HIGHWAY RESEARCH BOARD

Bulletin 250

Pavement Performance Concepts

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Pavement Performance Concepts

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Contents

Preliminary Analysis of Road Loading Mechanics

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A program for the development of a dynamic theory of road-vehicle systems is outlined. An analysis is presented of the basic problems involved in the development of a comprehensive treatment of road loading mechanics. The complete road loading system is defined and its various component elements are discussed. The development of a simple but realistic mathematical model of the vehicle as the road loading element is accomplished. The model is subjected to various stylized road inputs on an analog computer and the resultant steady-state responses are determined. The significance of the model response to certain inputs is discussed and conclusions and recommendations are drawn from the complete study.

RESEARCH IN ROAD LOADING MECHANICS

●THE INCREASING USE of highway transportation and the expanding highway system emphasize the importance of a thorough knowledge of those factors contributing to highway wear and deterioration. Although it has been customary to study road life through the medium of the classic road test, an increasing body of evidence suggests that the extrapolation of the road test results and a more fundamental understanding of the highway may be facilitated by a system type of analysis, properly relating all of the dynamic as well as static performance factors.

In August 1958 a conference was held at the Bureau of Public Roads for the purpose of discussing a basic research approach to the problem of highway life, with particular emphasis on the dynamic road loads produced by vehicles on highways and their interactions with the road profile. It was pointed out that among the many diverse and complex factors which affect highway performance, those physical effects characterized as "road loading mechanics" are among the more important because they bear directly upon road life, vehicle life, driver fatigue, cargo damage and vehicle handling capabilities. It was generally concluded that a real need exists for the long-range development of a dynamic theory, adequately substantiated by experiment, which would permit the prediction of road life from the characteristics of the traffic flow and which would also point up the effect on road life of changes in vehicles suspensions and parameters that determine road response dynamics. It was also felt that the availability of modern statistical analysis methods, dynamic instrumentation techniques and modern computing equipment would facilitate such an effort and argued well for its initiation.

A further conclusion of the conference was that the most productive approach would involve a "system concept" attack that presumes a coordinated effort on the part of many groups; notably those of government, highway constructors and the automotive industry. All are concerned with important components of the system, and optimum results will only be obtained by related and compatible modifications in these components. Although it is thus readily imaginable that an ultimate approach should be directed and financed jointly, it was also believed desirable to initiate certain efforts immediately.

As the result of this conference, Cornell Aeronautical Laboratory prepared the following outline of a comprehensive program.

PROGRAM OUTLINE

The general program is conceived as one leading to a broad and basic understanding of the transportation system as a whole. The program comprises several phases forming a logical sequence of development and, were it to be pursued, its completion would constitute a scientific framework for the examination of many highway operational problems. It will be noted that the vehicle and highway are treated separately until developments are sufficiently complete to warrant joint analysis or application of the consolidated system equations.

Phase I. Analysis of Basis Problem

1. Literature Survey. A complete survey of literature (see references for examples) pertaining to basic road mechanics, analytical and experimental evaluation of suspension components (including tires), and investigation of vehicle ride performance would be made to establish what work has been done, the type and quantity of information available, and to map out the areas that require further research and development.
2. Preliminary Analysis. Existing analyses or new simplified analysis would be made to establish the form of the basic equations and to determine the range of the various system parameters and the magnitude of the loads produced by several classes of vehicles for typical road inputs.

Phase II. Complete Vehicle Equations

1. Analytical Development. Based on the work of Phase I, a more complete set of vehicle equations would be formulated. They would be analyzed to determine the significant parameters and form the basis for the program of experimental verification.
2. Experimental Verification. An experimental program would be conducted to verify the equations previously developed. First, the values of the system parameters would be evaluated and then actual full-scale tests performed for comparison with analytical predictions. Undoubtedly, some modification of the equations would be required, either to yield more accurate results or to produce a simpler set of equations.

Phase III. Road Equations of Motion

1. Preliminary Analysis. The first part of this phase would attempt to establish a simplified set of equations describing a road as a dynamic system. Included would be an extension of the literature survey made in Phase I.
2. Analytical Development. After the feasibility of such an analytical treatment has been established a more complete set of road equations would be formulated. These would embody all the important variables that affect road performance. An analysis would be made to determine significant parameters and relationships. This examination would lead to the development of an experimental verification program.
3. Experimental Verification. An experimental program would be conducted to verify the equations developed in Phase III-2. First, the values of the system parameters would be evaluated and then actual full-scale tests performed for comparison with analytical predictions. Undoubtedly, some modification of the equations would be required, either to yield more accurate results or to produce a simpler set of equations.

Phase IV. Application of System Equations

Here, specific computational and predictive tasks similar to those already outlined would be undertaken. Specifically, a comparative analysis of the dynamic road loading of various classes of vehicles would be made. This would determine the fundamental reasons for differences and show ways of making improvements in both roads and vehicles.

The Bureau of Public Roads contracted with Cornell Aeronautical Laboratory for a program which essentially comprised Phase I of this outline. This research has been completed and reported (67) and forms the basis of the present paper. Additional

Bureau of Public Roads support has been subsequently given for a similar treatment of Step 1 of Phase III, which is now being actively pursued at Cornell Aeronautical Laboratory.

SYSTEM DEFINITION

The road loading system is composed of two major elements; vehicles and the roads on which they travel. In general, the performance of each element is dependent upon the performance of both elements. Loads are applied to the road in several ways. First, there is the static load of the vehicles. Second, the road profile, through its contact with the vehicle tire, acts as a forcing function of dynamic load variations. Third, the variation of tire elasticity around the circumference produces variations in road load. All of these loads act on the highway to produce variations in deflection and stress. Thus, the tire contact area is the connection between the two sub-systems, each of which consists of several additional factors, as shown in Figure 1.

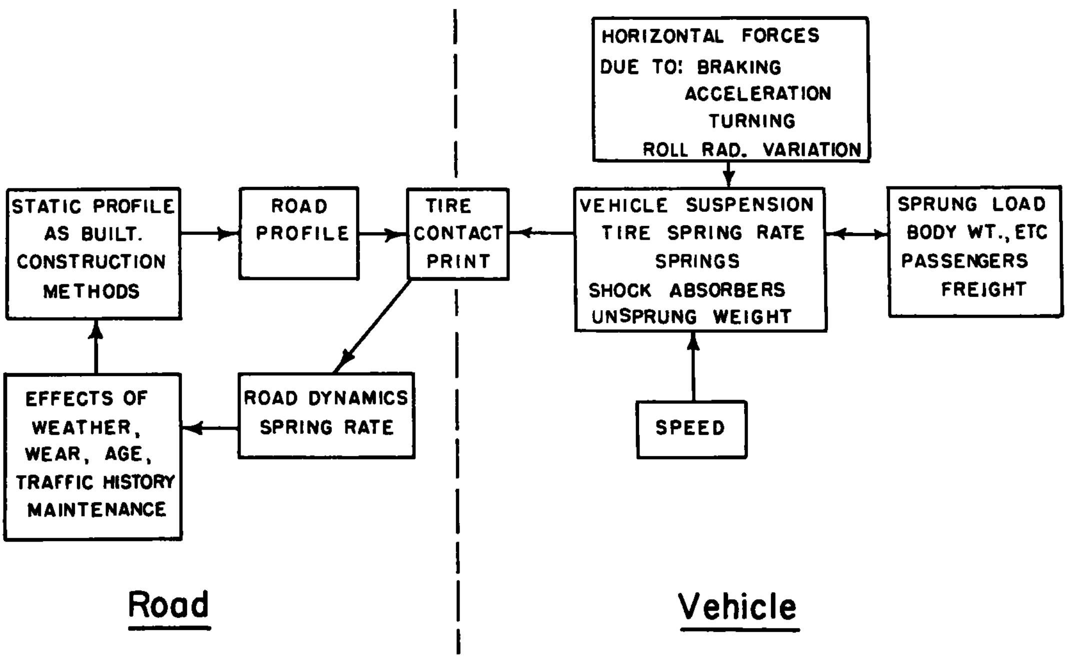

Figure 1. Road loading system.

The road profile presented to the vehicle tire is a function of its static profile as built and subsequently modified by the effects of weather, wear, age, traffic history, and maintenance, as well as the dynamics of the road as an elastically supported body. All these are in turn a function of the constructional details employed in building the highway. The type of surface, finishing methods, subgrade, subbase, and basement soil are all contributing factors. A definition of the loads applied at the tire contact print would allow investigation of this vehicle sub-system by itself. In its simplest form, the system contains one vehicle and one road model. The effects of numbers of vehicles and/or increased road theoretical complexity can be brought into the analysis by addition.

The vehicular system applies loads to the road through the tire contact print. Basically, the sprung mass of the vehicle compresses the suspension springs which load the unsprung mass, or axles, which in turn load the tires on the contact print. The sprung mass is composed of the chassis above the springs, the passengers, and the freight or luggage carried. Any change in the deflection of the elastic members is accompanied by a variation of load, thus as the tire contact print goes up and down over the road profile, the load applied to the road is varied. There is also a horizontal load applied to the road surface due to transient motions such as acceleration or braking, a side force resulting from steering action initiated by the driver, or camber, or superelevation of the road, as well as loads in the fore and aft direction due to change in rolling radius of the tires as they move over the undulating road profile. And, finally, since this is an elastically supported system, the effect of frequency must be taken into account. The output forces applied by the vehicle to the road are frequency dependent. Like many dynamic systems, mechanical resonance occurs at certain frequencies, which magnifies the loads transmitted.

This, then, as shown in Figure 1, is the complete system. A change in any one of the elements will affect the rest. The load variation on the road is the response of the vehicular sub-system to the apparent profile; the apparent road profile is the cumulative result of those factors embodied in the road sub-system. The interaction of the various elements may be expressed mathematically if sufficient information about their operation is at hand. Either sub-system may be investigated individually from the tire contact print outward.

Nomenclature

The symbols used herein, listed here for ease of reference, are as follows:

a = distance from the front axle to the center of gravity, in in.;
b = distance from the rear axle to the center of gravity, in in.;
b_{c_1} = front axle Coulomb friction force, in lb;
b_{c_2} = rear axle Coulomb friction force, in lb;
C_{c_1} = front axle viscous damping constant, in lb sec/in.,
C_{c_2} = rear axle viscous damping constant, in lb sec/in.;
F_f = front tire dynamic road loading force, in lb;
F_{fs} = front tire static road load force, in lb;
$\left.\frac{F_{fm}}{F_{fs}}\right)_{ss}$ = front tire steady-state maximum dynamic road load force ratio;
F_r = rear tire dynamic road load force, in lb;
F_{rs} = rear tire static road load force, in lb;
$\left.\frac{F_{rm}}{F_{rs}}\right)_{ss}$ = rear tire steady-state maximum dynamic road load force ratio,
f = road input frequency ($f = u/\lambda$), in cps;
g = gravity acceleration (386 in./sec^2), in in./sec^2;
I = body pitch inertia about the center of gravity, in in. lb sec^2;
k_1 = front tire vertical stiffness, in lb/in.;
k_2 = rear tire vertical stiffness, in lb/in.;
k_{c_1} = front axle suspension spring rate, in lb/in.;
k_{c_2} = rear axle suspension spring rate, in lb/in.;
l = wheelbase length, in in.;
m_c = sprung mass, in lb sec^2/in.;
m_1 = front axle unsprung mass, in lb sec^2/in.;
m_2 = rear axle unsprung mass, in lb sec^2/in.;
N = integral number of road wavelengths contained between front and rear axles;
n = fractional portion of a wavelength contained between front and rear axles;

u = forward velocity, in in./sec;
λ = road wavelength, in in.;
θ = body pitch attitude angle, in deg;
τ = time delay between road input to front and rear tires, in sec;
$\delta(t)$ = absolute road input amplitude to front tires, in in.;
$\delta(t-T)$ = absolute road input amplitude to rear tires, in in.;
δ_m = peak-to-peak value of road input amplitude, in in.;
δ_1 = absolute front axle position, in in.;
δ_2 = absolute rear axle position, in in.; and
δ_3 = absolute body position measured at the center of gravity, in in.;

SYSTEM COMPONENTS

The elements of the two sub-systems, as defined, were investigated in an effort to mathematically define the relationships within the two sub-systems. It was not the aim of this initial program to completely define the road sub-system. However, it was mandatory that this area be investigated sufficiently to gain a knowledge of road profiles and their variation as a result of dynamic loading in order to achieve realistic apparent road profiles as inputs to the vehicular sub-system.

Road Elements

The term "road" as used in this study covers any paved highway intended for motor vehicle travel. The pavement can be either the rigid type as exemplified by portland cement concrete or the flexible type containing various thicknesses of bituminous material. Regardless of type, it is the subsoil which eventually carries the load. The surface and intermediate structure merely serve to transmit the load from the vehicle wheels into the ground. The characteristics of the surface material do, however, determine the manner in which this load is transferred. In order to estimate the seriousness of the pavement deflections due to load, and any consequent alterations of the profile, both types of pavement have been investigated.

A survey of current literature was made to obtain the data necessary for consideration of the road elements. Among those examined, References 2 through 21 seemed most pertinent. The magnitude and seriousness of flexible pavement deflections to be expected is shown to vary with pavement age, thickness, vehicle speed, temperature, and the dynamic properties of both the surface and the subgrade. The stress and deflection data for rigid pavements, as given in these references or determined by methods indicated in them, show variations, with a major dependence on the modulus of subgrade reaction.

This study of the present state of road system definition, although not exhaustive, has provided some new insight into, and understanding of, the road loading problem. It has indicated that static deflections of approximately 0.030 in. are to be expected and that dynamic deflections can be considerably larger. Dynamic deflections of the order of 0.050 in. can be accommodated without undue deterioration, but larger values will usually be accompanied by premature surface breakup. (Improper matching of vehicle and road, that is, close correspondence of their natural frequencies, can produce large deflections and premature failure.) Consequently, the assumption of the static road profile as the input to the tire, without admission of road relative motion, is a reasonable procedure for calculating dynamic force variations occurring in the tire print.

The study has also substantiated the belief that a fundamental analysis of the road as a dynamic structure (including all the various elements from the base soil upward to the tire print) should enable a clearer understanding and definition of the actions and reactions which take place within it. The hard top surface merely transmits the wheel loads via the intermediate courses to the base soil over which the road is build. All the strata contribute to the total action by virtue of their individual characteristics, but it is the base soil which ultimately must carry the load. The intermediate structure is the means of spreading out the load to an extent required to avoid failure in the sometimes varying basement soil.

Vehicle Elements

The components in the make-up of motor vehicles which are of interest in this respect are largely contained in the suspension system. Generally, they bear similar functional relationships to each other regardless of size. The body is assumed to have mass and to be rigid. Between it and the axles are the suspension springs and shock absorbers. The axles carry the brakes, wheels, steering mechanism, and tires, and thus have mass. The tires carry the axle over the road surface and transmit road loading forces from the vehicle to the road. These are the elements which must be related mathematically in order to define the vehicle motions and force variation in the tire print.

Tires are all quite similar. They sustain a load by virtue of their deflection. Although the vertical deflection of a given tire is a function of inflation pressure, and generally speaking the contact pressure is not dissimilar from the inflation pressure, the nominal deflection at rated load and pressure is very nearly 1 in. for all highway vehicle tires. According to the Tire and Rim Association (22) a 10.00 x 20 twelve-ply truck tire is rated at 4,500 lb. Its vertical spring rate is 4,500 lb per in. Although damping is required in the tread material for satisfactory gripping properties (23), the carcass mainly acts as a container for an air spring, with negligible damping. The assumption of no tire damping has been reached by a number of other investigators (24-30).

The unsprung weight of a vehicle usually includes the wheel brakes, axles, and some portion of the springs, as well as the tires. With independent suspensions, the picture changes somewhat due to a reduction in axle weight. References 31 through 37 discuss the variations involved. The typical commercial vehicle which carries 9,000 lb on the front axle and 18,000 lb on the rear (or 32,000 lb on the bogie) will undoubtedly have solid axles for some time to come. The weight of the unsprung masses will vary from 800 to 1,200 lb on the front, with a good percentage being close to 1,000 lb (500 lb per wheel). The rear axle and associated unsprung parts will weigh about double this, with a large group showing 2,000 lb on a single rear axle carrying dual tires (30).

The springs of a vehicle fall into several categories. Primarily, there are the conventional leaf springs, which are found on most commercial vehicles and many passenger car rear suspensions. Leaf springs can satisfy the three main requirements of the connection between the axle and vehicle frame; they allow relative motion between the two members and provide a source for energy storage, they maintain the axle position both fore and aft and sideways within reasonable limits, and last, but by no means least, they do both jobs relatively inexpensively. The next class of springs is the single-purpose type, which forms only the resilient member, the axle being constrained to move in a manner prescribed by various linkages which connect it to the chassis. References 30 and 38 through 45 discuss the details and effects of different designs. Spring rates, of course, vary with the design. The leaf springs for the commercial truck previously mentioned will have a rate of about 900 lb per in. on the front axle and 2,000 lb per in. on the rear. These values are largely dictated by the space available over the axles. The values chosen reflect a static deflection of $4\frac{1}{2}$ in. on the front springs and $3\frac{1}{2}$ in. on the rear under full load conditions. Although overload or helper springs may be employed, or the shackle tilted to increase the rate as deflection increases, the physical limitations are such that the design variation of the hypothetical 27,000-lb truck when fully loaded will not be great.

The remaining factor in a vehicle suspension is the damping in the system. This is made up of several things. Coulomb friction or static friction comes from parts rubbing together and always opposes motion. It is generally agreed that this type of damping is not desirable due to its often irrational action as well as the reduction of its effect near a resonant frequency. Shock absorbers, which provide some form of viscous damping, are usually applied to the front axle of trucks, and to both axles of passenger cars. They can be designed for different damping ratios, but about 20 percent critical damping is very effective and not too rigid. The inter-leaf spring friction has been estimated by Janeway (30) as a function of spring load and seems to be the same whether the vehicle is empty or fully loaded.

The characteristics of the different elements discussed were used directly in a mathematical model in order to predict the system outputs. After a model was chosen, the parameters were evaluated and the expressions were set into an analog computer, which solved for the response to different forcing inputs. This is described in the succeeding sections.

SYSTEM MODEL

Ideally, one can set up the equations of motion for the complete road system, including both the vehicle and road elements, specify the system constants, and solve for the output forces to the road. Practically, this is not now possible, as there remains considerable work to be done toward understanding and mathematically defining the action and restraints imposed by the different portions of the road in whatever manner it may have been constructed. However, a good background of information is available on the vehicle sub-system; its equations of motion may be evaluated. Others have handled this problem with a different degree of completeness and complexity and have achieved a remarkable degree of correlation between theory and test. References 24, 26 through 29, and 46 through 54 are a few of the reports on this type of work. The current analysis has been aimed at simulating a vehicle in a sufficiently realistic manner that external conditions may be related to it, and its application to any given road profile will reliably illustrate the forces occurring in the tire contact print. The forces which the vehicle applies to the road surface may thus be determined for a given road profile. As previously mentioned, the static profile very nearly represents that which the vehicle experiences. The output forces which result from the application of the static road profile to the model may then be used with the road sub-system representation, when it is available, to determine the effect of dynamic road loading on the road itself.

Choice of a Model

There are a large variety of vehicles currently using the highways. Although certain roads may have only a marginal life expectancy under passenger car traffic, the majority of highways were planned to carry both commerical vehicles and passenger cars. This means that a fair life span is anticipated under present-day commercial loads, but probably very long life would be obtained under just the lighter automobile loadings. Granted that in a fatigue life problem, a very large number of small-magnitude inputs will have an appreciable effect, the relative dynamic stress or deflection caused by a 1,000-lb loaded tire of an automobile is several times less than that of a pair of dual truck tires carrying 9,000 lb. Thus, any dynamic magnifying factors would have to be several times as great on the smaller vehicle to approach the same road stress. This is very improbable, because in many ways they are very similar vehicles, one a smaller version of the other. Consequently, it seems reasonable to assume one vehicle as the model; other vehicles may be represented by changes in the vehicle parameters; and the results may be interpreted in the light of these variations. In the present work, a heavy truck was chosen as the model. It also has the advantages of large load variations being available in both the real and simulated case.

The data included in the WASHO Road Test Report (2) indicate that the loading due to an 18,000-lb single axle is equivalent deflection-wise to that of a 32,000-lb tandem on flexible pavements. This is further attested by the multiple regression analysis (55). The conditions under both types of axles on a concrete road have been investigated after the method of Westergaard (9) utilizing Mohr's circle (56) for computing the combined stresses (67). Although the effect of the additional axle is to produce a greater total deflection as a result of the greater total load on the slab, the stress seems to be critical under the 18,000-lb single axle. The results of these investigations led to the choice of a single 18,000-lb rear axle for the model to be simulated. The front axle was chosen to have the same tire loads on the same 10.00 x 20 size tires. This determined the 27,000-lb gross vehicle weight.

It was decided to use conventional leaf springs on both the front and rear of the vehicle, because they predominate in units of this size. Initially, shock absorbers were considered only on the front axle, as this is also common usage, but subsequently viscous dampers were also applied to the rear suspension to illustrate their effect.

Interpretation of Results

The road sub-system must endure repetitive loading of many different magnitudes. Although the actual traffic distribution for any given road is peculiar to itself, and the changing times and conditions will alter it from year to year on a given highway, a loading or traffic count may be obtained at any given time. An average of these traffic counts for a series of highways in the same class may be obtained to compute a typical road loading. This is about the only approach available for an estimate of the operating load under which a pavement must survive unless actual A.D.T. (Average Daily Traffic) figures are available. The problem is somewhat simplified through the use of Miner's cumulative damage criterion (57) and a fatigue curve for the road material. According to Miner, the number of cycles or load applications at a given stress level represents a portion or fraction of the life of the material. This same portion or fraction is obtained at different stress levels if the number of cycles applied is in the same proportion to the total number of cycles to cause rupture of the material at this stress level. The fatigue curve of the material defines the number of cycles to cause rupture at any given stress level.

As noted by Fabian (67), the stresses under various wheel loads may be calculated. From these stresses and a fatigue curve of the pavement material, the number of cycles to cause failure may be computed for each wheel load. By applying Miner's cumulative damage criterion with the number of cycles to rupture, an equivalent number of 9,000-lb static wheel loads may be determined. A typical traffic volume and wheel load distribution indicated that the total A.D.T. loading due to all vehicles was equivalent to 518 wheel loads of 9,000 lb being run down the road, roughly two-thirds the number of commercial vehicles in the analysis.

This example has not been worked out with the detail used by Moore (21) or others, but it does illustrate the point that a traffic loading or distribution may be interpreted in the light of an equivalent loading of a given model. Of course, many simplifying assumptions were made here, such as assuming dynamic similarity of all vehicles, but the method is at least valid as a first approximation and enables a much broader application of the results of one model. The key to the evaluation is the fatigue curve, which will have to be substantiated over a broader range for general application of this method. It does show that with similar vehicles application of 100 9,000-lb wheel loads (on duals) is roughly equivalent to 20 loads of 11,000 lb, five of 13,000 lb, or slightly more than one of 15,000 lb.

An analog computer was used to solve the equations of motion representing a mathematical model of the response of the vehicle to road inputs. The analog computer solutions are the vertical road forces that the vehicle suspension system transmits in response to a given road profile and speed, and are expressed as a ratio of the peak to the static load. They provide a more realistic estimate of the forces actually being imposed on the road surface through the tire print, if the profile is realistic. With vertical road load force as an input, a better understanding of the resultant stresses and strains in the road structure may be gained. It must be remembered, however, that the dynamic force variations will be accompanied by similar changes in print area. The larger load is applied at approximately the same contact pressure over a larger area of road, due to increased ground contact area with larger vertical tire forces. Therefore, the stress computations used with the various road loads to indicate the seriousness or degree of damage must take this into account. The stresses indicated by Westergaard's method, as used in this work, are computed for one tire print area. An increase in load does not increase the stress proportionally unless the area over which the load acts remains constant. If contact area is roughly proportional to load, the data developed by Westergaard (9, Table 3) can be used to indicate the effect of load ratio on stress ratio. Suffice it to say that a load ratio of 4:1 will increase the bending stress under the tire on a given concrete road by about 3:1.

Model Development

For reasons of simplicity, the model has been designed to indicate only the vertical forces on the road surface. It did not seem advisable in this preliminary analysis to try to account for the horizontal stresses due to acceleration, braking, cornering, or due to the mechanical design of the linkages which make up the suspension. They, like the thermal stresses in the pavement, are additive to those resulting from the vertical loads.

The problem is further simplified by the admission of only pitch and bounce degrees of freedom at steady-state speeds. Turning, rolling, and lateral translation are omitted. This seems a reasonable assumption, as it represents a majority of highway travel straight down a relatively flat road at constant speed. The excitation of the road profile merely causes vertical motion of the axles and consequently pitch and bounce of the vehicle.

The physical model chosen is a truck on 10.00 x 20 tires, singles front, duals rear. Because the vehicle is symmetrical about the vertical longitudinal plane, and because only motions in this plane are considered, only one-half of the vehicle need be used in the model. The front spring rate is 900 lb per in.; rear, 2,000 lb per in. The front unsprung weight (½ axle, one brake, wheel, tire, and spring) is 500 lb; the rear, 1,000 lb. The front sprung load is 4,000 lb and the rear 8,000, placing the center of gravity 96 in. aft of the front axle on this 144-in. wheel base rig. This vehicle is very similar to the CBE truck used as an example in Janeway's Truck Ride Analysis (30), from which some of the dynamic constants have been taken directly. A tire spring rate of 4,500 lb per in. per tire was assumed. Interleaf static or Coulomb friction is taken as 300 lb on the front axle, 400 lb on the rear, and viscous damping of approximately 20 percent critical was added as a shock absorber between the front axle and chassis frame. No shocks were used on the rear at first.

The geometry of the road is shown in an exaggerated view in Figure 2. The road profile is assumed to change elevation sinusoidally with distance along the road. Figure 3 shows a schematic diagram of the physical system from which the equations and the subsequent analog computer set-up were derived. The vertical displacement of the tire contact print as it follows the road profile $\delta(t)$ is taken as a function of time such that the rear tire print experiences the same displacement at the time $t + \tau$, where τ is the time required for the bump to traverse the wheel base at speed u. Thus, at the instant the front tire is at the displacement $\delta(t)$ the rear tire is traveling over the bump the front axle hit T seconds earlier, or $\delta(t-\tau)$. The analysis yields six equations with six unknowns, which can be solved simultaneously on an analog computer to determine the vertical forces in the tire prints, F_f and F_r, which are the result of the displacement of those prints by the road profile.

During the program, it was determined that two variations of the basic model should also be investigated. These are the unloaded vehicle weighing 8,400 lb and the fully loaded vehicle with shock absorbers contributing viscous damping to the rear suspension as well as the front.

The values of the various assumed truck parameters are given in Table 1. It is interesting to note that the bounce and pitch natural frequencies of the unloaded truck are in the range of human body resonance. This could be very uncomfortable, if not deleterious.

Road Inputs to the Vehicle

The actual vehicle traveling over the highway is subjected to many different types of bumps. The axle deflection magnitude depends on the amplitude of road roughness elements, the road wavelength, the suspension properties, and the forward speed of the axle. Without shocks, axle motion is a forced vibration with a highly peaked resonance, and there is enough random variation in surface profiles to offer excitation of approximately wheel hop natural frequency for almost any forward speed. A harmonic analysis of six road profiles recorded by Housel and Stokstad (61) was performed in an effort to locate any significant similarities or predominant wavelength contents. The effort proved futile, but it was observed that sections of the profiles could be closely approximated by simple wave functions of a sinusoidal, triangular, or square character for limited distances.

These simple wave forms were used as inputs to the computer, representing road profiles, and the frequency responses of the road forces to these three wave shapes were compared. There seemed to be little difference in the character of the results. There was a large magnification of the static load near the wheel hop frequency which attenuated symmetrically on either side. This led to the conclusion that the input wave form is not as important as frequency.

The harmonic analysis of road profiles had indicated that many different wavelengths are present with no definite pattern or content. The model response showed that the dynamic road load fluctuated at the wheel hop frequency relatively independent of input wave form. Consequently it was decided that the model response to simple sine waves was almost as meaningful and realistic as its response to most other inputs.

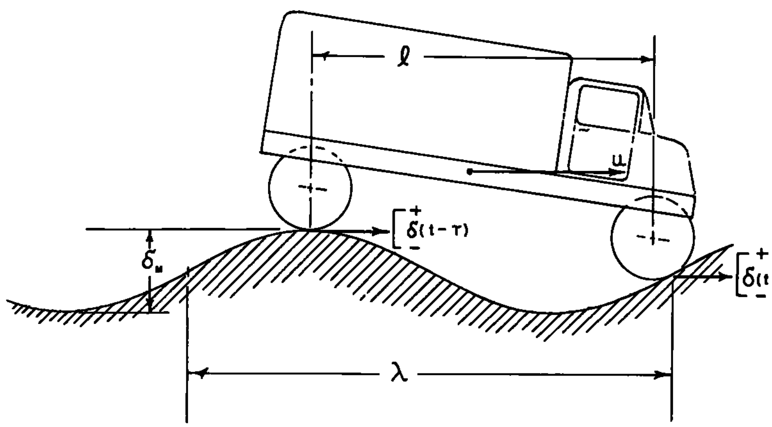

Figure 2. Sinusoidal road input.

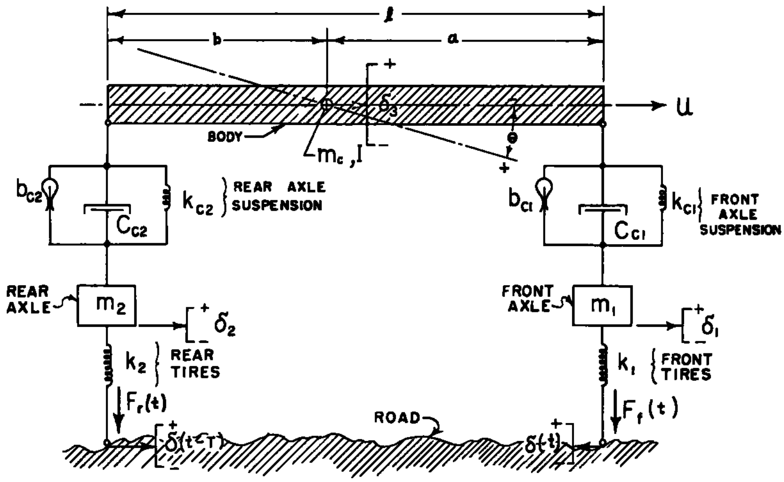

Figure 3. Mechanical analog of a truck.

It can be shown that the frequency response of a model which has a wheelbase equal to any fraction of a road wavelength is identical to that of the model having this same fraction of a wavelength plus any whole number of additional wavelengths contained between front and rear wheels. This is because the model senses only vertical displace-

TABLE 1

ASSUMED MODEL TRUCK PARAMETERS

Parameter	Truck Loaded	Truck Unloaded	Units
m_c	31.1	7.0	lb sec²/in.
m_1	1.30	1.30	lb sec²/in.
m_2	2.59	2.59	lb sec²/in.
k_{c_1}	900	900	lb/in.
k_{c_2}	2,000	2,000	lb/in.
k_1	4,500	4,500	lb/in.
k_2	9,000	9,000	lb/in.
C_{c_1}	100	100	lb sec/in.
C_{c_2}	0[a] 200[b]	0	lb sec/in.
b_{c_1}	300	300	lb
b_{c_z}	400	400	lb
I	87,000	28,700	in. lb sec²
a	96.0	53.3	in.
b	48	90.7	in.

[a]Without rear shock absorbers.
[b]With rear shock absorbers.

ment, which is a function of the distance along the wave. The same road input forcing frequency can be obtained for any wavelength by simply adjusting forward velocity. Consequently, the frequency response curves of Figures 5 through 10 apply to a large number of different wavelengths, and a complete picture may be gained from a relatively few frequency response curves.

The vertical amplitudes chosen were established to result in realistic road roughness. Waves of these magnitudes are not unusual. The total vertical amplitude per mile resulting from sine waves of ¼-, ½- and ¾- in. peak-to-peak amplitude is at least representative according to the road roughness figures of Moyer et al. (62, 63), Taylor (64), or the profiles which were harmonically analyzed (61).

Force Outputs to the Road

Figure 4 shows the form of the analog computer solutions obtained for steady-state response of the dynamic vertical road loading force to sinusoidal road displacement inputs. Although Figure 4 represents just one road displacement input amplitude at one value of frequency, several interesting conclusions can be deduced from it. The effect of rear shock absorbers in decreasing the peak dynamic

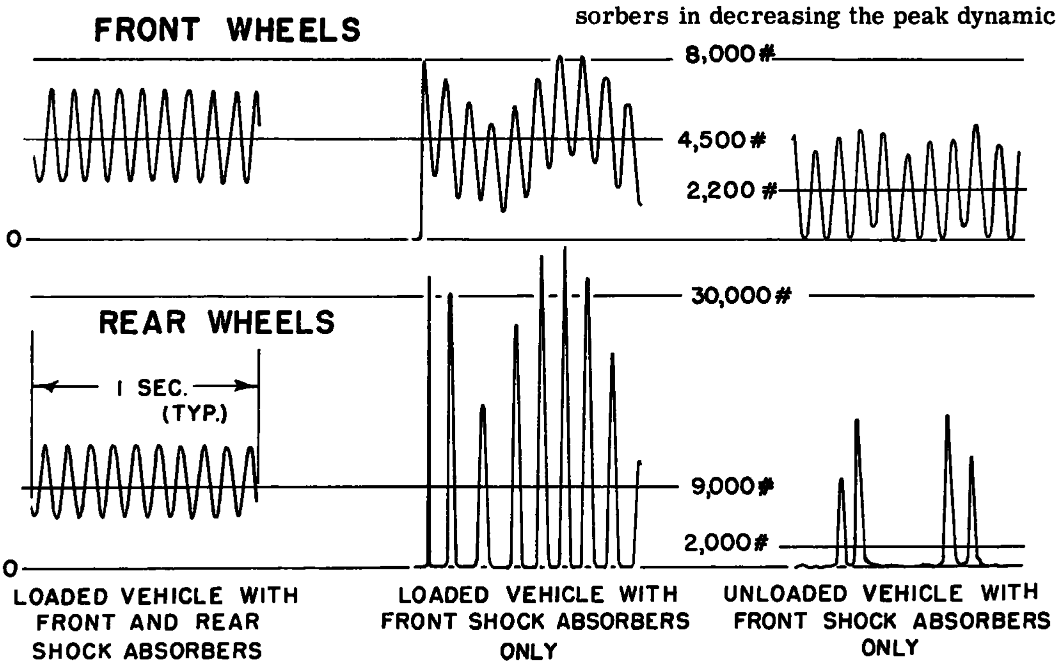

Figure 4. Truck time response to a sinusoidal road input; frequency 10 cps, amplitude 3/4 in. peak to peak.

road load forces is unmistakable in the left and center plots of Figure 4. With shock absorbers on all axles, the peak dynamic road load force under the rear tires is only 50 percent larger than the 9,000-lb static axle load. Without shock absorbers (all other things being equal) on the rear axle, the peak rear tire dynamic road load is more than 300 percent greater than the static axle load. It should be noted also that the tires actually leave the road every time the axle bounces. This condition is especially pronounced in the response of the unloaded truck to the same road displacement inputs. In this case, the peak-to-static rear axle road load force ratio is about 7.5 to 1 at wheel hop resonance (as shown in the right hand plot of Figure 4). The unloaded vehicle without shock absorbers exerts larger peak road loads under the rear tires than does the loaded vehicle with shock absorbers on all four wheels. Because road damage increases with some higher power of the stress amplitude (or road load force), the value of proper shock absorbers on all axles of even the largest vehicles in reducing cumulative road damage would seem apparent.

The ratio of the steady-state dynamic road load to the static load is plotted as a function of frequency (the ratio of road speed to road wavelength) in Figures 5 through 10. These plots represent both front and rear wheels for the loaded vehicle and road amplitudes of ¼, ½, and ¾ in. The use of the frequency parameter u/λ (speed/road wavelength) considerably extends the usefulness of the plots, since they can be applied to a multitude of speed and wavelength combinations, and it facilitates interpretation of the results. Plots for the unloaded vehicle (wheelbase of 12 ft) at a fundamental road wavelength of 24 ft are shown in Figures 9 and 10. The response of the fully loaded model with shock absorbers on both front and rear axles is shown in Figures 7 and 8. These plots all represent the dynamic loads which the vehicle imposes on the road.

The character of the standard loaded vehicle curves is not altered greatly by changes in wheelbase-to-wavelength ratio. Without rear axle shock absorbers, dynamic magnification factors of 2.9 or greater occur at the rear wheels at wheel hop natural frequency for a disturbance amplitude of ½ in. peak-to-peak. The peak amplitude ratio at wheel hop resonance is around 4 to 5 for a ¾-in. peak-to-peak input excursion and around 2½ to 3 for a ¼-in. peak-to-peak input amplitude. The significant factor is that at least twice the static load can readily be obtained over a fairly broad frequency range with moderate amplitude inputs. Most road profiles will excite the wheel hop mode to

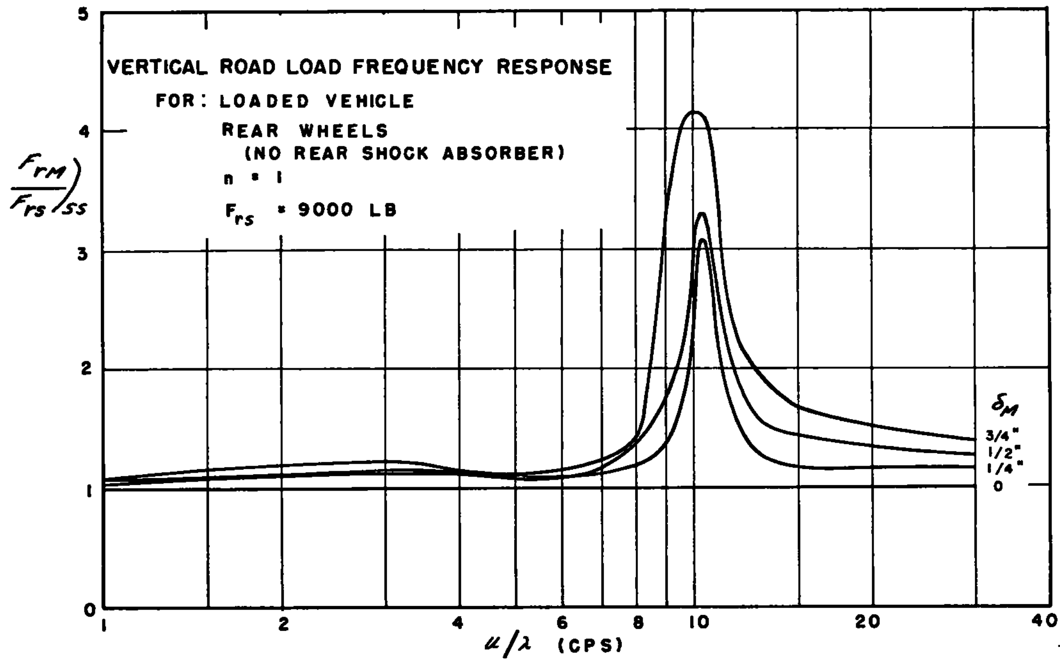

Figure 5.

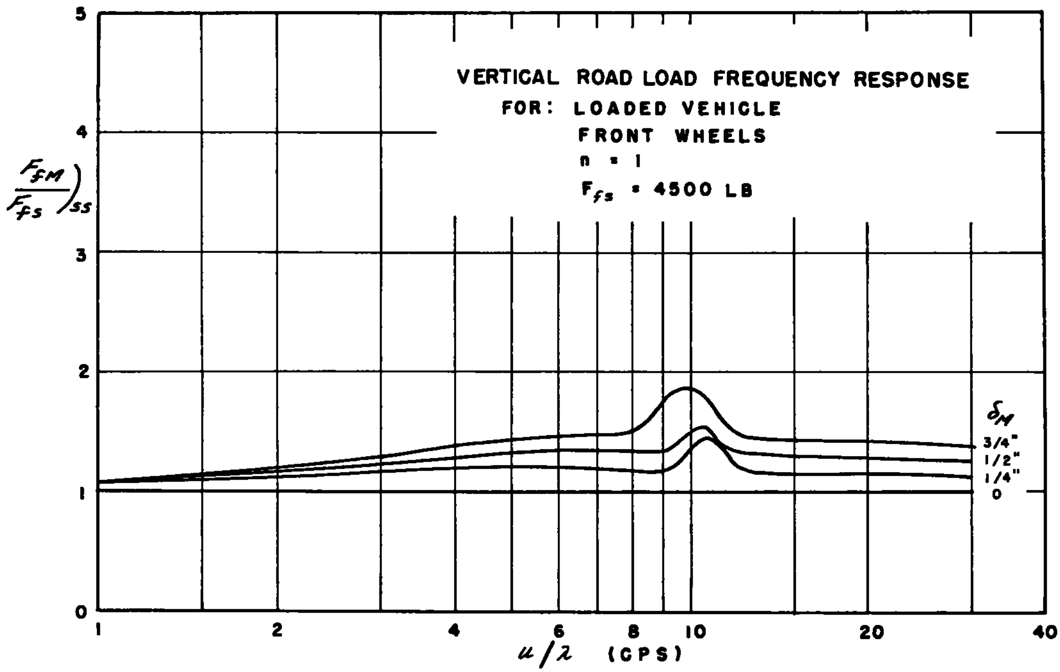

Figure 6.

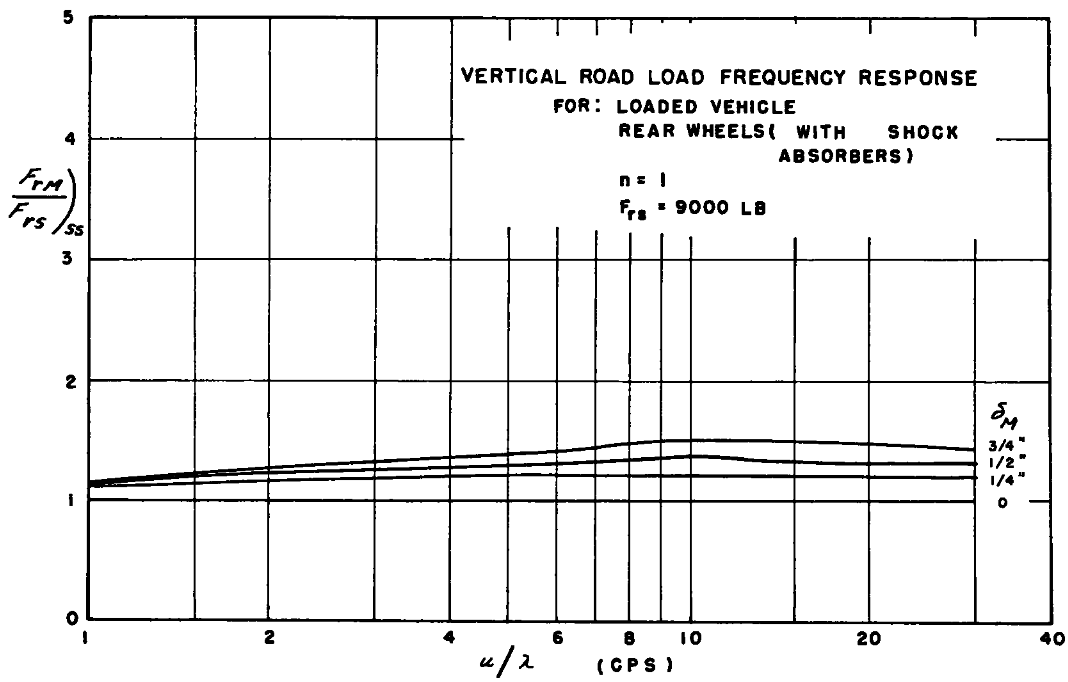

Figure 7.

some degree at almost any forward speed. The front axle dynamic loads, on the other hand, are down considerably at wheel hop resonance, and the magnification factor at very low and very high frequencies is the same. The effect of the shock absorbers in reducing the peak loads is evident, and it is felt that the higher values that do occur at the front axle natural frequency are in part due to pitching of the body excited by the rear axle motion. Conversely, the rear axle force amplitude ratios would be even higher without front shock absorbers.

The dynamic multiplier of the empty vehicle axle loads (Figures 9 and 10) is even greater than for the loaded vehicle. Fortunately for the road, the static load has been reduced sufficiently so that the actual load is considerably less than under the loaded truck. This is an example of what a poor suspension can do. The rear axle exhibits several extra peaks in its response which are the result of beating between the different natural frequencies within the system. The beating is excited by the non-linearities of the system.

The loaded vehicle with shock absorbers front and rear shows a considerably gentler response to road inputs. On the ½-in. amplitude road wave, the maximum dynamic load is 1.35 times the static value, only very slightly above the high frequency response on both the front and rear axles. The maximum value of 1.5 on the ¾-in. road wave is down to almost one-third the value of the truck without shock absorbers. The absence of any pronounced amplitude ratio peaking for either front or rear wheel road loads substantiates the opinion that the peak on the other configuration was due to the action of the rear axle, not the front. This example makes a good case for installing shock absorbers on the heavily loaded axles of commercial vehicles, as they can reduce road loading by a large factor.

CONCLUSIONS

The road loading system has been defined and resolved into two mathematically independent sub-systems, which are the road and the vehicle. By utilizing an approach common to the analysis of many dynamic systems, broad fundamental understanding of the interaction of the many road and vehicle elements may be obtained. If carried far enough, a mathematical representation relating all the elements of the road loading system may be developed.

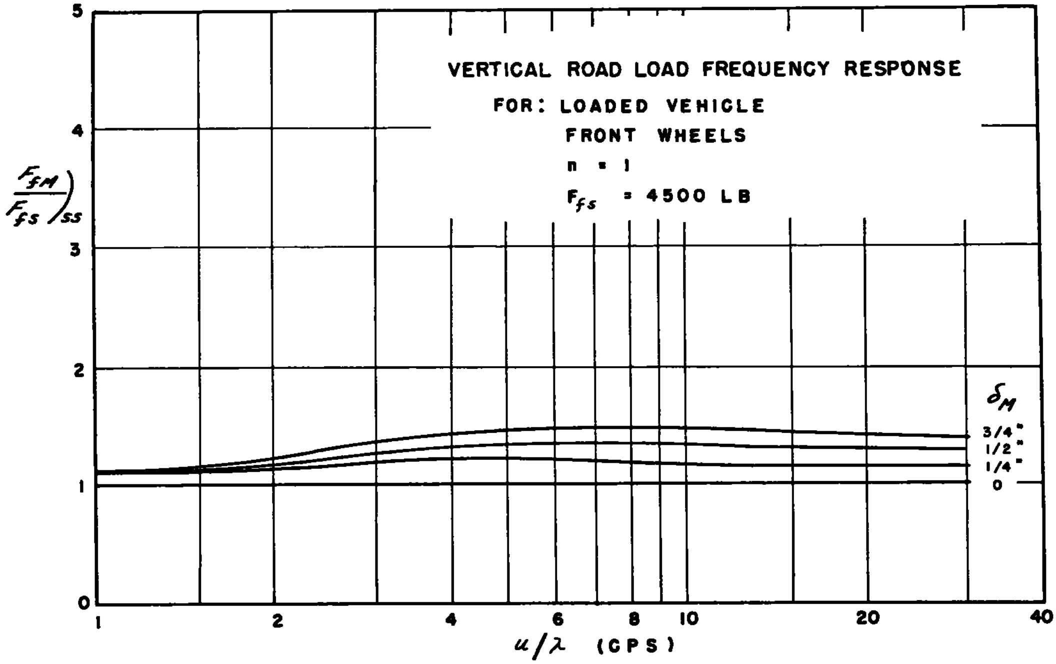

Figure 8.

A preliminary analysis has been performed on the vehicle sub-system. Basic equations of the mathematical model have been developed and the ranges of the parameters involved have been established. The dynamic road load may be significantly greater than the static road load. The dynamic road load magnitude is a function of vehicle dynamic properties and apparent road profile. Of particular significance is the effect of shock absorbers in reducing the peak road loading force.

The unloaded vehicle pitch and bounce natural frequencies are in the range of human body resonance, indicating an uncomfortable ride for the occupants.

RECOMMENDATIONS

It is recommended that development of analytical models of highway vehicles be continued and that a program of experimental verification of these models be initiated. The models developed in the present paper are adequate for preliminary studies, but considerable refinement and broadening of scope is necessary to accommodate the current operational vehicle types.

The major elements of suspension systems are capable of analysis. However, the detailed contribution of tires to the total loading mechanism is not well understood. Truck tires, in particular, have not been subjected to critical analytical or experimental investigation of the scope required here.

It is recommended that a program to set the highway in a dynamic system framework be carried out to provide analytical models commensurate with the vehicle models. It

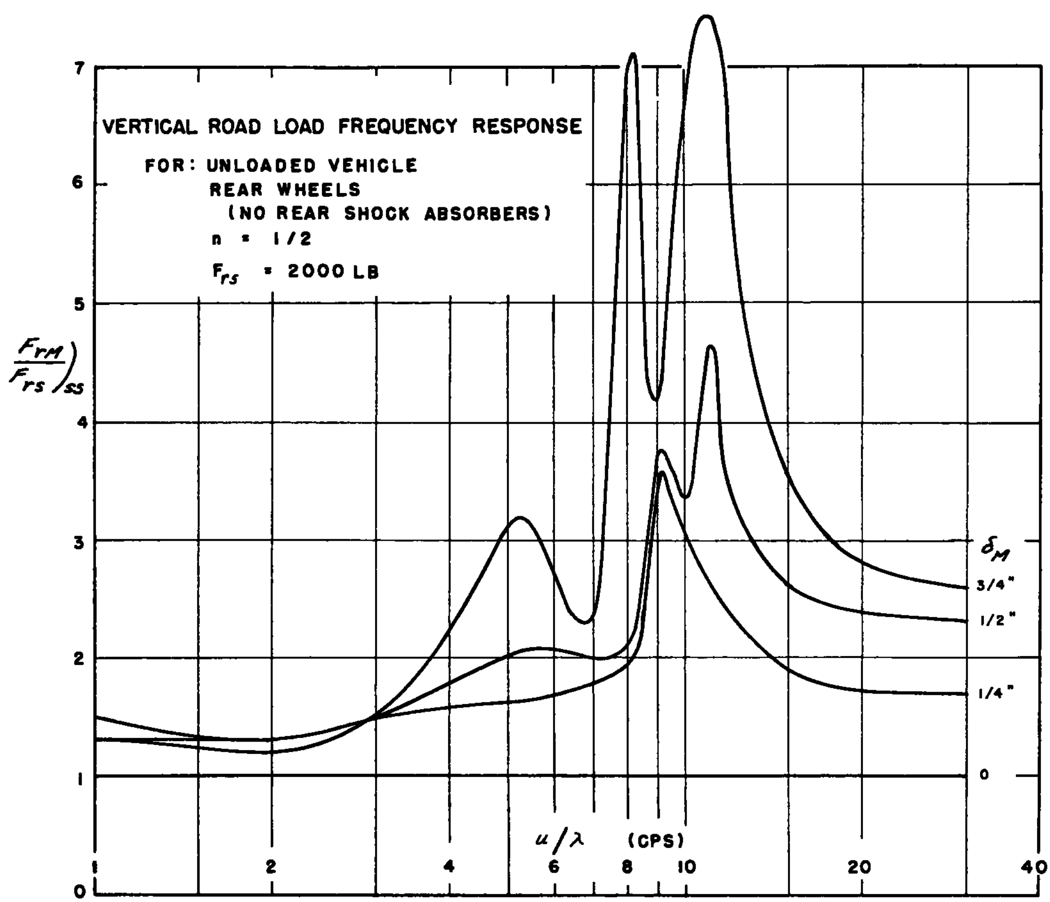

Figure 9.

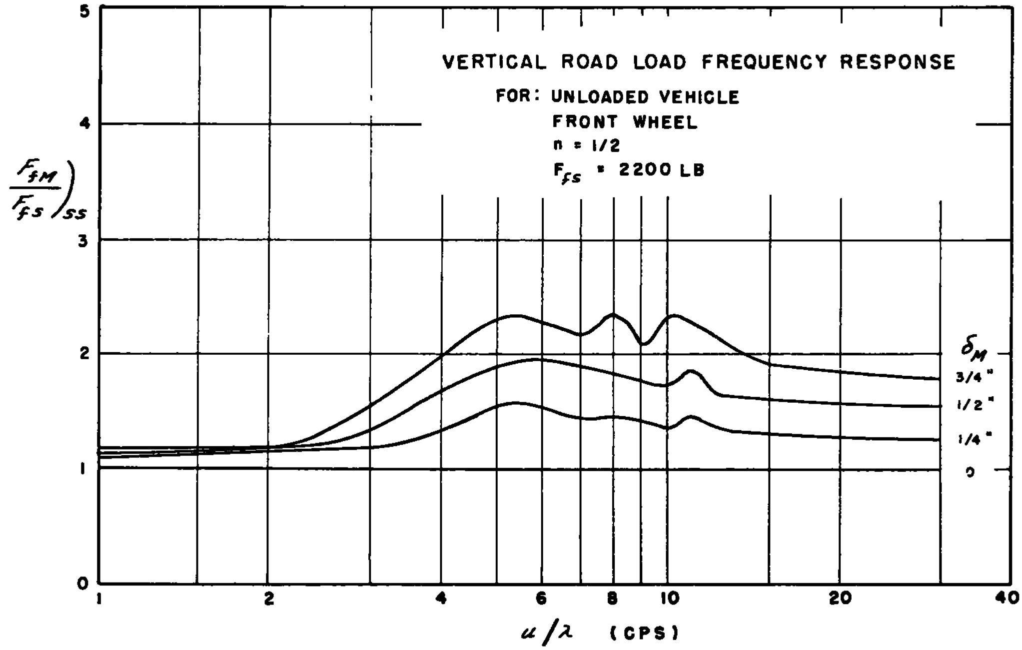

Figure 10.

is now clear that highway life must be considered in dynamic terms. Both the static axle loads and the dynamic variations must be considered, inasmuch as the road itself is a dynamic system that is sensitive to the frequency of the dynamic component of load.

The required program must define the highway elements that determine dynamic performance. It should be directed toward a comprehensive theory that will include static analysis techniques as special cases.

It is recommended that the interest and cooperation of the many groups and organizations concerned with efficient highway transportation be energetically enlisted for the support of the two broad programs outlined. It is necessary that all viewpoints be considered, and it is also necessary that all groups become aware of the objectives of this type of research and of the beneficial results that can accrue.

ACKNOWLEDGMENTS

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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;
$\omega = 2\pi/\lambda$, 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

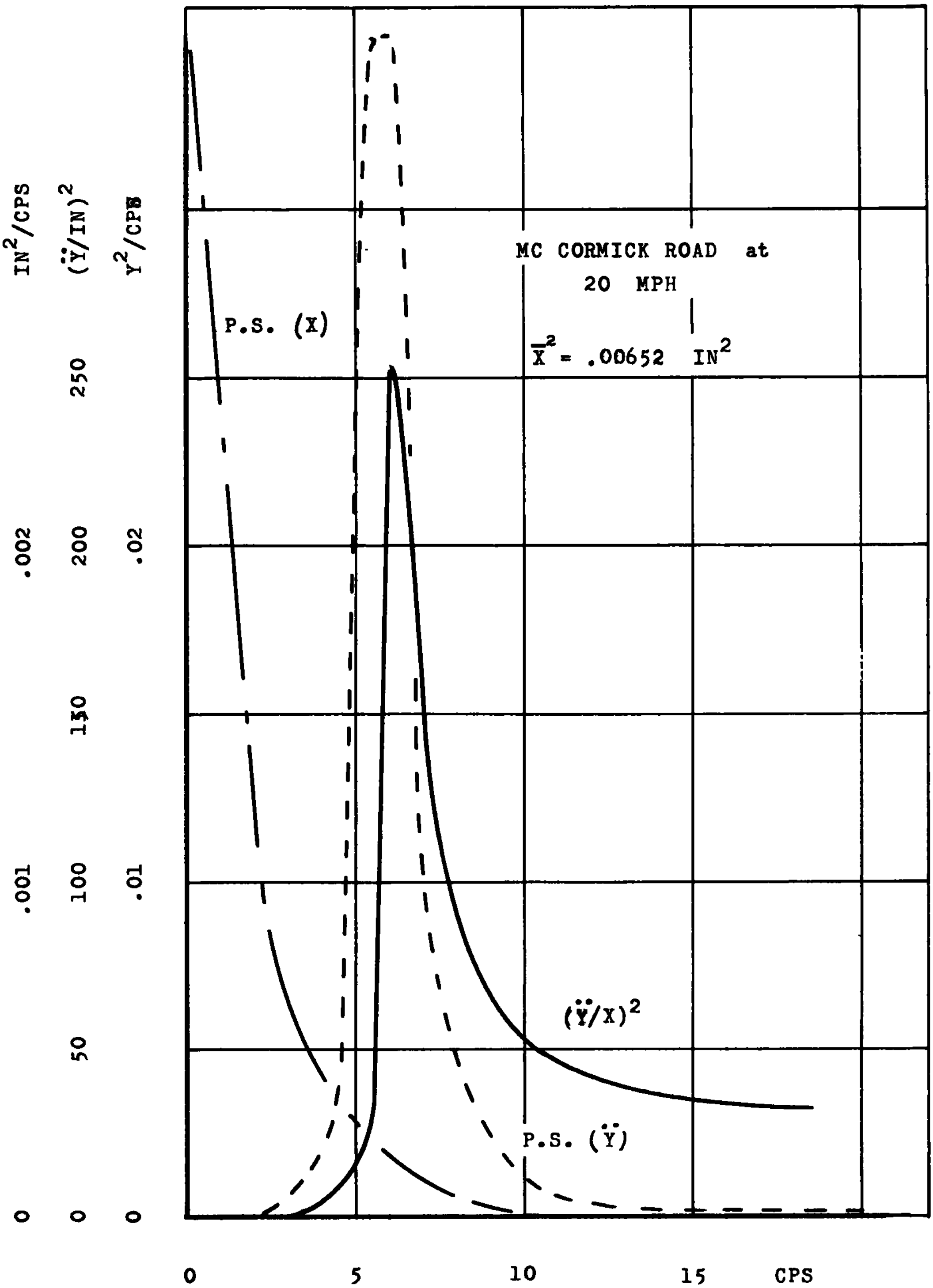

Figure 3. Dynamic measurement of highway profile power spectrum.

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 vi-

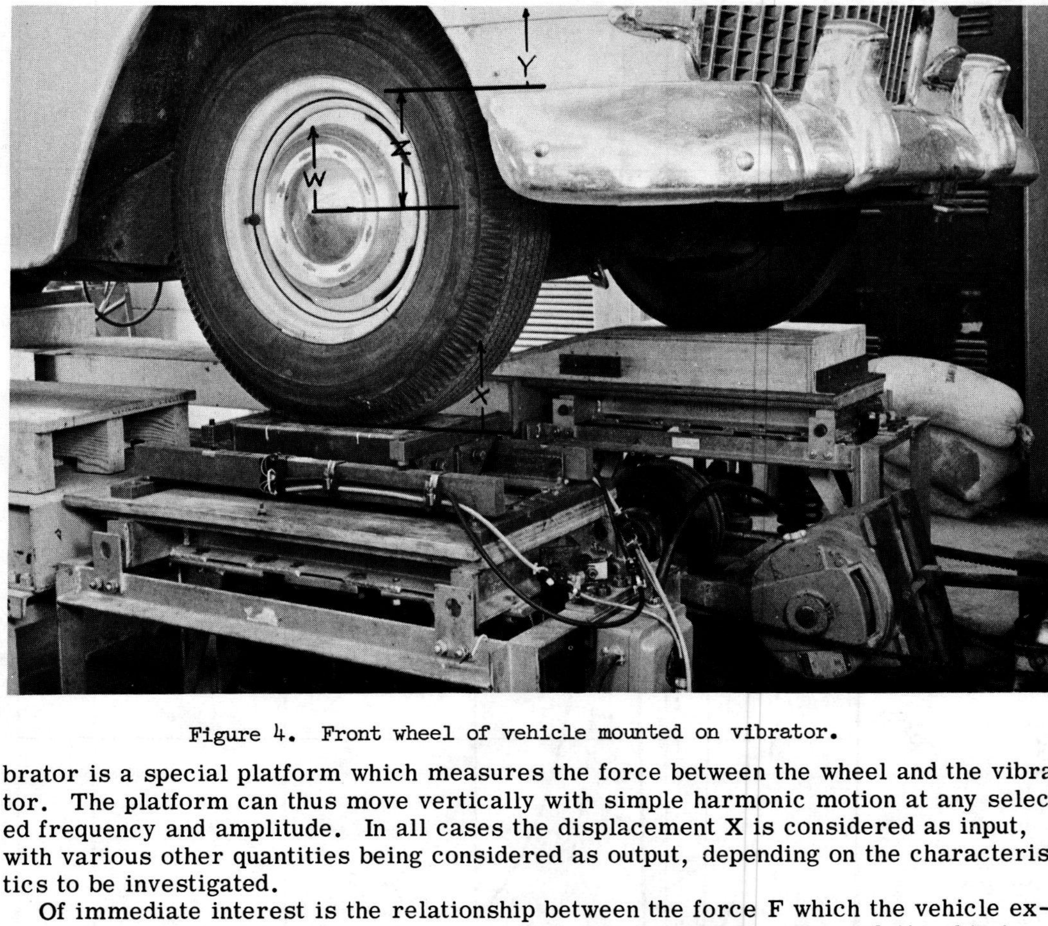

Figure 4. Front wheel of vehicle mounted on vibrator.

brator 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.

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.

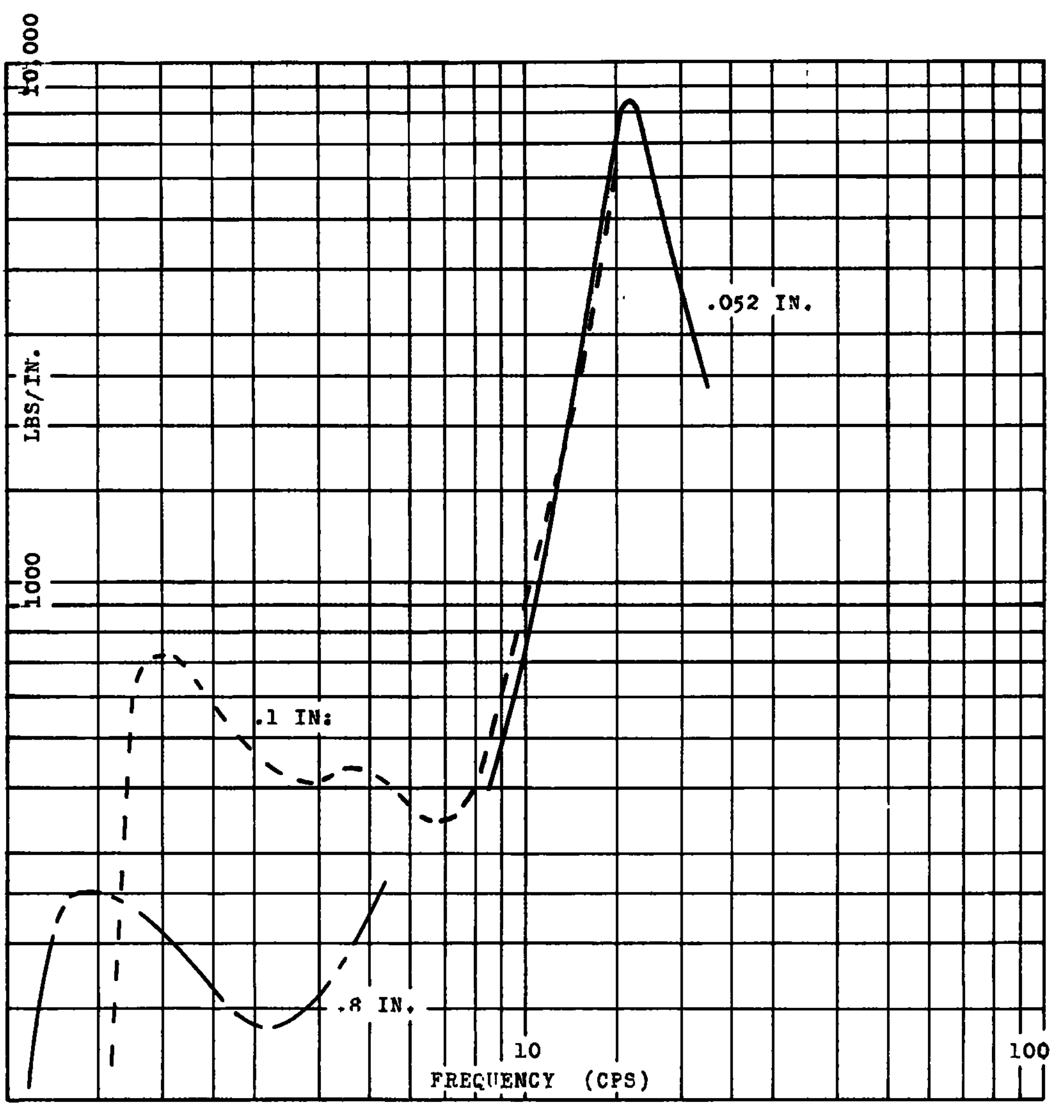

Figure 5. F/X versus frequency for 8-cylinder 1955 Chevrolet.

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.

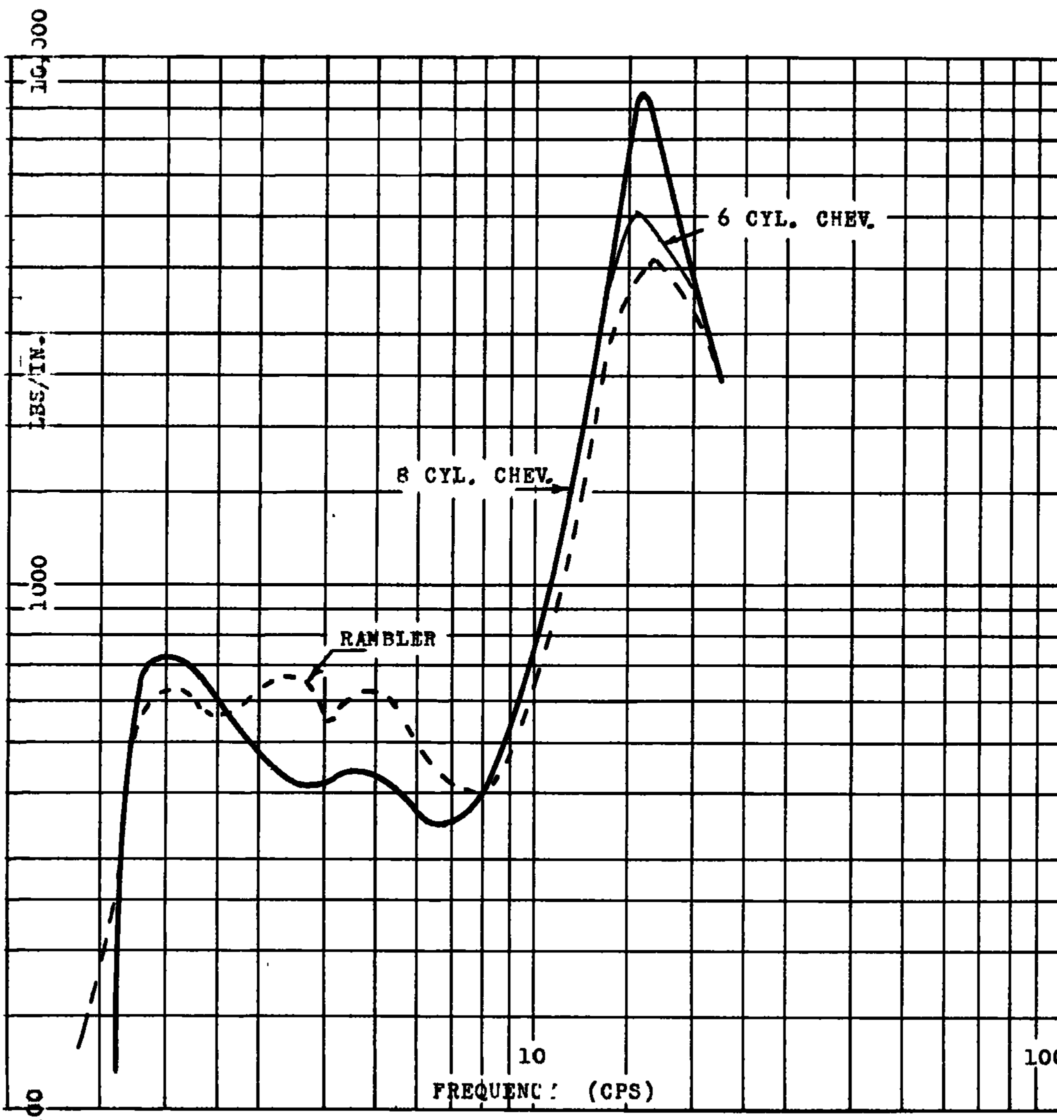

Figure 6. F/X versus frequency 0.1 in. (P-P).

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.

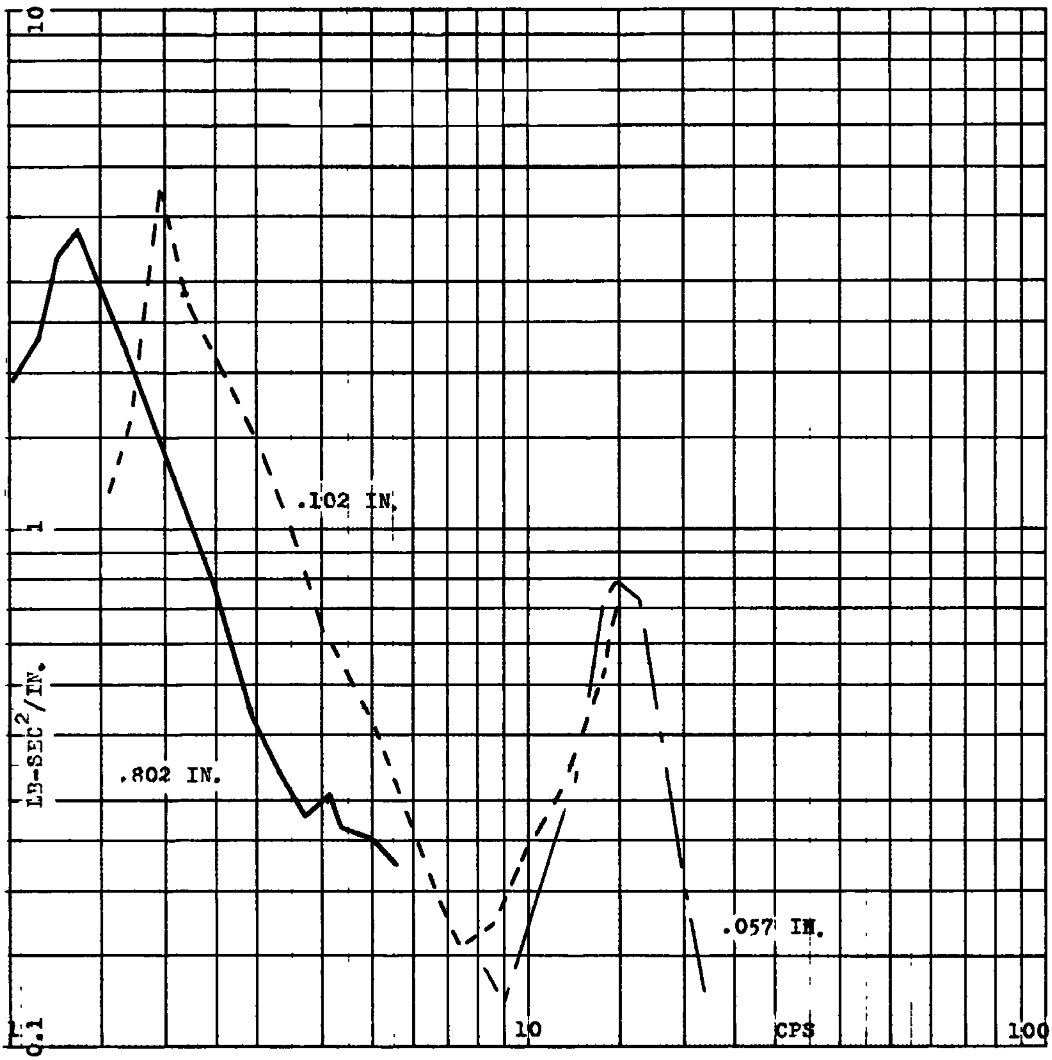

Figure 7. F/$\ddot{X}$ versus frequency for 8-cylinder 1955 Chevrolet.

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-

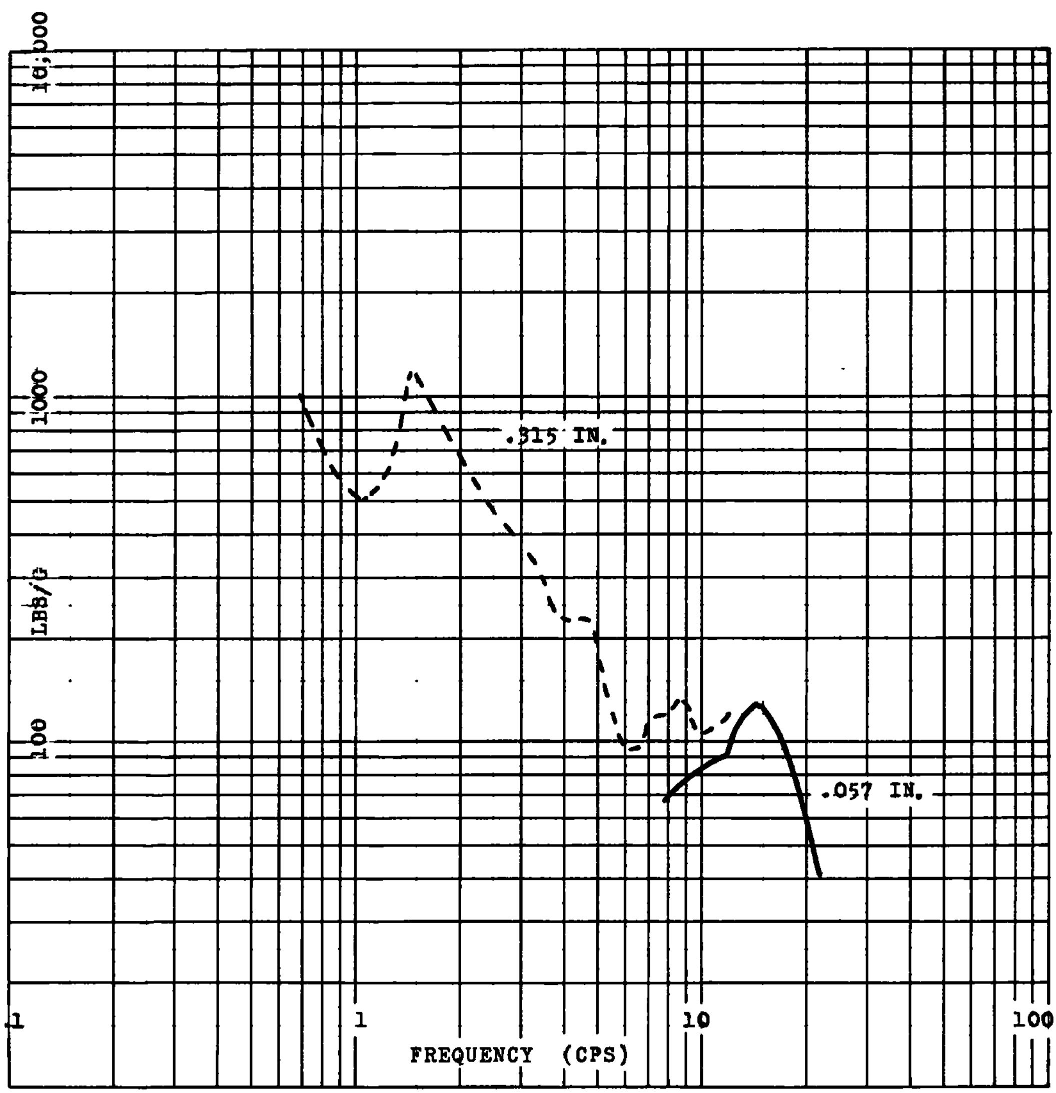

Figure 8. $F/\ddot{W}$ versus frequency for 8-cylinder 1955 Chevrolet.

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).

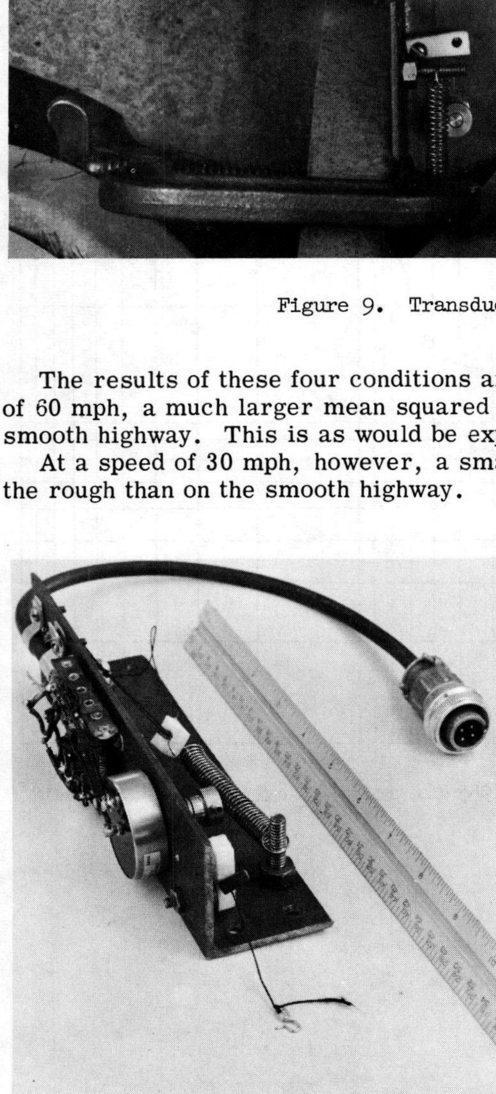

Figure 10. Transducer for measuring rela tive displacement between wheel and vehicle body.

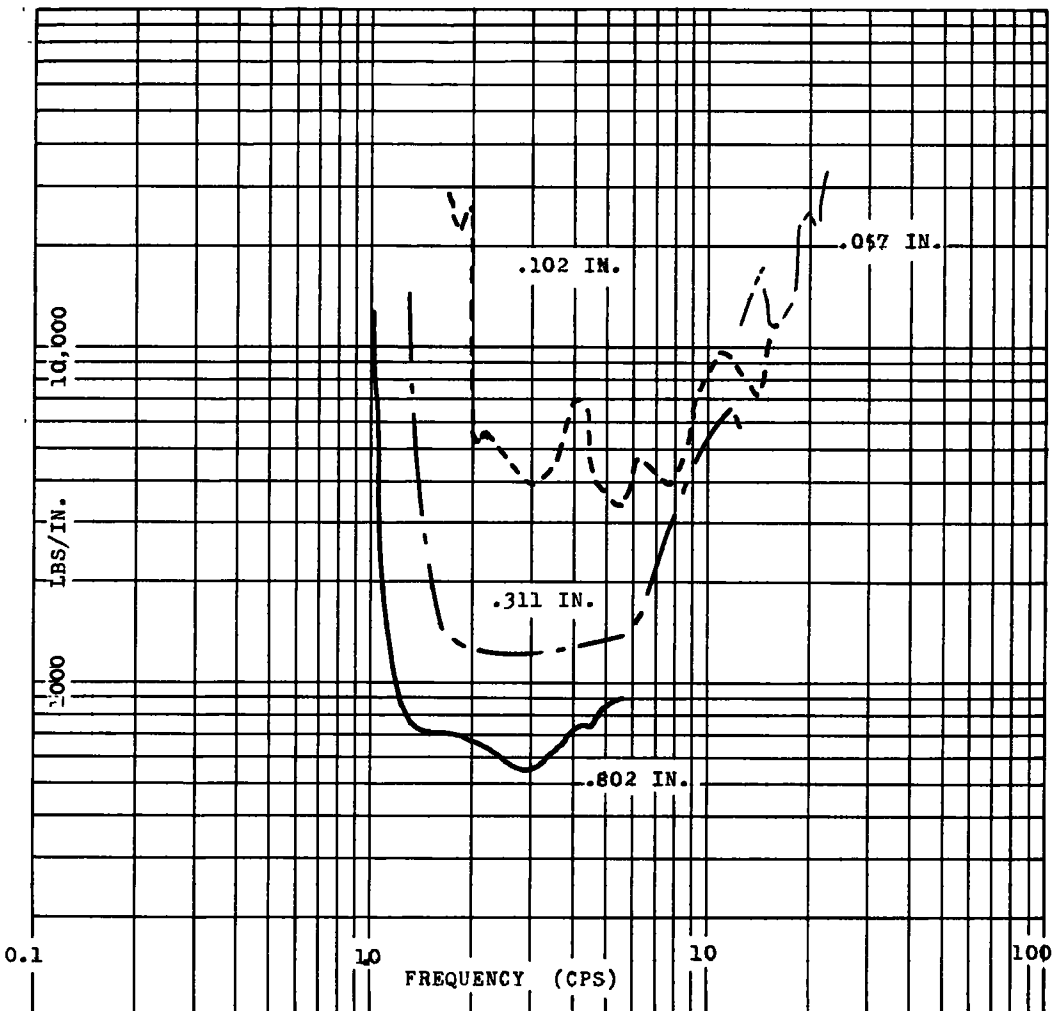

Figure 11. F/Z versus frequency 1955 Chevrolet— 8 cylinder.

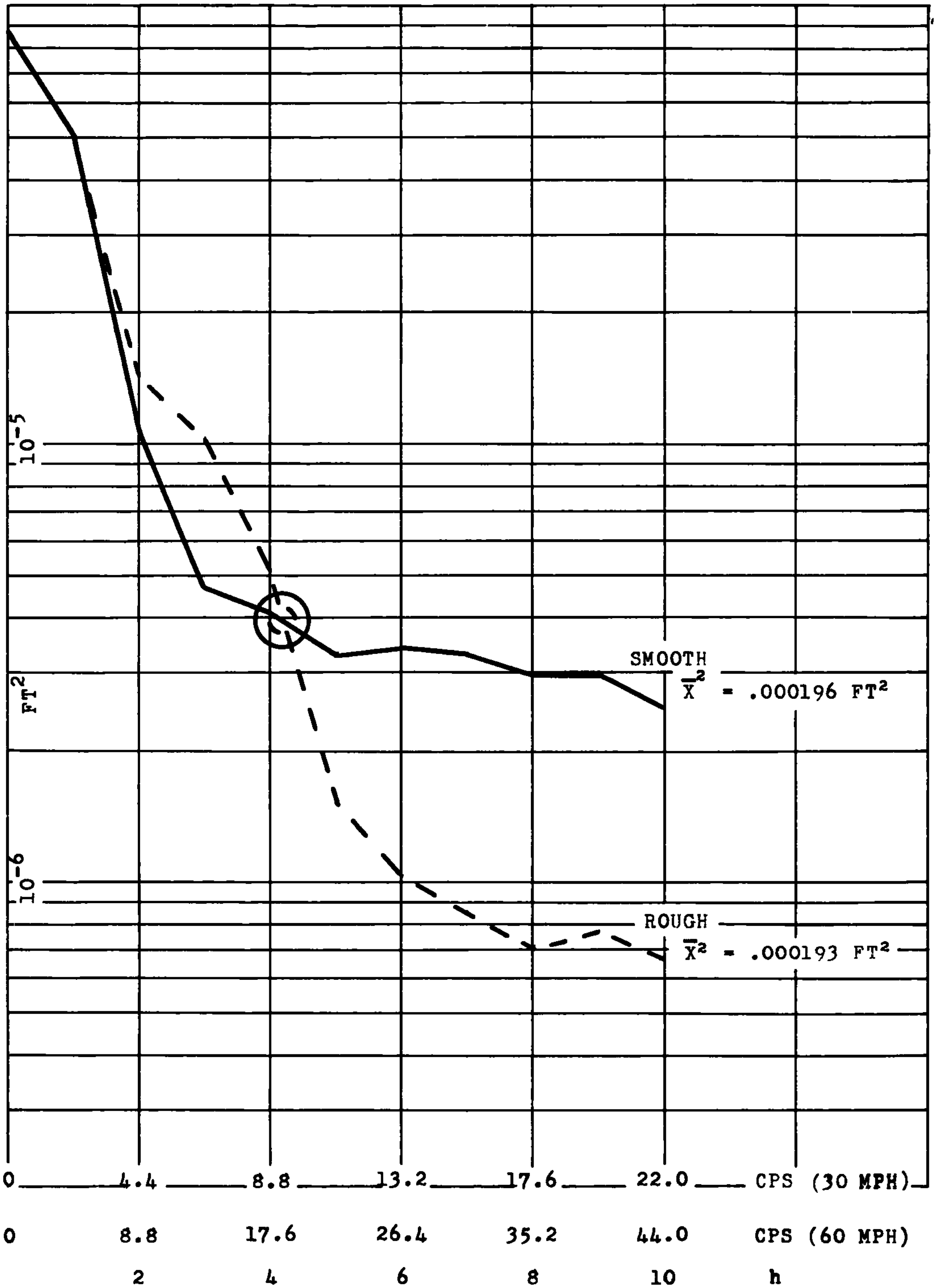

Figure 12. Modified power spectra of highway elevation data.

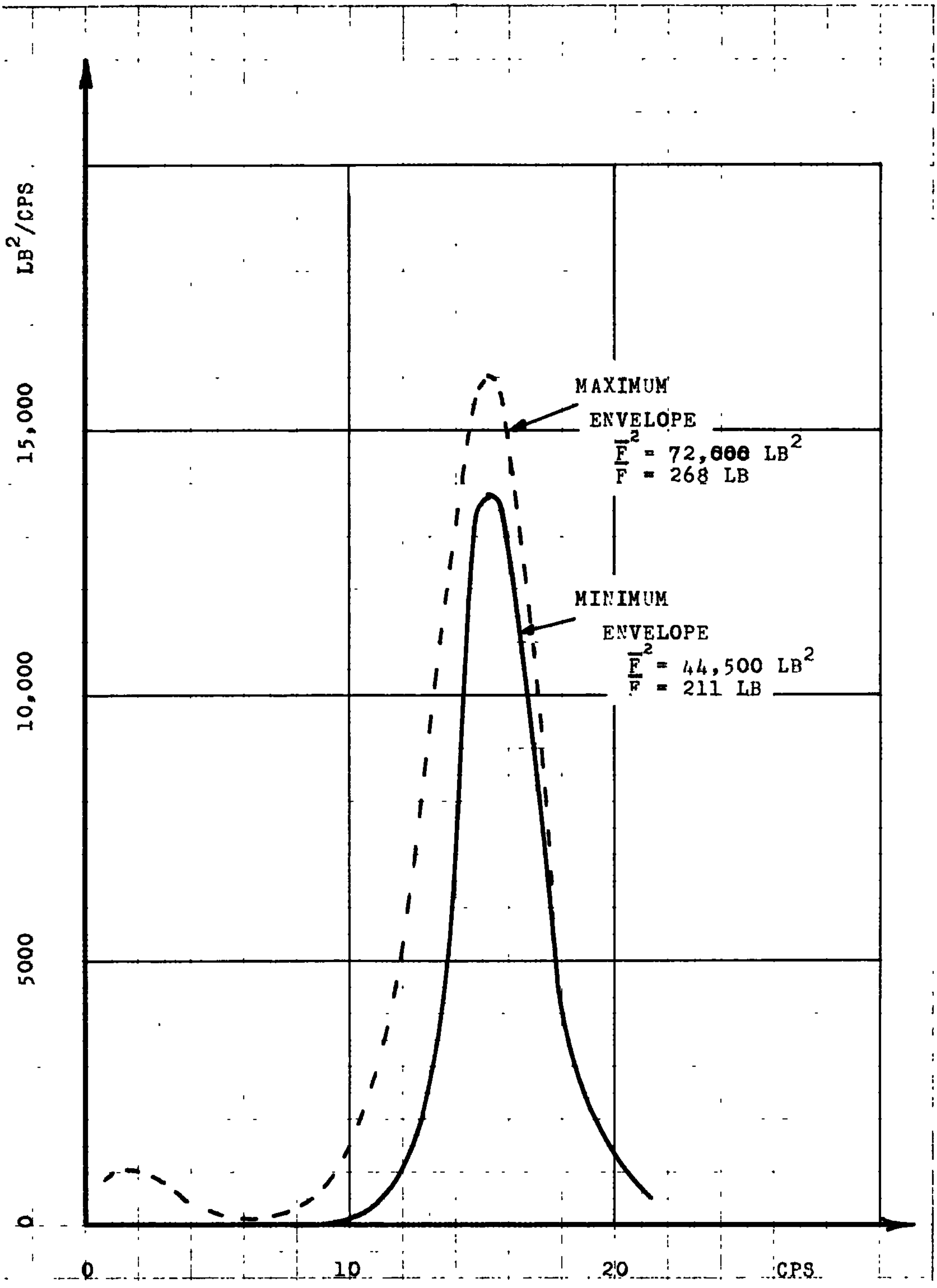

Figure 13. Force power spectra using maximum and minimum vehicle response characteristics (rough highway 60 mph).

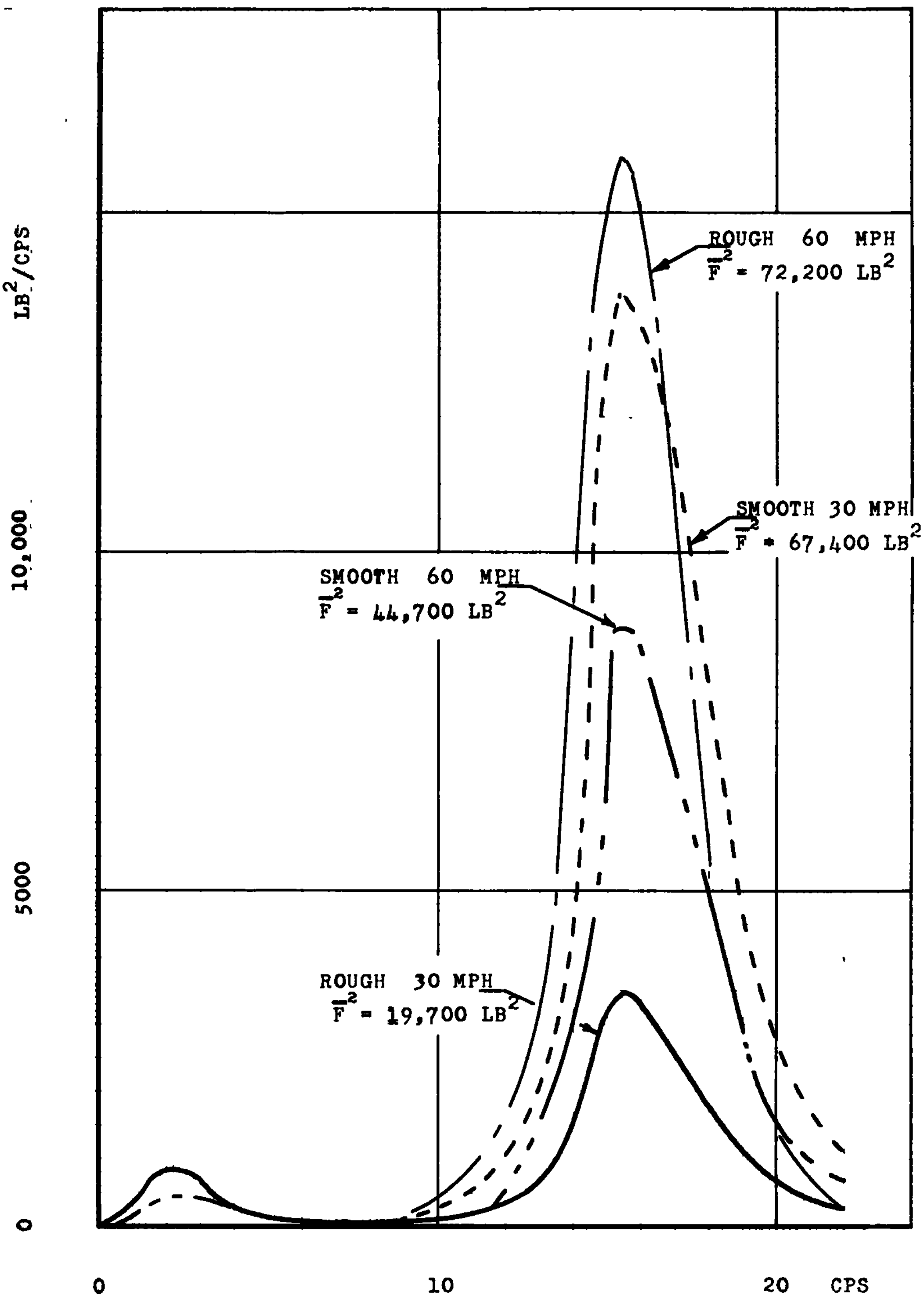

Figure 14. Power spectra of force on highway (using maximum vehicle response characteristics).

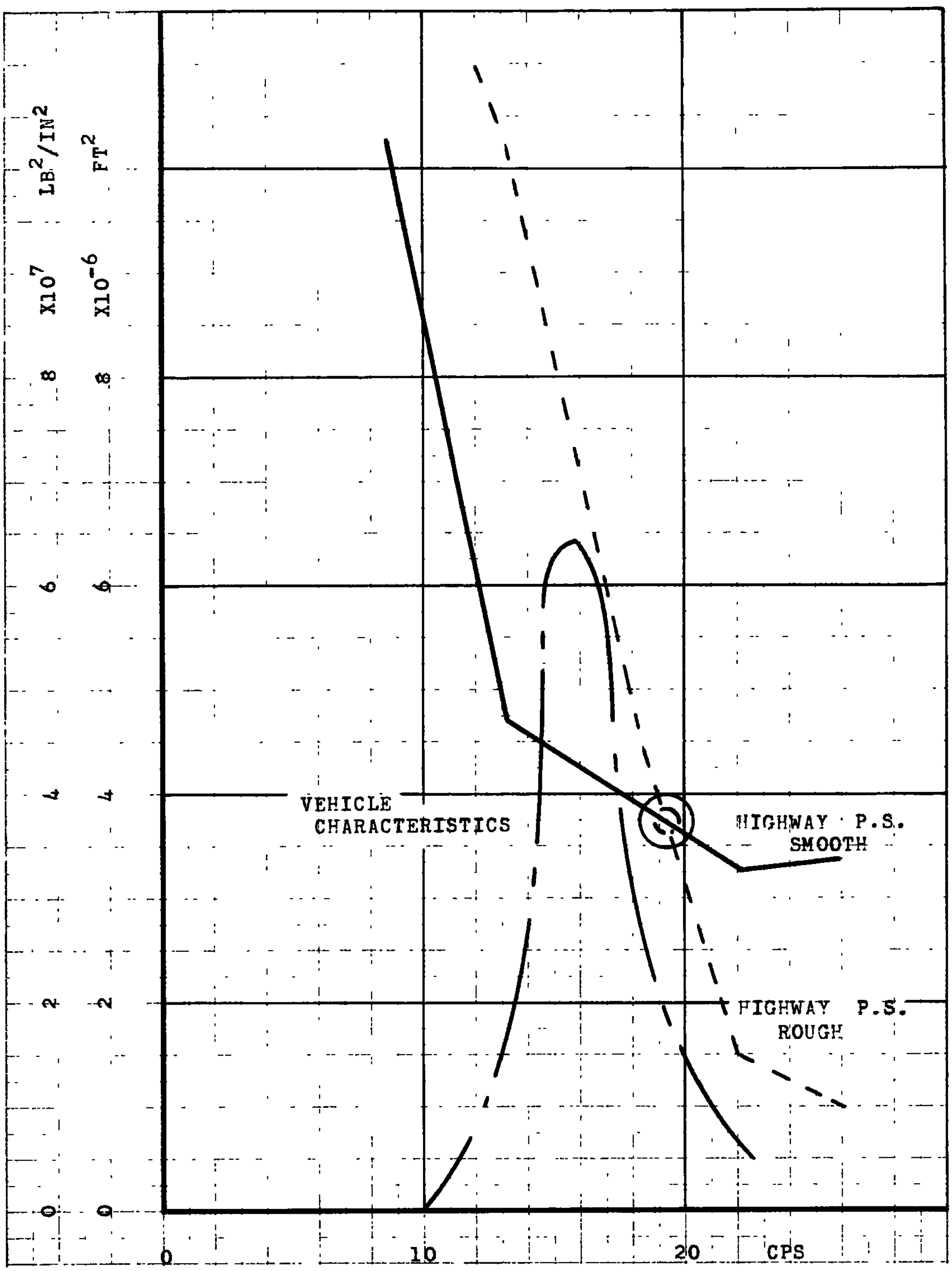

Figure 15. Relationship between vehicle characteristics and highway power spectra at 60 mph.

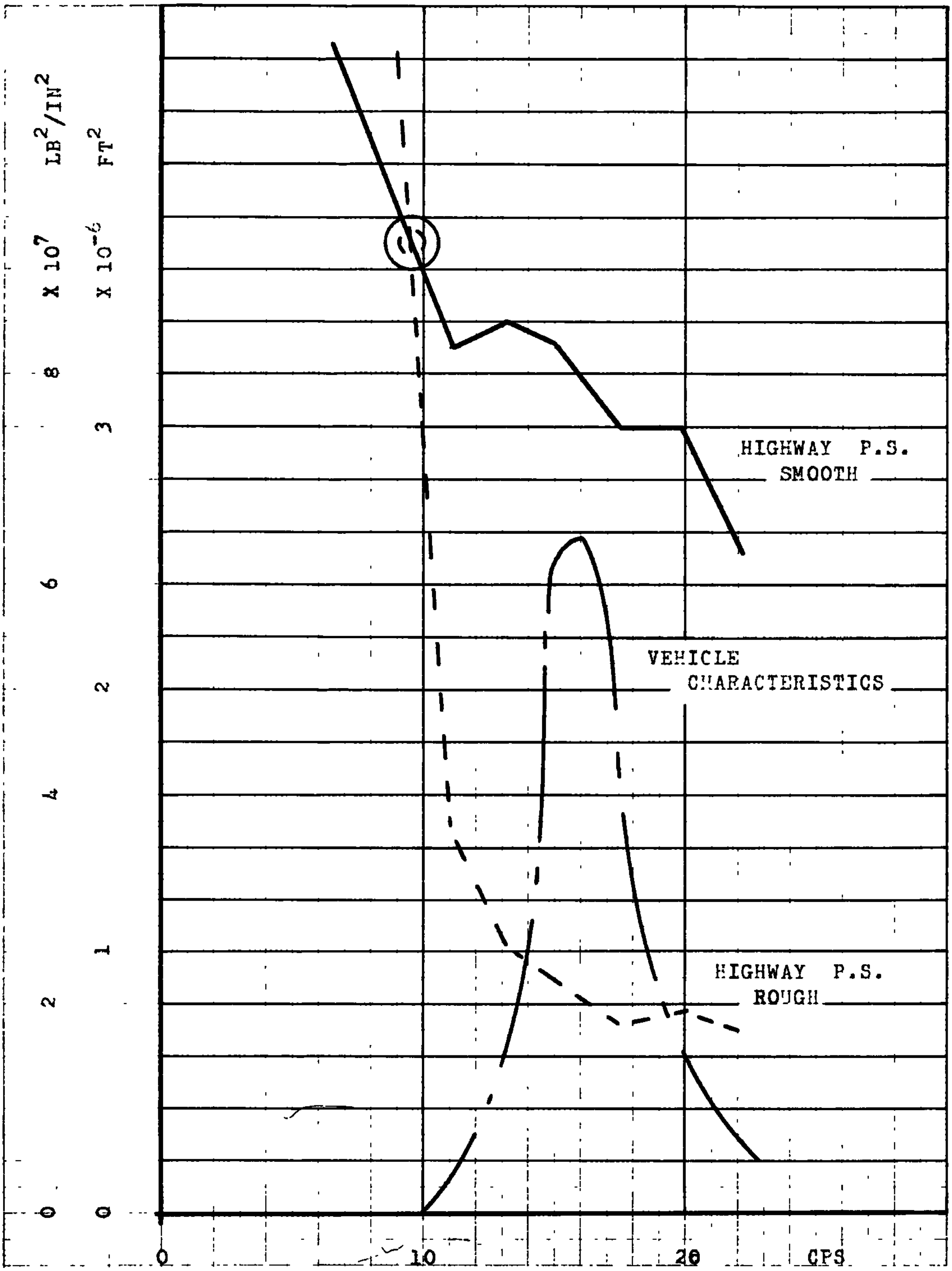

Figure 16. Relationship between vehicle characteristics and highway power spectra at 30 mph.

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

This report is based on the results of Research Contract No. CPR 11-5530, sponsored by the Bureau of Public Roads.

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.

The Pavement Serviceability-Performance Concept

W.N. CAREY, JR., Chief Engineer for Research, and
P.E. IRICK, Chief, Data Analysis Branch, Highway Research Board, AASHO Road Test

A system is described wherein the serviceability of pavements is rated subjectively by a panel made up of men selected to represent many important groups of highway users. Through multiple regression analysis a mathematical index is derived and validated through which pavement ratings can be satisfactorily estimated from objective measurements taken on the pavements. These serviceability indices (or the direct ratings) always refer to the conditions existing at the time the measurements (or ratings) are made. Performance of a pavement may then be determined by summarizing the serviceability record over a period of time.

The system, developed at the AASHO Road Test, has potential for wide application in the highway field, particularly in sufficiency rating, evaluation of design systems, and evaluation of paving materials and construction techniques through the provision of an objective means for evaluation of performance.

● THE RELATIVE PERFORMANCE of various pavements is their relative ability to serve traffic over a period of time. There have been no widely accepted definitions of performance that could be used in the evaluation of various pavements or that could be considered in the design of pavements. In fact, design systems in general use in highway departments do not include consideration of the level of performance desired. Design engineers vary widely in their concepts of desirable performance. By way of example, suppose that two designers were given the task of designing a pavement of certain materials for certain traffic and environment for 20 years. The first might consider his job to be properly done if not a single crack occurred in 20 years, whereas the second might be satisfied if the last truck that was able to get over the pavement made its trip 20 years from the date of construction. There is nothing in existing design manuals to suggest that either man was wrong. This is simply to demonstrate that any design system should include consideration of the level of serviceability to traffic that must be maintained over the life of the road. How long must it remain smooth and how smooth?

One popular design system involves determination of the thickness of slab required to hold certain computed stresses below a certain level. It is clear that cracks will occur if a pavement is overstressed, but nowhere can be found any reference to the effect of such cracks on the serviceability of the pavement. Engineers will agree that cracks are undesirable, and that they require maintenance, but the degree of undesirability seems to have been left dimensionless. It may be apparent that one pavement has performed its function of serving traffic better than another, but a rational answer to the question, "How much better?" has not been available.

To provide dimensions for the term "performance" a system has been devised that is rational and free from the likelihood of bias due to the strong personal opinions of groups or individuals. It is easily conceivable that such a system could be adopted by all departments, thus providing for the first time a national standard system for rating highways and pavements.

Before discussing the derivation and a particular application of the pavement serviceability-performance system, it is necessary to set down some fundamental assumptions upon which the system is based.

1. There is a statement attributed to D.C. Greer, State Highway Engineer of Texas, that "highways are for the comfort and convenience of the traveling public." A reasonable inference from this simple statement is that the only valid reason for any road or highway is to serve the highway users. Another definitive opinion is that "a good highway is one that is safe and smooth."

2. The opinion of a user as to how he is being served by a highway is by-and-large subjective. There is no instrument that can be plugged into a highway to tell in objective units how well it is serving the users. The measurement of damage to goods attributed to rough roads may provide an exception to this rule (but one of minor importance), as a road rough enough to damage properly packed and properly suspended goods would be classed subjectively so low by all users that little could be gained by an objective measure.

3. There are, however, characteristics of highways that can be measured objectively which, when properly weighted and combined, are in fact related to the users subjective evaluation of the ability of the highway to serve him.

4. The serviceability of a given highway may be expressed by the mean evaluation given it by all highway users. There are honest differences of opinion, even among experts making subjective evaluations of almost anything. Thus, there are differences of opinion as to which automobile in a given price range is best; differences among judges of a beauty contest; differences as to which bank, broker, grocery store, or bar to patronize; etc. Opinion as to the serviceability of highways is no exception. Economic considerations alone cannot explain these differences.

Thus, in order for normal differences of opinion to be allowed with the smallest average error for each individual highway user, serviceability, as previously stated, may be expressed in terms of the mean evaluation of all users.

5. Performance is assumed to be an over-all appraisal of the serviceability history of a pavement. Thus it is assumed that the performance of a pavement can be described if one can observe its serviceability from the time it was built up to the time its performance evaluation is desired.

AN EXAMPLE OF THE USE OF THE SERVICEABILITY-PERFORMANCE SYSTEM

In this section is described a typical example of the system which has been in actual field use at the AASHO Road Test. Definitions and detailed steps in the development and use of a Performance Index for evaluation of the Road Test pavements are included. It is emphasized that the case herein described is only one of many possible applications of the principles involved. It happened to relate to the performance of the pavements only, yet it would have been easy to extend the system to provide a measure of the sufficiency of the entire highway, including grade, alignment, access, condition of shoulders, drainage, etc., as well as characteristics of the pavement itself.

Purpose

The principle objective for the AASHO Road Test calls for significant relationships between performance under specified traffic and the design of the structure of certain pavements. To fulfill this objective, an adequate and unambiguous definition of pavement performance was required. For reasons previously mentioned none was available.

Special Considerations

In addition to the primary assumptions listed in the early paragraphs of this report, certain special considerations relating to the specific requirements of the Road Test were included.

Inasmuch as the project was designed to provide information relating to the pavement structure only, certain aspects of normal pavement serviceability were excluded from consideration, including surface friction, condition of shoulders, etc.

Test sections at the Road Test were as short as 100 ft, too short for a satisfactory subjective evaluation of their ability to serve traffic (most highway users consider a high-speed ride over a pavement necessary before they will rate it). Thus, objective measurements that could be made on the short sections had to be selected and used in such a way that pavements only 100 ft long could be evaluated as though they were much longer.

Definitions

To fulfill the requirements of the Road Test, rather ordinary terms were given specific definitions as follows:

Present Serviceability—the ability of a specific section of pavement to serve high-speed, high-volume, mixed (truck and automobile) traffic in its existing condition. (Note that the definition applies to the existing condition—that is, on the date of rating—not to the assumed condition the next day or at any future or past date.) Although this definition applies to the Road Test and may apply to any primary highway system, the system could easily be modified for use with city streets, farm roads, etc. Obviously, serviceability must be defined relative to the intended use of the road.

Individual Present Serviceability Rating—an independent rating by an individual of the present serviceability of a specific section of roadway made by marking the appropriate point on a scale on a special form (Fig. 1). This form also includes provision for the rater to indicate whether or not the pavement is acceptable as a primary highway. For the Road Test application, when rating highways other than those in the primary system, the rater was instructed to exclude from consideration all features not related to the pavement itself, such as right-of-way width, grade, alignment, shoulder and ditch condition, etc.

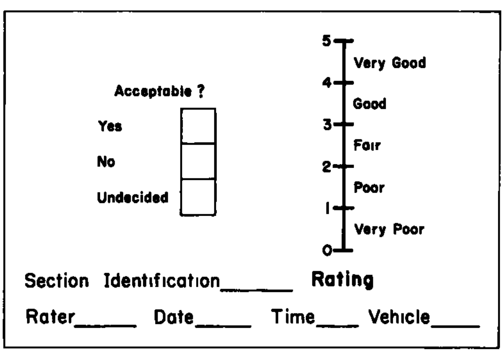

Figure 1. Individual present serviceability rating form.

Present Serviceability Rating (hereafter PSR)—the mean of the individual ratings made by the members of a specific panel of men selected for the purpose by the Highway Research Board. This panel was intended to represent all highway users. It included experienced men, long associated with highways, representing a wide variety of interests, such as highway administration, highway maintenance, a federal highway agency, highway materials supply (cement and asphalt), trucking, highway education, automotive manufacture, highway design, and highway research.

Present Serviceability Index (hereafter PSI)—a mathematical combination of values obtained from certain physical measurements of a large number of pavements so formulated as to predict the PSR for those pavements within prescribed limits.

Performance Index (hereafter PI)—a summary of PSI values over a period of time. There are many possible ways in which the summary value can be computed. Perhaps the simplest summary consists of the mean ordinate of the curve of PSI against time.

Steps in Formulation of a Present Serviceability Index

The following represents a minimum program for the establishment, derivation and validation of a PSI (or any similar index that may be considered for another purpose).

1. Establishment of Definitions—There must be clear understanding and agreement among all those involved in rating and in formulation and use of the index as to the precise meanings of the terms used (see preceding definitions for Road Test case). Exactly what is to be rated, what should be included, and what excluded from consideration?

2. Establishment of Rating Group or Panel—Because the system depends primarily on the subjective ratings of individuals, great care should be taken in the selection of the persons who will make up the rating group. Inasmuch as serviceability is here de-

fined to be the mean opinion of this group, it is important that the raters represent highway users. They should be selected from various segments of the users with divergent views and attitudes.

3. Orientation and Training the Rating Panel—An important step is that in which the members of the Panel are instructed in the part they are to play. They must clearly understand the pertinent definitions and the rules of the game. It has been found worthwhile to conduct practice rating sessions where the raters can discuss their ratings among themselves. Note that when they make their official ratings they must work independently, with no opportunity for discussion of the ratings until the entire session has been completed.

4. Selection of Pavements for Rating—Ratings are to be made of the serviceability of pavements; therefore, a wide range of serviceability should be represented among the pavements that are selected for rating. Moreover, represented among the sections selected should be pavements containing all of the various types and degrees of pavement distress that are likely to influence the serviceability of highways. Prior to a field rating session, engineers study the highway network in the area under consideration (say 200 mi or less in diameter) and pick sections of roadway such that a reasonable balance is obtained among sections, of which some are obviously in very good condition, some are good, some fair, some poor and some obviously very poor. The Road Test system was based on four rating sessions in three different states in which 138 sections of pavement were studied. About one-half were flexible pavement and one-half rigid. The Road Test Panel members agreed among themselves that the minimum desirable length of a pavement to be rated was 1,200 ft; however, in a few cases shorter sections were included. This length was sufficient so that the raters could ride over the section at high speed and not be influenced by the condition of pavement at either end of the section.

5. Field Rating—The members of the Panel are taken in small groups to the sections to be rated. They are permitted to ride over each section in a vehicle of their choice (usually one with which they are familiar), to walk the pavement and to examine it as they wish. Each rater works independently—there is no discussion among the raters. When each is satisfied as to his rating, he marks his rating card and turns it in to a staff representative. The group then moves on to the next section. Each group takes a different route in order to reduce the possibility of bias over the day (raters may rate differently in the afternoon than in the morning; therefore, the groups are scheduled so that some sections are rated by one or two groups in the morning and the same sections by the other groups in the afternoon). It has been found that, near metropolitan areas, sections with satisfactorily different characteristics can be found near enough together so that the raters can travel routes containing about 20 sections per day. When rating present serviceability of a pavement, raters have found it helpful to ask themselves: "How well would this road serve me if I were to drive my own car over roads just like it all day long today?" Here again, of course, serviceability is related to the intended use of the road (primary highway, city street, farm road, etc.).

6. Replication—It is necessary to determine the ability of the Panel to be consistent in its ratings. The Road Test Panel rated many sections twice, first on one day and again on another day near enough to the first so that the section did not change physically, yet remote enough so that all extraneous influences on the raters would be in effect. In general it might be expected that replicate ratings would differ more when separated by several months than when separated by only one day. For this reason it may be supposed that the replication differences observed in the Road Test Rating sessions are to some degree an underestimate of replication differences in a larger time reference frame. The difference between repeated ratings on the same section is a criterion for the adequacy of a present serviceability index derived from measurements.

7. Validation of Rating Panel—Because the Panel is intended to represent all highway users, it is necessary to test its ability to do so. To a limited extent such validation was obtained for the Road Test Panel by selecting other groups of users and having them rate some of the same sections that had been rated by the Panel. One such group consisted of two professional commercial truck drivers who made their ratings

based on the rides they obtained when driving their own fully-loaded tractor-semitrailer vehicles. Another group was made up of ordinary automobile drivers not professionally associated with highways. For the sections involved these studies indicated that the ratings given pavements by the Road Test Panel were quite similar to those that were given by the other user groups. Of course, if a greater number of sample groups had been studied, more positive statements could be made as to how well the Panel represents the universe of all users.

8. Physical Measurements—If it is practicable for the Panel to rate all roads in the area of interest often enough, no measurements need be taken. Analyses may be based on the PSR itself. Since it was not possible for the Panel to rate the Road Test sections (ratings were desired every two weeks), it was necessary to establish a PSI or index that would predict the Panel's ratings. To accomplish this, measurements of certain physical characteristics of the pavements were necessary. In order to determine which measurements might be most useful, the members of the Panel were asked to indicate on their rating cards which measureable features of the roadway influenced their ratings. This study made it apparent that present serviceability was a function primarily of longitudinal and transverse profile, with some likelihood that cracking, patching, and faulting would contribute. Thus, all of these characteristics were measured at each of the 138 sections in three states that were rated by the Panel. It should be noted that several other objective measurements could have been added to the list if other phenomena were permitted consideration by the established rules of the game. In this category might be skid resistance, noise under tires, shoulder and ditch conditions, etc.

Measurements fall rather naturally into two categories: those that describe surface deformation and those that describe surface deterioration. Of course, phenomena in the second category may or may not influence measurements in the first category. Measures of surface deformation will reflect the nature of longitudinal and transverse profiles—or may represent the response of a vehicle to the profile, as does the BPR roughometer. Supplemental profile characteristics, such as faulting, will ordinarily be measured. Present and past surface deterioration will be reflected through measures of cracking, spalling, potholing, patching, etc., and may include phenomena whose influence on present serviceability ratings range from negligible to appreciable.

9. Summaries of Measurements—There are many different ways to summarize longitudinal and transverse profiles. For example, longitudinal profile may be expressed as total deviation of the record from some baseline in inches per mile, number of bumps greater than some minimum, some combination of both of these, or by any number of other summary statistics involving variance of the record, power spectral density analysis, etc. Transverse profile may be summarized by mean rut depth, variance of transverse profile, etc. The variance of rut depth along the wheel paths is also a useful statistic. Cracking occurs in different classes of severity, as do other measures of surface deterioration, and measurements in any of these classes may be expressed in one unit or another.

10. Derivation of a Present Serviceability Index—After having obtained PSR's and measurement summaries for a selection of pavements, the final step is to combine the measurement variables into a formula that "gives back" or predicts the PSR's to a satisfactory approximation. Part of this procedure should consist in determining which of the measurement summaries have the most predictive value and which are negligible after the critical measurements are taken into account. The technique of multiple linear regression analysis may be used to arrive at the formula, or index, as well as to decide which measurements may be neglected. For example, it can turn out that a longitudinal profile summary will be sensitive to faulting so that faulting measurements need not appear in the index formula whenever this profile measure is included.

The decisions as to which terms should be in the serviceability formula and which terms should be neglected may be made by comparing the lack of success with which the formula "gives back" the ratings with a preselected criterion for closeness of fit—such as the Panel's replication error (see previous discussion, item 6). That is, there is no justification for a formula that can predict a particular set of ratings with greater precision than the demonstrated ability of the Panel to give the same ratings to the same pavements twice. Thus the multiple linear regression analysis will yield a formula that will combine certain objective measurements to produce estimates of the Panel's ratings to an average accuracy no greater than the Panels's average ability to repeat itself.

Performance

In the preceding section the steps in the formulation of a present serviceability index were delineated. The index is computed from a formula containing terms related to objective measurements that may be made on any section of highway at any time. At the AASHO Road Test these measurements are made and the index computed for each test section every two weeks. Thus a serviceability-time history is available for each test section beginning with the time test traffic operation was started. As can be seen from Figure 1, the present serviceability values range in numerical value from zero to five.

In order to fulfill the first Road Test objective, to find relationships between performance and pavement structure design, some summarization of the serviceability-time history is implied. Performance may be said to be related to the ability of the pavement to serve traffic over a period of time. A pavement with a low serviceability during much of its life would not have performed its function of serving traffic as well as one that had high serviceability during most of its life, even if both ultimately reached the same state of repair.

The Road Test staff studied many alternate techniques for summarizing the serviceability-time history into an index of performance. The performance index chosen consisted of the mean ordinate of the serviceability-time history record. The choice of mean ordinate of serviceability-time record was largely due to its simplicity and the ease with which it can be understood by those interested in the Road Test findings.

ROAD TEST INDEXES

The techniques previously described were used in the derivation of present serviceability indexes for the AASHO Road Test. This section of the report includes tabulations of the actual data obtained in the field rating sessions by the Road Test Rating Panel and data obtained from the objective measurements of the pavements rated. Relationships among the ratings and various measurements are shown graphically and the results of the regression analyses in which the serviceability indexes were derived are given.

The matter of precision required of an index and precision attained in the Road Test indexes is discussed. Alternate measurement systems are mentioned for the benefit of agencies not able to equip themselves with elaborate instruments.

Ratings for Selected Pavements

After the establishment of concepts, ground rules, and rating forms for present serviceability ratings, the AASHO Road Test Performance Rating Panel rated 19 pavement sections near Ottawa, Ill., on April 15-18, 1958; 40 sections near St. Paul-Minneapolis on August 14-16, 1958; 40 sections near Indianapolis on May 21-23, 1959; and 39 sections on and near the Road Test in Illinois on January 20-22, 1960. Ten Illinois sections, 20 Minnesota sections, 20 Indiana sections and 24 sections on and near the Road Test were flexible pavements, whereas all remaining sections were rigid pavements. Each section was 1,200 ft long except those on the Road Test, which averaged 215 ft. With the generous cooperation of the respective state highway departments, sections at each location were selected to represent a wide range of pavement conditions.

Coincident with the rating session, Road Test crews and instruments were used to obtain condition surveys and profile measurements for each section. Summaries for all evaluations of the 74 flexible pavement sections are shown in Table 1; corresponding evaluations for the first 49 rigid pavements are given in Table 2.

The principal objective of the fourth rating session was to rate flexible pavement sections that included rather severe degrees of rutting—a phenomenon not included in the previous sets of flexible pavement. A second objective of the fourth session was to rate a small number of rigid pavements only for the purpose of checking present serv-

TABLE 2

DATA FOR 49 SELECTED RIGID PAVEMENTS

Pvt Loc.	Sect Code	Present Serviceability Ratings: AASHO Panel: 1st PSR	AASHO Panel: Replic diff in PSR	AASHO Panel: std. dev of PSR among raters	Truck Drivrs PSR	Canad. Raters PSR	Acceptability Opinions: AASHO Panel Fraction: Yes	AASHO Panel Fraction: No	Longitudinal Roughness: $\overline{SV}$ Mean Slope Var'nce in wh'pth (x10⁶)	$\overline{AR}$ Mean AASHO Rom'tr @ 10 mh (in./mi)	F Fault'g in Wh'pth in in/1000'	Cracking: C Class 2 and Sealed Cracks ft/1000 ft²	Spalling: ft²/1000ft² for areas > 3" Dia	Patching: P Patch'd Area ft²/1000ft²	Transformations: Log (1+$\overline{SV}$)	Log $\overline{AR}$	Sq. root C+P	PSI 211 Pres Serv Index	Resid. Diff Betw'n PSR & PSI
Ill.	R1	2.0	.2	.6	1.5		.0	.8	52.0		2	53	4	8	1.72		7.8	1.7	.3
	R2	4.2		.3	4.5		1.0	.0	6.5		0	4	0	0	.88		2.0	3.7	.5
	R3	2.6	.3	.6	2.5		.2	.5	22.2		0	42	0	11	1.37		7.3	2.3	.3
	R4	2.3	.2	.3	2.5		.0	.5	26.2		7	46	0	7	1.44		7.3	2.2	.1
	R5	1.2		.4	1.5		.0	1.0	47.8		1	102	0	28	1.69		11.4	1.4	.2
	R6	2.8	.1	.6	2.5	3.0	.2	.1	25.5		3	15	2	1	1.42		4.0	2.5	.3
	R7	4.4	.0	.3	4.5	4.4	1.0	.0	3.2		0	0	0	0	.63		0	4.3	.1
	R8	1.1	.2	.4			.0	1.0	50.8		3	65	11	5	1.71		8.4	1.6	.5
	R9	0.9	.0	.3			.0	1.0	76.8		1	74	19	85	1.89		12.6	0.9	.0
Minn.	201	1.3	.1	.6			.0	1.0	43.3		1	40	60	59	1.65		10.0	1.6	.3
	202	1.8		.5			.0	1.0	24.2		0	23	4	66	1.40		9.4	2.1	.3
	203	2.1	.3	.6			.1	.9	24.7		0	47	1	41	1.41		9.4	2.1	.0
	204	4.1		.3			1.0	.0	2.4		0	4	0	0	.54		2.0	4.3	.2
	205	3.8	.3	.4			1.0	.0	4.0		0	2	0	0	.70		1.4	4.0	.2
	206	3.0	.0	.5			.6	.2	7.8		1	14	0	1	.95		3.9	3.4	.4
	207	3.0		.6			.4	.2	7.5		1	22	0	0	.93		4.7	3.3	.3
	208	2.9	.1	.6			.3	.4	9.7		0	14	0	0	1.03		3.7	3.2	.3
	209	2.5		.4			.1	.6	17.6		0	34	0	0	1.27		5.8	2.6	.1
	210	1.4		.5			.0	1.0	59.2		0	16	500	12	1.78		5.3	1.8	.4
	211	4.3		.2			1.0	0	3.0		0	0	0	0	.60		0	4.3	.0
	212	4.3	.0	.4			1.0	0	4.0		0	0	0	0	.70		0	4.1	.2
	213	3.7		.4			1.0	0	5.3		0	0	0	0	.80		0	4.0	.3
	214	3.6	.3	.5			1.0	0	4.4		0	0	0	0	.73		0	4.1	.5
	215	3.9		.4			1.0	0	5.3		0	0	0	0	.80		0	4.0	.1
	216	3.9	.0	.6			1.0	0	6.3		0	0	0	0	.87		0	3.8	.1
	217	1.3	.0	.4			.0	1.0	32.3		0	76	2	1	1.52		8.8	1.9	.6
	218	1.2		.4			.0	1.0	27.8		10	64	0	0	1.46		8.0	2.1	.9
	219	2.2		.6			.0	.9	25.6		4	97	0	1	1.42		9.9	2.0	.2
	220	4.4	.0	.3			1.0	.0	4.0		0	0	0	0	.70		0	4.1	.3
Ind.	401	4.0		.3			1.0	0	6.6	134	2	0	1	0	.88	2.13	0	3.8	.2
	402	3.8		.4			1.0	0	6.6	126	4	11	1	0	.88	2.10	3.3	3.5	.3
	403	3.6		.6			.9	0	6.8	113	1	2	4	0	.89	2.06	1.4	3.7	.1
	404	3.2		.6			.6	.2	9.8	131	4	1	1	2	1.03	2.12	1.7	3.4	.2
	405	2.6		.6			.3	.5	14.6	167	5	72	13	0	1.19	2.22	8.5	2.5	.1
	406	2.8		.6			.4	.3	10.4	151	5	70	10	1	1.06	2.18	8.4	2.8	.0
	407	1.8	.5	.6			.1	.8	49.4	268	1	41	4	29	1.70	2.43	8.4	1.6	.2
	408	1.8		.6			.1	.8	54.5	245	2	42	8	37	1.74	2.39	8.9	1.5	.3
	409	2.1		.6			.2	.8	36.6	276	1	50	7	29	1.58	2.44	8.9	1.8	.3
	410	2.2		.5			.2	.8	25.1	230	2	86	5	33	1.42	2.36	10.9	1.9	.3
	411	1.8		.5			.1	.8	45.4	286	0	40	6	65	1.67	2.46	10.2	1.5	.3
	412	2.7		.6			.4	.4	9.9	147	5	81	3	5	1.04	2.17	9.3	2.7	.0
	413	4.2		.4			1.0	.0	6.1	106	1	0	1	0	.85	2.03	0	3.9	.3
	414	4.3		.4			1.0	.0	5.2	112	1	0	0	0	.79	2.05	0	4.0	.3
	415	4.3		.4			1.0	.0	7.1	132	1	0	0	0	.91	2.12	0	3.8	.5
	416	1.2	.3	.6			.0	.9	81.9	338	8	54	1	219	1.92	2.53	16.5	0.5	.7
	417	2.2	.0	.6			.1	.7	32.2	252	18	36	1	0	1.52	2.40	6.0	2.2	.0
	418	4.3	.1	.3			1.0	.0	4.6	113	1	0	0	0	.75	2.06	0	4.1	.2
	419	2.8	.0	.7			.5	.3	12.6	126	2	5	2	13	1.13	2.10	4.2	3.0	.2
	420	2.7	.1	.4			.1	.3	17.8	137	2	5	7	16	1.27	2.14	4.6	2.7	.0
Sum		138.6	3.1												58.23		254.3	138.6*	12.5
Mean		2.83	.13												1.19		5.19	2.83*	.26
Sum of Square		57.92													7.55		905.70	53.08*	4.84*
Sum of Products with PSR															-19.70		-206.53		
Sum of Products with Log (1+$\overline{SV}$)																	71.7		

*Obtained from Unrounded Calculations

$$PSI\ 211 = 5.41 - 1.80 \log(1+\overline{SV}) - .09\sqrt{C + P}$$

iceability indexes derived from the first 49 sections. For these reasons, flexible pavements from all four sessions appear in Table 1, but Table 2 includes only rigid pavement sections from the first three sessions.

Present serviceability ratings given in Col. 3, Tables 1 and 2, are mean values for individual ratings given by the Road Test Panel. In general, each mean represents about ten individual ratings. It may be noted that for both pavement types the PSR values range from about 1.0 to 4.5, with nearly the same number of sections in the poor, fair, good, and very good categories. The grand mean PSR for all rated pavements was slightly less than 3.0 for both pavement types.

More than 40 of the sections were revisited by the Panel during the same rating session, and differences between first and second mean ratings are given in Col. 4, Tables 1 and 2. The replication differences ranged from 0 to 0.5, the mean difference being less than 0.2 for both flexible and rigid pavements. Col. 5, Tables 1 and 2, gives the standard deviation of individual PSR values for each section. These standard deviations are of the order 0.5, an indication that only about two or three individual ratings (out of ten) were farther than 0.5 rating points from the Panel mean PSR.

As mentioned earlier, certain of the Illinois sections were rated by two truck drivers, whose mean ratings are given in Col. 6. Col. 7 gives mean ratings given to selected Illinois sections by a group of about 20 Canadian raters. It can be seen that there is general agreement among the various rating groups.

The next two columns of Tables 1 and 2 represent summaries of the AASHO Panel response to the acceptability question. For a particular section the tables show what fraction of the Panel decided the present state of the pavement to be acceptable and what fraction decided the pavement to be unacceptable. By implication the remaining fraction of the Panel gave the undecided response.

Figures 2, 3, 4 and 5 show the connection between corresponding PSR values and acceptability opinions for the two types of pavement. Freehand curves indicate in Figures 2 and 3 that the 50th percentile for acceptability occurs when the PSR is in the neighborhood of 2.9, whereas the 50th percentile for unacceptability corresponds roughly to a PSR of 2.5, as shown in Figures 4 and 5.

Measurements for Selected Pavements

Following the acceptability opinion, Tables 1 and 2 give summary values for measurements made on the selected pavements. Measurements are shown in three categories—those that describe longitudinal and transverse roughness, those that summarize surface cracking and, finally, a measurement of the patched area found in the section.

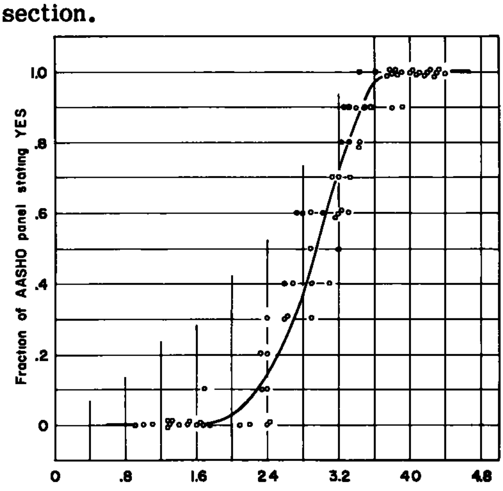

Figure 2. Acceptability vs present serviceability rating; 74 flexible pavements.

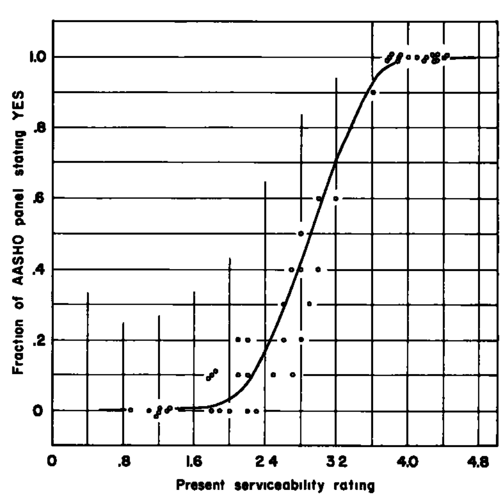

Figure 3. Acceptability vs present serviceability rating; 49 rigid pavements.

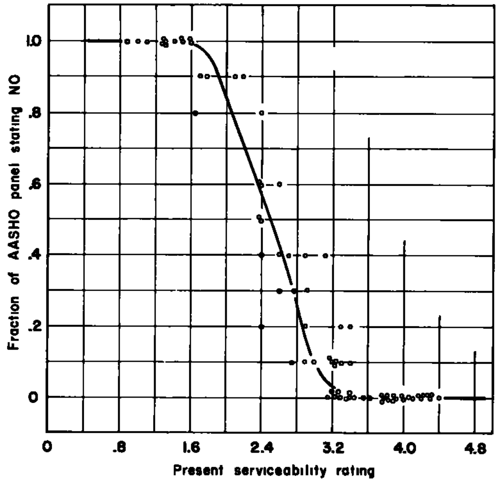

Figure 4. Unacceptability vs present serviceability rating; 74 flexible pavements.

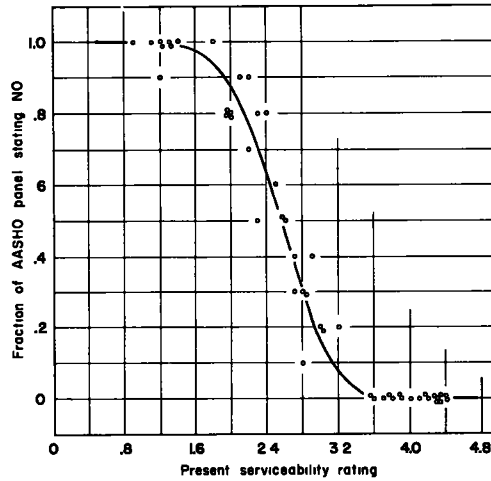

Figure 5. Unacceptability vs present serviceability rating; 49 rigid pavements.

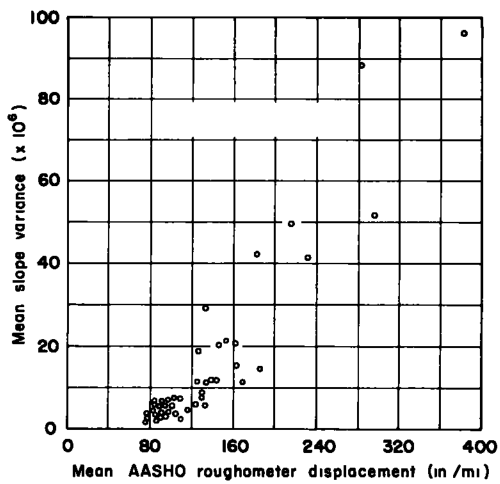

Figure 6. Slope variance vs AASHO roughometer displacement; 44 flexible pavements.

The symbol $\overline{SV}$ is used for the summary statistic of wheelpath roughness as measured by the Road Test longitudinal profilometer. For each wheelpath the profilometer produces a continuous record of the pavement slope between points 9 in. apart. For a particular wheelpath, the slopes are sampled, generally at 1-ft intervals, over the length of the record. A variance[1] is calculated for the sample slopes in each wheelpath, then the two wheelpath slope variances are averaged to give $\overline{SV}$.

A Bureau of Public Roads road roughness indicator, or roughometer, has been adapted for use at the AASHO Road Test, but this development was not made until just prior to the Indiana rating session and still more developmental work has been done on the AASHO roughometer since the Indiana session. The AASHO roughometer has a modified output and is run at 10 mph, so roughometer values shown in Tables 1 and 2 are not those that would be obtained with the BPR roughometer at 20 mph. Nevertheless, roughometer values in inches per mile are given in the tables so that it may be noted that the roughometer values averaged for both wheelpaths, $\overline{AR}$, are correlated with the corresponding mean slope variances. Figures 6 and 7 show the extent of this correlation for the last two rating sessions.

One other instrument, a rut depth gage, was used to obtain profile characteristics of the flexible pavement sections. This gage is used to determine the differential elevation between the wheelpath and a line connecting two points each 2 ft away (trans-

[1]The variance of a set of N sample values, $Y_1, Y_2, \ldots, Y_N$ is defined to be the sum of all N squared deviations from the mean divided by N-1. Thus the variance of Y is $\sum (Y-\overline{Y})^2/(N-1)$, where $\overline{Y} = \sum Y/N$ is the sample mean.

versely) from the center of the wheelpath. Rut depth measurements were obtained at 20-ft intervals in both wheelpaths. Average rut depth values, $\overline{RD}$, for the flexible sections are given in Table 1, where it may be noted that the values range from 0 to nearly 1 in. Variances were calculated for the rut depths in each wheelpath, then the two wheelpath variances were averaged to give the $\overline{RDV}$ values given in Table 1. Figure 8 indicates the correlation between $\overline{SV}$ and $\overline{RDV}$ for the 74 flexible sections.

Profile information for rigid pavements included a measure of faulting in the wheelpaths. These measurements are given in

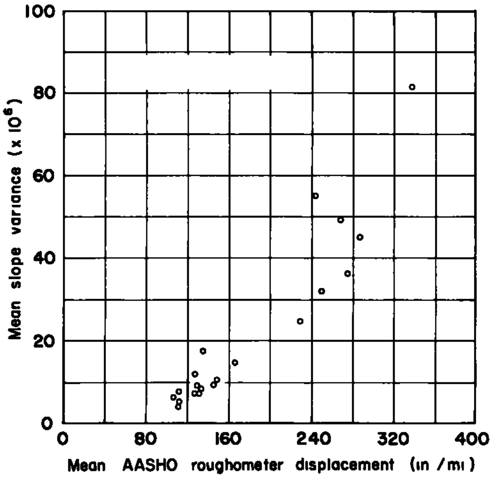

Figure 7. Slope variance vs AASHO roughometer displacement; 20 rigid pavements.

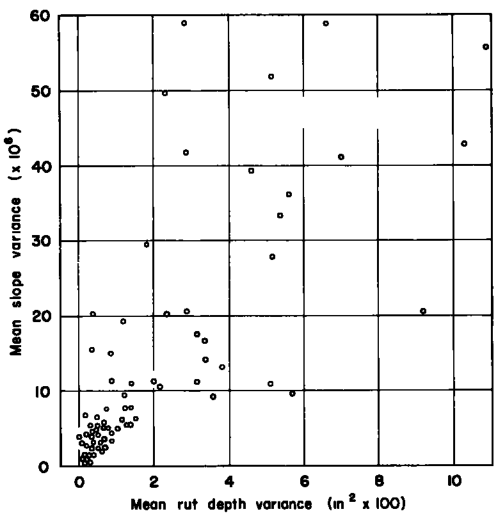

Figure 8. Rut depth variance vs slope variance; 74 flexible pavements.

Table 2, expressed in total inches of faulting (in wheelpaths only) per 1,000 ft of wheelpath.

The remaining measurements for flexible pavement sections are given in Table 1 under the headings of area affected by class 2 and class 3 cracking, length of transverse and longitudinal cracks, and patched area, where areas and lengths are expressed per 1,000 sq ft of pavement area. Corresponding measurements for rigid pavements are shown in Table 2 in terms of length of class 2 and sealed cracks, spalled area, and patched area. Lengths for rigid pavement cracks were determined by projecting the cracks both transversely and longitudinally, choosing the larger projection, then expressing the accumulated result in feet per 1,000 sq ft of pavement area. Only spalled areas having diameters greater than 3 in. were considered, and both spalling and patching are expressed in square feet per 1,000 sq ft of pavement area. Virtually any pair of measurements are intercorrelated to some degree, some more highly than others. Figures 9 and 10 indicate the degree to which $\overline{SV}$ is correlated with the sum of cracking and patching values. It is obvious that a stronger correlation exists in Figure 10 than in Figure 9. If either correlation were perfect, one or the other of the plotted variables would be redundant in an index of present serviceability.

The remaining columns in Tables 1 and 2 are connected with the development of present serviceability indices and will be discussed in succeeding paragraphs.

Hypothesis and Assumptions for Present Serviceability Index

It has been stated that one requirement for an index of present serviceability is that when pavement measurements are substituted into the index formula, the resulting values should be satisfactorily close to the corresponding present serviceability ratings. There are also advantages if the index formula can be relatively simple in form and if it depends on relatively few pavement characteristics that are readily measured.

Guided by the discussion of the AASHO Rating Panel as well as by results from early rating sessions, the general mathematical form of the present serviceability index was assumed to be

$$PSI = C + (A_1R_1 + A_2R_2 + \ldots) + (B_1D_1 + B_2D_2 + \ldots) \tag{1}$$

in which R_1, R_2,... are functions of profile roughness and D_1, D_2,... are functions of surface deterioration. The coefficients C, A_1, A_2,..., B_1, B_2,... may then be determined by a least squares regression analysis. It is expected, of course, that A_1, A_2, ..., B_1, B_2,... will have negative signs. To perform the analysis, the PSR for the jth of a set of sections is represented by

$$PSR_j = PSI_j + E_j \tag{2}$$

where E_j is a residual not explained by the functions used in the index. Minimizing the sum of squared residuals for all sections in the analysis leads to a set of simultaneous equations whose solutions are the required coefficients. The respective effect of adding or deleting terms in Eq. 1 will be to decrease or increase the sum of squared residuals. The change in residual sum of squares can be used to deduce the significance of adding or dropping terms from the index formula.

The model for PSI is linear in that if all functions save one are given a numerical value, then PSI versus the remaining function represents a straight line relationship.

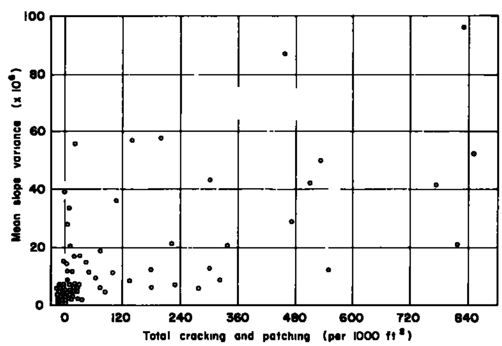

Figure 9. Mean slope variance vs cracking and patching; 74 flexible pavements.

for this reason it is desirable to choose functions R_1, R_2,..., D_1, D_2,..., that have linear graphs when plotted with PSR values. For example, logarithms, powers, etc., of the original measurements may be used as linearizing transformations.

It is important to note that a present serviceability index developed from observed ratings and measurements can only reflect the characteristics that were actually present in the observed pavements. And that for any particular characteristic, the index can only reflect the observed range of values for the characteristic. For example, if the selected pavements had no potholes, there is no objective way to infer how potholing would affect the present serviceability ratings, and the index cannot contain a function of potholing. As another example, if faulting in the selected pavements ranged from 0 to 10, there would be no way to infer the effect on PSR of pavements whose faulting was in the range 50 to 100. This same argument applies to the present serviceability ratings themselves. If PSR's for the selected pavements range only from 2.0 to 4.0, there is no way to infer

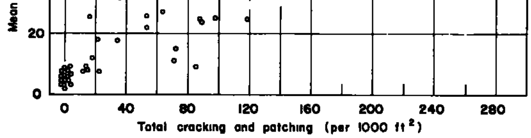

Figure 10. Mean slope variance vs crack- and patching; 49 rigid pavements.

what pavement characteristics must be like in order to produce a value of 1.0 or 5.0, say, except to extrapolate the index on the assumption that linearity holds over the full range of pavement characteristics.

For these reasons it has been stated that selected pavements should show all phenomena of interest, the complete range of interest for each phenomenon, and should be associated with PSR values that span the full range of interest.

Thus pavement selection amounts to the assumption that all interesting phenomena and ranges have been encompassed by the selections. Extrapolations of the index to measured values outside the range of those found in the selected pavements amounts to the assumption that the index formula remains linear in the region of extrapolation.

Choice of Functions for the Present Serviceability Index

Measurements from the Illinois and Minnesota sections were plotted in succession against corresponding PSR values to determine which measurements were essentially uncorrelated with PSR and to deduce the need for linearizing transformations. It was indicated that the mean wheelpath slope variance, $\overline{SV}$, was highly correlated with PSR, though curvilinearly. Figures 11 and 12 show the nature of this correlation for all selected pavements. From several alternatives, the transformation

$$R_1 = \log (1 + \overline{SV})$$

was selected as the first function of profile roughness to appear in the PSI model for both flexible and rigid pavements. The result of this transformation is shown in Figures 13 and 14, where PSR values are plotted against R_1 for flexible and rigid pavements, respectively.

For the flexible pavements, mean wheelpath rut depth, $\overline{RD}$, was included as a second profile measurement to appear in the PSI equation. The selected function of rut depth was

$$R_2 = \overline{RD}^2$$

The scatter diagram of PSR vs RD^2 is shown in Figure 15.

Although preliminary analyses considered the possibility of several functions of surface deterioration (say one function for each of the measured manifestations), it was

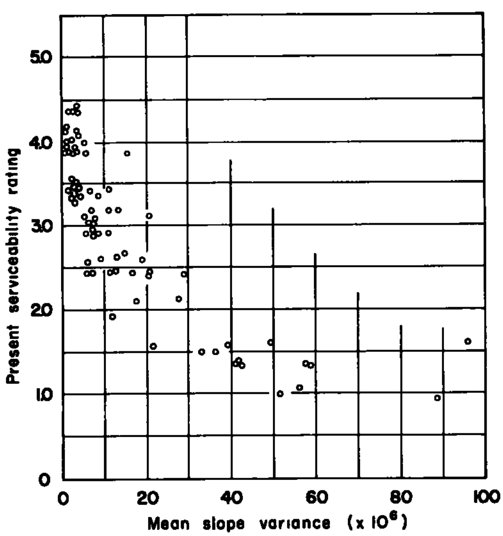

Figure 11. Present serviceability rating vs slope variance; 74 flexible pavements.

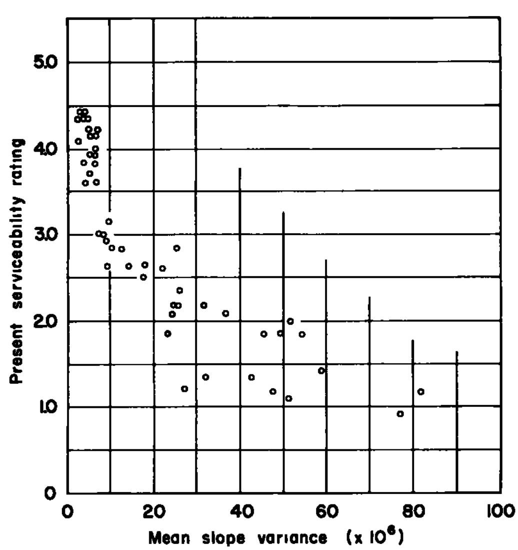

Figure 12. Present serviceability rating vs slope variance; 49 rigid pavements.

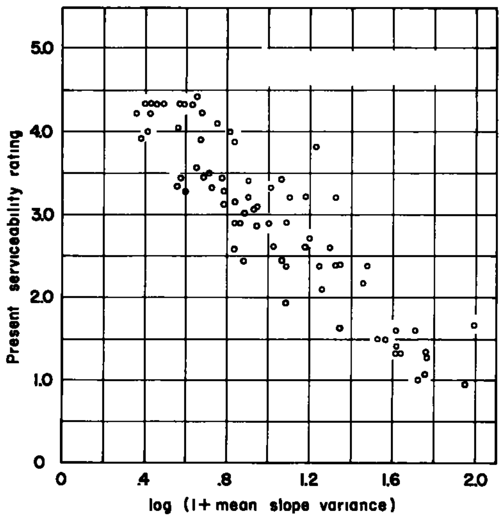

Figure 13. Present serviceability rating vs log (1 + mean slope variance); 74 flexible pavements.

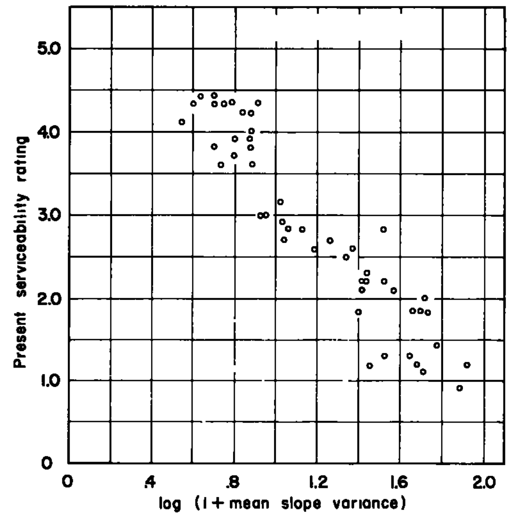

Figure 14. Present serviceability rating vs log (1 + mean slope variance); 49 rigid pavements.

apparent that no loss would be incurred by lumping all major cracking and patching into a single number to represent surface deteriorations. Values for this sum, C + P, are not shown in Tables 1 and 2, but may be obtained from cracking and patching measurements given in the tables.

Scatter diagrams for PSR versus C + P are shown in Figures 16 and 17. For whatever reasons, it is apparent that there is little correlation between PSR and C + P for the flexible pavements, but that a fair degree of correlation exists between these variables for the rigid pavements. For both flexible and rigid pavements the transformation

$$D_1 = \sqrt{C + P}$$

was selected as a linearizing transformation for C + P.

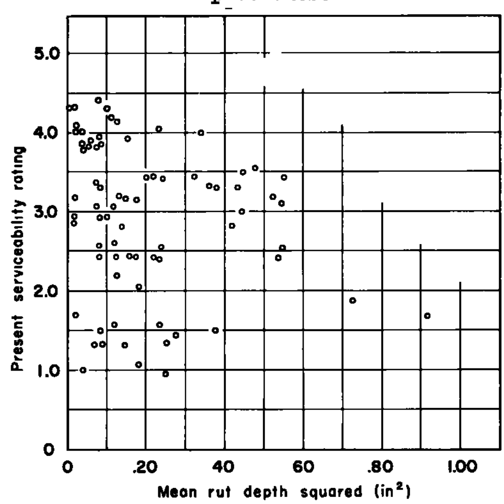

Figure 15. Present serviceability rating vs mean rut depth squared; 74 flexible pavements.

Thus the present serviceability index models to be used are

$$PSI = A_0 + A_1R_1 + A_2R_2 + B_1D_1 = A_0 + A_1 \log (1 + \overline{SV}) + A_2\overline{RD}^2 + B_1 \sqrt{C + P} \quad (3)$$

for flexible pavements, and

$$PSI = A_0 + A_1R_1 + B_1D_1 = A_0 + A_1 \log (1 + \overline{SV}) + B_1 \sqrt{C + P} \quad (4)$$

for the rigid pavements. It is not expected that the coefficients A_0, A_1, and B_1 have the same values for both Eqs. 3 and 4.

There are many other possibilities for Eqs. 3 and 4. Not only might other instruments be used to detect deformation and deterioration, but other summary values than

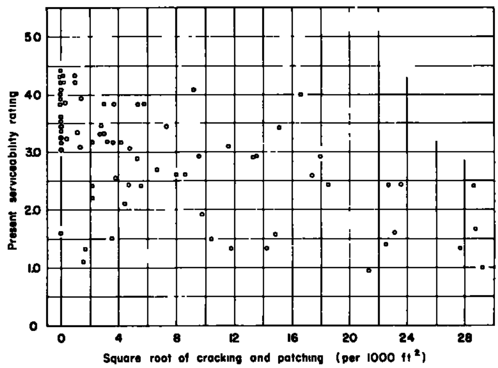

Figure 16. Present serviceability rating vs square root cracking and patching; 74 flexible pavements.

$\overline{SV}$, C+P and $\overline{RD}$ might be used. Moreover, one may choose different functions of $\overline{SV}$, C+P and $\overline{RD}$ than appear in Eqs. 3 and 4, or perhaps include still more functions of pavement measurements.

It is clear that one of the most important elements of pavement serviceability is its longitudinal profile in the wheelpaths. The profile of the road coupled with the appropriate characteristics of the vehicle (mass, tires, springs, shock absorbers, speed, etc.) produce the "ride" attained in that vehicle over that road. The actual profile of the wheel path as though taken with rod and level at very close spacing may be called the displacement profile, p. The first derivative of the displacement profile is the profile of the slope, p'. A plot of the slope profile would have the same abscissa as the displacement profile, distance along the road, and its ordinate would represent the rate of change of displacement, or slope of the road at any point. The second derivative of the displacement profile is the "acceleration" profile, p'', and represents the rate of change of slope, and the third derivative has been called the "jerk" profile, p''', the rate of change of acceleration. It has been suggested that jerk may be more highly correlated with a rider's opinion of his ride than any of the other representations. Perhaps this is true when one is seeking to define "ride" but the efforts at the Road Test were directed toward a definition of the "smoothness of a road" independent of the vehicle that might use it. No small amount of effort was spent in studying correlations of the variances of various profile derivatives with the present serviceability ratings, but there was no evidence that elevation variance, acceleration variance, or jerk variance has higher correlation with PSR than the slope variance. On the other hand, when a number of the slope profiles were subjected to generalized harmonic analysis to determine how variance was associated with the wavelength spectrum, there was some indication that slope variance in certain regions of the wavelength spectrum is more highly correlated with PSR than is the total slope variance. More study of this question is still under way at the Road Test.

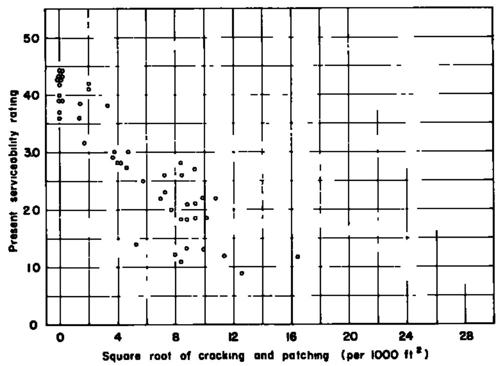

Figure 17. Present serviceability rating vs square root cracking and patching; 49 rigid pavements.

Coefficients for the Present Serviceability Index

Substitution of Eq. 3 in Eq. 2 gives

$$PSR_j = A_0 + A_1 R_{1j} + A_2 R_{2j} + B_1 D_{1j} + E_j$$

in which $R_{1j} = \log(1 + \overline{SV}_j)$, $R_{2j} = \overline{RD}_j^2$ and $D_{1j} = \sqrt{C_j + P_j}$ for the jth pavement.

Least squares estimates for A_0, A_1, A_2 and B_1 are found by minimizing the sum of squared residuals, E_j, through solving the following four simultaneous equations for A_0, A_1, A_2 and B_1.

$$A_1 \sum(R_1-\overline{R_1})^2 + A_2 \sum(R_1-\overline{R_1})(R_2-\overline{R_2}) + B_1 \sum(R_1-\overline{R_1})(D_1-\overline{D_1}) = \sum(R_1-\overline{R_1})(PSR-\overline{PSR}) \quad (5a)$$
$$A_1 \sum(R_2-\overline{R_2})(R_1-\overline{R_1}) + A_2 \sum(R_2-\overline{R_2}) + B_1 \sum(R_2-\overline{R_2})(D_1-\overline{D_1}) = \sum(R_2-\overline{R_2})(PSR-\overline{PSR}) \quad (5b)$$
$$A_1 \sum(D_1-\overline{D_1})(R_1-\overline{R_1}) + A_2 \sum(D_1-\overline{D_1})(R_2-\overline{R_2}) + B_1 \sum(D_1-\overline{D_1})^2 = \sum(D_1-\overline{D_1})(PSR-\overline{PSR}) \quad (5c)$$
$$\overline{PSR} = A_0 + A_1\overline{R_1} + A_2\overline{R_2} + B_1\overline{D_1} \quad (5d)$$

Summations in Eqs. 5 are over all pavements in the analysis, and bars over symbols denote arithmetic means. Sums like $\sum (R_1-\overline{R_1})^2$ are called sums of squares, while sums like $\sum (R_1-\overline{R_1})(D_1-\overline{D_1})$ are called sums of products. Eqs. 5 may be expanded to more terms and more equations if the index model contains more than three functions.

Since the model (Eq. 4) for rigid pavements has only three undetermined coefficients, only three simultaneous equations need be solved.
These equations are

$$A_1 \sum(R_1-\overline{R_1})^2 + B_1 \sum(R_1-\overline{R_1})(D_1-\overline{D_1}) = \sum (R_1-\overline{R_1})(PSR-\overline{PSR}) \quad (6a)$$
$$A_1 \sum(R_1-\overline{R_1})(D_1-\overline{D_1}) + B_1 \sum (D_1-\overline{D_1})^2 = \sum (D_1-\overline{D_1})(PSR-\overline{PSR}) \quad (6b)$$
$$\overline{PSR} = A_0 + A_1R_1 + B_1D_1 \quad (6c)$$

All means, sums of squares, and sums of products for Eqs. 5 and 6 are given in Tables 1 and 2, respectively.

For the flexible pavements, Eqs. 5 are:

$$13.27\ A_1 - 0.166\ A_2 + 171.63\ B_1 = -\ 26.69 \quad (7a)$$
$$-0.166\ A_1 + 1.34\ A_2 - 3.90\ B_1 = -\ 1.51 \quad (7b)$$
$$171.638\ A_1 - 3.90\ A_2 + 5255\ B_1 = -369.3 \quad (7c)$$
$$2.91 = A_0 + 1.02\ A_1 + 0.076\ A_2 + 7.64\ B_1 \quad (7d)$$

and the solution turns out to give

$$PSI = 5.03 - 1.91 \log (1 + \overline{SV}) - 1.38\ \overline{RD}^2 - 0.01\sqrt{C + P} \quad (8)$$

For the 49 rigid pavements the least squares equations are:

$$7.55\ A_1 + 71.71\ B_1 = -\ 19.70 \quad (9a)$$
$$71.71\ A_1 + 905.7\ B_1 = -206.5 \quad (9b)$$
$$2.83 = A_0 - 1.19\ A_1 - 0.087\ B_1 \quad (9c)$$

whose solution leads to the index

$$PSI = 5.41 - 1.78 \log (1 + \overline{SV}) - 0.09\ \sqrt{C + P} \quad (10)$$

It is noted in Tables 1 and 2 that the total variation in PSR is given by the sums of squares

$$\sum(PSR-\overline{PSR})^2 = 66.85 \text{ for the 74 flexible pavements, and} \quad (11a)$$
$$\sum(PSR-\overline{PSR})^2 = 57.92 \text{ for the 49 rigid pavements.} \quad (11b)$$

The variation in PSR as shown by Eqs. 11 may be separated into two parts, a sum of squares attributable to the measured variables and a sum of squares for residuals. Thus,

$$\sum(PSI-\overline{PSR})^2 = \sum (PSI-\overline{PSR})^2 + \sum(PSR-PSI)^2 \quad (12)$$

when the first term on the right side of Eq. 12 is generally called the sum of squares for regression, or the explained sum of squares. To obtain the sum of squares for regression for the flexible pavements,

$$\sum(PSI-\overline{PSR})^2 = A_1 \sum(R_1-\overline{R_1})(PSR-\overline{PSR}) + A_2 \sum(R_2-\overline{R_2})(PSR-\overline{PSR}) + B_1 (D_1-\overline{D_1})(PSR-\overline{PSR}) \quad (13)$$

is calculated, then the residual sum of squares is found by subtraction. For the rigid pavements, the term containing A_2 is omitted from Eq. 13. Sums of squares for regression are

$$(-1.91)(-26.69) + (-1.38)(-1.51) + (-0.01)(-369.3) = 56.42 \text{ for}$$

the flexible pavements, and

$$(-1.78)(-19.70) + (-0.087)(-206.5) = 53.08 \text{ for the}$$

rigid pavements.

Dividing regression sums of squares by the total variation given in Eq. 11 gives

$$\frac{56.42}{66.85} = 0.844 \text{ for the flexible pavements, and}$$

$$\frac{53.08}{57.92} = 0.916 \text{ for the rigid pavements.}$$

Thus, the PSI formulas account for 84.4 percent and 91.6 percent of the variation in PSR for flexible and rigid pavements, respectively. By subtractions, the respective sums of squared residuals are 10.43 and 4.84, so that the root mean square residuals are about 0.38 and 0.32, respectively.

The last columns of Tables 1 and 2 show calculated values for the present serviceability indexes, as well as for residuals. At the bottom of the last column of the tables it may be noted that the mean residual was 0.30 for flexible pavements and 0.26 for rigid pavements. In both cases, the mean residual is about twice the mean difference between replicate ratings given by the AASHO Rating Panel.

It may be noted from the residual columns of Tables 1 and 2 that six flexible and three rigid pavement residuals exceeded 0.5, the largest replication difference given by the Panel. However, the index formulas span ratings made more than a year apart, whereas all replicate ratings were made on successive days. As previously stated, it is quite possible that replicate PSR's would be more different when made over larger intervals of time.

When the fifteen rigid pavement PSR values from the fourth rating session were compared with PSI values given by Eq. 10, the sum of the algebraic deviations was practically zero while the mean discrepancy was 0.3. Inasmuch as only two of the deviations exceeded 0.5, it was inferred that Eq. 10 served to fit the new PSR values to about the same degree as it predicted those from which it was derived.

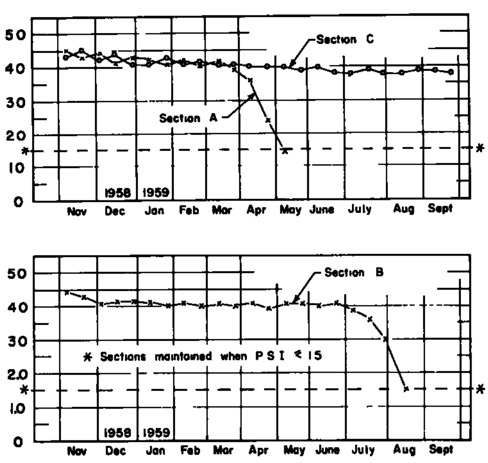

Figure 18. Present serviceability history of three selected test sections on the AASHO road test.

Case Histories of Present Serviceability Index

Figure 18 shows the present serviceability index history of three selected test sections at the AASHO Road Test. Sections A and B have been replaced since the beginning of the test; Section C was still in the test in October 1959. Abscissa values represent two-week intervals for which index values are computed by PSI 111 and PSI 211, respectively.

The performance indexes computed for four dates from these serviceability-time history curves are given in Table 3.

SUMMARY

The fundamental purpose of this paper has been to introduce concepts of present serviceability and performance that can be

TABLE 3

Date	Sect. A	Sect. B	Sect. C	For Service of Approximately
Dec. 1958	4.4	4.3	4.4	2 months
Mar. 1959	4.2	4.2	4.2	5 months
June 1959	3.4	4.1	4.1	8 months
Oct. 1959	2.3	3.4	4.0	1 year

clearly defined. Although the examples and illustrations are specific instances of the concepts, it has not been supposed that the procedures and indexes discussed herein represent any final goal. In fact, the details have been given only to illustrate the concepts.

If any highway department were interested in applying these principles to its own highway system with evaluation of pavement serviceability and/or performance in mind, the following steps should be taken:

1. Establish a rating panel or committee.
2. Decide which features of the roadway are to be considered.
3. Rate a large number of roadway sections that include among them a wide range of each of the selected features (that is, very rough to very smooth, deep ruts to no ruts, etc.)
4. Make objective measurements of the features considered.
5. Derive a serviceability index.

When the index has been derived, any section of highway in the state may be measured and the results of the measurements entered into the index, to obtain an estimate of the rating for that section without the need for the Panel to visit it. All highways in the state could be classified in this manner to provide an objective sufficiency rating system and an objective means to determine priorities for maintenance and reconstruction.

If the measurements were made and present serviceability indexes computed at several times during the lives of any particular set of pavements, their performance could be evaluated and compared to help the highway department check its design methods and compare various materials and construction techniques.

In this system, then, may be found the "dimension" for serviceability and performance that has been missing in design equations. The designer can be told to design for a specified performance level for a specified number of years and the means is provided to measure his success.

HRB: OR-338

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