Problems Encountered in Using Vehicle Ride as a Criterion of Pavement Roughness

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One criterion of pavement roughness has been the ride experienced in a passenger vehicle. This ride depends on the properties of the vehicle as well as those of the pavement. Recent changes in vehicle design (less weight and front-wheel drive) may affect this pavement criterion. To show the relationship between vehicle properties and ride, a simple mathematical model was selected for the vehicle. Vertical vehicle acceleration was used as a measure of the ride. For a pavement of known properties, the ride was determined for different speeds and different vehicle suspension characteristics. Significantly different values for the pavement criterion were obtained for the same section of pavement. It is believed that ride can still be used as a criterion of pavement roughness but that operating speeds and vehicle characteristics must also be considered in establishing this criterion.

For many years the ride experienced by the occupant of a vehicle has been used as a criterion of pavement roughness. A person traveling over a section of pavement in a passenger vehicle at a selected speed subjectively evaluates the experience. This evaluation is accepted as a criterion of the roughness of the pavement section in question.

In spite of the subjective nature of this procedure it has worked well for several years largely because passenger vehicles have been similar in design over this period of time. Moreover, cars used to be heavier and the weight distribution resulted in almost the same wheel loads on the front and rear wheels.

Within the past 5 years significant changes have been made in the design of passenger cars. The weight has been reduced in some models so that the weight of the passenger is now a higher proportion of the total weight. Of greater importance is the fact that with front-wheel drive the front wheels carry more of the total weight when only the front seat is occupied. In addition, the overall length of these vehicles has been reduced. As a result of these and other changes, there is a difference in the riding properties of the newer cars. Thus, it is possible to have different pavement roughness criteria for the same pavement if different vehicles are used to evaluate the ride.

In addition, the response of the vehicle to the pavement varies with vehicle speed. Depending on the properties of the pavement, it is possible to improve the ride by selecting the proper vehicle velocity. In general, the effects of short-wavelength disturbances can be minimized by traveling at higher velocities whereas long-wavelength disturbances become more objectionable at higher speeds.

The Kentucky Department of Highways has evaluated the riding quality of highways by measuring the acceleration experienced by a person riding in a vehicle (1, p. 14). A difference of 8 percent was observed between tests conducted with a full tank of gasoline and one conducted with a tank that was nearly empty. It is thus possible for vehicle properties to change measurably during the operation of the vehicle.

The purpose of this paper is to outline a method by which vehicle properties can be described in a meaningful way but the basic concept of evaluating a pavement based on ride can still be used.

DESCRIBING RIDE

The Kentucky Department of Highways used triaxial passenger acceleration as a criterion of ride. In this paper only vertical acceleration is considered. A more accurate description of ride requires a consideration of the allowable levels of acceleration at various frequencies.

DESCRIBING THE VEHICLE

A simple model of the vehicle is used (see Figure 1). The single wheel of the model is assumed to have no weight and to experience a vertical displacement y. This displacement is produced by the highway profile. To the wheel is attached the lower end of a linear spring of stiffness k that represents all the stiffness in the suspension system of the vehicle. In a similar way, all of the damping is represented by a linear shock absorber that has a damping constant c and is also attached to the wheel. To the upper ends of the spring and the shock absorber is attached a mass m that represents all of the sprung mass of the vehicle. The vertical acceleration of this mass is considered as the acceleration experienced by the passenger and, hence, the ride criterion.

The vehicle characteristic used in this analysis is the ratio of the passenger acceleration divided by the vertical displacement of the wheel plotted as a function of frequency (see Figure 2). This characteristic represents the application to a highway problem of a frequency response technique used in automatic control problems to describe a system of interest (2, p. 72). This technique requires that the input and the output of a given system be defined. A sinusoidal input is then applied at a selected frequency to produce a sinusoidal output. The ratio of the amplitude of the output to that of the input is then determined at the selected frequency to give one point on what is known as a frequency response curve.

This process is repeated until the curve is defined over the range of frequencies of interest. This curve describes the system under consideration

Figure 1. Simple model of a passenger vehicle.

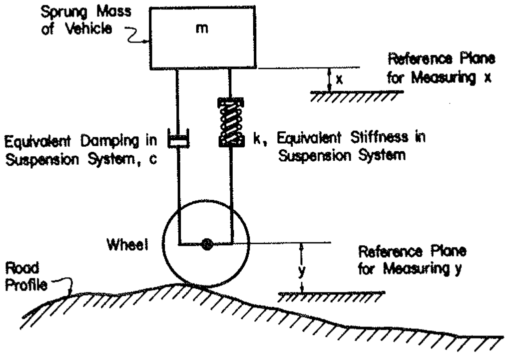


Figure 2. Vehicle characteristics used to predict ride.

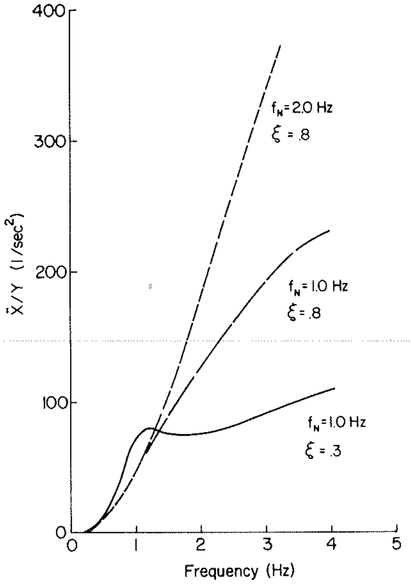
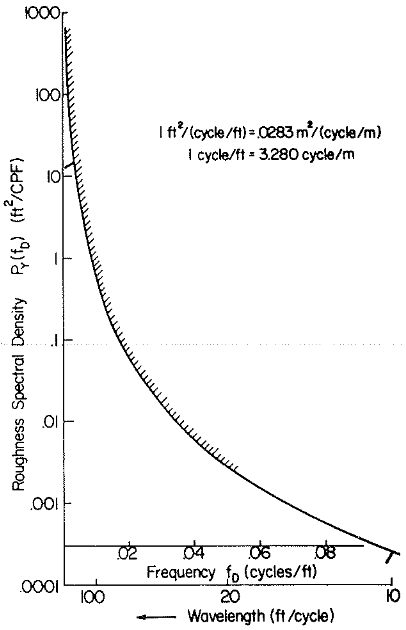


Figure 3. Pavement roughness spectrum.



and has many useful applications. By using the appropriate input and output quantities, curves of this type have been used to predict dynamic tire forces (3) and to determine pavement roughness spectra from vehicle motion (4). A response characteristic can be determined either mathematically or experimentally.

In this case the system under consideration is the vehicle. The input is defined as the displacement y at the wheel resulting from travel over the pavement surface. The output is the ride $\ddot{X}$, which has already been discussed. For this situation the frequency response characteristic has been computed mathematically, but it can also be determined experimentally, as has been done for actual passenger cars (5). The amplitude of the sinusoidal input displacement is represented by Y, and the amplitude of the sinusoidal output acceleration is represented by $\ddot{X}$.

The ratio of interest is $\ddot{X}/Y$, which is shown in Figure 2 for three different vehicle suspension conditions. The mathematical development of $\ddot{X}/Y$ is omitted here to conserve space and also because it is believed that a serious study of this problem should involve an experimental determination of actual vehicle properties.

The curves in Figure 2 show the effect on the $\ddot{X}/Y$ characteristic of the natural frequency of the vehicle (f_N) and also of the damping in the suspension system as indicated by the damping ratio (ξ). In general, larger values of ξ represent more highly damped suspension systems. The units of $\ddot{X}/Y$ are those of acceleration divided by displacement, which reduce to 1/sec².

DESCRIBING THE PAVEMENT

A pavement roughness spectrum is used to describe the pavement (6). This curve, shown in Figure 3, indicates the extent to which various wavelengths are present in the pavement profile. The ordinates of this curve represent the roughness spectral density in square feet per cycle per foot, and the abscissae represent the reciprocals of the wavelengths in units of 1/ft. The area under this curve represents the mean square value of the roughness in square feet. The reciprocal of the wavelength is referred to as a distance-based frequency (f_D) in contrast to the time-based frequency (f) used in describing the vehicle. [Information for Figure 3 was obtained by using instrumentation (7) calibrated in the units shown.] This description of the pavement depends only on the profile and is thus geometric in nature.

The question might be raised as to why the area under the pavement roughness spectrum could not be used as a criterion of pavement roughness. The reason is that not all wavelengths affect the riding qualities of a pavement. This is particularly true of long wavelengths, which usually make large contributions to the mean square value of the roughness. Going up over a hill and down into a valley introduces an enormous wavelength into the pavement profile, but if the pavement is free of very short wavelength distortions the ride will not be adversely affected. In this way ride serves to identify pavement distortions that are important to the user.

A pavement roughness spectrum can be computed from elevation measurements (6) or determined from the data obtained from any device that measures the pavement profile. It can also be measured directly by using special equipment (7). The advantage of using this description of the pavement is that it can be combined with the vehicle frequency response previously mentioned to predict the ride, which can then be used as a criterion of pavement roughness.

PROCEDURE FOR PREDICTING RIDE

Because the pavement is described in terms of cycles per foot, it is necessary to convert these units to cycles per second (hertz) in order to be able to combine the pavement roughness spectrum with the vehicle frequency response characteristic. To do this it is necessary to know the velocity (V) at which the vehicle is moving over the pavement. If V is known, the ordinates and the abscissae of the roughness spectrum can be transformed to produce a new roughness spectrum curve expressed in terms of a time-based frequency. This transformation can be achieved as follows:

$$f = V \times f_D \qquad (1)$$

$$P_Y(f) = P_Y(f_D)/V \qquad (2)$$

where

f = time-based frequency (cycles/sec or Hz),
f_D = distance-based frequency (cycles/ft),
$P_Y(f_D)$ = pavement roughness spectral density [ft²/(cycle/ft)], and
$P_Y(f)$ = transformed pavement roughness spectral density [ft²/(cycle/sec)].

The results of this transformation are shown in Figure 4, where two different velocities have been used as indicated and two separate and distinct curves have been obtained. This indicates that different operating speeds will result in different inputs to the vehicle and, hence, different vehicle outputs can be expected. The effects of the two velocities can also be seen in Figure 3, where that portion of the curve designated by the closely spaced tic marks above the curve is associated with the higher velocity and that portion lying within the two longer tic marks below the curve is associated with the lower velocity. Figure 3 shows that long wavelengths become more significant in the input to the vehicle at high velocities whereas shorter wavelengths become less significant. In terms of the input, the vehicle is exposed to different highways at different speeds even though the same section of pavement is involved, which introduces problems when ride is used as a criterion of pavement roughness.

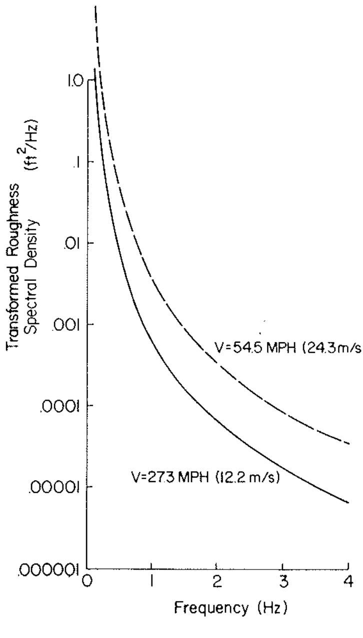
It is possible to determine the mean square value of the passenger acceleration by using the appropriate information in Figures 2 and 3. This requires the use of the following relationship (8, p. 197):

$$P_{\ddot{X}}(f) = P_Y(f) \times (\ddot{X}/Y)^2 \qquad (3)$$

where $P_{\ddot{X}}(f)$ is the acceleration spectral density [(ft²/sec/sec)²/Hz].

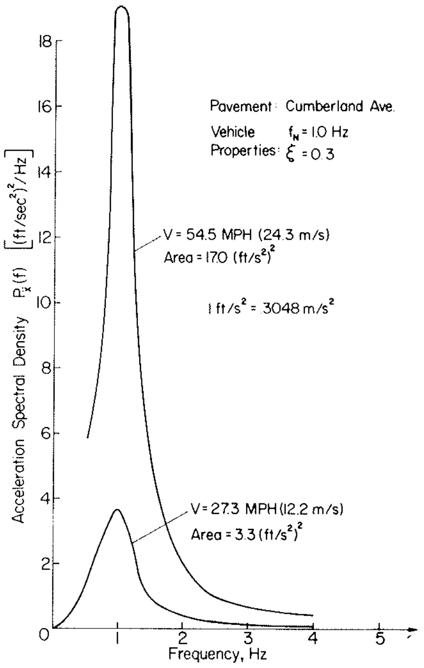
Acceleration spectral density curves are shown in Figure 5 for the vehicle characteristic shown by the solid line in Figure 2 for velocities of 27.3 mph (12.2 m/sec) and 54.6 mph (24.4 m/sec). The area under each curve represents the mean square value of acceleration experienced by the passenger at the velocity indicated. This is the criterion of pavement roughness mentioned previously.

Figure 4. Transformed pavement roughness spectra.



Because the mean square value of acceleration is the variance of acceleration, the standard deviation can be obtained by taking the square root of the variance. Tests (9, p. 129) have indicated that in an acceleration time record the amplitudes can be approximated by a normal distribution that has a zero mean. Once the standard deviation is available, it is possible to estimate the probability of encountering various magnitudes of acceleration and thus evaluate the ride in a more meaningful way.

Figure 5. Acceleration spectral densities for two speeds.



EVALUATING A LOCAL PAVEMENT

To illustrate the problems encountered, the roughness spectrum of a convenient pavement section was measured by using a modified BPR roughometer (7). This pavement was used daily but was generally considered to be rougher than average. The roughness spectrum, shown in Figure 3, was transformed to a time-based frequency for two different velocities, as shown in Figure 4.

Vehicles with various suspension properties were then investigated for natural frequencies ranging from 1 to 2 Hz. The lower frequency represents a vehicle with a soft suspension and, hence, a better ride. This is typical of heavier, higher-priced vehicles, in which ride is an important characteristic. The 2-Hz frequency is more characteristic of stiffly sprung vehicles such as those in which handling is most important. Damping ratios from 0.8 to 0.3 were selected to represent shock absorbers in good to poor condition.

The standard deviations of the accelerations were computed for different speeds, natural frequencies, and damping ratios (see Figure 6). The interior of the parallelogram in Figure 6 approximates the region of possible values for the standard deviations of passenger acceleration. Values ranging from 1.8 to 6.9 ft/sec^2 (0.55 to 2.1 m/sec^2) are indicated.

By selecting a vehicle with a natural frequency of 2 Hz and a damping ratio of 0.3 (the upper boundary of the region shown in Figure 6), standard deviations ranging from 3.1 to 6.9 ft/sec^2 (0.96 to 2.1 m/sec^2) can be obtained on the same pavement by varying the speed from 27.3 to 54.5 mph (12.2 to 24.4 m/sec). The statistical significance of this is shown in Figure 7, where (assuming a normal distribution) the probability density curves are plotted versus acceleration for the two velocities under consideration. Broken vertical lines are shown at 0.1 g (3.21 ft/sec/sec) and at -0.1 g. The probability of experiencing accelerations outside these limits is represented by the area bounded by the curve of interest that lies outside these vertical lines. At 27.3 mph this probability is 0.317; at 54.5 mph it is 0.617.

Figure 6. Standard deviation of acceleration as affected by vehicle properties and vehicle speed.

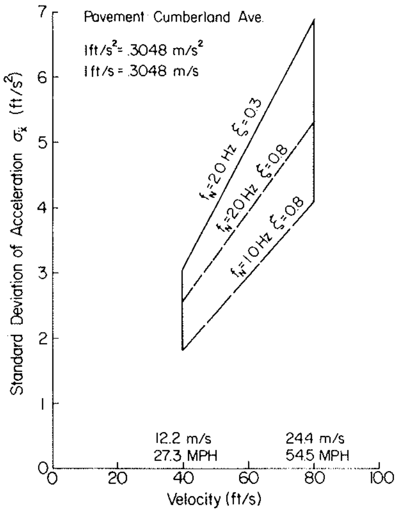
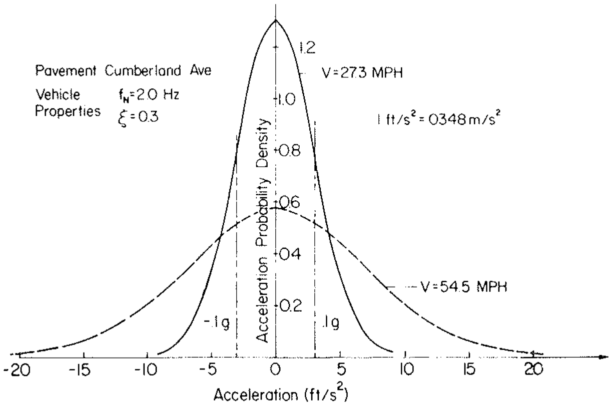


Figure 7. Probability density functions for accelerations experienced by a vehicle at two different speeds on the same pavement.



CONCLUSIONS

For the simple vehicle model used in this paper, a wide range of passenger accelerations was obtained even though the identical section of pavement was being evaluated in each case.

In the past, vehicle ride has been a satisfactory criterion for evaluating pavement roughness because there was relatively little change in the design of the most commonly used passenger vehicles. In recent years, however, many passenger vehicles have undergone extensive design changes. It is believed that the ride in these newer vehicles can still be used to evaluate pavements but that before this is done a careful study of the effect of the properties of the newer vehicles on ride should be undertaken. In addition, it is also desirable that certain standard conditions be established to obtain a measurement of pavement roughness that will reflect only the pavement properties.

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