RIDE QUALITY MEASUREMENT AND USER RATINGS: INITIAL ASSESSMENT OF IMPROVED TECHNIQUES

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Abstract

Improved techniques for assessing ride quality have been developed by the authors that closely simulate actual vehicle ride dynamics and the responses of humans to whole-body vibration. Using numerical models to simulate four generic road-user vehicle classes – passenger cars, heavy commercial vehicles (trucks), off-road recreational and sports utility vehicles (SUVs) and motorcycles – fundamental issues associated with current ride quality measurements are addressed leading to more robust and accurate estimates of pavement rideability. Initial field trials and tests of the proposed ride quality model for a passenger car were conducted. To assess the effectiveness of the model as a ride quality predictor, the overall modelled ride responses were compared with actual measured ride vibrations (objective measures) and road-user ride ratings (subjective measures), all taken on the same sections of pavements. For the objective measures of ride quality portable vibration measuring equipment, comprising accelerometers, event markers and a data logger were assembled, customised and tested. In later versions of the equipment, also described in this paper, GPS tracking was incorporated to provide precise time-based recordings of location and speed. Developed specifically for this project, the equipment is small in size, completely self-contained, and is readily adapted for use in both small and large vehicles (motorcycles, cars, SUVs and trucks). The initial study found there was good agreement between the modelled responses, vibration measurements and subjective ratings. A further larger study is planned, which is discussed in this paper.

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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 robust and accurate estimates of pavement rideability.

Initial field trials and tests of the proposed ride quality model for a passenger car were conducted and are described in this paper. Plans are in place for a larger study that will cover four vehicle classes – passenger cars, heavy commercial vehicles (trucks), off-road recreational and sports utility vehicles (SUVs) and motorcycles – as well as flexible (asphalt) and rigid (concrete) pavements.

To assess the effectiveness of the model as a ride quality predictor, the overall modelled ride responses were compared with actual measured ride vibrations (objective measures) and user ride ratings (subjective measures). All were taken on the same sections of pavements. For the objective measures of ride quality portable vibration measuring equipment, comprising accelerometers, an event marker and a data logger were assembled, customised and tested. In later versions of the equipment, also described in this paper, Global Positioning System (GPS) tracking was incorporated to provide precise time-based recordings of location and travel speed. Developed specifically for this project, the equipment is small in size, completely self-contained, and readily adapted for use on both small and large vehicles.

Research and Practical Significance

The introduction of a new set of ride quality indicators has potentially far reaching implications for road design, construction and maintenance engineers, and, therefore, requires careful consideration and testing. For example, there will most likely be pavements which previously were considered acceptable with respect to rideability that will be unacceptable when the new ride quality indicators are applied. Further, complex issues will naturally arise when ride quality indicators covering a wider class of vehicles is considered; rideability may be acceptable for one class of vehicle and unacceptable for another class. How to deal with these issues will be a challenge for road engineers. However, while there will be new engineering challenges to deal with, the direct benefits to all road users and the community is clear – improved levels of ride comfort.

This paper presents the next logical step in a series designed to demonstrate a range of important aspects of the new ride quality indicators and their practical implementation.

Description of Preliminary Tests

The primary purpose of the tests described in this paper was to demonstrate the ride quality model presented in Prem and Ayton (2005) and to provide initial verification of its predictive capability. This was achieved through a comparison of the outputs from the model with a number of independent objective and subjective ride measures. Testing was performed using newly developed equipment and was, by design, limited to a single (1) passenger car, two (2) test subjects and seven (7) test sections of pavement ranging in roughness from about 1.0 m/km to 6.0 m/km International Roughness Index (IRI). Road profiles were obtained on 5 of the 7 test sections.

Ride Quality Measures. Four separate, independent measures of ride quality and pavement rideability were used in this study, 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) The IRI of each test section (a single value); and,
d) Ride quality predictions from the passenger-car model proposed by Prem and Ayton (2005) (limited to test sections for which profile data were available).

Each 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 was based on actual measurement of ride vibration transmitted by the vehicle to the seat and seated occupant. Consistent with Prem and Ayton (2005), this measure was taken to be the vibration at the point where it enters the human-body from the seat cushion at the principal contact area[4]. In the field-trials ride vibration was measured along three mutually perpendicular axes in the vertical, lateral and fore-aft directions using a specially instrumented thin, flexible, circular pad placed on the seat and restrained from gross lateral and fore-aft movements by straps, as shown below in Figure 1. In the analysis only vertical vibration was considered.

[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.

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):

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

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). 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 (car, SUV, truck or motorcycle) is for vertical vibration at a specified point due to bounce motions and pitch rotations 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} (m/s^2)	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 an 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 scale at the point that best describes the vibration environment.

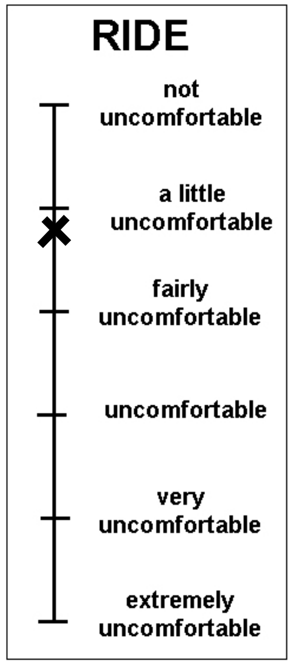

Figure 2 - Ride rating scale consistent with ISO 2631-1 and BS 6841.

c) Pavement Rideability. The third independent measure used in the analysis is the IRI (Sayers et al, 1995), and provides an important link to traditional measures of pavement rideability. The IRI was calculated for each test section for which profile data were available. In this pilot study 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 given by vehicle occupants 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 develop by Prem and Ayton (2005), shown below in Figure 3, 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).

Table 2 below presents a selection of parameters that are required to define the ride model and allow ride simulations to be performed. Of particular note is the parameter set in the column labelled "*Car*". This parameter set is designed to represent a generic, non-descript, "average" passenger car, which is compared in a later section of this paper with the actual values for the test car used in this study.

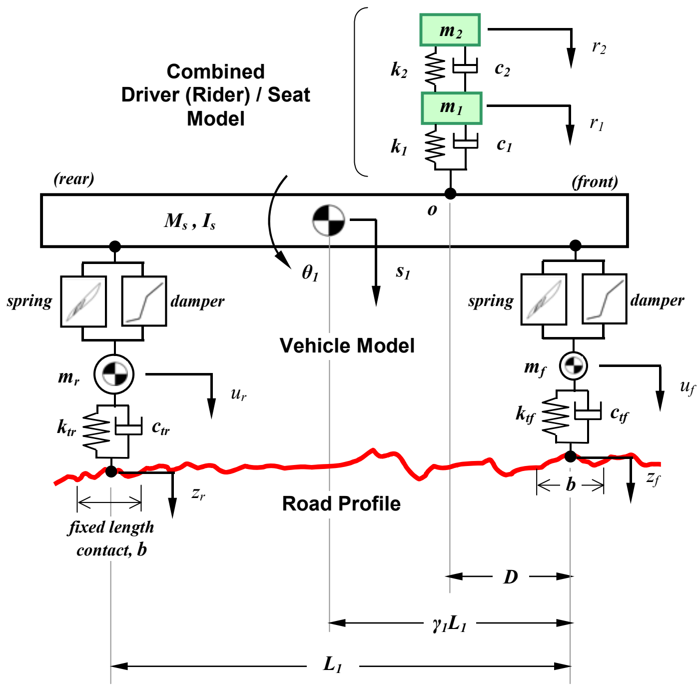

Figure 3 - Generic 2-axle ride model (from Prem and Ayton, 2005).

Table 2 - Ride Model Parameter Values (from Prem and Ayton, 2005)

Parameter	Motorcycle	Car	SUV	Truck
Gross Mass (kg), $M_s+m_f+m_r$	270	1,650	1,890	12,000
Wheelbase (m), L	1.45	2.75	2.70	4.72
Location of Point O (m), D	1.00	1.25	1.35	0.20
Front Spring Stiffness (N/m)	12,000	46,000	72,500	450,000
Rear Spring Stiffness (N/m)	26,500	53,750	60,000	635,000
Front Tyre Stiffness (N/m), k_{tf}	100,000	450,000	490,000	1,575,000
Rear Tyre Stiffness (N/m), k_{tr}	130,000	450,000	490,000	3,150,000

Test Equipment. The main items of equipment required for the study were relatively modest, comprising an instrumented seat pad, a hand operated switch to allow an event marker to be inserted into the recordings and thereby identify the start and end of each test section, associated signal conditioners, and a portable, light-weight data acquisition system operated on a standard laptop computer.

a) Ride Vibration Measurement and Recording. The instrumented seat pad was designed and manufactured specifically for the study, comprising a commercially available miniature 3-axis vibration sensor (accelerometers) and associated electronics. The sensor together with electronics were mounted on a custom printed circuit board (PCB), small enough to be integrated into the seat pad with a single cable for power and signals, as shown in Figure 4.

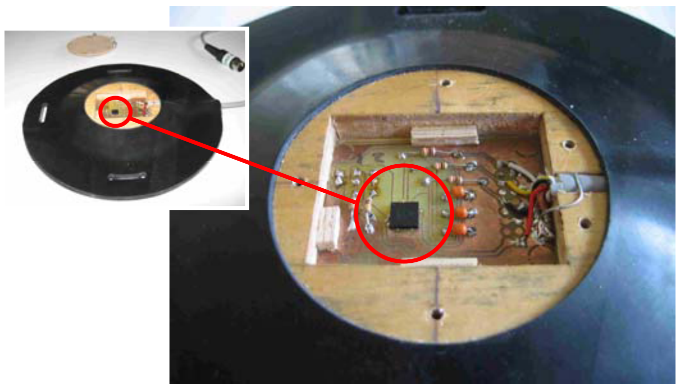

Figure 4 - 3-axis accelerometer (5x5x1 mm), selectable range ±1.5g/2g/4g/6g.

As shown below in Figure 5, the signals from the seat pad together with the hand-held push button event marker are connected by cables to a miniature multi-channel USB-based data acquisition system (DAQ), and via USB cable to a standard laptop computer for overall control and mass storage of data.

Figure 5 - Seat pad, laptop, USB-based DAQ and push button event marker.

***b) Test Vehicle*.** The vehicle used in the trials, shown below in Figure 6, was a two door hatchback (sports). The vehicle has a tare weight of 1420 kg, a wheelbase of 2519 mm, a firm seat and sports suspension running on low-profile 225/45R17 size tyres. Both the weight and dimensions compare favourably with the car values presented above in Table 2 but the seat, suspensions and tyres would be stiffer.

Figure 6 - Car used in the preliminary field trials.

Road Test Sections. A total of seven (7) test sections were used in the trials, all flexible pavement construction, though in the main experiment a mix of flexible and rigid (concrete) pavements will be used. These ranged in length from about 400 m to 500 m. Five of the seven test sections are used routinely for verification of roughness measurements for road network-level surveys, the remaining two (test sections 6 and 7) were selected during the trial, one being very rough and the other one very smooth (freeway). The general characteristics of each of these sections is summarised below in Table 3. As shown, the roughness levels range from about 1.0 to 5.3 m/km IRI. Road profiles were obtained for test sections 1 to 5. Two of the standard test sections are shown in Figure 7; these reveal a blue line in the wheel path near the centre of the road, which is used to assist the driver when repeat measurements are taken for routine roughness checks. In this study they were used to assist each test subject to follow as closely as possible the same path.

Table 3 - Characteristics of each Test Section

Section	Description	Test Speeds (km/h)	Length (m)	IRI (m/km)		NAASRA Roughness[5] (c/km)
				Left WP	Right WP	
1	Rural Road	75/90	496.0	1.39	1.28	36.6
2	Rural Road	80/100	497.0	2.99	2.29	65.2
3	Rural Road	80/100	399.4	2.03	2.61	74.3
4	Rural Road	80/100	499.0	2.60	2.74	78.0
5	Town Arterial	50/70	498.5	2.46	2.04	58.1
6*	Rural Road	80/100	500	5.3		140
7*	Freeway	110	500	1.1		28

* - Roughness estimates for test sections 6 and 7 are based on the subjective ratings.

Test Subjects. Two male test subjects (both engineers) were used it the field trials. Their pertinent characteristics are presented below in Table 4.

[5] Although the IRI is used throughout this paper, the Australian equivalent measure, NAASRA Roughness, and the IRI are conceptually identical (Prem, 1989). The findings presented in this paper are equally applicable to both the IRI and NAASRA Roughness.

Figure 7 - General views of two test sections showing the blue line (left of the centre line) to aid tracking repeatability.

Table 4 - Test Subject Characteristics

Characteristic	**Test Subject 1**	**Test Subject 2**
Age	49 years	33 years
Weight	95 kg	68 kg
Height	176 cm	180 cm
Occupation	Mechanical Engineer	Aerospace Engineer
Ride Background	Extensive	Nil

Test Procedures. Both test subjects were familiar with the key aspects of the project, and so, the main focus during the tests was to ensure uniform and consistent procedures were followed and, in particular, with respect to collection of the subjective ratings of ride vibration. Using the seat pad vibration levels were recorded during each test run. Additionally, a ride rating was obtained from the subject with the form shown in Figure 2 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, and with the assistance of the vehicle's cruise control, a constant speed could be maintained. At the start of the day each subject was given instructions to treat each test section as though it were part of a long journey and the vibration environment was to be rated accordingly.

Two test speeds were used on 6 of the 7 test sections, one at the posted maximum speed and a second at 15 to 20 km/h slower, as shown in Table 3. At least two runs were performed on each test section. At the conclusion of each run, and when safe to do so, the vehicle was slowed and parked off the road, and the driver (the test subject) was given sufficient time to consider and rate the ride vibration environment 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, including registering of the start and end points of each test section using the hand-held event marker switch. This was used to locate and retrieve recorded data specific to each test section for later reduction and processing.

It is important to note that the rating assigned to each test section by each test subject was not disclosed to the other test subject, and the ratings were only compared at the time of analysis a few days after the tests were performed.

Results and Discussion

Comparison of Subjective Ratings and Ride Vibration. The subjective ratings given by each of the two subjects are compared below in Figure 8 together with the measured ride vibrations. These show relatively consistent and close agreement between the subjective ratings (left graph in Figure 8) and highly correlated ride vibration levels (a_{zw}) from the measurements taken with the seat pad (objective measure of ride vibration) (right graph in Figure 8). Further, the red shaded areas in Figure 8 identify the regions that would be classified as "*uncomfortable*" by test subjects and international standards ISO 2631-1 and BS 6841. These results suggest that in absolute terms the subjective and objective "seat of the pants" ride measurements appear to be largely in agreement.

Further comparisons of the subjective ratings and measured ride vibration are presented in Figure 9, reinforcing the conclusions and comments present above. Figure 9 also identifies the test section with the highest level of roughness, test section 6, and very clearly illustrates the important influence that speed has on ride vibration. On this particular test section a reduction in speed of 20 km/h from 100 km/h leads to a reduction in ride vibration of about 20%.

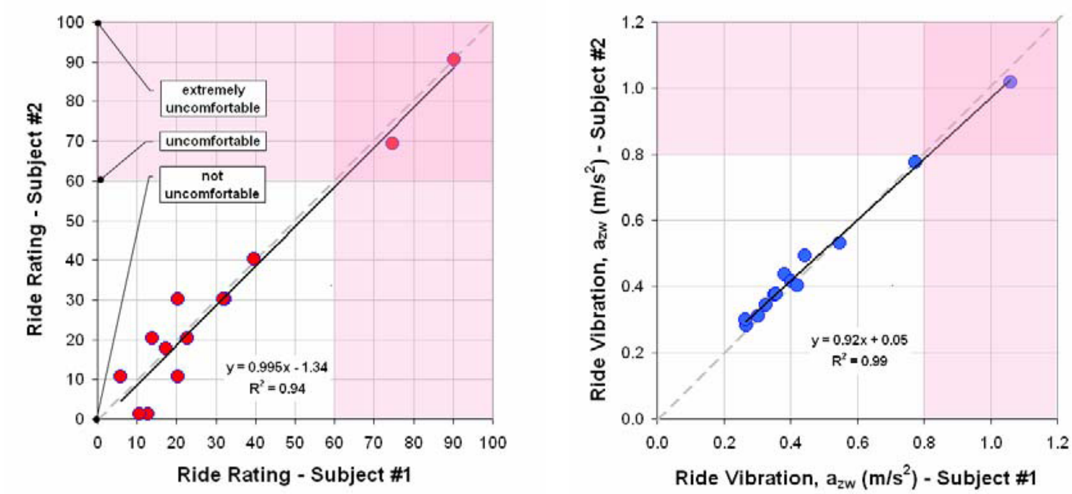

Figure 8 - Comparison of subject ratings (left) and measured ride vibration (right) between subjects (uncomfortable regions shown shaded).

Comparisons with the IRI. The subjective ratings of ride are compared in Figure 10 with the IRI[6,7]. This shows there is also general agreement between the ride ratings and the IRI. However, as each section of pavement has a fixed 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

[6] 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, the source of the ride vibration measurements and subjective ratings.

[7] 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*".

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. As before, this point is clearly illustrated by referring to the test section with the highest level of roughness shown in Figure 10. This has an estimated IRI roughness of 5.3 m/km, but clearly this section produces less intrusive ride vibration at the lower of the two speeds. This sensitivity to speed and road profile is apparent in the subjective ride ratings and measured ride vibration results presented in Figure 8 to Figure 10.

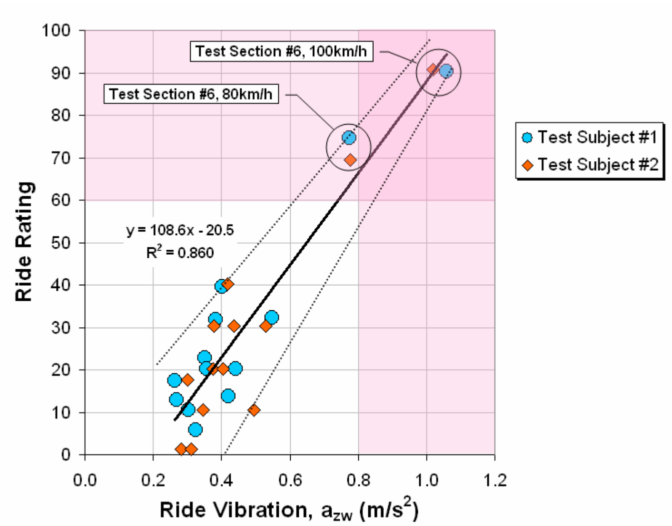

Figure 9 - Comparison between subjective and objective ride ratings.

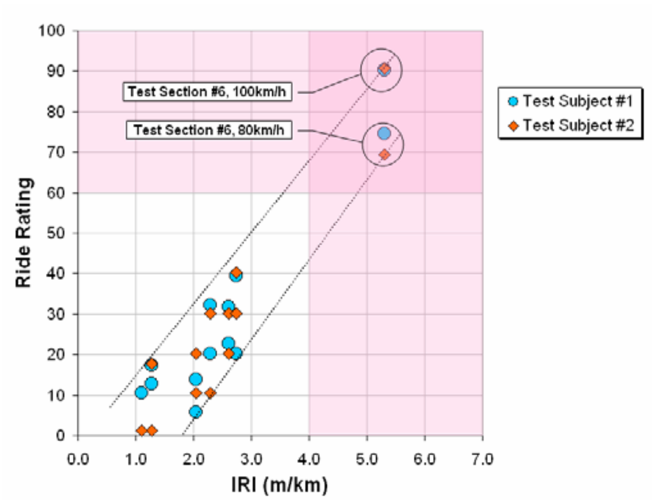

Figure 10 - Comparison between subjective rating of ride and the IRI.

An equally important and fundamental issue is apparent when comparisons are made between the measured ride vibration and the IRI, as shown in Figure 11. Three groupings of the data values have been circled and labelled "*a*", "*b*" and "*c*"; "*a*" has higher ride vibration levels than "*b*" and "*c*", but "*b*" has a higher IRI value.

That is, rankings based on ride vibration measurements would list "*a*" as the worst section of the three groupings and "*b*" and "*c*" as being near identical. Rankings based on the IRI would list the groupings in order of increasing roughness as "*c*", "*a*" and "*b*". Test speeds for the data shown in the "*a*" and "*b*" groupings are identical, so the differences described above are the nett result of interactive effects between road profiles and vehicle dynamics.

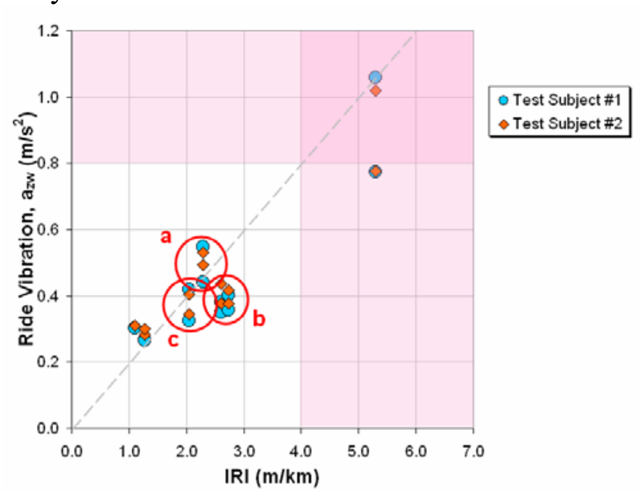

Figure 11 - Comparison between measured ride vibration and the IRI

Modelled Ride Responses. The final comparisons that are made consider the ride vibration predicted by the ride model shown in Figure 3 and the ride ratings. Profile data were not available for test section 6 and 7, so the modelled ride responses for the smoothest and roughest test sections could not be determined. Nonetheless, Figure 12 shows that the modelled ride vibration correlates well with the subjective ride ratings, and with less scatter than the relationship between ride rating and the IRI shown in Figure 10.

It is important to note that the slope of the regression equation shown in Figure 12 is about 20% greater than the slope of the regression equation shown in Figure 9, and there is a bias in the measured ride vibration (additional offset in the data points to the right). This indicates that the magnitude of the modelled response is generally about 20% smaller than the measured response. The slope and intercept differences can be attributed to a number of factors, as follows:

- The model is only responding to a single wheelpath of road profile – by choice this is the profile on the driver's side of the road – whereas the actual car is responding to the profile in both wheelpaths. Table 3 shows the passenger side profile (left wheelpath) has a higher IRI value on test sections 1, 2 and 5;
- The test car has firmer seating and stiffer suspensions and tyres than the generic, non-descript, "average" modelled car and, therefore, vibration levels are expected to be lower in the modelled car; and
- There is a range of other sources of vibration in the real car (engine and structural, for example) not present (or simulated) in the modelled car.

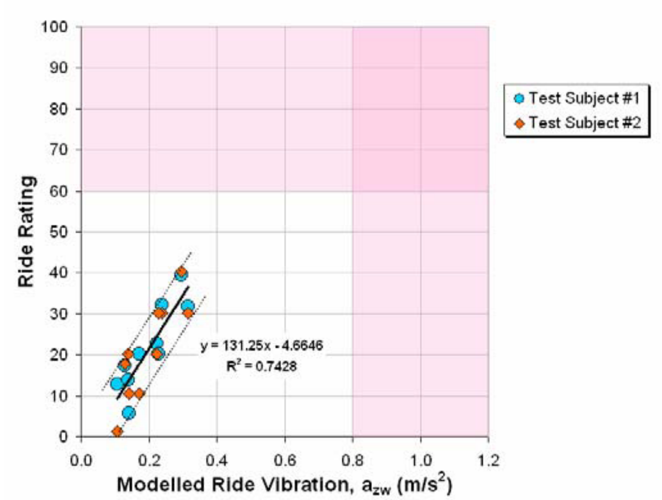

Figure 12 - Comparison between modelled ride vibration and ride rating.

To illustrate the above points, it can be shown that increasing the modelled suspension and tyre stiffness values by 25% leads to an increase of about 12% in the modelled ride vibration. These changes would be akin to converting the proposed "average" car model to a "sports" version. Further increases in modelled ride vibration could also be achieved through adjustments to the seat suspension. Taking this point one step further, consistent with the discussion dot points presented above, Figure 13 illustrates the level of agreement that can be achieved by increasing the modelled ride vibration values by 19% and introducing a constant vibration component of 0.15 m/s^2. However, one aim of this research is to establish a representative "average" car that will provide representative ride vibration values that are in reasonable agreement with the majority of cars in the vehicle population. For the moment, and until a wider selection of vehicles can be tested, it is proposed to retain the original passenger car parameter set.

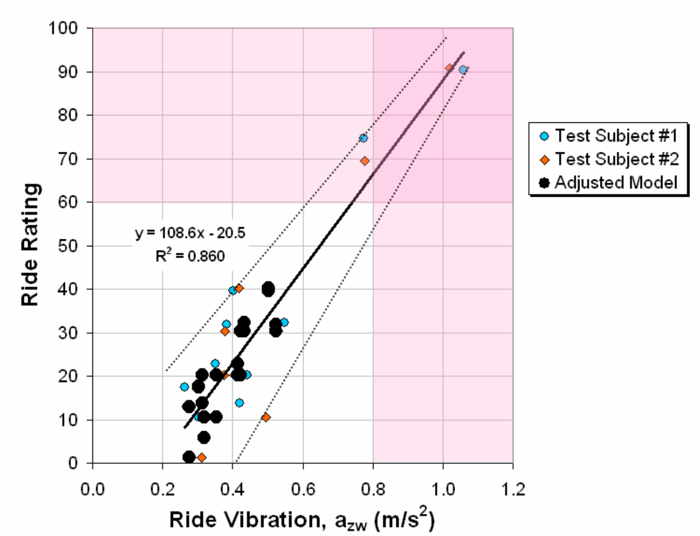

Figure 13 – Illustration of level of agreement between ride rating and measured and adjusted-modelled ride vibrations.

Outline of Planned Main Test Program

The results presented thus far in this paper have concentrated solely on vibration in a passenger car. The proposed ride models developed by Prem and Ayton (2005) are designed to simulate four generic road-user vehicle classes – passenger cars, heavy commercial vehicles (trucks), off-road recreational and sports utility vehicles (SUVs) and motorcycles. Figure 14 is based on the work of Prem and Ayton (2005) and illustrates the results that can be expected when a much wider range of vehicles is considered, consistent with the longer term aims of this project. As can be seen, the vibration levels across this range of vehicles are expected to be much broader than those recorded for a car.

To address this particular issue a much larger experiment is planned, the main details of which are summarised below in Table 5. In broad terms an approach will be used similar to the study described in this paper, but the number of test pavements, vehicles and test subjects will be increased. Assuming that each vehicle is used on each test pavement at least once, and travelling at the posted maximum speed, the total number of runs will be at least 140. Subjective ratings and measurement of ride vibration will be taken concurrently. Ride vibration measurements will be taken using a seat pad that incorporates GPS tracking. This feature has been incorporated into the current seat pad and an example output is given in Figure 15. This records the precise location of the seat pad and its speed, thereby assisting with identification of each recording and the start and end of each test section.

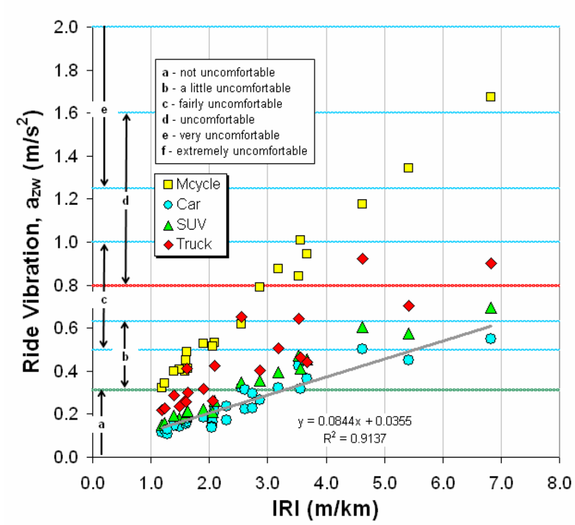

Figure 14 - Full range of vehicles to be considered in the main experiment, adapted from Prem and Ayton (2005).

Table 5 – Key Parameters for Main Experiment

Variable	Total Number	Specifics
Pavements	20	10 flexible, 10 concrete
Vehicles	7	1 truck, 2 SUVs, 2 cars, 2 motorcycles
Test Subjects	6	4 male, 2 females

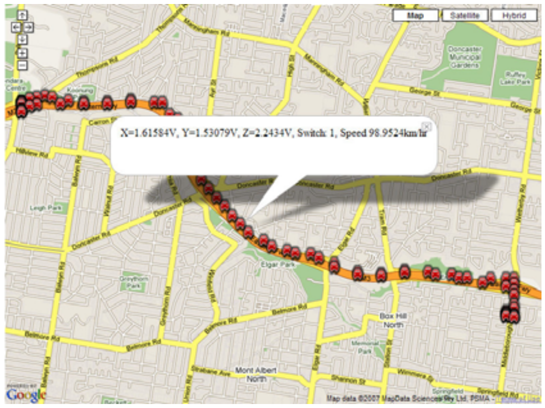

Figure 15 - Position and speed output from new instrumented seat pad with GPS-based tracking.

Summary and Concluding Comments

Preliminary field trials and tests were conducted of the ride quality model for a passenger car proposed by Prem and Ayton (2005). To assess the effectiveness of the model as a ride quality predictor, the overall modelled ride responses were compared with actual measured ride vibrations (objective measures) and road-user ride ratings (subjective measures), all taken on the same sections of pavements. Ride vibration was measured with portable vibration measuring equipment, comprising accelerometers, event markers and a data logger. Subjective ratings of ride vibration were obtained with a standardized rating form.

Analysis of the ride ratings, and the modelled and measured ride vibrations found there was close agreement between the subjective and objective measures of ride vibration. In particular, in absolute terms, the subjective and objective "seat of the pants" ride measurements were in close agreement.

However, when the ride rating and ride vibration measurements were compared with the IRI, while there was broad general agreement between the measures, some important subtleties were lost 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 concerns associated with the IRI and similar roughness metrics that this research is attempting to address.

The study found that the modelled ride responses correlated well with the subjective ride ratings, with less scatter than the relationship between ride rating and the IRI, and additionally picking up important subtle differences that the IRI was not able to detect.

Overall, the findings of this study are very encouraging and support the planned larger study, involving a larger sample of pavements (rigid and flexible), vehicles and test subjects.

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