958 - 1960), the AASHO developed the experimental phase of the AASHO Road Test. A full-scale trial whose main objective was the evaluation of the performance of two types of structures with defined characteristics was initiated, namely pavements (rigid and flexible) and bridges (reinforced concrete and structural steel) subjected to dynamic loads of known magnitude and frequency (AASHO 1962a).

Considering that the fundamental function of a pavement is to serve traffic, and that, it is the users who can best evaluate this service, the AASHO proposed the concept of serviceability. The serviceability of a road represents the quality of the road as perceived by users, in terms of comfort (ride quality) and can be related to the different measurable distresses (e.g., roughness, cracking, and rutting) on the pavement surface (Paterson 1987).

Due to the subjective nature of the serviceability concept, it was necessary to numerically summarize the users' opinions and, as far as possible, find their relationship with quantifiable physical characteristics (i.e., roughness, cracking, rutting, and patching areas) of the pavement. Two fundamental indicators emerged from this process, namely the Present Serviceability Rating (PSR) and the Present Serviceability Index (PSI). The PSR represents the average of the user ratings for each pavement section on a 0 to 5 scale (i.e., $0 \leq PSR \leq 5$), using the rating form shown in Figure 1 (for all pavement types). The PSI represents the result of the relationship between the PSR and pavement objective parameters such as the IRI or the PCI. In other words, the PSI is used to describe/predict the serviceability (PSR) through statistical models.

***** FIGURE 1 BY HERE *****

As a result of the AASHO Road Test, the first pavement serviceability models were introduced in 1960 (Carey and Irick 1960). The models proposed served as the basis for the pavement design procedure adopted by AASHTO. Equation (1) presents the model proposed for flexible pavements, while Equation (2) is used for rigid pavements.

- Flexible pavements:

$$PSI = 5.03 - 1.91\log(1+SV) - 1.38(RD)^2 - 0.01\sqrt{C+P} \quad (1)$$
$$R^2 = 0.84,\ \ SEE = 0.38$$

- Rigid pavements:

$$PSI = 5.41 - 1.78\log(1+SV) - 0.09\sqrt{C+P} \quad (2)$$
$$R^2 = 0.92,\ \ SEE = 0.32$$

Where SV = slope variance over the pavement section from CHLOE profilometer measurements; RD = mean rut depth (in); C = cracking (m^2/1000 m^2) (flexible); C = cracking (m/305 m^2) (= 1ft/1000 ft^2) (rigid); P = patching (m^2/ 1000 m^2); R^2 = coefficient of determination; and SEE = standard error of estimate – where 1 ft ≅ 0.305 m and 1 ft^2 ≅ 0.093 m^2.

In the AASHO Road Test, it was demonstrated that from the different variables contemplated in the field experiment to evaluate the overall pavement condition, the surface roughness of the longitudinal pavement profile, described in terms of SV, was the variable that best described the users' ratings (AASHO 1962b). Since then, different concepts have been explored to relate the pavement surface roughness to pavement serviceability. The IRI is one such concepts that plays a key role in the pavement condition assessment in many countries around the world (Múčka 2017).

ASTM E1927-98 (2018a) describes a procedure for obtaining subjective numerical ride ratings for a group of pavement sections. The standard defines the guidelines for the field experiment, particularly with aspects related to the suitable selection of pavement test sections and panel raters. In the ASTM standard, the average value, for each pavement section, of ride quality ratings assigned by the panel is called the Mean Panel Rating (MPR). The MPR is equal, by definition, to the PSR developed in the AASHO Road Test. Key considerations in ASTM E1927-98 standard include the following aspects (for both flexible and rigid pavements):

- A minimum number of 20 pavement sections should be selected for each pavement type.
- Each section should have homogeneous physical characteristics throughout its length.
- The group of test sections should be well distributed by distress level.
- Pavement sections should be of equal length, long enough to provide an appropriate time of panel raters exposure.
- The panel size should be selected as a function of acceptable error in MPR units.
- The rating panel should be representative of the road user population.
- The preparation and provision of appropriate/adequate rating forms.
- The formulation and issuing of appropriate instructions to the raters regarding the use of rating forms.
- The processing of the data to obtain the MPR values.

In general, the above considerations should be adhered to when conducting pavement rating studies. An important use of the resulting experimental data is to determine the ability of hypothesized functions of the physical pavement parameters, such as profile roughness, distresses indicators, etc., to provide appropriate and realistic estimations of the users' perception about ride quality (ASTM, 2018a).

3.2 Ride quality and pavement roughness

Ride quality refers to the level of comfort experienced by vehicle (car) passengers when traveling on a road. This level of comfort is strongly dependent on the in-vehicle vibrations, especially vertical accelerations, induced by the pavement surface roughness (Ahlin and Granlund 2002). Pavement surface unevenness causes vibrations on the users' whole-body during vehicle motion, adversely affecting the ride quality and comfort. For these reasons, the study of the pavement-vehicle-human interactions and the physical analysis of the vibration phenomena are both critical aspects, particularly for quantitatively relating pavement surface roughness to ride quality (Cantisani and Loprencipe 2010). As discussed subsequently, studies conducted to formulate mathematical representation of pavement surface roughness relative to travel quality, and support the PMS decision-making processes, yielded the well-known and widely used IRI concept (Múčka 2016, Múčka 2017).

3.2.1 The International Roughness Index (IRI)

Based on the International Road Roughness Experiment (IRRE) in Brazil, the World Bank, in 1986, published a document entitled "Guidelines for Conducting and Calibrating Roughness Measurements" – a calibration manual to introduce and extend the IRI internationally (*Sayers et al.* 1986). The IRI is a mathematical model based on the response of a quarter-car model (QCM) as it traverses a longitudinal pavement profile at a constant speed of 80 km/h (Sayers 1995). For the simulation, the parameters of the QCM are set and normalized to represent a typical passenger car called "the Golden Car". The simulated motion between the sprung and unsprung masses (passengers and vehicle components masses) is accumulated and divided by the distance traveled by the QCM during a simulated ride at the standardized speed of 80 km/h – see Equation (3) below.

$$IRI= \frac{1}{L}\int_{0}^{L/V} |\dot{z}_s - \dot{z}_u| dt \tag{3}$$

Where *IRI* is the pavement surface roughness indicator presented in units of slope, namely mm/m, m/km or in/mi; $\dot{z}_s$, $\dot{z}_u$ = time derivatives of height (vertical coordinate) of sprung and unsprung masses, respectively; L = pavement profile length; and V = simulation speed (i.e., 80 km/h).

The mathematical processing of the longitudinal pavement profiles to calculate the IRI is described in the ASTM E1926-98 (2015) standard. The algorithm developed in the IRRE study and reported in the World Bank technical reports (*Sayers et al.* 1986) and summarized by Sayers (1995), consists of solving in time domain, the differential equations that represent the QCM, riding on the pavement section profile (measured through any of the methods described by the ASTM E950/950M-09 (2018b) and ASTM E1364-95 (2017) standards), at 80 km/h.

In a study carried out by Fuentes *et al.* (2019), the authors, based on the traditional approach of predicting serviceability using the IRI, formulated probabilistic and deterministic serviceability models for urban roads in Colombia. However, some studies have been reported that the IRI presents certain limitations that warrants addressing, particularly on low-speed roads (Ahlin and Granlund 2002, La Torre *et al.* 2002, Arhin *et al.* 2015, Múčka 2016, Abudinen *et al.* 2017). Some of these challenges and limitations include the following:

- The IRI was developed on rural roads based on pavement sections of 320 m. However, on urban roads, the length of pavement sections is defined mainly by intersections or junctions, which are usually found every 150 m. Since the IRI is sensitive to the base length over which it is calculated, it is common to obtain IRI values significantly higher than what the pavement condition actually reflects (La Torre *et al.* 2002).
- The IRI model adopts a constant modeling speed of 80 km/h. However, on urban roads, the vehicle operating speeds are significantly lower. For example, in the Colombian case (City of Barranquilla), the vehicle speeds on urban roads within the city limits are usually less than 60 km/h. In addition, motorist comfort is strongly related to the vehicle speed and, therefore, IRI values can overestimate (or underestimate) the users' real subjective perception about the road condition.
- The IRI is influenced by particular characteristics associated with urban roads such as drainage provisions, frequent intersections, speed humps, roundabouts, frequent stop-go zones (i.e., braking/accelerating), pedestrian stops/crossings, and numerous interfaces with utility access boxes that affect the IRI significantly without representing greater impact on the perception of the users about the road quality (Fuentes *et al.* 2019). In other words, these characteristic factors hardly influence the users' judgement of the road quality and ride comfort despite being quantitatively detrimental in terms of magnifying the IRI values. The high IRI values for urban areas can exaggerate the scope of *M&R* activities required if these are not programmed based on appropriate/adequate indicators and thresholds for each specific context (Arhin *et al.* 2015). For example, the adoption of conventional IRI scales or international IRI thresholds such as the roughness thresholds used by the Federal Highway Administration (FHWA 2015), in urban areas, can overestimate the actual surface-roughness condition of the pavements, leading to inappropriate and costly decisions by the road authorities.
- Lastly, for ride comfort evaluation, the mathematical formulation of the IRI has some disadvantages. For the same IRI value, the users can be exposed to totally different travel experiences if these are performed at different speeds (Abudinen *et al.* 2017). In this way, it is

possible to obtain significantly different users' perception of a set of pavements with the same IRI value. In addition, the QCM is used to calculate the suspension relative motion of a simulated vehicle ride. However, the ride comfort is related to vehicle vibration rather than displacements (Múčka 2016).

Given these challenges and limitations associated with the IRI concept, this study aims to propose the use of a recognized alternative indicator, which can be more suitable for modeling user perception about the pavements in the urban areas. As discussed subsequently, the envisioned alternative/supplementary indicator is based on the whole-body vibration concept.

3.2.2 The whole-body vibration concept

The vehicle industry practice shows that ride quality assessment is preferably based on car vibrations, rather than suspension strokes, which corresponds to the displacement accumulation encompassed in the IRI model (Ahlin and Granlund 2002). In the same way, road agencies should identify and/or formulate appropriate indicators to manage the road networks and guarantee acceptable levels of service. Considering the IRI limitations in urban roads, alternative approaches are required for the travel quality assessment of pavements, particularly those located within the city limits.

The ISO 2631 standard (ISO 1997) proposes a methodology to quantify the vibrations that have an influence on human comfort and health. This method allows for modeling of the whole-body vibration (WBV) into a single parameter from the analysis of accelerations perceived by users when traveling on a road. Specifically, the RMS value of the frequency-weighted acceleration time history, called a_w, is one such parameter for effectively accomplishing this (ISO 1997). The frequency weighting is the mathematical process to represent the manner in which vibration affects human health and comfort differently depending on the vibration frequency and loading time history (Ahlin and Granlund 2002).

It is important to highlight that the ISO 2631 (ISO 1997) defines a procedure for processing the acceleration data from a real travel experiment. On a car trip, pavement surface unevenness causes translational and rotational vibration on the users in all directions. However, as in the case of the IRI and other roughness indicators, the most used approaches in the literature for roughness assessment consist of the riding mathematical simulations based on a measured road profile. In this way, it is not only possible to define the simulation parameters according to the real travel conditions, but also study hypothetical scenarios of interest. In the case of the QCM, which is used subsequently in this study, the model can only describe the vertical accelerations experienced by the sprung and unsprung masses (Sayers 1995). To avoid confusion and differentiate from a_w, the parameter to model the vibrations in this study will be denoted as a_{wz} and mathematically expressed as shown in Equation (4):

$$a_{wz} = \sqrt{\sum_i (W_{k,i} \times a_{iz}^{RMS})^2} \tag{4}$$

Where a_{iz}^{RMS} = vertical RMS acceleration values on the users' body calculated by means of the power spectral density (PSD) for each *i*th octave thirds band; $W_{k,i}$ = frequency weighting factors for a_{iz}^{RMS}, according to Table 3 of ISO 2631-1 standard guide/manual; and a_{wz} = vertical frequency-weighted acceleration.

The vertical accelerations of the sprung mass (passengers) can be extracted from the QCM in order to compute a_{wz} according to the ISO standard (ISO 1997). As it can be observed, the a_{wz} model, defined by Equation (4), has some advantages over the IRI model, including the following:

- The IRI computation is standardized to a reference speed of 80 km/h, while the a_{wz} can be computed for any specific operational speed conditions of the given road.
- The parameters of the QCM for the IRI computation are fixed to the golden car parameters. However, for the a_{wz} mathematical processing, the accelerations can be measured in a field experiment or estimated from calibrated simulation models to represent the real travel conditions.
- For some applications, the IRI-based models can provide misleading estimates when assessing travel quality. It has been shown that it is possible to experience different levels of vibrations when traveling on pavements with the same IRI values (Ahlin and Granlund 2002). The a_{wz} allows to differentiate and quantify this effect.

3.3 Ride quality related studies on urban roads

Over the last decades, several authors have proposed different approaches to assess the level of service offered by pavement to users in the urban-road context (Ahlin and Granlund 2002, La Torre *et al.* 2002, Cantisani and Loprencipe 2010, Arhin *et al.* 2015, Abudinen *et al.* 2017, Kırbaş and Karaşahin 2018, 2019). These studies have shown a wide variety of analytical techniques for ride quality data processing, with the aim of enhancing the decision-making processes within PMS.

Ahlin and Granlund (2002) estimated some relationships between pavement surface roughness, in terms of IRI and a PSD indicator, vehicle speeds and the WBV experienced by users based on analytical ride simulations. These models can be used to convert the WBV limit values to correspondingly approximate the IRI values for an IRI-based PMS. However, for some applications where the IRI cannot be accurately approximated, the authors recommended implementing direct calculations based on accelerations measurements.

La Torre *et al.* (2002) developed a correlation between user acceptability of pavement condition, user ratings on a PSR scale, and pavement surface roughness. The study was based on data from 17 sections of flexible and articulated pavements. The roughness was characterized by a modified IRI* model (the IRI model using a base length of 50 m and a riding speed of 50 km/h instead of 80 km/h) for a more approximate representation of the real travel conditions on urban roads.

Cantisani and Loprencipe (2010) proposed and calibrated a "full car model" to represent a complete real vehicle. This model was used to calculate the WBV (a_{wz} values) for a sample of pavement sections and various speeds (30 – 90 km/h). In total, 124 pavement sections extracted from the Strategic Highway Research Program (SHRP) Long-Term Pavement Performance (LTPP) were analyzed. The authors developed correlations between the standardized IRI model and the a_{wz} values for each speed considered. Based on the indicative comfort values of the ISO 2631 standard (ISO 1997), they proposed speed-related IRI thresholds to evaluate ride quality on low-speed roads.

Arhin *et al.* (2015) developed a model to predict the IRI based on the PSR in urban areas. 122 flexible pavement sections selected from the District Department of Transportation (DDOT) were used in the study. The authors also proposed IRI thresholds based on user perception and compared with the IRI values defined by the FHWA. In their recommendations, the authors emphasize the need to define suitable thresholds based on the actual pavement surface roughness perceived by motorists.

Abudinen *et al.* (2017) described a methodology for the travel quality assessment for urban roads. The authors, using a database with information on more than 80 rigid pavements, estimated linear regression models to relate the IRI with the a_{wz} values for various riding speeds (30 – 100 km/h). In their findings, the authors proposed speed-related IRI thresholds for pavement management activities.

Kırbaş and Karaşahin (2018, 2019) investigated the influence of a distress indicator, the PCI, on ride comfort. In their studies, PCI and vibrational measurements were performed on flexible urban asphalt-concrete pavements, according to the PAVER system and the ISO 2631 standards. Using logistic regression, artificial neural network (ANN), and fuzzy logic techniques, they proposed some threshold values of PCI for ride comfort.

Finally, Table 1 summarizes the findings of the different studies related to ride quality on urban roads, emphasizing on the proposed thresholds for pavement sections that have an operating speed of 50 km/h.

***** TABLE 1 BY HERE *****

4. Study methodology and research approach

The urban roads in the City of Barranquilla (Colombia) served as the case study and encompassed over 50 city roads – all with rigid (concrete) pavement structures. The field data measured and collected included road profiles, pavement distresses (PCI), users' perceptions (PSR), and acceptance responses regarding the condition of the pavement sections (Fuentes *et al.* 2019). A two-phase approach was devised and executed for collecting the field data. Phase I comprised of a subjective evaluation where a riding quality experiment was conducted following the guidelines defined by ASTM E1927 (ASTM 2018a). In particular, the ASTM E1927 standard procedures for the adequate selection of road test sections and conformation to the evaluation panel (raters) requirements were compliantly adhered to. More than fifty (50) rigid pavement sections, generally 3.5 m wide with lengths ranging between 50 and 200 m, were selected from a representative group of roads, based on certain physical characteristics (surface roughness and distresses), of the City of Barranquilla, Colombia. Note that over 90% of urban roads in the City of Barranquilla comprise of rigid pavement structures and thus, only rigid pavement sections were included in the study matrix.

In addition, the panel size was defined to be 15 based on 0.3 MPR maximum error with a normal distribution, according to the ASTM specification (ASTM 2018a). The raters were representatively selected from the road user population based on age, sex, driving experience, and occupation; this taking into account that these variables could influence the perception of users regarding road condition (Arellana *et al.* 2019). The panel members (raters) were trained before the experiment following the ASTM guidelines. The average rating of the panel members for each pavement section was reported as the MPR and subsequently, used for serviceability estimations.

Phase II of the research approach comprised of an objective evaluation where performance indexes such as the IRI and the PCI were evaluated on each pavement section. Detailed results and data documentation for these evaluations can be found in Fuentes *et al.* (2019). However, for a better subjective characterization of the users' perception of ride quality in the urban-road context, an additional parameter, namely the vertical frequency-weighted RMS acceleration (a_{wz}), was calculated in this study. The a_{wz} was used for the serviceability estimations in this study in order to propose an alternative approach for the functional evaluation of pavements within the PMS' framework in urban areas.

For field measurements and data collection, pavement profiles were measured continuously using a SurPro walking profiler along the outside wheel path. Thereafter, the vertical whole-body vibrational values were simulated/modeled using the QCM at the typical vehicle operating speeds prevalent on Barranquilla's urban roads, namely 30 – 60 km/h. Using an algorithm developed in the MATLAB programing platform (MATLAB 2017), the a_{wz} values were computed and determined in accordance with the ISO 2631 standard procedure (ISO 1997).

5. Pavement serviceability modeling and statistical analysis

This section discusses the pavement serviceability modeling and estimations including statistical analysis. Model formulation included both the deterministic and probabilistic methods. The tentatively proposed serviceability thresholds based on the whole-body vibration concept are also presented and discussed in this section.

5.1 Deterministic modeling

As documented in Fuentes *et al.* (2019), the data collected was compiled in a database that included the estimated a_{wz} values at typical operating speeds on Barranquilla's urban roads (30 – 60 km/h with an incremental step of 10 km/h), MPR, and acceptance responses regarding the road infrastructure.

Figure 2 depicts the relationship between a_{wz} and PSI at the indicated vehicle speeds by means of four exponential models. As theoretically expected, pavement serviceability decreases as the vibrational levels represented by a_{wz} increases.

***** FIGURE 2 BY HERE *****

It is important to highlight that the exponential models defined by Equation (5) to (8), as derived from Figure 2, are restricted to a PSI maximum value of 5.0 when a_{wz} is 0.0. This is based on the theoretical argument that a pavement in optimal conditions is one that does not generate discomfort to its users.

$$PSI = 5e^{-1.164(a_{wz(30)})} \tag{5}$$
$$R^2 = 0.60$$

$$PSI = 5e^{-0.785(a_{wz(40)})} \tag{6}$$
$$R^2 = 0.72$$

$$PSI = 5e^{-0.478(a_{wz(50)})} \tag{7}$$
$$R^2 = 0.84$$

$$PSI = 5e^{-0.382(a_{wz(60)})} \tag{8}$$
$$R^2 = 0.74$$

Where a_{wz} is expressed in m/s^2. Additionally, Figure 3 shows the sensitivity analysis for the coefficient of determination considering a wide range of modeling speeds (20 – 90 km/h). It is also worth noting that as illustrated in Figure 3, the coefficient of determination (R^2) between PSI and a_{wz} for different speeds is 50% and higher. The highest R^2 value is 84% for 50 km/h and the lowest (50%) corresponds to 90 km/h. These R^2 values indicate a good correlation-ship and suggest that PSI can be estimated to a minimum accuracy of 50% from a_{wz}. Based on Figure 3 and Equations (5) to (8), the highest PSI prediction accuracy and statistical confidence, would therefore be for 50 km/h vehicle speed with an R^2 value of 84%.

***** FIGURE 3 BY HERE *****

Mathematically, it should be considered that exponential models constitute a particular form of linear regression models. A linear model accounts for both a deterministic component and a probabilistic (random error) component (Arhin *et al.* 2015). However, for practical reasons, one usually uses regression models to obtain the expected value of the dependent variable (in this case PSI), assuming that the error term has a mean equal to zero – hence, ignoring the random nature of the dependent variable.

The ability of the a_{wz} parameter to reflect the user perception in terms of pavement serviceability, for each considered speed, was quantified using R^2 concept. The R^2 value calculated for a simple linear regression is a statistical measure of how well the regression line describes the real data points (Navidi 2008). As one can observe from Figure 3, based on the highest R^2 value (i.e., 84%), the model that best adjusts the user ratings in the present study is defined by Equation (7), which corresponds to a modeling speed of 50 km/h.

The above results/findings are consistent with the contributions made in previous studies regarding the importance of the 50 km/h speed when studying urban roads, particularly in developing countries (La Torre *et al.* 2002, Kırbaş and Karaşahin 2018, Fuentes *et al.* 2019). In fact, the user comfort is highly dependent on the vehicle speed. Therefore, the user ratings are influenced by their travel experience, particularly in a situation where the average speed limit is 50 km/h. For all these reasons, the pavement serviceability analysis of urban roads in this study will thus be based on simulated vertical accelerations at 50 km/h ($a_{wz(50)}$). Figure 4 shows the distribution of the reported average user ratings for each rigid pavement section and their corresponding simulated $a_{wz(50)}$ values.

***** FIGURE 4 BY HERE *****

From Figure 4 and Equation (7), it is possible to define the a_{wz} ranges based on the subjective serviceability scale shown in Table 2.

***** TABLE 2 BY HERE *****

5.2 Probabilistic modeling

The model defined in Equation (7) can be used to determine the serviceability of urban roads based on the vertical vibrations experienced by users, quantified in terms of the a_{wz} parameter. However, this model was proposed using a deterministic approach, and in its formulation, the subjectivity of the ratings in the range of the measured data was not considered.

To address this limitation, a probabilistic approach was used to predict the likelihood of obtaining a given serviceability rating based on the vertical accelerations. Specifically, an ordered logit model was formulated to study the relationship between PSI and $a_{wz(50)}$. The ordered logit model was chosen considering the ordinal nature of the dependent variable (PSI subjective levels), which was modeled using an unobserved variable (PSI*), according to Equation (9).

$$PSI^* = \beta_{awz} \times a_{wz(50)} + \varepsilon \tag{9}$$

Where β_{awz} is the regression coefficient and ε is the random disturbance variable. The predicted ordinal PSI level can be obtained using the results of Equation (9) and the estimated thresholds τ found in Table 3 according to Equation (10).

$$PSI = \begin{array}{lll} 1\ (Very\ Poor) & if & -\infty < PSI^{*} \le \tau_1 \\ 2\ \ (Poor) & if & \tau_1 < PSI^{*} \le \tau_2 \\ 3\ (Fair) & if & \tau_2 < PSI^{*} \le \tau_3 \\ 4\ (Good) & if & \tau_3 < PSI^{*} \le \tau_4 \\ 5\ (Very\ Good) & if & \tau_4 < PSI^{*} \le \infty \end{array} \tag{10}$$

The model parameters were estimated using the maximum likelihood procedure (Hosmer *et al.* 2013) in the SPSS statistical software (SPSS 2017), and the relevant results are summarized in Table 3.

***** TABLE 3 BY HERE *****

The coefficient β_{awz} in Table 3 can be used to estimate the odds ratio. In logistic regression models, the odds ratio (OR) is used to measure the association between the dependent variable (i.e., a_{wz}) and the independent variable (i.e., PSI) (Hosmer et al. 2013). Specifically, it tells you how an increment of 1 m/s^2 in a_{wz} has an effect on the PSI. However, considering the range of the a_{wz} values (the order of magnitude seen in Figure 4), a change of 1 m/s^2 is too large and 0.1 m/s^2 is a more realistic change for a given pavement in consecutive years. Hence, to provide a useful interpretation, the odds ratio for a change of 0.1 m/s^2 in a_{wz} is OR(0.1) = exp(-3.74×0.1) = 0.69. This estimate implies a 31% reduction in the odds of assigning a higher PSI level per 0.1 m/s^2 increase in a_{wz}, or mathematically, 31% reduction in the odds of (PSI > k) over (PSI ≤ k), where k represents one of the five possible levels for the categorical variables of the PSI.

Additionally, Equation (11) can be used to estimate the cumulative probability of observing a specific PSI level based on the discomfort experienced by users due to the prevailing pavement condition. In this sense, one could modify Equation (11) to obtain the probability of observing a specific PSI level of a pavement section given the simulated acceleration.

$$P(PSI \le k|a_{wz(50)}) = \frac{e^{(\tau_k - \beta_{awz} \times a_{wz(50)})}}{1+e^{(\tau_k - \beta_{awz} \times a_{wz(50)})}} \tag{11}$$

The negative value of β_{awz} implies that the probability of ranking a pavement section with a high PSI value (4 or 5) decreases as the $a_{wz(50)}$ increases, i.e., increasing discomfort. As an example, according to the estimated logit function, a pavement whose irregularities generate vertical accelerations of $a_{wz(50)}$ = 0.15 m/s^2, presents the following probabilities of being rated by users as follows: Probability (PSI = 1) = 0.0%, Probability (PSI = 2) = 0.1%, Probability (PSI = 3) = 2.6%, Probability (PSI = 4) = 32.4%, and Probability (PSI = 5) = 64.9%, respectively.

Additionally, Figure 5 presents a sensitivity analysis conducted using Equation (11) that allows the understanding of the effect of the discomforts generated by the pavement in the users, measured by a_{wz}, in their subjective criteria when evaluating a pavement with a specific PSI level.

***** FIGURE 5 BY HERE *****

It is important to note that the PSI levels were grouped into five categories according to the qualitative scale of the serviceability. Therefore, the results must be interpreted cautiously considering that each category considers a range of values. For example, PSI = 1 corresponds to user ratings of 1 or below (≤ 1), PSI = 2 corresponds to ratings between 1 and 2 (1 < PSI ≤ 2), and so on, until the last category, which is PSI = 5.

As seen in Figure 5, pavements in excellent conditions (a_{wz} values close to zero) are more likely to be rated with high PSI values (4 to 5), while pavements in poor conditions are more likely to be quantitatively/numerically rated with PSI values less than two.

A similar analysis to that used in the deterministic approach can be used to define the a_{wz} ranges based on the subjective serviceability scale. Using Equation (11), it is possible to determine the $a_{wz(50)}$ ranges for which the probability of users qualifying the pavement at each PSI level reaches the highest values – see Table 4.

***** TABLE 4 BY HERE *****

5.3 Formulation of WBV-based acceptance criteria and thresholds

An analysis was conducted using the information of the users regarding the acceptance or rejection of a rigid pavement section given its prevailing condition with the aim of proposing and recommending some acceptance thresholds for vertical accelerations. In the field experiments, raters were asked to identify whether the pavement sections were acceptable in terms of riding comfort. The two possible answers and response outcomes, namely "accept" or "reject" were modeled in the SPSS statistical software (SPSS 2017) as a binary variable Z.

Considering Z=1 for acceptance, and Z=0 for rejection, a binary logit model, expressed in Equation (12), was formulated to obtain the critical $a_{wz(50)}$ values.

$$P(Z = 1|a_{wz(50)}) = \frac{1}{1 + e^{-(\beta_0 + \beta_1 \times a_{wz(50)})}} \quad (12)$$

Where Z is the dependent variable; $P\ (Z=1)$ is the predicted probability that the binary variable takes a numerical value of one – that is, accept the vibration levels; and β_0, β_1 are regression coefficients.

The maximum likelihood procedure was then used to estimate the model parameters, namely β_0 and β_1 (Hosmer *et al.* 2013). The relevant details of the modeling are presented in Table 5. In general, the results show a good fit for the model with a *p-value* significantly less than 0.05 at 95% confidence level.

***** TABLE 5 BY HERE *****

From Table 5, the estimated OR for an increase of 1 m/s^2 in a_{wz} is 0.04. However, as discussed before, 0.1 m/s^2 was used considering that it represents a more realistic change of pavement condition in consecutive years. Therefore, the odds ratio OR(0.1) = exp(-3.22*0.1) = 0.72, implies a 27% reduction in the odds for accept pavement condition per 0.1 m/s^2 increase in a_{wz}. In other words, for every increase of 0.1 m/s^2 in the vertical accelerations experienced by users, the ratio of the probability that users accept a given pavement section over the probability that they reject it decreases 27%.

Additionally, the predicted probability of acceptance was computed using Equation (12) with the parameters from Table 5 as inputs. The corresponding results are graphically plotted in Figure 6.

***** FIGURE 6 BY HERE *****

As recommended in previous investigations by Fuentes *et al.* (2019), a value of $P=0.85$ was used to define the acceptability thresholds. This value is also convenient because, below this value (i.e., less than 85%), the probability decreases significantly for a small change in the predictor variable – see Figure 6. From Figure 6, one can also observe a critical value of $a_{wz(50)}$ = 0.98 m/s^2. However, depending on the local conditions and available resources, the road authorities can define thresholds for different acceptance probabilities. Table 6 summarizes some proposed values of interest that can be used in the PMS decision-making process to improve the ability of the road infrastructure to satisfactorily serve its users in terms of safety and comfort.

***** TABLE 6 BY HERE *****

6. Synthesis and discussion of the results

The definition of ride comfort varies depending on personal expectations and perceptions about the pavement conditions and user traveling experience. The ISO 2631 standard (ISO 1997) gives approximate indications of the likely reactions to various magnitudes of the WBV for application in public transport, as presented in Table 7. However, considering the subjectivity in the opinion of users in different contexts such user travel experience, comfort thresholds are not defined in the ISO 2631 standard (Kırbaş and Karaşahin 2018, Arellana *et al.* 2019). In fact, the limit values for the acceleration's ranges are often in conflict due to multiple overlaps in the a_{wz} values – see Table 7. For example, according to the ISO, a_{wz} values between 0.8 and 1.0 m/s^2 can be qualitatively described as '*Fairly Uncomfortable'* or '*Uncomfortable*'.

***** TABLE 7 BY HERE *****

Figure 7 summarizes the most relevant findings of this study. The graph shows the results obtained from the deterministic and probabilistic modeling including the proposed a_{wz} thresholds for pavement condition acceptance and the values suggested by the ISO 2631 standard (ISO 1997) for the evaluation of the vibrations that affect the travel quality and ride comfort.

***** FIGURE 7 BY HERE *****

It is interesting to note that the thresholds summarized in Figure 7 are consistent and/or overlapping with the ISO 2631 standard (ISO 1997). For example, for a_{wz} values greater than 2 m/s^2, which mean approximately PSI qualitative categories of '*Poor*' and '*Very Poor'* pavement condition according to the deterministic and probabilistic approaches, correspond to unacceptable acceleration values according to the acceptance threshold, and an '*Extremely Uncomfortable*' level of comfort. Similarly, a_{wz} values lower than 0.5 m/s^2, qualitatively describe roughly a pavement in '*Very Good*' condition, with a high probability of acceptance ($P \geq 0.85$), and a ride experience qualitatively described as '*Not Uncomfortable'*.

Considering that Colombian local road agencies have yet to establish a PMS that defines the policies for the programming, timing, and scheduling of *M&R* activities, the thresholds proposed in this study as summarized in Figure 7 could be tentatively used to define a prioritization criteria that take into considerations how users perceive the urban road conditions.

7. Conclusions and recommendations

Using the City of Barranquilla's urban rigid (concrete) pavements as the datum source, this study was conducted to formulate some alternative pavement serviceability criteria for low-speed roads (30 – 60 km/h) in an urban setting. Deterministic and probabilistic modeling of PSI, in the SPSS statistical software, were executed based on the WBV concepts, and thereafter, the results were compared with the ISO 2631 standard. The key findings and recommendations drawn from the study, based on an analysis of over 50 rigid (concrete) pavement sections, are summarized as follows:

- The formulated frequency-weighted root-mean-square acceleration (a_{wz}) parameter, based on the WBV concept and accounts for simulated vertical acceleration, offers a more realistic representation for modeling the serviceability and ride quality of low-speed urban roads. The robustness and flexibility of the a_{wz} parameter allow it to accommodate and compute PSI values for any operating vehicle speed within an urban setting. Plausible results were obtained in this study for a speed range of 30 to 60 km/h.

- For the vehicle speeds considered in this study (i.e., 30–60 km/h), deterministic modeling yielded high PSI prediction accuracy (84%) and statistical confidence for an operating vehicle speed of 50 km/h. This finding aligns well with the fact that the speed limit for most urban roads in cities such as Barranquilla rarely exceeds 50 km/h, i.e., speed limit < 50 km/h.

- Various serviceability thresholds based on both deterministic and probabilistic modeling were successfully formulated for the a_{wz} parameter, which corresponding to a PSI scaling range of 0 to 5.0 and pavement condition rating range of "*Very Poor*" to "*Very Good*".

- Using the WBV concept for an operating vehicle speed of 50 km/h, an a_{wz} criterion and threshold of 0.98 m/s^2 at a probability acceptance of 85% was proposed. Thus, in lieu of the traditional perspective for travel quality assessment (i.e. the IRI-based models), this study recommends to consider this tentative criterion proposed herein for quantifying and rating the serviceability and ride quality of low-speed urban rigid (concrete) roads.

Overall, this study has demonstrated that for accurate estimation of the ride quality and comfort, in terms of PSI, of low-speed urban roads, the evaluation criteria should correspondingly be based on low vehicle speeds that are more representative of urban field conditions. For road agencies such as the City of Barranquilla, the proposed a_{wz} criteria and thresholds can potentially serve as cost-effective supplements for efficient PMS decision making and optimize *M&R* timing.

Although the WBV-based parameter used for pavement serviceability estimations offers a more accurate representation of real travel conditions than traditional approaches, the model includes several simplifications that could be the subject of future studies. For example, the estimation of more complex vehicle models that accounts for both translational (in all directions) and rotational vibration that are experienced in a real vehicle ride.

Lastly, although the results and findings reported herein pertain to the rigid (concrete) pavements evaluated in the study, the methodology and concepts adopted can be replicated to urban flexible pavements.

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The contents of this paper reflect the views of the authors who are responsible for the facts and accuracy of the data presented herein and do not necessarily reflect the official views or policies of any agency or institute. This paper does not constitute a standard, specification, nor is it intended for design, construction, bidding, contracting, tendering, certification, or permit purposes. Trade names were used solely for information purposes and not for product endorsement, advertisement, promotions, or certification.

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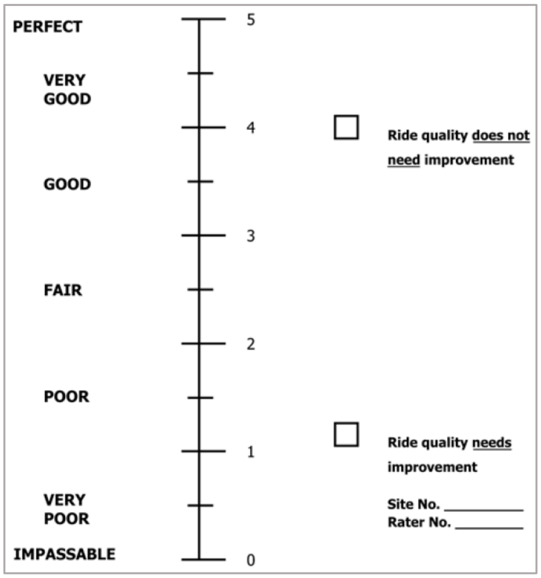

Figure 1: Rating Form for Serviceability Study (ASTM 2018a).

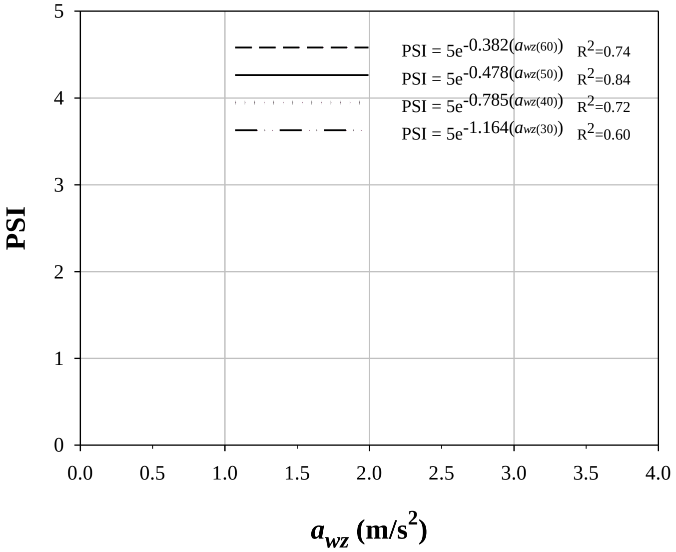

Figure 2: Relationship Between PSI and a_{wz}.

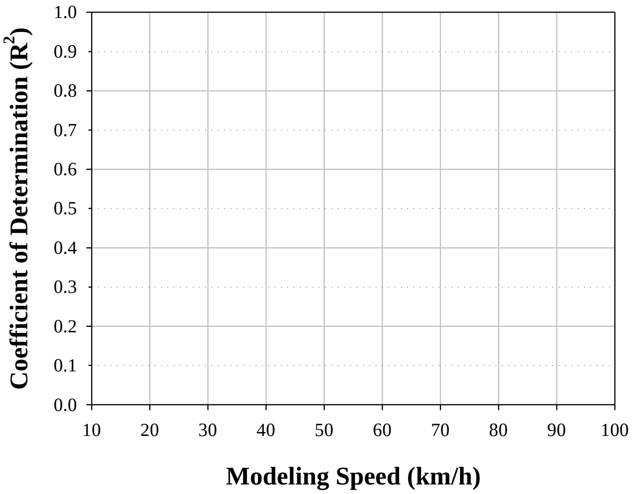

Figure 3: Sensitivity Analysis for the Coefficient of Determination.

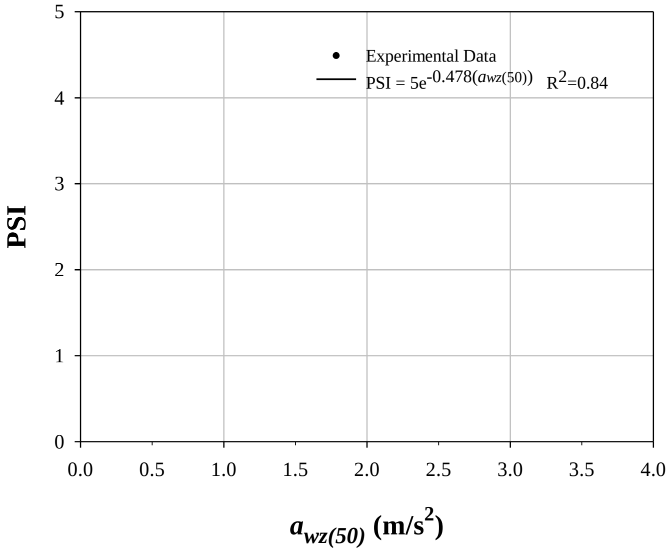

Figure 4: Relationship Between PSI and $a_{wz(50)}$.

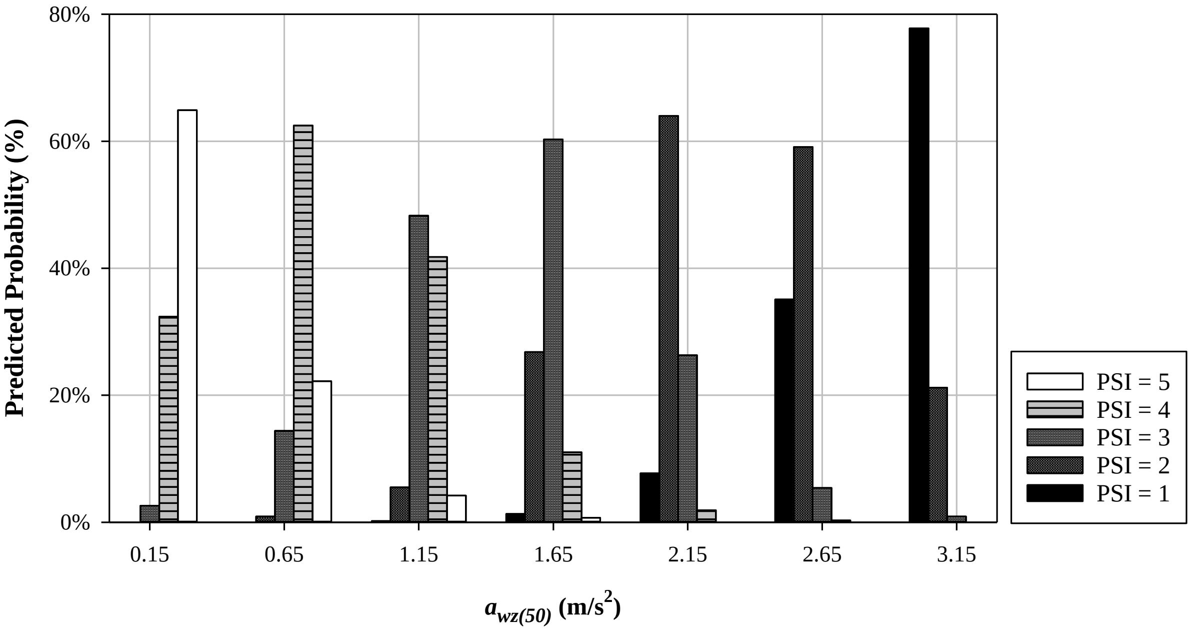

Figure 5: Sensitivity Analysis for Ordinal Logistic Model Based on the $a_{wz(50)}$.

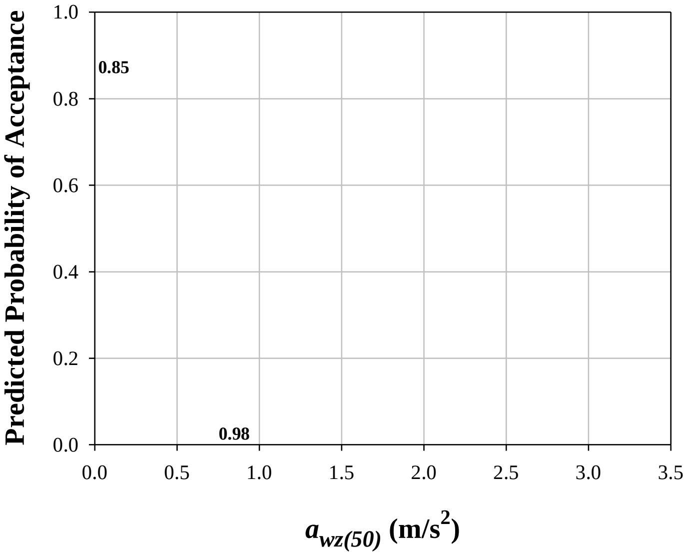

Figure 6: Predicted Probability of Acceptance Based on the $a_{wz(50)}$.

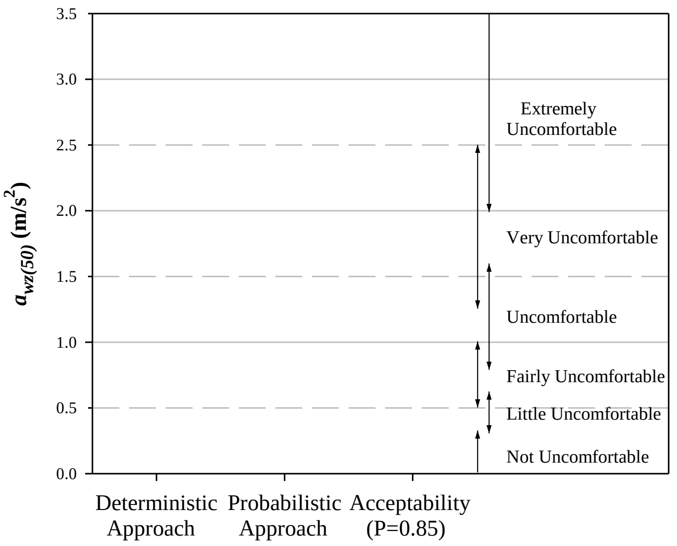

Figure 7: Travel Quality and Ride Comfort Thresholds (Rigid Pavements).

List of tables

Reference Source	Speed	Indicator	Criteria	Proposed Thresholds
(La Torre *et al.* 2002)	50 km/h	IRI* (m/km)	Percentage of Users Satisfied (%)	4.1 (85%), 5.2 (75%), 6.9 (60%), 8.2 (50%)
(Cantisani and Loprencipe 2010)	50 km/h	IRI (m/km)	Pavement Condition Based on Indicative Comfort Values of ISO 2631 Standard	<2.98 (Very Good), 2.98-5.95 (Good/Fair), 5.95-8.51 (Mediocre), >8.51 (Poor)
(Arhin *et al.* 2015)	—	IRI (in/mi)	FHWA Pavement Condition Scale and IRI-Based Serviceability Models	Freeways: <2.0 (Good), 2.0-3.4 (Acceptable) Arterials: <2.9 (Good), 2.9-4.4 (Acceptable) Collectors: <3.0 (Good), 3.0-5.0 (Acceptable)
(Abudinen *et al.* 2017)	50 km/h	IRI (m/km)	Pavement Condition According to IRI-awz models and ISO 2631 Comfort Values	<2.05 (Very Good), 2.05-4.1 (Good), 4.1-5.86 (Regular), >5.86 (Bad)
(Kirbaş and Karaşahin 2018)	50 km/h	PCI	Indicative Comfort Values of ISO 2631 Standard	<51 (Fairly Uncomfortable), 51-78 (A Little Uncomfortable), >78 (Not Uncomfortable)
(Kirbaş and Karaşahin 2019)	50 km/h	PCI	Indicative Comfort Values of ISO 2631 Standard	<45 (Fairly Uncomfortable), 45-78 (A Little Uncomfortable), >78 (Not Uncomfortable)
(Fuentes *et al.* 2019)	50 km/h	IRI(m/km)	Probabilities of Pavement Condition Acceptance (%)	3.9 (95%), 5.9 (85%), 6.9 (75%), 8.7 (50%), 10.5 (25%)
		PCI		71 (95%), 61 (85%), 55 (75%), 46 (50%), 37 (25%)

Table 1. Studies Related to Ride Quality on Urban Roads.

PSI	Pavement Condition	$a_{wz(50)}$
(4 , 5]	Very Good	< 0.46
(3 , 4]	Good	(0.46 , 1.06)
(2 , 3]	Fair	(1.06 , 1.91)
(1 , 2]	Poor	(1.91 , 3.36)
[0 , 1]	Very Poor	> 3.36

Table 2: a_{wz} Thresholds for Serviceability Based on Deterministic Approach.

Parameter	Estimate	S.E.	Z	p-Value	Odds Ratio	95% CI (α = 0.05)
τ1	-10.52	2.41	-4.36	< 0.001		
τ2	-7.11	1.36	-5.23	< 0.001		
τ3	-4.14	0.76	-5.45	< 0.001		
τ4	-1.17	0.54	-2.18	0.03		
β_{awz}	-3.74	0.78	-4.78	< 0.001	0.02	(0.01 , 0.11)

Legend: S.E.= Standard Error; Z = Standard Score; CI = Confidence Interval; α = Significance Level.

Table 3: Estimation Results of Ordered Logit Model.

PSI	Pavement Condition	$a_{wz(50)}$
(4 , 5]	Very Good	< 0.35
(3 , 4]	Good	(0.35 , 1.11)
(2 , 3]	Fair	(1.11 , 1.89)
(1 , 2]	Poor	(1.89 , 2.80)
[0 , 1]	Very Poor	> 2.80

Table 4: a_{wz} Thresholds for Serviceability Based on Probabilistic Approach**.**

Parameter	Estimate	S.E.	(W^2)	p-Value	Odds Ratio	95% CI (α = 0.05)
β_0	4.904	1.242	15.601	< 0.001		
β_1	-3.22	1.109	8.428	0.004	0.04	(0.004 , 0.351)
Likelihood Ratio Test Statistic: 25.15						
P-value: < 0.001						

Legend: S.E.= Standard Error; W = Wald Statistic; CI = Confidence Interval; α = Significance Level.

Table 5: Estimation Results of Acceptance Logit Model.

Predicted Probability of Acceptance (%)	$a_{wz(50)}$ (m/s^2)
95	0.61
85	**0.98**
75	1.18
50	1.52
25	1.86

Table 6: Proposed Pavement Acceptance Thresholds Based on the a_{wz} Parameter.

a_w (m/s^2)	Expected Comfort Level
< 0.315	Not Uncomfortable
0.315 - 0.63	A Little Uncomfortable
0.5 - 1.0	Fairly Uncomfortable
0.8 - 1.6	Uncomfortable
1.25 - 2.5	Very Uncomfortable
> 2.0	Extremely Uncomfortable

Table 7: ISO 2631 Indicative Acceleration Values for Ride Comfort.

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