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Effects of Vehicular Speed on the Assessment of Pavement Road Roughness

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Featured Application: In many roads, the level of discomfort perceived by users as a result of surface roughness is not adequate. The works to restore acceptable comfort conditions would often require large investments. In this study, a method to define a speed acceptable to users in relation to the deterioration conditions found for the pavements is proposed.

Abstract: Good ride quality is a fundamental requirement for all road networks in modern countries. For this purpose, it is essential to monitor and evaluate the effect of irregularities on road pavement surfaces. In the last few decades, many roughness indices have been proposed, with the aim to represent shortly the pavement surface characteristics and the relative performances, using a single number and a correspondent scale of values. In this work, a comparison between three different evaluation methods (International Roughness Index, ISO 8608 road profile classification and frequency-weighted vertical acceleration a_{wz} according to ISO 2631) was carried out, applying these methods to some real road profiles. The similarities and differences between the obtained results are described, evaluating the effect of the road characteristic speed on the roughness thresholds. In fact, the specific aim of the analyses is to underline the need to use different thresholds depending on the speed at which the vehicular traffic can travel on the road sections. In this way, it will be possible to identify appropriate thresholds for the various types of roads, having for each of them a specific range of design or operating speed.

Keywords: pavement roughness; assessment methods; threshold limit; vehicular speed

1. Introduction

Good ride quality on road networks is required in all modern countries. In order to achieve this outcome, large amounts of synthetic indices have been proposed by researchers during last few decades, with the aim to represent roads geometric characteristics and effects on vehicles (consumption and wear), passengers (comfort and safety), and pavement (dynamic loads increment). Among these, the most popular and widely used one is the International Roughness Index (IRI), proposed by Sayers [1,2], which is a measure of the effects induced by road pavement irregularities on a conventional vehicular suspension. This index is calculated considering a simulated passenger car (also known as "golden car") travelling at 80 km/h.

Many authors, like Kropáč and Múčka [3,4], have studied mutual relationships between IRI and other similar indices (e.g., Three Band Indicators), with particular attention to unevenness index (C) and waviness (w) defined in the ISO 8608 standard [5], where a road surface profiles classification is provided. These studies are focused on the use of artificial profiles, which can be used to evaluate many specific issues, like, for example, the influence of different wavelength contribution on the various examined indices. The use of artificial profiles also allows having the full control over their characteristics (e.g., roughness level, profile length) [6–8]. Besides, to validate the models, a huge number of samples are necessary, which generally are not always obtainable from real surveys that require, furthermore, considerable costs and time. Thus, starting from the equation provided by ISO 8608 for fitted Power Spectral Density (PSD) calculation, it is possible to generate random road profile belonging to the desired ISO class, through the implementation of various methods. Among them, two of the most commonly adopted ones are the so-called shaping filter and the sinusoidal approximation, described by Feng et al. [9]. Many studies are based on the use of these theoretical road profiles in order to evaluate, for example, dynamic loads on road pavements due to the roughness [10–12] or to calculate the transfer function needed to estimate road roughness using vehicle acceleration measurements [13].

Other authors also have underlined the need to consider indices different from IRI, in particular for the assessment of roads having maximum legal speed limits lower than 80 km/h, for which the use of IRI is not fully appropriate. To overcome this problem, Loizos and Plati [14] suggested a new index, named Vehicle Response Index (VRI), which is based on the PSD of profile slope and on the response gain of a quarter-car model to road input. In this way, it is possible to take into account both pavement surface characteristics and vehicle parameters in the ride quality evaluation; also being able to assess the effects on the vehicle running at different speeds.

In order to correspond to these needs, other methods have been proposed in the literature. For example, Yu et al. [15] developed a speed-related ride quality IRI thresholds, while other authors, like Ahlin and Granlund [16] and Cantisani and Loprencipe [17], focused their works on the relation between road roughness and human whole-body vibration (WBV), calculated starting on the vertical accelerations recorded in a vehicle riding on a rough pavement. The last approach gives to road agencies the opportunity to assess comfort level perceived by road users, evaluating the possibility to reduce speed limits or taking suitable actions in order to improve road features. Furthermore, this approach allows estimating the speed at which users can travel along a road section while suffering a tolerable level of discomfort. In other words, it can be possible to assess the velocity reduction needed in order to maintain the comfort and quality of travel considering actual road pavement conditions.

It has to be underlined that real road profiles are quite different from the artificial ones because, in the first ones, generally, not all the harmonic components appear along the entire length of the pavement. Furthermore, the equation describing the theoretical road profiles, also used for the ISO 8608 classification, is a consequence of a smoothing and fitting process.

In this paper, some real profiles belonging to Italian road network, having an overall length of about 200 km, are analyzed according to the technical standards. The general aim is to highlight the mutual relationships between ISO 8608 classification and vertical accelerations transmitted to road users, evaluated as specified by ISO 2631 [18]. The obtained results are also compared with IRI values. Special attention is then paid to the importance of the assessment of the proper speed at which road users will probably decide to travel on a specific ISO class pavement profile, by estimating the comfort level perceived by a passenger on a car. Thus, the opportunity of using a driving comfort indicator as the main index for road roughness evaluation is described.

2. Materials and Methods

The present work focuses on the analysis of real road profiles measured on four different roads (Table 1) having legal speed limit between 60 and 90 km/h. For every lane, two paths (right and left) at the main rutting alignments were measured using high-speed profilometer. Each profile was divided into sections of 320 m and pre-processed as specified in the draft European standard prEN 13036-5:2006 [19], applying a band-pass filter (cut frequencies 0.02–2 cycles/m) and re-sampling them using a step length dx = 0.05 m. While lengths of road sections less than 320 m are frequently used, in this study this length value was considered in order to have homogeneous comparisons with previous studies.

Table 1. Length of examined roads and number of sections.

Road	Total Length (km)	Number of Sections (320 m Length)
01	28.8	90
02	42.8	134
03	66.2	207
04	60.8	190
Total	**198.6**	**621**

Then, for the two paths over each section (right and left), IRI, road profile classification (according to ISO 8608) and the frequency-weighted vertical acceleration on users' body of a passenger car were calculated, as described in the following sections.

2.1. International Roughness Index (IRI)—ASTM E 1926

The IRI was proposed in consequence of a World Bank study in the 1980s [1] with the objective to harmonize pavement roughness data coming from different Countries. It is based on a mathematical model called quarter-car and developed in order to assess the effects of roughness on maintenance and pavement design. A mathematical model, calculating the simulated motion on a profile and dividing the sum by the distance traveled according to the following Equation (1), performs the evaluation:

$$\mathrm{IRI} = \frac{1}{l}\int_0^{l/v} \left|\dot{z_s} - \dot{z_u}\right| dt \quad (1)$$

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 IRI is expressed in slope units (e.g., m/km or mm/m).

In this study, the IRI calculation for the examined pavement sections reported in Table 1 was performed by means of a specific Matlab code, in which the algorithm proposed by ASTM E1926 standard [20] was implemented. For each section the IRI value was calculated as the average of the two profiles (left and right) using Equation (2):

$$\mathrm{IRI} = \frac{\mathrm{IRI}_{left} + \mathrm{IRI}_{right}}{2} \quad (2)$$

It has to be considered that the use of IRI index for the road unevenness evaluation, linking it to the comfort levels induced on road users, sometimes can lead to incorrect and not accurate results because in the IRI calculation the contribution provided by some excitation frequencies is underestimated or even not considered. Thus, it can happen that two pavements profiles having the same IRI value can induced completely different acceleration levels [17].

For this reason, in order to analyze the whole characteristic frequency range of pavements, the use of other assessment methods seems to be advisable. At any rate, in the next subsections, in the same road pavement sections where the IRI calculus was performed, also other roughness evaluations were presented with the aim to investigate the combined effect of the completely characteristic frequency range of pavements and the speed.

2.2. Road Surface Profiles Classification—ISO 8608

To evaluate the road surface profiles classification according to ISO 8608 standard, the Power Spectral Density (PSD) was calculated using Welch periodogram, which is a method used for the estimation of the power of a spectral signal, based on the use of the Fast Fourier Transform (FFT). The two steps that characterize this method consist in splitting up the signal into overlapping segments and, then, windowing them with an appropriate window function. In the performed analysis, the Hanning window and an overlapping zone equal to 50% were used. Then, the smoothing process described in the ISO 8608 standard was performed.

Finally, through the implementation of a Matlab code, the fitted PSD was evaluated by means of the general formula Equation (3):

$$G_d(n) = G_d(n_0)\left(\frac{n}{n_0}\right)^{-w} \quad (3)$$

where G_d. is the displacement PSD [m^3], $n_0 = 0.1$ cycles/m is the reference spatial frequency and "w" is the exponent of the fitted PSD, also known as waviness (Figure 1).

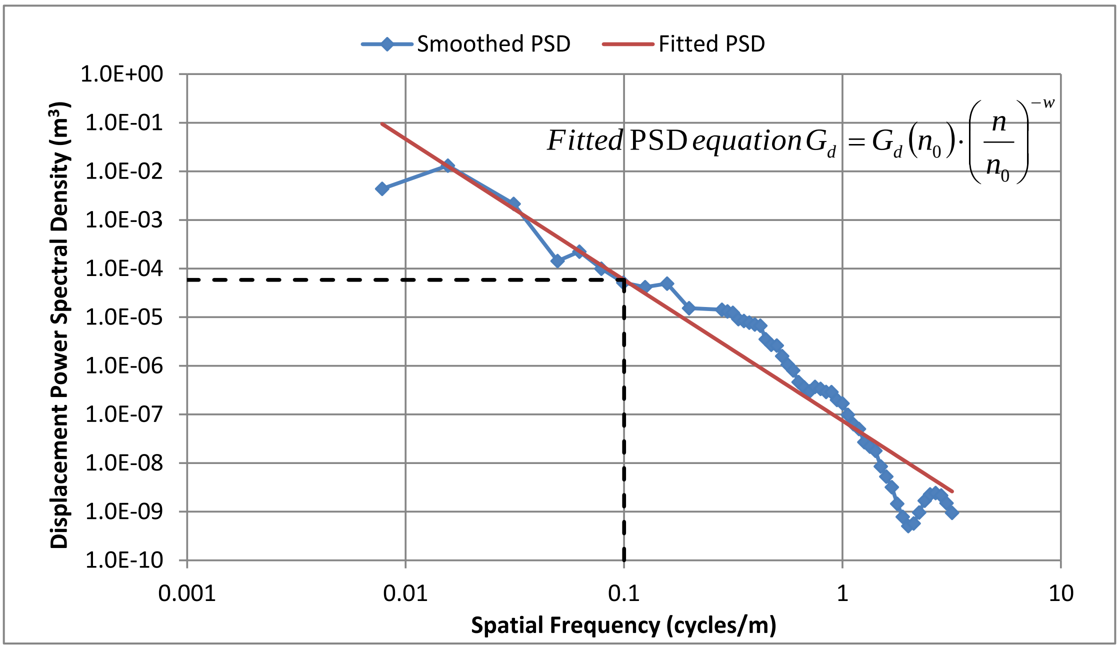


Figure 1. Smoothed and Fitted Power Spectral Density (PSD) according to ISO 8608.

As stated by Kropáč and Múčka [21], recent road network extensive measurements, performed in some countries like Sweden [22], have revealed that for most of the roads waviness values vary between 1.5 and 3.5 with a mean value close to 2.5. Considering all the measured path of 320 m (both left and right), it was found that, for the examined profiles, the mean value of the exponent w is 3.16.

As specified by Múčka and Granlund [23], the two parameters that define the fitted PSD, $G_d(n_0)$. and w, are independent and in particular, the second one provides information about the wavelength distribution in the spatial frequency range of interest. In fact, values greater than 2 mean that long waves are prevalent, while if the waviness (w) value is lower than 2, the short wavelengths are predominant.

Based on the values of the $G_d(n_0)$. parameter, as found for all the examined profiles, they were classified as belonging to one of the classes (from A to H) provided by ISO 8608.

Usually, paved road profiles hardly belong to class worse than D because road agencies set intervention thresholds (using specific ride quality index like IRI) above which optimal conditions are restored. For this reason, the ISO classes that in general should be taken into account are the first four. As is going to be shown in detail in the next section, the real roads profiles analyzed in this study belong to class A (*very good*), B (*good*), C (*average*) and D (*poor*).

The classification proposed by ISO 8608 presents critical aspects because it does not take into account the speed at which vehicles travel on the road. Thus, it does not properly consider the different vibration levels affecting road users at different speeds, while this fact influences drivers ride quality perception. This aspect can be faced by evaluating pavement performances related to comfort levels, through both measurements inside vehicles or using simulation models. In this way a global assessment of the vertical acceleration induced on road users, due to the presence of irregularities on the pavement surface, can be provided. One of the available simulation models is going to be described in the next section.

2.3. Whole-Body Vibration—ISO 2631

To determine the frequency-weighted vertical acceleration on users due to road roughness, several simulations were performed using the 8 d.o.f. full-car model (Figure 2) developed by Cantisani and Loprencipe [24,25] and calibrated in order to represent the behavior of a common passengers car [26].

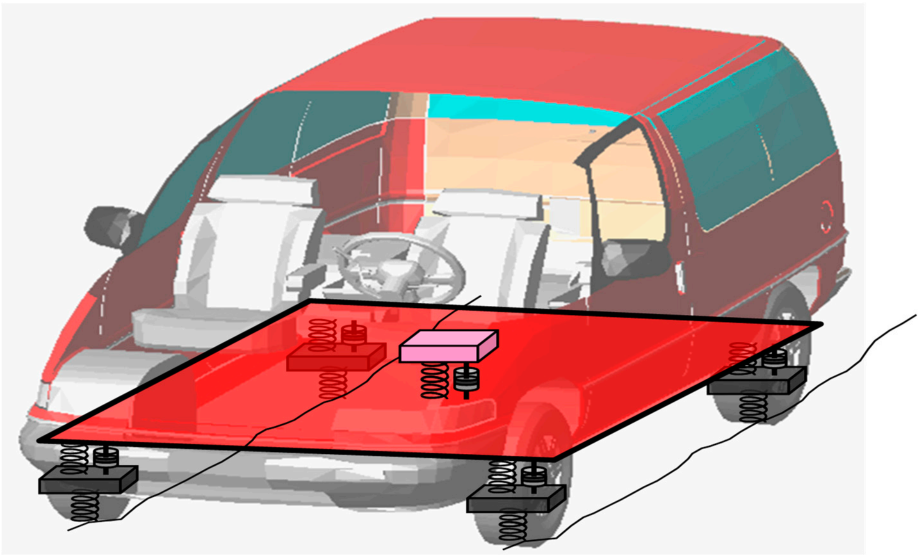


Figure 2. Scheme of the full-car 8 d.o.f.

Starting from the vertical accelerations in the time domain, calculated by this model, it is possible to determine the root mean square (RMS) accelerations through the evaluation of the PSD for all the frequency range of interest for the human response to vibrations (between 0.5–80 Hz), analyzed by a spectrum of 23 one-third octaves bands. This procedure, in fact, is specified by the technical standards currently in use.

Once the RMS accelerations are known, it is possible to calculate the vertical weighted RMS acceleration (a_{wz}) using Equation (4):

$$a_{wz} = \sqrt{\sum_{i=1}^{23} \left(W_{k,i} \cdot a_{iz}\right)^2} \quad (4)$$

where $W_{k,i}$. are the frequency weightings in one-third octaves bands for the seated position, provided by the standards and a_{iz} is the vertical r.m.s. 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, also considering several speeds of transit.

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

a_{wz} Values	Comfort Level
less than 0.315 m/s^2	not uncomfortable
0.315–0.63 m/s^2	a little uncomfortable
0.5–1 m/s^2	fairly uncomfortable
0.8–1.6 m/s^2	uncomfortable
1.25–2.5 m/s^2	very uncomfortable
greater than 2 m/s^2	extremely uncomfortable

The current standards do not clearly define vibration exposure limits between adjacent comfort levels because many factors (e.g., user age, acoustic noise, temperature, etc.) contribute 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 ones. In any case, the RMS value of the frequency-weighted vertical acceleration in the vehicle may be compared with the values in Table 2, giving approximate indications of likely reactions to various magnitudes of overall vibration total values in public transport.

In order to define specific limits to be used by road agencies, it is necessary to link a_{wz} values to IRI ones as proposed by Cantisani and Loprencipe [17]. In this way, it is possible to relate comfort perception (also influenced by vehicle characteristics) with a parameter that represents the condition and performance of road pavements surfaces.

3. Results and Discussions

3.1. Road Pavements Evaluation Methods Comparison

The first step of the analysis concerns the study of the correspondence of the results provided by all the three methods previously described (IRI by ASTM E1926, PSD by ISO 8608 and a_{wz} by ISO 2631).

In order to compare the results obtained using the different pavement assessment methods, four different ride quality levels were defined, identifying specific threshold limits for each index.

The IRI thresholds taken in account were the limit values proposed by Yu et al. [15] for speed equal to 80 km/h; which is also the speed at which the vertical weighted acceleration (named $a_{wz,80}$) was calculated for this comparison. These IRI thresholds are very close to those proposed for the same speed by Cantisani e Loprencipe [17]. The choice of this speed is based on the velocity range characterizing the examined roads (i.e., 60–90 km/h) and on the fact that IRI is frequently used for the evaluation of roads having legal speed limit equal or higher than 80 km/h.

In Table 3 it can be noted that, in order to compensate the absence of specific limitations between the comfort levels provided by ISO 2631, it was chosen to consider the mean value of each overlapping zone as the limit between two adjacent comfort levels (for example 0.565 is the mean of 0.63 and 0.5 m/s^2).

Finally, for the ISO 8608 approach the ride quality levels correspond to the road profiles classes defined in the same standard, as shown in Table 3.

A first comparison between the abovementioned pavement evaluation methods concerns the analysis of the percentage distribution of all the analyzed pavement sections (621) among the four ride quality levels defined in Table 3. The results are shown in Figure 3, where it can be noted that except for the ride quality level "*Very Good*" there is a significant variability in the assessment of the pavement sections. For example, the percentage of sections judged as "*Poor*" varies from 3% to 27% depending on the evaluation method used. Similar differences can be also observed for the other classes "*Good/Fair*" and "*Mediocre*".

Table 3. Pavement ride quality comparison using International Roughness Index (IRI), a_{wz} and ISO 8608 roads profiles classification.

Ride Quality	IRI Thresholds (80 km/h) [15,17]	ISO 2631 Comfort Levels [18]	a_{wz} Thresholds (m/s^2)	ISO 8608 Class [5]	G_d (n_0) (10^{-6} m^3)
Very good	<1.43	Comfortable	<0.315	A	<32
Good/Fair	1.43–2.84	Little comfortable	0.315–0.565	B	32–128
Mediocre	2.84–4.05	Fairly uncomfortable	0.565–0.90	C	128–512
Poor	>4.05	Uncomfortable (Very and Extremely)	>0.90	D	512–2048

Figure 3. Ride quality percentage distribution for the 621 real road sections.

In particular it can be seen that adopting IRI or ISO 8608 approaches more than 50% of the total sections belongs to "*Very Good*" and "*Good/Fair*" classes, while using the $a_{wz,80}$ index as the evaluation method more than 60% of the sections are rated as "*Mediocre*" and "*Poor*".

This great variability found in terms of profile classes distribution highlights how the choice of the evaluation criterion is very important and significantly affects the road maintenance plan.

The main differences found between the three assessment methods depend on the contribution provided by each kind of discontinuity to the global comfort level perceived by users. In particular, in ISO 8608 classification, there is not an evaluation of the various wavelengths contribution to the vibration level perceived by users. IRI, instead, was developed with the aim to represent the effects of roughness related to both drivers comfort and forces transmitted from wheels to road pavements. In IRI calculation, however, mechanical parameters that do not represent real vehicles are used. On the contrary, the introduction of frequency weighting coefficients in the calculation of the a_{wz} index reflects the perception of vibration by human beings.

Furthermore, the presence of punctual discontinuities along each pavement profile affects in a different way the correspondent value of the three indices. In particular, the IRI is designed for the assessment of distributed irregularities, while it is not suitable to properly evaluate punctual ones. In the calculation of the other two indices, which are both based on the use of the Fast Fourier Transform, the presence of this kind of discontinuities affects the trend and the magnitude of the Power Spectral Density.

Regarding the classification method provided by ISO 8608, it is necessary to specify that the straight line fit (in bilogarithmic plane, see Figure 1) suggested in the standard, does not always provide a good representation of the longitudinal PSD of real road profiles. For this reason, other fitting approximations (like two-and three-wave bands) have been proposed in literature [27].

The ISO 8608 classification is based only on geometrical characteristics of the road profiles. For this reason, it is interesting to evaluate IRI and a_{wz} values dispersion for each of the four analysed classes. Thus, starting from the ISO classes which the 200 km of measured profiles belong to (class A to class D), IRI and $a_{wz,80}$ normal distributions were calculated for each of them and reported in Figures 4 and 5. As it is possible to note in both above-mentioned figures, moving to worst profiles classes, the probability density curve assumes wider shapes and various overlapping zones can be observed. This means that considering, for example, two profiles having similar IRI values, the use of the ISO 8608 approach can lead to define them as belonging to different ISO classes.

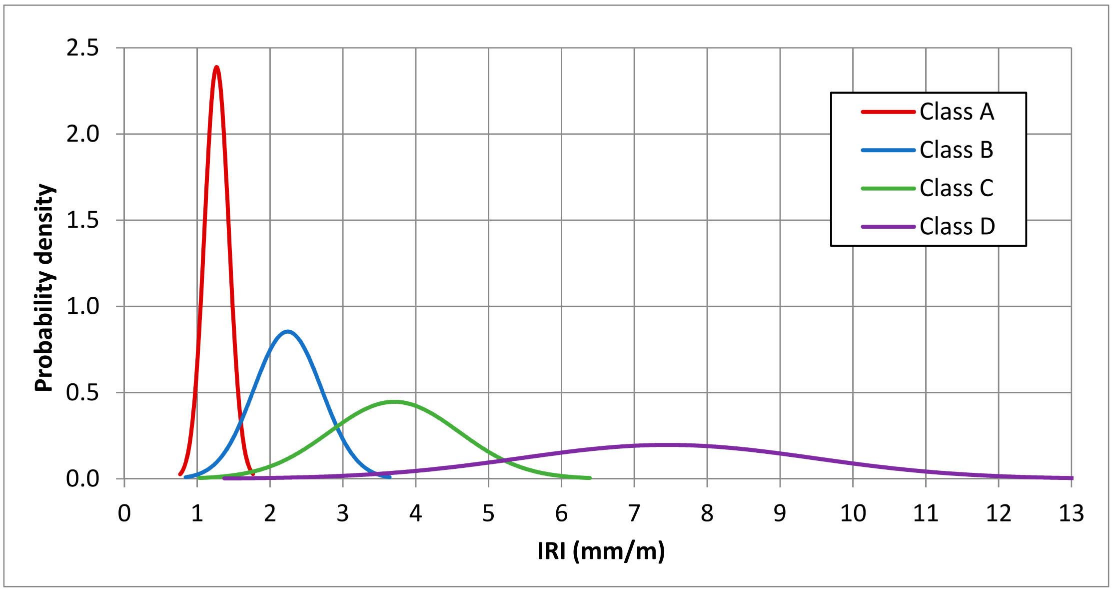


Figure 4. International Roughness Index (IRI) distribution for ISO class A–D (examined pavement sections).

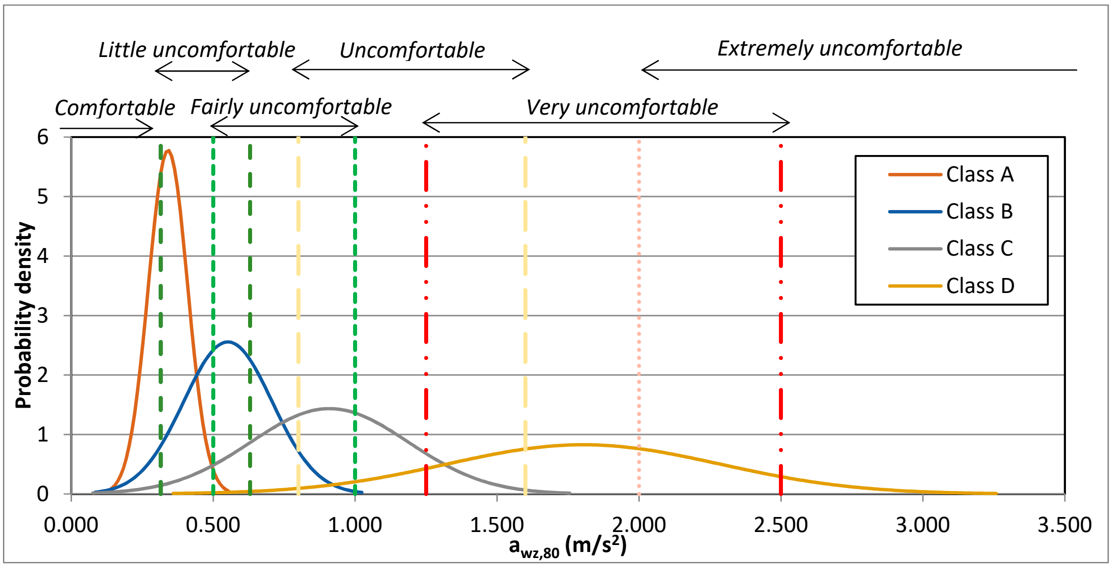


Figure 5. $a_{wz,80}$ distribution for ISO class A–D at V = 80 km/h.

3.2. Analysis of Speed Influence

As stated before, the $a_{wz,80}$ distribution reported in Figure 5 was calculated for a traveling speed equal to 80 km/h, which is the fixed velocity considered for the IRI quarter-car model. Assessing the ride quality using the ISO 2631 approach calculated by means of a full car simulation model, it is possible to evaluate the effects of different speeds on the comfort perceived by road users. Then, analyzing the vertical weighted acceleration a_{wz} within the speed range characterizing the examined roads (i.e., 60–90 km/h), it was possible to study the ride quality as a function of the velocity parameter. This type of analysis can be useful to assess the possible effect of roads unevenness on traffic flows also identifying the most critical sections. As it is shown in Figure 6 when vehicles travel at lower speeds the number of sections judged as belonging to "*Very Good*" and "*Good*" ride quality levels increases. In particular, compared to the results obtained with the maximum legal speed allowed for the examined roads (i.e., 90 km/h) a consistent reduction of perceived poor sections was obtained just traveling at 80 km/h (a speed very close to the maximum allowed for this kind of road). This speed could be reasonably accepted considering the actual speed diagrams that can be obtained for the analyzed roads as a function of their geometric and technical characteristics.

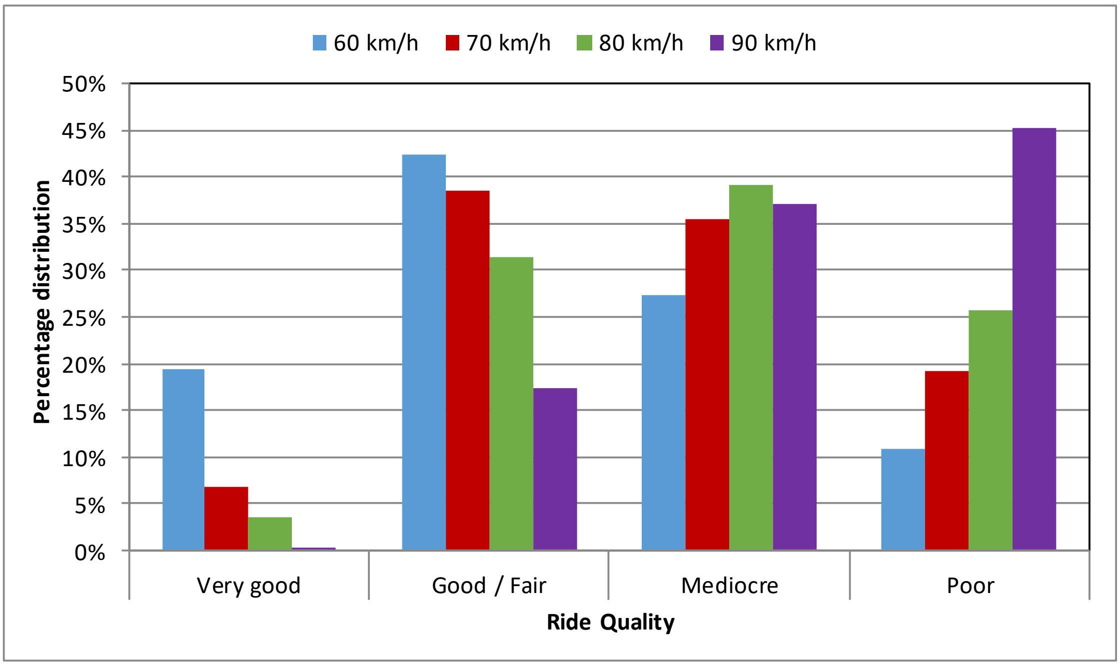


Figure 6. Ride quality percentage distribution for $a_{wz,V}$ index at several speeds.

As expected, for speeds below 80 km/h (i.e., 60 and 70 km/h), there is an increase in the percentage of sections falling in the categories of good ride quality (*Very Good* and *Good/Fair*) and a decrease in the categories of poor ride quality (*Mediocre* and *Poor*). On the contrary, the results obtained at a speed of 90 km/h decrease in the percentage of sections in the categories of good and mediocre ride quality (*Very Good*, *Good/Fair*, and *Mediocre*) and an increase in the category of *Poor* ride quality were found.

The trend described above confirmed what could be expected. Considering this result, it was decided to calculate a_{wz} values for the sections belonging to classes C and D for a speed range of 40–90 km/h. It was found that, in order to achieve an adequate comfort level for passenger car users (see Figures 7 and 8), vehicles should transit at speed between:

- 50–60 km/h along class C sections;
- 40–50 km/h along class D sections (speed lower than along sections belonging to class C).

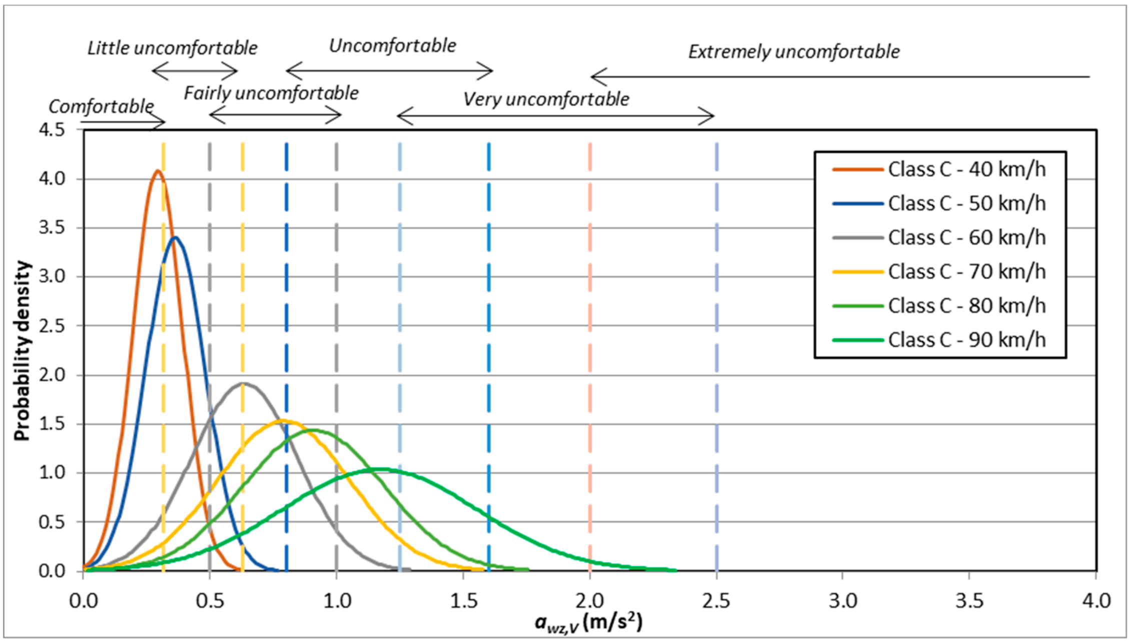


Figure 7. $a_{wz,V}$ distributions for class C road sections considering several speeds.

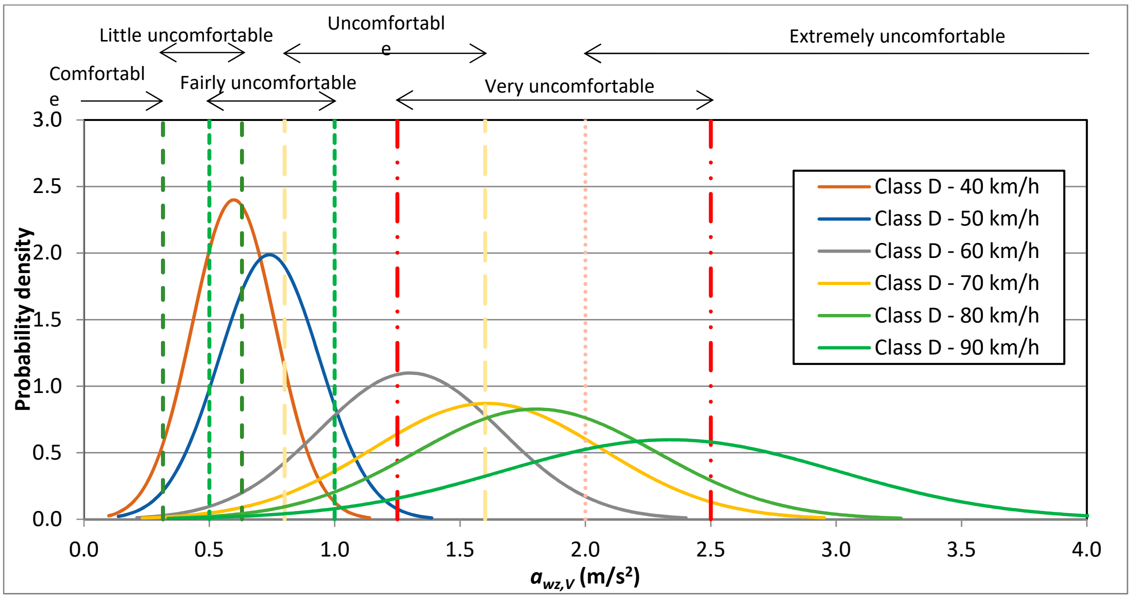


Figure 8. $a_{wz,V}$ distributions for class D road sections considering several speeds.

With regard to these results, it is reasonable to assume that road users, travelling on the last mentioned two ISO classes sections, will decrease vehicle speed not only as a consequence of the desired level of comfort, but also to avoid possible damages to the vehicles mechanical components. In fact, considering fixed road surface profile and vehicle mechanical characteristics, the vertical acceleration magnitude becomes lower if the traveling speed decreases.

This fact underlines the chance of accepting these ride quality classes in case of roads having very low legal speed limits, like urban roads, while for another kind of roads, like those examined in this research, the speed transit for class C and D profiles cannot be tolerable.

Most of the Pavement Management Systems are based on IRI that is calculated at fixed speed (i.e., 80 km/h) and, as already stated before, such index is usually used to evaluate roughness on different road categories (e.g., highways, primary, local) characterized by different speed ranges.

Comparing IRI values with the a_{wz} ones calculated at different speeds falling within the speed range of the examined roads (i.e., 60–90 km/h), it was observed how sections with similar IRI values can induce different acceleration levels on road users, as can be noted in Figure 9. This aspect remarks the difficulties of IRI index to capture the road users' perception of the irregularities present along the road as it is significantly affected by the traveling speed that works as a filter (together with vehicles mechanical parameters) applied to the wavelength content of longitudinal road profiles.

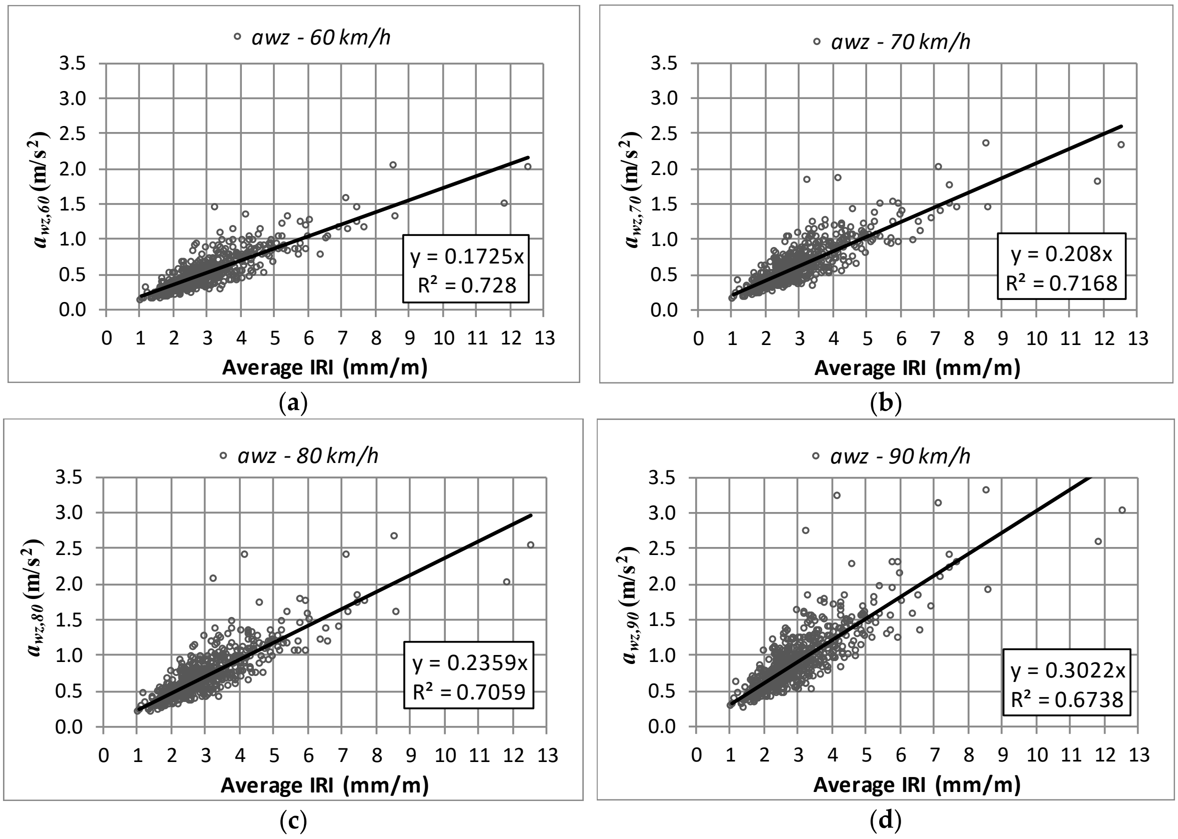


Figure 9. Linear regression $a_{wz,V}$–IRI for different speed: (**a**) V = 60 km/h, (**b**) V = 70 km/h, (**c**) V = 80 km/h, and (**d**) V = 90 km/h.

In addition, IRI cannot properly capture the presence of punctual discontinuities that can induce a considerable discomfort to road users.

Applying linear regression to the examined data, slope values very close to the ones found by Cantisani and Loprencipe [17] were obtained and reported in Table 4. This result seems important, considering that the profiles sample analyzed in this research is particularly representative because it belongs to real roads. The similarity of the slopes obtained by the linear regression underlines the possibility of using the speed-related IRI limits proposed in the last-mentioned paper, in order to relate IRI values to the level of comfort perceived by users.

Table 4. Linear regression $a_{wz,V}$–IRI for different speed: slope comparison.

	Slope–V = 60 km/h	Slope–V = 70 km/h	Slope–V = 80 km/h	Slope–V = 90 km/h
Cantisani & Loprencipe [17]	0.169	0.200	0.220	0.270
Present work	0.172	0.208	0.235	0.302

As previously explained, in this research sections with a length of 320 m were considered to make comparisons with homogeneous data compared to previous studies. In fact, for the evaluation of road roughness pavements, lengths of less than 320 m are generally used (over the World, a length of 100 m is adopted [28]) to better highlight the presence of punctual irregularities in the road section.

On the other hand, the main benefit of finding and using IRI thresholds consists in the fact that many road agencies commonly use profilometers that can be used for IRI calculation. On the contrary, adequate instruments to measure accelerations levels inside road vehicles are not actually common, and above all, there are no regulations for the pre-and post-processing of acquired data.

However, in the opinion of the authors, the best approach to the problem would be to directly use the measurements of the acceleration levels as, through this method, it is possible to obtain additional information about ride quality and the effects of road condition on the driving speed.

3.3. Estimation of Road Users Running Speed

Using the approach described in ISO 2631, it is possible to estimate for each road section the speed values according to which the road users may accept a particular level of discomfort due to road roughness.

In this sense, the first step should consist in defining the target comfort level but this activity presents certain difficulties since it depends on several aspects as also confirmed by the overlapping zones between adjacent levels provided in ISO 2631 standard. For these reasons, it was decided to consider for this analysis, two different target comfort levels:

- *Fairly uncomfortable* or better (a_{wz} < 1 m/s^2);
- *Little uncomfortable* or better (a_{wz} < 0.63 m/s^2)

Considering for example the 190 sections of Road 04, the maximum speed values for which the perceived comfort level is equal or better to the target comfort level defined above were determined for all the sections adopting the procedure described in Figure 10. The results are reported in Figure 11.

Once the estimated road users speed is calculated along the whole road for each of the two comfort levels, the results can be compared with the design speed to found the sections where the unevenness level does not allow running at speeds compatible with the specific speed range of the examined road.

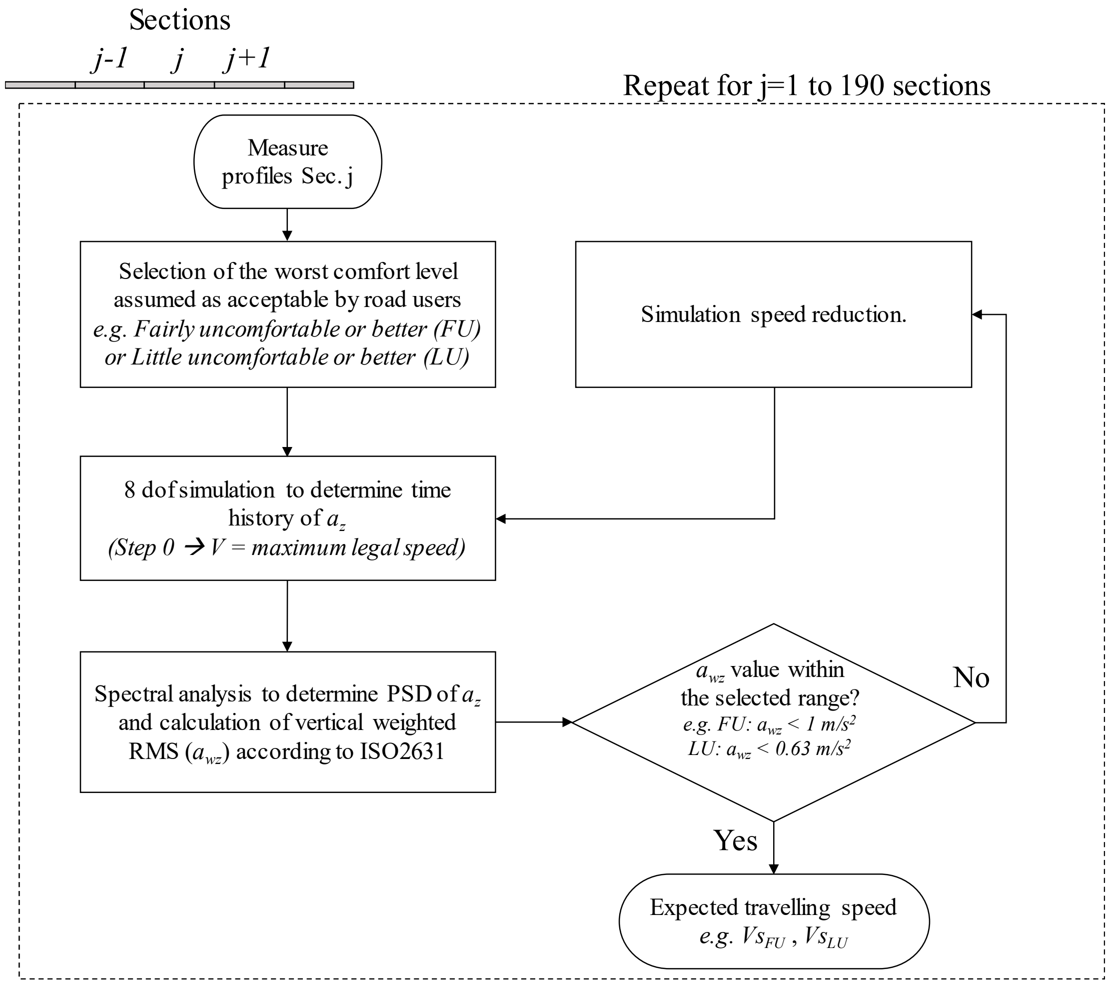
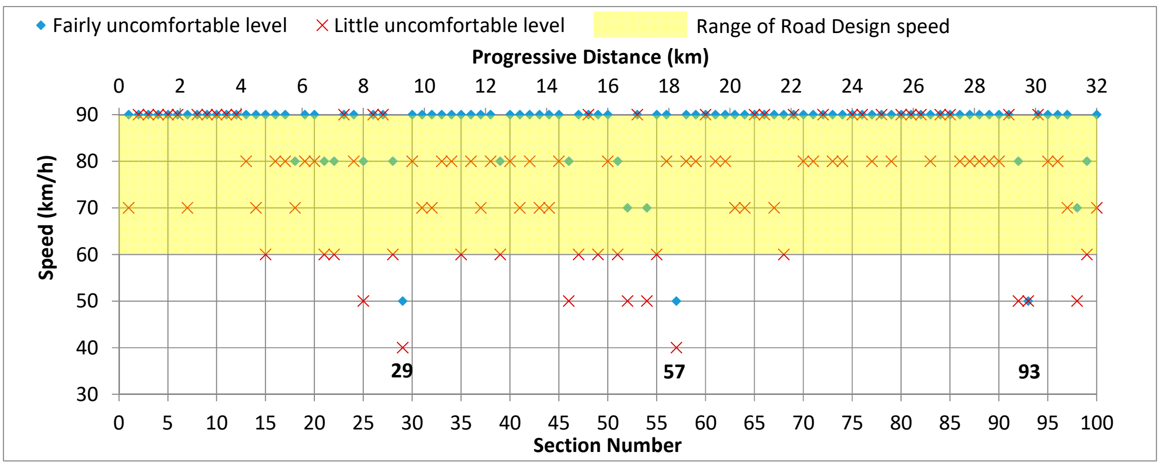
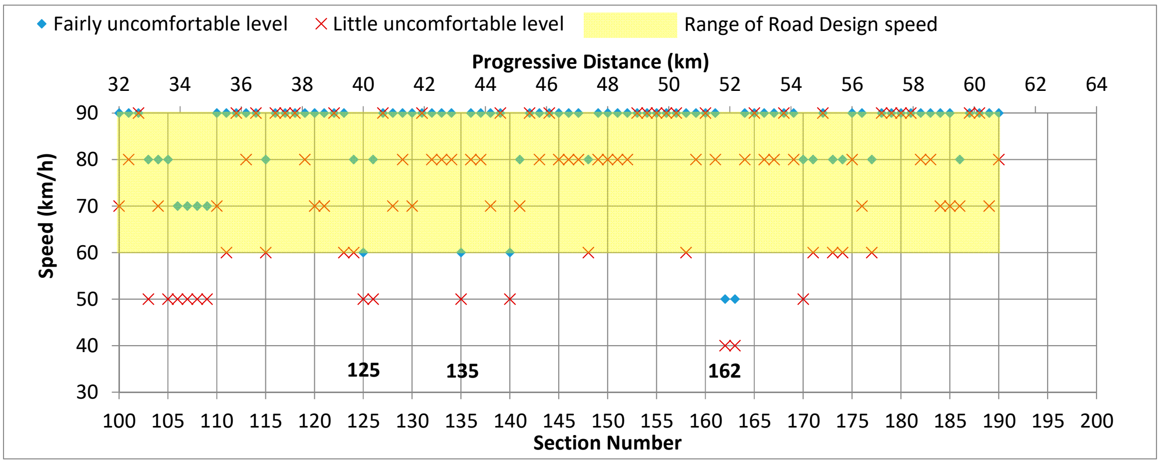


Figure 10. Methodology adopted to estimate traveling speed.



(a)

Figure 11. *Cont.*



(**b**)

Figure 11. Speed values for fairly and little uncomfortable level perceived by road users (**a**) for the road sections of Road 04 from 1 to 100; (**b**) for the road sections of Road 04 from 100 to 190.

Analyzing the graphs in Figure 11, the sections that are expected to be run at speed lower than the minimum value of the design speed interval of the examined road (equal to 60 km/h) can be located. Furthermore, it is possible to compare the speeds of adjacent sections, assessing if the transition between them is adequate and acceptable in terms of safety and performance criteria.

In this way, road agencies can properly locate the priority needs, also evaluating the overall level of service (LOS) through a comparison with the geometric characteristics of the road.

The results obtained with the aforementioned approach were then compared with the ones obtained for the same sections using the IRI approach. In particular, the comparison concerns the application to Road 04 of the speed-related thresholds found for IRI and the traveling speed estimated considering the a_{wz} method. Thus, the speed obtained (with an approximation of 10 km/h) considering a "*Fairly uncomfortable*" level (or better: $a_{wz} < 1$ m/s^2) for each section of Road 04 and the corresponding IRI values are reported in Figure 12. In the same figure, the IRI threshold between *Fair* and *Mediocre* ride quality (IRI = 2.31–3.30 mm/m) proposed by Cantisani and Loprencipe [17] or Yu et al. [15] (these limits are very close) for a maximum value of design speed is also reported.

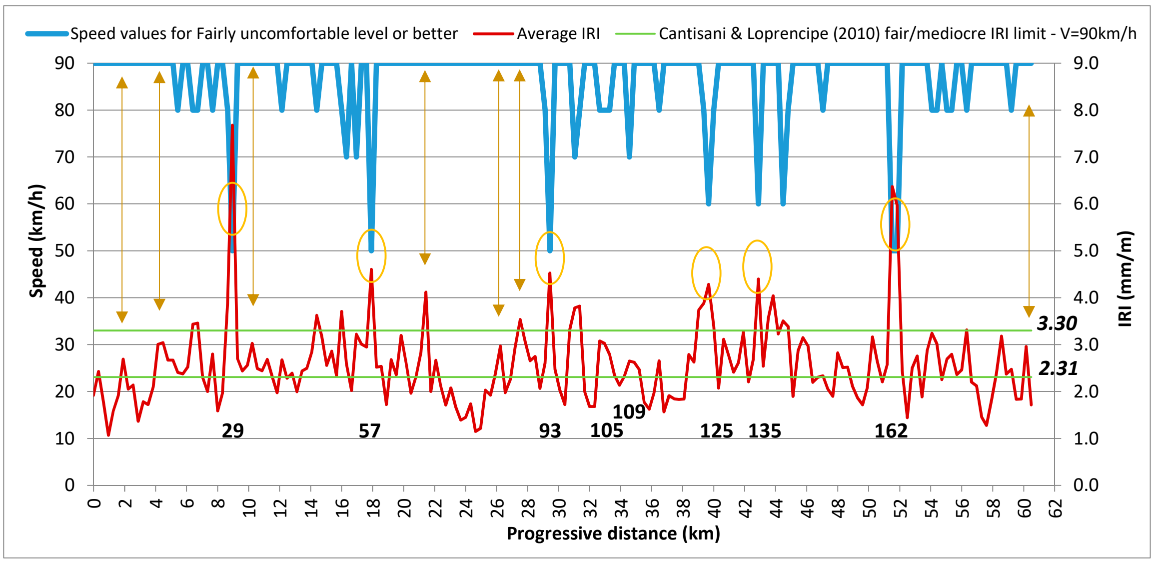


Figure 12. IRI thresholds and speed values comparison for *Fairly uncomfortable* level (IRI = 2.31–3.30 mm/m) for Road 04.

The indications provided by IRI threshold seems, in general, to be in agreement with the ones provided by the speed diagram (for *Fairly uncomfortable* level or better, see Figure 12) but, for some sections, they can induce the road agencies to intervene while speed and users comfort could still be acceptable. This circumstance should be considered also because, in general, this kind of choices is influenced by financial constraints and availability of resources.

In these sections (highlighted with arrows), there is no correspondence in the diagram between the exceeding of the proposed IRI threshold and the occurrence of a speed reduction to guarantee an acceptable level of comfort. For these cases, we can consider that the linear regression between values of a_{wz} and IRI is not able to fully explain the phenomenon or the different value of reference speed, affected by the adopted approximation of 10 km/h, does not allow to appreciate the required speed reduction.

In other sections, where the exceeding of thresholds is more evident, the proposed methodology rightly proposes very large speed reductions to guarantee the expected level of comfort.

In addition, it is possible to note that for these most critical sections in Road 04 (see Table 5), the measures required to reduce discomfort level is similar for sections having quite different IRI values (e.g., Section 29 and Section 57). On the other hand, the results in terms of maximum allowable speed capable to grant a certain comfort level can be different even for sections having very close IRI values, like sections 57, 93, 125, and 135.

Table 5. Results in some critical sections in Road 04.

Section Number	IRI (mm/m)	Max Speed for Fairly Uncomfortable Level (km/h)	Max Speed for Little Uncomfortable Level (km/h)
29	7.67	50	40
57	4.60	50	40
93	4.53	50	50
125	4.28	60	50
135	4.39	60	50
162	6.36	50	40

Besides, considering sections 105 and 109 (in Figure 12), which apparently present very good IRI values (both lower than 3 mm/m, respectively 2.79 and 2.65 mm/m), the speed diagrams show that for *Fairly uncomfortable* level, both sections can be traveled at speeds within the design speed range characterizing the examined road. However, if a better comfort level is desired (*Little uncomfortable*), the speed should be lower than the minimum value (60 km/h), precisely equal to 50 km/h (see Figure 11), and this condition could not be accepted. In particular, this can be a sign that a significant degradation in the next future can be expected to happen on these sections before than on others. Such indications would be very useful to develop a proper maintenance plan.

As already stated before, it is important to highlight that vertical weighted accelerations on road users can provide more information to road agencies. In fact, in addition, to assess road roughness on pavements surface, also relating it to the comfort levels, road agencies can evaluate the possibility to impose a decrease of the allowed speed in order to have an acceptable ride quality until the optimal road conditions will be restored.

Finally, a general overview of the advantages and disadvantages for each of the three methods (ISO 8608 classification, IRI, a_{wz}) considered in this work is reported in Table 6.

Table 6. Comparison between ISO 8608, IRI and ISO 2631 evaluation profiles methods.

Method	Usable in All Road Categories	Thresholds Independent by Speed	Calculation Not Influenced by Profile or Section Length	Consolidated Index for Pavement Management	Computational Ease	Comfort Assessment
ISO 8608	**	*	**	**	**	*
IRI	*	*	*	***	***	**
ISO 2631	***	***	***	*	*	***

* Poor ** Average *** Good.

4. Conclusions and Future Developments

A correct and timely identification of the road pavements conditions and performances is fundamental in order to allow road agencies to draw up an appropriate maintenance plan, according to their financial resources and to road user performance requirements [29–32].

In this paper, a total of about 200 km of real road profiles, belonging to four different Italian roads, were analyzed comparing the results obtained using various indices: International Roughness Index, ISO 8608 road profile classification, ISO 2631 vertical frequency-weighted vertical acceleration on users a_{wz}.

The obtained results, especially referring to Figures 7 and 8, highlight the need of transit at very low speed (<50 km/h) on pavement belonging to road profile class C (mediocre) and D (poor), which can only be generally accepted in the case of urban roads.

As underlined by other authors, like Yu et al. [15] and Cantisani and Loprencipe [17], for the analysis of roads with speed limit lower than 90 km/h it is necessary to use additional indices or to find adequate speed-related IRI thresholds that consider comfort level exposure of road users. In this sense, the a_{wz} index seems to be an appropriate tool for the assessment of the ride quality. In fact, the measure of the acceleration levels inside road vehicles provides a direct evaluation of the driver's comfort and of the effects on users due to the presence of irregularities on the pavement surface. Furthermore, implementing an adequate peak detection algorithm, the measured vertical acceleration signal can be used to locate and assess the magnitude of punctual irregularities, along with the longitudinal profile.

In this paper, it was shown that using a 8 d.o.f. model, representative of a common passenger car, it is possible to estimate the probable speed trend along a road. In this way, it is easy to identify the critical sections that may affect the traffic flow density, requiring then a priority level that should be considered in the road improvement intervention plan to be developed by road agencies.

All the analyses were performed considering only a specific vehicle type. It will be therefore advantageous to consider, in the future, other vehicle categories whose transit is permitted on the examined roads, in order to obtain a complete analysis of the road pavement performances. In this way, it will be possible to find the most critical type of vehicle and the correspondent traveling speed, then evaluating the possible effects on the Level of Service (LOS) of an examined road.

Further and more detailed indications could be obtained collecting road geometry data and comparing the estimated traveling speed with the speed diagram of the specific examined road.

In addition to the described procedure based on the use of simulation models that can be easily implemented upon measurement of the road longitudinal profiles, the ISO 2631 approach could be applied to accelerations registration carried out inside real vehicles in order to gather data on the effective behavior of road users. Such application would also reduce road-monitoring costs.

Other future applications could also concern the crowdsourced data collection and/or the real-time data procession, which may give to users the chance to set navigation tools to search for the most comfortable path and to provide to road agencies a continuous monitoring of roads.

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