

Ride Quality Measurement and User Ratings: Results from Main Field Trials

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Abstract

Improved techniques for assessing ride quality have been developed by the authors that more closely simulate the responses of humans to whole-body vibration and vehicle ride dynamics across a broad range of vehicle classes. The new ride model aims to address some fundamental issues related to road unevenness measurements which frequently do not correlate well with subjective ratings of pavement rideability. Field trials were conducted to test the models on a total of twenty-one pavement sections covering a wide range of roughness levels. Nine vehicles were used in the main trials, two from each of four vehicle classes (motorcycles, cars, SUVs and trucks) and an extra car, and a further two cars were added from an earlier pilot trial. In total, ten test subjects were recruited with a range of driving backgrounds, each driving one of the test vehicles. The modelled ride responses were compared with measured ride vibration and user ride ratings, all were taken on the same pavement test sections. Portable vibration measuring equipment was used to record ride vibration comprising accelerometers and a data logger and incorporating GPS. Subjective ratings of ride vibration on each pavement section were obtained from test subjects during the conduct of tests.

Introduction

Traditional mechanical response-type road roughness measuring systems, and road profile measuring systems that either simulate response-type systems or characterise some geometric aspects of a profile, only provide indirect indications of pavement ride quality. Generally, these measures of pavement rideability have been established through correlation studies. Furthermore, as the unevenness measurements have traditionally been taken in passenger cars and correlated through studies with subjective highway-user ratings (Al-Omari and Darter, 1994), ride quality indicators would only apply to the same specific class of vehicle used in those studies. Consequently, when considered across a broad range of vehicle classes and road users, current road roughness measurements frequently do not correlate well with subjective ratings of pavement rideability.

Improved techniques for assessing ride quality have been developed by the authors that more closely simulate actual vehicle ride dynamics and the responses of humans to whole-body vibration (Prem and Ayton, 2005). These models attempt to address the fundamental issues outlined above leading to more accurate and robust estimates of pavement rideability.

Initial field trials using a single passenger car to test the proposed ride quality model were performed and reported in a previous paper (Prem, Tu and Ayton, 2008).

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That study found there was good agreement between the modelled responses, vibration measurements and drivers' subjective ratings.

This paper describes a much larger field trial aimed at further testing the models across a much broader and more challenging set of conditions. A total of twenty-one pavement sections (both flexible and rigid) covering a wide range of roughness levels and characteristics were considered³. The flexible sections outnumbered the rigid sections merely because within the geographic area of the trials there were insufficient sections of rigid pavement with roughness levels high enough to cover the desired range. Also, for safety reasons, it was desirable to carry out the bulk of the testing on lightly trafficked roads, but rigid pavements were not available on those routes. Notwithstanding, it could be argued that the outcomes have greater significance for concrete pavements than flexible pavements because, given the material properties of concrete together with the typical construction practices (at construction joints, for example) and the relative difficulty of correcting a poor ride profile, it is important for concrete paving teams to have assessment models which enable early corrective action to their paving processes.

Road profile measurements on each test section, which form an essential input to the modelled ride responses, were taken with a high-speed inertial laser profiler. In addition to traditional analysis of the road profiles used in the study with the International Roughness Index (IRI), spectral analysis was also performed and revealed more clearly the nature of the unevenness characteristics of the roads – contrasting examples are given in this paper. Nine vehicles were used, two from each of four vehicle classes (motorcycles, cars, SUVs and trucks) and an extra car. A further two cars were added from the trials conducted in the lead-up preliminary trials to the main trials. The vehicles represent a wide range of characteristics across different road users groups. In total, ten test subjects were recruited with a range of driving backgrounds, each operating one of the test vehicles.

To assess the effectiveness of the model as a ride quality predictor, the overall modelled ride responses were compared with actual measured ride vibration (objective measures), and user ride ratings (subjective measures). All measurements were taken on the same twenty-one sections of pavements.

For the objective measures of ride quality portable vibration measuring equipment comprising accelerometers and a data logger were used to record ride vibration. GPS tracking was incorporated in the system to provide precise time-based recordings of location and speed, and to automatically synchronise data logging (start/stop) to each test section. Further, additional software features allow the vibration recordings to be overlaid on standard terrain mapping software providing novel and potentially useful methods of linking harsh vibration events to specific sections of pavements. Examples of this feature are presented in this paper.

For the subjective measures a rating form was completed by each test subject providing an indication of the level of ride discomfort. Ratings took place immediately after travelling in the test vehicle at the prescribed test speed on the particular test section of pavement.

Research and Practical Significance

The introduction of a new ride quality indicator potentially has implications for road design and construction and for maintenance engineers, and, therefore, requires careful consideration and testing. For example, there may be some pavement sections

³ The total number of rigid pavements and construction type used in the trials was largely set by RMS.

which will be rated for rideability as "*comfortable*" for one class of vehicle and at the same time be rated as "*uncomfortable*" for another class. Notwithstanding, one of the potential benefits from the adoption of these advanced indicators will be overall improved levels of ride comfort for all road users.

This paper builds on and supports earlier work and demonstrates a range of important aspects of the new ride quality indicators and their practical implementation.

Description of Main Field Trials

The primary purpose of the tests described in this paper was to further demonstrate the ride quality model presented in Prem and Ayton (2005), build on the results of the initial trials described in Prem, Ayton and Tu (2008), and test the model across a much broader and more challenging combination of driver/rider, vehicle and road conditions. Key aspects of this larger study are presented below.

Ride Quality Measures. Consistent with the earlier study by Prem, Ayton and Tu (2008), four separate and independent measures of ride quality and pavement rideability were used in the main trials, comprising:

- a) Direct measurement of actual ride vibration experienced by the vehicle occupant (an objective measure);
- b) Subjective ratings of ride vibration experienced by the vehicle occupant. These were obtained via a standardized rating form completed by each test subject (a subjective measure);
- c) International Roughness Index (IRI) of each test section; and,
- d) Ride quality predictions from the ride model for each of four vehicle classes proposed by Prem and Ayton (2005).

Each of the above is described in more detail in the following sections of this paper.

a) Objective Rating of Ride Vibration. The first independent measure of ride quality is based on actual measurement of ride vibration transmitted by the vehicle through the seat to the seated occupant. Consistent with Prem and Ayton (2005), this measure is taken to be the vibration at the point where the stimuli is transmitted to the human-body from the seat cushion at the principal contact area⁴. In the field-trials ride vibration was measured along three mutually perpendicular axes in the vertical, lateral and fore-aft directions using an instrumented thin, flexible, circular pad placed on the seat and restrained from gross lateral and fore-aft movements by adhesive tape, as shown below in Figure 1 for typical truck (left image) and motorcycle installations. In the analysis only vertical vibration was considered.

The primary quantity for expressing ride vibration magnitude is the frequency-weighted root-mean-square (*rms*) acceleration for vertical (*z*-direction) translational vibration, a_{zw} , defined in general form by Eqn (1):

$$a_w = \left[\frac{1}{T} \int_0^T a_w^2(t) dt \right]^{1/2} \quad (1)$$

⁴ Hand-arm and foot vibration do not feature in the ride model, or in the vibration measurements that were taken, though in some applications these may be significant.

Where $a_w(t)$ is the frequency-weighted acceleration at time t expressed in metres per second squared (m/s^2), and T is the duration of the measurement in seconds.



Figure 1 - Instrumented seat-pad for measurement of ride vibration

The frequency weightings to be employed for different applications can be found in ISO 2631-1 and BS 6841 (International Standards Organisation, 1997; British Standards Institution, 1987). The weightings emphasise some frequencies and de-emphasise other frequencies consistent with the findings from a large number of studies of human perception of vibration (see Griffith, 1990). In the present application, the principal weighting to be applied for the assessment of the effects of vibration on a seated person in a vehicle (motorcycle, car, SUV or truck) is for vertical vibration at a specified point due to up/down (bounce) motions and rotations about a transverse (pitch) axis of the vehicle sprung mass. As noted by Prem and Ayton (2005), the vertical acceleration-based ride indicator outlined above is considered a more transparent and direct measure of the road users' vibration environment than traditional ones used in pavement analysis, such as the IRI. It provides, in literal interpretation, a "seat-of-the-pants" measure of ride quality.

Probable subjective reactions of persons to whole-body vibration in public transportation taken from the standards are listed below in Table 1. It is useful to note that fifty percent of alert, sitting or standing, healthy persons can detect vertical vibration with frequency weighted acceleration of 0.015 m/s^2 .

Table 1 - Likely reactions of seated persons to various levels of a_{zw} acceleration (from ISO 2361-1 and BS 6841)

$a_{zw} \text{ (m/s}^2\text{)}$	Reaction
< 0.315	not uncomfortable
$0.315 - 0.63$	a little uncomfortable
$0.5 - 1.0$	fairly uncomfortable
$0.8 - 1.6$	uncomfortable
$1.25 - 2.5$	very uncomfortable
> 2.0	extremely uncomfortable

b) Subjective Rating of Ride Vibration. The second independent measure of ride quality was the subjective ratings given by each test subject. The standardized rating form shown below in Figure 2 was completed after each test providing a relative indication of the level of discomfort for travel in the test vehicle at the prescribed test speed on the particular section of pavement. As shown, the form requires the test subject to simply place a cross along the continuous scale at the point that best describes the vibration environment.

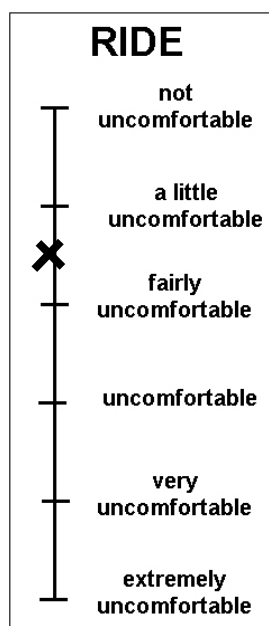


Figure 2 - Ride rating scale consistent with ISO 2631-1 and BS 6841

c) Pavement Rideability. The third independent measure used in the analysis is the International Roughness Index, or IRI, (Sayers et al, 1995), which provides an important link to traditional measures of pavement rideability. IRI was calculated from the profile data taken on each test section. In this and the previous studies only a single value was used corresponding to profile data for the entire length of the test section. More conventional reporting of IRI, taken at 100 m intervals and averaged, was not considered at this stage because the subjective ratings of ride are specific to the entire test section and would include any local “smooth” or “rough” patches. IRI values reported at intervals of 100 m, or shorter, are typically used to identify local increases in unevenness. However, the methods presented in Prem and Ayton (2005) for detecting local increases in unevenness that have a direct impact on rideability are recommended as they are considered more effective for locating and dealing with problem areas.

d) Modelled Ride Vibration Response. The final independent measure of ride quality, which is central to this study, is the modelled ride vibration response. This measure is based on the numerical model described in Prem and Ayton (2005), which mathematically replicates the process described above under the header “*Objective Rating of Ride Vibration*”. That is, the modelled ride response is designed to closely simulate actual vehicle ride dynamics and the responses of humans to whole-body vibration. The outputs from this measure are identical in form to those for the measured ride vibration, namely, the frequency-weighted root-mean-square (*rms*) acceleration for vertical (*z*-direction) translational vibration, a_{zw} , defined above by Eqn (1).

Test Equipment. The main items of equipment required for the study were relatively modest, comprising an instrumented seat pad, a portable, light-weight data acquisition system operated on a standard laptop computer, an external GPS unit with wireless link to the computer, associated signal conditioners and electronics integrated into the system.

a) Ride Vibration Measurement and Recording. The second generation instrumented seat pad was designed and manufactured for the main trials, comprising a printed circuit board (PCB) with USB port, integrated vibration sensor (accelerometers), signal processing and CPU. The “USB Smart Sensor” was small enough to be integrated into the seat pad, as shown in Figure 3. Three identical pads were manufactured for the main trials; one was used as a spare.

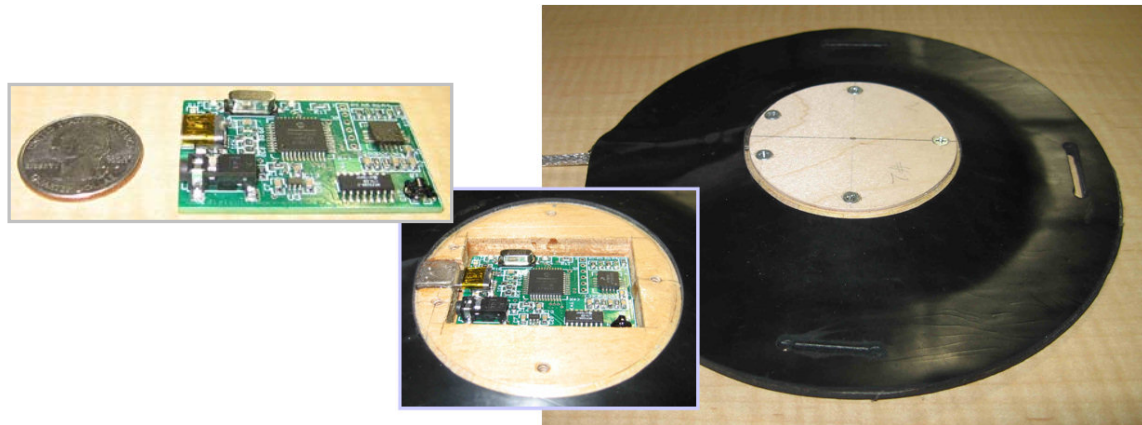


Figure 3 – Instrumented seat pad used in the trials

As shown below in Figure 4, the signals from the seat pad are connected by a USB cable to a standard laptop computer. GPS information is supplied to the system by wireless Bluetooth link to a small, remote GPS receiver.



Figure 4 - Seat pad with USB link to laptop and wireless GPS receiver

b) Test Vehicles. The vehicles used in the trials are shown below in Figure 5, comprising, two (2) motorcycles, five (5) cars, two (2) SUVs and two (2) trucks (2-axle and 3-axle rigids). Cars “CAR4” and “CAR5” were from preliminary trials conducted in the lead-up to the main trials. The preliminary trials were performed under exactly the same test conditions as the vehicles used in the main trials. There were no subjective ratings given for “CAR3”. Truck “TRK2” was speed limited to 100 km/h.



Figure 5 - Vehicles used in the main field trial (MC1, MC2, CAR1, CAR2, CAR3, SUV1, SUV2, TRK1 and TRK2) and lead-up preliminary trial (CAR4 and CAR5)

Road Test Sections. A total of twenty-one (21) test sections were used in the trials from two principal locations in New South Wales, Australia - Road Number 79 (Braidwood Road) and Road Number 3 (Federal Highway). The roads and the mix of rigid and flexible were chosen by the Roads and Maritime Services agency of New South Wales (RMS). The test sections were selected to cover a wide range of roughness, and each section checked for relatively uniform ride vibration along its length. Test sections ranged in length from 611 m to 625 m.

Sixteen (16) of the test sections used in the trials were flexible construction, three (3) were plain concrete pavements (PCP), and the remaining two (2) were continuously reinforced concrete pavements (CRCP). Road profiles were measured on all test sections with a high-speed inertial laser profiler.

The general characteristics of each of the tests sections is summarised below in Table 2. As shown, the roughness levels range from about 0.89 to 5.14 m/km IRI⁵ (25.3 to 135.1 c/km NAASRA Roughness).

Test Subjects. Ten (10) test subjects with a range of backgrounds were recruited by the RMS to participate in the trials. Participation in the trials was voluntary. Eight (8) subjects were male and two (2) were female. They ranged in experience from 9 to

⁵ Except where explicitly stated, all comparisons that are made in this paper involving road profiles are based on the right wheelpath profiles, which is the wheelpath closest to the driver/rider, the source of the ride vibration measurements and subjective ratings.

45 years and per annum exposure (kilometres driven in the last 12 months) varied from about 10,000 to 100,000 km. Each subject was licensed to drive/ride the vehicle they chose to operate. In the trials each subject operated only one vehicle.

Test Procedures. All test subjects were supplied with a formal briefing document beforehand and a verbal briefing was given each day of testing. The briefings explained the background to the project and provided an overview of the trials. Briefing notes covered safety considerations, test procedures, subjective ratings, and short questionnaire.

All the vehicles were tested over a period of about 1 week and each test subject was required for no more than a day with breaks taken for lunch and comfort stops as required. Two vehicles could be tested in a day.

Vibration levels were recorded with the seat pad in each vehicle during each test run. Additionally, a ride rating was obtained from each subject with the form shown in Figure 2 immediately at the conclusion of each test run. Each run on each test section was performed at a nominated constant speed. As there was little or no interference from other traffic a constant speed could be maintained, which was later checked using data logged from the GPS transmission.

Table 2 - Characteristics of each Test Section

Section	Description	Test Speeds (km/h)	Length (m)	IRI (m/km)		NAASRA Roughness ⁶ (c/km)
				Left WP	Right WP	
1	Flexible	100	625	2.55	2.35	64.4
2	Flexible	80/100	625	4.23	3.78	102.4
3	Flexible	100	625	1.85	1.72	45.9
4	Flexible	80/100	625	3.74	3.26	96.4
5	Flexible	100	625	3.67	3.26	89.0
6	Flexible	100	625	4.47	3.71	106.5
7	Flexible	100	625	4.26	3.83	103.1
8	Flexible	80/100	625	3.51	3.17	92.3
9	Flexible	100	625	2.66	2.37	57.3
10	Flexible	100	625	1.85	1.58	45.9
11	Flexible	80/100	625	5.14	4.94	135.1
12	Flexible	80/100	625	2.45	2.36	56.6
13	Flexible	110	611	1.32	1.50	37.1
14	Flexible	80/110	611	1.80	1.97	49.9
15	Flexible	80/110	611	2.84	2.79	75.2
16	Flexible	110	611	1.00	1.15	29.7
17	PCP	110	611	1.87	1.96	58.3
18	PCP	110	611	1.41	1.50	42.8
19	CRCP	80/110	611	0.89	0.88	25.3
20	CRCP	80/110	611	1.09	0.96	29.4
21	PCP	110	611	1.92	1.61	52.9

Test Sections 1 to 12 are from Braidwood Rd, 13 to 21 are on the Federal Highway.

⁶ Although the IRI is used throughout this paper, the Australian equivalent measure, NAASRA Roughness, expressed in units of counts per kilometre (c/km), and the IRI are conceptually identical (Prem, 1989a). The findings presented in this paper are equally applicable to both the IRI and NAASRA Roughness.

Two test speeds were used on 9 of the 21 test sections, one at the posted maximum speed and the other at either 20 or 30 km/h slower, as shown in Table 2. At the conclusion of each run, and when safe to do so, the vehicle was slowed and parked off the road well clear of other traffic, and the driver/rider (the test subject) was given sufficient time to consider and rate the ride vibration for that particular test. That is, each traverse of each test section was rated by the test subject immediately after the run was completed. Data recording was handled by the passenger with data logging automatically triggered (start/stop) by GPS position approximately 100 m on each approach to the test section. This gave about 100 m of vibration data lead-in to each recorded run with start and end points for each test section precisely linked to GPS position within each recording.

Results and Discussion

Comparison of Ride Vibration and Subjective Ratings. The measured ride vibration for each vehicle and the associated subjective ratings given by test subjects are compared below in Figure 6. These are given for individual vehicles (graph on left), and for averages taken across vehicles within each vehicle class (graph on right). The red shaded areas in Figure 6 identify the regions that would be classified as “uncomfortable” by test subjects (scale and labels shown on the horizontal axis) and international standards ISO 2631-1 and BS 6841 (scale and labels shown on the vertical axis).

The results present a complex picture and reflect, as they do, the fact that there are clear differences in ride dynamics and the perception of ride vibration between vehicles both within a class and across the four vehicle classes considered. For some vehicles this leads to relatively high levels of scatter⁷ (motorcycles and trucks, for example). Despite this, the underlying general trends from lines-of-best-fit between the subjective ratings and ride vibration levels (a_{zw}) from the measurements appear to be consistent; ride discomfort (perception of ride vibration) increases with measured ride vibration.

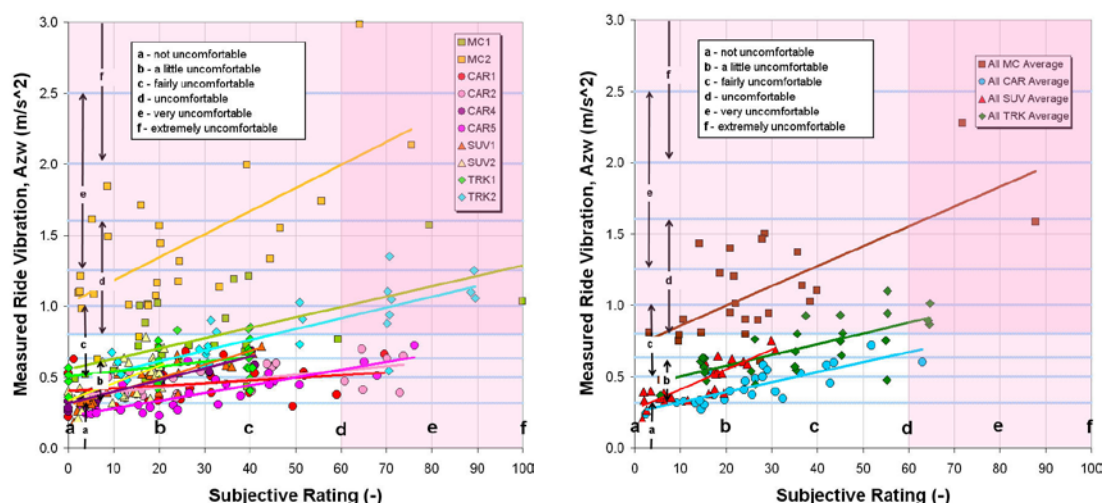


Figure 6 - Comparison of subject ratings and measured ride vibration

The differences between vehicle classes are more evident in the averaged results (graph on right in Figure 6). Motorcycles are experiencing more vibration

⁷ This result is not inconsistent with other studies referred to in the literature using similar psycho-physical rating procedures (Griffin, 1990).

than the other vehicles but it's not reflected in the subjective ratings except when it's "very uncomfortable". That is, motorcycles appear to be least sensitive to vibration. Trucks experience higher vibration levels than SUVs and cars. The underlying trends for trucks and SUVs are largely consistent with international standards ISO 2631-1 and BS 6841. Cars on the other hand experience the least vibration levels and the underlying trend indicates they are more sensitive to vibration – subjective ratings of "d - uncomfortable" on the horizontal axis falling between "b – a little uncomfortable" and "c – fairly uncomfortable" on the vertical axis.

There is also a clear difference in the subjective ratings range (horizontal axis), with the highest ratings for cars and trucks both slightly exceeding "d - uncomfortable", SUVs falling between "b – a little uncomfortable" and "c – fairly uncomfortable", and motorcycles exceeding "e – very uncomfortable". That is, when compared with motorcycles, cars and trucks, one might conclude that SUVs are the least sensitive to ride vibration. This could be the result of SUV drivers spending more time off-road being subjected to harsher vibration than was presented to them in this study, though it is not known if this was the case for the SUV test drivers.

Figure 7 presented below compares the measured ride vibration and the associated subjective ratings when averaged across all vehicles on each test section. The average for all cars is shown in Figure 7 for reference. The results for all vehicles reflects, in broad terms, the overall (average) reactions of (seated) subjects used in this study to the (average) measured ride vibration (a_{zw}) on each test section. As can be seen, there is reasonably good agreement between the average reactions of subjects from this study (horizontal axis on the graph) and the associated likely reactions of seated persons to various levels of a_{zw} acceleration put forward in international standards ISO 2631-1 and BS 6841 (from Table 1). That is, the results shown in Figure 7 support the link between the vibration level groupings and associated likely reaction descriptors from the standards as presented on the vertical axis of the graph. Figure 7 also clearly highlights the greater (subjective) sensitivity of cars to vibration when compared with all vehicles considered in this study.

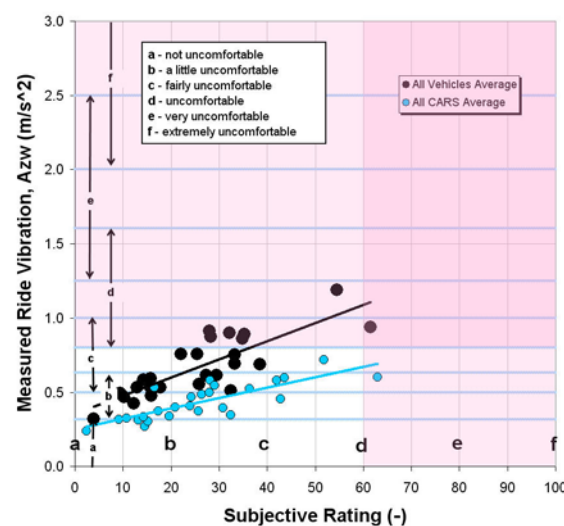


**Figure 7 – Average for all vehicles and cars
(measured vibration versus subjective ratings)**

Comparison of Subjective Ratings and the IRI. The subjective ratings are compared in Figure 8 below with the IRI. As before, the red shaded areas identify the regions that would be classified as "uncomfortable" by test subjects (scale and labels shown

on the vertical axis) and the IRI⁸. The results show considerable scatter but the underlying trends indicates general agreement between the subjective ratings and the IRI – perception of ride vibration increases with IRI. However, as each section of pavement has one value of IRI – and hence by definition (under the IRI roughness scale) pavement rideability has a single fixed value – some important subtleties are lost that are associated with interactive effects between road profile (pavement unevenness characteristics), vehicle mechanical properties (ride dynamics) and travel speed. These subtleties are largely responsible for most of the issues associated with the IRI and similar roughness metrics that this research is attempting to address. This point can be illustrated by referring to the test section with the highest level of roughness shown in Figure 8, which has a right wheelpath IRI roughness of 4.94 m/km. This test section produces less intrusive ride vibration for the SUVs than the motorcycles, cars and trucks. The sensitivity to speed is also apparent for the cars and motorcycles in the right-hand graph shown in Figure 8, with lower perceived vibration at the slower of the two test speeds; the data points for the lower speed (80 km/h) sit below the points for the higher speed (100 km/h) – more on this later.

The subjective ratings indicate the trucks generally experienced the greatest discomfort followed by motorcycles and cars (almost equal), and then SUVs.

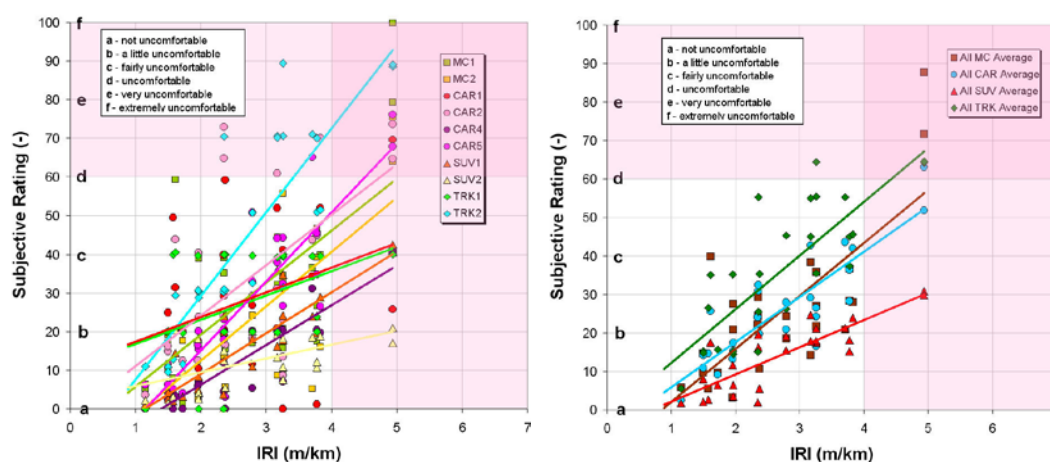


Figure 8 - Comparison between subjective ratings of ride and the IRI

Figure 9 compares the subjective ratings with the IRI averaged across all vehicles, and, as before, separately for cars, on each test section. The results are in contrast to the earlier result shown in Figure 7, and suggest there is no difference between subject ratings for all vehicles and subject ratings for cars. However, this loses some of the subtleties associated with differences between the vehicle classes evident in Figure 6, Figure 7 and Figure 8, and discussed earlier, and appears to be an artifact of the subject ratings. That is, even though motorcycles experience the highest vibration levels their subjective ratings are low.

Comparison of Ride Vibration and IRI. The measured ride vibration for each vehicle and the IRI are compared in Figure 10 for individual vehicles (graph on left) and averages within each vehicle class (graph on right). When compared with results presented earlier in this paper there is less scatter in these data, and the underlying

⁸ A terminal IRI roughness value of 4.0 m/km has been assumed consistent with a NAASRA roughness value in Australia of about 110 counts/km for functional Class 1 and 2 roads. That is, IRI values greater than 4.0 m/km are assumed to be “uncomfortable”.

trends in Figure 10 show a clear ranking of vehicles – motorcycles and trucks experience the highest vibration followed by SUVs and cars. Vibration for motorcycles is significantly greater than for the other vehicles and IRI as low as 1.5 m/km are seen to produce “uncomfortable” ride vibration. For trucks an IRI of about 3.0 m/km also results in “uncomfortable” ride vibration under some conditions. By contrast, the threshold value for cars and SUVs appears to be greater than 5.0 m/km IRI, which is more than the terminal roughness value of 4.0 m/km assumed in this paper based on current guidelines in Australia.

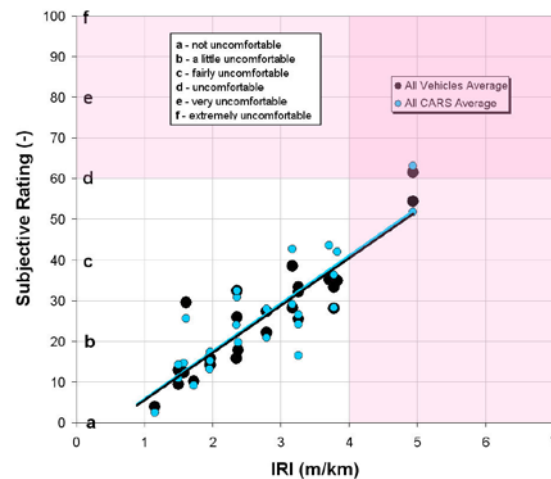


Figure 9 - Average for all vehicles and cars (subjective ratings versus the IRI)

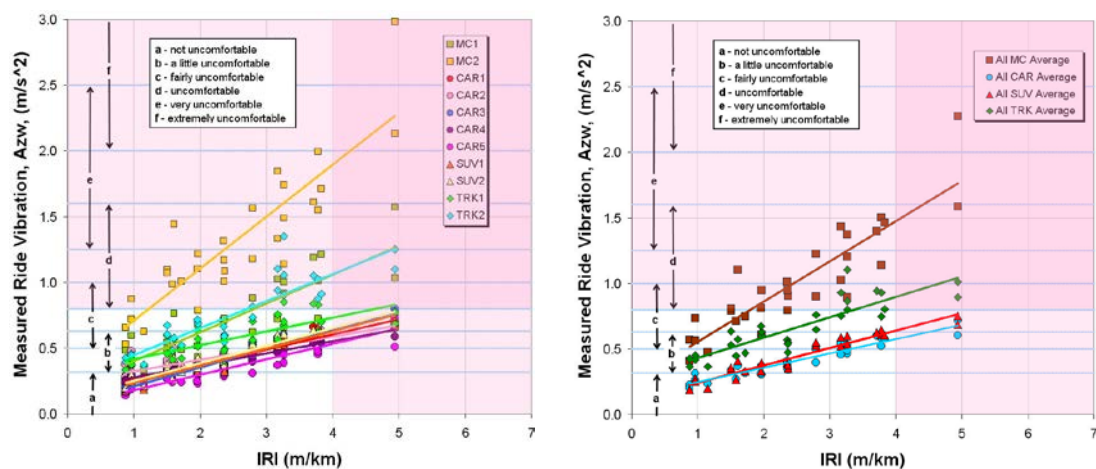


Figure 10 - Comparison between measured ride vibration and the IRI

Figure 11 shows measured ride vibration and the IRI averaged across all vehicles and, separately, cars, on each test section. The results indicate that ride vibration experienced in cars are significantly less than the overall average of the other vehicle classes considered in this study. The results also show that the assumed terminal roughness of 4.0 m/km may be conservative for cars and a higher value, greater than, say, 5.0 m/km, would also be acceptable. This should, however, be treated with caution. If current ride quality indicators and unevenness standards for road construction, maintenance and rehabilitation are based on correlation studies based solely on passenger cars, the performance levels may be well below limits required to achieve acceptable pavement rideability for other vehicle classes. The

lower limit of the “uncomfortable” boundary for measured ride vibration intersects the line-of-best-fit for all vehicles at an IRI of about 3.5 m/km, and this may be a more appropriate roughness intervention level to cover all vehicles.

Modelled Ride Responses. The final comparisons consider the ride vibration predicted by the ride model (Prem and Ayton, 2005) and the measured ride vibration, these are shown in Figure 12 for each vehicle (graph on left) and vehicle class averages (graph on right). Figure 12 shows there is good agreement between predicted and measured ride vibration.

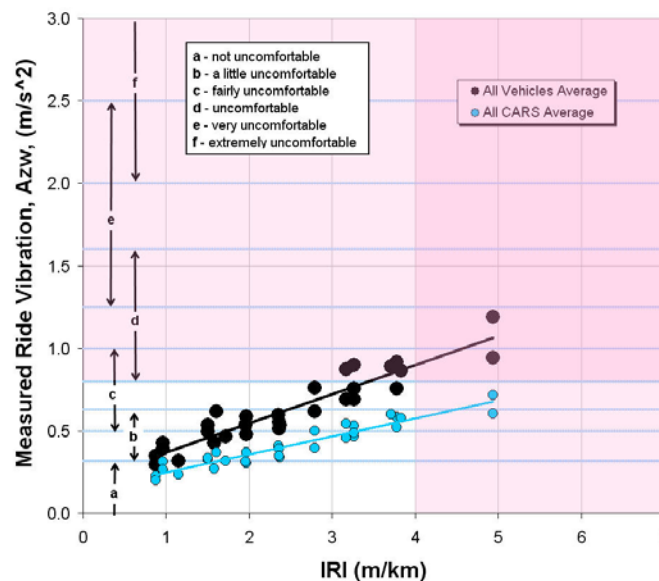


**Figure 11 - Average for all vehicles and cars
(measured ride vibration versus the IRI)**

It is important to note that the final result shown in Figure 12 was achieved by adjusting the baseline (starting) values for some of the vehicle parameters. The final sets were slightly different from the original ones presented in Prem and Ayton (2005) and more recently Prem, Tu and Ayton (2008). For each vehicle class only a single set of (generic) parameter values was used to cover all vehicles in that class. Specific changes to some vehicles included changes to tyre vertical stiffness in the range 5 to 15%, adjustments to suspension stiffness in the range 5 to 25%, and changes to suspension damping of up to 15%. While the final parameter values were not compared with specific values for individual vehicles – considered beyond the scope of this project – the above adjustments would be typically associated with different brand tyres, sizes, inflation pressures and suspensions (springs and dampers).

There is a range of other sources of vibration in each vehicle (engine and structural, for example) not present (or simulated) in the ride model. Though not physically measured (something not straightforward to do and beyond the scope of this project), the offsets shown in Figure 12 were assumed to be due to these other sources of vibration, with the highest levels associated with motorcycles and trucks. An equal and opposite amount of offset was added to the modelled ride vibration leading to the final result shown in Figure 13.

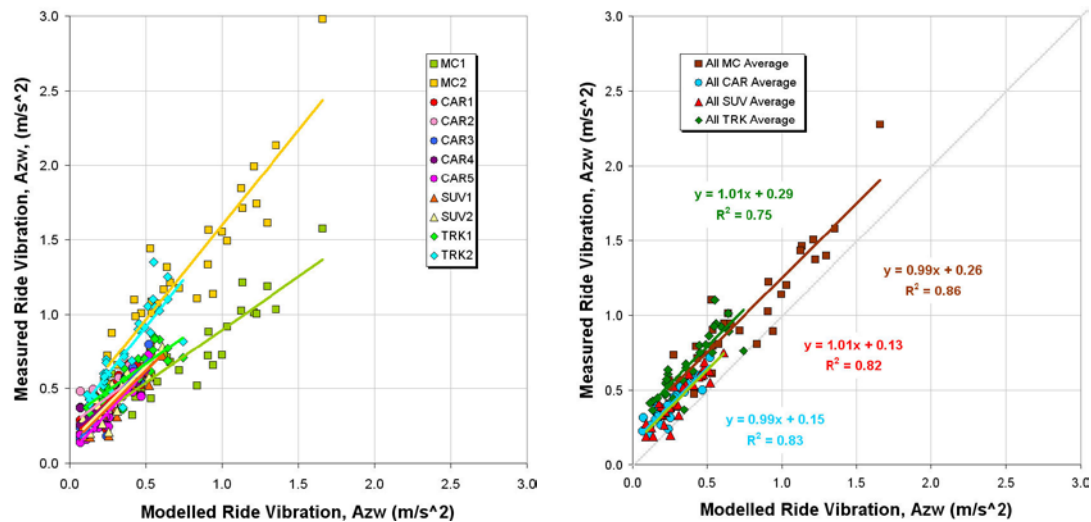


Figure 12 - Comparison between measured and modelled ride vibration

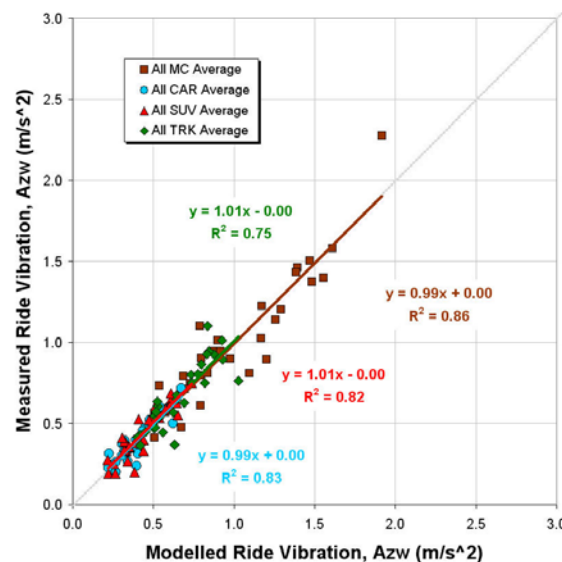


Figure 13 - Measured and modelled ride vibration

Influence of Speed on Ride Vibration. The influence of speed on ride vibration was touched on briefly earlier in this paper. It warrants closer examination as the interaction between vehicle ride dynamics and road surface unevenness is complex. Table 2 shows that on some test sections ride measurements were taken at two different speeds, one at the posted maximum speed and the other at either 20 or 30 km/h slower. Two examples of the effect of speed on the measured ride vibration are given in Figure 14 for test sections 15 and 20. Test section 15 (graph on left of Figure 14) is a flexible pavement and, as shown, ride vibration increases with speed across all vehicles tested. The magnitude of the increase in vibration depends on interactive effects between the characteristics of the pavement and the vehicle; on a given pavement some vehicles will exhibit a greater sensitivity to speed than others, sometimes tuning into specific (usually periodic) unevenness features.

By contrast to test section 15, test section 20 (graph on right of Figure 14), which is continuously reinforced concrete pavement (CRCP), exhibits a mix of ride vibration responses to an increase in speed. As can be seen, for some vehicles ride

vibration increases (MC1, MC2, CAR1, CAR5 and TRK1), for the other vehicles ride vibration decreases (CAR2, CAR4 and SUV1, SUV2 and TRK2).

In order to gain further insight into the unevenness characteristics of these two test sections and help to explain these phenomena further analysis of road profile was performed using spectral analysis, identical to that used in other studies (see Prem, 1989b). The results of this further analysis are presented below in Figure 15, which shows the distribution of unevenness over a wavelength range from 100 m to 0.1 m. These wavelengths correspond to wave numbers, spatial frequencies, from 0.01 to 10 cycles/m. To further assist interpretation of the results, the wavelength ranges for roughness, megatexture and macrotexture have also been identified (labels along the top of each graph). Also shown in Figure 15 is the weighting function (transfer function gain –vertical axis label on right) of the IRI quarter-car for two travels speeds, 80 km/h (bold red curve), which formally defines the IRI, and a second higher speed, 110 km/h (the bold grey curve to the left of the red curve). This illustrates how the IRI quarter car “sees” the profile.

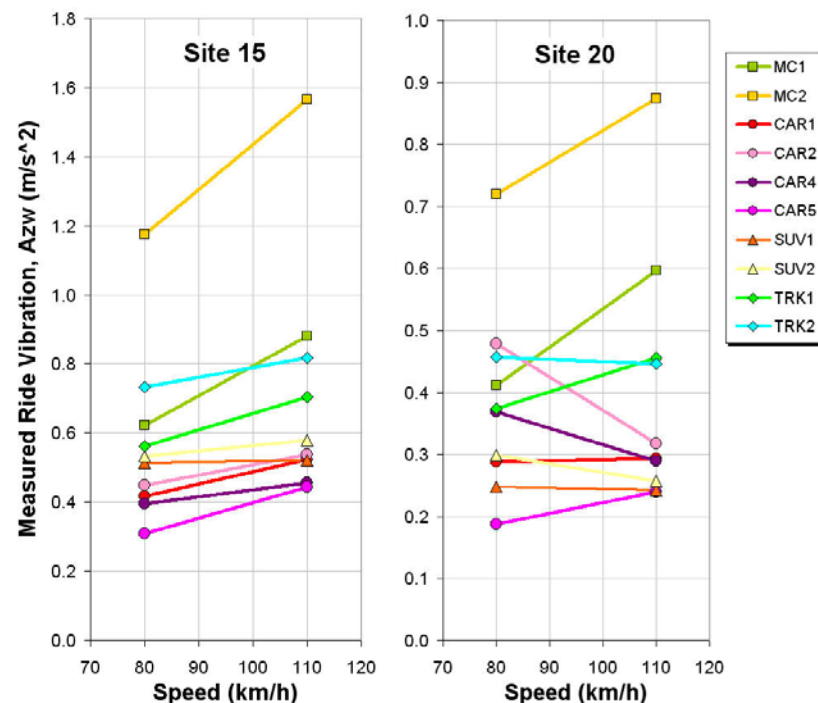


Figure 14 – Examples of the effect of speed on ride vibration

The spectral characteristics of test section 15 are typical, and an increase in speed from 80 to 110 km/h shifts the vehicle’s response weighting function to the left thereby increasing the overlap and sensitivity to the higher levels of roughness and increasing in-vehicle vibration.

By contrast the spectral characteristics of test section 20 exhibit strong periodic components with the largest peak centered on 2.0 cycles/m, consistent with the 0.5 m spacing of the transverse reinforcing bars in the CRCP. An increase in speed from 80 to 110 km/h moves the vehicle’s weighting function further to the left and away from the megatexture leading to a reduction in vibration. As each vehicle used in these trial has a specific weighting function linked to its mechanical properties (mass, wheelbase, suspension and tyre vertical stiffness, etc), the overlap with megatexture will be different from one vehicle to another. Where the overlap is

significant and the sensitivity of the vehicle is high, the reduction in megatexture induced vibration with speed will be greater.

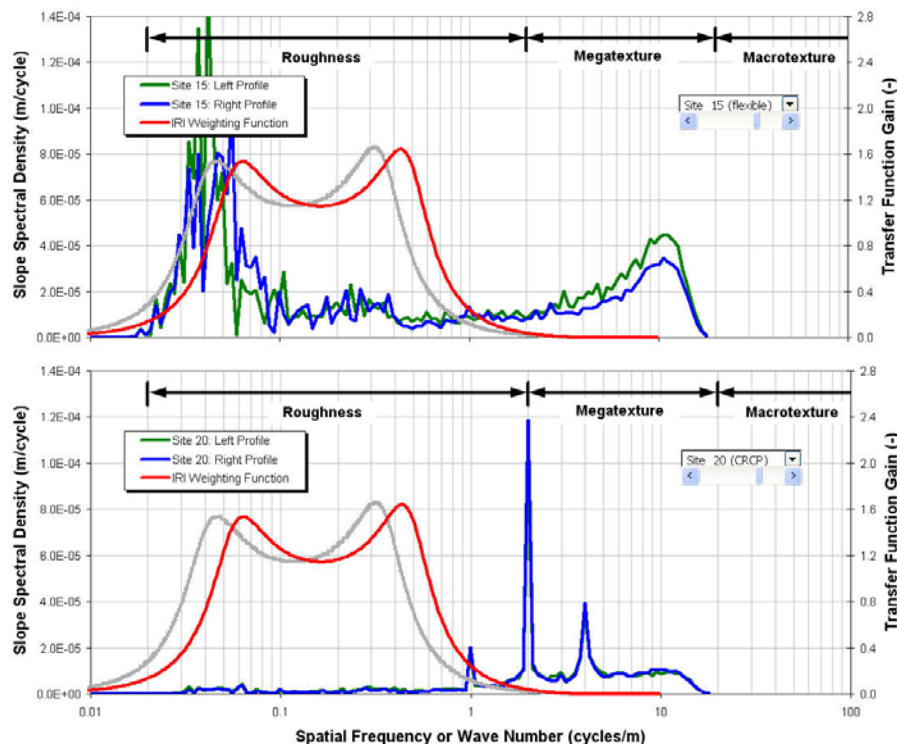


Figure 15 – Spectral characteristics of test sections 15 (top) and 20 (bottom)

It is important to note that two of the test sections used in these trials exhibit megatexture, test sections 19 and 20, both are CRCP. These two test sections appeared to cause confusion in the subjective ratings of vibration for some subjects and for this reason the subjective ratings for these two test sections were not used in this study.

A further important point needs to be considered in relation to the influence of speed on vibration. Fundamentally the IRI is the vibration response of a vehicle travelling at 80 km/h. On roads where the local traffic speed is not 80 km/h the IRI “reports” roughness in a different wavelength range to that experienced by the vehicles and it may completely miss unevenness that the prevailing traffic is detecting when operating at slower or faster speeds. This provides additional support for ride indicators that are vehicle class specific and speeds consistent with prevailing traffic conditions.

Data Presentation Techniques. During the course of this project several novel techniques were considered to review and check ride vibration data. Software was used to create a file compatible with Google Earth⁹ allowing both the vibration and GPS data to be imported into that program. These files and method of checking and reviewing the data proved to be very useful and were considered to have potential for much wider application. An example of this technique is given below in Figure 16, which shows vibration data for a bridge crossing taken in one of the trucks on a road section not used in the study. As can be seen in Figure 16, with the 3D terrain

⁹ Google Earth is a virtual globe, map and geographical information program.

mapping feature selected, the vibration recordings simply appear above the road showing general vibration levels and making areas of particularly intense vibration activity apparent. In the example shown the bridge crossing occurs a little to the left of the centre of the main image with vibration more or less uniform either side of the bridge between the labelled icons for the starting and finishing points.

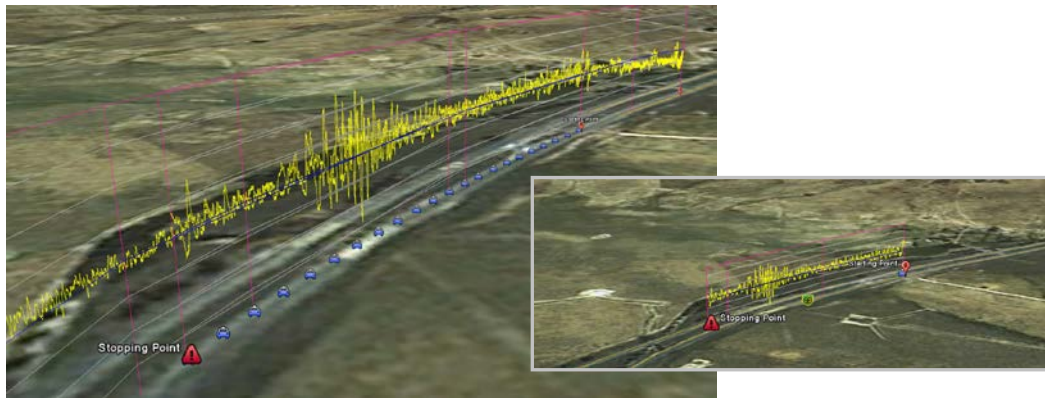


Figure 16 – Vibration recording of bridge crossing displayed in Google Earth

Summary and Concluding Comments

A large field trial was conducted to further test the ride quality model proposed by Prem and Ayton (2005) across a broad and challenging set of conditions. A total of twenty-one pavement sections (both flexible and rigid) covering a wide range of roughness levels and characteristics were used in the study. Eleven (11) vehicles from each of four vehicle classes were used (motorcycles, cars, SUVs and trucks). Ten (10) test subjects were recruited with a range of driving backgrounds, each operating one of the test vehicles. Ride vibration was measured with portable vibration measuring equipment comprising accelerometers, a data logger and GPS tracking. Subjective ratings of ride vibration were obtained with a standardized rating form.

Motorcycles were found to experience the highest vibration followed by trucks, SUVs and cars, in that order. When the measured vibration was compared with the subjective ratings, motorcyclists appear to be least sensitive to vibration and car drivers the most sensitive to vibration. That is, motorcycles experienced the highest vibration but this was not reflected in the riders' subjective ratings. Cars on the other hand experienced the lowest vibration but the drivers' subjective ratings suggested harsher conditions. The underlying ride-vibration/subjective-rating trends across all vehicles were found to be largely consistent with international standards ISO 2631-1 and BS 6841.

When the subjective rating were compared with the IRI, truck drivers were found to experience the greatest discomfort followed by drivers of motorcycles and cars (almost equal), and then SUVs.

When ride vibration was compared with the IRI there was a clear ranking of vehicles – motorcycles and trucks experienced the highest vibration followed by SUVs and cars. Vibration for motorcycles was found to be significantly greater than for the other vehicles and IRI as low as 1.5 m/km can produce vibration which is deemed “uncomfortable” by current standards. For trucks, an IRI of about 3.0 m/km produces vibration under some conditions which is deemed “uncomfortable” by current standards. By contrast, the threshold value for cars and SUVs appears to be greater than 5.0 m/km IRI.

For measured ride vibration and the IRI averaged across all vehicles the results indicate that ride vibration experienced in cars are significantly less than the overall average of the other vehicle classes considered in this study. The results also show that the assumed terminal roughness of 4.0 m/km may be conservative for cars and a higher value, greater than, say, 5.0 m/km, would also be acceptable. This should, however, be treated with caution. If current ride quality indicators and unevenness standards for road construction, maintenance and rehabilitation are based on correlation studies based solely on passenger cars, the performance levels may be well below limits required to achieve acceptable pavement rideability for other vehicle classes. The lower limit of the “uncomfortable” boundary for measured ride vibration suggests an IRI of about 3.5 m/km may be a more appropriate roughness intervention level to cover all vehicles.

Good agreement was found between the modelled and measured ride responses across all four vehicles classes providing support for the proposed new ride quality indicators.

The influence of speed on ride vibration was also investigated. On most test sections ride vibration was found to increase with speed. On test sections with megatexture there was a mix of vibration response across vehicles; for some vehicles ride vibration was found to decrease with an increase in speed.

Overall, the findings of this study are very encouraging and provide strong further support for the general thrust of this research.

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