State of the Art of Pavement Condition Evaluation

•PAVEMENT CONDITION is a subject of concern throughout the United States. Certainly many civil engineers including pavement designers and maintenance personnel are interested in the subject. But by far the largest interested group is composed of pavement users. Every user seems to rate pavement condition either consciously or unconsciously every time he rides in a motor vehicle or during the ground run of an airplane. There are a great many reasons for evaluating pavement conditions and even more ways of doing it. The names applied to the process are varied and many of the definitions are unclear. Terms like performance, serviceability index, condition survey, sufficiency rating, performance rating, and others are often bandied about by engineers and laymen alike. The definitions of such terms, however, are not precise and differ for the various interested parties.

In this paper every attempt will be made to be precise in use of terms and definitions. These will be chosen in an attempt to agree with predominant usage and will be given as precisely as possible in order to establish a springboard for future work in this area.

In the study of pavement evaluation, two major categories emerge. These are (a) serviceability-performance studies of functional behavior, and (b) mechanistic evaluation for structural adequacy. Regardless of the method used to make the evaluation, most studies can be listed in one of these two main categories. In general, serviceability-performance studies concern themselves primarily with the overall behavior of the pavement, that is, how well it is performing its function as a riding surface for vehicular traffic. By and large this also seems to be the area of major concern to the user.

On the other hand, the mechanistic evaluation for structural adequacy of pavements with a view to current load capacity and future performance is a vitally important area of interest to pavement engineers, pavement designers, and maintenance engineers. The understanding of the interrelationship between these two categories is of interest and importance to us.

Pavement condition is studied for several reasons. A few of these are:

1. To furnish information needed for sufficiency ratings and needs studies. This involves a comprehensive study of pavement systems within an area such as a state.
2. To aid the design engineer in the determination of the degree of success with which his design has met the design criteria and to help him learn causes for failure.
3. To aid in the establishment of priority for major maintenance, reconstruction and relocation. The object of this type of survey is to rank various pavement sections in terms of their importance and their current ability to serve traffic.
4. To assist the maintenance engineer and administrator in the determination of an optimum maintenance program.
5. To assist in the determination of the load-carrying capacity of the pavement both as to volume of traffic and loads. This involves an evaluation of structural adequacy of the pavement structure, climatic effects, materials, and drainage.
6. To serve as a basis for new concepts and design.

SERVICEABILITY-PERFORMANCE STUDIES

Serviceability—Subjective Rating

The evaluation of pavement performance involves a study of the functional behavior of a stretch of pavement in its entirety. For functional behavior or performance analysis, information is needed on the trend of the effect of load applications on the ability of the entire pavement to serve traffic. It can be determined by periodic observations and measurements of the pavement surface coupled with records of traffic history. Such studies are extremely important in the evaluation of pavement design.

Up until the time that the present serviceability index (6) was developed in conjunction with the AASHO Road Test, little attention was paid to evaluation of pavement performance per se. A pavement was either satisfactory or in need of repair; the ideas of relative performance were not adequately developed. Most pavement design concepts in general use did not consider the level of performance desired. Design engineers as a group vary widely in their concepts of desirable performance. As an example, suppose that two designers are asked to design a pavement for a certain traffic environment for 20 years. The first might consider his job to be properly done only if not a single crack occurred in twenty years, whereas the second might be satisfied if the last truck which was able to get safely over the pavement made its trip at the end of the twentieth year after construction.

Many popular design systems involve determination of the pavement thickness required to hold certain computed stresses below certain levels. It is clear that cracks will occur if the pavement is overstressed, but not much information was available prior to the time of the AASHO Road Test to relate such cracks to functional performance. The "pavement serviceability-performance concept" developed by Carey and Irick (6) for use at the AASHO Road Test is a well-defined technique for evaluating pavement performance.

Philosophy of Ratings— A rating implies the construction of some type of arbitrary scale to be used in the rating. Teachers often rate students on a scale of 100 percent; amateur golfers are rated by an arbitrary system called a handicap which is derived as a percentage of their average score over par for a period of time. Many such arbitrary scales in use today could be cited as examples. For many years the "roughness index" was used as a rating scale for pavements. This roughness index is rather arbitrary, and a "good value" depends largely on the particular piece of equipment used in the evaluation.

If some absolute roughness standard were available, this problem would be minimized. It is not likely, however, that such an absolute standard will ever be developed. As a result, "scaling factors" have been developed to provide a basis for comparing ratings from many sources throughout the world. Although many scales could have been chosen, a scale of 0-5 is in current use throughout the United States (5). Anyone rating a pavement is asked to scale his judgment from 0 to 5 using 5 as a possible perfect score.

PSI Developments—At the WASHO Road Test it proved to be especially difficult to establish a failure condition for pavements subjected to the test traffic. As a result of these difficulties the idea of average pavement ratings was conceived. As stated by Carey and Irick (6), there are five fundamental assumptions associated with the pavement serviceability concept. These may be summarized as follows:

1. Highways are for the comfort and convenience of the traveling public. Stated another way, "a good highway is one that is safe and smooth."

2. The user's opinion as to how he is being served by highways is on the whole subjective.

3. There are, however, characteristics of highways that can be measured objectively which, when properly weighed and combined, are in fact related to the user's 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 by all highway users. Honest differences of opinion preclude the use of a single opinion in establishing serviceability ratings. The mean evaluation of all users, however, should be a good measure of highway serviceability.

5. Performance is assumed to be an overall appraisal of the serviceability 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 until the time its performance evaluation is desired.

Based on these fundamental assumptions, Carey and Irick developed the PSI system used at the AASHO Road Test. Their evaluation shows that pavement roughness or the pavement profile is closely related to pavement serviceability ratings. Furthermore, the AASHO Road Test (1) showed that performance measured in this manner is correlated with certain pavement design factors.

Human Sensibilities—Hutchinson (16) discusses some of the problems associated with subjective ratings. Care must be taken in the development of such rating systems and improved rating scales can no doubt be developed if additional attention is given to this subject.

The evaluation of riding quality is a complex problem, depending on three separate complex systems plus interactions between them: pavement user, vehicle, and pavement roughness. Hutchinson (14) has described the problems associated with analyzing the subjective experience of highway users in deriving an absolute measure of riding quality. These require (a) the development of a suitable mathematical model to characterize pavement roughness, (b) the development of a suitable mathematical model to describe the suspension characteristics of highway vehicles that may be used along with the roughness model to predict the dynamic response of vehicles, and (c) a quantitative knowledge of the response of humans to motion.

In order to improve our subjective rating systems it will be necessary to objectively evaluate human sensibilities including the effect of motion sickness and its causes. These no doubt will involve studies of frequency, wavelength, and amplitude.

Surface Evaluation

Present serviceability is largely a function of pavement roughness. Studies made at the AASHO Road Test (6) have shown that about 95 percent of the information about the serviceability of a pavement is contributed by the roughness of its surface profile. That is to say, the correlation coefficients in the present serviceability studies improved only about 5 percent when cracking and patching were added to the index equations. Hveem (17) discusses this problem in several papers. He states that "there is no doubt that mankind has long thought of road smoothness or roughness as being synonymous with pleasant or unpleasant." Road surface roughness is not easily described or defined, and the effects of a given degree of roughness naturally vary considerably with the speed and characteristics of the vehicle.

Roughness Defined—What is pavement roughness? It is a phenomenon produced by a pavement surface and experienced by the passenger and operator in a vehicle or airplane traveling over that surface. Pavement surface roughness is a function of the profile of the road surface, the parameters of the vehicle including tires, supension, body mounts, seats, etc., and the acceleration and speed sensibilities of the passenger. All of these factors undoubtedly affect the phenomenon of roughness. Safety considerations will also influence our acceptance of roughness. Most people refer to pavement roughness as "the distortion of the pavement surface which contributes to an undesirable or uncomfortable ride." This definition then refers to the pavement alone and divorces itself from subsequent considerations. The evaluation of pavement roughness by this definition cannot of course be made until a great deal more is known about true profile, vehicle dynamics, and human response. For the purposes of this report, however, this definition will suffice.

To completely define the roughness function some evaluation of the roughness of the entire area of the pavement should be made. However, for most purposes this roughness can be divided into three components: transverse variations, longitudinal variations, and horizontal variations of pavement alignment. In other words, any functional roadway which imparts acceleration to the vehicle or to the passenger must be examined. More particularly of interest are those functions which influence the comfort and safety of the passenger. There are many previous studies which have shown that longitudinal roughness is probably the major contributing factor to undesirable vehicle forces (6). The next greatest offender is transverse roughness (e. g., the roll component transmitted to the vehicle). The general curvature of the roadway which imparts yaw forces to the vehicle is considered to be the least offensive and one which is normally handled by following good highway alignment practices. Since most vehicles (approximately 70 percent) travel in a well-defined wheelpath with their right wheel

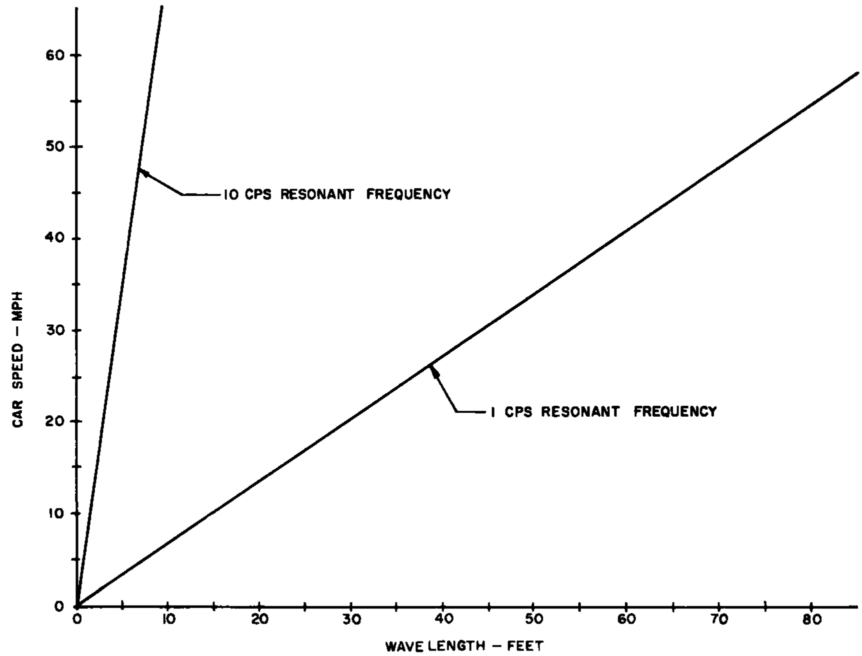

Figure 1. Relationship between wavelength, car speed, and car resonant frequency.

located 2½ to 3½ feet from the right-hand lane line, we are tempted to conclude that measurements of longitudinal profile in the two respective wheelpaths 6 feet apart might provide the best sampling of roadway surface roughness. Furthermore, comparison between the two wheelpaths can provide some measurement of the cross slope or transverse variations which are also important.

A passenger riding in a vehicle passing over a road surface experiences a ride sensation. This ride sensation is a function of the road profile, the vehicle parameters, and the vehicle speed. A variation of any one of these three variables can make a rough road appear smooth. Then we might say that from a vehicle passenger's viewpoint, roughness is an unfortunate combination of road profile, vehicle parameters and speed. Riding characteristics of airplanes are also affected by the properties of the

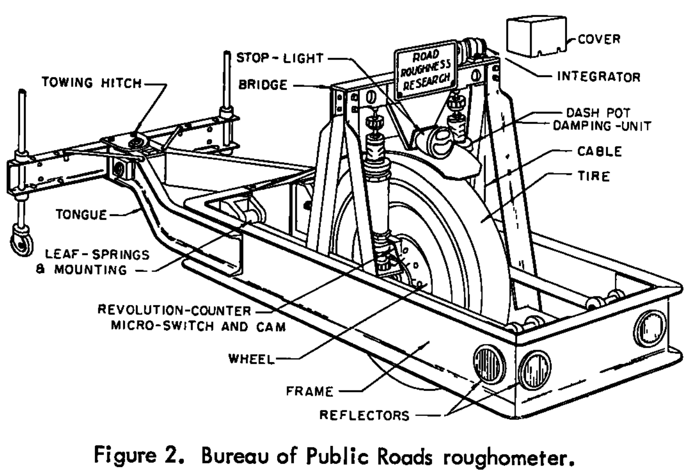

Figure 2. Bureau of Public Roads roughometer.

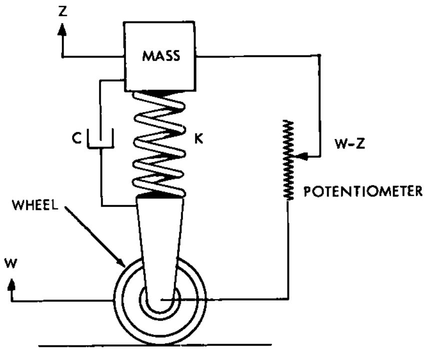

Figure 3. Mechanical vibrometer.

pavements and of the equipment. Accelerations of sufficient magnitudes to critically affect safety of operations are sometimes measured over poor pavements.

In general, most passenger-car ride characteristics are much alike, and the vehicle parameters (tires, suspension, body mounts, seats, etc.) are not changed sufficiently to make a significant change in passenger comfort. With the limitation of relatively fixed vehicle parameters it becomes apparent that ride sensation is almost completely a function of the car excitation generated by the various combinations of road profile and vehicle speed. Most drivers have experienced the sensation of either slowing down or speeding up to improve the ride on a particular road. This indicates that the road has a wavelength content that when driven over at some speed produces an excitation into the car at one of the car's resonant frequencies. The typical passenger car has resonant frequencies at approximately 1 and 10 cycles per second. The relationship between wavelength, car speed, and car resonant frequency is shown in Figure 1. This relationship indicates that at any speed there is a road wavelength that will cause an excitiation at one of the car resonant frequencies. If the amplitude of that wavelength is large, the car ride will be noticeably affected.

We have said that, in general, most passenger-car ride characteristics are very much alike. We can also say that for any particular road most cars will be driven at about the same speed. With two of these variables held relatively fixed, the excitations into the car and thus the riding characteristics of the car are strictly a function of the wavelength content of the road profile surface.

We have discussed the interrelationship between the roadprofile, vehicle parameters, and vehicle speed in producing a ride sensation. The final ingredient in the road roughness picture is passenger sensibility. So far, we do not know enough about the passenger to know what he or she objects to in the ride sensation, but we can feel sure it is related to the road profile and more directly to the wavelengths in the road that cause the car to resonate.

Roughness Equipment—Researchers in the highway roughness area have long realized that it is important to study the characteristics of the highway surface over which the car is driven. Hveem (17) in 1960 presented a good survey of early road surface measuring devices. Many of the devices mentioned in his paper are no longer being used. Most of the present-day research in road surface evaluation in the United States involves the use of one of the following devices: Bureau of Public Roads roughometer, rolling straightedge, slope measuring device, or GMR profilometer.

The Bureau of Public Roads roughometer (Fig. 2) is essentially a mass, spring, and damper combined to form a device called a mechanical vibrometer. These components are arranged as shown in Figure 3. In effect, the device is a simulation of one wheel of a passenger car. The displacement of the wheel with respect to the mass is measured as the device passes over the road surface at 20 mph. This displacement is accumulated over a distance interval and is called the roughness index with units of inches of displacement per mile. A transfer function for this device is shown in Figure 4. The roughometer reduces the amplitude of road wavelengths longer than 17 feet and shorter than 2 feet. Wavelengths of 3 feet are amplified by a factor of 10. Figure 5 compares the amplitude measured by the roughometer at 20 mph with the amplitudes felt by the car passenger at 60 mph. This figure shows that the roughometer amplifies the shorter wavelengths or wavelengths that cause car shake but attenuates wavelengths that are considered in the ride frequency range. As the car speed goes up it would appear that the roughometer measurements, which are made at 20 mph, would have less meaning.

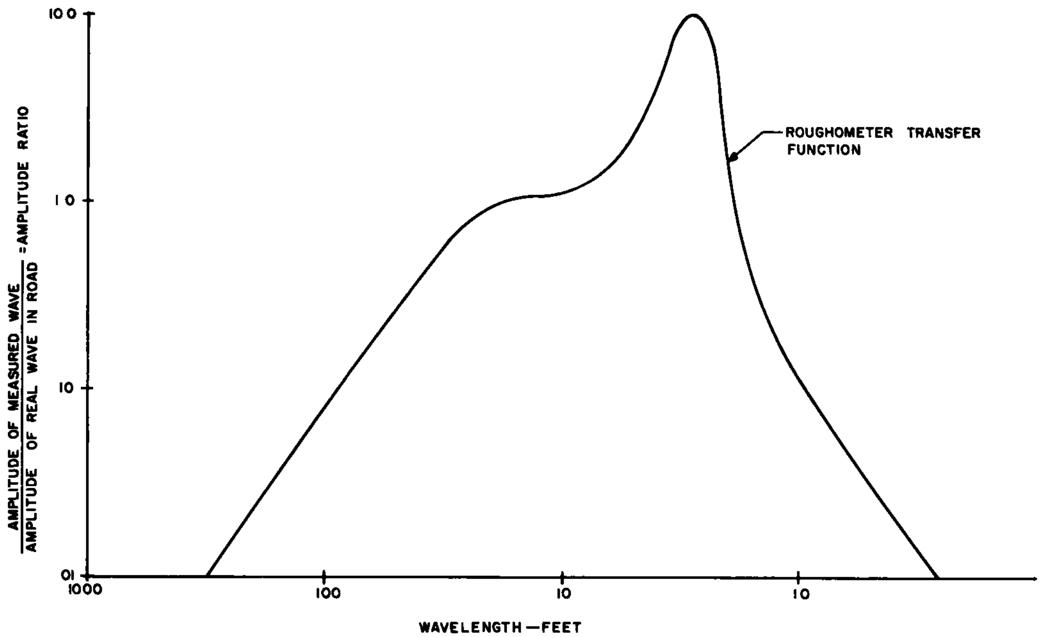

Figure 4. Roughometer transfer function.

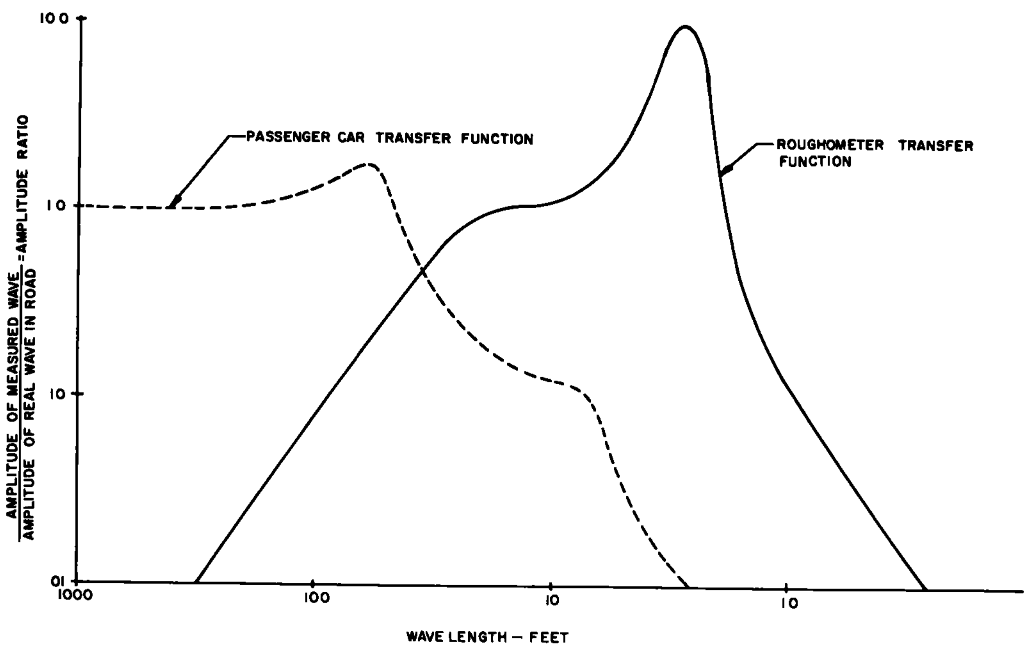

Figure 5. Comparison of amplitude measured by roughometer at 20 mph with amplitude felt by passenger at 60 mph.

Figure 6. Michigan profilograph.

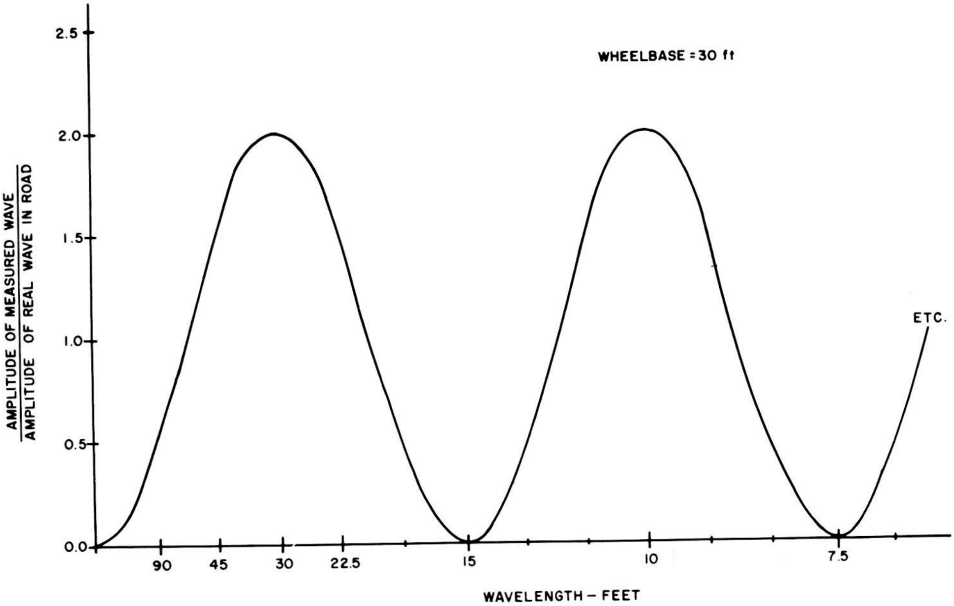

Figure 7. Rolling straightedge transfer function.

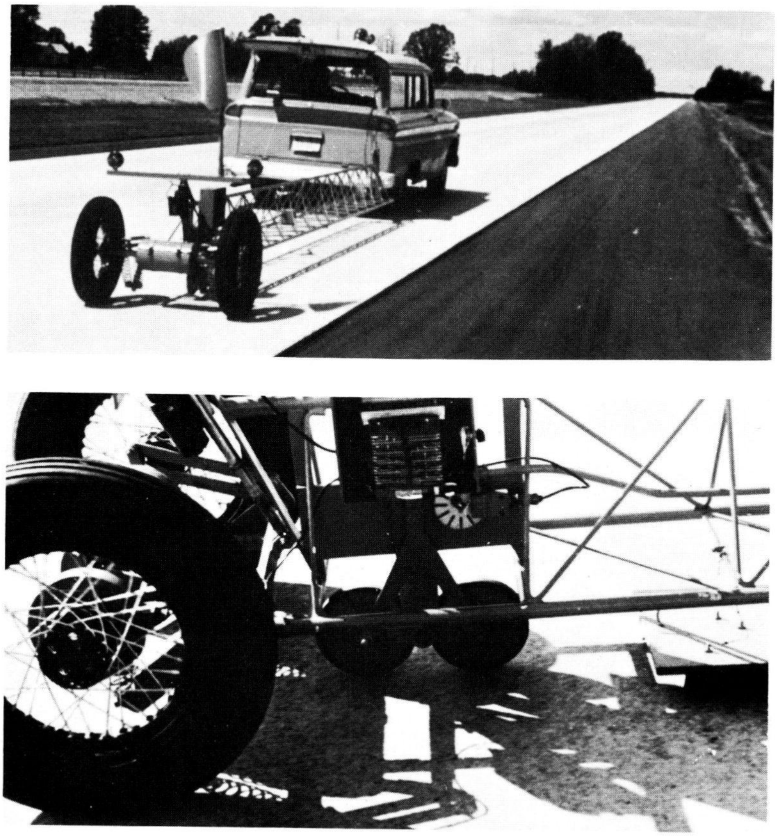

Figure 8. CHLOE profilometer.

The rolling straightedge (Fig. 6) is used by several groups in this country. Both the California Highway Department and the University of Michigan have truck versions of this device. It has been useful in extensive road condition studies at the University of Michigan. Figure 7 shows the transfer function of this system. The simple rolling straightedge has the serious disadvantage of badly distorting the wavelength content of the road profile it measures. Figure 7 shows that the rolling straightedge does not tend to respond to waves whose lengths are $\frac{1}{2}$, $\frac{1}{4}$, $\frac{1}{6}$, $\frac{1}{8}$, etc., of the overall wheelbase of the machine. Since the road wavelength information that is desired may fall in this area, it appears that this device would have limited usefulness in the evaluation of road roughness.

The CHLOE profilometer (Fig. 8) developed for use in the AASHO Road Test is a good example of the slope measuring vehicle. In this device the change in angle between two reference lines is the measure of the pavement profile roughness. One reference line is determined by two slope wheels which follow the road and are relatively close together. The second reference line is determined by a 20-ft long member which is supported by a trailer hitch on the back of a towing vehicle and a wheel which supports the rear end of the member.

A transfer function that relates the slope measured and actual slope is not available for the CHLOE profilometer. But considering the geometry of the device, it appears that wavelengths shorter than the distance between the two slope wheels will not be measured accurately. It also appears that information on the longer wavelengths will be lost completely. The determination of the transfer function for the CHLOE profilometer is complicated by the motions of the towing vehicle which must be included since it is also following the road profile.

Figure 9. General Motors profilometer.

The GMR road profilometer (Fig. 9) is a recent development in road surface measuring equipment (32). This device measures the profile of the road surface over which it passes. The wavelength content of the road profile is measured accurately from the very short waves to the longer waves (up to 400 ft). Figure 10 is the transfer function for the GMR profilometer for a measuring speed of 40 mph. Since this device measures all the wavelengths in the road that are important to vehicle ride, it appears that this device should be usable in future road roughness studies.

Of the four devices discussed for measuring road profile characteristics, the GMR road profilometer is the only device whose output contains information on all of the

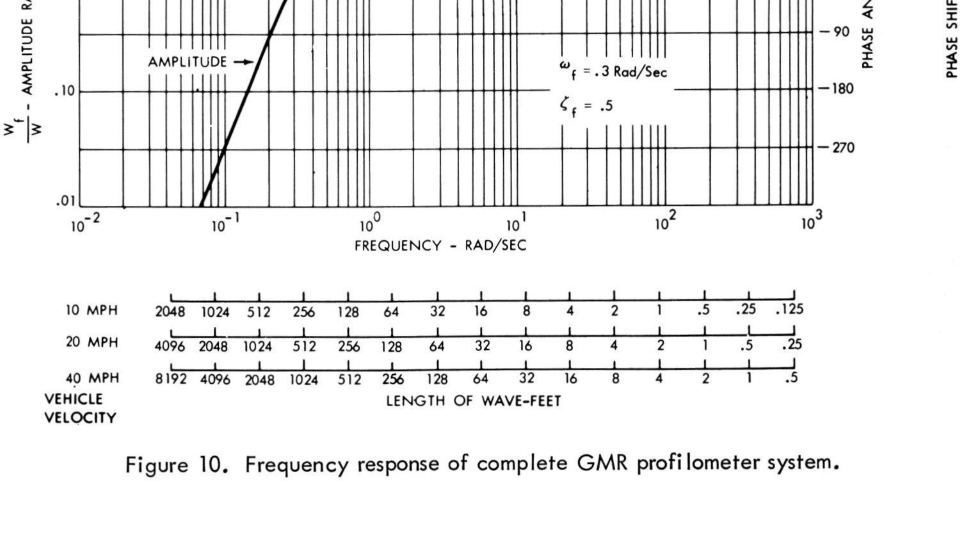

Figure 10. Frequency response of complete GMR profilometer system.

wavelengths important to vehicle ride. Accurate measurement of the road profile, however, does not tell the user of the device anything about the roughness or ride characteristics of the road. It is in this area that research activity is needed. Considering the system of the vehicle and human body riding in the vehicle, we have the ability to measure the input to the system, the road profile, and the output of the system—the passenger's opinion of the ride sensation.

However, the passenger's opinion is subjective and requires the use of a passenger or group of passengers to evaluate each road for roughness. Through future research it is hoped that an objective ride criterion can be formulated that will allow the completely objective evaluation of a road system. The complete evaluation procedure would consist of measuring the road profile, using the road profile as an input into a simulation of a typical vehicle, using the motions of the typical vehicle as an input into a simulation of a typical human body, and the monitoring of the outputs of the simulated body to determine its reaction to the road. It may be that the simulation of both the vehicle and human body can be reduced to an instrument box whose input would be the measured road profile and whose output would be a road roughness evaluation in the form of a number or a curve. It is obvious that there is much work between the present status and the desired future position. A major step has been taken in our newfound ability to measure and record road surface profiles. The simulation of a typical vehicle does not appear to present a problem but the final step of obtaining an objective passenger ride criterion will require an extensive amount of research. The sooner we start on this research the sooner we will have the ability to rate road roughness objectively.

While it is true that none of the existing roughness equipment is perfect, it can all be put to good use. Many agencies throughout the United States are making estimates of pavement serviceability and thence performance. They are using the roughometer, the CHLOE profilometer, and many other approximate devices. Until better equipment is developed, the continued use of existing methods is essential to pavement evaluation.

Needed Research—In order to make further advances in this area it will be essential that equipment for measuring "true profile" of the pavement surface be developed. These true profiles will make it possible to characterize pavements very accurately and in subsequent correlations with studies of human sensibilities should provide improved serviceability index equations. Additional research is also needed in human response to motion since psychologists have pointed out that it is very difficult to obtain realistic subjective ratings from human subjects. Operational and safety requirements of airplanes in relation to pavement roughness is also a subject which requires extensive research.

Condition Surveys

Condition surveys are important to the mechanistic evaluation of highway pavements. They will be thoroughly discussed in the next section. Studies at the AASHO Road Test (6) showed that condition surveys were also helpful in improving correlations in the present serviceability index. All the studies to date have shown that an evaluation of surface cracking and patching of all pavements and the addition of faulting measurements on portland cement concrete pavements will provide adequate information to improve correlation coefficients between pavement ratings and serviceability indexes by about 5 percent. More detailed condition surveys do not seem to be warranted for serviceability-performance studies.

Traffic History (Loads)

Among the many diverse and complex factors which affect pavement performance, the number and magnitude of loads has a very direct effect on road life. An accumulative record of serviceability ratings has also been shown to be a measure of the performance of a pavement (6, 1). Therefore, the relationship of accumulative serviceability ratings and number of axle loadings provides a means of evaluating the actual performance of the pavement to the expected or designed pavement life.

The importance of knowing the number and magnitude of axle loads for purposes of evaluating pavement performance therefore becomes apparent. The ideal situation of course would be axle loads of constant magnitude; thus procurement of data would be simply recording the number of axle load applications. Unfortunately, this is not the case for the mixed traffic which travels the nation's highways. It becomes necessary therefore to accumulate information on volumes of traffic for the pavements in question and to derive some relationship of number and magnitude of loadings for various classifications and volumes of mixed traffic.

The AASHO, Maryland, and WASHO Road Tests (1, 20, 35) have shown that the frequency of application of heavy loads directly affects the service lives of highways. Results of these complete studies provide a means of relating the destructive power of one wheel loading to another; for example, two applications of a 30,000-pound axle loading is considered equivalent to six applications of an 18,000-pound axle load. The number and rate of application of heavy axle loads therefore is an important aspect of highway evaluation. Several test tracks built and tested by the U. S. Army Corps of Engineers for the U. S. Air Force verified the same concept and established the relationship between airplane gear loads, land applications, and airfield pavement designs. These relationships were later extrapolated for the design and evaluation of military roads and streets.

Most states are making studies of the number and magnitude of axle loads, but it is not possible to obtain such information continuously for all highways and streets. Therefore, the available data must be expanded and assumptions made to apply the information acquired to a statewide basis.

To establish an approximation of number and magnitude of loads for a particular pavement, it is first necessary to determine the volume and classification of the traffic. Traffic volumes generally follow cyclic variations such as the season of the year, the day of the week, and the hour of the day. Also, it is known that traffic volume has been increasing and is expected to continue. Traffic volume is influenced by many factors, such as national economy and international relations, and therefore is difficult to predict with any degree of accuracy. Past experience has shown that predictions of increases have generally been conservative.

The highway traffic stream is composed of passenger cars, light trucks, medium trucks, heavy trucks, and buses, and the amount of each is subject to variations due to type and location of the road or land use along the road. The percentage of total number of vehicles that each of the various types of vehicles represent also varies by time of day and week. Periodic measurements of traffic movement therefore are necessary to maintain as reliable a basis as possible for predictions.

To complete the accumulation of necessary information, the vehicles are weighed by various means. The methods used in obtaining the weights of these vehicles vary from weighing the vehicle while moving slowly over a scale to use of small portable scales which measure the load on each wheel. Many states operate permanent scales at strategic locations on primary highways on a periodic or continuing basis, and the majority of the weight information comes from these stations. Generally, all trucks are required to cross permanent scales during the period of operation, whereas random sampling of vehicles is used for the portable scales.

Since total numbers of axles and axle loads are extrapolated from these samplings of vehicle weights, it is important that the samples be reliable. In a report by Shook et al (31), it was pointed out that the reliability of the samples is governed by such factors as:

1. Size of sample: (a) percent of the daily total count which is weighted; (b) number of stations at which surveys are made; (c) number of stations included for each type of highway; and (d) number of observations made each year at each station for each highway type.
2. Method by which specific vehicles are selected.
3. Time of day and year during which weighings are made.
4. The specific locations of the weighing stations (a) relative to the character of the traffic, and (b) relative to the type of highway they represent.

Shook (31) also points out that axle load and truck type distributions varied not only from state to state but within a state for different types of highways. Therefore, extrapolation of data from one location to another or to a relatively large area requires recognition of the assumptions which are applied and the errors which may be introduced.

Continual load studies by the states will result in more accurate estimates of the loading history of the particular section of pavement being evaluated. However, the ultimate goal will be a continuing record of actual magnitude and number of loads being applied. Norman and Hopkins (25) reported on an electronic weighing device which measured axle weights, axle spacings, and speeds of vehicles moving at their normal speeds along highways. Electronic and structural problems developed during the study, but the potential of such a scale was demonstrated. More recently a report by the Kentucky Department of Highways (19) describes the construction, installation, testing and performance analysis of three types of dynamic electronic scales: the Taller-Cooper, a commercially developed four load cell scale; the broken bridge, an adaptation of a German prototype employing two load cells; and the beam-type scale, an experimental prototype that uses a pair of instrumented aluminum beams as the weight sensors. The report concludes that all three scales will accurately measure the applied load, but that the broken bridge and beam scales appeared to be more suited for collection of data for use in pavement design and highway planning. The Taller-Cooper scale appeared to be better suited to research in pavement and vehicle dynamics. All three scales were equally suited for collection of statistical axle load data and enforcement of axle weight limitations. The report also includes an excellent bibliography with synopses of some of the more pertinent entries.

It is readily apparent from the available information that highway agencies are currently expending considerable research effort in the field of traffic loadings and that methods of obtaining a continuous record of axle loadings at a particular site without interfering with traffic are being developed.

Performance

A definition is needed for the term "performance." Several definitions have been proposed in recent years. In general, these definitions agree that the "performance" of a pavement is the "ability to serve traffic safely over a period of time." Webster defines performance as "the execution of the functions required of one; often, effective operation, as of a motor." Applied to pavements then, the term pavement performance means "the effective operation of the roadway in its function of carrying traffic." Carey and Irick (6) define performance as the "trend of serviceability index with time." They define performance index as "a summary of PSI values over a period of time."

Since the AASHO Road Test and the use of the serviceability-performance concept in analysis of the road test data, considerable misunderstanding of the basic concept has been demonstrated. No one ever intended a single PSI value to be a measure of pavement performance. Just as the runs scored in any particular inning of a baseball game do not indicate the final outcome of the game, the PSI does not indicate the performance of a pavement, nor was it intended to. However, just as the accumulation of runs throughout the course of a baseball game ultimately adds up to the final score, the accumulation or total evaluation of the serviceability history of a pavement can be evaluated to measure final performance of the pavement.

MECHANISTIC EVALUATION FOR STRUCTURAL ADEQUACY

Condition Surveys

Although it may not be a matter of record, one can state with a fair degree of certainty that condition surveys must have developed about the same time in history as the turning wheel. Once the advantages of the wheeled vehicle became apparent, the road builder or the highway engineer certainly was needed.

As roads developed it was, no doubt, a keenly observant individual who first saw the advantages of using strong granular materials over the less stable natural fine-grained soils for building roads. His knowledge was not based on elaborately equipped laboratories and libraries but came through an understanding of what was available for him to see, that is, through observations of pavement condition. Since that time the engineers and pavements have progressed a long way, but it is still important today to evaluate the various elements that make up today's pavement on the basis of actual field performance. Condition surveys provide the necessary information to compare the role played by each element in the overall performance of the pavement. The designer, the builder, the user, and the maintenance engineer all have an important stake in pavement performance.

The full impact of the use of the serviceability index to rate pavements will possibly not be fully realized for many years. Certainly we should seek ways to improve and extend its usefulness and to develop a better system. It is not, however, intended (nor likely) to do away with the making of condition surveys, which is one of the most basic tools for extending our knowledge of highway engineering.

It is recognized that a series of PSI values obtained on a particular section of pavement over a period of time, when correlated with traffic histories and environment, is an indicator of design, materials, construction, and maintenance variables that exist. However, conditions seldom prevail except on special test projects where there is not a strong influence of each of these factors on the performance of the pavement. Yet, since not all pavements have the same capacity to perform, it becomes necessary that critical inspections be made by knowledgeable personnel to establish the cause, or causes, for the variation in performance. Pavements often fail to perform satisfactorily for a combination of reasons. These are the difficult ones, and often no single solution is easily obtained. In many other cases they have been correctly analyzed, and additional information is made available. Thus, each one of our thousands of miles of pavements serving under a great variety of traffic and environmental conditions serves as one more element in a vast proving ground.

Condition surveys made to establish the structural adequacy of a pavement usually are made in more detail than is normally required for establishing the PSI of a pavement. They generally include not only a record of all locations or the number of times a particular kind of distress is observed, but also indicate the degree to which the distress has developed, such as class 1, 2, or 3 cracks. Types and condition of maintenance operations are also important data.

Most pavement engineers have at one time or another been involved in making condition surveys, or at least have been exposed to reports made on the basis of information obtained from them. There appears to be no single method of making a condition survey that is used universally. Because of the many uses made of this information, an extremely wide variation exists in the manner in which the surveys are obtained, recorded, analyzed, summarized, and stored. Each perhaps has its special advantages and/or disadvantages. It is not within the scope of this report to list or judge their merits. It does seem important, however, that a list of standard definitions of items included on condition surveys be agreed upon and used. In most respects this has been done and has been reported in HRB Special Report 30 (26), which also contains a variety of suggested forms that can be used. Some examples of reports prepared from condition surveys are given elsewhere (2, 7, 12, 22, 27, 28, 29), and there are others available in the literature.

Improvements in the methods and techniques used in obtaining data from condition surveys are slow to develop. One area that is presently receiving some attention is the retrieval of construction information. In some cases this information is being placed on IBM cards, which should cut down the time in the office needed to dig this information out. In addition to readily supplying the information on a specific project, this method is also extremely useful in helping to select the proper sections to survey.

Another area in which there has been some relatively new developments is the use of pictures or strip maps made by special cameras mounted on a truck. We should encourage the development of any idea which would tend to reduce the time required, improve the accuracy or cut down on the cost of condition surveys.

Nondestructive Tests

An evaluation of the structural adequacy of the various components of an existing pavement without disturbing or destroying these components is highly desirable. To accomplish this, measurements must be obtained on or above the surface of the pavement and the results related to the structural properties of the underlying elements. Measurements of responses of a pavement structure to an external force or energy are referred to as "nondestructive" since the structure of the pavement is not altered and such measurements can be repeated at the same location. Nondestructive testing methods can be separated into three general categories: measurements of response to a selected static load or a single application of a slow-moving load, response to a repeated load, and response of a mass to a controlled source of nuclear energy.

The response to a single application of load is generally obtained by measuring the deflection of the pavement surface. Pavement deflection under a wheel load is usually measured by means of a Benkelman beam. The Benkelman beam was developed at the WASHO Road Test (35); it is a portable instrument which produces measurements of deflection to a thousandth of an inch. Results of a study in California (18) indicated that when surface deflections of flexible pavements as measured by the Benkelman beam exceeded a certain value, the subject pavements generally showed signs of distress. A similar study in Virginia (23) resulted in the same general conclusions. Comparison of surface deflections to a critical deflection value, therefore, provides a means to program maintenance for flexible pavements. Studies at the AASHO Road Test (1) indicated that relations existed between surface deflections and performance of flexible pavements; thus surface deflections can also be used as a means of evaluating pavement performance. The Benkelman beam is a simple instrument to operate, but variables such as temperature of the pavement and curvature of the deflection basin (9, 10) require careful consideration when interpreting the results.

Plate bearing tests have also been used by agencies to obtain deflections of pavement under load. The Portland Cement Association (38) has developed and used a method to determine values of modulus of subgrade reaction of underlying layers by plate loading of rigid pavements and measuring strains at the surface of the pavement as well as deflections.

Deflections of surfaces under repeated moving loads have been measured by means of linear variable transformers installed within a pavement structure. Considerable information on this method has been published (1). Although nondestructive, the method does require a permanent installation at one point in a pavement. The influence of such an installation, which is foreign to the surrounding media, raises the question of the effect on the results.

A series of vibration measurements was conducted on flexible pavements at the AASHO Road Test and the results reported by Nijboer and Metcalf (24). Initially the procedure consisted of exerting an alternating vertical force on the surface of the pavement and measuring the deflection of the surface or the velocity of wave propagation.

Measurement of the surface deflection provides an elastic stiffness value for the total structure being loaded whereas the wave velocity values can be interpreted to determine the stiffness of the various layers. Heukelom and Klomp (11) have reported on such measurements for soils and stabilized and unstabilized base courses in various European locations. These reports by Nijboer and Metcalf (24) and Heukelom and Klomp (11) provide extensive bibliographies.

Vibratory equipment was used by the U. S. Army Engineer Waterways Experiment Station (33) to determine the elastic modulus of soils under pavements. The method used was basically that developed by the Shell Oil laboratory in Amsterdam, Holland, which consists of setting up a steady state of vibrations at a given frequency and measuring the velocity of the propagated waves. This is essentially the same method as mentioned in the preceding paragraph.

The Experiment Station used an empirically developed half-wavelength procedure for interpretation of velocity. By using the E modulus developed by these techniques and resorting to the elastic theory, computations were made to determine pavement strengths. Although relative strengths of pavements could be obtained by these methods, it was questioned that the procedures were developed to the point where pavement strength could be accurately evaluated.

A report by Scrivner and Moore (30) describes a study conducted in Texas using a dynamic loading system and measuring surface deflections by means of geophones placed in contact with the surface. Deflections of the surface produced by the dynamic loading are compared to Benkelman beam deflections under a single load application. Results of the study indicate that a relatively good correlation existed between the two methods of determining pavement deflections. The dynamic deflection equipment is quite rugged and can be operated in the field by one man. The mobility of the dynamic equipment and the short time required for actual testing are favorable factors to consider.

At the present time, nuclear testing provides measures of density and moisture content of pavement materials (3). Nuclear equipment has been used experimentally for determination of asphalt content of bituminous mixtures (34) as well as compacted density of hot asphalt pavement (3). The normal use to date of nuclear equipment is in maintaining control of construction procedures, although it is conceivable that application may develop toward evaluation of constructed pavements as well. One example is measurement of changes in density of a base course subjected to traffic for a year before the surface material is placed. A limited program of this type was recently conducted in Wisconsin.

At the present time the nondestructive methods of testing, briefly described above, provide good indications of the structural adequacy of the pavement material itself and that of the underlying layers. Certainly none of these methods can be considered as producing accurate measures of the strength properties of the underlying layers. Recent advances in the field of electronics and nuclear detection may yield new methods of nondestructive testing that will provide more accurate measurements of the structural capacity of the various components. However, considerable research and development is necessary before such methods become available to highway agencies.

Destructive Testing

Although the performance of pavements can be evaluated by measurements of surface irregularities or the logging of pavement defects such as cracking and rutting, it becomes necessary occasionally to remove portions of the pavement structure to ascertain just where the failures are occurring and why. The term "destructive testing" is applied to these evaluation methods since the original structure of the complete pavement is destroyed with respect to future testing at that particular location. In general, such evaluation procedures are restricted to pavements that show evidence of distress; however, they have been used on test roads (1, 20, 35) to determine the evolution of distress.

The techniques used depend on the type of information desired, but generally involve cutting into each pavement layer and removing samples for testing. At times the objective is to obtain undisturbed samples of the various layers. However, the successful attainment of this objective may not always be realized due to the circumstances involved.

The actual cross section of the various layers of rutted flexible pavements can be studied to analyze the behavior of each layer and the functioning of the system. One such study in Kentucky (8) revealed that subgrade soil had intruded into the waterbound base course material, thus suggesting changes in the gradation of the base course material and modifications of certain construction procedures.

Trenches were cut transversely across flexible pavements at the AASHO Road Test to obtain information concerning the amount of wheelpath rutting at the top of each of the component structure layers as well as to obtain information on the existing condition and strength of the materials. It was found that rutting of the pavement was due principally to decreases in thickness of the component layers attributed to lateral movement of the materials. These results along with density and strength tests on samples of the removed material provided considerable information on the structural capabilities of the pavement.

Several states are currently conducting research on degradation of base course materials after subjection to service under traffic. Samples are removed from the base course layer at various intervals of time and tested in the laboratory to determine what increase, if any, in fines has occurred. Removing the existing surface to allow sampling of the base material is undesirable; however, the information gained by sampling and testing material exposed to actual service conditions counterbalances this detrimental aspect.

The authors believe that many states excavate and examine isolated trouble spots in pavements to determine the cause of the particular problem and take steps to correct the situation. These individual investigations are rarely reported in publications; in fact, the information rarely goes beyond the individual group involved in the actual problem. Consequently, the available information concerning destructive testing methods and the attendant results is limited to those occasions where these methods were incorporated into an overall program of evaluation such as at Road Tests.

The advantages of opening up pavements for detailed investigations below the surface must be weighed against the disadvantages of removing portions of the pavement and replacing with patches. It is important that all variables that affect pavement performance be evaluated before definite conclusions are reached. Too great a reliance on the appearance of defects at the surface should not be made, for many times this may give misleading results. Surface defects can be used as general guides to the underlying conditions; however, it is often necessary to determine the true position and cause of failure for a completely reliable analysis.

COMPARISON OF FUNCTIONAL EVALUATION VS MECHANISTIC EVALUATION

Pavement condition can clearly be analyzed from two different points of view. The first of these embodies a study of the functional behavior of a stretch of pavement in its entirety, while the second is a study of the mechanics of pavement behavior at specific locations. Many names have been applied but, based on the statement of committee activities published by Highway Research Board Committee D-B5 (Pavement Condition Evaluation), we have referred to these two points of view as a functional evaluation and a mechanistic evaluation. There is some honest difference of opinion and considerable misunderstanding between these two evaluation techniques. Much of the misunderstanding seems to arise from engineers who have used one or the other of the methods of evaluation extensively, but have never used the other method and therefore are not familiar with it.

Much of the misunderstanding comes from the ingrained feeling among engineers with a background of structural experience that a crack in a structural unit designed by engineers is an indication of failure. In some instances cracking is synonymous with failure; yet such is not the case with all engineering structures and certainly not in the case of pavements. For example, many properly designed prestressed concrete beams continue to function well and carry their designed loads for many years after cracks appear in the concrete itself. As another example, continuously reinforced concrete pavements function well with cracks. Many designers (21) feel that they function better with fairly close crack spacing, thus improving "performance." The pavements are in fact designed to crack at these spacings rather than at longer spacings.

A crack per se may or may not affect the function of a pavement. In some cases, certainly continuously reinforced pavements as cited above, cracking is not detrimental and may be helpful. Data cited by Carey and Irick (1) in developing PSI concepts show that pavement raters pay scant attention to cracks. A rough crack (spalled or faulted) will, however, add roughness to the longitudinal profile and will result in a higher roughness measurement, and thus a lower serviceability index. It can be seen that it is not the crack itself but more particularly the condition or roughness of the crack that affects the function of a pavement.

On the other hand certain cracks, no matter how fine, may be indicators of structural inadequacy to engineers of trained judgment. This depends on the type of crack and its cause. Mechanistic evaluation of pavements is involved with the investigation of such cracks and other pavement deterioration and specifically with the determination of the causes.

It should be reiterated in this summary that pavement performance cannot be predicted from a single PSI value. Trends of the PSI or serviceability history are required, and thus some loss in serviceability must be observed and some mathematical model must be employed to make life or performance predictions. Some engineers today are doing this by using the Road Test equation as a mathematical model and estimates of the initial or starting serviceability of the pavement sections being evaluated. Such efforts may be helpful in predicting average or "possible" pavement life. But such predictions can be misleading and have in the past given some users the idea that pavement performance was being predicted from a single PSI determination. Such is not the case.

Determination of failure mechanism is difficult even though some important work has been done in this area. Ex post facto observations are usually confounded by rapid destruction of pavements near failure, the difficulty and expense of so-called destructive sampling, and the fact that undisturbed samples are very hard to obtain. Furthermore, there are indications that failure mechanisms exist on a microscopic scale whereas sampling and testing procedures take place on the larger macroscopic scale.

SUMMARY

Pavement condition has been judged for centuries, but until recently these judgments have been subjective and qualitative instead of objective and quantitative. Functional observations, for example, involve statements such as "this is a good road," "poor road," "best road," "worst road," etc. Pavement engineers have likewise made mechanistic evaluations of almost every road ever built. These have varied in approach in detail and in results gained. However, much of what we know about pavements has come from such observations. Early test roads and experimental pavement sections relied heavily on such evaluations and the interpretation of such results. Many mechanistic evaluations were made at the AASHO Road Test (1) and were helpful in determining mathematical models and other phases of data analysis.

The establishment of a failure criterion is essential for all test sections and tracks such as the AASHO Road Test. The PSI or Present Serviceability Index is the result. The history of PSI with traffic or axle application is termed "performance." The clarification and use of such a system as the serviceability-performance system is essential in any Road Test satellite program or any nationwide study of pavement performance. Only through such common denominator factors can the multitude of variables across the nation be compared.

Present Practice

At the present time a good many states are observing functional behavior of highway pavements. Many are using PSI determinations as evidenced by the ownership of 17 CHLOE profilometers and 25 roughometers plus various other devices in current use. These functional evaluations are being put to various uses, but many of them are involved in the nationwide Road Test satellite program in an attempt to better define factors affecting pavement design and performance.

Mechanistic evaluation of pavement conditions is also continuing. Nondestructive tests are becoming more and more important in such mechanistic studies as the problems and expenses associated with destructive testing techniques increase. The difficulties involved with digging test pits or making other destructive tests in the main lanes of an interstate highway make the use of nondestructive tests more and more desirable. Such studies of mechanistic failures and search for possible causes will continue to be an important aspect of pavement condition evaluation.

Future of Pavement Condition Evaluation

The future of pavement condition evaluation will undoubtedly lead to solutions of many of the current problems facing pavement researchers. Research problem statements submitted by the HRB Pavement Condition Evaluation Committee include the following items (the statements are numbered for convenience; no attempt has been made to list them in order of priority or importance):

Problem No. 1: To develop a more rapid and reliable procedure for evaluating pavement condition. The objective of this project is to produce a method for evaluatin pavements which eliminates the need for annual measurements for such defects as cracking and patching. Such a procedure would make it possible for a great many mor pavements to be evaluated than is now possible for most highway departments. This would results in a corresponding increase in the usefulness of such data in decision-making processes.

Problem No. 2: To devise improved control techniques for pavement smoothness during construction. The objective of this research would be to develop better method of specifying and controlling pavement smoothness during construction in order to establish construction control specifications for pavement quality.

Problem No. 3: To develop evaluation techniques for determining the load-carryin capacity of existing pavements and thus the needs for preventive maintenance. The objective of this research is to seek better methods for predicting future serviceabilit and thus for predicting load-carrying capacity of existing pavements.

Problem No. 4: To establish a psychologically based subjective rating scale for use in determining the relative riding quality of a pavement. The objective of this research is to establish a more realistic scale for pavement rating based on recently developed information. Such a scale should account for "lenient errors," "central tendency effect," and "halo effects" that are normally present in subjective ratings performance by human beings.

Problem No. 5: To clarify the serviceability performance concept. The objectives of this research would be (a) to clarify the pavement serviceability concept, (b) to develop the best way for evaluating serviceability as a method of determining performance of pavements, and (c) to differentiate between highway sufficiency ratings and serviceability ratings.

Problem No. 6: To determine the effects of environment and time variations on roughness equipment. The objectives of this research are (a) to determine the effect of environment, particularly temperature and humidity, on the operating characteristics of roughness-measuring devices used to measure pavement serviceability; (b) to collect available data necessary to establish control charts pertinent to the behavio of the various kinds of roughness equipment in current use; and (c) to evaluate the causes and effects of instrument variations throughout their operating life that may appear to be variations in pavement serviceability.

Problem No. 7: To determine factors in the pavement profile that affect passenger ratings of pavement serviceability. The objectives of this research are (a) to evaluat human response in an effort to determine the factors in riding quality which most influence subjective rating of the ride, (b) to make a detailed analysis of pavement profiles in an effort to break them into many components which are found to influence the subjective rating given by automobile occupants, and (c) to combine the evaluations in (a) and (b) to develop a riding quality evaluation which will more accurately predict the rider's acceptance of the quality of the ride and hence the present serviceability.

The accomplishment of the research set out plus many other factors which need studying will ultimately lead to improved methods of evaluating pavement condition. For functional evaluations these must lead to better equipment, better rating methods, more knowledge of pavement profiles, vehicle characteristics and the effects of motion on the human mind and body. For mechanistic evaluation these studies must lead to a more thorough knowledge of the mechanics of pavement load-carrying capabilities and pavement failure, better knowledge of the strength and physical properties of the various components of the pavements, and better methods of determining the strength and physical properties of these pavement layers nondestructively.

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