greater and can be on the order of 50-100 percent. On the other hand, roadmeter systems demonstrate better accuracy on rougher roads (5 percent and better) (1).

REPORTING ARV MEASUREMENTS

In all, three classes of ARV statistics have been presented. The first, ARV as obtained with a roadmeter, will include effects of meter hysteresis and individual vehicle response properties as well as the pavement properties and measurement speeds. Raw ARV measurements from different systems do not quantify roughness on a common scale, and any comparisons between ARV measures from different systems are not valid. The second class is RARV, a well-defined property of pavement profile at a given (simulated) measuring speed. It requires a profilometer, together with the vehicle simulation shown in Figure 8. Its precision is limited only by the precision of the profilometer; errors less than one percent (0.01 in/s) are easy to maintain with current profilometers (1). The third class is the CARV measurement that is obtained by using the regression relation between raw ARV values from a given roadmeter system and the true RARV values. CARV is the best estimate of RARV that can be made with a particular roadmeter system.

CARV measures taken by different systems can be compared directly because they are based on the same RARV scale. Measures taken at different speeds are also comparable if they are taken at typical traffic speeds. Because the ARV measure is dependent on speed, roughness measurement practice with roadmeters will be improved by subscripting measurements with the test speed (e.g., $CARV_{35}$ = 1.6 in/s).

The validity of the RARV statistic for all types of pavement has not yet been completely established in the field, although the limited data gathered during a correlation program show no bias for different pavement types (1). Because the RARV statistic is influenced by the same roughness features that cause typical ride and suspension motions, unlike the CHLOE profilometer and BPR roughometer, there is no obvious reason to suppose that the RARV is biased by pavement type. Hence, it is suggested as a single objective measure of pavement serviceability for all conditions until a better measure can be developed through further research to relate subjective ratings to specific road roughness qualities.

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Road Roughness: Its Evaluation and Effect on Riding Comfort and Pavement Life

A.A.A. MOLENAAR AND G.T. SWEERE

This paper describes the evaluation of road roughness and its influence on driving comfort and pavement deterioration. Distinction is made between an inventory and a diagnostic survey. The equipment used for both surveys is described. They are a ridemeter for the inventory survey and a high-speed profilometer for the diagnostic survey. Since the ride index, which is given by the ridemeter, is dependent on the measuring vehicle, relations are established between the ride index and fundamental indicators of road roughness as determined with the high-speed profilometer. Based on measurements with the high-speed profilometer, the impact of road roughness on the structural deterioration of the pavement and on the riding comfort is calculated. Also, the impact of road roughness on the safety of the road user is described. By using the results of these calculations and the relation that exists between ride index and fundamental indicators of road roughness, acceptance levels for the ride index were established. These acceptance levels can be used as a guide in the evaluation of the results of the inventory survey.

In order to know whether pavement is still in a good condition, the highway engineer should frequently perform condition surveys. Those condition surveys should consist of monitoring the strength characteristics (e.g., deflection, cracking, and rutting), skid resistance, and roughness of pavements (1). Since road roughness affects, to a large extent, the dynamic loading of the pavement caused by the tire, it also affects the development of the structural deterioration of the pavement and the safety of the road user. So road roughness should be taken into account in evaluating the strength of the pavement and the safety of the road user (Figure 1). Because evaluation of a whole road network will result in a mass of data, the survey should be done in two phases:

1. An inventory survey and
2. A diagnostic survey.

The inventory survey can be done by means of measurements that are easy and cheap to use and can be executed at high speed. To this group of measurements one can count the Mays meter, the Portland

Figure 1. Relation of pavement roughness evaluation to evaluation of pavement strength and safety.

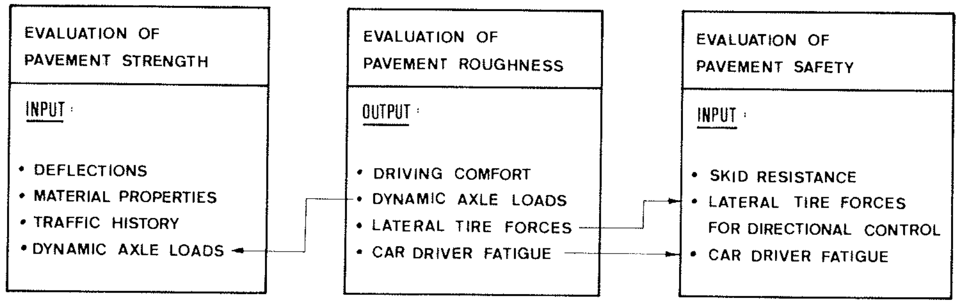
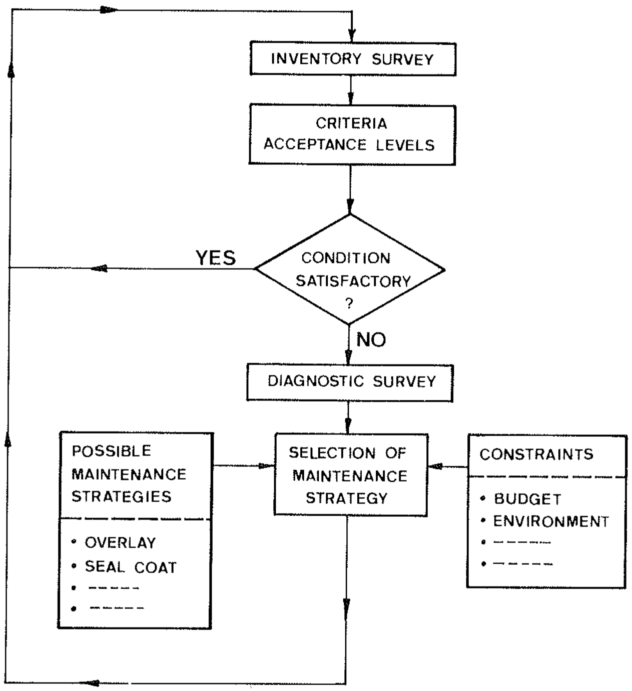


Figure 2. Survey system for pavement management system.



Cement Association (PCA) meter, the Delft University ridemeter (which is used in this study), and even the Bump Integrator [also called the U.S. Bureau of Public Roads (BPR) roughometer]. Each of these is easy to use and rather cheap to operate; besides that, the measurements can be done in a short time. The disadvantage of this type of measurements is that only an indication of road roughness is obtained in terms of vehicle response; so in fact it is not the road profile that is measured by the interaction between the road and the vehicle. The diagnostic survey should be done by means of measurements that will give the exact profile of the road. This road profile can be used as input for all kinds of calculations, such as power spectrum calculations or simulation of vehicle behavior. Based on the results of this type of measurement, we can determine what kind of maintenance activity should be applied in order to reduce pavement roughness to an acceptable level.

For the diagnostic survey, use can be made of the leveling methods for profile determination, which are slow in operation. Sophisticated high-speed profilometers such as the surface dynamics profilometer, originally known as the General Motors profilometer, the APL developed in France, and the Delft University high-speed profilometer, which is used in this study, are much more suited for this type of survey. By using one of these systems one can get the exact road profile on which one can execute all kinds of calculations, as for instance simulation of the vehicle behavior. Disadvantages of these systems are that they are complex and expensive and require an analog computer to interpret the results.

Measurements with a high-speed profilometer should be seen as diagnostic surveys. Although these measurements can be executed at high speed, specially trained personnel and complex and expensive equipment are needed. Most highway authorities are not in the position to have such equipment.

In order to know from the inventory survey whether or not the pavement is in a satisfactory condition, one should have an insight into the extent to which the results of these inventory measurements will give information about more fundamental properties of road roughness, such as the power spectrum and the slope variance of the road profile, as determined by diagnostic survey methods. In other words, relations between the inventory and diagnostic survey methods are needed.

Furthermore, the results of the diagnostic survey should be translated into values that are meaningful to the road user and highway engineer. The power spectrum of the road profile needs to be translated into, for instance, a present serviceability index and a load safety factor. The latter should represent the damaging effect of a dynamic axle load in comparison with the effect of a static axle load. Once pavement roughness is translated into effects on driving comfort, road user safety, and pavement deterioration, we can set up acceptance levels for the results of the inventory survey. An unacceptable level of road roughness in the inventory survey will result in a diagnostic survey. The results of the diagnostic survey should be taken into account for the selection of the proper maintenance strategy to be applied. This process of the interactions between both survey methods and planning of maintenance works is illustrated in Figure 2. Although the approach illustrated in Figure 2 seems attractive, in general only little work is done to make such a procedure operational. Therefore, a research program was started at the Delft University to work out the approach illustrated in Figure 2. The main goals of this project were as follows:

1. To study the effectiveness of the Delft University ridemeter for inventory road roughness surveys;
2. To determine how the roughness of roads can be translated in such a way that the results can be used directly for the evaluation of the structural pavement deterioration, driving comfort, and road user safety influenced by car-pavement interaction; (Road profiles measured with the Delft University high-speed profilometer were used as input for this study).
3. To determine whether relations exist between

Figure 3. Delft University ridemeter.

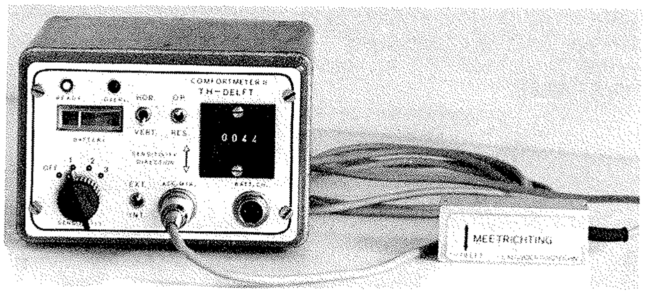


Figure 4. Filter characteristics ridemeter.

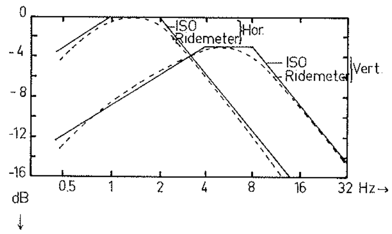


Table 1. Specifications of Delft University ridemeter.

Item	Specification
Criteria	Horizontal and vertical according to International Standardization Organization proposal
Accelerometer	Bruël and Kjaer type 4332
External input	Calibration value, 100 mV/g; input impedance, 1.5 MΩ; acceleration, ±8 g (0.8 V)
Attenuation factors	1 - 2.5 - 6.25 for switch-position 3 - 2 - 1
Ratio horizontal versus vertical	1.4 x
Current consumption	Reset, 40 mA; operate, 40 - 60 mA
Batteries	4 x DEAC -5/500 DK2; voltage-control by means of a meter with zero suppression
Operating time	Fully charged batteries, 8 - 10 h
Recharge time	Discharged batteries, 14 h
Measuring time	15 s
Dimensions and weight	Ridemeter 157 x 107 x 170 mm, 2050 g; external accelerometer including preamplifier, 31 x 31 x 80 mm, 130 g
Purchase cost	About $3500

the ridemeter values and the factors described in item 2;

4. To set up acceptance levels for the ridemeter values based on road roughness effects on pavement deterioration, driving comfort, and road user safety influenced by road roughness; and

5. To determine relations between the ridemeter values and the results of measurements with equipment that is commonly used in the Netherlands, such as viagraph, straight edge, and bump integrator.

The project described is part of a current project of the Delft University on the development of a pavement management system. The project is sponsored by the Civil Engineering Department. This paper will deal with the first four items.

EXPERIMENTAL PROGRAM

In order to fulfill the objectives mentioned above, 18 different road sections were measured with both the Delft University ridemeter and Delft University high-speed profilometer. All measured roads had an asphaltic concrete top layer. The condition of the pavement structures, both in terms of magnitude of deflection and amount of visible cracking, varied from excellent to marginal. Some sections needed an overlay very much. The quality of the subgrade, expressed in its dynamic modulus of elasticity as determined by means of deflection measurements, varied from 50 MN/m^2 to 250 MN/m^2. In other words, both weak and strong subgrades were considered.

The ridemeter measurements were performed by two men, one driving and one writing down the ridemeter values. The high-speed profilometer measurements were also performed by two men, one driving and one operating the equipment. Note, however, that, with some small modifications, both measurements can be performed by one person.

Delft University Ridemeter

The ridemeter (Figure 3) developed by the Vehicle Research Laboratory of the Delft University is a compact, light-weight instrument for evaluating the riding comfort of vehicles as far as mechanical vibrations are concerned. The vibrations may be measured at various locations within a moving vehicle, such as the floor or the seat. The ridemeter evaluates comfort based on the comfort criteria proposed by the International Organization for Standardization (ISO). Accordingly, the ridemeter is comprised of two weighting networks (filters) based on the ISO proposal: one for horizontal and the other for vertical vibrations (Figure 4).

Accelerations are normally measured by a standard built-in accelerometer. If desired, an external optional transducer can be used. The accelerometer output is weighted by the appropriate network depending on the measuring direction. Subsequently, the average root-mean-square value of the signal is determined over a period of 15 s. This value, which may be termed as ride index, is displayed on the counter of the ridemeter. A relatively high value of the ride index indicates poor comfort and vice versa.

The sensitivity direction is marked by an arrow on the front-panel. Measurements in the desired direction may be carried out simply by turning the ridemeter so that the direction of sensitivity is in line with the desired direction. In case an external accelerometer is used, the sensitivity direction of this device is brought in line with the direction in which measurements are desired. In both cases the appropriate network, depending on the measuring direction, is chosen with the help of the filter selector-switch.

A warning light shows up should an accidental overloading occur, in which case the signal from the accelerometer may be attenuated in two steps. The ridemeter is thereby suited to evaluate comfort over a large variety of operating conditions and for a broad category of vehicles. A second indicator lamp marks the end of the measuring period of 15 s. The counter can be reset to start the next measurement. The power supply of the ridemeter consists of built-in, rechargeable batteries. A recharging device is supplied as a separate unit. Table 1 gives the specification of the ridemeter.

For the ridemeter measurements in this study, use was made of the external accelerometer, which was placed on the floor at the right-hand side of the car beneath the front seat. The car used for the measurements was a normally maintained Opel Kadett passenger car. The tires were inflated to the specified pressure. The measuring speed was 48 km/h, which means that, given the measuring time of 15 s, each 200 m, a ridemeter value was obtained. As mentioned before, the main criteria for equipment to be used in the inventory survey are as follows:

1. Easy to handle,
2. Measurements have to be done at reasonable speed, and
3. Low operating costs.

The ridemeter seems to fulfill these requirements excellently.

Delft University High-Speed Profilometer

This profilometer, which is also developed at the Delft University Vehicle Research Laboratory (2), is an acoustical system for measuring road roughness. It consists of the following:

1. A measuring system firmly mounted on a vehicle (Figures 5 and 6),
2. An electronic device to process the measured signals, and
3. A magnetic tape recorder.

The principle of the system (Figure 7) is based on the measurement of acceleration (a) and the simultaneous measurement of distance (h) between the device and the road surface. The displacement (e) of the measuring device is obtained by integration of the acceleration (a) twice. The distance (h) is measured by means of an acoustical system. Acoustical pulses are sent to the road surface by a transducer (T). The reflected pulses are focused on a microphone (M) by means of an elliptical reflector (R). The distance is calculated from the delay in time between transmitted and received pulses. The pulses have a repetition rate of 860/s and a frequency content of 20-70 kHz. By subtracting h from e without phase errors the road profile is obtained, as follows:

$$y = e - h + c = \int_0^t \int_0^t a\, dt\, dt - h + \text{constant} \quad (1)$$

This calculation is performed by an electronic device. The system has been designed for measuring at speeds of 63, 80, or 100 km/h. A suitable nominal speed may be chosen depending on the driving conditions. In order to facilitate measurements, a variation in the test speed of up to 20 percent of the nominal speed is automatically corrected by the electronic device. This is achieved by using the vehicle speed signal as a control input to the electronic system and to the recorder motor drive and modulators.

The measured road profile is obtained in the form of a recorded tape that is IRIG-compatible. To obtain a better signal-to-noise ratio for the shorter wavelength, a prewhitening technique is used before recording. The measurements for this study were performed at a speed of 63 km/h, which means that the road profile was sampled at distances of about 0.02 m. The accuracy of the measuring system is either 2 percent of the measured amplitude or 1 mm depending on which value is the largest.

The great advantage of this system over other high-speed profilometers is believed to be the absence of physical contact between the measuring system and the road surface. Note, however, that the measurements can only be performed on dry roads and during dry weather. Otherwise, moisture in the microphones will cause unusable signals on the tape recorder.

Ridemeter Measurements

As mentioned before, ridemeter values were obtained for 200-m long sections of the 18 roads considered (3). On some roads the measurements were also done by using cars other than the standard Opel Kadett.

Figure 5. Acoustical system.

Figure 6. View of the electronics: (a) oscilloscope, (b) electronic device to process measured signals, and (c) magnetic recorder.

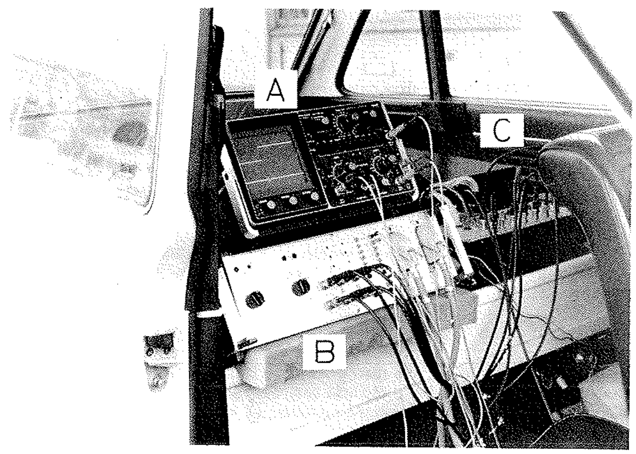
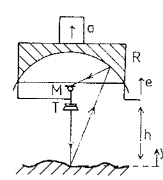


Figure 7. Principle of acoustical high-speed profilometer.



This was done in order to establish relations between ridemeter values measured by using different cars. These relations are shown in Figure 8. For some sections relations were also set up between the ridemeter values as measured with the Opel Kadett and the results of measurements with the bump integrator (4) (see Figure 9). The ridemeter values were related to the present serviceability index (psi) by using the bump integrator versus psi scale given by Auschek (5). This is shown in Figure 10.

It was concluded from this study that

1. The ridemeter is a very simple tool for qualifying road roughness in terms of riding comfort;
2. Although the type of car will influence the results, it is possible to determine which road sections are in a good, marginal, or bad condition in terms of riding comfort; and

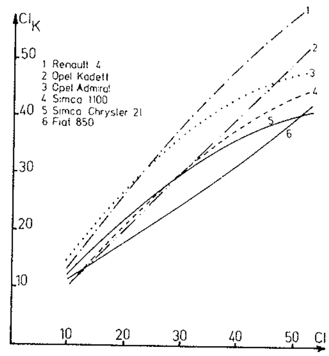


Figure 8. Relation between ridemeter values as measured by using an Opel Kadett (CI_K) and those measured by using other cars (CI).

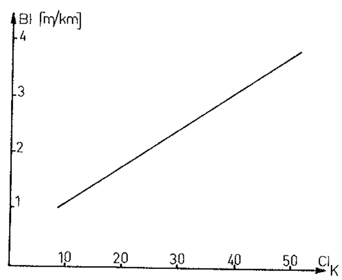


Figure 9. Relation between ridemeter values measured by an Opel Kadett (CI_K) and the results of bump integrator measurements.

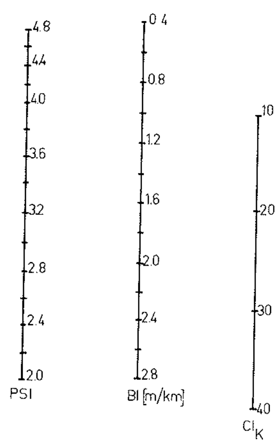


Figure 10. Relation between ridemeter values measured by using an Opel Kadett (CI_K) and psi.

3. If the ridemeter value is 30 or higher, a diagnostic survey of the road roughness is recommended.

Measurements with High-Speed Profilometer and Calculation of Road Roughness Parameters

The longitudinal profile of the road sections considered was measured by means of the high-speed profilometer (6). From the road-profile signal, which is stored on magnetic tape, energy density spectra were derived by using the fast Fourier transform technique. The energy density $[A(\lambda)]$ was determined as a function of the wave length (λ). An example of a typical plot of energy density is given in Figure 11. According to Stenschke (7), energy density relations can be described with

$$A(\lambda) = A(\lambda_0)\,(\lambda/\lambda_0)^N \quad (2)$$

where

$A(\lambda)$ = energy density |m| at wavelength λ |m|;
$A(\lambda_0)$ = energy density at a specific wavelength λ_0, λ_0 = 5 m; and
N = a constant.

All energy density relations were described in this way.

For all roads but one, the correlation coefficient squared of this relation was higher than 90 percent. For one road the correlation coefficient was much lower. This was because in that specific section the road surface consisted of both bricks and asphalt.

Furthermore, the slope variance of each road profile was calculated with

$$SV = \int_0^\lambda F^2(\lambda) \cdot A(\lambda)\,d\lambda \quad (3)$$

where

$F(\lambda) = (2/l)\,|\sin(\pi l/\lambda) - (l/L)\sin(\pi L/\lambda)|\,|1/m|$ = transfer function of the American Association of State Highway Officials (AASHO) profilometer,
l = 0.24 m,
L = 7.77 m, and
|SV| = |radian|² x 10^{-6}.

Next, psi was calculated with

$$psi = 3.27 - 1.37\,(\log SV - 0.78) \quad (4)$$

From these calculations it was determined that psi of the road sections considered varied between 1.98 and 4.1. A relation was determined between the

Figure 11. Example of a power spectral density curve and its representation by a straight line.

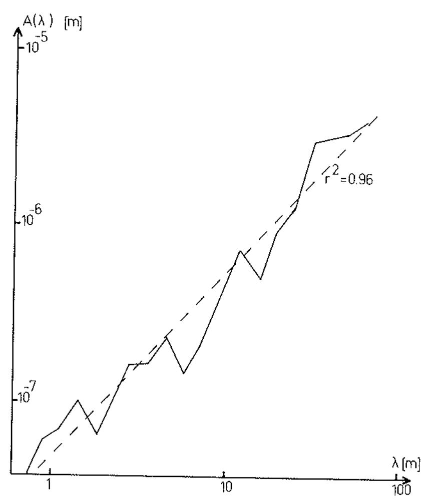


Figure 12. Relation among constants $A(\lambda_0)$, N from the power spectral density curve, and slope variance (SV).

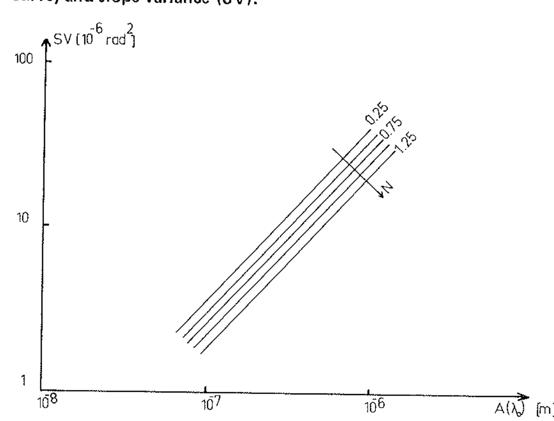


Figure 13. Used mass spring dashpot model in the vehicle simulation.

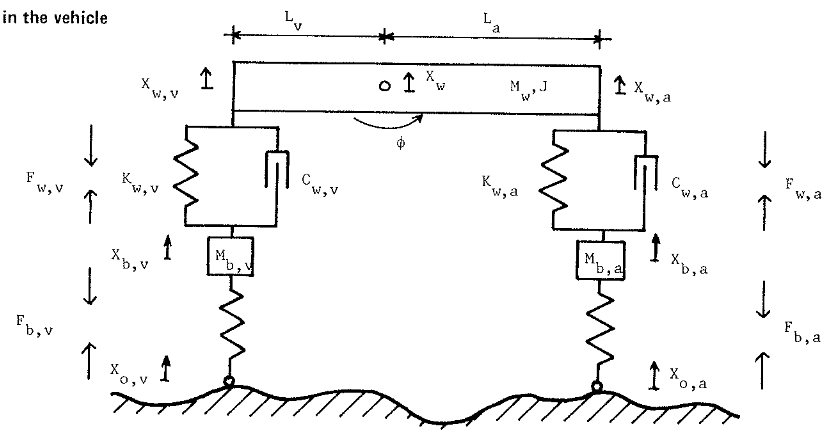
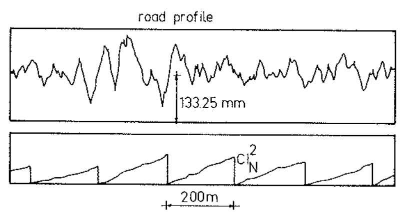


Figure 14. Example of results of passenger car simulation.



factors $A(\lambda_0)$ and N from Equation 2 and the slope variance calculated from Equation 3. This relation could be described with

$$\log SV = 7.977 + 1.046 \log A(\lambda_0) - 0.302 N \quad R^2 = 0.99 \qquad (5)$$

With SV, $A(\lambda_0)$, and N as previously defined, the equation is valid for the following

$64.2 \times 10^{-9} \leq A(\lambda_0) \leq 982 \times 10^{-9}$ and
$0.06 \leq N \leq 1.28$

A graphical representation of the equation is given in Figure 12. Since the relation between the energy density and the slope variance is excellent, it is stated that representation of road roughness in terms of slope variance is accurate enough to be used in the further analysis.

VEHICLE SIMULATIONS

In order to establish the effects of road roughness on vehicle performance, vehicle simulations were carried out on an analog computer with the road profile, measured with the high-speed profilometer and stored on magnetic tape, as input (8).

Two types of vehicle simulations were performed:

1. Simulation of a passenger car and
2. Simulation of a loaded and unloaded truck.

The simulated speed was 63.0 km/h for the passenger car and 63.0 and 31.5 km/h for the truck.

Simulation of Passenger Car

Figure 13 gives a schematical representation of the car model that was used in the simulation. The used values for the spring and dashpot characteristics were those of an average passenger car and not those of the Opel Kadett that was used for the ridemeter measurements. The output signal $(X_{w,v})$ was differentiated twice with respect to time. With the resulting signal $(\ddot{X}_{w,v})$, an analog model of the ridemeter was fed; this resulted in a simulated ridemeter value CI_N.

Figure 14 gives a graphical representation of the results of the simulation for a rough road. From the growth of the CI_N^2 line (i.e., squared simulated ridemeter value), it has been possible to determine those points within a section that caused sudden discomfort (e.g., railroad crossings or potholes).

Simulation of Truck

This simulation was carried out in order to establish the effects of road roughness on the dynamic tire loading. The simulation was carried out by using the same basic car model as shown in Figure 13 but now with the spring, dashpot, and other characteristics of a two-axle DAF truck (distance between axles is 3.2 m).

Two speeds were used for the simulation of a loaded truck (rear axle load of 100 kN) and an unloaded truck (rear axle load of 30.5 kN). Figure 15 gives a graphical representation of the results of the simulation. For each simulation, the distribution of the axle loads was determined. The standard deviations were calculated from these distributions. It could then be concluded that the effect of road roughness on the dynamic tire loads was the same for the loaded truck driven at a speed of 63 km/h and the loaded and unloaded trucks driven at a speed of 31.5 km/h. Only the unloaded truck driven at a speed of 63 km/h caused very large dynamic forces.

RELATIONS BETWEEN RIDEMETER VALUES AND THE INFLUENCES OF ROAD ROUGHNESS ON DRIVING COMFORT AND PAVEMENT DETERIORATION

One of the goals of the research program was to relate ridemeter values to parameters that are directly related to driving comfort and pavement deterioration. In the previous sections we described how the ridemeter values were obtained, how psi of the road sections considered was calculated from road profile measurements, and how road roughness influences the dynamic axle loads of a given truck. Given these results, now we can relate ridemeter values to driving comfort and pavement deterioration. First, a relation was set up between the slope variance, which proved to be a good indicator of road roughness, and the standard deviation of the dynamic axle loads as calculated for the truck, used in the simulation, driven at a speed of 63 km/h (9). These relations are shown in the southwest corner of Figure 16. They are as follows:

$$\sigma_{loaded} = 0.302 + 0.057SV - 0.000\,85SV^2 \qquad R^2 = 0.85 \tag{6}$$

$$\sigma_{unloaded} = 0.611 + 0.164SV - 0.0036SV^2 \qquad R^2 = 0.70 \tag{7}$$

where σ_{loaded} is the standard deviation of the dynamic axle load caused by the loaded truck (metric ton) and SV is the slope variance (radian^2 x 10^6). Both equations are valid for $1.51 \leq SV \leq 22.65$.

Next, the relation between the ridemeter value of a given section as determined by the vehicle simulation ($\overline{CI_N}$) and the slope variance was determined. This relation is shown in the northwest corner of Figure 15 and can be described with

$$SV = 2.185 - 6.081\overline{CI_N} + 704.468\,\overline{CI_N}^2 \qquad R^2 = 0.90 \tag{8}$$

The simulated ridemeter value $\overline{CI_N}$ was used because this value correlated better with SV than the measured CI values.

The measured ridemeter values CI_k as determined by using the Opel Kadett were related to the simulated ridemeter values CI_N, which resulted in

$$CI_N = -0.0511 + 0.0107\,CI_k - 0.000\,13\,CI_k^2 \qquad R^2 = 0.66$$
$$\text{and } 7 < CI_k < 42 \tag{9}$$

or, by using the mean ridemeter values over a given section,

$$\overline{CI_N} = -0.0807 + 0.0136\overline{CI_k} - 0.000\,18\overline{CI_k}^2 \qquad R^2 = 0.89$$
$$\text{and } 10 < \overline{CI_k} < 35 \tag{10}$$

The first relation is poor mainly because the simulated values were obtained by using a two dimensional vehicle model, which means that roll movements were excluded. The relation between the mean values of CI_k and CI_N is, of course, much better because the influence of peak values is reduced here. The mean value relation is shown in the northeast corner of Figure 16.

Finally, the relations between the ridemeter values as measured by using different cars (see Figure 7) and those measured with the Opel Kadett, are shown in the southeast corner of Figure 16. From this correlation study we concluded that, if ridemeter values are measured at 40 and higher, the pavement needs to be maintained since the psi is lower than 2. This latter value is often used as a minimum acceptance level. Note that this ridemeter value is in close agreement with the value that can be read from Figure 10.

In order to compare the established ridemeter value acceptance level with the comfort and car driver fatigue criterion developed by ISO, reference is made to Figure 17, in which the ridemeter values are related to those criteria. From this figure it can be determined that, after a 20-30 min drive on a road with psi = 2 (ridemeter value = 40), the car driver will classify the road as not comfortable. After a 3-h drive the car driver will show symptoms of fatigue.

In order to quantify the damaging effect of dynamic axle loads on pavement structures, a damage factor (S) was determined by using the calculated dynamic loads caused by the rear axle (P_{stat} = 100 kN) of the loaded truck traveling at a speed of 63 km/h.

S is calculated in the following way:

1. Determine the standard deviation of the dynamic axle loads from ridemeter measurements by using Figure 16 and
2. Once the axle load distribution is known, calculate the damage factor (S) by using the following equation:

$$S = \sum_{i=110}^{170} (p_i/100)^4 \tag{11}$$

where S is the damage factor and p_i is the magnitude of the axle loads in group i (kN).

In other words, S is calculated by using only the dynamic loads that are larger than the static axle load of 100 kN.

The relation between the measured ridemeter value (CI) or simulated ridemeter value (CI_N) and S is shown in Figure 18. Figure 18 shows that the influence of road roughness on the number of equivalent 100-kN axle loads is limited. Due to road roughness, the number of 100-kN load applications is at the most 1.3-1.4 times the number of static load applications. Figure 19, which is taken from

Figure 15. Example of results of truck simulation.

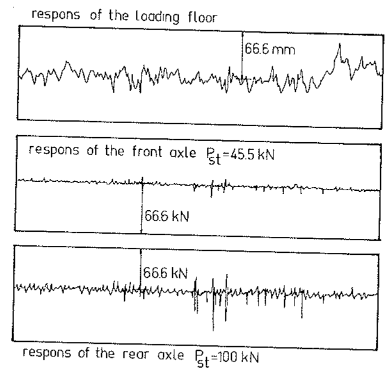


Figure 16. Relation between ridemeter values, slope variance, and standard deviation of the dynamic axle loads of a loaded and unloaded truck.

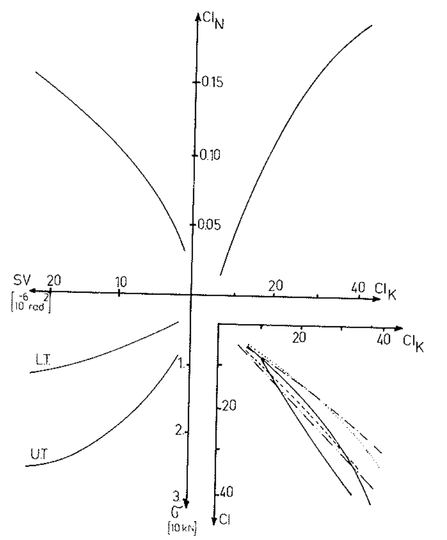


Figure 17. Ridemeter values in relation to ISO levels of comfort and fatigue.

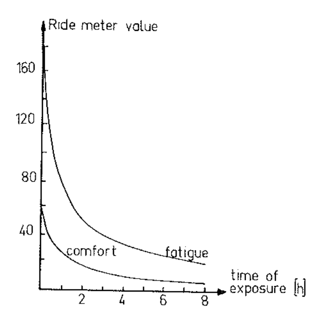


Figure 18. Relation between ridemeter values and damage factor.

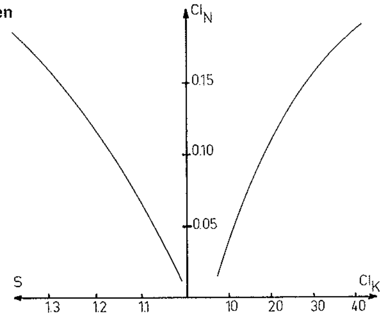
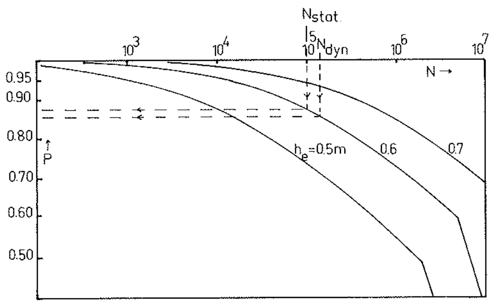


Figure 19. Influence of number of dynamic equivalent 100-kN single-axle loads on the structural deterioration expressed by the probability of survival (P) of the pavement.



Pavement is a three layer system

Type of asphaltic concrete: Dense Asphaltic Concrete

Stiffness of the mix: 5×10^9 N/m^2

Stiffness of the subgrade: 1×10^8 N/m^2

$h_e = 0.9\, h_1 \sqrt[3]{E_1/E_3} + 0.9\, h_2 \sqrt[3]{E_2/E_3}$

another paper (10) shows that the influence of the dynamic axle loads on pavement deterioration is limited.

INFLUENCE OF ROAD ROUGHNESS ON ROAD USER SAFETY

For the safety of the road user, the magnitude of the lateral tire forces is an important factor because those forces are necessary for the directional control of the vehicle. The magnitude of the lateral tire force depends on the normal tire force, the tire slip angle, the tire camber angle, and the coefficient of friction between tire and the road surface. By using the information given elsewhere (11-13), lateral tire force distributions were derived for the different pavement sections from the distributions of the normal tire loads. This approach will lead to rather stringent minimum acceptance levels for the road roughness. For instance, if the psi of a road is 2.0, this would be unacceptable for safety reasons; however, this value is only just below the minimum acceptance level established for other reasons.

It is hard to establish criteria for road roughness based on road user safety because the needed lateral tire forces will depend on the need for directional control. In other words, roads that have a relatively large amount of curves or roads that carry both slow traffic (for instance bicycles or agricultural tractors) and fast traffic, which will lead to a relatively large amount of passing movements, need a smoother pavement than roads that do not have such features.

More study is needed to establish roughness criteria based on road user safety. Based on this study, however, we recommend that the psi should not be lower than 2.5 for reasons of safety, which means that the ridemeter values should be lower than 30.

CONCLUSIONS

From the study described in this paper the following conclusions have been drawn.

1. In order to establish the roughness of a road network, inventory and diagnostic surveys should be carried out.
2. The inventory survey can be carried out with simple equipment, such as the ridemeter described in this study.
3. Relations exist among the ridemeter values on the one hand and the psi, damaging effect of dynamic tire loads, and standard deviation of dynamic tire loads on the other hand.
4. These relations show that, if the ridemeter values are higher than 40, the road should be maintained for reasons of low serviceability index (psi < 2).
5. Ridemeter values should preferably be lower than 30 for reasons of road user safety.
6. Based on conclusions 4 and 5, we recommend that a diagnostic survey should be carried out if the ridemeter values are between 25 and 30.
7. Energy spectra can be accurately described by two parameters, $A(\lambda_0)$ and N.
8. The slope variance and so the psi can be accurately calculated from $A(\lambda_0)$ and N.
9. Road roughness has only a limited effect on the structural pavement deterioration.
10. Road roughness seems to have a marked effect on road user safety.
11. More study should be done in order to establish road user safety-based roughness criteria.

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Reflex-Percussive Grooves for Runways: Alternative to Saw-Cutting

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The presence of transverse grooves in runway surfaces helps alleviate aircraft hydroplaning during landing operations. The Federal Aviation Administration has recommended installation of 0.25-in square-grooves spaced at 1.25 in center-to-center on runways where potential of hydroplaning exists. However, many runways remain nongrooved, primarily because the cost of grooving by the conventional saw-cutting method, currently in widespread use, is high. This paper describes the braking effectiveness of an aircraft tire on reflex-percussive grooves produced by a newly developed low-cost groove-installation technique called the reflex-percussive cutting process. This process is based on the principle of controlled removal of concrete. The cutting head causes the material directly under the area of impact to pass through a rapid compression-tension cycle. Because it is weak in tension, the concrete fractures in the localized area of impact without damaging the surrounding concrete. The braking effectiveness of an aircraft tire on these grooves is comparable to conventional saw-cut grooves under similar conditions of wetness, and both types of grooves alleviate hydroplaning. The cost of installation of the reflex-percussive grooves in portland cement concrete, however, can be as low as half the cost of installation of conventional saw-cut grooves at the recommended groove spacing.

The braking performance of an aircraft during landings on water-covered runways depends on the level of friction developed in the contact area between the aircraft tire and the runway surface. The friction level developed in the contact area is affected by aircraft speed, design of the tire tread, runway finish and drainage capacity, characteristics of the braking system, and the amount of water on the runway. Under flooded runway conditions, aircraft may hydroplane whereby very low levels of friction are available and the braking capability is significantly reduced. Loss in braking capability can be considerable even if runways are covered with only a thin film of water.

During hydroplaning, the physical contact between the tire and the runway is lost, and the tires are supported on the intervening layer of water. Hydroplaning occurs as a result of rapid buildup of hydrodynamic and viscous pressures in the tire-runway contact area. Dynamic or viscous hydroplaning are identified according to whether inertial forces or viscous forces, respectively, are predominant. In all cases of hydroplaning, however, both effects are present to some degree. Dynamic hydroplaning can be minimized by a rapid removal of water from the tire-runway contact area; runway grooves accomplish this effectively by providing escape channels for water forced out of the contact area during tire passage over the grooves. Viscous hydroplaning can be alleviated by providing adequate microtexture in the runway surface.

The Federal Aviation Administration (FAA) has recommended (1) 0.25-in wide by 0.25-in deep grooves spaced at 1.25 in between centers and has encouraged airport managers, operators, and owners to groove runways where potential of hydroplaning or overrun exists. However, many runways have not been grooved. The major deterrents to the use of runway grooves are the high cost of grooving by the conventional saw-cutting method and the availability of only limited evidence as to the effectiveness of grooved surfaces at the touchdown speeds of jet aircraft.

The objective of the research described in this paper is to evaluate the braking effectiveness of an aircraft tire on grooves produced by a new and less expensive reflex-percussive cutting process and to compare the performance of these grooves with the conventional saw-cut grooves.

GROOVES PRODUCED BY REFLEX-PERCUSSIVE PROCESS

The reflex-percussive method of controlled removal of concrete was recognized by the Concrete Society of Great Britain in 1972. This method was first developed for providing a very rough finish in the runway surface. When the cutting head strikes the surface of the concrete, it causes the material directly under the area of impact to deflect downward and thus creates a momentary and localized compression. The compressive strain is primarily elastic, and almost immediately the concrete rebounds and passes into tension nearly equal to the initial compression. However, because it is very weak in tension, the concrete fractures and releases the elastic energy as the kinetic energy of the flying fragments. The great advantage of this method of cutting is its ability of not loosening the aggregate particles within the matrix or creat-