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Functional thresholds for design-maintenance of urban pavements

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Subject review

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Functional criteria for sustainable design of urban pavements

Functional criteria have been mostly defined in urban pavements using subjective methods, rather than by means of objective and repeatable procedures. The Whole Body Vibration, the Heart Rate Variability, and new technologies to determine the IRI (International Roughness Index), are nowadays available. For that, an analysis of available technologies is made under a PC-O (Pavements Clients-Oriented) integral perspective, including simulations with the HDM-4 computer program. The IRI criteria for speeds allowed on urban roadways, i.e. the so-called IRIcity criteria, are proposed in the paper.

Key words:
pavements, functionality, design, maintenance, IRI, HDM-4

Pregledni rad

Mauricio Pradena, Lambert Houben

Funkcionalni kriteriji za održivo projektiranje gradskih kolnika

Funkcionalni kriteriji na gradskim prometnicama uglavnom se definiraju subjektivnim metodama, a ne pomoću objektivnih i ponovljivih postupaka. Danas su dostupne nove tehnologije za određivanje vrijednosti indeksa ravnosti (IRI), poput metode vibracije cijelog tijela (WBV) i metode varijabilnosti srčane frekvencije. Provedene su analize dostupnih tehnologija prema cjelovitom pristupu PC-O (eng. Pavements Clients - Oriented) uključujući simulacije pomoću računalnog programa HDM-4 (eng. Highway Development and Management system). U radu su predloženi IRI kriteriji za brzine dopuštene na gradskim prometnicama, takozvani IRIcity kriterij.

Ključne riječi:
kolnici, funkcionalnost, projektiranje, održavanje, IRI, HDM-4

Übersichtsarbeit

Mauricio Pradena, Lambert Houben

Funktionale Kennwerte zum nachhaltigen Entwurf städtischer Fahrbahnen

Funktionale Kennwerte bei städtischen Fahrbahnen werden hauptsächlich mittels subjektiver Methoden definiert und nicht aufgrund objektiver und wiederholbarer Verfahren. Heute sind neue Technologien zur Ermittlung des Rauigkeitsindex (IRI) verfügbar, z.b. Vibration des Gesamtkörpers (WBV) , und auf Herzfrequenzvariation basierende Methoden. Analysen der verfügbaren Technologien wurden mit dem integralen Verfahren PC-O durchgeführt, einschliesslich Simulationen mit dem Computerprogramm HDM-4. In dieser Arbeit werden IRI Kennwerte für zulässige Geschwindigkeiten auf städtischen Fahrbahnen vorgeschlagen, sogenannte IRIcity Kriterien.

Schlüsselwörter:
Fahrbahnen, Funktionalität, Entwurf, Instandhaltung, IRI, HDM-4

1. Introduction

The term "functional" generally refers to the idea of being practical and useful. In road engineering, functional performance is defined as a pavement"s ability to provide a safe and smooth riding surface [1]. Thenoux and Gaete [2] expand this definition to the general condition of pavements taking into account the serviceability, safety, and user costs.

The client satisfaction is a goal toward which any service or product provider should strive [3]. In terms of quality, this basically involves application of the customer focus principle as specified in ISO 9000:2005 [4]. Although structural capacity seems to be a major concern of many pavement engineers, road users primarily judge road quality based on its roughness or riding quality [5], i.e. based on the functional condition of pavement. Together with road users, the owners or agents acting on their behalf (such as transport agencies) are the largest groups of clients for pavements [3], and they both assign priority to riding quality. In addition, the transport agencies also assign priority to the life-cycle cost effectiveness [3]. The Road Infrastructure Maintenance Evaluation Study (RIMES) defines maintenance standard as a standard according to which it is necessary to "carry out a specified maintenance action at specified condition levels for specified pavement and bridge classes" [6]. A maintenance standard has a treatment type, defect type, and intervention level based on the defect type [7]. Considering the priority assigned by pavement clients to riding quality, an intervention level (threshold) must be defined on the basis of riding comfort. Riding comfort depends on road roughness, vehicle response to road, and human response to vibration. The International Roughness Index (IRI) was developed [8] in 1982 as a standardized, objective measure of the drivers" perceptions of road roughness. Since then the IRI has become widely accepted as a measure of roughness on interurban pavements, and it is also being used for establishing maintenance and rehabilitation priorities. In fact, the IRI is an indicator of the global condition of pavement, because it is actually affected by other deteriorations [9-11]. However, urban roadways have different characteristics compared to interurban ones, i.e. they are characterized by features such as manhole covers, frequent intersections, shorter sections, traffic signals, and stop signs. Functional maintenance thresholds have traditionally been defined on urban roads based on subjective rating or indices such as the PSR (Pavement Serviceability Rating) and PCI (Pavement Condition Index). Nevertheless, the data collected in this way vary in reliability, repeatability, portability, precision, comparability, etc. Thus, there is a clear necessity for an objective, repeatable, reliable, precise, portable, cost-effective, and functional urban maintenance threshold, which incorporates measures relevant to pavement clients, road users, and municipal transport agencies. In effect, maintenance interventions need to be made in an optimal way not only because of the municipal Pavement Management System (PMS), but also due to current trends favouring the use of integral design that includes functional analysis throughout the life-cycle of road pavements. In both cases, the objectivity is of crucial significance. But, in order to be useful, the functional threshold needs to be based on practical performance indicators. New possibilities for correlating pavement condition with driving comfort are currently available. These possibilities include the Whole Body Vibration (WBV) [12-15], the Heart Rate Variability (HRV) [16] and different technology advances that make field measurements more cost-effective, adaptable, reliable, easy, and practical. The aim of the present study is to propose functional thresholds for maintenance of urban pavements in order to facilitate objective design-maintenance of municipal pavement networks. Correlations between the pavement condition, driver comfort, and factors normally applied on urban roadways, are evaluated for that purpose. Furthermore, a PC-O (Pavements Clients-Oriented) integral perspective is defined in order to explicitly include the needs of pavement clients in the proposal. This integral perspective includes *inter alia* the Highway Development and Management system HDM-4 [17] as a means to respond to the life-cycle effectiveness requirements of clients (municipal transport agencies).

2. Methodology to propose the functional maintenance threshold

The riding comfort is particularly difficult to evaluate objectively because it needs to consider the user"s perception of dynamic effects transmitted to the vehicle [15]. There are numerous studies with measurement of pavement profiles, simulations, and evaluations of vehicle vibration, all this in order to correlate the pavement condition and driver comfort in the presence of factors that can be encountered on urban roadways. The methodology used in the present work includes an analysis of these correlations and the application of a PC-O integral perspective for the definition of functional threshold**.**

2.1. Correlations between pavement condition and driver comfort for urban roadways

2.1.1. Subjective evaluation

Functional urban maintenance thresholds have traditionally been defined using the PCI or PSR, and are therefore dependent on particular human judgment. When a relationship is made with pavement deterioration modalities, the slope variance, associated to the pavement surface irregularity, is the most influential deterioration [18]. This means that the surface irregularity has the greatest effect on the user"s evaluation. Some authors, such as Shafizadeh and Mannering [19] and Rens and Staley [20], have checked this in the presence of factors that can be found on urban roadways, relating the subjective evaluation with an objective index.

2.1.2. International roughness index (IRI)

The IRI is based on the simulation of the roughness response of a generic user car, the so-called quarter-car, travelling at 80 km/h. It was proposed in 1982 as a statistic indicator of surface irregularity and as a reference scale that can be used to compare riding quality of pavements throughout the world [8]. Nowadays, the IRI is a widely known and used measure in numerous countries and an acceptable standard for road profile measurements [5] allowing engineers to make objective and consistent comparisons with regard to other regions [21]. Hence, although roads may have different names and visual characteristics around the world, researchers can compare vibration analyses results for roads with similar IRI [22]. In addition, the IRI is defined as a mathematical transform of the longitudinal profile, which makes the measurement independent of the device and stable over time [23]. These particularities make the IRI a unique parameter compared to different ones related to riding quality, such as the RN (Ride Number), RI (Ride Index), MRN (Mays Ride Number) and RQI (Ride Quality Index). However there are some concerns regarding the use of IRI for urban pavements because such pavements usually exhibit speeds lower than 80 km/hr, and they have some specific features (manhole covers, speed reducers, etc.). In addition, the available length of homogeneous sections in urban roadways is often shorter than the 320 m typically used in the International Road Roughness Experiment IRRE [24].

2.1.3. Whole body vibration (WBV)

The ISO 2631-1 [13] "Mechanical vibrations - Evaluation of human exposure to whole-body vibration - Part 1: General requirements" specifies how to determine the vertical acceleration in a vehicle (α_{WZ}, vertical weighted RMS acceleration), and gives reference limits for approximate evaluation of the effects of vehicle vibration on human comfort. The α_{WZ} can be calculated for different speeds, including the ones occurring on urban roadways.

2.1.4. Heart rate variability (HRV)

HRV is the key parameter for describing the balance state of sympathetic-parasympathetic tension, representing a cyclical phenomenon of heart rate within a certain time period [16]. By measuring the HRV, it is possible to evaluate physiological response of a driver, as a result of pavement condition at different speeds, including those occurring on urban roadways. Zhang *et al* [16] use an electrocardiogram tester to determine HRV parameters, such as RMSSD, the square root of the mean squared difference of successive R-R (heartbeat) intervals.

2.2. PC-O integral perspective

The term functional generally refers to the idea of being practical and useful. In particular, in road engineering a functional pavement condition is directly related to the road user. But the definition of a functional threshold based on riding comfort is complex due to the need to relate pavement condition, vehicles dynamic response, and human physiological reaction in the presence of factors that can be encountered on urban roadways. In addition, the functional threshold needs to be objective in order to be useful for the purposes of municipal PMSs and integral design of urban pavements.

In summary, the functional urban maintenance threshold needs to be relevant for pavement clients, i.e. for road users and municipal transport agencies. An integral PC-O perspective is applied in the present work taking into account requirements of pavement clients, problem complexity and limitations, and assumptions and simplifications of correlations given in Section 2.1. In order to explicitly include the life-cycle cost effectiveness, as relevant for the clients (municipal transport agencies), a Pavement Management (PM) perspective is defined as a part of the PC-O integral approach.

The application of the PC-O integral perspective includes an analysis of the relevance of correlations presented in Section 2.1. The PM perspective results are obtained by modelling the pavement deterioration and the Road Users Costs (RUC) from typical roads using the Highway Development and Management system HDM-4 [17]. Finally, the functional threshold value is defined after adequate interpretation of the results of the components of the integral perspective.

3. Pavement management perspective

The PM perspective allows explicit inclusion of the needs of life-cycle cost effectiveness of the municipal transport agencies in the PC-O integral perspective. To define an optimum moment of maintenance intervention, one must identify the "critical phase" or "critical point" where the rate of deterioration of pavement rapidly increases, together with the associated road expenditures and user costs. Accordingly, the "critical phase" or "critical point" in the curves that describe pavement deterioration (Figure 1) or RUC is a good candidate for the proposal of functional threshold.

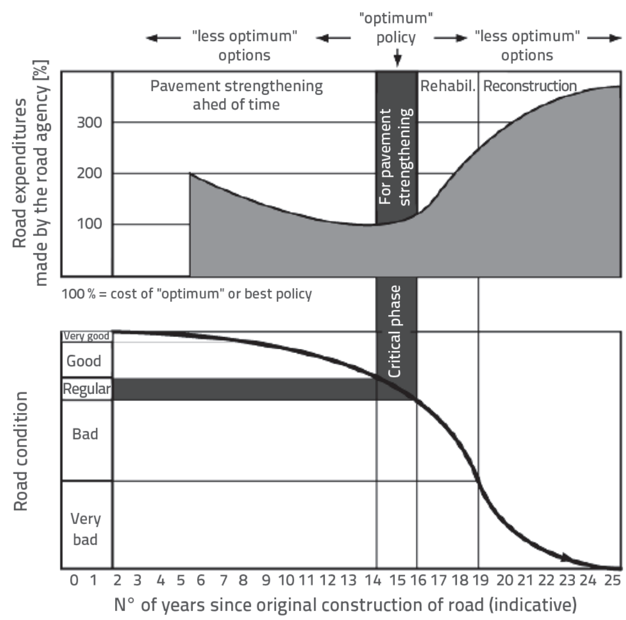

Figure 1. Optimum and less optimum intervention options – road agency costs [25]

Lee and Chatti [26] use the "critical point" of distress accumulation due to higher dynamic axle loads to establish RQI thresholds for highways. Fernandez and Neves [27] use the sharp increase in accident risk to define thresholds values of the international friction index, coefficient of friction, and texture depth. Finally, Papageorgiou and Mouratidis [28] define the IRI threshold from the inflection point of the curve that correlates IRI with Travel Time Costs (TTC), where the TTCs were calculated using a simplified model based on the HDM-4 speed model, i.e. the effects of Vehicle Operation Costs (VOC) are not considered. In the PC-O integral procedure, the HDM-4 management system is used (not a simplification) for calculating pavement deterioration and RUC (VOC + TTC). Hence, the functional threshold is defined from the curve that describes pavement deterioration, i.e. it is associated to financial costs of maintenance activities (as in Figure 1) and the curve of the RUC, associated to economic costs for the society.

4. Proposal of maintenance functional threshold

4.1. Performance parameter for definition of functional threshold

Under a PC-O integral perspective, the functional threshold needs to be based on a parameter relevant to the necessities of urban pavement clients. Pavement roughness is strongly related to pavement performance providing a good, overall measure of pavement condition, and correlating well with subjective assessments of the users [5, 29]. In effect, the IRI is the single best predictor of driver-perceived road roughness and driver acceptability [30]. Various types of equipment are nowadays available for making economical, adaptable and practical IRI measurements. Haas *et al* [31] stated at the conference on "Best Practices in Urban Transport Planning: Measuring Change" that the misuse of the IRI for PM implications can cause a loss of its objectivity, even when the IRI is an objective parameter. Still, to improve driving conditions on roadway systems, pavement roughness should be addressed with priority [32]. This contributes to rational PM, decreasing the maintenance expenditures of urban road networks [33].

Since its creation in 1982, the IRI has been widely accepted as an objective measure of roughness on interurban pavements, and it has been used on urban pavements of Canada [34, 35], Poland [36], Brazil [37], Chile [38], Colombia [39], China [40], India [41, 42] and in many other countries. According to Tighe *et al* [34] 60 % of Canadian cities, consulted for development of the Canadian pavement asset design and management guide, prescribe the use of the IRI in their municipal PMS. In the U.S.A., aside from the use of the IRI in Denver [20], Utah [43], Wisconsin [32], Louisiana [44] and New York [45], Dewan and Smith [10] developed a model to determine the IRI from pavement distresses in order to calculate the VOC in streets for the agencies' PMS of the cities of the San Francisco Bay Area. In effect, other pavement deteriorations affect the IRI, and the IRI is directly related to the RUC. For instance, the Eq. 1 is used by HDM-4 to calculate the IRI in Jointed Plain Concrete Pavements (JPCPs) [9]. It is possible to observe how other deteriorations affect the IRI (it is similar for asphalt pavements), as the IRI is also an indicator of global condition of a pavement.

$$IRI = IRI_0 + 0{,}00265 \cdot (TFAULT) + 0{,}0291 \cdot (SPALL) + 0{,}15 \cdot 10^{-6} \cdot (TRACK)^3 \quad (1)$$

where:

IRI - International Roughness Index [m/km]
IRI_0 - initial roughness at construction [m/km]
TFAULT - transverse joint faulting [mm/km]
SPALL - spalled joints [%]
TCRACK - transverse cracks [No/km].

For the reasons explained in this section (and the following ones), in this paper the IRI is the performance indicator used for the proposal of the functional maintenance threshold for urban pavements. The singularities present on urban roadways (manhole covers, frequent intersections, speed reducers, etc.) can be either eliminated or incorporated in the IRI evaluation. The elimination is possible with the currently available equipment and software. The incorporation of singularities requires their quantification as proposed by Rens and Staley [20], Caro and Peña [46], and Reggin *et al* [47]. Similarly, the effects of geometric design can also be either eliminated or incorporated in the IRI evaluation. This geometric effect can be isolated, for instance, in the manner proposed by Pradena *et al* [48]. The decision to incorporate or eliminate the effects of singularities and geometric design is however at the discretion of individual municipal transport agencies. In any case, the basis for the IRI evaluation presented in this paper is the same. Individual municipal transport agencies are also responsible for deciding on the length of the representative section for the IRI evaluation in the city (for instance 100 m). Again, the basis for the IRI evaluation presented in this paper is the same.

According to objection made by La Torre *et al* [24], the 320 m used in the IRRE is conservative for the equipment used; current inertial profilers can produce valid results with as little as 94 m (or 50 m with filter lead-in pre-processing) [47].

4.2. Performance parameter for definition of functional threshold

4.2.1. Relevance of WBV and HRV correlations and subjective evaluation

Because the IRI is an objective, practical, easily collectable, time stable, reliable, accurate, transportable, and cost-effective performance indicator, used widely all over the world, various studies of WBV, HRV and subjective evaluation include correlations with the IRI [14-16, 19, 20].

However, the subjective evaluation depends on the perception of particular users. Nevertheless, this perception can be different

Table 1. Critical IRI points for different roads according to PM (Pavement management) perspective

Road - Region	Latitude	Climate	Traffic 20 years [millions ESALs]	IRI PM [m/km]
A-Metropolitan	33° 27' S	Mediterranean. dry-summer	7.66	2.76
B-Metropolitan	33° 27' S	Mediterranean. dry-summer	1.88	2.63
A-Bio Bio	36°47' S	Mediterranean with oceanic influence	4.91	2.87
B-Bio Bio	36°47' S	Mediterranean with oceanic influence	1.36	2.72
A-Magallanes	53°8' S	Oceanic	0.62	2.73
B-Magallanes	53°8' S	Oceanic	0.31	2.67

depending on the environment, experience and expectations of specific users. For instance, Shafizadeh and Mannering [19] provide empirical support to the IRI thresholds of the US Federal Highway Administration based on drivers" perceptions on urban highways at Washington State. However, these results are not necessarily valid for other users. Therefore, even when it is fundamental that the IRI has a strong correlation with the drivers" perception in different parts of the world, the IRI threshold defined using the PC-O integral perspective has a necessary objective character, with possibilities of (objective) adjustment to realities present at various road networks. The WBV and HRV correlations with the IRI fulfil these objective requirements.

Ahlin and Granlund [14] indicate that the WBV calculations include several simplifications with respect to real riding conditions. One of these simplifications is the application of the quarter car model that does not necessarily represent the current extensive and variable automotive park. According to Shafizadeh and Mannering [19], it "is important to recognize that our understanding of these assessments is still developing". In addition, the former version of ISO 2631-1 [12] included limits for evaluation of riding comfort based on α_{wz}. However, due to improved understanding of the complexity of the problem, the present version of ISO 2631-1 [13] presents, in its annex, "approximate indications of likely reactions to various magnitudes of overall vibrations values in public transport". In effect, the problem is complex and every correlation has limitations, simplifications and assumptions that differ from real ride conditions. In addition, the parameter to define a threshold needs to be objective, practical, useable, cost-effective (measurements) and client-oriented. Hence, in the present work it is recognized that one approach is insufficient for this complex phenomenon, and that an integral perspective is necessary. Therefore, for an objective definition of the IRI threshold from a PC-O integral perspective, it is necessary to use WBV and HRV correlations with the IRI, together with the PM perspective.

4.2.2. IRI threshold from PM perspective

From the PM perspective, the IRI threshold can be objectively defined as a single value or a range of values, depending on whether the definition is made from a critical phase (conceptually as shown in Figure 1) or a critical point [26-28]. The decision will depend on each municipal transport agency, taking into account its reality and/or preferences between having different IRI thresholds levels (as alert, intervention, critical) or a single IRI threshold value. In any case, the PM perspective is basically the same and useful to particular preferences. For illustration purposes, a critical point is defined in this paper with the HDM-4 default calibration factors for typical cases of JPCPs. They correspond to usual characteristics of Chilean roads [49] where there are important differences in climatic conditions and traffic (expressed in Equivalent Single Axle Loads, ESALs). Table 1 shows similarities of the IRI-values, where a sharp increase of the IRI curve is produced.

For every case presented in Table 1 the change in the RUC curve coincides exactly with the change in the IRI curve. This can be explained by the fact that the IRI is a global pavement condition indicator that affects the road users.

4.2.3. IRIcity threshold from a PC-O integral perspective

Riding qualities will not likely be the same when a vehicle travels at 40 km/h on an urban street with IRI of 2 m/km, and when another vehicle travels at 120 km/h on a highway with the same IRI [50]. The correlations presented by Cantisani and Loprencipe [15] and Zhang *et al* [16] allow IRI calculation at different speeds, as the ones occurring at urban roadways. Both correlations present similar equations for the α_{wz}, which are based on the limits proposed in ISO 2631-1 [13]. In addition, Zhang *et al* [16] obtained a relationship with HRV in terms of RMSSD. The results obtained by Zhang *et al* [16] are presented in Eqs. 2 and 3.

$$\alpha_{wz} = 0{,}121 \cdot IRI + 0{,}006 \cdot V - 0{,}189 \quad (2)$$

$$RMSSD = 6{,}7967 \cdot \alpha_{wz}^{-0{,}4122} \quad (3)$$

where:

- α_{wz} - vertical frequency-weighted root-mean-square acceleration [m/s²]
- V - vehicle travel speed [km/h]
- IRI - International Roughness Index [m/km]
- $RMSSD$ - square root of the mean squared difference of successive R-R (heartbeat) intervals [ms].

The calculation of IRI for speeds different from the original 80 km/h is designated as IRI_{city} in this paper. The α_{WZ} limit that defines the end of a little uncomfortable zone for road users according to ISO 2631-1 is 0.63 m/s^2. The IRI associated with this α_{WZ} limit is 2.84 m/km (obtained using the WBV-IRI correlations presented by Cantisani and Loprencipe [15] and Zhang *et al* [16]), which is very similar to the values obtained from the PM perspective. In addition, using equation 3, the RMSSD associated to the α_{WZ} limit of 0.63 m/s^2 corresponds to 8.22 ms, which is very close to 9.26 ms that is the RMSSD limit defined by Liu *et al* [51] as the limit when the driver begins to feel uncomfortable according to medical literature. Therefore, the IRI threshold obtained by the PC-O integral perspective (WBV, HRV and PM perspectives) can be established as 2.8 m/km, at the vehicle speed of 80 km/h.

The functional threshold based on IRI_{city} can be calculated using the Eq. 2, with the α_{WZ} limit of 0.63 m/s^2 and different speeds found on urban roadways (Figure 2).

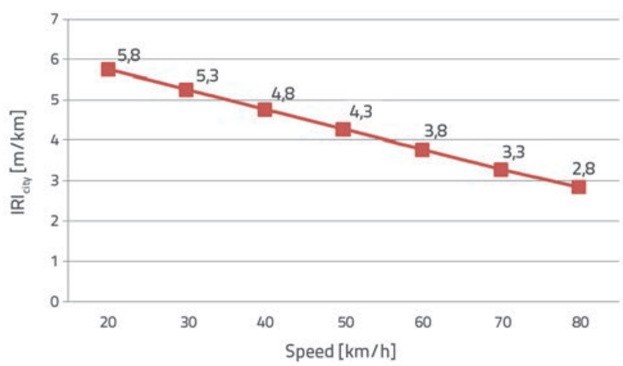

Figure 2. IRI_{city} threshold for different speeds

As could have been expected, the results show that is possible to accept higher values of IRI_{city} for streets with lower operational speed.

5. Practical relevance and potential applications

The IRI_{city} allows objective and practical decision-making concerning intervention planning on pavement networks, even without the knowledge of the exact pavement condition. For instance, in British Columbia, Canada, the funding for pavement maintenance is tied to the IRI. In effect, the IRI limit is 3.5 m/km and the municipalities are allowed to have 15 % of their major pavement network fail this criterion. This performance based funding mechanism has changed the way roadways are managed in these municipalities [47]. But, even more, there is nowadays an increase in public private partnership, performance based specifications, contracts for specific level of service, DBFM (Design, Build, Finance and Maintain), different types of roadway concessions, etc. In this context, the proposed IRI_{city} thresholds allow the planning, integral design, control and payment for investments in urban pavements in an objective way.

Currently there are wider equipment-related possibilities for a cost-effective determination of the IRI_{city}. Even equipment class 3 in the World Bank classification can be used, if well calibrated, for pavement network maintenance purposes [6, 46].

Although a practical application of the PC-O integral perspective for JPCPs is shown in this paper, the perspective can be applied to different types of pavements. In effect, even small-element pavements are included in the last version of HDM-4.

6. Conclusion

A functional maintenance threshold based on IRI has been defined from a PC-O integral perspective. This means that the needs of pavement clients, urban roadway users, and municipal transport agencies, have been considered from different perspectives, such as the WBV, HRV and PM. The WBV was calculated according to ISO 2631-1, the HRV was determined using the RMSSD, and the IRI threshold from a PM perspective was determined using the HDM-4 system.

From a PC-O integral perspective, the IRI was found to be an optimal practical parameter for facilitating fulfilment of design/maintenance objectives of municipal road networks (integral design and PMS). In effect, the IRI is an objective, relevant to urban pavements clients, practical, easily collectable, time stable, reliable, accurate, transportable, and cost-effective performance indicator applicable to urban roadways. Thus, IRI_{city} maintenance thresholds have been proposed for speeds applicable on urban roadways, using a correlation between the IRI threshold at 80 km/h (2.8 m/km) and the α_{WZ} defined by ISO 2631-1. For instance, the proposed IRI_{city} is 4.3 m/km in a street with the posted speed limit of 50 km/h.

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