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Ride Quality Due to Road Surface Irregularities: Comparison of Different Methods Applied on a Set of Real Road Profiles

Giuseppe Loprencipe * and Pablo Zoccali

Department of Civil, Constructional and Environmental Engineering, Sapienza University of Rome,
Via Eudossiana 18, 00184 Rome, Italy; pablo.zoccali@uniroma1.it
* Correspondence: giuseppe.loprencipe@uniroma1.it; Tel.: +39-064-458-5112

Abstract: Road roughness evaluation can be carried out using different approaches. Among these, the assessment of ride quality level perceived by road users is one of the most-used. In this sense, different evaluation methods have been developed in order to link the level of irregularities present on road surface profiles with the induced detrimental effects in terms of discomfort. In particular, relationships between wavelength content of road profiles and consequent level of comfort perceived had been investigated by using, in general, a mean panel ratings approach. In this paper, four ride quality evaluation methods (Ride Number, Michigan Ride Quality Index (*RQI*), Minnesota Ride Quality Index and frequency-weighted vertical acceleration, a_{wz}, according to ISO 2631 were applied to a set of real road profiles. The obtained results were analyzed, investigating a possible relation between the different indices, comparing them also with the most-used road roughness method worldwide: the International Roughness Index (*IRI*). The analyses carried out in this work have highlighted how the various rating scales may lead to a different ride quality assessment of the same road pavements. Furthermore, comparing the a_{wz} with the values obtained for the other three methods, it was found that their rating scales are set for speeds within the range 80–100 km/h. For this reason, it is necessary to identify new thresholds to be applied for lower speeds, as in the case of urban roads. In this sense, the use of the ISO 2631 approach would seem to be a useful tool.

Keywords: ride quality; ride Number; Michigan *RQI*; Minnesota *RQI*; road surface irregularities; ISO 2631; *IRI*; real road profiles

1. Introduction

Road roughness is an important issue for the assessment of road pavement condition [1,2], and an important aspect to be included in any Pavement Management System (*PMS*) [3–6]. Road roughness evaluation can be carried out using a number of different approaches. Among these, the most common ones are based on the assessment of detrimental effects induced by irregularities on road surfaces, like the dynamic increment of loads transmitted to pavements [7], road users' comfort [8] and noise generated due to road traffic [9].

The International Roughness Index (*IRI*) is the most used method worldwide and it was developed to take into account general effects (both on pavements and users) induced by irregularities of road pavement surface [10]. Some authors, like Kropáč and Múčka [11] and Loizos and Plati [12], have highlighted some limits of the applicability of IRI as a method for the evaluation of road roughness. In particular, in [13], the inability of *IRI* to describe car body vertical vibration due to the presence of certain wavelengths (i.e., >20 m) of road profile was described. In recent decades, several indices have been developed as alternative methods to consider various effects [14]. Particular attention

has been paid to the assessment of the influence of road unevenness on vehicles and passenger vibrations [15,16], and the evaluation of possible correlations between existing roughness indicators and vehicles vibration response [17].

Cantisani and Loprencipe [18] proposed calculating the whole body vibration induced on passengers inside road vehicles, by means of the process described in the ISO 2631 standard [19], to assess ride quality. In this way, it would be possible to reflect the comfort perceived by road users. Many authors have analyzed existing relations between *IRI* and vertical accelerations measured on driver and/or passenger seats, considering different types of vehicles and different velocities [17,20–22]. Most of these studies found a linear regression with R^2 values within the range from 0.76 to 0.99. Other indicators, like the Ride Number (*RN*) and the Michigan and Minnesota Ride Quality Index (*RQI*), have been developed through Mean Panel Rating (*MPR*) tests, in order to take into account road customers' opinions.

In the literature, to the best of our knowledge, no relationships or comparisons between the latter indices are present. In some studies, on the other hand, it is possible to find some relationships between each of the aforementioned ride quality indices and *IRI*. In particular, Sayers and Karamihas [2] found a relationship between *IRI* and Profile Index (*PI*), which is a parameter at the base of *RN* calculations, having an R^2 value of 0.82. In this case, the *IRI* range considered was from 0.5 to 7 m/km. A similar range was also considered in [23] where, in addition to the comparison between *IRI* and *PI* (R^2 variable 0.96–0.98), a direct relationship between *IRI* and *RN* (R^2 = 0.98) was provided, although related to a narrower range of *IRI* values (from 0.5 to 1.6 m/km).

In [24], relationships between Michigan *RQI* (RQI_{Mich}) and *IRI* for different types of pavement (i.e., flexible, rigid, composite) are depicted, although corresponding equations and R^2 values are not reported (but the result seems to be good). The calculation of the Minnesota *RQI* (RQI_{Mn}) is instead, as will be described in the following section, based on *IRI* values.

In this paper, a comparison of the *RN*, RQI_{Mich} and RQI_{Mn} was carried out, applying them to a set of 3905 samples of real road (asphalt pavement) profiles, having section lengths equal to 100 m. These indices were selected because they are based on *MPR* and the corresponding threshold values currently adopted in certain countries are available in literature. The final purpose is to compare the different ride quality thresholds defined for each method, also evaluating the existence of possible correlations between them. Furthermore, the capability of the ISO 2631 [19] approach as a road unevenness indicator was investigated, comparing the results with those obtained using the consolidated methods (*RN*, RQI_{Mich} and RQI_{Mn}). Finally, all the aforementioned approaches were compared with *IRI*, which is the most-used road roughness evaluation method worldwide, as stated in [25], where *IRI* specifications around the world are reported. In this way, this work intends to highlight the need of standardizing mean panel tests, adopting also homogeneous speed-related threshold values to be used for ride quality evaluation.

2. Ride Quality Evaluation Methods

Most of the ride quality indices taken into account in the present work are based on *MPR*. Each of them was developed by in-situ experiments, where different samples of drivers and road pavement sections were considered. The calculation of the above-mentioned indices for the road profile samples analyzed in the present work was performed as described in the following sections.

2.1. Ride Number (RN)—ASTM E 1489

The Ride Number (*RN*) is a mathematical processing of longitudinal profiles that allows the estimation of the subjective ride quality perceived by road users. The calculation is performed by means of the following Equations (1) and (2), reported in the ASTM E1489 standard [26] and developed by Karamihas and Sayers [27]:

$$RN = 5 \times e^{-160 \times (PI)} \tag{1}$$

where

$$PI = \sqrt{\frac{PI_L^2 + PI_R^2}{2}} \tag{2}$$

where PI_L and PI_R are the Profile Indices of the left and right wheel paths. They are the computed Root Mean Square (*RMS*) of the filtered slopes of the measured elevation profiles of the both wheel paths. The range of *RN* values is from 0 to 5.0, where an *RN* of 5.0 is considered to be a road inducing a perfect ride quality. With some exceptions, the wavelengths' range of interest for *RN* is similar to that of *IRI*, as reported in [2]. In particular, *RN* presents a higher sensitivity to low wavelengths than *IRI*, which has a greater sensitivity to wavelengths of 16 m or longer than *RN*.

2.2. Michigan Ride Quality Index (RQI*Mich*)

RQI_{Mich} is a roughness evaluation method developed by the Michigan Department of State Highways (Lansing, MI, USA) in order to predict users' opinions from road profiles [28]. The calculation is based on a research study where users' opinions were linked to wavelength content of the profile elevation Power Spectral Density (*PSD*) functions. In particular, three significant wavebands were identified: 0.61–1.52 m for the short waveband; 1.52–7.62 m for the medium waveband; and from 7.62 to 15.24 m for the long waveband. The variance in each waveband is calculated using a filter process. Finally, the Michigan *RQI* is calculated using the following Equation (3):

$$RQI_{\text{Mich}} = 3.077 \times \ln(VAR_1 \times 10^8) + 6.154 \times \ln(VAR_2 \times 10^8) + 9.231 \times \ln(VAR_3 \times 10^8) - 141.85 \tag{3}$$

where VAR_1, VAR_2 and VAR_3 are, respectively, the variances of the profile in the long, medium and short wavebands. As reported by Lee et al. [24], an RQI_{Mich} value between 0 and 30 indicates excellent ride quality, a value from 31 to 54 it indicates good ride quality, while values from 55 to 70 indicate fair ride quality. Pavements having RQI_{Mich} values greater than 70 are considered to have poor ride quality.

2.3. Minnesota Ride Quality Index (RQI*Mn*)

RQI_{Mn} is a roughness evaluation method developed by the Minnesota Department of Transportation (Mn/DOT, St. Paul, MN, USA) in order to take into account customer's opinion; correlating it with *IRI* values calculated for over 120 test sections as reported in the document "2015—Pavement Condition Annual Report" compiled by Mn/DOT [29]. As already stated, *IRI* is the roughness evaluation method that is most used worldwide, and the algorithm used for its calculation was developed by Sayers [30] and reported in ASTM E1926 [31]. Two different correlation equations were found, Equation (4) for bituminous pavements and Equation (5) for concrete pavements as specified in the document "An Overview of Mn/DOT's Pavement Condition Rating Procedures and Indices" [32]:

$$RQI_{\text{Mn,flexible}} = 5.697 - (2.104) \times \sqrt{IRI} \tag{4}$$

$$RQI_{\text{Mn,rigid}} = 6.634 - (2.813) \times \sqrt{IRI} \tag{5}$$

where *IRI* value is in (m/km). Considering the kind of road pavements analyzed in this work, only Equation (4), related to bituminous pavements, was taken into account. As for *RN*, the scaling rate range of RQI_{Mn} varies from 0 to 5.0, with the different ride quality categories specified in Table 1.

Table 1. Minnesota *RQI* categories and ranges.

Numerical Rating	Verbal Rating
4.1–5.0	Very Good
3.1–4.0	Good
2.1–3.0	Fair
1.1–2.0	Poor
0.0–1.0	Very Poor

2.4. Whole-body Vibration (a_{wz})—ISO 2631

An additional method that can be used for the evaluation of road customers' comfort is the process provided by ISO 2631 for comfort assessment in public transport. This method is based on the measurement of vertical acceleration inside road vehicles, which are used to determine *RMS* accelerations through the evaluation of *PSD* with regard to all 23 one-third-octave bands that represent the frequency range of interest for human response to vibrations (0.5–80 Hz) described in the ISO 2631 [19]. Once the *RMS* accelerations are known, it is possible to calculate the vertical weighted *RMS* acceleration (a_{wz}) using the following Equation (6):

$$a_{wz} = \sqrt{\sum_{i=1}^{23} \left(W_{k,i} \times a_{iz}^{RMS} \right)^2} \tag{6}$$

where $W_{k,i}$ are the frequency weightings in one-third-octave bands for seated positions, provided by the standard; and a_{iz} is the vertical *RMS* acceleration for the *i*-th one-third-octave band. Then, the calculated values can be compared with the threshold values proposed by ISO 2631 for public transport (Table 2), in order to identify the comfort level perceived by users in all roads sections.

The current standard does not contain clearly-defined vibration exposure limits between adjacent comfort levels, because many factors (e.g., user age, acoustic noise, temperature, etc.) combine to determine the degree to which discomfort will possibly be noted or tolerated. For this reason, the ISO standard provides several comfort levels introducing an overlapping zone between two adjacent levels. To determine the frequency-weighted vertical acceleration on users due to road roughness, several simulations were performed using the 8 degree of freedom (d.o.f.) full-car model developed by Cantisani and Loprencipe [18] and calibrated in order to represent the behavior of a common passenger car. In particular, a speed range from 30 to 130 km/h was considered in order to evaluate correlation trends between the a_{wz} and the other three aforementioned methods (*RN*, *RQI*$_{Mich}$ and *RQI*$_{Mn}$) as a function of the traveling velocity.

Table 2. Comfort levels related to a_{wz} threshold values as proposed by ISO 2631 for public transport.

a_{wz} Values (m/s^2)	Comfort Level
<0.315	Not uncomfortable
0.315–0.63	Little uncomfortable
0.5–1	Fairly uncomfortable
0.8–1.6	Uncomfortable
1.25–2.5	Very uncomfortable
>2.5	Extremely uncomfortable

3. Data Set of Road Profiles and Performed Comparative Analyses

3.1. Data Set of Road Profiles

A set of about 200 km of real road profiles, belonging to the Italian road network, was sampled with a spatial increment of 2.5 cm. For each lane, two paths (right and left) at the main rutting alignments were measured using a high-speed laser/inertial profilometer. Each profile path was divided into profile sections of 100 m, which is the most common length reference for road roughness evaluation (with regards to *IRI*) used in several countries, as reported by Múčka [25]. Thus, 1987 sections were taken into account. In order to characterize and classify the profile sample available, a preliminary analysis based on the ISO 8608 standard [33] was carried out. In particular, to classify road surface profiles according to the aforementioned standard, the *PSD* of elevations was calculated using Fast Fourier Transform (*FFT*) and the Hanning window. Then, the smoothing and fitting processes described in Loprencipe and Zoccali [34] were performed. As reported in Table 3, the real road profiles considered

in this study belong only to the following classes: A (very good), B (good), C (average) and D (poor); with a significant predominance of the second one (class B profiles).

Table 3. Percentage of real profiles belonging to a specific ISO 8608 class.

Class A (Very Good) (%)	Class B (Good) (%)	Class C (Average) (%)	Class D (Poor) (%)
18.1	57.9	22.6	1.4

3.2. Comparative Analyses and Thresholds Adopted

The comparison of the different approaches previously described, involved both the search for possible correlations between these indices and by evaluating their ability to assess each single profile in the same way. For this reason, a study about possible ride quality evaluation agreements provided by RN, RQI_{Mich} and RQI_{Mn} methods was also carried out. To perform this kind of analysis, it was decided to consider, for each index, four ride quality levels as defined in Table 4; comparing, then, the assessment provided by the various comfort indices for each available profile data.

The adopted thresholds described in Table 4 had already been reported in some documents for RQI_{Mich} limit values [24], RQI_{Mn} [31] and a_{wz} [18]. In contrast, for RN the division of the rating scale reported in [26] was performed in order to be consistent with the four ride quality levels considered.

Table 4. Ride quality thresholds considered for evaluation agreement analysis.

Ride Quality Level	RN	RQI_{Mich}	RQI_{Mn}	a_{wz} (m/s^2)
Very Good	4.1–5.0	0–30	4.1–5.0	<0.315
Good/Fair	3.1–4.0	31–54	3.1–4.0	0.315–0.565
Mediocre	2.1–3.0	55–70	2.1–3.0	0.565–0.9
Poor and Very Poor	0.0–2.0	>70	0.0–2.0	>0.9

The resulting percentage of agreement (*PoA*) between the two different methods was then calculated according to Equation (7):

$$PoA_{IJ} = \frac{N_{IJ,verygood} + N_{IJ,good} + N_{IJ,mediocre} + N_{IJ,poor}}{N_{tot}} \times 100 \tag{7}$$

where $N_{IJ,verygood}$, $N_{IJ,good}$, $N_{IJ,mediocre}$, and $N_{IJ,poor}$ are the number of profiles evaluated as providing, respectively, a very good, good, mediocre and poor ride quality level by both ride quality evaluation methods I and J ($I \neq J$). N_{tot} is the total number of examined road profile samples.

It is useful to remember that the ride quality level thresholds for RN, RQI_{Mich} and RQI_{Mn} are not speed-related. Although the limits provided by the ISO 2631 are the same, the a_{wz} value strongly depends, by means of the mechanical model used, on the velocity considered for its calculation.

In order to provide a more detailed analysis of the examined ride quality assessment approaches, these indices were also compared to *IRI*, which is the world's most popular road roughness evaluation method.

3.3. International Roughness Index (IRI) Thresholds

The IRI was elaborated from a World Bank study in the 1980s [30]. It is based on a mathematical model called quarter-car and was developed in order to assess not only the ride quality on road pavements, but also other detrimental effects, such as dynamic load increment (on both vehicle and pavement) due the presence of irregularities on road surfaces. The calculation is performed using

a model that calculates the simulated suspension motion on a profile and divides the sum by the distance traveled according to the Equation (8):

$$IRI = \frac{1}{l} \int_0^{l/v} \left| \dot{z}_s - \dot{z}_u \right| dt \tag{8}$$

where l is the length of the profile in km, v is the simulated speed equal to 80 km/h, $\dot{z}_s$ is the time derivative of vertical displacement of the sprung mass in m, and $\dot{z}_u$ is the time derivative of vertical displacement of the unsprung mass in m. The final value is expressed in slope units (e.g., m/km or mm/m). In the present work, the algorithm proposed by the ASTM E1926 standard [31] for *IRI* calculation was used.

As reported in [25], there is a high heterogeneity of *IRI* thresholds adopted around the world. In fact, *IRI* limit values mainly depends from several aspects: road surface type (i.e., asphalt or cement concrete pavements), road functional category, average annual daily traffic (*AADT*), legal speed limit and segment length considered for *IRI* calculation. In addition, they change depending on whether we talk about new, reconstructed or in-service roads. As already stated, the most common segment length indicated in non-US countries is equal to 100 m [25].

Between the different parameters affecting *IRI* specifications, surely the most important is the maximum traveling velocity allowed on the road, whose roughness level is meant to be assessed. For this reason, some authors [18,35] have proposed speed-related *IRI* thresholds to be used for the evaluation of ride quality. In particular, Yu et al. [35] defined five ride quality levels providing for each of them the corresponding limit values based on the jolt and jerk experienced by the raters within a speed range from 10 km/h to 120 km/h. They analyzed 102 longitudinal profiles with a length of 150 m collected in the Strategic Highway Research Program (*SHRP*) Long-Term Pavement Performance (*LTPP*). In Table 5, the suggested thresholds found in correspondence of some velocities are shown.

Table 5. IRI thresholds at different speeds suggested by Yu et al. [35].

Ride Quality Level	IRI Thresholds at Different Speeds (m/km)					
	20 km/h	**40 km/h**	**60 km/h**	**80 km/h**	**100 km/h**	**120 km/h**
Very Good	<5.72	<2.86	<1.90	<1.43	<1.14	<0.95
Good	5.72–8.99	2.86–4.49	1.90–2.99	1.43–2.24	1.14–1.79	0.95–1.49
Fair	9.00–11.39	4.50–5.69	3.00–3.79	2.25–2.84	1.80–2.27	1.50–1.89
Mediocre	11.40–16.16	5.70–8.08	3.80–5.40	2.85–4.05	2.28–3.24	1.90–2.70
Poor	>16.16	>8.08	>5.40	>4.05	>3.24	>2.70

Cantisani and Loprencipe [18] examined 124 *LTPP* profiles of 320 m, defining four ride quality levels and calculating the corresponding thresholds from the relation found between *IRI* and the vertical frequency-weighted acceleration (a_{wz}) at several speeds (from 30 to 90 km/h), by means of the 8 d.o.f. full-car model previously described in Section 2.4. As can be seen by comparing the *IRI* thresholds suggested in [18] (reported in Table 6) with the ones in Table 5, a generally good agreement between the two aforementioned studies can be found.

Table 6. IRI thresholds at different speeds suggested by Cantisani and Loprencipe [18].

Ride Quality Level	IRI Thresholds at Different Speeds (m/km)						
	30 km/h	**40 km/h**	**50 km/h**	**60 km/h**	**70 km/h**	**80 km/h**	**90 km/h**
Very Good	<4.17	<3.41	<2.98	<1.87	<1.60	<1.42	<1.15
Good/Fair	4.17–8.34	3.41–6.83	2.98–5.95	1.87–3.73	1.60–3.20	1.42–2.84	1.15–2.31
Mediocre	8.34–11.92	6.83–9.75	5.95–8.51	3.73–5.33	3.20–4.58	2.84–4.06	2.31–3.30
Poor	>11.92	>9.75	>8.51	>5.33	>4.58	>4.06	>3.30

The importance of considering appropriate speed-related *IRI* thresholds is also underlined by Múčka in [25], where a suggested relation for *IRI* threshold values as function of velocity limit is reported. In particular, Múčka did not suggest any specific *IRI* limit values, but he provided Equation (9) to be adopted:

$$IRI(v_2) = \left(\frac{v_1}{v_2}\right)^{0.5} \times IRI(v_1) \tag{9}$$

which is based on the assumption that the same level of vibration response can be achieved for two different speeds v_1 and v_2. Adopting the aforementioned equation would mean that the condition of the same quarter-car suspension relative velocity response for the two different speeds (v_1 and v_2) is met.

4. Results and Discussion

A preliminary study concerning the analysis of the *IRI* relation reported in Equation (9), which was introduced by Múčka [25], talking about international *IRI* specifications for new/reconstructed roads. Specifically, it was decided to compare the ratio between *IRI* thresholds at two adjacent velocities (e.g., *IRI*(30)/*IRI*(20) or *IRI*(80)/*IRI*(70)), calculated using Equation (9), and obtained by employing both the threshold values suggested by Yu et al. [35] and those suggested by Cantisani and Loprencipe [18] with regard to very good ride quality level. It can be supposed, in fact, that this ride quality level characterizes new or reconstructed roads. The results of the above-mentioned comparison are then depicted in Figure 1, where the results obtained by applying the procedure described by Cantisani and Loprencipe [18] to the real profile samples considered in the present work and taking into account a segment length of 100 m are also reported.
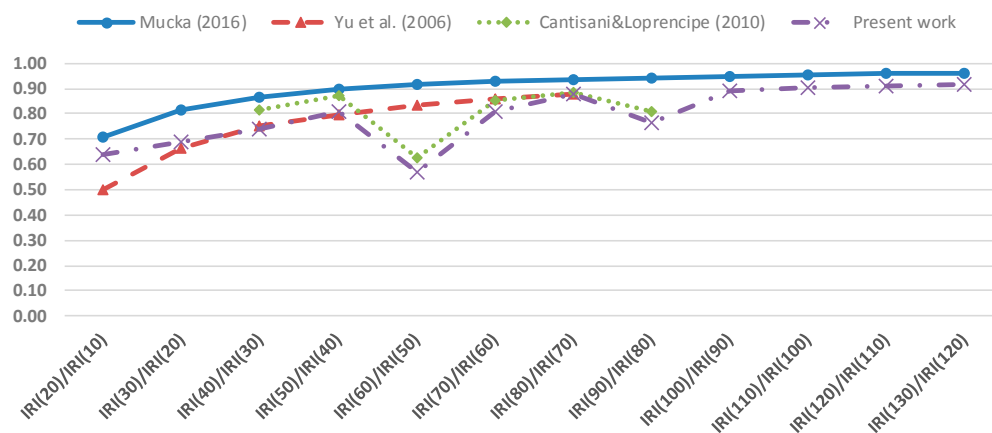

Figure 1. Ratio between *IRI* thresholds at different speeds provided by various studies.

As can be seen, similar trends are found for all of the examined studies and, in particular, values very close to the ones presented in [18] are found in the present work, where the same simulation model but different road profile samples were used. Furthermore, some anomalies in both of the latter approaches' trends can be noted to correspondend to the *IRI* thresholds ratio between speeds of 60 and 50 km/h, and between 90 and 80 km/h. This unexpected behavior was probably due to the mechanical parameters considered in the simulation model at these speeds (i.e., the mechanical properties were defined as a function of the traveling velocity).

Before proceeding with the analysis of the a_{wz} values at different speeds, a comparison between the results obtained for the other three users' comfort evaluation methods was performed. Because no indications were found about section length to be used for their calculation, it was decided to consider the same length of 100 m as commonly adopted for *IRI* calculation. In this way, all the wavelengths' contents of interest for the various examined ride quality methods are taken into account. In particular,

pretty good correlations between them were found, as can be seen in Figures 2–4 where R^2 values within 0.78–0.95 are shown. The highest R^2 value (0.95) was obtained for RQI_{Mich}-RN regression equation (Figure 2).
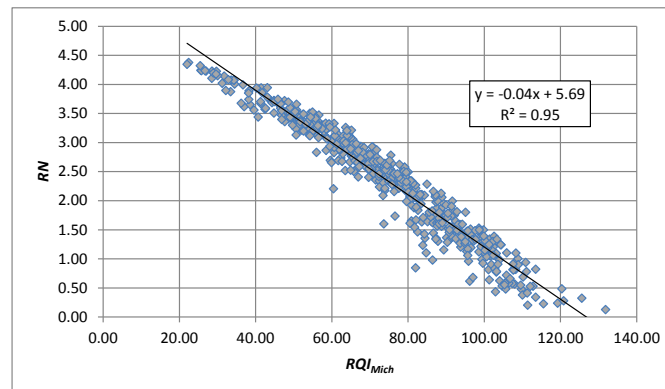

Figure 2. Correlation between RQI_{Mich} and RN.
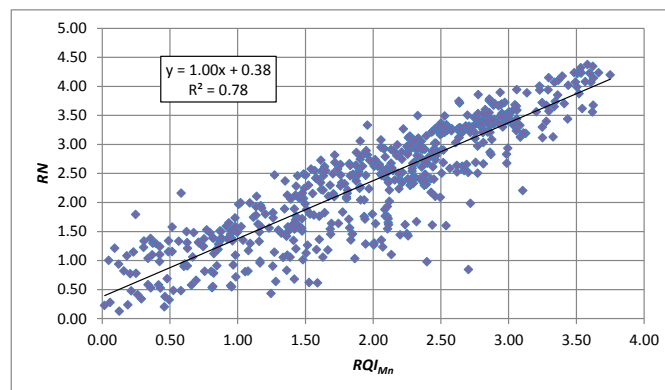

Figure 3. Correlation between RQI_{Mn} and RN.
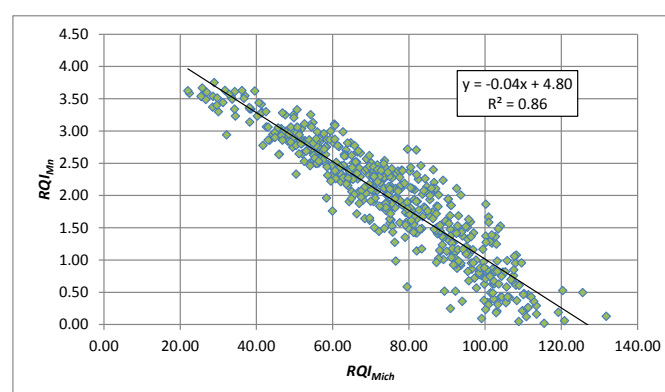

Figure 4. Correlation between RQI_{Mich} and RQI_{Mn}.

Although quite good correlations were found between these indices, each index presents a specific scale rating based on the performed panel rating tests, for which a standardization does not exist.

In fact, different distributions of the real profile samples among the four ride quality levels were obtained, based on the method that was being considered, as can be seen in Figure 5. Thus, the choice of road ride quality evaluation method meaningfully influences the maintenance actions planning.
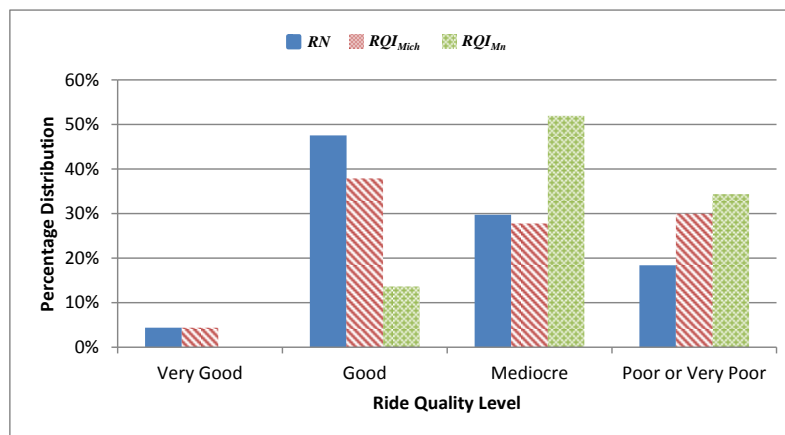
**Figure 5.** Ride Quality Level Percentage Distribution for the real profiles samples.

Counting the amount of profiles evaluated in the same way by the different indicators, a percentage of agreement (*PoA*, calculated according to Equation (7) for each pair of indices) greater than 60% was obtained just for RQI_{Mich} and RQI_{Mn} comparison (see Figure 6). The worst agreement, instead, was found between *RN* and RQI_{Mn}. This result could be expected by looking at Figure 3. In fact, both these indices have the same rating scale (from 0 to 5.0) and ride quality categories (see Table 4), but the linear regression equation found presents an intercept value equal to 0.38; which means that a switch between the rating scales of the two methods exists. In particular, the RQI_{Mn} provides a more severe evaluation of road profiles, as highlighted by the results shown in Figure 5.
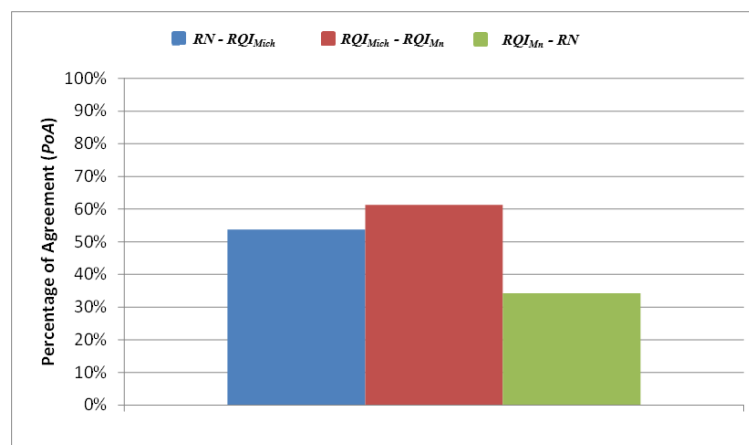
Figure 6. Percentage of agreement (*PoA*) between the three ride comfort evaluation methods.

As already stated in Section 2.4, the results obtained for *RN*, RQI_{Mich} and RQI_{Mn} were also compared with the vertical frequency-weighted acceleration a_{wz} calculated at several speeds (from 30 to 130 km/h). By analogy with the study of profile evaluation percentage agreement (*PoA*), calculated according to Equation (7), reported above, the same analysis was also carried out for the a_{wz} method, using the thresholds shown in Table 4, defined as the middle point of the overlapping zone provided by ISO 2631 for two adjacent comfort levels.

As can be seen in Figure 7, varying the traveling speed of the simulation vehicle, significant changes in the percentage agreement were found for all three methods with regards to a_{wz} index values.
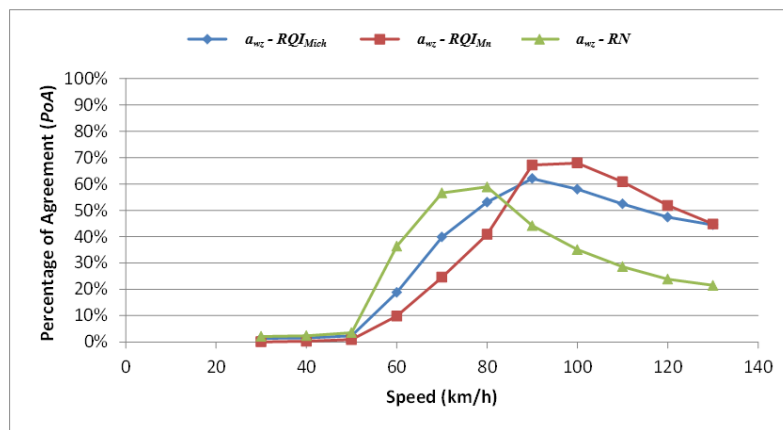
Figure 7. Percentage of agreement (*PoA*) between *RN*, RQI_{Mich} and RQI_{Mn} with ISO 2631 a_{wz}.

The highest values of the percentage agreement between a_{wz} and each of the other three ride quality evaluation methods were found to be within the range 55%–70%. Although these results are not too high, due to the fact that the panel rating tests have been performed using different vehicles, general considerations can be deduced. The best percentage agreement for the three ride quality evaluation methods, in fact, was found to correspond to different velocities. In particular, for *RN* it was found for a vehicle traveling at 80 km/h, while for RQI_{Mich} at 90 km/h. For RQI_{Mn}, the greatest percentage was found for simulation speeds equal to 100 km/h. These results could be an explanation of the different correlations found between the three indices (*RN*, RQI_{Mn} and RQI_{Mich}), which were in all cases lower than 65%. In fact, the ride quality thresholds of the aforementioned methods seem to be calibrated for different speeds of reference. A confirmation of the goodness of the results obtained can be found in the algorithm for the calculation of the *RN*, where a parameter similar to the velocity used in *IRI* calculation is set at 80 km/h, which is the value of the speed found for the maximum percentage agreement.

Looking at Figure 7, it can be noted that none of the three consolidated indices (*RN*, RQI_{Mich} and RQI_{Mn}) seem to be adequate for evaluating users' comfort on urban roads or, in general, on roads having maximum legal speed limits lower than 50 km/h.

In addition to the profile evaluation agreement study, the correlations between the three consolidated ride quality evaluation methods and a_{wz} were investigated. The R^2 values found in correspondence of the speeds at which the highest profile assessment agreements varies from 0.66 (*RN*-a_{wz}) to 0.75 (RQI_{Mn}-a_{wz}); as can be noted in Figures 8–10.
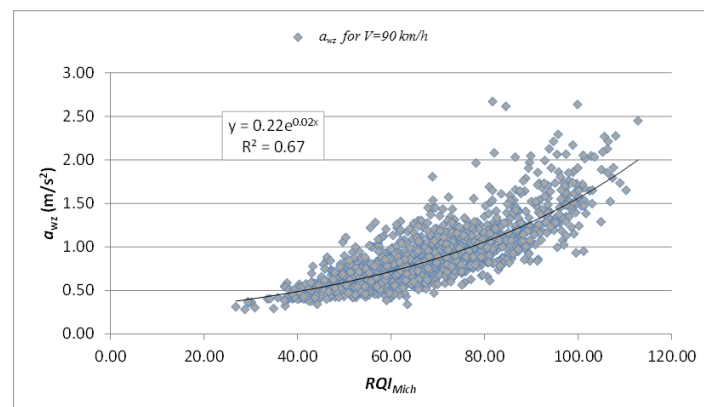
Figure 8. Correlation between RQI_{Mich} and a_{wz} at 90 km/h.
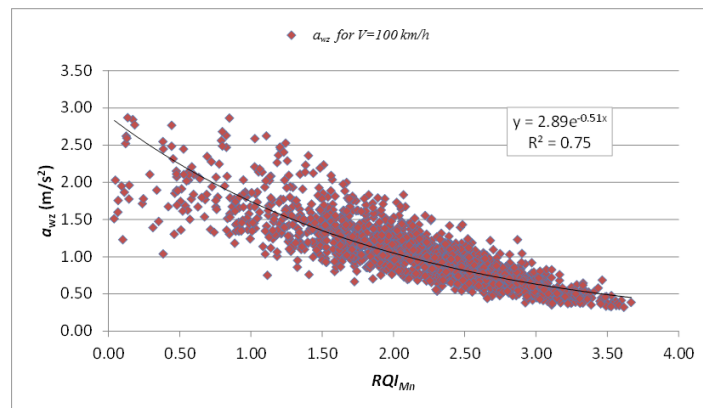
Figure 9. Correlation between RQI_{Mn} and a_{wz} at 100 km/h.
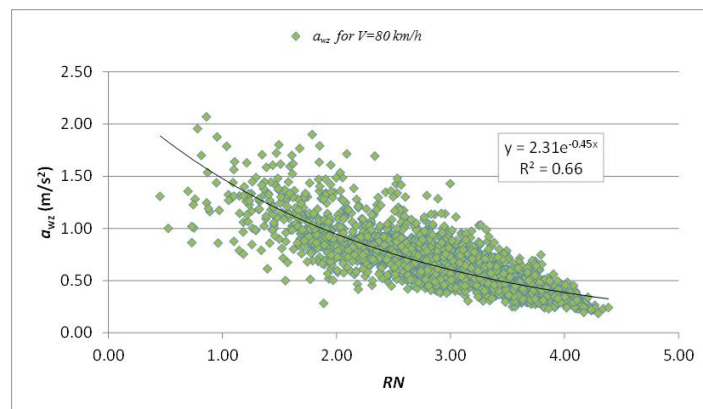

Figure 10. Correlation between RN and a_{wz} at 80 km/h.

Unlike for the other methods, the use of the a_{wz} allows the taking into account of the different users' perceptions of road conditions based on the traveling speed, as can be noted in Figure 11, where the distribution among the four ride quality levels of the real profiles set is reported for different velocities. To simplify the vision of the plot, not the whole range of speed considered (30–130 km/h), but just speeds within the range from 70 up to 110 km/h are represented. As can be seen, significant variation in ride quality judgement is obtained.
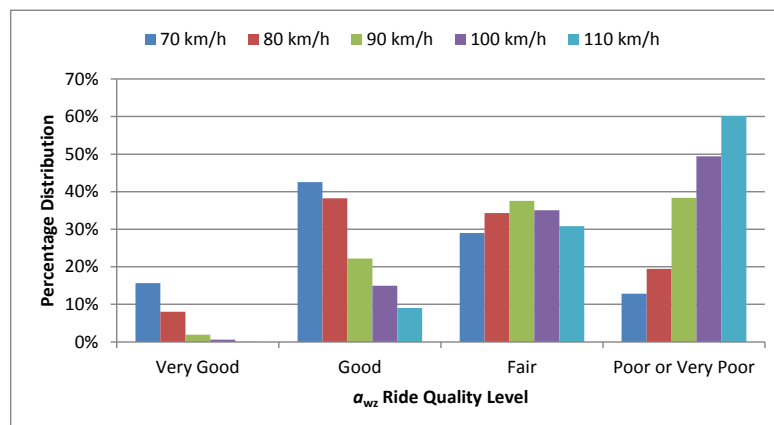

Figure 11. Ride quality level percentage distribution for the real profile samples calculating the a_{wz} at different speeds.

Evaluating the correlation between the various ride quality methods considered in this paper with *IRI*, R^2 values of 0.78 and 0.85 were found respectively, for *RN* (Figure 12) and RQI_{Mich} (Figure 13).
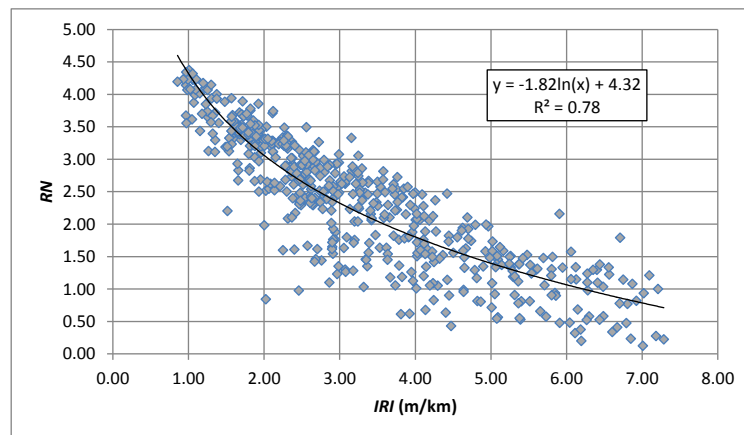

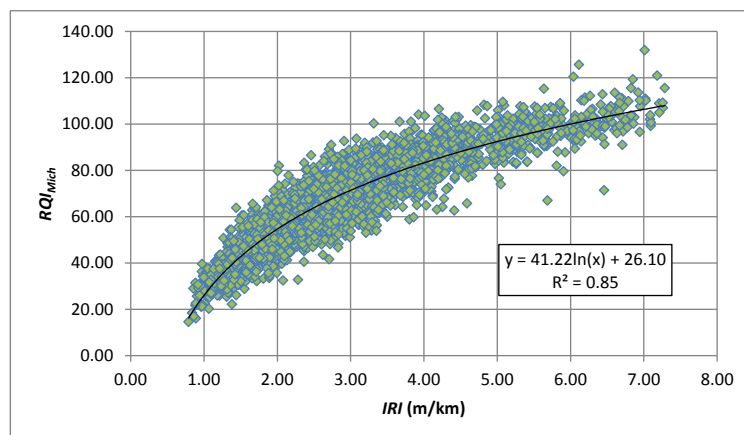**Figure 12.** Correlation between *RN* and *IRI*.

Figure 13. Correlation between RQI_{Mich} and *IRI*.

Obviously, a perfect correlation ($R^2 = 1$) was found between RQI_{Mn} and *IRI* (Figure 14), since the calculation of the first one is based on *IRI* values using Equation (4) previously described.
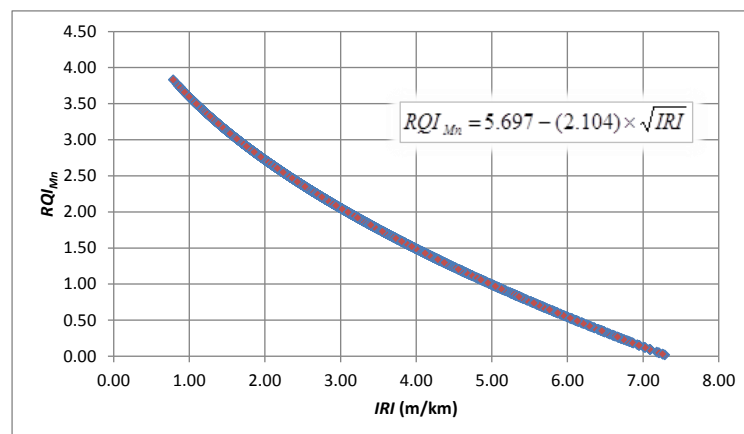

**Figure 14.** Correlation between RQI_{Mn} and *IRI*.

Starting from the regression equation found for each ride quality evaluation index and the thresholds reported in Table 4 for the different ride quality levels (very good, good, mediocre and poor), it is possible to determine the corresponding *IRI* limit values. The results are then reported in Table 7.

Table 7. *IRI* thresholds based on the different ride quality indices limit values in (m/km).

Ride Quality Level	*IRI* (*RN*)	*IRI* (*RQI*$_{\text{Mich}}$)	*IRI* (*RQI*$_{\text{Mn}}$)
Very Good	<1.13	<1.10	<0.58
Good/Fair	1.13–1.95	1.10–1.97	0.58–1.92
Mediocre	1.95–3.39	1.97–2.90	1.92–2.92
Poor and Very Poor	>3.39	>2.90	>2.92

As can be seen, looking at the thresholds related to the very good ride quality level the *RQI*$_{\text{Mn}}$ was confirmed to be the more conservative approach, while the *RN* represents a less conservative approach. Although there is not perfect matching between the *IRI* thresholds calculated from each method and the limit values suggested by Yu et al. [35] and/or Cantisani and Loprencipe [18] corresponding to all ride quality levels, it is nevertheless possible to note that all aforementioned ride quality evaluation methods were mainly developed to be used on roads characterized by speed limits within the range from 80 to 120 km/h.

Considering, then, the *IRI* specifications suggested by the two aforementioned studies, already reported in Tables 5 and 6, the percentage agreement in the evaluation of the examined real profile samples between *IRI* and a_{wz} approaches at various speeds was evaluated. As can be seen in Figure 15, in this case for all the considered velocities percentages greater than 50% were always found.
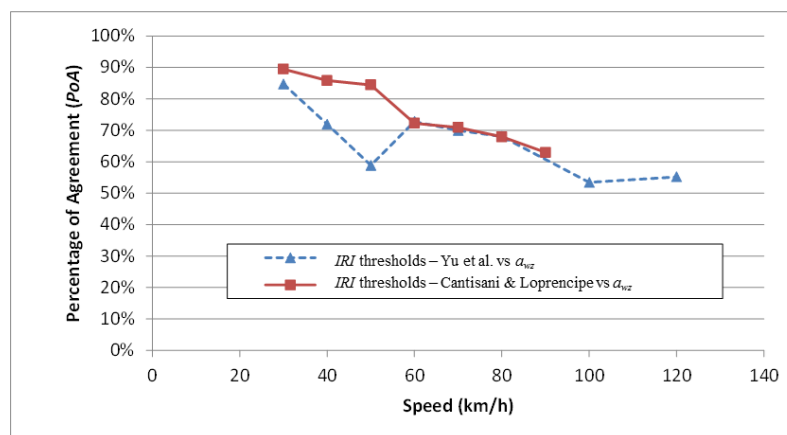
Figure 15. Percentage agreement between *IRI* thresholds suggested by Yu et al. [35] and Cantisani and Loprencipe [18] with ISO 2631 a_{wz}.

These results highlight the chance of using the a_{wz} approach for road ride quality evaluation for a wide range of traveling speeds as an alternative method to *IRI*, mainly for velocities lower than 50 km/h, where the percentage agreement is greater than 80%. Of course, the proposed approach will need calibration and validation phases in order to be correctly used; in fact, the a_{wz} is strongly affected by the type of vehicle considered for the measurement.

In addition, Kirbaş and Karaşahin [36] found a good correlation between a_{wz} and Pavement Condition Index (*PCI*). Therefore, using the a_{wz} approach at a preliminary step in order to locate priorities along road networks seems to be possible, although some distresses (e.g., crack distress) do not meaningfully affect this index. Once critical sections have been located, it would be then possible

to plan adequate inspections and surveys in order to understand the causes of the distresses, and then select the most appropriate maintenance actions.

All of the analyses related to the *IRI* method have also underlined the need to homogenize its threshold values by defining appropriate speed-related limits to be adopted by road agencies.

5. Conclusions

In this paper, the analysis of a set of real road profiles was carried out according to different ride quality evaluation methods, comparing then the assessment provided by each of them.

In particular, the agreement in the assessment of road profiles and their correlation was investigated. The main results can be summarized as follows:

- Although pretty good correlations (R^2 = 0.78–0.95) exist between the three consolidated ride quality evaluation methods (*RN*, RQI_{Mich} and RQI_{Mn}) taken into account in the present work, the assessment of the same examined road profile can significantly differ according to the approach used. In this sense, the need to standardize *MPR* in order to obtain homogeneity in ride quality evaluation is clear.
- The RQI_{Mn} was found to be the most conservative indicator; in fact, its scale rating seems to be calibrated for a speed greater than 80 km/h (around 100 km/h), as shown by the results obtained using a simulation model representative of the behavior of a typical passenger car. Similar results were found evaluating the relations and correlations between *RN*, RQI_{Mich} and RQI_{Mn} with *IRI* (R^2 respectively equal to 0.78, 0.85 and 1). Using the regression equations found *IRI* thresholds corresponding to each ride quality index limit values were calculated. This analysis confirmed that the RQI_{Mn} is the most conservative approach among the three ride quality assessment methods. It is also important to highlight that the RQI_{Mn} calculation is based on *IRI* values, which is the most-used road roughness index worldwide.
- None of the consolidated methods (*RN*, RQI_{Mich} and RQI_{Mn}) present thresholds appropriate for use on urban roads that have legal speed limits lower than 50 km/h. By contrast, some *IRI* specifications intended for use on urban roads have been adopted in some countries and more specific speed-related threshold values have been suggested in literature. Although much attention is paid to this aspect of the use of *IRI* for road roughness evaluation, there is still the need to homogenize the criteria and the values to be adopted for the various road categories.

Considering the last point, the use of the a_{wz} method seems to be a promising and valid alternative for the evaluation of ride quality, with particular attention to urban road networks, where the use of the common profilometers (both contact and no-contact types) presents some application limits. Furthermore, it is a speed-related approach, which means that road sections having different legal speed limits can be properly assessed. However, deeper studies on the influence of different types of road vehicle and of irregularities at different velocities should be carried out, together with panel rating tests, in order to define appropriate a_{wz} thresholds to be used for ride quality evaluation.

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Abbreviations

The following abbreviations are used in this manuscript:

a_{wz}	Frequency-weighted vertical acceleration
IRI	International Roughness Index
LTPP	Long-Term Pavement Performance
MPR	Mean Panel Rating

PCI	Pavement Condition Index
PI	Profile Index
PoA	Percentage of Agreement
PMS	Pavement Management System
PSD	Power Spectral Density
RMS	Root Mean Square
RN	Ride Number
RQI	Ride Quality Index
RQI_{Mich}	Michigan Ride Quality Index
RQI_{Mn}	Minnesota Ride Quality Index
SHRP	Strategic Highway Research Program

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