Road and Track Roughness Factors for Bicycle Usage

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ABSTRACT

Assisted by funding from the State Bicycle Committee, cycle ways in Victoria have grown to the extent that their maintenance will soon become a pressing problem. Rational allocation of funds to maintenance rather than to new construction, as well as rational allocation of the available maintenance funds to specific projects, can only be achieved when objective measures of cycle way condition are available. These measures will allow objective criteria, which bear a known relationship to user opinion of the quality of the cycle way surface, to be established. This project evaluated the feasibility of developing an inexpensive and practical system, based on signals from an accelerometer mounted on the bicycle frame, to fulfill these objectives.

The driver rating of road surface acceptability is a basic performance indicator for road system management and has repeatedly been shown to correlate closely with the physical roughness of the road surface. Investments in bicycle-specific facilities are now at a level that necessitates better routine monitoring and construction standards. It is not possible to transfer road roughness measurement methods directly to bicycle facilities because road roughness indices are affected by automobile ride dynamics and road speeds typical of automobiles. The aim of this joint Victorian State Bicycle Committee and Australian Road Research Board (ARRB) feasibility study was to determine appropriate road and track surface assessment methods for cycle facilities, to develop and test an accelerometer-based system for measuring cycle way roughness, and to explore the effects of different types of bicycles and tires on surface condition ratings and accelerometer-based measurements.

SPECIFICATION OF THE PROBLEM

Bicycles have not always been treated as normal parts of the traffic stream, but this situation has been changing during the last few years. In Victoria, the Ministry of Transport State Bicycle Committee (SBC) has undertaken a continuing research program as a small fraction of the construction, education, and encouragement programs. This program has contributed to improved bicycle and helmet standards, better technical bases for bicycle lighting, and a sound basis for considering bicycle use in a transport context through a study of travel time and exposure in all of Melbourne (1).

As part of this program special attention has been directed at operational management and assessment of bicycle expenditures and facilities. The SBC Research Committee initiated studies in 1985 of the statistical requirements for monitoring usage and ownership of bicycles and of the requirements for routinely assessing and maintaining the large and growing network of facilities constructed in Melbourne with financial aid from the SBC.

This paper covers the feasibility study phase of the latter initiative. The objectives were to set up and test, on a small sample of people and bicycle facilities, a set of test procedures, which might be used for regular monitoring, and standards for maintenance and construction of cycle facilities. A further dimension was added to the study by using two bicycles that differed radically in design and quality of ride.

The need for special treatment of bicycle way surfacing and maintenance standards to suit the distinctive suspension and speed characteristics of these vehicles is beginning to be appreciated more widely and is one of the specific recommendations of the Perth Metropolitan Region Bikeplan (2). This quantitative study of possible operational standards setting and surface maintenance requirements is therefore particularly timely.

The essential elements of the feasibility study were therefore to

1. Specify, construct, and test suitable measurement equipment;
2. Select suitable sections of cycle ways for test purposes;
3. Obtain rider ratings of these conditions;
4. Carry out tests on the selected cycle way sections;
5. Carry out calibration tests using the standard automobile-based roughness meter at a typical cycle speed;
6. Report on the results and the feasibility of a standard cycle facilities rating and monitoring system based on these findings; and
7. Specify the requirements of an operational system based on this approach.

INVESTIGATION

Accelerometer-Based Instrumentation System

For large-scale surveys roughness has traditionally been measured by accumulating the relative displacement between the rear axle and the body of a standard vehicle as it traverses a road section at a standard speed. Although the inadequacies of this technique have been recognized and addressed (3), its simplicity, wide acceptability, and reasonable correlation with user evaluation guarantee its use by road authorities into the foreseeable future. Because bicycle wheels are attached directly to the frame of the machine, it is not possible to make exactly analogous measures, and movements in the vertical

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plane must be taken as absolute movements rather than relative movements between two components connected by a suspension system that acts to damp this movement. A convenient way of achieving this is by taking the output of an accelerometer firmly attached to the frame of the bicycle and oriented to measure vertical accelerations. This has the advantage of directly measuring the vibration pattern experienced by the rider (with the exception of the damping effect provided by the saddle), so that a good correlation between user evaluations and a suitably processed form of the accelerometer output might be expected.

The detailed debates on the different methods of measuring road roughness and rider acceptability have been concentrated on the need to be able to calibrate such measures for management and monitoring purposes. Gillespie et al. (3), Queiroz et al. (4), and Gillespie (5) provide detailed discussions of the different ways of measuring road roughness and the problems inherent in the measurement procedure.

The use of root mean square vertical acceleration (RMSVA) produced a potential direct link to the International Standards Association (ISO) (6) vibration comfort levels and to passenger serviceability ratings based on such values (7,8). At the standard highway speeds at which the National Association of Australian Road Authorities (NAASRA) roughness measures (9) are normally taken, there is a reasonable expectation of a close relationship between RMSVA measured within the automobile and NAASRA roughness meter values. On the bicycle, RMSVA is measured without most of the vehicle suspension benefits that contribute to automobile passenger comfort at the point of measurement of in-car RMSVA.

A major objective of automobile manufacturers is to improve the occupant comfort levels within a vehicle, and as a result the relationship between the road surface itself and the vehicle body is designed to reduce the transmission of road irregularities to the occupants. The only suspension system between a track surface and a cyclist is the tires. The conventional bicycle frame and forks are characteristically of low torsional and deflection rigidity, but the tire compliance levels are generally an order of magnitude greater than that of these structural elements. The pressures specified to be used by the manufacturer for different types of bicycle tires can therefore be expected to have a significant effect on rider comfort. Two different types of bicycles and tires were tested to explore the rider comfort relationships between different bicycles.

An Entran model EGEX semiconductor accelerometer with a range of ±5 g was attached to an aluminum mounting that was firmly clamped and bolted to the bicycle frame next to the rear wheel mounting. Block diagrams of instrumentation used to measure and record and then to analyze the accelerometer output are shown in Figures 1 and 2. Output from the accelerometer was fed through an amplifying circuit

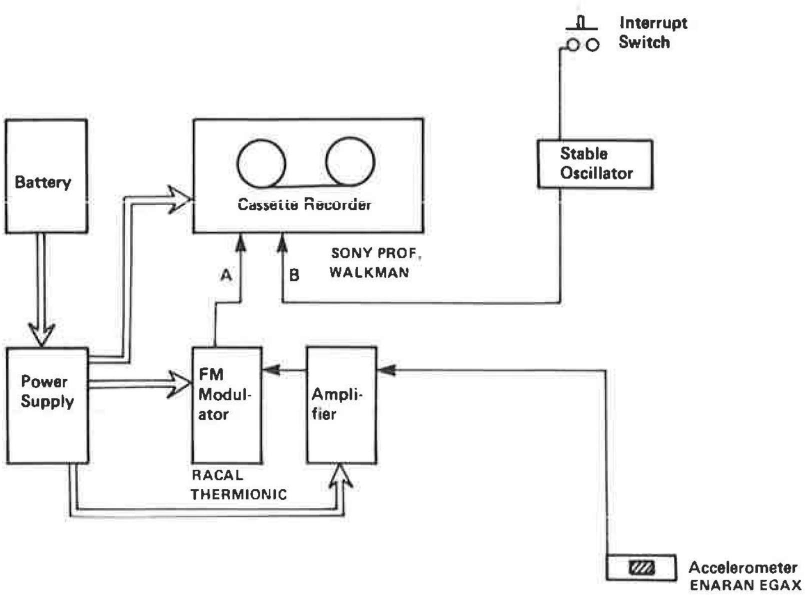

FIGURE 1 Instrumentation used to measure accelerometer output.

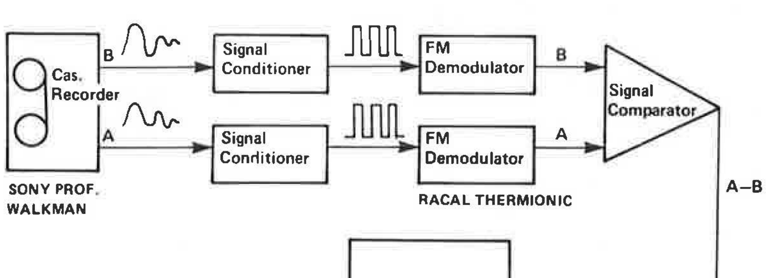

FIGURE 2 Instrumentation used to analyze accelerometer output.

and the amplified signal fed into an FM modulator extracted from a 1977 vintage Racal 7 track FM recorder. The FM signal was then recorded on one track of a two-channel audio cassette recorder. On the other track, the output of a stable oscillating circuit was recorded: a handlebar-mounted switch allowed this signal to be interrupted, so that it acted as a signal to the operator at the analysis stage for the beginning and end of the recordings of interest, as well as a stable reference against which the accelerometer output could be compared.

Analysis of the results was conducted by playing both of the recorded signals first through a signal conditioning circuit, which improved the edge definition characteristics of the FM signal, then through an FM demodulating circuit to convert the signals back to analog form.

The FM demodulator was also taken from the Racal FM recorder. The reference signal from the stable oscillator (B) was then subtracted from the accelerometer output (A). This corrected for any variations in the signal due to the physical movement of the cassette recorder and consequent variations in recording speed. The corrected signal was then fed into a signal analyzer: the maximum signal occurring in each of the time-base periods of 0.0025 sec was then fed into the ARRB's CYBER 815, which calculated the RMSVA that was expressed as proportion of gravitational acceleration (9.81 msec^2 or 1 g). A fuller description of the analysis system may be found in George (10). Identification of the recording intervals of interest was achieved by having the rider depress the interrupt switch until the beginning of the test section was reached, when it was released, and depressing it once more at the end of the section. These breaks in the stable oscillating signal were located and used as markers in the course of analysis.

The amplifier, FM modulation circuits, and oscillator, together with a battery and power supply, were mounted on a board attached to a carrier on the bicycle by means of aluminum clamps secured by butterfly nuts to allow easy transfer between machines. To minimize vibration and consequent recording speed variations, the cassette recorder was mounted on a web harness that held it securely against a foam rubber pad on the rider's back. The same rider was used to obtain all of the accelerometer measurements. Two different ENTRAN acceleration sensors were used that required several recalibration tests when transferring equipment between bikes. It is recommended that, once mounted effectively, the acceleration sensors should remain undisturbed indefinitely on any future test or field machines. Furthermore, the equipment put together for this study was at minimum cost and does not represent what can be done with modern, largely off-the-shelf, but more expensive equipment.

Cycle Ways

The initial investigation of bike tracks located in the Melbourne metropolitan area was based on a bike path survey conducted by the Bicycle Institute of Victoria (11). Numerous tracks cited in the survey were investigated by the SBC Executive Planner and a representative from ARRB. Designated bike way sections at St. Kilda, Albert Park, Ivanhoe, and Yarra Bank were considered a representative sample of differing conditions and surface types and were selected for investigation. Very smooth areas, which were not part of the cycle track system but which were conveniently close to test sections, were included as reference sections. Descriptions of the locations are given in Appendix A and the physical locations are shown in Figure 3. The calibration with the vehicle-based roughness meter was carried out on the ARRB test pavement sections at Cranbourne, Victoria. These consecutive pavement sections vary widely in roughness and are routinely used to calibrate State Road Authority roughness measurement vehicles against the ARRB standard vehicle.

The two bicycles used in the investigation were (a) a conventional touring bike with a wheelbase of 1.05 m and with narrow tires inflated to a pressure of 580 kPa throughout the experiment and (b) a Peugeot mountain bike with a wheelbase of 1.12 m and wide tires inflated to 210 kPa. A suitable gear was selected at the start of the experiment, and the same gear was used by all the panel of riders and on all the measurement runs. The touring bike was fitted with a commercial electronic multifunction speedometer that allowed monitoring of speed during the measurement runs and accurate measurement of the length of the test sections.

Rider Evaluations

Riders

A total of 12 subjects were used, including both regular and occasional cyclists. Information about personal riding habits, knowledge of local facilities, and other demographic information was collected at the start of the experiment. The panel used could not possibly be representative of the overall or even the regular cycling population, and the rider characteristics were collected mainly to test the form design. However, the information is relevant to this paper and is therefore briefly discussed here. Fuller details are given in Appendix B.

The age range of the trial test panel was between 30 and 43 years of age, and all but two were from households without children under 18 years of age. The level of 1978 Melbourne bicycle ownership by this age group for adult-only households was between 10 percent (30 to 35 years) and 20 to 25 percent (35 to 45 years) (1), and these age groups represented only a small amount of the bicycle travel time in Melbourne. However, the 30 to 45 year old age group has the highest level of adult bicycle ownership, and the panel is therefore less unrepresentative than would otherwise be the case. The dominance of male riders is also reasonably representative because Australian female participation rates in cycling are typically lower than that of males in both the 26 to 34 and the 35 to 49 year old age group.

The "last used bicycle" question is important because its lack significantly reduces the otherwise substantial value of interview surveys as a basis for cycle travel analysis (1). Only two of the 12 were "everyday" cyclists, and only half traveled any more recently than "last month." Bad weather clearly affects the enthusiasm of this group for cycling, and the near-universal access to at least one motor vehicle in the household clearly provides for an alternative mode of travel, in addition to public transport. Most cyclists rode for recreation, and half also used cycles for commuting purposes at least some of the time.

Procedure

Each participant rode both of the bikes over all sections: subjects rode a measured 100 m at free speed to a marker, turned, and rode back to the starting point. On completion of the run, subjects rated the run on that bike on a six point scale going from 0 = impassable to 5 = perfect; they then indi-

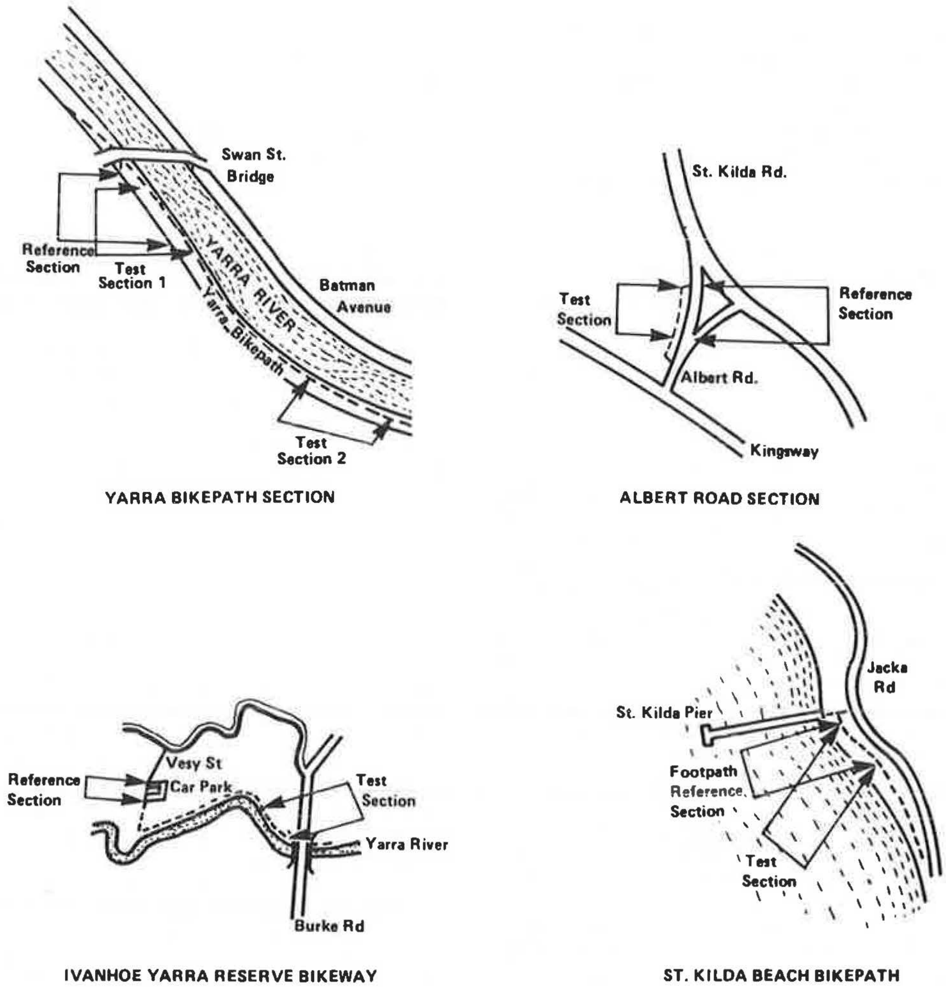

FIGURE 3 Locations of test sections.

cated whether they thought the present condition of the path was acceptable and gave a confidence rating for their answer on a three point scale going from "very sure" to "not sure" (Appendix C).

Data were collected in two separate sessions, with the orders in which the tracks were visited reversed on the second occasion to counterbalance any effects of practice, fatigue, or boredom.

Results of Rider Evaluations

Two measures of rider opinion were used

- The average value of the ride quality ratings awarded by the riders (serviceability level) and
- The percentage of the riders prepared to rate the section as "acceptable" (tolerability level).

The mean values of the participants' ratings for each section are given in Table 1 along with the results of matched-pairs t-tests for differences between the bikes and the tolerability scores (i.e., the proportion of respondents judging that section as offering an acceptable ride).

The Ivanhoe section was clearly rated better than all of the others, and the Albert Park track rather worse than all of the others. For three of the four sections for which data are available, the rating of the section was significantly better when traversed on the mountain bike rather than the touring bike.

Turning to the tolerability scores in the last two columns of Table 1, the Yarra Bank section attracted most "acceptable" responses followed closely by the Ivanhoe track. The Albert Park track fared poorly with both machines, with a few more riders saying the ride on the mountain bike was more acceptable.

However, in the case of the St. Kilda track, there is a large discrepancy, with 80 percent of the riders stating the ride was acceptable with the mountain bike and only 30 percent saying it was acceptable with the touring bike. Although the reasons for this discrepancy are not clear, it appears likely that the constant, small undulations were experienced as particularly uncomfortable on the hard tires of the touring bike, which effectively obviated the suspension cushioning offered by softer inflated tires.

The plot of the mean serviceability rating against the tolerability scores shown in Figure 4 shows good agreement between the two measures, with all mean serviceability ratings greater than 3 attaining tolerability scores of 0.80 or above, the two serviceability ratings close to 2 having a tolerability score of 0.3, and the lowest serviceability score at 1.6 having a tolerability score of only 0.1. Thus there would appear to be a high degree of consistency between the two scores. The one exception to this pattern is the gravel surfaced Ivanhoe recreational track, which despite its high serviceability rating had lower tolerability than some of the other sections. The surface structure was a compacted sand and gravel surface that provided a smooth riding

TABLE 1 Rider Ratings of the Cycle Ways Tested

	Serviceability			Tolerability	
Location	Tour Bike	Mountain Bike	t-Test Outcome	Tour Bike	Mountain Bike
Yarra Bank	3.0	3.2	−0.83 NS[a]	86	86
Albert Park	1.6	2.1	−2.44 p = 0.03	10	30
St. Kilda	2.3	3.1	−3.24 p = 0.01	30	80
Ivanhoe	3.2	3.8	−3.11 p = 0.03	82	80

[a]NS = no significant difference between the two bicycles.

surface with little or no loose gravel material apparent.

It is probable that some respondents perceived the unsealed surface as an inferior form of construction and judged the track as unacceptable on this basis rather than on the quality of ride. It should be noted that the geometric standard of the Ivanhoe section was markedly inferior to that of all the other sections and that several riders commented on the "drag" effects of the surface, although at the same time recording (marginally) the highest average free speed of all the tracks investigated. These two factors distinguished Ivanhoe from all of the other sections listed and suggest that further work on the relative acceptability of such recreational surfacings and geometric standards is required. The width and the general environment of the different tracks may also have affected the responses.

The panel riders were not given any specific instructions about speed, other than a request to ride as they normally would, at an appropriately comfortable speed. No doubt some reduced their chosen speed to accord with their perceptions of an appropriate speed for an experiment of this kind.

The average speeds recorded over the sections for both bikes all lay within the range of from 17.6 to 22.5 km/hr, and the overall average speeds on the mountain (19.8 km/hr) and touring (19.7 km/hr) bikes were extremely close, so that a standard speed of 20 km/hr was subsequently specified for the accelerometer data collection trials. The (marginally) highest average speed (22.5 km/hr) was recorded for the touring bike at Ivanhoe on a twisty section, with poor sight lines and a significant slope, that was shared with pedestrians.

Clearly, as a separate exercise, it would be sensible to collect a more systematic series of average free speed values for cyclists on tracks of various types, surfaces, sight lines, and geometric standards controlled for weather conditions.

Cycle Track Measurements

Procedure

After the rider panels had been run, a separate series of measurements was obtained for each cycle track section using the accelerometer system. The same rider was used to collect all of the RMSVA measurements.

At the start of each run, the accelerometer was calibrated by slowly inverting it with the bike held vertical, holding it in position for 10 sec, and then returning it to the upright. As well as being recorded on cassette, the output was monitored on a digital voltmeter during this stage. A reference signal of 1 v was then fed onto the tape. At the conclusion of the calibration procedure, the rider pressed the button suppressing recording, made his approach run, and released the button when passing a traffic cone marking the beginning of the test section. The test section was ridden at as near a constant 20 km/hr as was possible. Observation of the speedometer on the touring bike showed that speeds never fell below 18 km/hr or went above 24 km/hr and were generally between 19 and 22 km/hr. No speedometer was available on the mountain bike, and the rider had to try to match the time taken to ride on the mountain bike with that measured on the touring bike.

When the traffic cone marking the end of a section was reached, the rider depressed the cut-out switch and maneuvered the bike so as to have reached a speed of 20 km/hr before passing the cone again on the

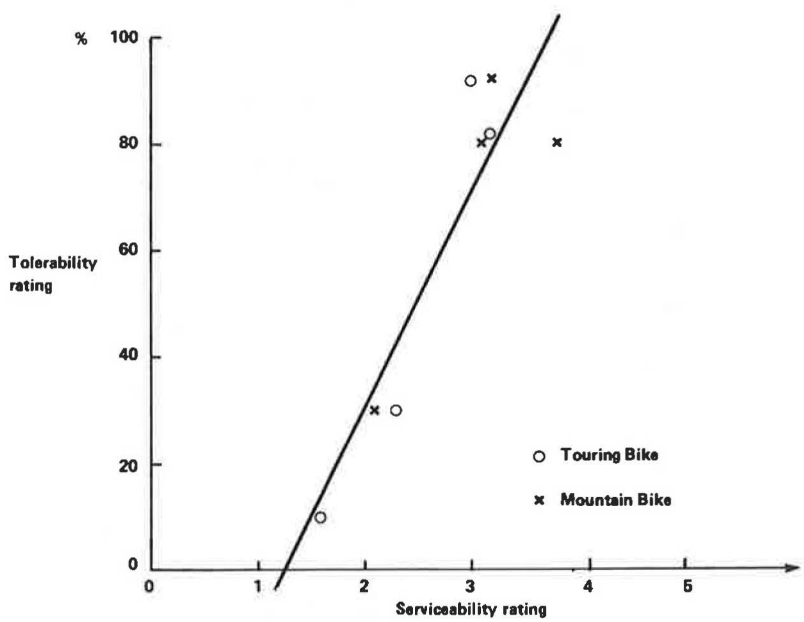

FIGURE 4 Mean serviceability rating versus tolerability.

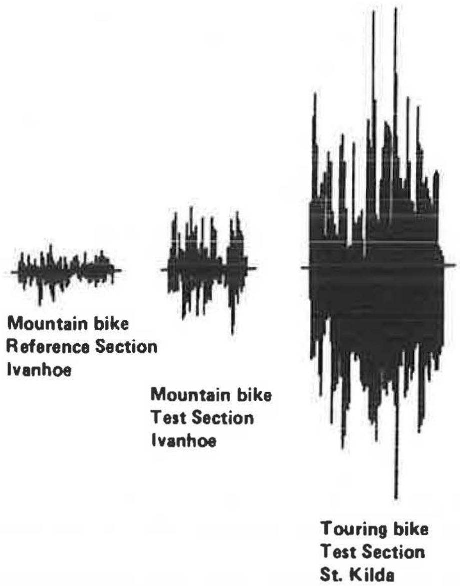

FIGURE 5 Typical accelerometer output.

return trip. On passing the cone the rider released the switch, and subsequently depressed it once more at the end of the section. The RMSVA for the section was aggregated over runs in both directions. Figure 5 shows a set of typical traces of the accelerometer outputs.

Results

The values of RMSVA measured by the prototype equipment on the bicycle are shown for both bikes on all of the test sections in Figure 6. Because these points represent one observation each, no measure of repeatability of the RMSVA can be derived and no statistical analysis is justified, but two salient points are evident from the graphs apart from the generally high levels of RMSVA recorded. First, the touring bike recorded consistently higher RMSVA than did the mountain bike. For the Yarra Bank and Albert Park sections, and for two of the reference sections, the difference is approximately 0.1 g, and for the very corrugated St. Kilda sections, the difference is 0.2 g. In the case of the very smooth track surfaced with a rolled fine gravel at Ivanhoe there was little difference between the machines.

The consistency of the difference between the bikes is encouraging and argues for the validity of the technique. Although the lack of difference on the rolled gravel track is to be expected, the large difference on the two rougher sections may be of greater interest and suggests as yet uncontrolled resonance factors related to the location of the accelerometer mounting.

The second point is that there is considerable variation among the sections. The St. Kilda track section gave approximately double the RMSVA level of the gravel track of Ivanhoe and approximately 1.6 times as much acceleration as did the best of the asphalt surfaces (the Yarra Bank section). All of the reference sections were smoother (i.e., lower values of RMSVA) than the bike track sections, with the sole exception of the Ivanhoe gravel path. The technique is therefore sensitive enough both to detect variations in surface condition that are characteristic of the bicycle path network and to discriminate between the rider comfort levels of the different types of bicycle used. In general, the confidence in the acceptability ratings awarded when riding the mountain bike was higher than when riding the touring bike (see Appendix B), and there were fewer complaints of "continuous small bumps," as might be expected from the larger and softer tires fitted to the mountain bike.

Relationship to Rider Evaluations

The serviceability and tolerability ratings discussed previously are plotted against RMSVA in Figure 7.

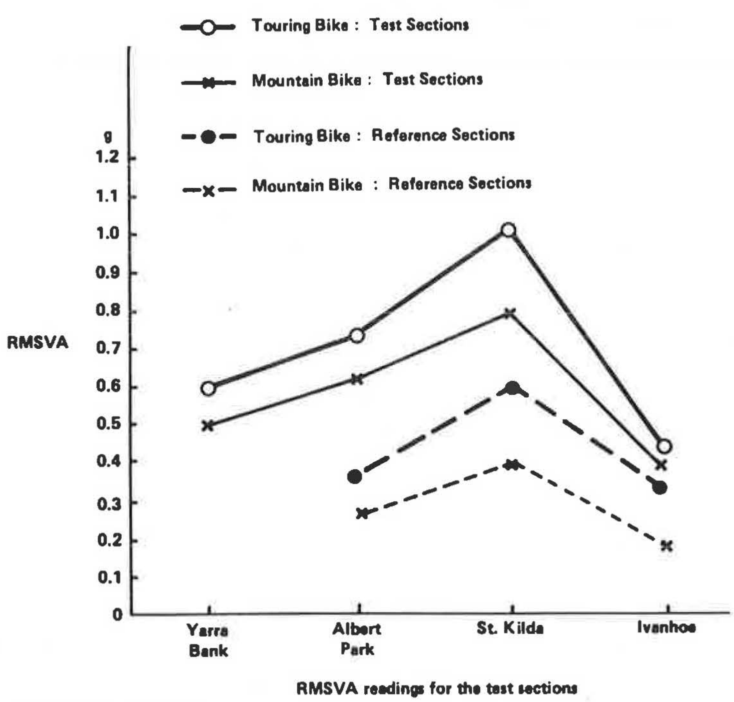

FIGURE 6 RMSVA measurements for both bicycles.

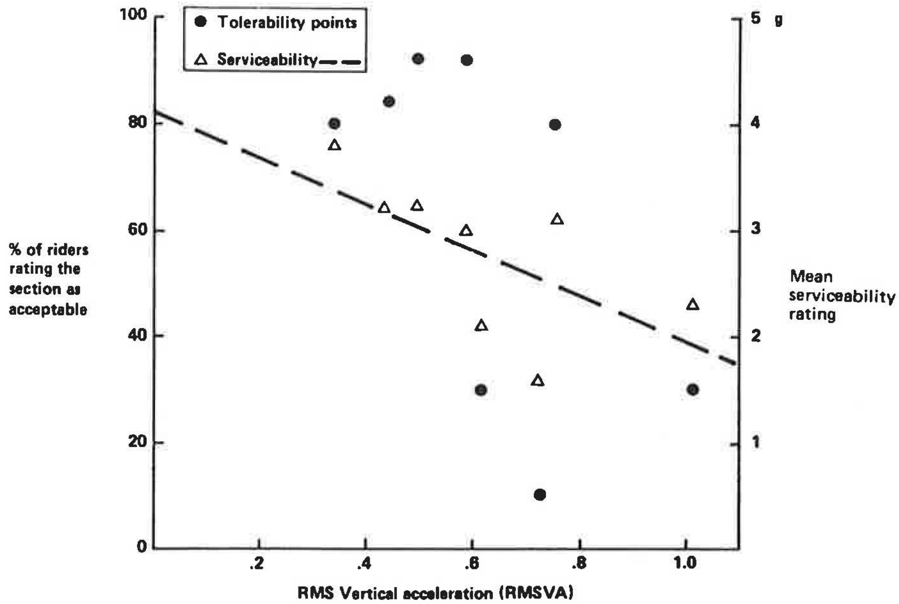

FIGURE 7 Serviceability and tolerability ratings versus RMSVA.

Good agreement is evident between the RMSVA and serviceability ratings. Taking all eight points into consideration (i.e., four sections with both bikes), a correlation of 0.65 was obtained, which indicates a significant degree of agreement between the two variables. Moreover, the slope of the regression line is such that RMSVA can be related in a meaningful way to the user evaluation responses.

The tolerability (i.e., the percentage of the sample of riders to whom the section was acceptable for commuting) ratings, on the other hand, produced no such clear pattern; one group of sections attracted high acceptability ratings and the other group attracted low acceptability ratings, with no suggestion of a regular linear relationship. Cluster analysis confirms that these are two distinct groups of responses, and it is not justifiable to assume a linear relationship. Tolerability probably covers a wider range of factors than RMSVA. Details of the regression equations obtained using SYSTAT (12) are shown in Figure 8. SYSTAT is a comprehensive statistical package, comparable to SPSS, that runs on most small computers (in this case an OTRONA Attache 8-16 under MSDOS). The correlation between tolerability and RMSVA is -0.6, and the correlation between serviceability and tolerability is 0.92, but these values should be treated with caution for the reasons discussed.

With one exception, tracks with RMSVA levels of over 0.6 *g* had very low acceptability, and those with less than 0.6 *g* had an equivalent degree of high acceptability. Results from many more sections would be required before the nature of the relationship and the criteria for acceptability adopted by different types of riders could be adequately established.

Although the correlation between RMSVA and serviceability is lower than the 0.80 or 0.90 generally found in studies involving sprung vehicles (13), it is sufficient to suggest that there is a predictable relationship between user evaluation and roughness as measured by the accelerometer system. It is possible that higher correlation will be found with a wider range of bike tracks, more experience for participants in the rating task, improved instrumentation, and better control of speed variation between RMSVA and panel runs over the sections.

A major need for follow-up work is to establish the reliability of the RMSVA results. This could readily be achieved by taking readings from several runs over the same section and computing the variability in the RMSVA measures. As well as demonstrating that the results are acceptably reliable, such data provide an indication of the degree of precision of the measurements. In view of the results obtained it is recommended that such work be undertaken at an early date.

Calibration Against the Standard Roughness Vehicle

Procedures

The calibration was carried out on a stretch of road near Cranbourne, Victoria, which ARRB, by arrangement with the Victorian Road Construction Authority, uses to calibrate road authority roughness meters against its own standard vehicle. It is divided into 11 consecutive sections, which vary considerably in roughness. Sections are identified by paint spots in the middle of the carriageway, and the wheel tracks to be followed by narrow longitudinal lines. Two additional sections on the adjacent Princes Highway form part of the standard calibration set but were excluded from this study.

Standard roughness measurements were obtained by driving the ARRB roughness vehicle, a Holden Commodore station wagon equipped with a standard NAASRA roughness meter over the sections at a constant 20 km/hr and again at 80 km/hr (the normal calibration speed). Further details may be found in the NAASRA guide to the measurement of road condition (9), which also provides for a speed of 50 km/hr.

Bicycle measurements were obtained by riding close behind a vehicle, with a roof-mounted flashing light, which traveled at a constant 20 km/hr. Following the calibration procedure outlined earlier, the rider followed the lead vehicle over the whole series of test sections, releasing the cut-out button as he entered the first section, and depressing the button for approximately 5 sec as he passed from one section to the next. The rider followed the line of the left wheel path as closely as possible. Observation of the bicycle speedometer showed that speed was generally held between 19 and 22 km/hr and never fell below 18 km/hr or rose above 24 km/hr. Outward and return

(i) Tolerability rating (T) .v. Serviceability rating (S)

T = - 55.2	+	S (41.9)
(s.e.) (19.6)		(7.0)
(sig.) (.026)		(.001)
R^2 = 0.84		Adjusted R^2 = 0.81

(ii) All Mountain Bike RMSVA values (MR) .v. All touring bike RMSVA values (TR).

MR = - 0.034	+	TR (0.706)
(s.e.) (0.046)		(0.090)
(sig.) (0.485)		(0.000)
R^2 = 0.87		Adjusted R^2 = 0.86

(iii) Mountain Bike calibration RMSVA values (MCR) .v. NAASRA Car NRM values at 20 km/h (N20)

MCR = 0.067	+	N20 (0.003)
(s.e.) (0.099)		(0.001)
(sig.) (0.518)		(0.032)
R^2 = 0.42		Adjusted R^2 = 0.35

(iv) Touring bike calibration RMSVA value (TCR) .v. NAASRA car NRM values at 20 km/h (N20)

TCR = 0.347	+	N20 (0.002)
(s.e.) (0.083)		(0.001)
(sig.) (0.000)		(0.072)
R^2 = 0.15		Adjusted R^2 = 0.11

(v) Mountain Bike calibration RMSVA values (MCR) .v. NAASRA car NRM values at 80 km/h (N80)

MCR = 0.233	+	N80 (0.001)
(s.e.) (0.096)		(0.001)
(sig.) (0.039)		(0.412)
R^2 = 0.076		Adjusted R^2 = 0.00

(vi) Touring Bike calibration RMSVA values (TCR) .v. NAASRA Car NRM values values at 80 km/h (N80)

TCR = 0.476	+	N80 (0.000)
(s.e.) (0.072)		(0.001)
(sig.) (0.000)		(0.750)
R^2 = 0.005		Adjusted R^2 = 0.00

(vii) NAASRA Car NRM values at 20 km/h (N20) .v. NAASRA Car NRM values at 80 km/h (N80)

N20 = 22.19	+	N80 (0.625)
(s.l.) (6.04)		(0.66)
(sig.) (0.002)		(0.000)
R^2 = 0.82		Adjusted R^2 = 0.81

(viii) Tolerability (TOL) of the test sections .v. Bicycle RMSVA levels

TOL = -115.49	+	RMSVA (88.21)
(s.e.) (31.2)		(47.66)
(sig.) (0.01)		(0.11)
R^2 = 0.36		Adjusted R^2 = 0.26

(ix) Serviceability (SERV) of the test sections .v. Bicycle RMSVA levels RMSVA

SERV = 4.13	+	RMSVA (-2.16)
(s.e.) (0.68)		(1.04)
(sig.) (0.001)		(0.084)
R^2 = 0.42		Adjusted R^2 = 0.32

(s.e.) = Standard error

FIGURE 8 Regression equations.

trips were made on the touring bike (22 sections in all); only the outward trip was made with the mountain bike, which produced data for 11 sections.

Results

Some of the analyses were carried out on the ARRB Cyber 815 using SPSS (14) and the majority on a small portable computer using SYSTAT (12) to save time and speed up the work. The RMSVA obtained with the touring bike is plotted against RMSVA acceleration with the mountain bike in Figure 9. Equation (ii) in Figure 8 shows that a good linear fit was obtained to these data, with an R^2 value of 0.87, which is highly significant.

The plots of the RMSVA readings for the touring bike and the mountain bike taken individually against the 20 km/hr automobile roughness meter output are shown in Figures 10 and 11, respectively, and the results of the regression analyses are given in Equations (iii) and (iv) in Figure 8. Although the relationship is significant in both cases, the adjusted R^2 values of 0.11 with the touring bike and 0.35 with the mountain bike indicate that the two measurement devices do not predict each other's output very well. The mountain bike gives a higher adjusted R^2 value than does the touring bike: with its wide, low-pressure tires it may be behaving more like the sprung motor vehicle carrying the NAASRA roughness meter, and there is a good case for comparing the ride dynamics of the bicycle with the NAASRA vehicle on known surface profiles, perhaps using "quarter car" models. Adjusted R^2 is the value of R^2 adjusted (downward) for the limited degrees of freedom on which the R^2 values had been computed and therefore provides a conservative view of the quality of the fit.

Because these R^2 values are not particularly high, it must be concluded that poor agreement between RMSVA as measured at the rear axle of a bicycle and the output from the roughness meter at present precludes the specification of cycle track standards in a form that can be readily related to conventional roughness measurements. The potentially high levels of acceleration "noise" present in the current bicycle measurement setup could, however, still be disguising the true relationship: it is not clear how much of the level is signal from the appropriate source. A full list of regression equations is presented in Figure 8.

These bicycle-automobile results generally reflect the known problems of automobile-automobile road roughness calibration at different speeds (3,4), and the relationship between the NRM counts at 20 and 80 km/hr shows the expected variations (Figure 12). The development of standards must therefore proceed by reference to bicycle-mounted measurement systems alone unless the acceleration noise can be markedly reduced and the relationship reexamined. On the other hand, it is important to note that consistent results have already been achieved using bicycles with very different characteristics, despite the prototype status of the equipment and procedures used.

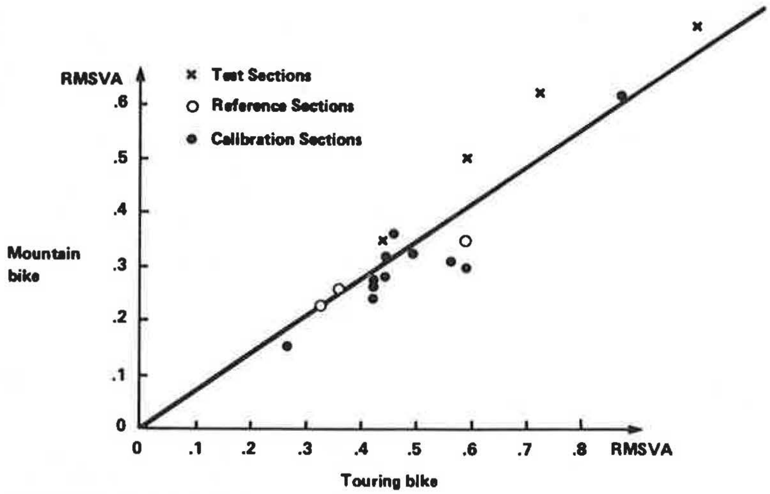

FIGURE 9 Relationship between RMSVA for touring and mountain bicycles.

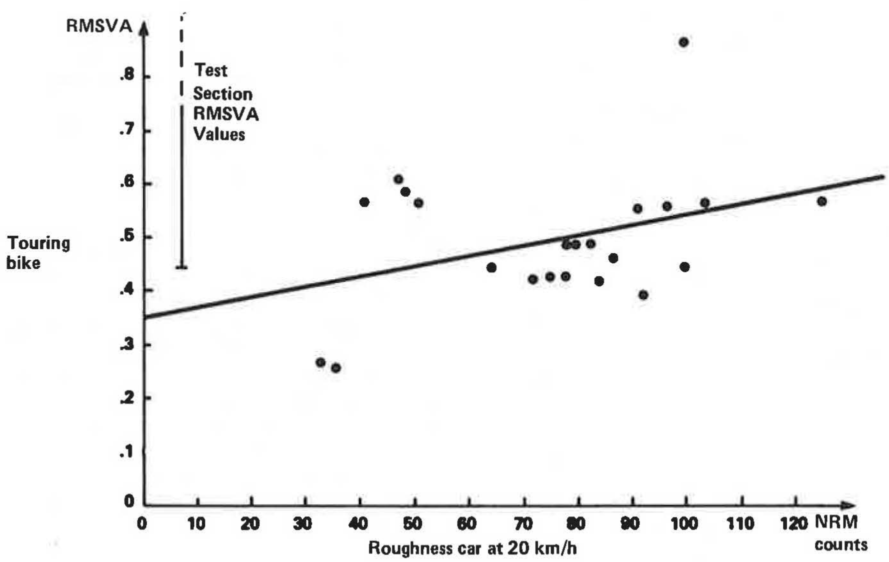

FIGURE 10 Relationship between RMSVA and NAASRA roughness meter output at 20 km/hr for touring bicycle.

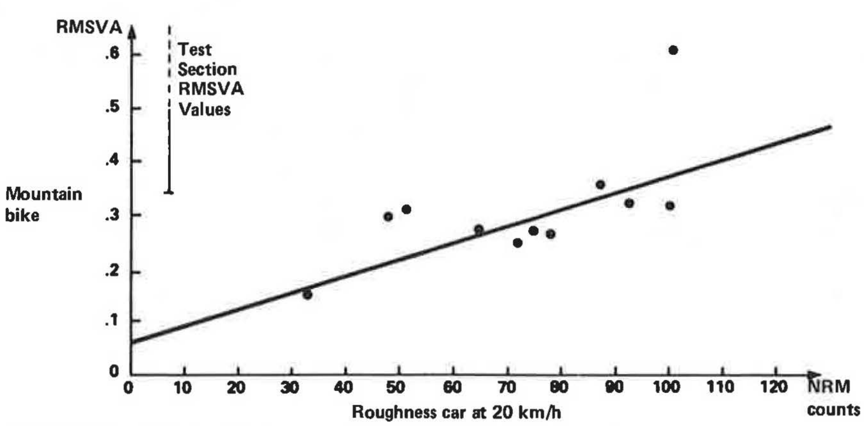

FIGURE 11 Relationship between RMSVA and NAASRA roughness meter output at 20 km/hr for mountain bicycle.

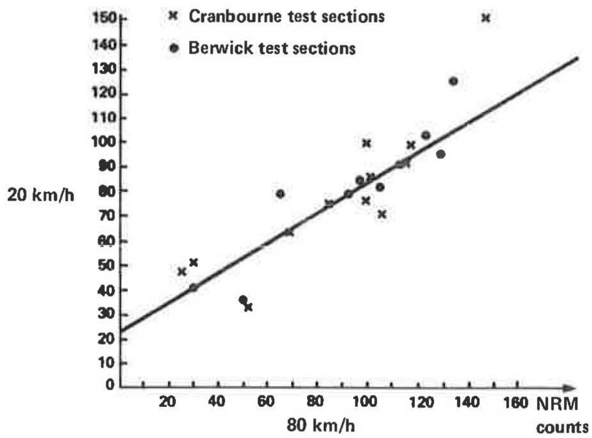

FIGURE 12 Effect of speed on NAASRA roughness values.

Comparison of Bike Track Sections and On-Road Calibration Sections

The ranges of RMSVA levels measured for the bike track sections have been added to Figures 10 and 11 for comparison purposes. In both cases it can be seen that the bike tracks were generally rougher (i.e., led to higher values of RMSVA) than the road sections, and the worst of the track sections could not even be accommodated on the graph. Even the smoothest bike track section was bettered by some of the road sections. The road test sections cover a wide range of roughness levels, with the worst sections so rough that they would seldom be encountered on the road system. Nevertheless, one of the cycle tracks gave readings much worse than the highest value obtained on the Cranbourne reference sections, and one of the others intended as a high-volume commuter track approached it in roughness. Systematic survey work is required before any systematic comparison can be made between the general surface condition of bike tracks and roads. The small number of test sections covered in this feasibility study is clearly inadequate for this purpose.

The correlations between the two series of automobile measurements of NAASRA roughness and the two bicycle-based RMSVA measurements are given in Table 2. The high level of correlation between the touring and mountain bikes (0.93) and the automobile at 20 and 80 km/hr is not apparent when the two types of measure are related. Neither bike gave satisfactory correlation coefficient values with the automobile at 80 km/hr (the standard NAASRA automobile measurement speed); this cannot be dismissed as the result of the automobile automatically averaging over the roughness levels along the two wheel tracks whereas the bicycle follows only the inner track because the correlations with the automobile at 20 km/hr are reasonable, if not acceptable, notwithstanding the differences between bicycle and automobile dynamics.

A varimax rotated factor analysis was used to check the association among the four different roughness ratings. Table 3 gives the results and demonstrates quite clearly that the two automobile measures taken together and the two bicycle measures taken together explain 98 percent of the variance, about half each.

Two simple cluster analysis trees were produced. Figure 13a is based on the (unscaled) Euclidean distance measure for clustering, and Figure 13b uses the Pearson correlation coefficient as a (normalized) distance measure. In both cases the same degree of association shown in Table 3 is visible in an easily appreciated form.

Table 4 shows the remarkably high degree of consistency in the ranking of the road roughness level by each of the measures used. The level of confidence that can be placed on these relative rankings indicates that the fundamental approaches adopted for road roughness rating purposes can produce excellent results for between-vehicle rankings. These results also accord with the subjective views of those taking the measurements.

Spectral Analyses of the Bicycle-Mounted Accelerometer Results

The spectral power densities of the accelerometer recordings were used to clarify the different characteristics of the different types of roughness encountered.

The RMSVA values may have been affected by resonance effects produced by the bicycle accelerometer mounting and by various attachments on the bicycle. The operational development stage of this work will require some systematic investigation of the best means of reducing such energy input to the accelerometer. However, all of the results presented in this paper are consistent with each other.

Spectral analysis was used to examine the nature of the vibrations recorded by the accelerometer. A Hewlett-Packard spectrum analyzer was used to determine the power distribution of the accelerometer signal against the frequency of the vibrations. Figures 14-17 show a set of such spectral analyses. The vertical scales are slightly different for the touring and mountain bikes as a result of the different accelerometers.

The reference section of road used beside the Yarra Bank bike path showed (Figure 15) greater low-frequency effects (0 to 15 Hz) than the bike path (the bike path exceeded the reference section by from 20 to 50 Hz). These frequencies correspond approximately to surface undulations shorter than 0.2 m (for the 20 to 50 Hz range), which gives some clues as to the composition of the pavement roughness.

At Albert Park (Figure 14) the reference and cycle way sections were far more closely comparable, and the consistent pattern of the track exceeding the reference section is clear from 2 to 55 Hz.

The extremely irritating St. Kilda track (Figures 16 and 17) showed large concentration of energy in the low-frequency range, corresponding to the wavelengths of most of the surface undulations.

TABLE 2 Pearson Correlation Matrix of Calibration Section Roughness Measures

	Automobile at 80 km/hr (NRM)[a]	Automobile at 20 km/hr (NRM)	Touring Bike (RMSVA)	Mountain Bike (RMSVA)
Automobile at 80 km/hr (NRM)	1.0			
Automobile at 20 km/hr (NRM)	0.86	1.0		
Touring bike (RMSVA)	−0.01	0.42	1.0	
Mountain bike (RMSVA)	0.28	0.65	0.93	1.0

[a]NRM = NAASRA roughness measure (counts).

TABLE 3 Varimax Rotated Factor Analysis of Calibration Section Results

	Factor			
	1	2	3	4
Automobile at 80 km/hr	−0.02	−1.00	0.10	0.02
Automobile at 20 km/hr	0.40	−0.90	−0.21	0.07
Touring bike	0.99	−0.01	−0.04	−0.10
Mountain bike	0.95	−0.29	−0.03	0.13
Percentage of total variance explained	51	47	1	1

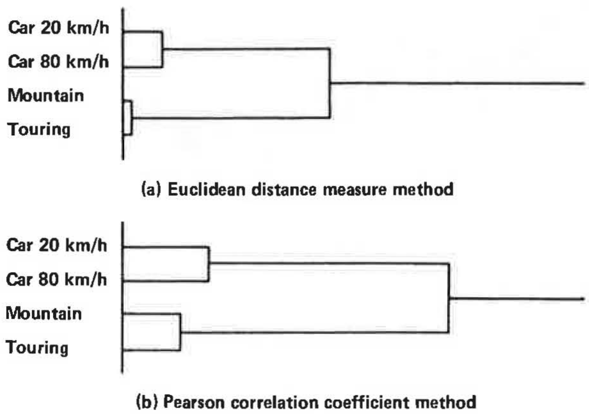

FIGURE 13 Cluster analysis.

TABLE 4 Freidman Two-Way Analysis of Variance of Calibration Sections Results

	Rank Sum	Remarks
Automobile at 80 km/hr	41.5	
Automobile at 20 km/hr	35.5	Kendall coefficient of concordance = 0.93
Touring bike	22.0	Significance = 0.000 with 3 degrees of freedom
Mountain bike	11.0	

These diagrams illustrate the different nature of roughness of different types of surfaces and show the first steps of the process of relating rider comfort to surface characteristics.

The highly consistent relationship between user ratings and RMSVA results for the two types of bicycles also provides a practical basis for comparing the rider comfort levels of different bicycles. Unfortunately, perhaps, the key variable is probably tire pressures used because the average speeds chosen by the riders were similar.

It is important to note that the 20-km/hr standard speed that was adopted after the first series of field trials is not necessarily the most appropriate speed to use for all types of bicycles and cycle ways. The changes in methods and results that use of different speeds might require are as yet uncertain, but different speeds definitely must form part of any subsequent implementation project.

DISCUSSION

The results of this exploratory investigation are sufficiently encouraging to suggest that a bicycle-mounted accelerometer system could be developed into an appropriate measurement tool for the routine assessment of cycle way condition. Good agreement between the RMSVA obtained with the two machines was evident on both the on-road calibration sections and the cycle tracks, allowing for a constant difference between them, and the measurements appeared to be sensitive enough to discriminate between cycle track sections.

Furthermore, the accelerometer measurements agreed sufficiently well with the serviceability ratings of the sections to suggest that the system could be developed to adequately predict user evaluation. The degree of relationship with tolerability scores for the sections was less clear, and more data are needed before any firm relation can be established. The findings reported here are sufficient to suggest that the methods developed are valid. That no useful relationship with the conventional vehicle-based

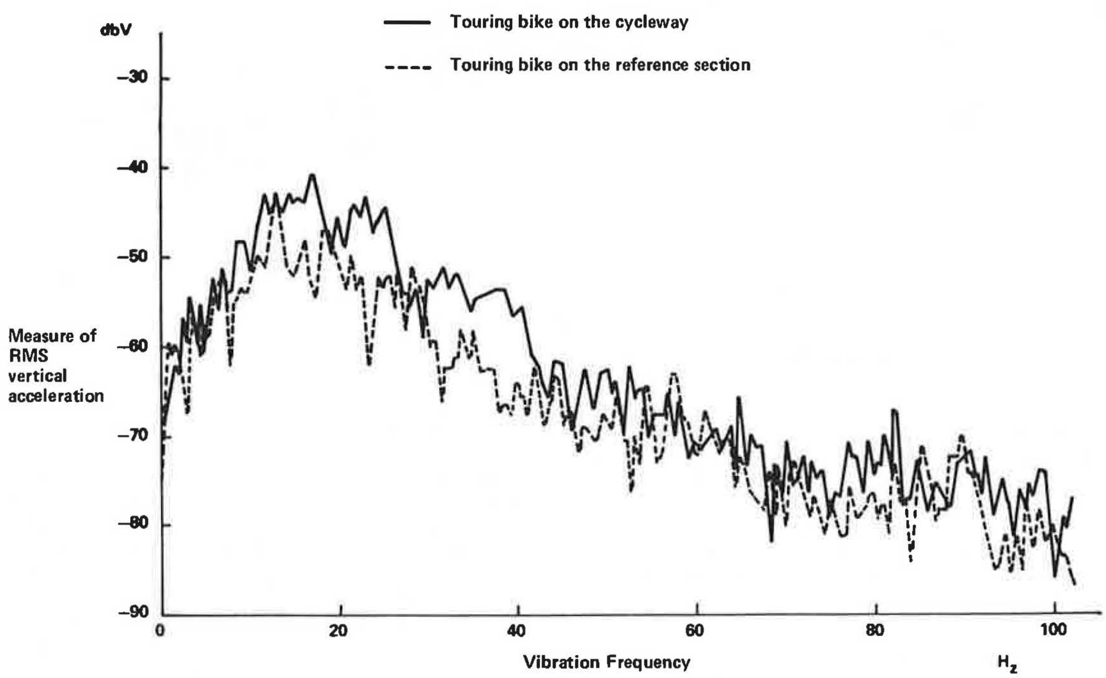

FIGURE 14 Spectral analysis—Albert Park.

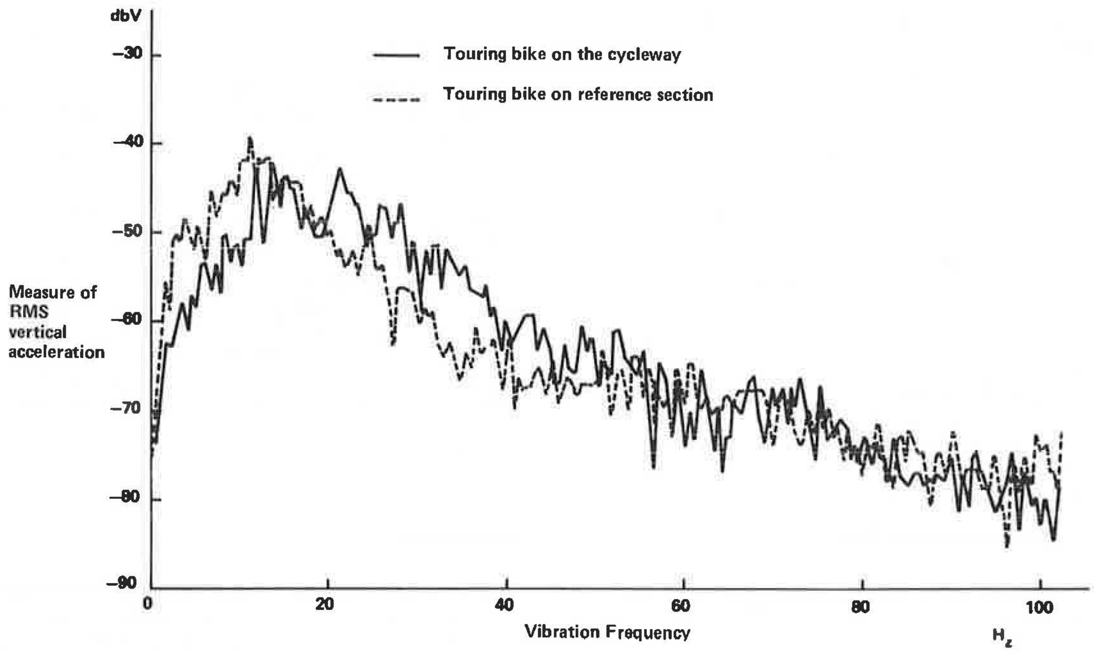

FIGURE 15 Spectral analysis—Yarra Bank.

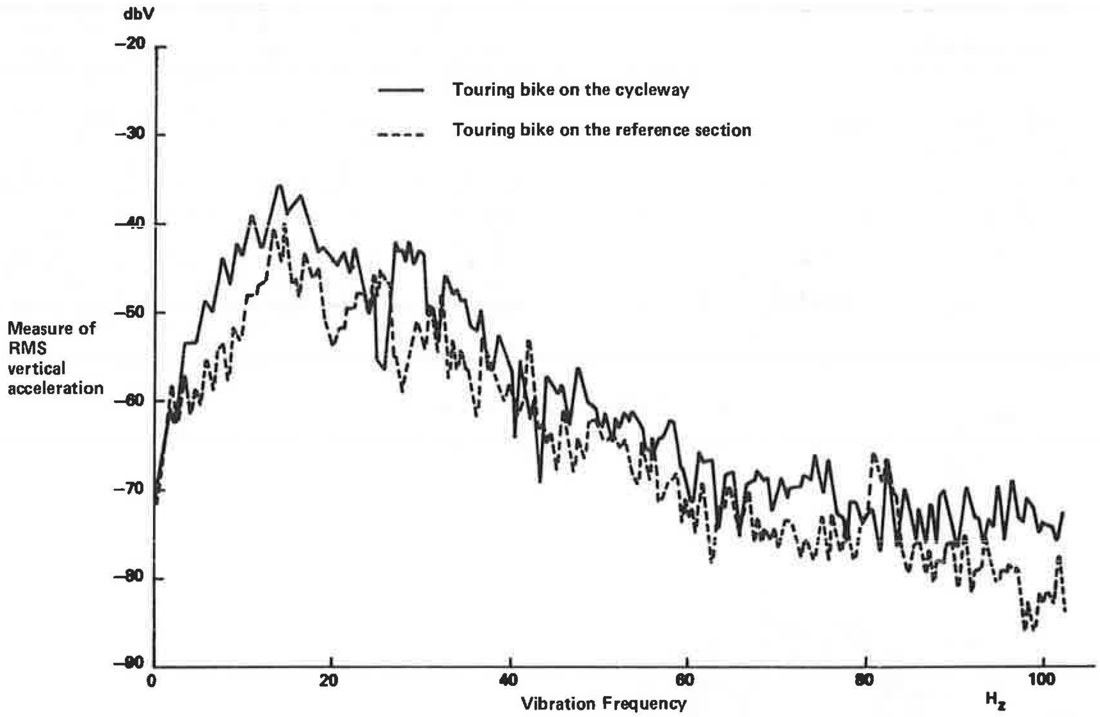

FIGURE 16 Spectral analysis—St. Kilda.

roughness measurements could be established does not detract from this validity, and the problems of cross calibrating automobile roughness levels measured at different speeds is well known.

Consequently it does not now appear to be productive to work toward standards for cycle tracks expressed in terms of roughness counts or their equivalents. Instead, standards should be expressed in terms of RMSVA using a standard bike, standard rider, standard tire pressure, and perhaps specific pavement wheel track profiles for calibration. This feasibility study has shown that this is a reasonable goal.

There has been a considerable amount of work done on determining the acceptable levels of vertical acceleration for transport vehicles (7), and an international standard has been produced (6). Figure 18 is derived from this ISO standard and shows the special sensitivity of the human body to vertical acceleration in the 4 to 8 Hz range. The vertical scale is RMSVA--the chosen roughness indicator--and illustrates the practical and direct link between this measure and rider comfort and fatigue. The two continuous curves shown correspond to the RMSVA tolerance levels for 1-min and 1-hr exposures, which cover the majority of cycle journey stages.

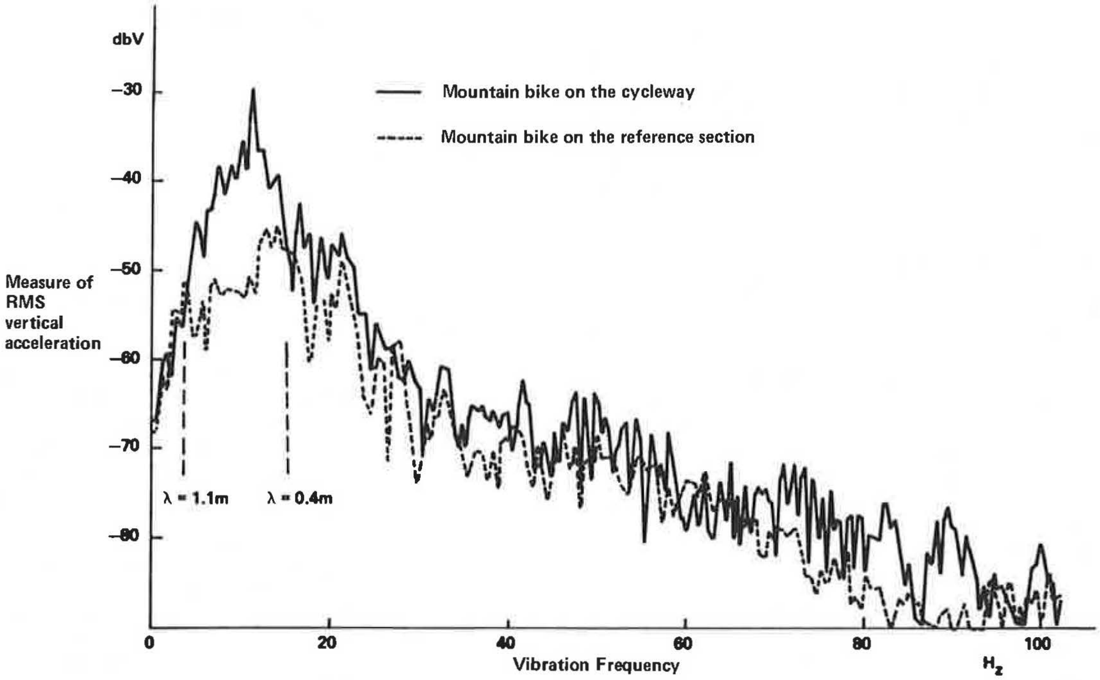

FIGURE 17 Spectral analysis—second example from St. Kilda.

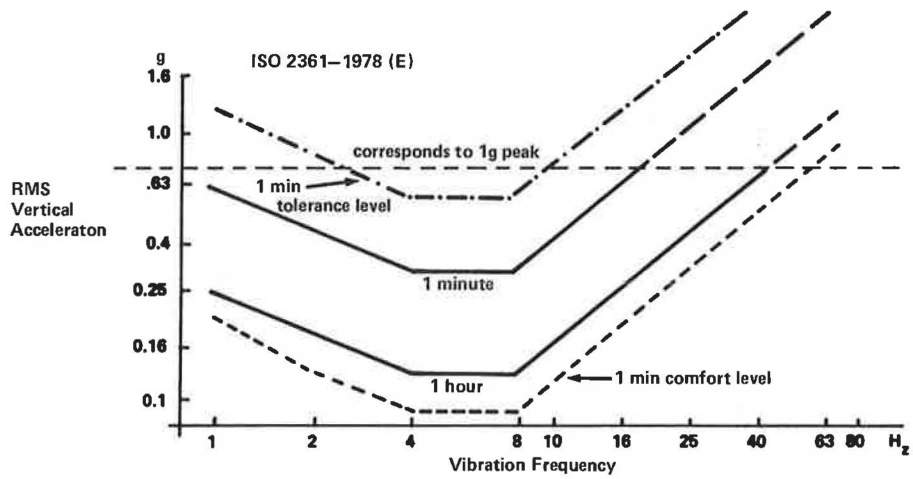

FIGURE 18 Sensitivity of the human body to vertical acceleration (4 to 8 Hz) *(6)*.

The two dotted lines show how the comfort levels are set at much lower values of the RMSVA. The dashed line shows the comfort level for 1-min exposure periods. The tolerance limits for 1-min exposure are shown as a dashed-and-dotted line.

Unfortunately, the relationship between the RMSVA g-levels as measured and the ISO RMSVA g-values is not easily established because the broad band vibrations recorded in this feasibility study require each third-octave frequency interval to be analyzed separately. This analysis can be done at ARRB but was not justified in this case because of the large and presently unidentifiable "noise" components of the acceleration spectra.

More work is needed to tie down the relationships between ISO comfort and tolerability levels and bicycle RMSVA results. It should not be assumed that bicycle rider comfort can be adequately accommodated by the ISO standard, although it is not possible to say at this stage how this particular vibration environment is likely to differ from the standard. On the one hand, the vibration experienced by cyclists is likely to be rather severe because vibrations are transmitted not only through the seat but through the arms and their associated joints as well. If the cyclist is leaning forward, vibration at the heavily loaded shoulder joints may well be a serious source of discomfort. On the other hand, users' perceptions of the benefits of cycling and the enjoyment of the activity may well make them more tolerant of discomfort.

This study was designed simply to investigate the feasibility of using a bicycle-mounted accelerometer system, and many questions remain to be answered before a monitoring system can be established. The first of these concerns the accuracy and repeatability of the measurements. A number of runs were made over a section of road on ARRB premises to check that the system was giving stable and consistent results before the data collection runs were made. No formal record was kept of this, and clearly more work is needed to formally establish the accuracy of the system.

The second point concerns the accuracy of the user ratings. Initially, an attempt was made to obtain RMSVA over each section for each of the riders who contributed the views used to construct the serviceability rating. Teething troubles with the circuitry prevented this. The result was a lot of delays for the initial rider panel due to repeated calibration procedures and the need to transfer the whole electronic package between machines. The result was boredom, fatigue, and several drop-outs by the time the last section was reached.

A faster, more efficient procedure for obtaining the serviceability ratings is necessary, although the second panel, with reference sections added to each test site, was able to move through the tests far more quickly.

Third is the question of an appropriate operating speed for measuring the accelerometer readings. In some cases, restricted sight distance and conflicting pedestrian movements made the standard 20-km/hr speed uncomfortably high and possibly unrepresentative of probable operating speeds. There was insufficient time to investigate the effect of speed on RMSVA, and this question ought to be addressed as a high priority in any further work.

A final practical problem not resolved by this initial study concerns the ability of the accelerometer system to detect sections of track where condition has deteriorated. Routine use of RMSVA as a monitoring tool implies that the bicycle would be ridden over a stretch of track, section by section. Periodic monitoring of the track would then allow an assessment of the rate at which sections are deteriorating to complement the visual rating with consistent ride quality RMSVA values.

The present investigation has shown that the system is capable of detecting differences among sections in a way that systematically relates to user evaluation. Whether it is practical to do more than this and to identify lengths of track within sections with particularly poor surfaces remains to be demonstrated, although there is no reason to anticipate any special difficulties.

Although the RMSVA method now promises to provide a fairly rapid means of assessing bicycle way surface conditions and the use of this RMSVA technique to provide a surface smooth run standard for future new construction would appear to be feasible for obtaining serviceability ratings, it does not readily serve as a basis for evaluating user complaints. A 1.5-m straight edge was therefore used to measure bumps and surface fluctuations on the several test sections, as was done for the BIV survey (11). The vertical separation of the edge from the surface is a convenient measure and fairly easily reproduced. Measurements were taken at each of the test sections, but the results did not provide any consistent relationship with the servicability levels of the sections as a whole. Consequently, such a method could no doubt be used to establish if a particular short section of track had broken up to a level that warranted immediate action, but it would unfortunately be too labor intensive and time consuming to be used for regular surface rating and monitoring over a whole network of on- and off-road cycle ways.

The use of this RMSVA technique to provide a surface smoothness standard for future new construction would appear to be feasible. This process effectively reestablishes passenger and ride servicability measures and is of wide interest and value for all types of vehicles and road and track surfaces. As laser profilometry and quarter-car simulators both become available for joint use, human factors once again become the key issue to work on for field standards assessment and monitoring. It is not impossible that a lightweight LaTrobe laser profilometer system (15) might, at a later stage, prove usable for bicycle ways.

IMPROVEMENTS TO THE INSTRUMENTATION SYSTEM

Several possible improvements to the system have become evident through the experience gained in operating it. These are

1. Changes to the accelerometer mounting. The rather loose frame mounting attached near the rear wheel may be susceptible to resonance effects and will tend to be subject to accelerations different from those experienced at the saddle, because of its location. A solid block mounting clamping around the saddle post might minimize these problems, but acceleration spectra are needed for several different possible mounting points to determine the best and most practical compromise.
2. A voice-over facility that allows comments and site identification information to be recorded on one channel of the tape recorder. This channel can be used for both the commentary and, when the measurements are in progress, the stable oscillating signal. This modification is essential if the system is to be developed for routine monitoring of cycle ways. Experience demonstrated that it was difficult and time consuming to locate sections by relying on the interrupt signal alone. The detailed record keeping necessary to achieve this would not be practical in a field situation.
3. Mounting the cassette recorder on the rider's chest instead of his back would allow the system to be operated by one person, and the use of a cassette multichannel FM recorder would simplify and improve the data acquisition system.
4. Inclusion of a direct RMSVA computation module would obviate the present reliance on laboratory analysis equipment and give immediate feedback of results in the field.

CONCLUSIONS

An accelerometer-based roughness monitoring system (RMSVA) is feasible and can provide consistent results with different types of surfaces and bicycles.

The accelerometer-based system is capable of discriminating between cycle track sections.

The RMSVA statistic based on acceleration measured at the rear axle of a bicycle appears to correlate poorly with NAASRA roughness measures.

There is good accord between the RMSVA measure and riders' serviceability ratings.

The subjective differences in comfort between the two types of bicycles, derived from the rider panel opinions, were confirmed by the RMSVA results.

Redevelopment of the data capture equipment into an improved package is clearly practical because the costs of FM recording and analysis equipment have dropped considerably.

A full field survey of a wide range of cycle ways is now required.

A much larger and more widely based panel of up to 50 to 100 people is needed to establish standard reference tolerability and serviceability levels and statistically reliable relationships with RMSVA.

The use of RMSVA to provide a surface smooth run standard for future new construction would now appear to be feasible.

RECOMMENDATIONS

This feasibility investigation has been considerably more successful than could reasonably have been expected from the continuing difficulties with the other related road equipment and methods and their calibration. The prospects for producing a robust piece of field equipment with a matching data reduction procedure are good, but the development of appropriate methods for reducing the acceleration noise in the present mounting system could be time consuming, and effort must be spent on developing faster and less time-intensive methods of processing of the acceleration recordings.

The consistent relationship between the two bicycles and the roughness measure rankings suggests that it might yet be possible to establish an NRM-RMSVA relationship if the masking acceleration noise in the measured RMSVA values can be reduced and the type effects of the automobile can be better identified.

The next phase of development of track quality standards is to run over extended lengths of track and develop a method of quickly and automatically identifying areas that do not meet standards (yet to be specified).

Because the RMSVA measure already shows a sound relationship with the actual surface character ties, separate attention should now be given to establishing the rider tolerability and serviceability criteria for a representative--and much larger--sample of locations, types of surface roughness characteristics, and types of riders.

Consequently a program should be set up to deal with the following points:

- A full development project should be set up to obtain reference standard tolerability and serviceability values.
- The accelerometer system should be redesigned.
- An on-bicycle direct analysis module should be developed to remove the need for recording of signals for later analysis.
- Steps to reduce acceleration noise should be taken.
- Tests of data collection and reduction over long sections of cycle way surface should be made and an operational monitoring and standards procedure should be developed.
- Bicycle plan and facility standards should be revised to accommodate such independent testing procedures.
- Closer investigation is needed of RMSVA and speed dependencies for ordinary road roughness measures for different types of vehicles.

ACKNOWLEDGMENTS

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APPENDIX A--TEST CYCLE PATH LOCATIONS

The Yarra Bank bikeway is situated adjacent to the Yarra River as a segregated waterfront recreational facility used by cyclists, pedestrians, and runners. The geometric standards are sometimes constrained by the physical problems of a riverside location. The path is surface scaled but is not all in good condition. The sections used were effectively flat and straight. The reference section used was a section of well-surfaced highway adjacent to the bike way.

The Albert Park bike track is an on-road segregated section of bicycle route, separated from the main carriageway by fairly wide islands used as mountings for parking meters for automobile parking on the main carriageway. The surface is sealed asphalt but has large areas of poorly reinstated surface due to disturbance of the road surface for utilities work and maintenance. The track lies on a downward curving slope. The reference section used was the main carriageway adjacent to the reserved bike way.

The St. Kilda seafront bicycle path is part of a recent extensive foreshore sealed path, essentially straight and flat but with early development of a short-frequency periodic undulation of the surface. The path is used by pedestrians and cyclists, although an adjacent parallel concrete slab footpath has also attracted both cyclists and pedestrians.

The Ivanhoe recreational bike way is a compacted gravel path with sharply undulating and twisting geometry, much used by pedestrians and cyclists alike. The vegetation and the geometry were formed to be fairly light for cyclists traveling at more than 10 to 15 km/hr. The reference section used was a smooth, flat, and well-surfaced asphalt automobile parking area 200 m from the test section of the recreational bike way.

APPENDIX B--RIDER CHARACTERISTICS

Survey Form

What is your age? Are you: Male Female

1. When did you last use a bicycle?
   Yesterday Last week Last month Last year
2. Do you normally ride a bicycle every day?
3. How often do you ride to work?
   Every day More than once a week Once a week
   Less often Never
4. On days when you ride, do you travel?
   Less than 5 km Less than 10 km
   More than 10 km
5. Do you wear a helmet?
6. How well informed are you about bicycle facilities?
   Well informed A bit informed
   Not at all informed
7. Have you personally sought out information about local bike facilities from:
   State Bicycle Committee Local councils
   Street directories Other local residents
8. How many members are there in your household?
   Over 18 yr Under 18 yr
9. How many motor vehicles are usually parked at your house?
10. How many bicycles (not toys) are kept at home?
    Owned by people over 18 yr
    Owned by people under 18 yr
11. Are the bikes used for? Commuting to work
    Recreational purposes
12. In which suburb do you live?
13. Do you know of any bike tracks near your home?
    Yes No If yes, please give details
14. If the weather is bad, do you use your bicycle regardless?
    Usually Sometimes Never
15. Any other comments you would like to include?
16. If you would like a summary of this study, please provide your name and address.

Rider Characteristics Summary

Weight: 80.5 kg (mean) 54 to 100 kg (range)
Age: 36.8 yr (mean) 30 to 43 yr (range)
Sex: 9 male (75%) : 3 female

Last used bicycle:
- Yesterday : 3 (25% cumulative)
- Last week : 3 (50% cumulative)
- Last month : 5 (92% cumulative)
- Last year : 1 (100% cumulative)

Normally rides daily:
Yes : 2 No : 10

Frequency rides to work:
- Every day : 1 (8% cumulative)
- Once a week : 0 (33% cumulative)
- Less often : 2 (50% cumulative)
- Never : 6 (100% cumulative)

Cycling distance per riding day:
- Less than 5 km : 3 (27% cumulative)
- 5 to 10 km : 5 (73% cumulative)
- Over 10 km : 3 (100% cumulative)

Helmet usage:
Yes : 8 (73%) No : 3

Bicycle facilities knowledge:
- Well informed : 4 (25% cumulative)
- A little : 5 (75% cumulative)
- Not at all : 3 (100% cumulative)

Facilities information sought from:
- State Bicycle Committee : 5
- Local councils : -
- Street directory : 2
- Other : -

Subject Responses in Person Sequence

Household membership												
Over 18:	2	4	2	1	2	3	2	1	3	4	2	2
Under 18:	-	-	2	-	-	-	2	-	-	-	-	-
Number of motor vehicles usually parked:	2	2	2	-	4	1	1	1	2	2	1	1
Bicycles owned by those												
Over 18:	3	2	2	1	2	2	1	-	2	2	8	8
Under 18:	0	-	2	-	-	-	2	-	-	-	-	-
Bicycle used for												
Commuting:	2	*	-	*	*	*	-	-	-	-	-	*
Recreation:	*	*	*	*	*	*	-	*	*	*	*	*

Awareness of local facilities: 10 Yes 2 No

Cycling in poor weather
- Usually: : 2 (12% cumulative)
- Sometimes: : 8 (83% cumulative)
- Never: : 2 (100% cumulative)

The responses from single individuals are arranged in the vertical columns.

APPENDIX C--RIDING SURFACE RATING FORMS

Q1. For a commuting cycle track, would you say that this section is acceptable in its present condition? Yes No

Q2. How sure are you of your answer? Very sure Quite sure Not sure

TABLE C1 Summary of Rider Surface Ratings

	Yarra Bank		Albert Park		St. Kilda		Ivanhoe	
	Touring Bike	Mountain Bike	Touring Bike	Mountain Bike	Touring Bike	Mountain Bike	Touring Bike	Mountain Bike
Q1. Acceptability (Yes:No)	7:1	7:1	3:6	4:6	4:7	8:3	6:3	4:1
Q2. Confidence (Very:Quite:Not sure)	–:5:3	1:4:3	2:6:1	2:6:2	3:5:2	4:4:2	1:6:3	3:2:–
Q3. Dislikes (Bad bumps:Constant small bumps:Potholes: Slippery:Vegetation/other)	1:6:–:–:–	3:4:–:–	7:5:2:–:–	7:3:1:–:–	–:11:–:–:–	–:10:–:–:–	–:2:–:4:1	–:–:–:2:1
Q4. Range of ratings	2.0-4.7	2.0-4.5	0.8-3.8	0.-3.5	1.5-3.0	1.5-4.5	2.0-3.5	3.5-4.5

Q3. What (if anything) didn't you like about the section? The responses offered included: a few really bad bumps, constant minor bumping, potholes, slippery track, and vegetation or other obstruction.

Q4. Perfect

Very good

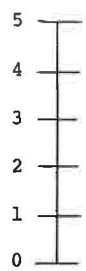
Good

Fair

Poor

Very poor

Impassable



Completion of Q4 entailed making a mark on the vertical line.

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