ROUGHNESS AND NOISE CHARACTERISTICS OF NEW ZEALAND CONCRETE BLOCK PAVEMENTS

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SUMMARY

An on-road experimental programme was carried out to investigate the vehicle ride characteristics of concrete block pavements. The five road sections selected for study ranged from moderately smooth (84 NAASRA counts/km) to rough (167 NAASRA counts/km). From a spectral analysis of vehicle axle and body accelerations, it was identified that an increase in ride harshness results whenever the paver pattern induces tyre vibrations which coincide with either a natural frequency of the tyres or vehicle body. However, the principal cause of pavement roughness was attributed to long wavelength (>1 m) undulations present in the base layers, and not the surface texture of the pavers. Noise measurements were also performed which showed, that for concrete block pavers, in-vehicle noise increases at a lower rate with vehicle speed than for conventional road surfaces. The interior noise level was found to correlate strongly with the degree to which tyre vibrations are transmitted to the vehicle body. The findings from both the roughness and noise investigations have been combined to derive recommendations for the design and the laying of concrete block vehicular pavements.

Introduction

The roughness of a road is of particular interest to those responsible for road management because it has a direct influence on vehicle operating costs by affecting vehicle fuel economy through its effect on rolling resistance and vehicle condition through wear resulting from road induced vibrations. Furthermore, rough roads may necessitate a reduction in speed due to a deterioration in ride quality which can result in undesirable decreases in the capacity of a road to carry traffic. Roughness also has a significant effect on the road surface itself. The higher dynamic wheel loads applied to rough roads by the vehicles travelling over them often result in increased degradation of the road surfaces. Two common examples of this are the formation of potholes and corrugations, both of which can grow rapidly, once initiated. Therefore road roughness affects both road user costs and road surfacing selection.

If concrete block pavements are to be used more extensively in New Zealand, they must be able to be laid to road roughness standards equivalent to that obtained using bitumen based materials. Pavement roughness values expected by New Zealand roading authorities are a maximum of 50 NAASRA counts/km for asphaltic concrete and a maximum of 70 NAASRA counts/km for granular base and chipseal. These roughness measures are equivalent to approximately 3-4 mm average deviation under a 3 metre straight edge.

Besides road roughness, the surface characteristics of road pavements also influence skid resistance, tyre wear, and road traffic noise. Figure 1 presents a classification of different sized road surface irregularities relative to typical tyre contact length (assumed to be 0.1 m) and the effect that they have on vehicle operation.

This paper presents the results of an on-road experimental programme undertaken to investigate roughness and noise characteristics of road sections utilising concrete block pavers. The five road sections selected for study ranged in length from 100 to 300 m, with the pavers laid in a 45° herringbone pattern. They included "interlocking" concrete pavers of two different shapes (38 and 40 per square metre) and an orthodox rectangular paver 100 mm wide by 200 mm long (50 per square metre).

In order to quantify the roughness and noise differences between the road surfaces, spectral techniques were used to analyse axle and body accelerations of Central Laboratories' NAASRA roughness vehicle, a VN Holden Commodore station wagon, over a frequency range of 0 to 150 Hz. Such an analysis is necessary because pavement profiles generate vehicle vibrations which are typically random in nature.

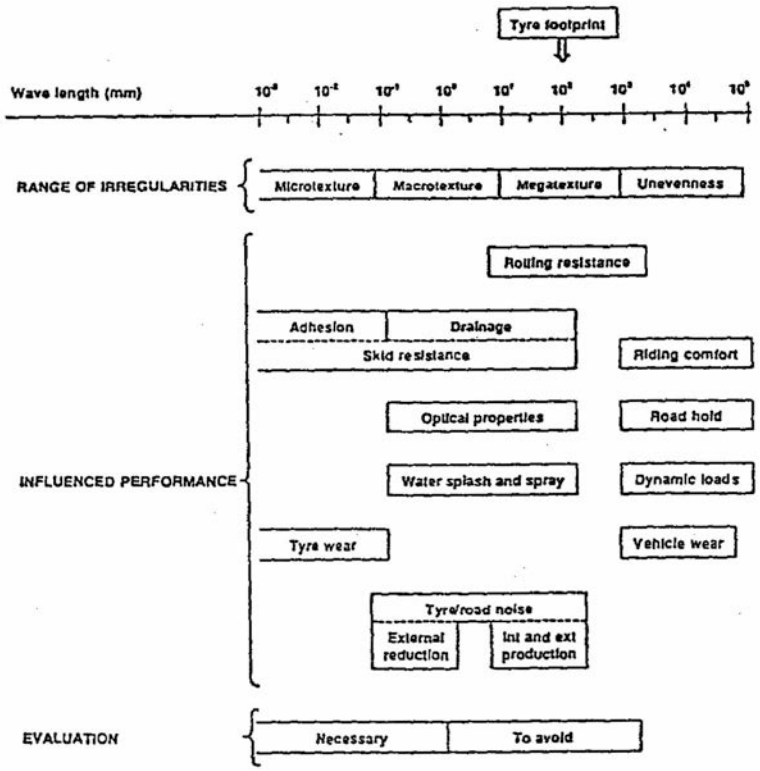


FIGURE 1: Relationship between the characteristic size of road surface irregularities and their effect on vehicle operating environment (after Jull, 1989)

Theoretical Considerations

The main type of tyre construction in use in New Zealand is the radial ply. Figure 2 shows the attenuation of vertical and longitudinal vibrations in the range 10 to 600 Hz for such tyres. The critical exciting frequencies for vertical tyre vibrations are shown to be centred around 22 Hz, 40 Hz and 100 Hz, whereas for longitudinal vibrations the main excitation occurs at 12 Hz and over a broad frequency range from 25 to 100 Hz. However, Figure 3 shows that longitudinal tyre vibrations centred at 15 Hz and 44 Hz are most readily transmitted to the motor car body.

For both longitudinal and vertical tyre vibrations, attenuation falls off sharply after 100 Hz. Therefore to reduce both road noise and harshness, the joint spacing of pavers should be such that the frequency of induced vibrations is greater than 100 Hz over the required speed range, typically 30 to 50 km/h for residential and industrial areas. This implies that the joint spacing should ideally be 0.07 m or less.

New Zealand pavers are typically 0.2–0.25 m long and 0.1–0.14 m wide. When laid in a 45° herringbone pattern, the spacing in the vehicles' wheelpath can range from 0.04 m to 0.160 m, the larger joint spacing being predominant. It was therefore expected that the block pavements selected for study would display harsh rides, the harshness decreasing with increasing vehicle speed.

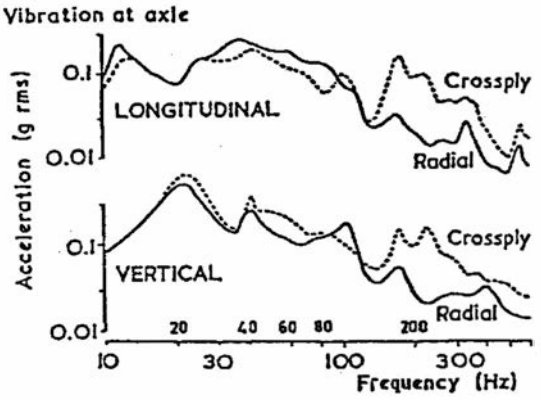


FIGURE 2: The attenuation of vertical and longitudinal vibrations achieved by radial ply tyres (after Bastow, 1980)

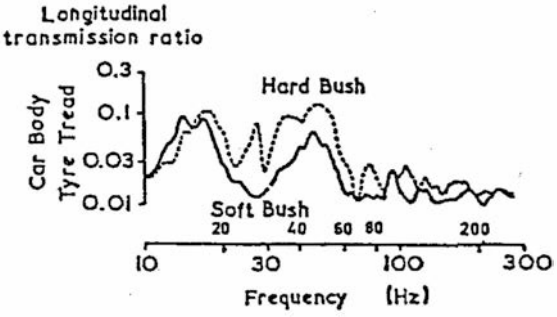


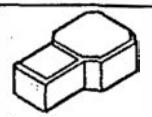
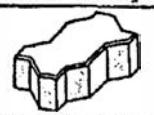
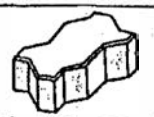
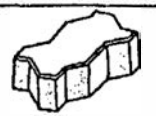
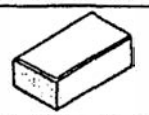
FIGURE 3: Longitudinal transmission efficiency for radial ply tyres (after Bastow, 1980)

Experimental Details

The five block pavement sections were surveyed using Central Laboratories' NAASRA roughness vehicle. This vehicle is routinely used to measure the roughness of New Zealand's state highway network. It is a VN Holden Commodore station wagon fitted with a response type meter designed to sum the relative vertical displacements between the vehicle's rear axle (midway between the two rear wheels) and a point on the vehicle body directly above the rear axle centre. The meter gives output in terms of counts, where a single count corresponds to a measured axle-to-body displacement of 15.2 mm in the upward direction only. Road roughness measurements are normally taken at either of two principal standard speeds, 80 or 50 km/h, the latter being used in urban areas, and are reported in counts per kilometre of distance travelled.

For this experimental programme, the NAASRA roughness vehicle was also fitted with two strain gauge accelerometers, one mounted directly onto the rear axle housing and the other on the floor of the vehicle's cargo tray adjacent to the NAASRA roughness meter to monitor accelerations of the running gear (comprising wheel, spring and suspension links) and the vehicle body respectively. The accelerometers used had a flat frequency response up to 150 Hz, and so were capable of detecting high frequency vibration components that are induced by a tyre encountering height variations in the block paving. These height variations are caused by

TABLE 1: Details of Block Pavement Sections

Section No.	Street Name/Location	Estimated Age (years)	Test Section Length (km)	Paver Type	Estimated Chamfer (°)	Estimated Joint Width Between Pavers (mm)	Description of Wheelpath Appearance
1	Barraud Place, Rotorua (residential cul de sac)	Less than a year	0.150	 e.g. Firth's Keystone	35	3	Recently laid appearance with sharp edges and clean gaps
2	Perrindale Drive, Hamilton (residential cul de sac)	Between 10 and 14	0.215	 e.g. Firth's Stockholm	45	15	Weathered appearance with rounded edges and gaps entirely filled with debris/moss
3	Lakewood Crescent, Auckland (residential cul de sac)	Between 6 and 7	0.150	 e.g. Firth's Stockholm	45	5	Gaps entirely filled with sand/debris though chamfer of paver clearly distinguishable
4	Nandina Avenue, Auckland (industrial area)	Between 6 and 7	0.270	 e.g. Firth's Stockholm	18	2	Clean gaps with edges of pavers well rounded, probably as a result of heavy vehicle traffic
5	Ferntree Terrace, Auckland (residential cul de sac)	Around 1	0.100	 e.g. Firth's Holland	45	3	Recently laid appearance with sharp edges and clean gaps

joints between the pavers, which are in turn a function of the laying pattern and size of the pavers and the chamfered edges of the pavers. The output from the accelerometers were simultaneously recorded on a multi-channel analogue recorder to enable digital signal processing via a computer system.

In addition, a Rion NL10 sound level meter was positioned at ear level in the centre of the front passenger seat of the NAASRA roughness vehicle to measure noise levels within the vehicle.

The block pavement sections used in this experimental programme were selected with the following considerations in mind:

1. The pavement sections had to be uniform along the entire length of each section but different between sections.

2. Each site should have enough distance between the point of access and the beginning of the section to allow the vehicle to develop the required test speed of 50 km/h.

3. Each section should be of nearly constant longitudinal slope, straight, and more than 100 m in length.

The block pavement sections that met these requirements are summarised in Table 1.

The instrumented test vehicle was run over each section five times. The resulting measurements were found to be very repeatable, with a coefficient of variation (standard deviation/mean) of no more than 7% for the NAASRA roughness measurements. For one block pavement section, Nandina Avenue, acceleration, interior vehicle noise, and roughness measurements were made at three different vehicle speeds (30 km/h, 50 km/h and 70 km/h) so that any speed dependent effects could be identified. In addition, the same measurements were performed on two conventional chipseal road sections having comparable NAASRA roughness to the block pavements for a vehicle speed of 50 km/h, thereby permitting any differences in the excitation mechanisms that cause tyre and vehicle body vibrations to be highlighted.

Results

General Performance of Block Pavements

The results of the 50 km/h axle and body accelerations, roughness and interior vehicle noise measurements for the five block pavements investigated are presented in Table 2. With reference to Table 2, there is a high degree of linear correlation between NAASRA roughness and the root mean square (RMS) of the axle and body accelerations as expected; the correlation coefficients being 0.98 and 0.97 respectively. Similarly, vehicle interior noise appears to be strongly correlated to the degree with which vertical axle vibrations are transmitted to the vehicle body, the linear correlation coefficient in this case being 0.96.

If the results for the oldest and most worn surface of Perrindale Drive are excluded, it will be noted that the RMS axle accelerations do not vary significantly between the pavements studied (the coefficient of variation is approximately 4%). However, there is a wide variation in roughness (84-101 NAASRA counts/km) and road noise (66-83.9 dB(A)), indicating that paver shape and laying pattern both influence the degree to which vibrations are transmitted to the vehicle body.

With regard to internationally recognised acceptability criteria for noise inside passenger vehicles, the sound levels measured at 50 km/h range from quiet (66 dB(A)) to annoying to vehicle occupants at 83.9 dB(A).

TABLE 2: Results of 50 km/h Measurements

Section No.	Street Name	NAASRA Roughness (c/km)	RMS Body Accelerations (m/s^2)	RMS Axle Accelerations (m/s^2)	Vertical Transmission Ratio (RMS Body Acc/ RMS Axle Acc)	Vehicle Interior Noise Level (L_{eq} dB(A))
1	Barraud Place	101	0.85	4.72	0.180	83.9
2	Perrindale Drive	167	1.07	6.38	0.168	69.3
3	Lakewood Crescent	123	0.85	4.97	0.171	77.6
4	Nandina Avenue	96	0.77	4.65	0.166	66.7
5	Ferntree Terrace	84	0.73	4.42	0.164	66.0

Effect of Vehicle Speed

The results presented in Table 3 for Nandina Avenue show that the magnitude of both axle and body vibrations increase with increasing vehicle speed. However, more of the axle vibrations are transmitted to the body at 50 km/h than either 30 km/h or 70 km/h, suggesting that at 50 km/h the pavement corrugations cause excitation of one or more of the vehicle's fundamental vibration modes. This effect is not observed in the NAASRA roughness measurements which ideally should not vary with vehicle speed. However, the NAASRA roughness meter, being a response type meter, is highly dependent on the temporal frequency of the road profile input. Therefore higher operating speeds result in an increase in the frequency of this input. Because the NAASRA roughness meter has an estimated natural frequency of about 11 Hz (Brown and Cenek, 1989), vibrations with a higher frequency become attenuated, thereby biasing the roughness measurement to a limited frequency range. The result is that NAASRA roughness values associated with one particular speed cannot be converted to equivalent values at a different speed without first performing a complete set of calibrations at both required speeds. Further, the macrotexture (as defined in Figure 1) of the calibration section must display similar characteristics to the test section otherwise the vehicle response could be significantly different, resulting in misleading roughness values. Both calibration and response effects are responsible for the variation in NAASRA roughness values shown in Table 3, highlighting a serious limitation of response type roughness meters.

Table 3 also shows that the vehicle interior noise level increases approximately 1 dB(A) per 10 km/h. This compares favourably with other New Zealand pavements which typically increase at a rate of 1.3 to 1.5 dB(A) per 10 km/h (Cenek and Shaw, 1990). At the maximum speed the sound measurements were made, 70 km/h, the interior noise level is still quiet at 68 dB(A), the noticeable sound level being regarded as 73 dB(A) (Pottinger et al, 1986).

TABLE 3: Influence of Vehicle Speed on Measured Parameters - Nandina Avenue

Vehicle Speed (km/h)	NAASRA Roughness (c/km)	RHS Body Accelerations (m/s^2)	RMS Axle Accelerations (m/s^2)	Vertical Transmission Ratio (RMS Body Acc/ RMS Axle Acc)	Vehicle Interior Noise Level (L_{eq} dB(A))
30	108	0.51	3.38	0.150	64.2
50	96	0.77	4.65	0.166	66.7
70	83	0.83	5.59	0.148	68.0

Spectral Analysis

Background

To handle a set of random vibrations, as arise with road roughness, it is necessary to consider the power spectrum over the entire frequency range of vibrations present. By analogy with probability and probability density, a power spectral density (PSD) is defined, where PSD is the power per unit frequency over the frequency range. For a finite and statistically constant total power input, the PSD may be used to estimate the proportion of the power being input in each frequency range.

The PSD function of a measured parameter is the variance of the parameter divided by the spatial frequency of the measured parameter. Therefore, where the parameter is acceleration in units of m^2/s, then the variance of the acceleration has units of m^4/s^2 and the spatial frequency (the inverse of the wavelength) units of cycles/m, resulting in a PSD function with units of $(m^4/s^2)/(cycle/m)$.

The acceleration PSD's were computed for a maximum spatial frequency of 10.8 cycles/m which corresponds to an input of approximately 150 Hz at 50 km/h.

Since the RMS acceleration is the square root of the variance about the mean, and the mean is zero, the variance is numerically equal to the area under the PSD curve between 0 and 10.8 cycles/m. Generally PSD curves are normalised with respect to the variance of the acceleration signal so that the total area under a spectral plot is equal to unity.

Axle and Body Acceleration Spectra

Normalised axle and body spectra for Barraud Place, Perrindale Drive and Ferntree Terrace are presented in Figures 4 to 6. It will be observed that these spectra generally display the same features, namely predominant spatial frequencies for the axle accelerations are centred around 0.8 and 4.0 cycles/m corresponding to inputs of 11 Hz (natural frequency of the unsprung mass) and 56 Hz at 50 km/h. In comparison, the predominant spatial frequencies for the body accelerations are centred around 0.15, 1.5 and 8.5 cycles/m corresponding to inputs of 2 Hz (natural pitch frequency of the vehicle body), 21 Hz, and 118 Hz at 50 km/h. The higher critical exciting frequencies for both types of acceleration are attributed to characteristics of the vehicle's radial ply tyres, discussed previously.

The 45° herringbone pattern of pavers is expected to cause vibrations over spatial frequencies ranging from 6.3 cycles/m to 25 cycles/m for a vehicle speed of 50 km/h. The more consistent the joint spacing between pavers, and the sharper the paver edges, the more defined the spectral peak will be.

With reference to the spectral plots, it can be seen that clearly defined peaks occur at 7.5 cycles/m for Ferntree Terrace and 8.5 cycles/m for Barraud Place in the axle spectra. However, no such peak occurs for Perrindale Drive, probably as a consequence of the worn edges of the pavers.

The greater road noise and harshness of the block pavement located at Barraud Place when compared to that at Ferntree Terrace is attributed to the 0.12 m spacing of the pavers which, at a vehicle speed of 50 km/h, induces tyre vibrations that coincide with a natural frequency of the vehicle body.

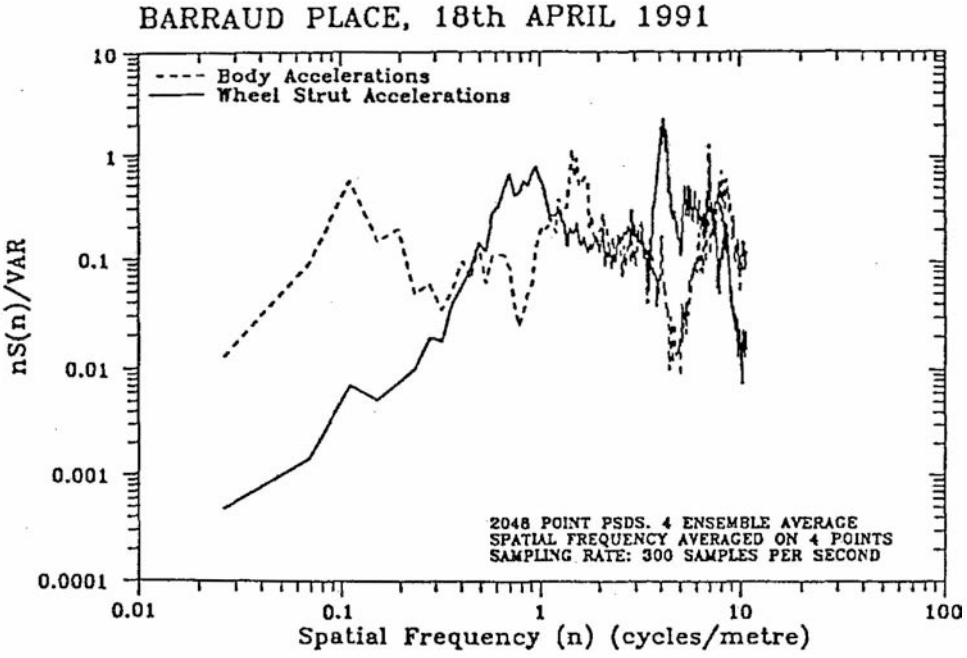


FIGURE 4: Normalised Axle and Body Acceleration Spectra for Barraud Place

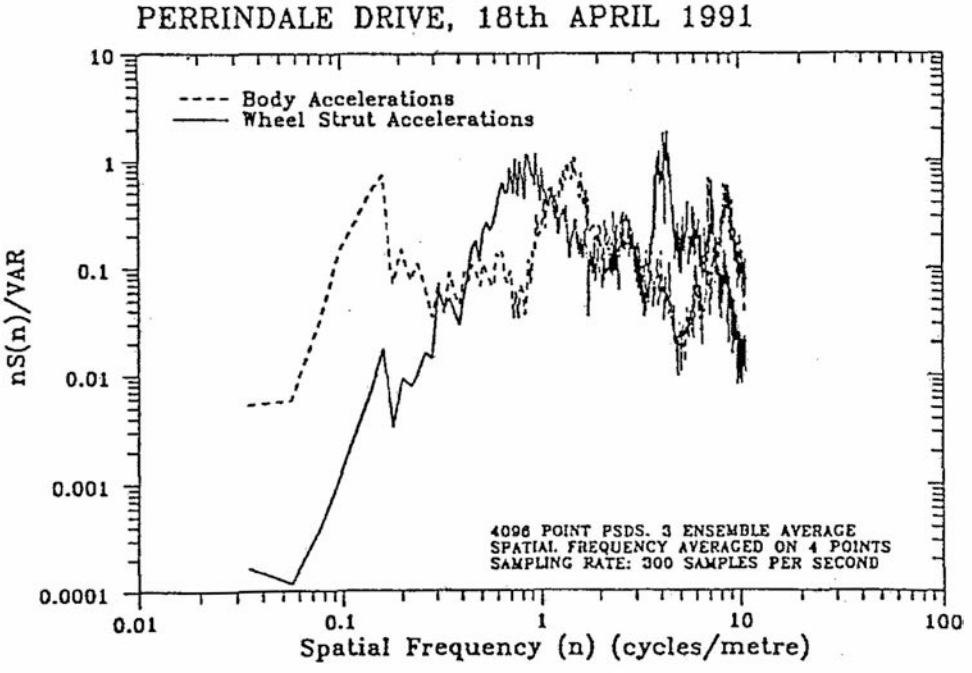


FIGURE 5: Normalised Axle and Body Acceleration Spectra for Perrindale Drive

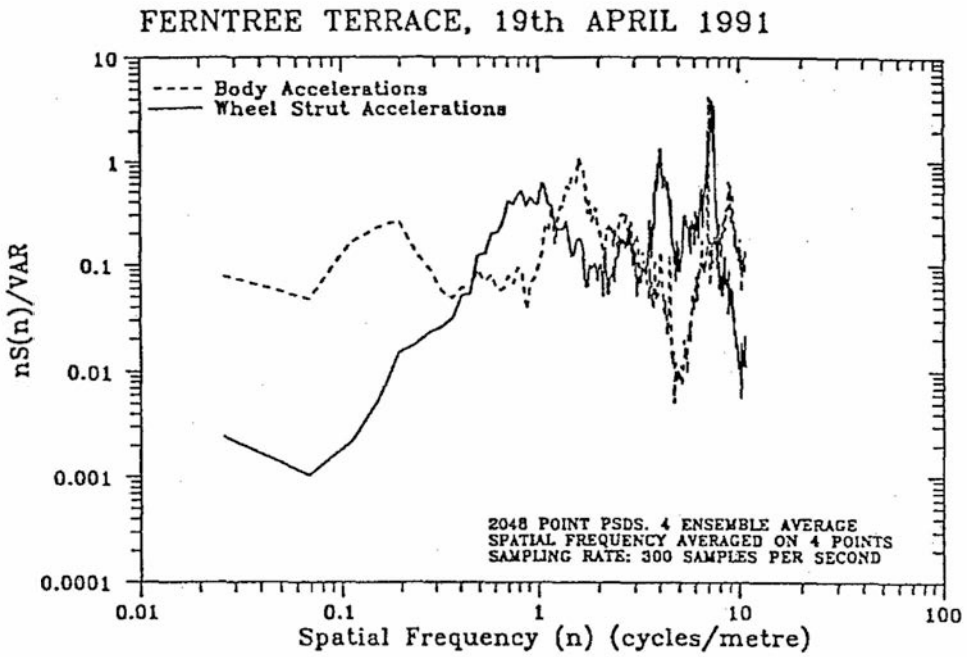


FIGURE 6: Normalised Axle and Body Acceleration Spectra for Ferntree Terrace

Comparison of Block Pavement and Chipseal Acceleration Spectra

Two long chipseal road sections were located which had NAASRA roughness levels comparable to the Perrindale Drive and Ferntree Terrace block pavements, thereby enabling the vibration inducing mechanisms of both pavement types to be directly compared. A summary of the axle and body RMS accelerations, NAASRA roughness, and interior vehicle noise measurements for the four road surfaces compared are presented in Table 4.

The PSD functions presented in Figures 7 to 10 are not normalised so as to permit direct comparisons, and are for a constant road speed of 50 km/h. With reference to Figures 7 and 8, it can be seen that there is no discernible difference in the spectral distributions between the worn concrete block surface of Perrindale Drive and the coarse chipseal surface of Paekakariki Road for spatial frequencies greater than 0.2 cycles/m. Suspension movement of the test vehicle is caused by road induced vibrations centred around 0.8 cycles/m and 4 cycles/m corresponding to frequencies of 11 Hz and 55 Hz at 50 km/h respectively. Body movement is primarily caused by vibrations centred around 0.1 cycles/m and 1.5 cycles/m (corresponding to frequencies of 1.4 Hz and 21 Hz respectively at 50 km/h), with the contribution of the lower spatial frequencies (i.e. the longer wavelengths) to the PSD function being greater than that of the higher spatial frequencies.

This result highlights the importance of having a base layer that is relatively free of repetitive long wavelength roughness, particularly over 1 to 30 m lengths, irrespective of whether the pavement is based on a bitumen surfacing or concrete blocks.

A significant difference between chipseal and block pavements is highlighted in Figure 9 which shows the presence of an additional spectral peak at 7.5 cycles/m in the axle acceleration PSD function for the block paving caused by the regular 0.13 m joint spacing of the pavers. However, Figure 10 clearly shows that this vibration component is not transmitted to the vehicle body.

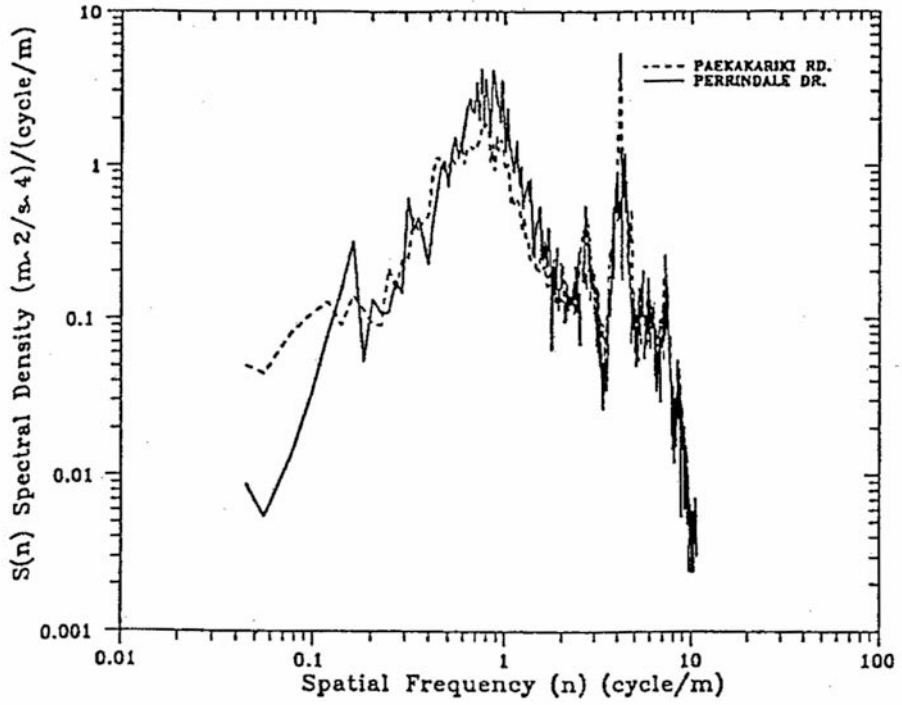


FIGURE 7: Comparison of axle acceleration for "rough" chipseal and concrete block pavements

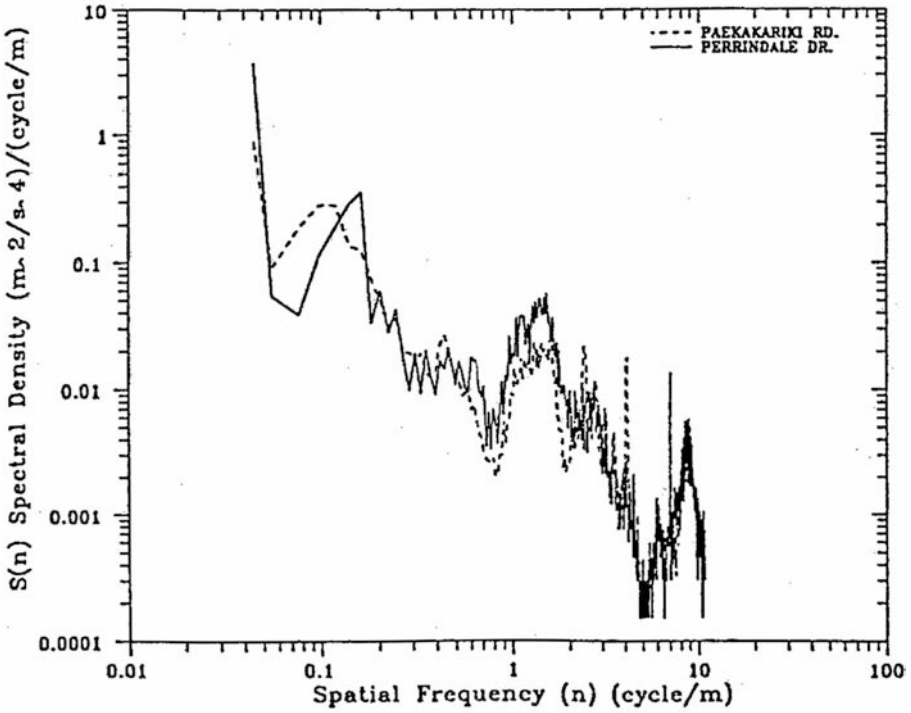


FIGURE 8: Comparison of body acceleration spectra for "rough" chipseal and concrete block pavements

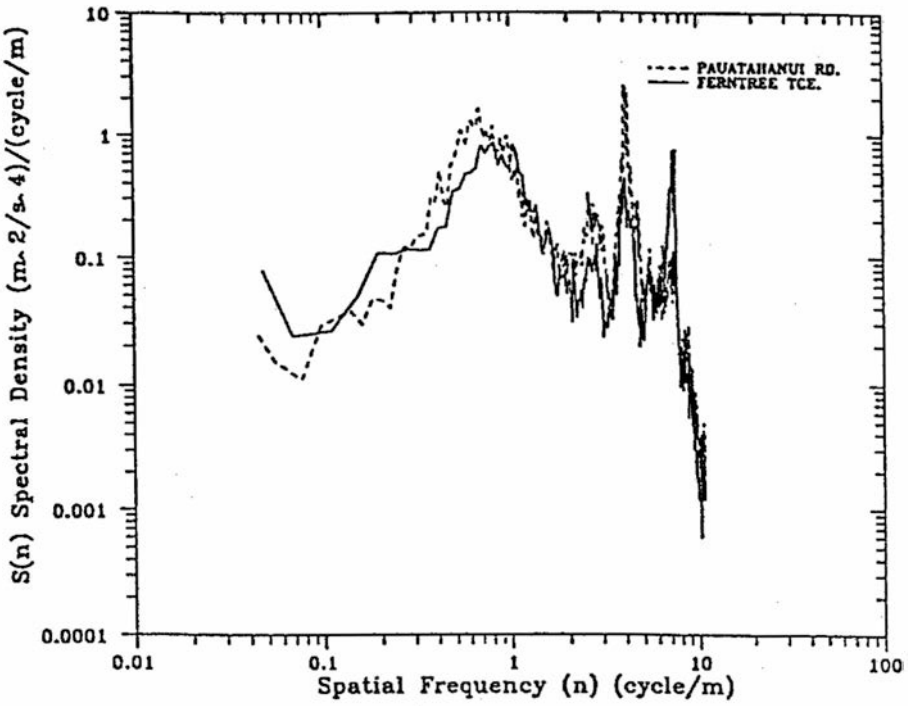


FIGURE 9: Comparison of axle acceleration for "smooth" chipseal and concrete block pavements

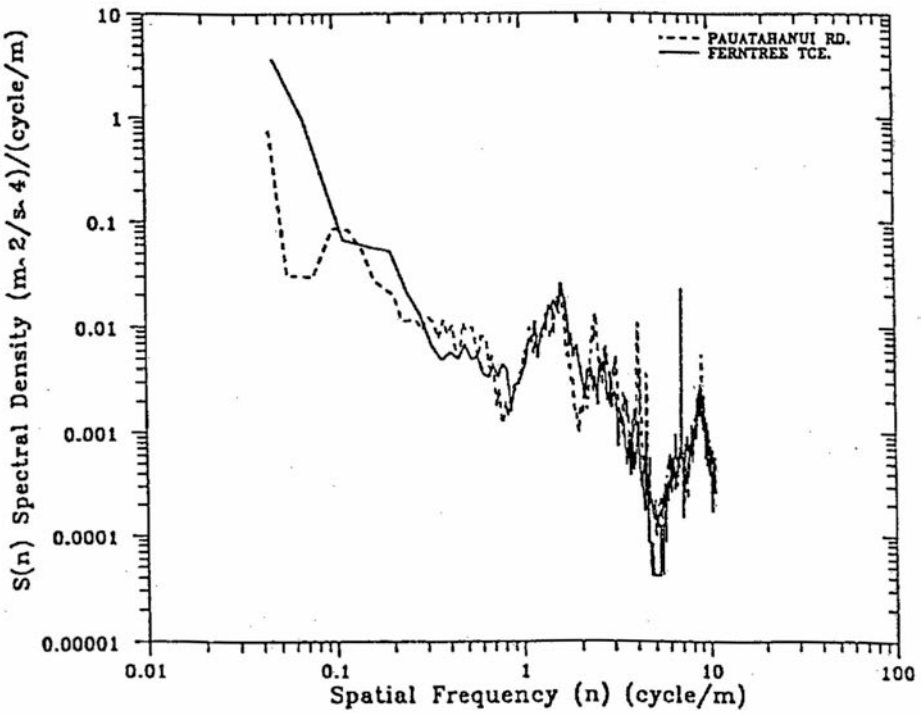


FIGURE 10: Comparison of body acceleration spectra for "smooth" chipseal and concrete block pavements

A comparison of the magnitude of the spectral density of the axle accelerations presented in Figures 7 and 9 for a spatial frequency of 0.8 cycles/m, corresponding to the resonant frequency of the NAASRA roughness metre, shows Perrindale Drive to have the highest value and Ferntree Terrace the lowest. As expected, this is consistent with the NAASRA roughness measurements.

The in-vehicle noise measurements presented in Table 4 show that at vehicle speeds at around 50 km/h, the noise levels associated with block paving are very similar to that generated by chipseal surfaces where the road surface is dry.

TABLE 4: Results of Chipseal/Block Pavement Comparative Measurements for a Road Speed of 50 km/h

Street Section	Section Length (m)	NAASRA Roughness (c/km)	RMS Body Accelerations (m/s^2)	RMS Axle Accelerations (m/s^2)	Vertical Transmission Ratio (RMS Body Acc/ RMS Axle Acc)	Vehicle Interior Noise Level (L_{eq} dB(A))
Paekakariki Road (chipseal)	7.900	147	0.97	6.30	0.154	68.6
Perrindale Drive (concrete block)	0.215	167	1.07	6.38	0.168	69.3
Pauatahanui Road (chipseal)	5.700	87	0.69	5.03	0.137	68.0
Ferntree Terrace (concrete block)	0.100	84	0.73	4.42	0.164	66.0

Surface Texture Aspects of Concrete Block Pavements

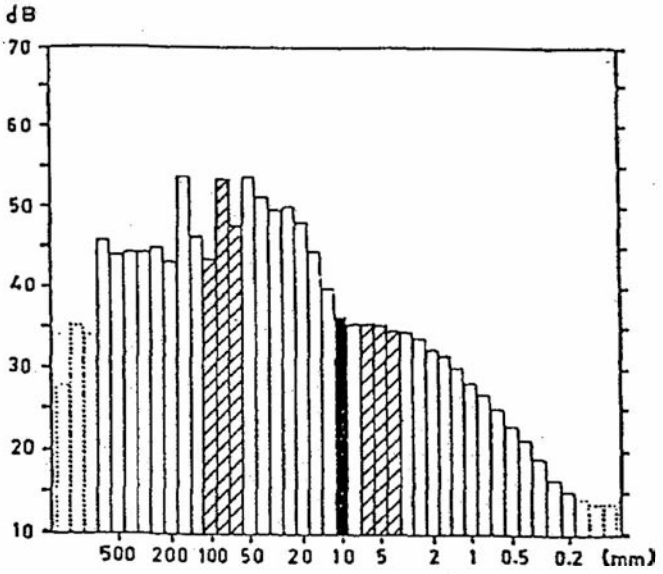
Texture Spectrum

During 1988, as part of an international collaborative experiment investigating road surface texture and tyre/road friction, detailed profile measurements of the concrete block pavement used on Nandina Avenue, Auckland, were made with a stationary laser profilometer (Sandberg, 1990). This instrument, developed by the Swedish Road Traffic Institute (VTI) allows the texture of a pavement surface to be measured over two wavelength ranges: 0.2-5 mm corresponding to the first part of the macrotexture and the roughest part of the microtexture, and 2-1000 mm corresponding to macrotexture and megatexture. At the time of the stationary laser profilometer measurements, the NAASRA roughness of Nandina Avenue was 102 counts/km compared to 96 counts/km measured during the course of this experimental programme, suggesting that the roughness of the surface has not changed significantly over a three year period.

Figure 11 shows a texture spectrum plot of the Nandina Avenue block paving, covering the range of texture wavelength 0.2-1000 mm and derived from a third-octave band analysis of 10 traces, each trace being 1 m long.

The "nominal" width of the concrete block pavers used on Nandina Avenue is 112 mm, but since they are placed at a diagonal angle, the wavelength is longer. With reference to Figure 11, the dominant spacing in this case is 160 mm, corresponding to a spectral frequency of 6.25 cycles/m. Also shorter wavelengths 80 mm (12.5 cycles/m) and 50 mm (20 cycles/m) are visible since often the laser trace hits edges close to corners of the blocks. The low "plateau" of 2-10 mm wavelength is caused by the very smooth macrotexture of the blocks.

When compared with similar texture spectra for other New Zealand road surfacings, the spectral distribution and magnitude of the concrete block paving of Nandina Avenue most closely resembles newly laid (one year old) very rough textured grade 2 chipseal over a wavelength range from 50 to 500 mm. This result therefore suggests that there is no reason why a concrete block paving cannot be laid to achieve similar NAASRA roughness levels as for chipseals on a granular base.



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Analyser lower limit 5 dB
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Frequency range 0.8 Hz - 10 KHz
Input spectrum function contin.

Horizontal scale: Texture wavelength (mm)
Vertical scale: 10 dB to 70 dB
(mm) - scale refers to input data speed 1 m/s
Shadowed bars mark L05 and L80
Black bar marks 10 mm wavelength

FIGURE 11: Texture Spectrum for Nandina Avenue Concrete Block Pavement (after Sandberg, 1990)

Overseas research has established that tyre noise is proportional to the texture of the road surface. In particular, low texture in the wavelength range 2-8 mm induces a considerable amount of high frequency "air pumping" noise because of its smoothness, especially for rather open tyre treads, and high texture in the wavelength range 40-125 mm causes tyre vibrations to be readily transmitted to the vehicle body. Unfortunately, concrete block pavements display both these undesirable features. Therefore, to reduce road noise levels, concrete block pavers should either be made more porous to better absorb sound, or their surface made rougher, so that the texture in the wavelength range 2-8 mm is increased to eliminate "air pumping" noise.

Block laying patterns are primarily dictated by the block shape and design traffic loading. However, in order to minimise road noise and harshness, a secondary consideration is that, wherever possible, the laying pattern should not induce tyre vibrations which coincide with either a natural frequency of passenger car tyres (50-60 Hz) or the vehicle body (100-120 Hz) over the vehicle speed range of interest.

Unevenness Effects

Roughness values for the concrete block pavements investigated in this experimental programme ranged between 84 and 167 counts/km. From the spectrum analyses of axle and body accelerations, and surface texture, it is apparent that these high roughness values are caused primarily by long wavelength roughness, defined as unevenness in Figure 1, which is present in the base layers.

For motor cars, the critical exciting frequencies are centred around 1-2 Hz (natural pitching frequency) and 11-13 Hz (natural wheel bounce frequency). The suspension systems of heavy commercial vehicles also display similar characteristics, their natural pitching frequency typically lying in the range of 2-5 Hz and the wheel bounce frequency 13-15 Hz. Therefore, for a given vehicle speed, V (km/h), the wavelengths (Ω) in the base layers that can cause resonant vibrations can be derived from:

$$\Omega_{1,2}\ (m) = 0.28\ V\ (km/h)\ /\ n_{1,2}$$

where n_1 = natural pitching frequency of vehicle
n_2 = natural wheel bounce frequency

For a motor car travelling at 50 km/h, Ω_1 = 7-14 m and Ω_2 = 1-1.3 m, whereas at 100 km/h, Ω_1 = 14-28 m and Ω_2 = 2-2.6 m.

Conclusions and Recommendations

The primary objective of the research undertaken was to determine whether or not concrete block vehicular pavements could be laid to roughness levels that are expected by New Zealand roading authorities and routinely achieved by bitumen based pavements. A secondary objective was to identify design improvements and changes to laying practices for concrete block pavers that would result in improved vehicle ride quality and a reduction in vehicle road noise. Accordingly, the following conclusions and recommendations derived from the results of the reported on-road experimental programme have been divided between these two disparate research objectives.

(a) Compliance with Roading Authorities' Expectations for New Pavement Roughness Levels

Conclusions

1. Nothing from this experimental programme shows that concrete block pavements cannot be laid to roughness levels equivalent to bitumen bound pavements.

2. The five concrete block vehicular pavements surveyed did not achieve roughness levels that are acceptable to roading authorities such as Transit New Zealand. The principal cause of the surveyed pavements having high roughness levels appears to be not due to the texture of the concrete blocks but rather to the presence of long wavelength undulations in the base layers which promote resonant excitation of both the vehicle body and wheels.

3. Response type meters, such as the NAASRA roughness meter, are not suited for the direct comparison of the roughness characteristics of different pavement types. Although they give a measure of the ride comfort level experienced by vehicle occupants, they are incapable of providing information on the distribution of variations in the road profile associated with a particular roughness value. For example, where two roads are characterised by the same NAASRA roughness value, one may be very smooth except for the occasional severe pothole, while the other may have an unbroken surface with long "waves" which result from instability of the subgrade. Such road profile information is required to establish whether a particular pavement type is more likely to induce the temporal frequencies that are responsible for pavement damage and vehicle wear.

   The NAASRA roughness measure only characterises the response of a chosen vehicle to the road profile. However, what is required for comparing different pavement types is a measurement system that characterises the road profile itself. Non-contact road profile systems, for example the Australian Road Research Board's laser based high speed profilometer, appear the most appropriate for this purpose.

Recommendations

1. To obtain roughness levels similar to bitumen based surfaces, the base surface on which the concrete block pavers are laid should not contain long wavelength roughness of around 1-1.3 m and 7-14 m for 30 to 50 km/h speed zones, and 2-2.6 m and 14-28 m for 80 to

100 km/h speed zones as these wavelengths tend to excite the vehicle wheels and body respectively. These wavelengths also significantly influence roughness measurements made with vehicle fitted NAASRA response type meters.

2. Roughness levels specified for newly laid pavements should ideally require the determination of discrete narrow wave band roughness numerics associated with road profile wavelengths which affect vehicle occupant comfort, vehicle wear, and pavement damage. This would allow more rational roughness criteria to be specified for different pavement types and road use. It is envisaged that the criteria required for low speed residential streets would be different than for high speed heavy traffic motorways. The former would be primarily concerned with long (13-40 m) wavelengths associated with occupant comfort, whereas the latter with all wavelengths over a range spanning 1 to 40 m.

(b) Ride Harshness and Road Noise Considerations

Conclusions

1. The ride harshness often present with concrete block pavements was found to be caused by the vehicle tyre encountering regularly spaced height variations in the block paving. These height variations are caused by joints between the pavers which are in turn a function of the laying pattern and size of the pavers and the chamfered edges of the pavers.

2. The degree to which pavement induced tyre vibrations are transmitted to the body of a vehicle is dependent on the frequency of the vibration. For conventional radial tyres, there is a noticeable dropoff in attenuation above 120 Hz for both longitudinal and vertical vibrations. The critical exciting frequency ranges for inducing ride harshness were found to be between 50-60 Hz and 100-120 Hz corresponding to tyre and vehicle body natural frequencies respectively. For a vehicle speed range of 30 to 50 km/h, the 120 Hz vibration restriction requires that the maximum preferable joint spacing for pavers in the wheelpath should be no more than about 70 mm. Herringbone patterns utilising existing pavers result in joint spacings between 100-160 mm and so the harshest rides for passenger cars are likely to occur at speeds between 20 and 70 km/h. This result suggests that existing concrete block pavers may be better employed on high speed road sections than in urban areas. The experimental programme also showed ride harshness to be influenced by the size of the joint between pavers; the larger the joint, the harsher the ride.

3. Unfortunately, a spectral analysis could not be performed on the vehicle interior noise measurements, and so it has not been possible to identify which tyre vibration frequency is the primary source of the road induced noise. However, the measurements showed that if the transmission of axle/wheel vibrations to the vehicle body are minimised, lower noise levels will result.

4. In-vehicle noise levels for concrete block pavements were found to be comparable to those generated by chipseal surfaces where the road surface is dry. In addition, the noise level was shown to increase approximately 1 dB(A) per 10 km/h. This rate of increase is 30 to 50% less than for bitumen bound pavements.

Recommendations

Design refinements to concrete block pavers suggested from the research include a 30% reduction in paver size from 200 mm by 100 mm to 140 mm by 70 mm, and a less dense structure resulting in a paver that has a fairly open texture but without compromising strength and abrasion resistance.

The following recommendations are also made regarding the laying of block pavements:

1. The width of the joint between adjacent pavers should be no more than 2-3 mm at most. In addition, the deviation from a 3 m straight edge should not exceed 3-4 mm on average, and the difference in level between adjacent pavers should be less than 1 mm. These requirements are considerably more stringent than those presented in the code of practice for design and construction of interlocking block paving, NZS 3116 : 1991.

2. The repetitive spacing between pavers in the vehicle wheelpath should ideally be no more than about 70 mm for vehicle speeds greater than 30 km/h. This is not possible with existing pavers, which generally are 200 mm long by 100 mm wide. Therefore, after due consideration to traffic loading requirements, the laying pattern must be optimised for a specific vehicle speed. For example, at 50 km/h regular joint spacings at either 120 mm or 252 mm should be avoided. These critical spacings (λ) are calculated from:

$$\lambda_{1,2}\ (\text{mm}) = \frac{278 \times \text{vehicle speed (km/h)}}{f_{crit_{1,2}}}$$

where $f_{crit_1} = 55$ Hz
$f_{crit_2} = 115$ Hz

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