Highway Characteristics as Related to Vehicle Performance

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The performance of a vehicle on a highway depends on the characteristics of both the highway and the vehicle. In this paper the term "performance" pertains to the vertical dynamic force that the wheels of a moving vehicle exert on the highway as a result of variations in the pavement profile.

A fundamental problem considered in this investigation is that of selecting highway and vehicle characteristics that will enable a prediction of the dynamic force to be made. The power spectrum of the highway elevations is found to be useful for this purpose, and an experimental procedure is described for obtaining this information.

The vehicle characteristic of greatest usefulness is the steady-state sinusoidal relationship between the vertical displacement, X, of the bottom of the tire and the vertical force, F, that the tire exerts on the supporting surface. This F/X relationship is determined experimentally for three different vehicles and is found to be non-linear inasmuch as it varies with the amplitude of the displacement, X. Other vehicle characteristics involving F are also presented.

The effect of vehicle speed is seen to be significant in the special situation in which a section of highway considered "smooth" produces a higher mean squared force than a section considered "rough."

● THE SMOOTHNESS of a highway profile is usually judged by the behavior of a car or truck as it passes over the highway, even though the suspension characteristics of the vehicle have considerable influence upon this behavior. It is therefore necessary to consider both the highway profile characteristics and the vehicle characteristics when the condition of a highway is to be investigated. A fundamental problem thus encountered is that of defining the significant characteristics of both highway and vehicle, and of obtaining useful relationships in order to predict vehicle performance.

DETERMINATION OF SIGNIFICANT HIGHWAY CHARACTERISTICS

The problem of determining significant highway profile characteristics is greatly aided by the fact that a large number of highway elevation profiles have been accurately measured. Visual examination of these profiles will usually reveal whether or not the highway profile is periodic. For highway profiles exhibiting well-defined periodicity a Fourier series analysis can be made. Such an analysis describes the highway profile in terms of a fundamental wave length (or period) and integer multiples thereof. Wave lengths existing in the highway that are not integer multiples of the fundamental can not be identified. The selection of the fundamental wave length is thus important in the Fourier series analysis, as this determines the wave lengths that will be used to describe the profile.

Other highway profiles, however, do not display a well-defined period and therefore do not lend themselves to this type of analysis. In these cases it is convenient to assume that the highway elevations are random and to apply a statistical analysis commonly used in dealing with random phenomena. One of the first steps in such an analysis is to compute the autocovariance function given by

$$C(\tau) = \lim_{T \to \infty} \frac{1}{T} \int_{-T/2}^{T/2} X(t) \quad X(t + \tau)\, dt \tag{1}$$

in which

$X(t)$ = highway elevation measurement (from the mean) at station t;
$X(t + \tau)$ = highway elevation measurement (from the mean) at distance τ from station t;
T = total length of highway profile being analyzed;
$C(\tau)$ = autocovariance function (different for each value of τ); and
τ = lag value.

This quantity is extremely useful because it indicates whether or not the highway profile can be considered a random function. The well-behaved autocovariance function will approach zero as the lag values are increased.

One method of characterizing a random function is by use of the power spectrum. Inasmuch as the power spectrum is the Fourier transform of the autocovariance function, it is thus possible to obtain a power spectrum of the highway elevation measurements if the autocovariance function is well-behaved. In this paper only those highway profiles that are random are considered, and the power spectrum of the highway elevations is used to characterize the highway profile.

The relationship for the power spectrum is given by

$$P_x(\omega) = \frac{1}{\pi} \int_{-\infty}^{\infty} C(\tau) \; e^{-iw\tau} d\tau \tag{2}$$

in which

$P_x(\omega)$ = power spectrum of the highway elevations;
ω = $2\pi/\lambda$, in radians per ft; and
λ = wave length, in ft $^{-1}$.

The power spectrum describes the highway profile in terms of virtually all wave lengths. It can be used to obtain the mean squared value of the profile, and it shows the contribution to this value that various ranges of wave lengths make. The nature of the autocovariance function, needed to obtain the power spectrum, indicates whether or not a power spectrum description of the highway is valid. The actual calculations of power spectra require the use of additional relationships that are not included in this paper.

Although the power spectrum can be computed from rod and level measurements, a quicker and less expensive method for obtaining profile data is desirable. To obtain this information more conveniently a simple trailer (Fig. 1) was designed. This trailer is towed behind a passenger vehicle and the vertical accelerations of the trailer are measured by an accelerometer (Fig. 2). Although this trailer exerts little force upon the highway it would be possible in this fashion to simulate any magnitude of wheel loading and to obtain a measurement of the dynamic profile of the highway if necessary.

The vertical acceleration measurements obtained from the trailer are used to compute the power spectrum of the acceleration shown by the dotted curve of Figure 3. This measurement includes not only the highway profile characteristics but also the trailer characteristics. It is possible, however, to remove the trailer characteristics and the effect of trailer velocity and thus obtain a power spectrum of the highway. The solid curve in Figure 3 indicates the steady-state sinusoidal trailer characteristics that were determined in the laboratory. Removal of these from the power spectrum of the acceleration, gives the dash-dot curve in Figure 3, representing the power spectrum of the highway elevations. This dash-dot curve could also be obtained by measuring the highway elevations with a rod and level and by making the proper mathematical calculations on these data as previously indicated.

Figure 1. Trailer for making highway profile measurements.

Figure 2. Accelerometer mounted on trailer.

DETERMINATION OF SIGNIFICANT VEHICLE CHARACTERISTICS

The steady-state sinusoidal frequency response characteristics of a system have been found to be very useful in predicting the response of the system to various inputs. In this case, it is therefore interesting to consider the frequency response characteristics of a vehicle. In defining the frequency response it is necessary to specify the input and the output of the system involved. For a vehicle it is logical to consider that the vertical displacement of the wheels constitutes the input from the highway. The

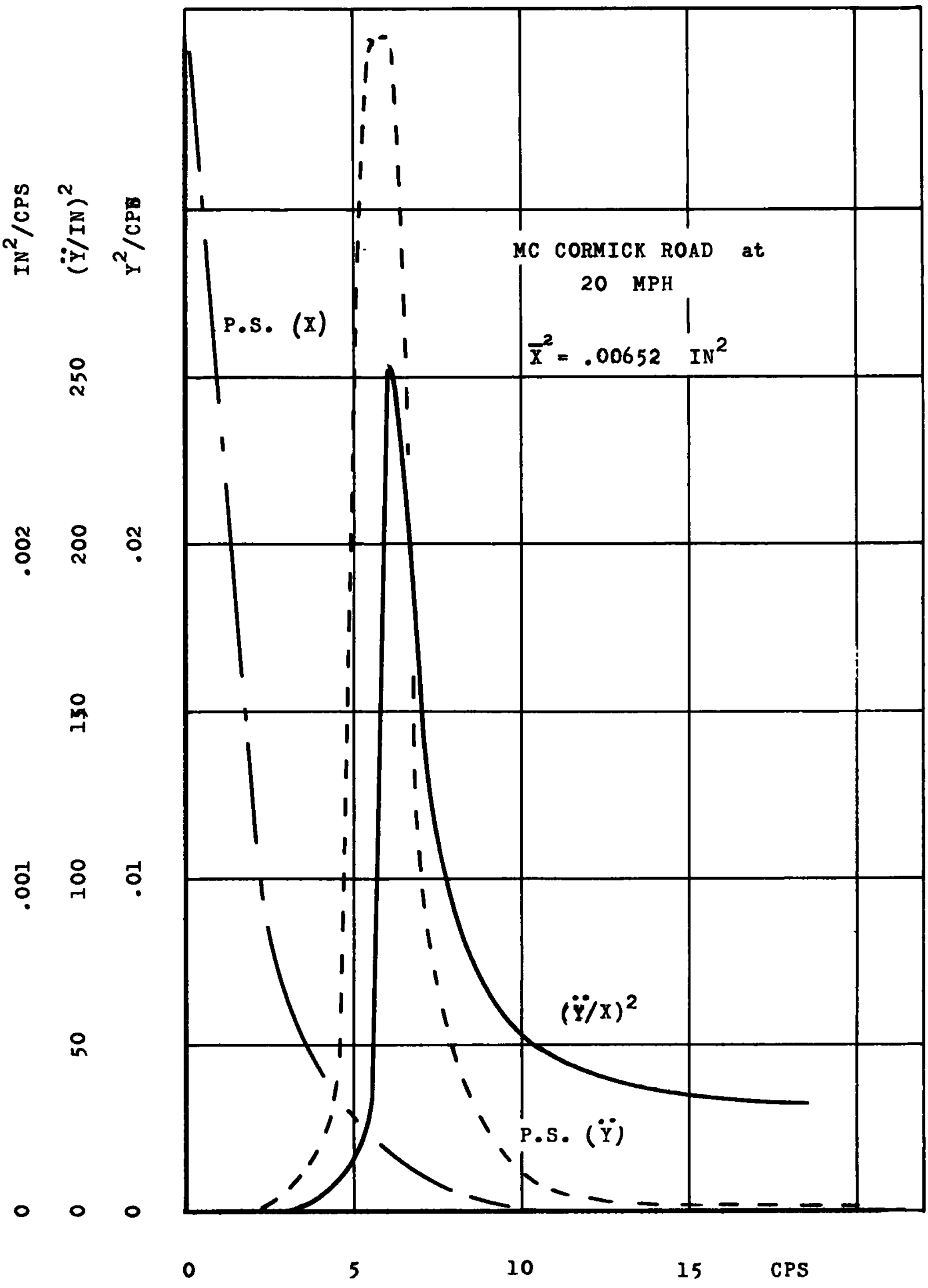

Figure 3. Dynamic measurement of highway profile power spectrum.

output of the vehicle can be defined in various ways, depending on the area of interest. In this case the output is considered to be the force which the wheel of the vehicle exerts upon the highway. Some work has been done, however, in which the output has been considered to be the vertical acceleration experienced on the seat of the vehicle.

Figure 4 shows the front wheel of a passenger car mounted on a vebrating platform, with the input to the vehicle defined by the vertical displacement X. Imparting a sinusoidal displacement to the wheel produces other sinusoidal displacements in the vehicle. Thus, the displacement of the center of the wheel is indicated by W, the displacement of the sprung mass of the vehicle is indicated by Y, and the relative displacement between the wheel and the sprung mass is indicated by Z. Mounted on the vehicle vibrator is a special platform which measures the force between the wheel and the vibrator. The platform can thus move vertically with simple harmonic motion at any selected frequency and amplitude. In all cases the displacement X is considered as input, with various other quantities being considered as output, depending on the characteristics to be investigated.

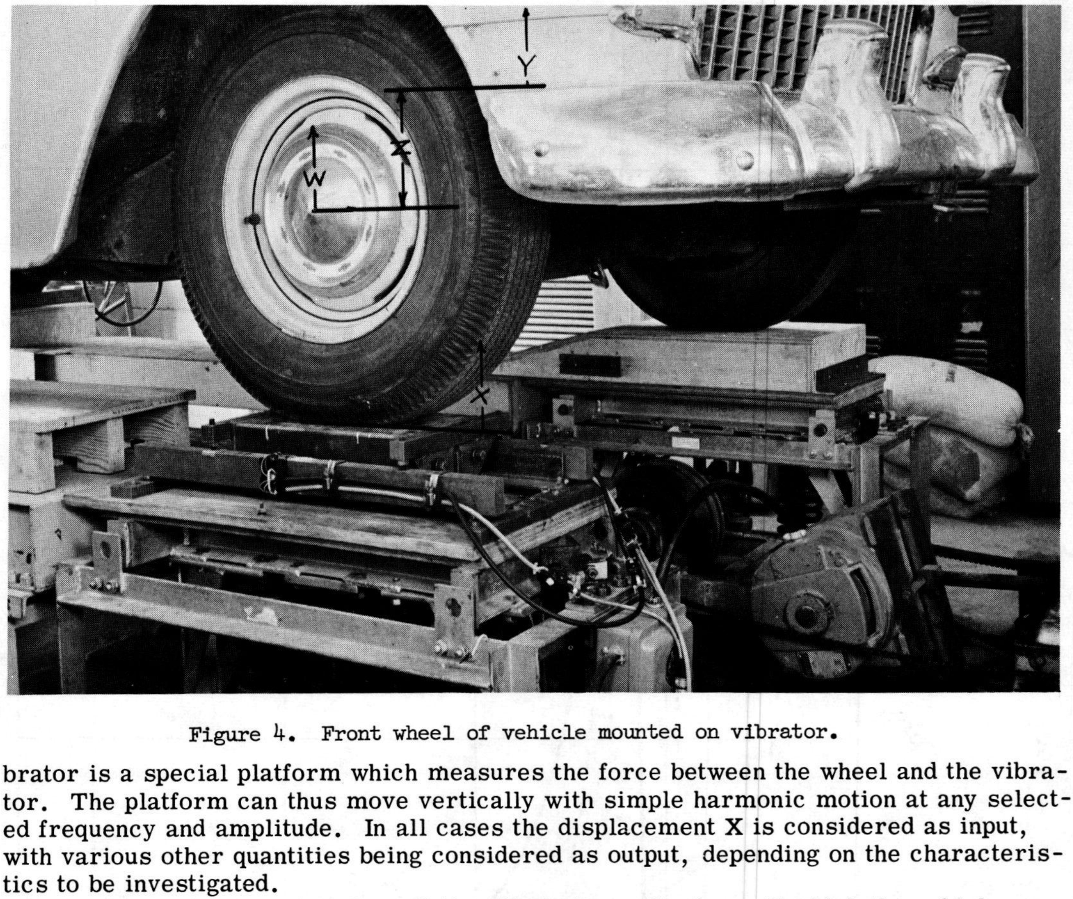

Figure 4. Front wheel of vehicle mounted on vibrator.

Of immediate interest is the relationship between the force F which the vehicle exerts upon the platform and the displacement X of the platform. This relationship is shown in Figure 5. It is of interest to note that this characteristic depends on the amplitude of X. Three values of peak-to-peak input displacement are shown. Also of interest is the fact that at lower frequencies higher ratios of F/X are encountered at small input displacements than are encountered at large input displacements. A very large F/X ratio is produced at a frequency of 16 cycles per second (cps). This ratio decreases, however, as the frequency is further increased.

It is interesting to consider the F/X characteristic for other vehicles. Figure 6 shows this relationship for a 1955 8-cylinder Chevrolet, a 1955 6-cylinder Chevrolet, and a 1959 Rambler. The curves in Figure 6 were taken at a constant input of 0.10 in. peak-to-peak. It is evident from Figures 5 and 6 that the vehicle suspension system is non-linear.

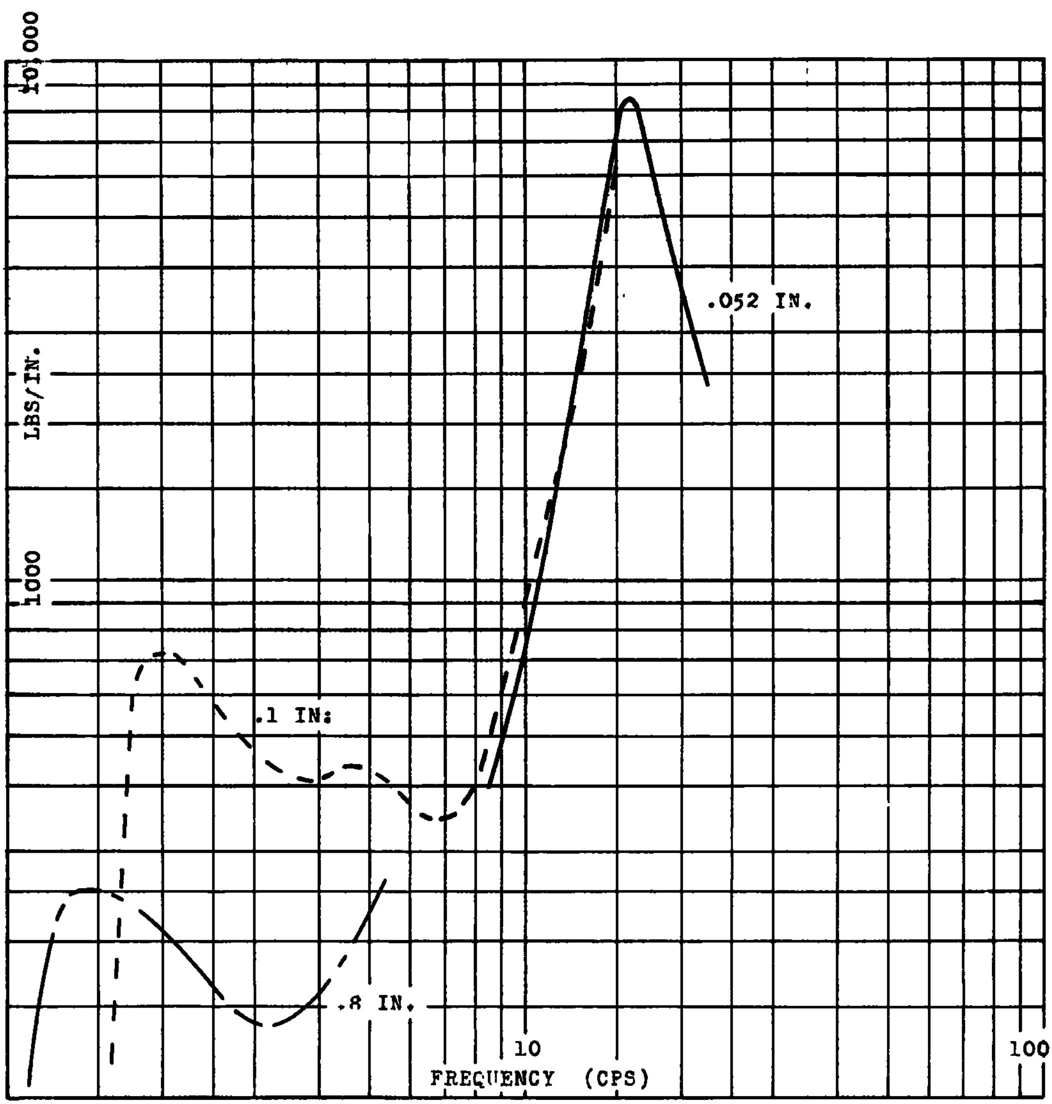

Figure 5. F/X versus frequency for 8-cylinder 1955 Chevrolet.

Another characteristic of interest is that of force vs vertical acceleration ($F/\ddot{X}$). This characteristic is shown in Figure 7 for two different input displacements and also reveals a non-linear behavior.

Although it is possible to use the highway power spectrum and the F/X relationship to determine the force that the vehicle exerts on the highway, it is also desirable to obtain an independent check on the values thus obtained. For this purpose additional vehicle response characteristics are considered.

One such characteristic is shown in Figure 8, in which the relationship between force and wheel acceleration $\ddot{W}$ is given. The value of $\ddot{W}$ can be measured when the vehicle is in motion by placing an accelerometer on the A-frame that supports the front wheel. Insufficient information is available at present to evaluate the usefulness of this characteristic.

It was hoped that the Z displacement could also be used to check the predicted force. A special transducer built to measure this quantity is shown mounted on the vehicle in Figure 9. The transducer itself (Fig. 10) consists of a displacement-sensitive potentiometer connected in a bridge circuit.

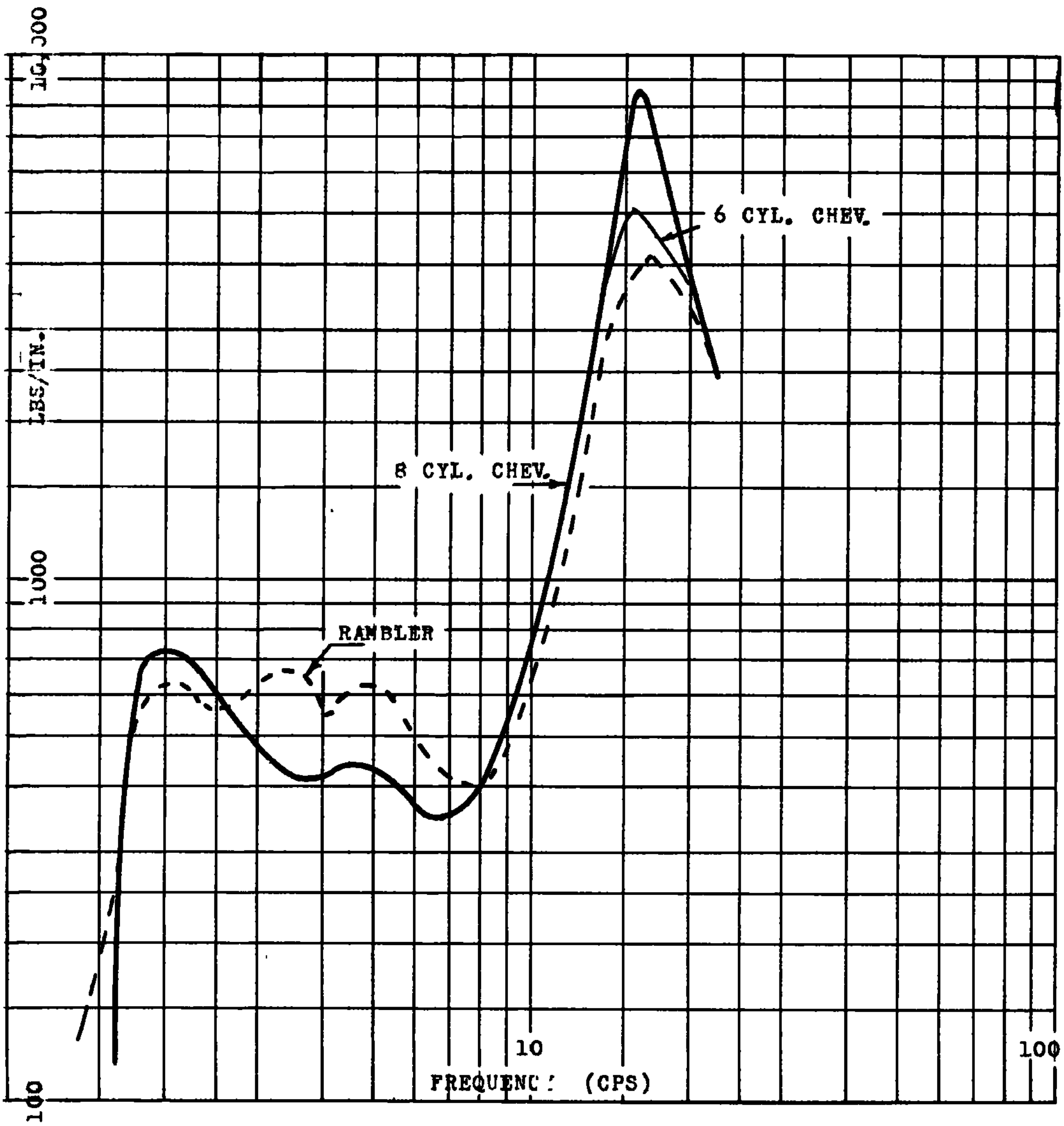

Figure 6. F/X versus frequency 0.1 in. (P-P).

Accurate highway tests of this transducer yielded excellent records, but unfortunately the laboratory response characteristics (Fig. 11) leave much to be desired. They are not only very sensitive to input amplitude but also appear to have extremely large values in both the low-frequency and high-frequency regions, characteristics which seriously limit the usefulness of the Z displacement measurements.

These characteristics clearly indicate that a vehicle is not a linear system. This is unfortunate, because the task of predicting the response of a non-linear system to a random input is formidable.

Fortunately, the greatest amount of non-linearity in the F/X characteristics occurs in a region where the amplitudes are small.

This indicates that an approximate characteristic may be used without introducing an unreasonable amount of error.

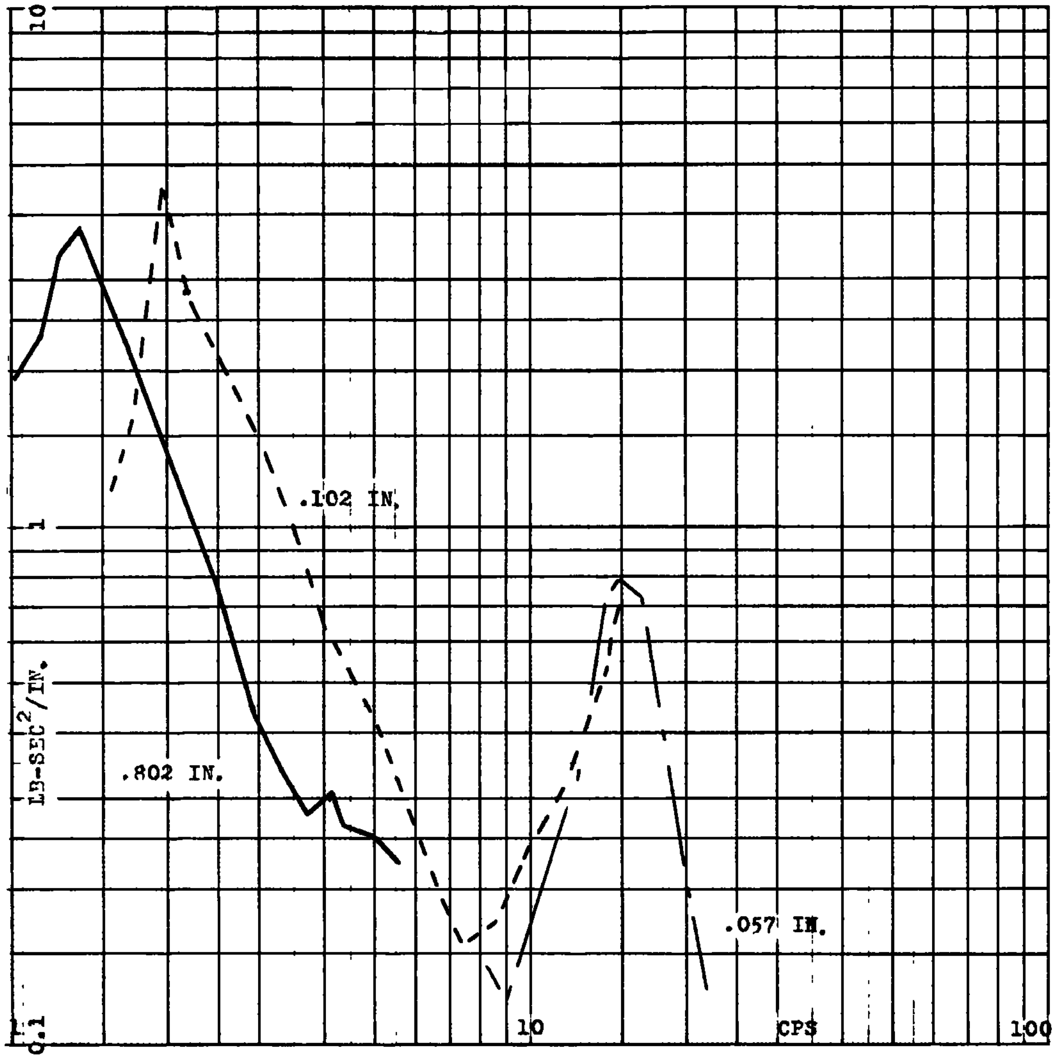

Figure 7. $F/\ddot{X}$ versus frequency for 8-cylinder 1955 Chevrolet.

PREDICTING VEHICLE REACTION

Techniques have been developed for predicting the response of a linear system to a random input. By making certain assumptions it is possible to use these techniques to obtain an estimate of vehicle response when traveling over a given highway.

As previously mentioned, it is possible to characterize certain highways by use of the power spectrum analysis. Figure 12 shows the power spectrum of two sections of a highway that exhibited interesting characteristics. The section indicated as "smooth" produced no unusual disturbances in the vehicle. The section indicated as "rough" produced a very undesirable vibration in a new Buick Roadmaster when traveling at 60 mph. Inasmuch as the mean squared value of the "roughness" is approximately the same for both sections, the question can be raised as to whether or not the F/X relationship can be used to explain this difference in vehicle performance.

At the bottom of Figure 12 are two frequency scales, one for a speed of 30 mph the other for a speed of 60 mph. It is evident that a highway profile is a geometrical quan-

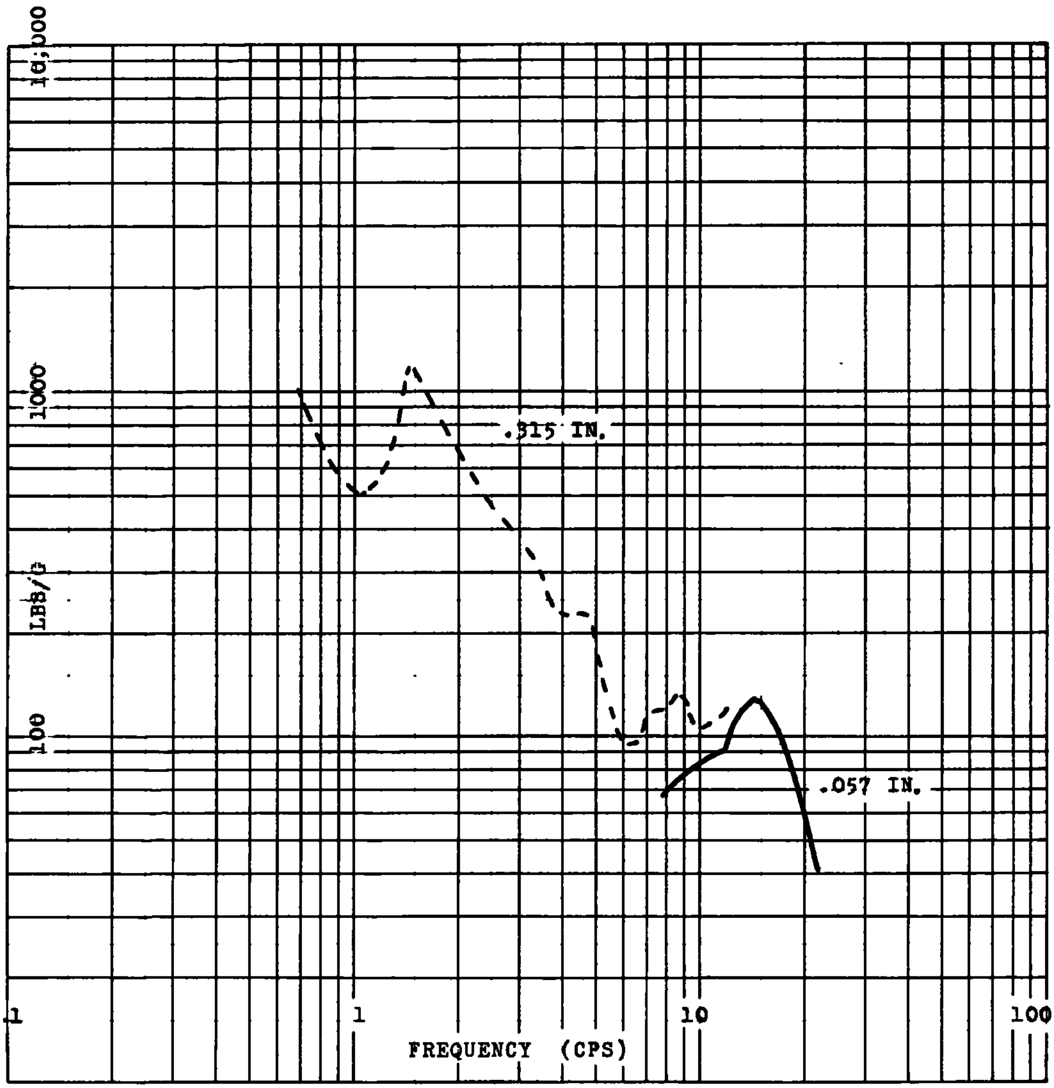

Figure 8. $F/\ddot{W}$ versus frequency for 8-cylinder 1955 Chevrolet.

tity and does not involve any concept of time. Thus, a disturbance of a given wave length in the highway can correspond to any frequency, depending on the velocity of the vehicle. It is therefore necessary to indicate the frequency scale on Figure 12 that is associated with the vehicle velocity that is of interest.

If the vehicle response characteristics shown in Figure 5 are to be used to predict the force that will be exerted on the highway, a problem is immediately encountered. This is due to the fact that the vehicle characteristics depend on the amplitude of the input disturbance, and are therefore non-linear. It is thus necessary to approximate these characteristics in some convenient manner. If the envelopes of the maximum and minimum values in Figure 5 are used, force power spectra of the type shown by the dotted line and the solid line, respectively (Fig. 13), are obtained. It should be noted that the areas under the curves in Figure 13 represent the mean squared values of the force that the vehicle exerts on the highway.

Using the maximum vehicle response characteristics shown in Figure 5, the force of this vehicle on the two sections of highway shown in Figure 12 can be predicted. This is done for two different vehicle speeds.

Figure 9. Transducer mounted on vehicle.

The results of these four conditions are shown in Figure 14. Traveling at a speed of 60 mph, a much larger mean squared force is experienced on the rough than on the smooth highway. This is as would be expected.

At a speed of 30 mph, however, a smaller mean squared force is encountered on the rough than on the smooth highway. This is the opposite of what would be expected.

This situation can be explained by considering the characteristic of the highway profile and the vehicle.

The relationship between the force power spectrum and the highway power spectrum is given by

$$P_F(f) = P_X(f)\,|\,T_{F/X}(f)\,|^2 \qquad (3)$$

in which

$P_F(f)$ = force power spectrum as a function of frequency;

$P_X(f)$ = power spectrum of highway elevations as a function of frequency (and not ω as previously shown); and

$T_{F/X}(f)$ = steady-state sinusoidal relationship between F/X and frequency (vehicle characteristics).

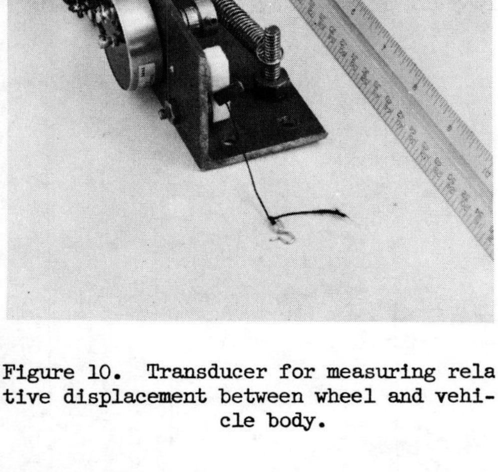

Figure 10. Transducer for measuring relative displacement between wheel and vehicle body.

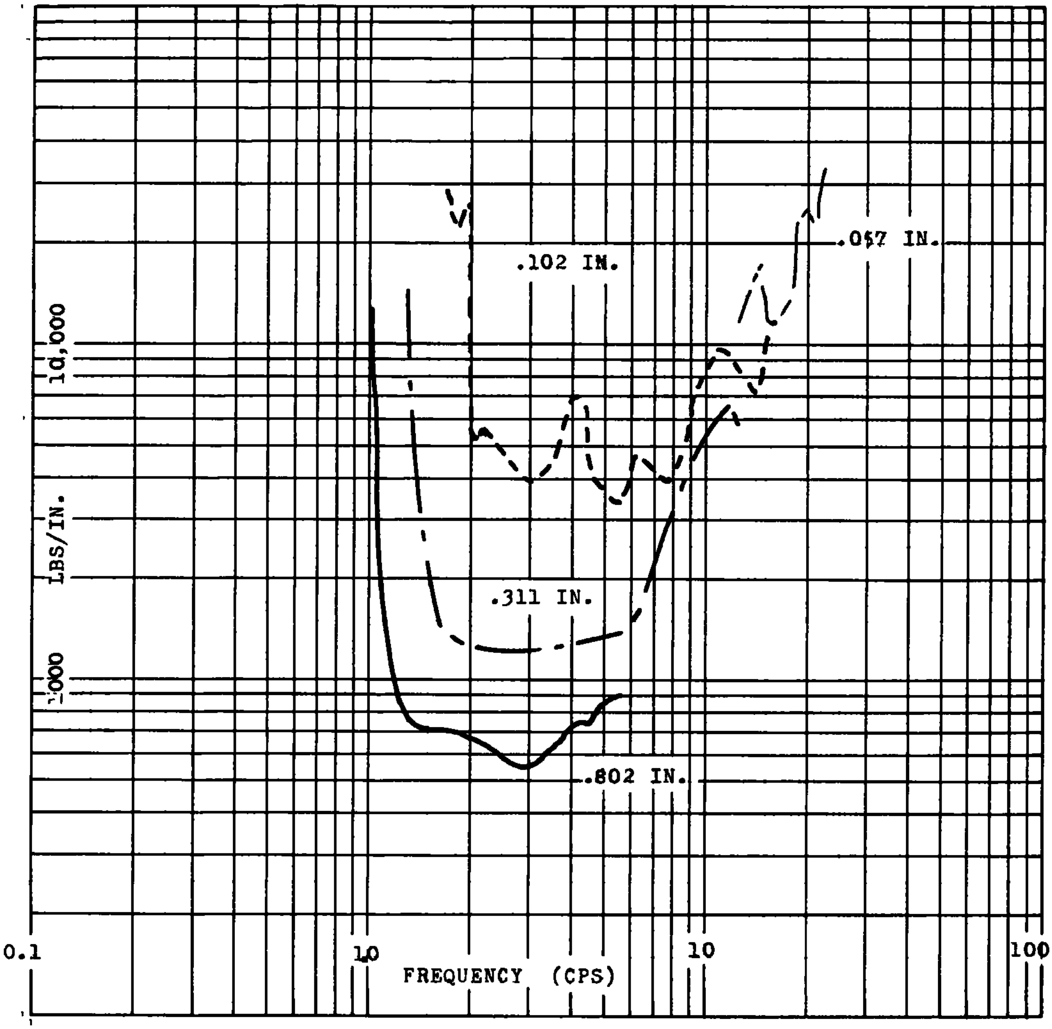

Figure 11. F/Z versus frequency 1955 Chevrolet—8 cylinder.

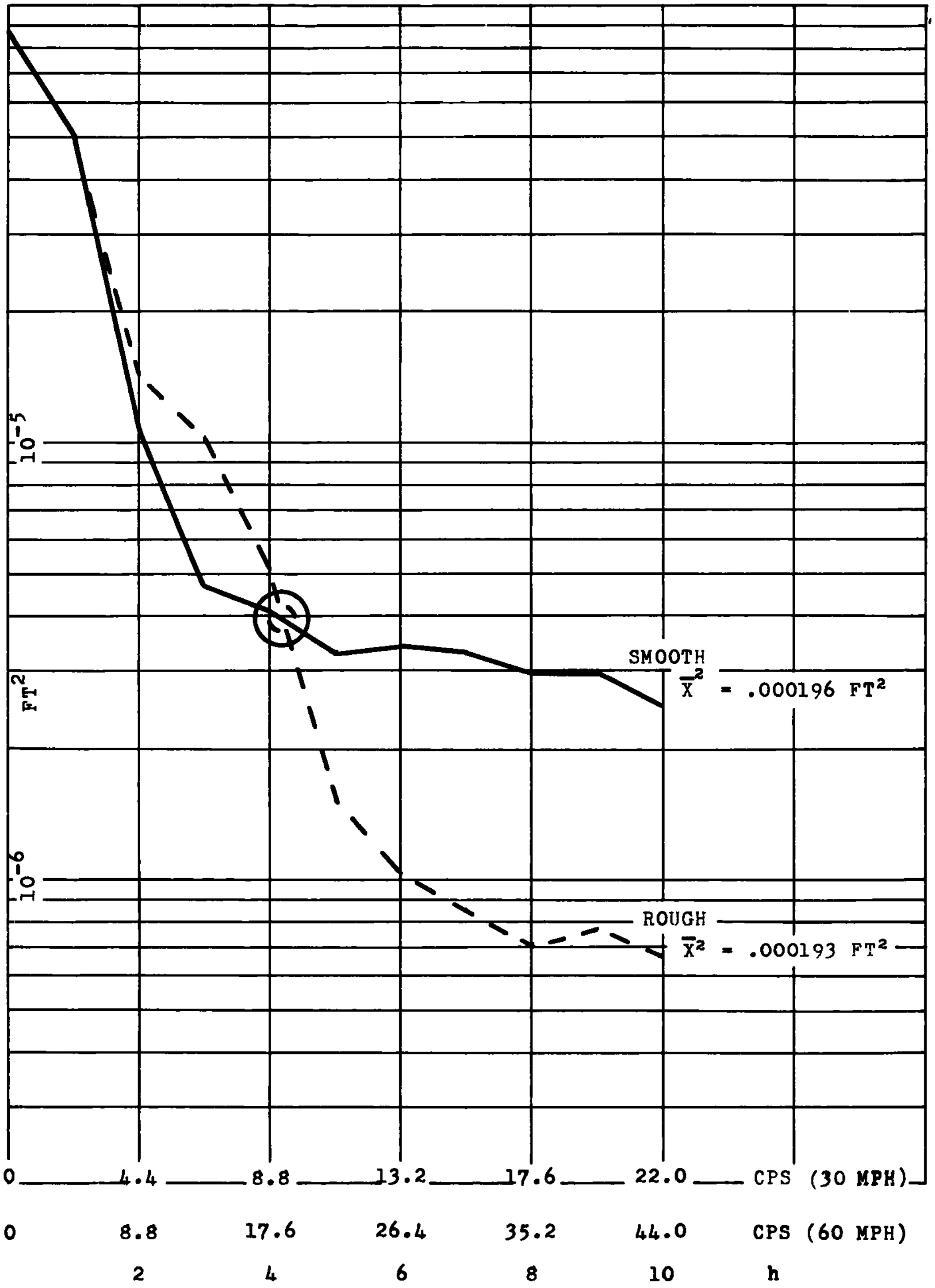

Figure 12. Modified power spectra of highway elevation data.

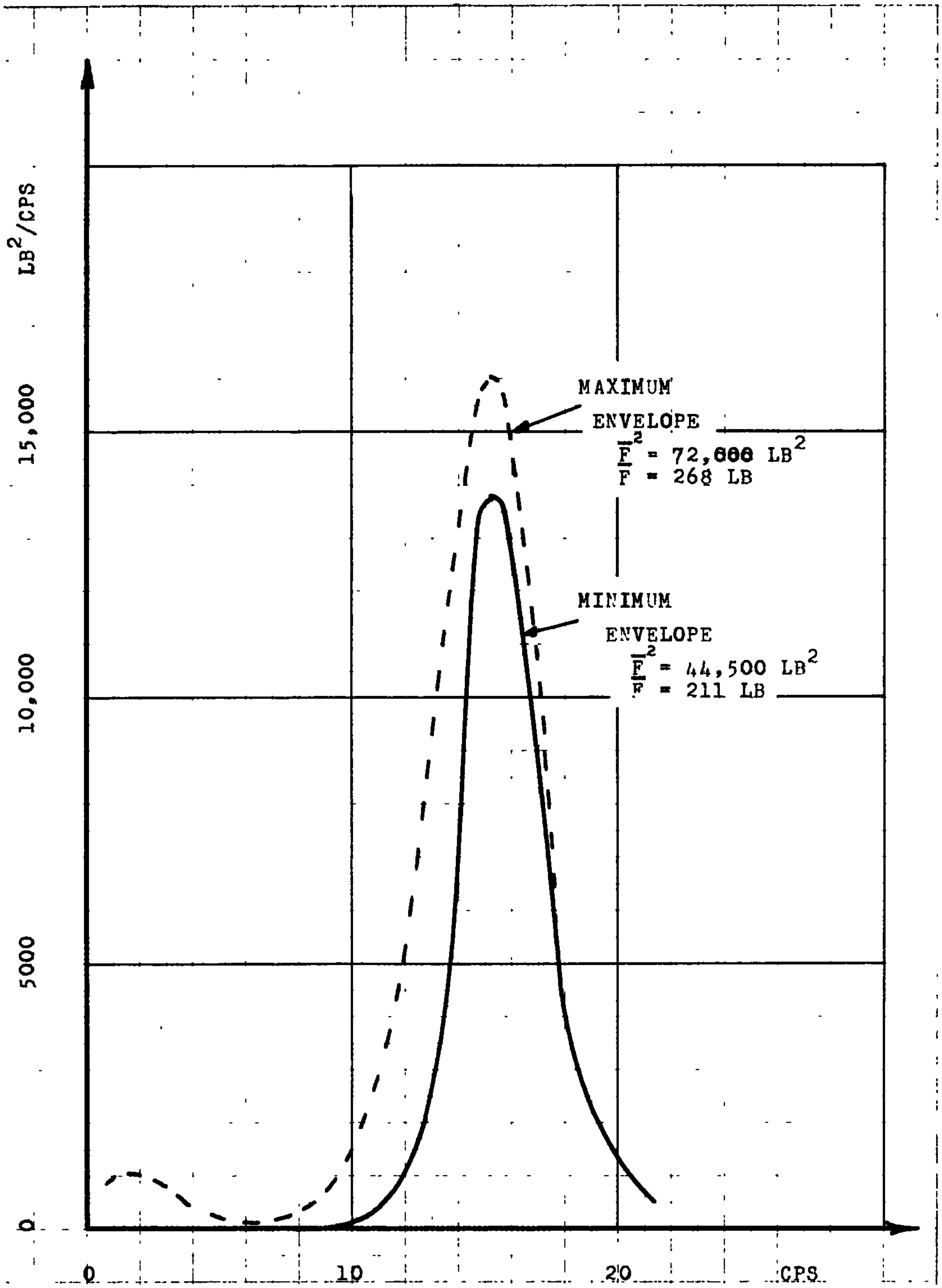

Figure 13. Force power spectra using maximum and minimum vehicle response characteristics (rough highway 60 mph).

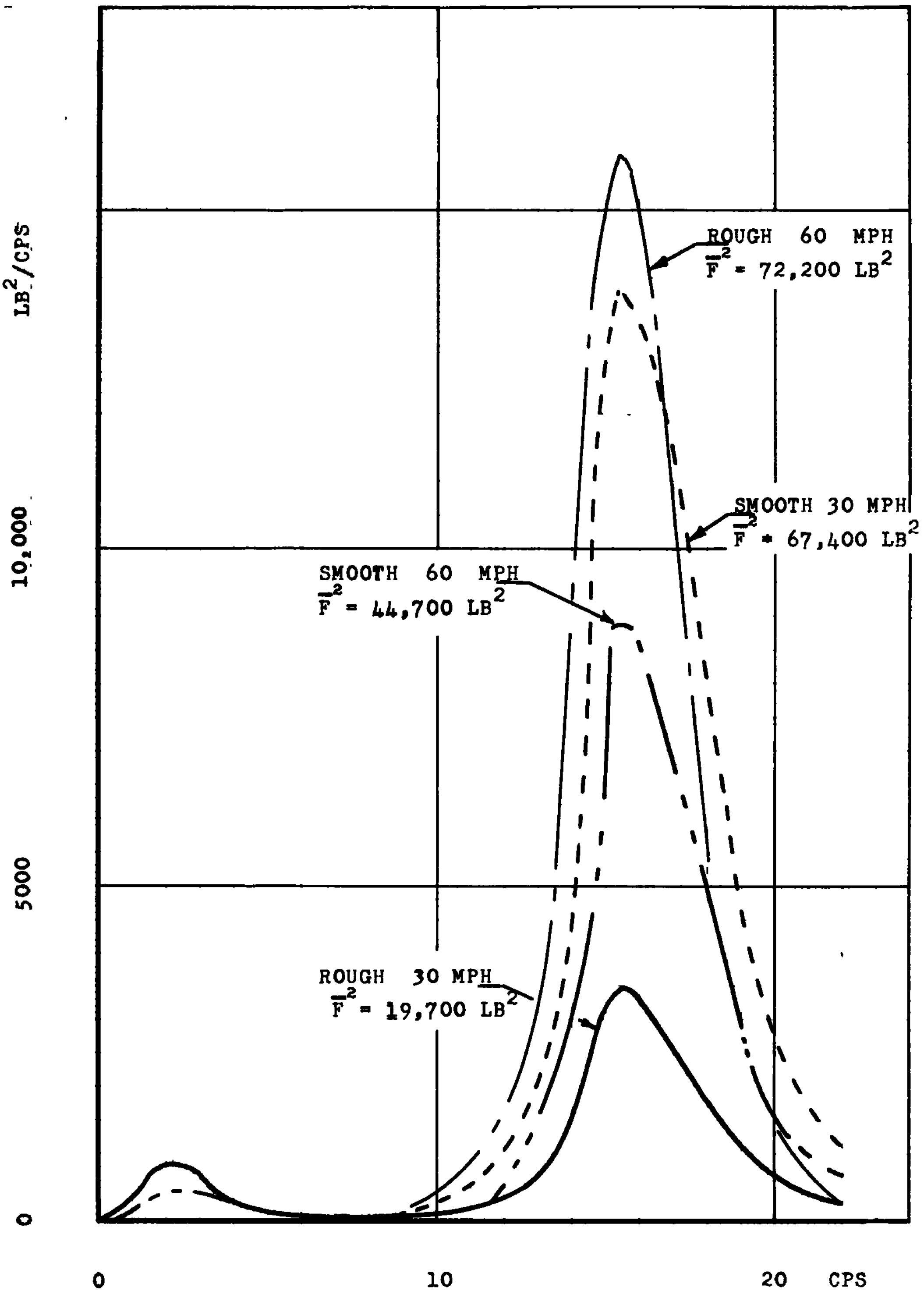

Figure 14. Power spectra of force on highway (using maximum vehicle response characteristics).

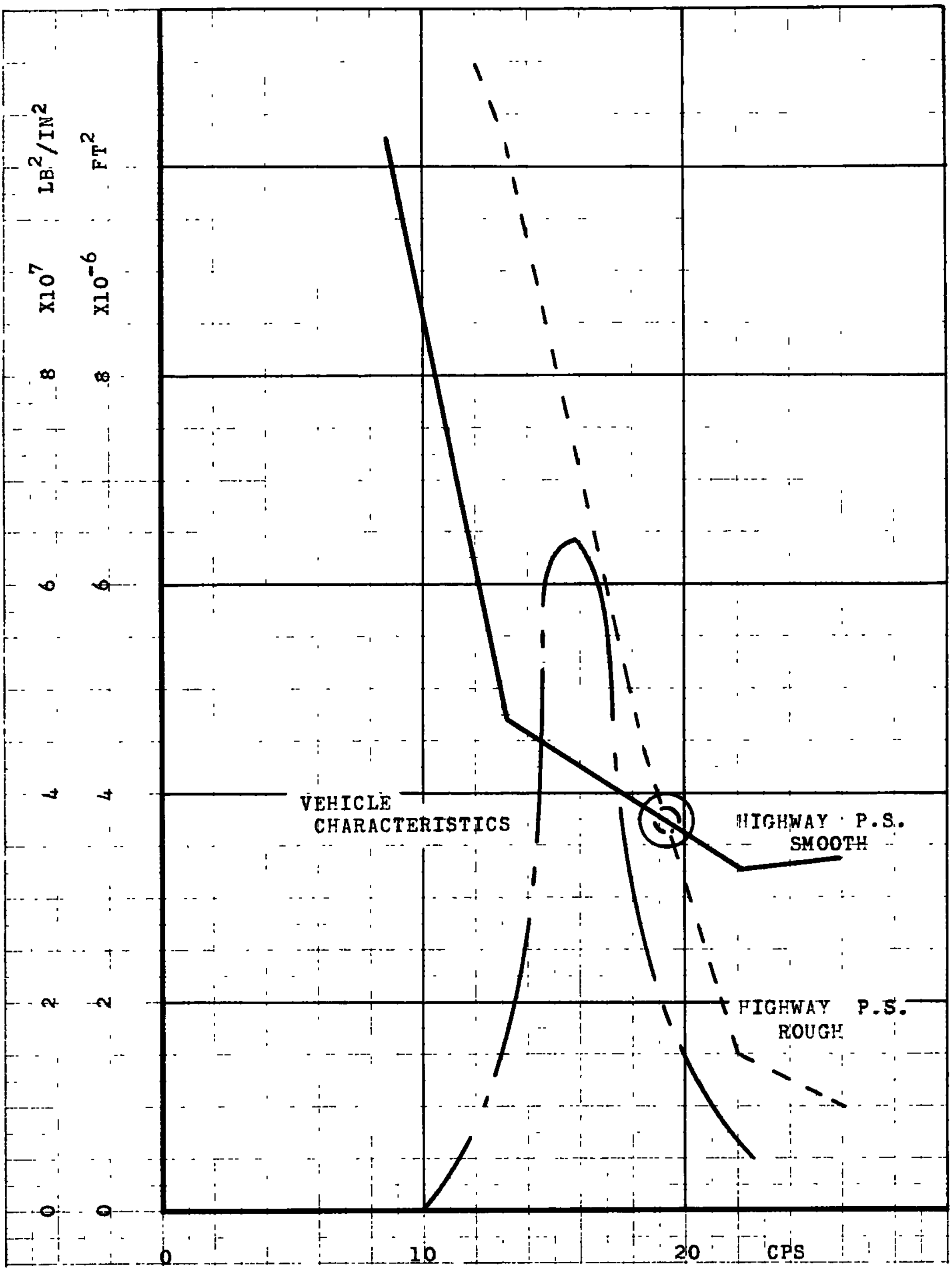

Figure 15. Relationship between vehicle characteristics and highway power spectra at 60 mph.

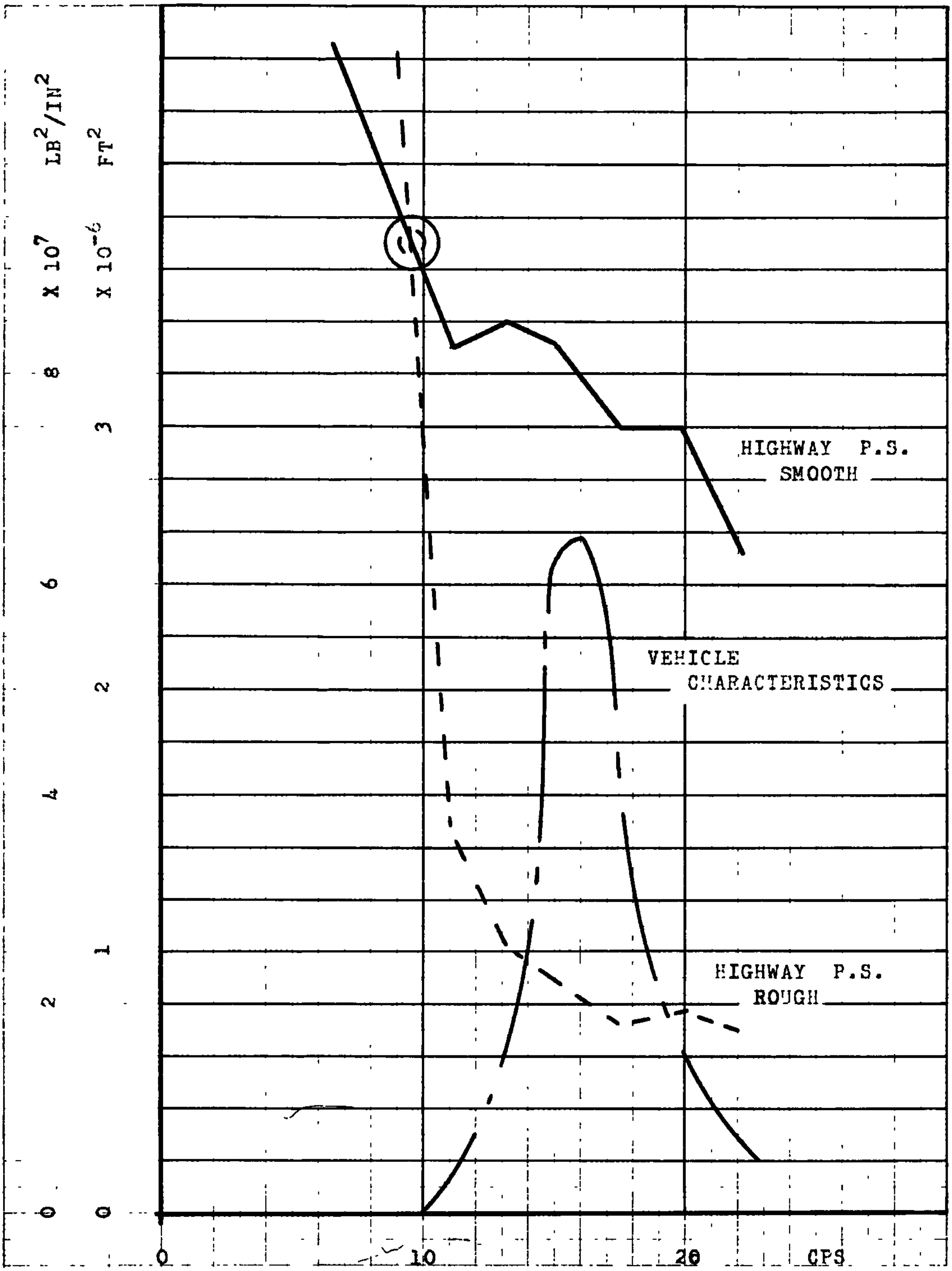

Figure 16. Relationship between vehicle characteristics and highway power spectra at 30 mph.

Figure 15 shows the relationship between the vehicle characteristics and the highway power spectrum at 60 mph. It should be noted that the circle indicating the intersection of the smooth and rough highway power spectra is to the right of the maximum value of the vehicle characteristic. Because the force power spectrum is the product of the vehicle characteristic and the highway power spectrum, it is evident that below 10 cycles per second this product will be zero. Inasmuch as the rough highway power spectrum is larger than the smooth highway power spectrum over that range of frequencies where the vehicle characteristics have significant values, it can be seen that larger values of this product will be obtained for the rough highway section than for the smooth section. This is as would be expected.

If, on the other hand, a speed of 30 mph is considered, the necessary relationships are shown in Figure 16. Here the circle lies to the left of the maximum value of the vehicle characteristic and the ordinates of the smooth highway power spectrum are much larger than the ordinates of the rough highway power spectrum. Thus, the product of the vehicle characteristic and the smooth highway power spectrum is much larger than the product of the vehicle characteristic and the rough highway power spectrum.

It is therefore evident that the reaction of a vehicle on a highway can be predicted if the highway characteristics and the vehicle characteristics are known. From the preceding example it appears as if vehicle reaction on the highway is also related to vehicle riding qualities.

CONCLUSION

Under certain conditions a highway may be described by power spectrum analysis. The data for such an analysis can be obtained in several different ways. The steady-state sinusoidal vehicle response characteristics are non-linear, but have been approximated for the purpose of estimating the force that the vehicle will exert upon a given highway.

With this information it is possible to compute a force power spectrum. This characteristic indicates not only the mean squared force exerted on the highway but also the extent to which various frequency ranges contribute to this force. The results of this investigation so far indicate that this type of analysis could be applied to many different vehicles to determine the dynamic force that they exert upon the highway.

ACKNOWLEDGMENTS

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The vehicle vibrators described were built by the AASHO Road Test in order to further this investigation.

Discussion

CARL F. KOSSACK, IBM Research. —This paper's significance stems from the fact that it presents a technique for bringing together vehicle performance characteristics and highway characteristics in a way that yields positive results. The method suffers from the fact that it involves an almost purely empirical approach, but has the virtue that the required data can be readily obtained and the analysis evolved without undue complication and expense.

It should be noted that one must recognize the dilemma that exists in making the basic assumption regarding the distribution of the highway profile. It appears that at present one is faced with the decision as to whether to assume periodicity or randomness. Under a periodic assumption the usual Fourier analysis is available although, as mentioned in the paper, the fundamental wave length requirement introduces some awkwardness. In the random assumption the applicability of power spectrum analysis has been shown in this paper. One cannot help but raise the question as to how one might combine these two opposing approaches. Surely a highway is neither purely periodic nor completely random as far as its profile is concerned. One working under the periodic assumption wonders how to handle large shocks; in case of the random assumption the question of the length of pavement to use for each power spectrum analysis needs to be resolved. It would be worthwhile to assume the possibility of combining these two approaches so as to have an analysis that is more sensitive to actual conditions. For example, could one not run a Fourier analysis on the original profile data taking out the two or three major frequencies and then treat the residuals as being randomly distributed and thus amenable to a power spectrum analysis? The existence of two different forms in the analysis may complicate the transfer function problem, but with some attention this problem would be resolved.

A second remark also seems in order. The attraction of the present paper lies in its proposal of a fairly straightforward method of obtaining the necessary data and in making the required analysis.

The weakness in the paper is the lack of any theoretical structure to the procedure. Although one can make the indicated analysis for any given vehicle and any given section of highway, the basic parameters of both the vehicle and the highway enter implicitly in the analysis and thus make generalizations and predictions difficult. On the other hand, there are approaches to this problem in which a deterministic method of analysis is attempted and one soon recognizes that the large number of variables involved and the complexity of the several systems forces so many simplifying assumptions in order to mathematically set up the required equations, that serious doubts exist as to the true worth of the theoretical solution. Can one here again combine the stochastic empirical approach of the present paper with certain aspects of the theoretical, thus yielding a useful method? As a first suggestion, can one introduce some general functional form to represent the power spectrum of a highway and then correlate the parameters of the function form with highway variables? Similarly can the vehicle performance characteristics be correlated with structural characteristics of the vehicle? Such a "statistical" approach is felt to be the only feasible approach to this type of problem.

One cannot help but notice how sensitive the response of the vehicle is to the speed of travel of the vehicle. This brings into sharp focus the true system nature of the transportation problem. In fact, there are at least three primary systems involved: the structural system of the road, the vehicle characteristics, and finally the packaging system of the load being transported by the vehicle. Highways must be multi-purpose in their use pattern; thus, generally, one cannot design the highway for a single type of traffic. The types of vehicles, the loads being carried, and the speeds traveled differ. What is needed is some worth function to enable design decisions to be made scientifically. In such a consideration all the usual problems of decision-making are encountered, thus attention must be given as to what criteria are to be used.

In making system studies of this type, difficulty is usually always encountered when an attempt is made to obtain data to be used in the evaluations. Data that are available are often not only spotty in their time coverage, but also relate to an inappropriate set of variables.

It appears that this same difficulty is likely to be present in the transportation problem. Highway design engineers have developed or are developing a set of criteria relating to the performance characteristics of a highway which through studies such as the AASHO Road Test are being correlated with the several design factors involved in highway construction. Highway maintenance engineers are at the same time accumulating measures of the status of sections of highway under their jurisdiction, along with measures of the traffic characteristics to which each section is subject. Automotive design engineers are modifying the design characteristics of motor vehicles as measured by simulated inputs or road test performance experience. Finally, packaging engineers are advancing the science of design of packaging and actually recommending package design on the basis of expected shock and vibration environment for the package.

It seems quite apparent that all of these activities are imbedded in a general highway transportation model and as such are closely interrelated. The traffic patterns assumed by the highway design engineer should tie in with those measured by the highway maintenance engineer; the automotive design engineer should use highway profile assumptions compatible with present-day conditions. The packaging design should reflect the environment that is actually encountered. There is, however, evidence that there is at present no general understanding on measurement methods to be used in these overlapping areas. That this is the situation surely follows from the existence of the periodic and the random models for highway profile analysis.

It is beyond the scope of this discussion to develop a suggested method of interrelating the activities encountered in this general area. It is desired, however, to stress the need for careful work to be done in evolving some generally accepted method of measuring the various phenomena encountered in the field, because until this is done one cannot expect that so-called improvements in designs in any one area will truly be an improvement in the general system.

BAYARD E. QUINN and THOMAS W. DE VRIES, Closure—It is recognized that variations in the surface of a highway will cause a vehicle moving over it to exert forces on the highway in addition to the static weight of the vehicle. Predicting the magnitude of these forces is desirable for many reasons but is unfortunately a formidable task because it requires a characterization of a highway that can be used with a characterization of a vehicle suspension system to yield these forces. The fundamental question is, therefore, that of determining appropriate characterizations for both highway and vehicle.

The possible use of a power spectral density function for characterizing a highway is attractive for many reasons. The calculation of the autocovariance function (needed to compute the power spectrum) provides a criterion as to whether or not the highway under consideration can be characterized by this method. Highways not suited for this type of analysis can thus be identified.

The existence of a periodic component in a highway does not necessarily exclude the use of a power spectrum analysis, however. Filtering techniques are available for removing periodic components, and in some cases the frequency and amplitude of the periodic component can be estimated if it is not already known. If frequency and amplitude are known the filtering procedure is relatively simple. The proper length of pavement to use for a power spectrum can be determined by selecting confidence limits for the ordinates of the resulting power spectrum analysis.

Theoretically there are large differences between a highway characterization obtained by making a power spectrum analysis as compared to that obtained by making a Fourier series analysis. The big question, however, is to what extent these differences are significant when characterizing actual highway profiles. It is the opinion of the authors that this question can best be answered by applying these methods to actual highway profile data and by comparing the resulting analyses. Information concerning orders of magnitude is necessary in order to resolve the question as to which type of analysis is practical.

Because both the power spectrum and the Fourier series analysis characterize the highway in the frequency domain, it seems logical to characterize the vehicle suspension system in this domain also. For a simple linear system this presents relatively few difficulties, inasmuch as the differential equations that describe the system in terms of mass, stiffness, and damping will yield the frequency response with little effort. A vehicle is more complicated, because both stiffness and damping are not constant (as in a simple linear system) but vary over a range of values. These quantities are not parameters in the same sense as applied to the linear system, and attempts to use them as such usually require the use of an averaging technique. If they are treated as functions they can no longer be considered as system constants. The characteristics of a passenger vehicle shock absorber cannot be described by a simple mathematical equation with one constant, as is usually assumed in linear vibration theory. The determination of the significant parameters of a non-linear system can be a difficult undertaking.

In view of these problems it is logical to examine the response of a system and to attempt to establish parameters from this information. The response contains the interaction of the various system components, which may be difficult to determine if an attempt is made to characterize the system using the method previously discussed.

In this paper no attempt was made to represent the response curves by mathematical equations. An undertaking of this nature is being conducted by another group at

Purdue University, and the authors are cooperating with this effort because of the possible value to this project. Mathematical equations of the response curves contained in this paper would be highly desirable and attempts are being made to obtain them. The constants contained in these equations would serve as system parameters.

Predicting the dynamic forces that a vehicle exerts on a highway will require vehicle and highway characteristics that are compatible and significant. The purpose of this paper is to show that such characteristics can be determined and can be used for this purpose.