Effect of Pavement Condition on Dynamic Vehicle Reactions

BAYARD E. QUINN and DAVID R. THOMPSON, respectively, Purdue University and Lockheed Aircraft Corporation

A vehicle traveling over a highway containing surface irregularities experiences vertical motion as well as horizontal motion. Associated with the vertical motion are forces between the highway and the vehicle that are developed in addition to the static weight of the vehicle. These forces are frequently referred to as the dynamic reactions or the dynamic forces. They depend on the vehicle suspension characteristics, the condition of the pavement, and the velocity of the vehicle.

Laboratory tests were conducted to determine the frequencies of vibration at which passenger vehicles would develop large forces between the tires and the pavement. The relationship between force exerted by the tire and vertical displacement of the tire tread was measured at all frequencies at which any appreciable force was developed. The vehicle characteristic thus obtained included the actual effects of all components of the vehicle suspension system.

A criterion of pavement condition was established by making power spectral density analyses of highway elevation measurements. A brief description of the physical significance of this criterion is included.

A procedure is discussed for combining the vehicle characteristics with an elevation power spectrum (pavement condition criterion) at a selected vehicle velocity to obtain a dynamic force power spectrum. The usefulness of this result is discussed and curves of the root-mean squared value of the dynamic force vs vehicle velocity are included for three different pavement conditions.

By using the criterion of pavement condition as defined in this paper it is possible to estimate the dynamic force that one wheel of a vehicle will exert on a highway.

• A VEHICLE parked on a smooth, level highway will exert a force on the pavement that is equal to the combined weight of the vehicle and the cargo. This force is frequently referred to as the static force. If the vehicle moves at a constant velocity over the highway there will be no increase in this force if the tires of the vehicle are properly balanced.

If, however, the vehicle moves along a highway containing pavement irregularities, the vehicle will also experience vertical motion. This motion will be very abrupt if sudden discontinuities such as chuckholes or faults are present. The larger the highway discontinuities, the more violent will be the resulting vertical motion. If large vertical displacements are accompanied by large accelerations, it is evident that the vehicle must experience large forces that will have their origin in the highway. These forces will be in excess of the static force and will be referred to as the dynamic forces.

Although large discontinuities may produce large vertical accelerations and hence generate large forces between the vehicle and the highway, it is possible to reduce the magnitude of these forces by reducing the velocity of the vehicle. Thus, if the vehicle travels slowly enough over a very rough highway, the increased force between the vehicle and the highway may be held within desired limits.

Large vertical accelerations can also result from smooth undulations in the highway. If the speed of a vehicle is increased sufficiently, a variation in the highway profile that may be unnoticed at a slower speed may result in a violent pitching of the vehicle at a higher speed. It is thus possible for the vehicle to experience large vertical forces from conditions other than discontinuities in the pavement.

Also, characteristics of the vehicle suspension system will influence the behavior of the vehicle. A vehicle with very hard tires will react much more violently to an irregularity than will a vehicle with soft tires. Moreover, the springing between the body of the vehicle and the axles will influence the response of the vehicle on the highway. It is thus evident that the dynamic reaction between a vehicle and a highway will be influenced by the condition of the pavement, the vehicle suspension characteristics and the velocity with which the vehicle is operated.

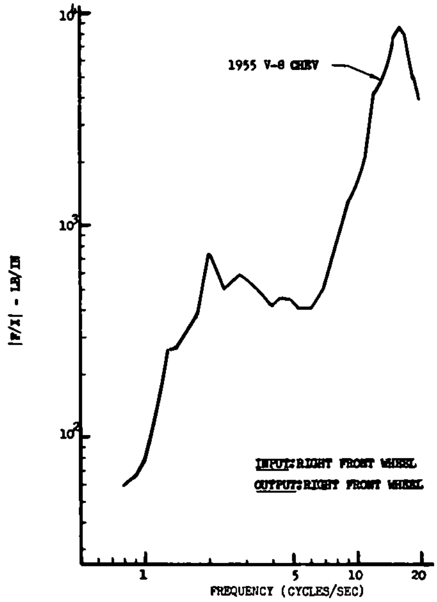

Figure 1. Maximum envelope vehicle response characteristics.

DETERMINING SIGNIFICANT WAVE LENGTHS IN PAVEMENTS

A highway profile contains a tremendous range of wave lengths; close examination reveals very small irregularities in the surface due to finishing. These may have a wave length in the order of a fraction of an inch and a correspondingly small amplitude. On the other hand, the highway may go over hills and down valleys containing wave lengths several miles in length. Between these extremes are undulations having intermediate wave lengths. It is, therefore, necessary to determine the wave lengths in the profile that will be significant in influencing the dynamic force that the vehicle exerts on the pavement.

To determine the significant wave lengths, it is necessary to determine the significant frequencies of vibration of the vehicle. To do this, it is convenient to consider the ratio of the force F which the vehicle exerts on the highway to the vertical displacement X of the tread of the tire. This can be done by constructing a platform that will move up and down with simple harmonic motion having a controlled frequency and an adjustable amplitude X. An electronic scale can be placed on the platform to measure the resulting reaction F. If a wheel of a vehicle is driven onto the platform and the platform is excited, the ratio of F to X can be obtained (1).

A typical vehicle characteristic is shown in Figure 1. It is evident that the vehicle responds to a much greater extent to certain frequencies of vibration than to others. When the wheel is excited at frequencies below 1 cycle per sec (cps), very little force is developed in excess of the static force. At 2 cps a relatively large force is generated, and as the frequency is increased, this force decreases slightly. At 7 cps the force again increases and reaches its maximum value at 15 cps. With a further increase in frequency the force decreases rapidly, and no further increase in force has been observed up to 20 cps. A curve of this type obtained experimentally thus describes the suspension characteristics of a vehicle and includes the effect of tires, springs, shock absorbers, and all other components of the vehicle.

Variations in the highway profile that will excite frequencies of 2 or 15 cps will thus generate large forces between the vehicle and the highway. These frequencies are therefore of interest in predicting the influence of the pavement on the reaction of the vehicle.

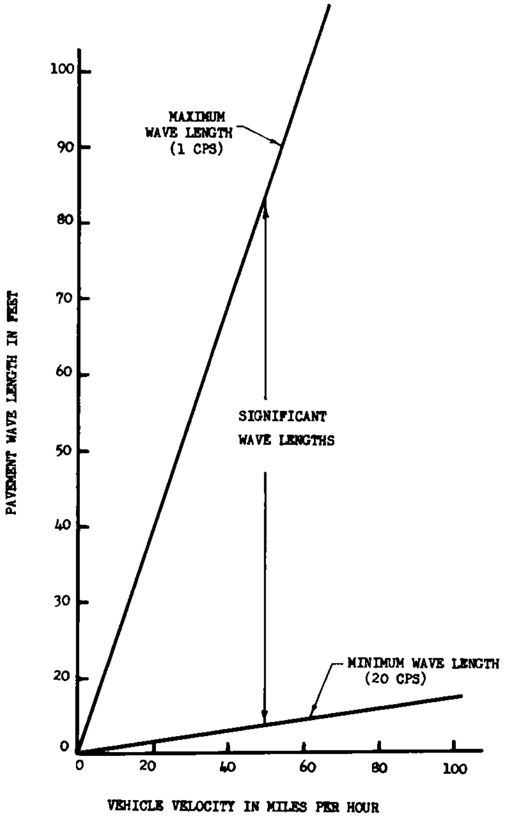

Figure 2. Pavement wave lengths exciting frequencies from 1 to 20 cps in vehicle.

The velocity of a vehicle will influence the frequency of excitation that is received from the highway. For example, a certain highway profile is an endless succession of sine waves each having a wave length of 5 ft. If the vehicle described in Figure 1 travels over this highway at 10 ft per sec it will pass over two complete sine waves per second. Excitation of the vehicle at 2 cps will thus result. If the velocity is increased to 75 ft per sec the vehicle will pass over 15 complete sine waves in 1 sec thus experiencing a 15 cps excitation. A fixed wave length can therefore induce any exciting frequency in the vehicle if the appropriate vehicle velocity is selected.

From Figure 1, it is evident that the range of frequencies causing large dynamic forces between the highway and the vehicle extends from 1 to approximately 20 cps. Wave lengths that excite frequencies of less than 1 cps will cause no appreciable increase in the dynamic force, and wave lengths that excite frequencies appreciably greater than 20 cps will also make very little contribution to this reaction. Thus, only frequencies lying between 1 and 20 cps are of much interest in predicting the dynamic force. A curve showing the significant wave lengths vs vehicle velocity is given in Figure 2. In this figure, the longest wave length of significance (which would generate a disturbance at 1 cps) and the shortest wave length (which would induce a disturbance of 20 cps) are shown by the two lines. At any given velocity the vertical distance between the two lines represents the range of wave lengths that are significant in inducing appreciable forces between the vehicle and the highway. From Figure 2 it is evident that the shortest wave length at 50 mph is of no interest at 80 mph, whereas the long wave length at 50 mph is still effective in producing dynamic force when the vehicle is traveling at 80 mph. It is also evident from Figure 2 that higher vehicle velocities introduce longer wave lengths into the response of the vehicle while eliminating the shorter wave lengths. Having the information shown in Figure 1 for any vehicle would therefore define the region of interest in Figure 2.

DESCRIPTION OF PAVEMENT CONDITION

A suitable criterion is needed to describe the condition of the pavement. This criterion should be based on measurements and should be of such a nature as to be readily used with the vehicle characteristic shown in Figure 1.

A statistical procedure (2) is available for describing random processes, and it is interesting to consider the possible use of this technique for describing pavement conditions. Although a pavement does not completely satisfy all of the requirements, it comes reasonably close in many respects. In the process of applying this procedure it is possible to check the extent to which the pavement fulfills an important necessary condition, and the analysis can be discontinued if the pavement does not display the proper characteristics.

The procedure under consideration is that of making a power spectral density analysis. Because many references (3, 4) are available that give detailed discussions of this technique no attempt will be made to present these details in this paper. The important considerations in applying the procedure to highway problems will be presented, however.

Although this analysis can be applied to any type of measurement, it is instructive to apply it to highway elevation measurements made at 1-ft intervals using a rod and level. The spacing of these elevations is arbitrary and depends on the wave lengths that are to be resolved. Elevation measurements will not attenuate the long wave lengths that become increasingly important at higher vehicle velocities, and when made with this spacing include wavelengths down to 2 ft.

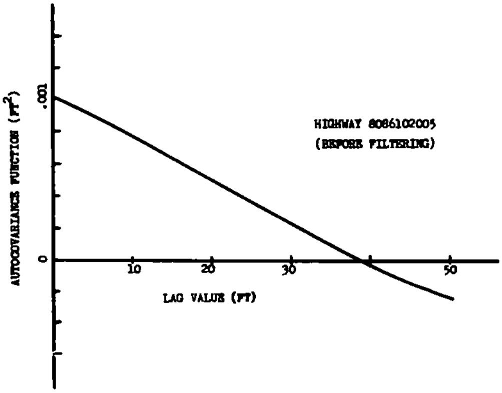

Figure 3. Typical pavement autocovariance function.

An initial data processing operation is necessary to obtain the difference between each elevation measurement and a properly selected base line. From the differences thus obtained the autocovariance function is computed. This can most easily be done on a digital computer, and a typical function for a highway is shown in Figure 3. This function should approach zero and remain at zero as the lag values increase, and the function should not be periodic. The extent to which the autocovariance function fulfills these conditions determines whether the pavement profile is sufficiently random to be described by this technique. An unsatisfactory autocovariance function can frequently be improved by performing a filtering operation on the original data to remove existing periodicity. Errors in the original data can usually be detected from this function. Having obtained the autocovariance function, it is then possible to compute the power spectrum.

To understand the physical significance of a power spectrum analysis of highway elevation measurements, it is important to realize that the power spectrum is computed from the variations in these measurements. If the highway is smooth and level so that the elevation measurements are all the same, all values for the power spectrum will be zero. It is thus evident that only variations in elevations spaced 1 ft apart will be obtained in this analysis. If between two successive elevation measurements a pavement surface should rise sharply and then return to its original elevation, the power spectrum would not be aware of this condition. At first thought, this may appear to be a very severe limitation on the accuracy of a power spectrum based on measurements made at 1-ft intervals to describe pavement conditions, as it is evident that there are irregularities in the highway profile that are smaller than 1 ft in length. Figure 2 shows, however, that at any appreciable velocity the very short wave lengths will have very little effect on the behavior of the vehicle. Thus, a pavement irregularity smaller than 1 ft in length would have to be of appreciable amplitude in order to have a discernable effect on the vehicle. It should thus be realized that the power spectrum contained in this paper can only account for pavement irregularities that would be detected by making elevation measurements at 1-ft intervals.

The variation in the elevation measurements (a measure of pavement roughness) is most easily measured in terms of feet squared, and the ordinates of the power spectrum curve are in terms of feet squared per cycle per foot. The abscissae are in units of feet per cycle, which is the reciprocal of the wave length. A highway power spectrum is thus a purely geometric quantity and does not contain any units of time. When the power spectrum is plotted, the total area under the power spectrum curve will represent the mean squared value of the variation in the elevation measurements, and this value can also be used as a criterion of pavement condition. Of greater importance is the fact that the area under the power spectrum curve between any two selected wave lengths will indicate the contribution to the total roughness or variation in the highway elevation measurements that this range of wave lengths produces. Thus, from the

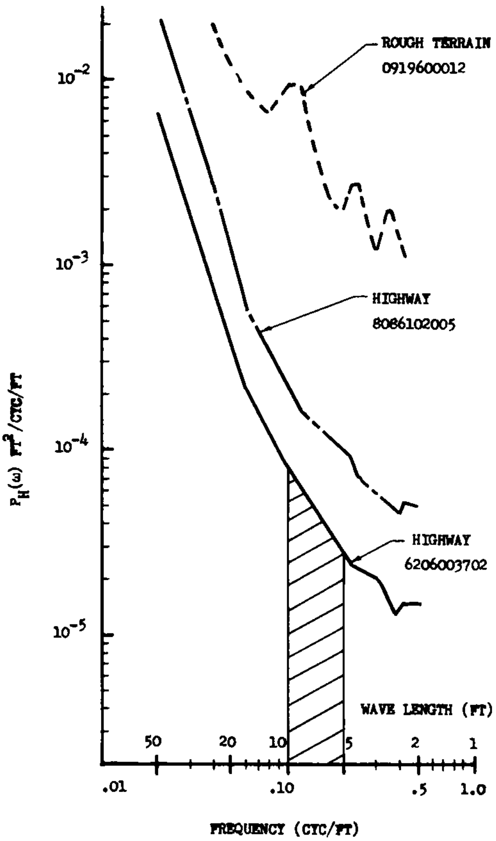

Figure 4. Highway power spectra.

power spectrum curve, it is possible to determine the wave lengths in the pavement that make the greatest contribution to the variation in the elevation measurements.

Typical power spectra curves are shown in Figure 4. The lowest curve in this figure is the power spectrum of an extremely smooth highway. This is to be expected because the area under this curve is less than the area under the other curves shown in the figure. The dotted curve shown at the top of the figure is the power spectrum for rough terrain comparable to a cow pasture. Two extremes are thus represented in Figure 4. Virtually all highways could be expected to lie between these two curves. A highway in fair condition is represented by the middle curve in Figure 4.

Along the horizontal axis is a special scale showing values of wave length. The wave length increases to large values moving from right to left along the horizontal axis. These curves indicate that the greatest variation in the elevation measurements is due to long wave lengths present in the highway. It can thus be seen that large variations are associated with long wave lengths and relatively small variations are associated with short wave lengths. The shaded area lying between wave lengths from 5 to 10 ft long represents the amount of irregularity or roughness that these wave lengths contribute to the total variation in the highway profile. Because at higher vehicle velocities the longer wave lengths become more significant as shown in Figure 2, it is a little disturbing to note that the longer wave lengths tend to increase the excitation to which the vehicle is subjected.

A highway elevation power spectrum can be used with the vehicle characteristics shown in Figure 1, if the velocity of the vehicle is introduced. This is done by multiplying the abscissae of the power spectrum curve by the vehicle velocity to obtain the frequency in cycles per second, and by dividing the ordinates of the power spectrum curve by the vehicle velocity to obtain the units of feet squared per cycle per second. A different curve will thus result for each velocity. By making this transformation, it is now possible to plot the power spectrum curve with the vehicle characteristic shown in Figure 1. This is done in Figure 5 where the vertical axis on the left side indicates the F/X ratio of the vehicle while the vertical axis on the right side indicates the power spectrum values for the highway. This has been done for two different vehicle velocities, and it is evident that as the velocity of the vehicle increases, the longer wave lengths make more of a contribution to the total excitation of the vehicle. Having the information shown in Figure 5, it is now possible to compute the dynamic reaction of the vehicle on the highway.

COMPUTING THE DYNAMIC FORCE

Another property makes these characteristics for the vehicle and the highway very useful. It is possible to combine them to obtain an estimate of the dynamic force that the vehicle will exert on the highway. To do this, it is first necessary to modify the highway characteristic by introducing the vehicle velocity as previously described. An additional modification must also be made to convert the units of the highway power spectrum from feet squared to inches squared. If this is done, the relationship (5, p. 197) that can be used to determine a power spectrum of the dynamic force that the vehicle will exert on the highway is

$$P_F(f) = P_H(f) \; | \; F/X\,(f) \; |^2$$

in which

$P_F(f)$ = power spectrum of the dynamic force as a function of frequency in cycles per second (units: lb^2/cps);

$P_H(f)$ = power spectrum of the deviations of the pavement elevations as a function of frequency in cycles per second (vehicle velocity included, units: $in.^2/cps$); and

$F/X(f)$ = ratio of dynamic force to tire tread displacement (vehicle characteristic) as a function of frequency in cycles per second (units: lb/in.).

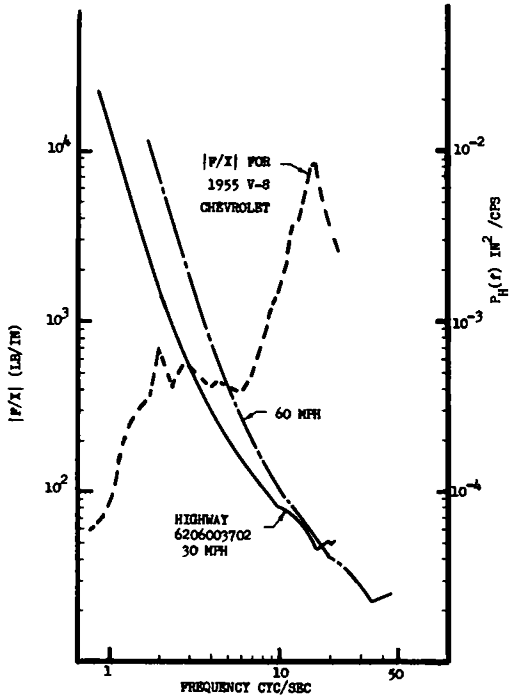

Figure 5. Pavement and vehicle characteristics shown as a function of frequency.

This procedure is shown in Figure 6. The vehicle characteristics must be squared when performing this mathematical operation. This results in extremely large peaks in the vehicle characteristic and makes the maximum values much more significant than they appear from the characteristic curve shown in Figure 1.

A typical result of these calculations is shown in Figure 7, in which the dynamic force power spectrum is plotted. The area under this curve represents the mean squared value of the force that the vehicle exerts on the highway. In addition, the curve shows the contributions to this mean squared force that are made by various ranges of frequency. From the curve in Figure 7, it is evident that two frequency bands make the largest contributions to the dynamic force. It is no coincidence that the center frequencies of these bands occur at the natural frequencies of the vehicle as determined from Figure 1. Also, a large amount of dynamic force is generated at the lower natural frequency of the vehicle as well as at the higher natural frequency. From Figure 1, it would be logical to expect the largest contribution to occur at the highest natural frequency. Allowing for the distortion that results from the use of the log-log plot shown in Figure 7, it is evident that the larger highway excitation occurring at the lower frequencies tends to develop a large amount of dynamic force at the lower frequency even though the vehicle is less responsive to this frequency. Large amounts of excitation at frequencies at which the vehicle is relatively unresponsive can produce a final result of the same order of magnitude as smaller amounts of excitation will produce at frequencies at which the vehicle is extremely responsive.

From Figure 7, it would appear that a record of dynamic force vs time would contain two predominating frequencies. This has been verified experimentally by making tire pressure measurements in which a record of tire pressure vs time was obtained for a typical passenger vehicle. This vehicle was not the same as the one shown in Figure 1 and thus exact agreement is not possible. Figure 8 shows that two frequencies predominate in the record. These two frequencies coincide fairly closely with the frequencies predicted by the power spectrum calculation shown in Figure 7. Steps are

2

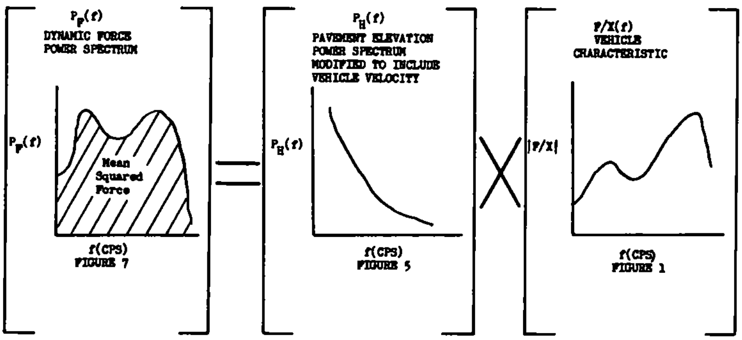

Figure 6. Procedure for computing dynamic vehicle reaction.

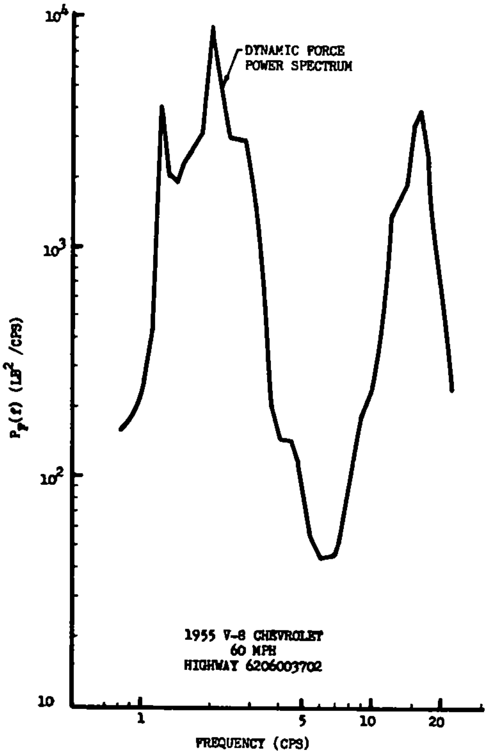

Figure 7. Right front wheel power spectrum.

being taken to obtain additional records of the type shown in Figure 8 so that an experimental check can be made of the predicted values of dynamic force obtained by using the vehicle and highway characteristics just described.

Having the mean squared value of the dynamic force it is easy to determine the root-mean squared value. Using this value, the results of operating the vehicle (shown in Fig. 1) over different highways at various speeds are shown in Figure 9. At certain vehicle velocities an increase in the speed will produce proportionally greater changes in the dynamic force than will occur at other velocities. There are also regions in which increasing the vehicle velocity will result in a decrease in the dynamic force. Using the curves shown in Figure 9, it would be possible to establish vehicle speeds that would result in the same value of dynamic force being generated for the same vehicle on different highways. Vehicle speed limits could thus be based on the allowable amount of dynamic force.

Inasmuch as root-mean squared values are shown, it is evident that larger values for the dynamic force must exist at any given velocity than those shown in the

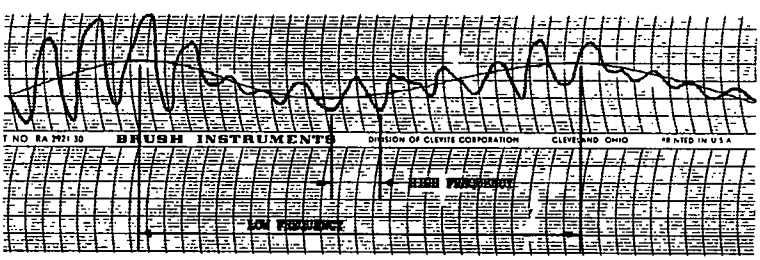

Figure 8. Record of tire pressure vs time on Highway 8086102005.

curves. It would be interesting to know how much larger these forces become and how frequently they reach these larger values. In addition, the curves are based on a pavement roughness criterion (power spectrum) that can only detect pavement variations through elevation measurements made 1-ft apart. Therefore, this calculation results in a conservative estimate of the dynamic force between the vehicle and the pavement, inasmuch as all of the pavement roughness will not be detected.

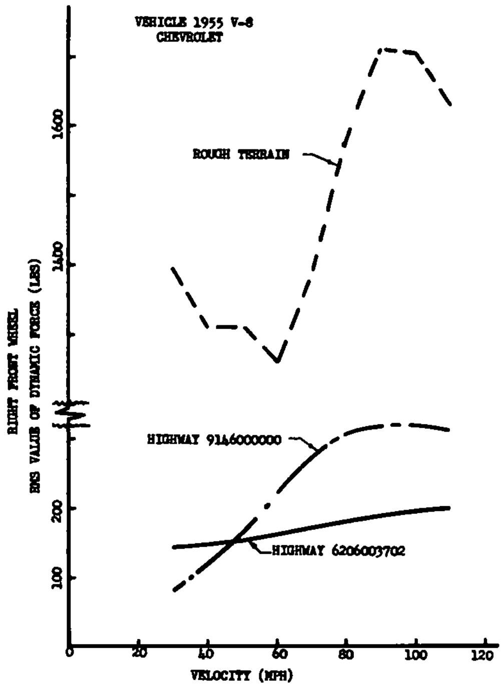

Figure 9. Root-mean squared value of dynamic force vs vehicle velocity.

CONCLUSIONS

By using the procedures described in this paper it is possible to obtain vehicle and pavement characteristics that can be used to compute the power spectrum of the dynamic force that a vehicle will exert on the pavement at any selected velocity. Because these characteristics are determined experimentally, there are relatively few assumptions involved in obtaining the dynamic reaction. Nevertheless the question as to the accuracy of the predicted dynamic force can still be raised. Fortunately, it appears possible to check this force experimentally by using the tire pressure measuring technique mentioned in connection with Figure 9, and steps are being taken to do so.

Although the root-mean squared value of the dynamic reaction can be found, the question as to the maximum value is still unanswered. The validity of assuming that this force has a normal distribution (6) is worthy of additional consideration so that the frequency of occurrence of larger values can be estimated. This can also be studied from tire pressure measurements.

A knowledge of the dynamic reaction between a vehicle and a highway may be of practical value in establishing permissible speed limits for various classes of vehicles. Of the three quantities that influence the dynamic reaction (pavement condition, vehicle characteristic, and vehicle velocity), the velocity of the vehicle is the easiest to change.

A paramount question remains to be answered, however: what is the significance of the dynamic vehicle reaction in terms of the effect on the highway? Is a large force associated with a high vehicle velocity more detrimental than a smaller force at a lower velocity? A knowledge of the behavior of the highway under these conditions is needed.

ACKNOWLEDGMENTS

The support of the Bureau of Public Roads through Contract CPR 11-7941 made possible the research investigation on which this paper is based. This support is gratefully acknowledged.

The authors also wish to thank the AASHO Road Test, William N. Carey, Jr., and Paul E. Irick for assistance in determining vehicle characteristics; E.A. Finney and his staff at the Michigan State Highway Department Laboratory, East Lansing, for assistance in making tire pressure measurements; the Indiana State Highway Department for obtaining elevation measurements from which highway power spectra were computed; and the Highway Research Board for including this paper in the program at the Annual Meeting.

REFERENCES

1. Quinn, B. E., and DeVries, T. W., "Highway Characteristics as Related to Vehicle Performance." HRB Bull. 250, 20-39 (1960).
2. Solodovnikov, V. V., "Introduction to the Statistical Dynamics of Automatic Control Systems." Dover (1960). (Translated by J. B. Thomas and L. A. Zadeh.)
3. Blackman, R. B., and Tukey, J. W., "The Measurement of Power Spectra." Dover (1958).
4. American Society for Quality Control and American Statistical Assoc., Technometrics, 3:No. 2 (May 1961).
5. Lanning, J. H., and Batten, R. H., "Random Processes in Automatic Control." McGraw-Hill (1956).
6. Quinn, B. E., and Van Wyk, R., "A Method for Introducing Dynamic Vehicle Loads into Design of Highways." HRB Proc., 40:111-122 (1961).