# High-Speed Road Profile Equipment Evaluation

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The importance of evaluating the relative smoothness of pavements is well recognized in the highway profession, but such evaluation is largely a matter of qualitative judgment. These evaluations are useful in serviceability-performance studies and in studies of mechanistic evaluation of pavements for structural adequacy. Pavement surveys are used by maintenance engineers, design engineers, and highway administrators to help make many decisions with reference to the highway system.

This paper discusses the parameters affecting the measurement of roughness profiles, the evaluation of these parameters by various techniques, and the importance of measuring these profiles at high speeds. Several types of available equipment are discussed and associated data-processing techniques are described.

•HIGHWAY design speeds, which have increased steadily with the development of the automobile, demand that long, flowing ribbons of pavement be maintained in a very smooth condition so that the traveling public will be served adequately. Evaluation of the relative smoothness of pavements is largely a matter of qualitative judgment, but there is a recognized need for developing equipment capable of providing a quantitative measure of pavement smoothness for use in pavement evaluation studies such as those which are being conducted in Texas and which are expected to continue for the next several years.

Equipment available for measuring pavement roughness is limited in the accuracy with which the true road profile can be measured and in the speed with which measurements can be made. In general, the slower equipment gives greater accuracy; however, there is a need for a device capable of measuring road roughness more rapidly, as well as more accurately, than is now possible. Particular attention should be given to long-wavelength roughness (over 25 ft) because this characteristic is not presently being evaluated satisfactorily.

Recent developments in the electronics and directional control instrumentation field may help satisfy the need for faster and more accurate measurement, but no concerted effort has been made in the past to use these developments for highway pavement surface evaluation. The study discussed herein proposes to evaluate the feasibility of utilizing these developments and other recent technology in the development of high-speed road profile measuring equipment.

## PURPOSE OF PAVEMENT EVALUATION

Pavement condition is a subject of concern to highway engineers, including designers and maintenance personnel, but by far the largest interested group is composed of highway users. Each one seems to rate pavement condition either consciously or subconsciously every time he rides in a motor vehicle. There are a great many reasons for evaluating pavement condition, and even more ways of doing it. The names applied

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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.

## Philosophy of Pavement Evaluation

Two major categories of evaluation emerge: (a) serviceability-performance studies (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, the serviceability-performance studies are concerned 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 highway user. Studies made at the AASHO Road Test (1) have shown that some 95 percent of the information about the serviceability of a pavement is contributed by the roughness of the surface profile. That is to say, the correlation coefficients in the present serviceability studies at the Road Test improved only about 5 percent when cracking and patching were added to the index equation.

The second category, mechanistic evaluation for structural adequacy, which is concerned with the evaluation of the load-carrying capacity of a small segment of pavement and the mechanics or method of carrying the load, is an important phase of pavement evaluation but will not be discussed in detail.

## Use of Pavement Roughness and Evaluation

Pavement condition and/or roughness profiles are studied for several reasons, a few of which can be stated from records of the Highway Research Board Committee on Pavement Condition Evaluation:

1. To measure acceptability for newly constructed pavements.
2. To assist the maintenance engineer and the highway administrator in the determination of optimum maintenance programs.
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 furnish information needed for sufficiency ratings and needs studies. This involves a comprehensive study of pavement systems within a given area.
5. To assist in determination of the load carrying capacity of the pavement as to both volume of traffic and loads. This involves an evaluation of structural adequacy of the pavement structure, climatic effects, materials and drainage.
6. To aid the design engineer in determination of the degree of success with which his design has met the design criteria and to help him learn causes for failure.
7. To serve as a basis for new concepts and design.

This broad basis for use of pavement roughness information points to the need for better and faster methods of roughness measurement. All equipment in current use for the measurement of highway roughness suffers from limitations which need to be removed.

The evaluation of riding quality is complex, depending on three separate systems and the interactions between them; the highway user, the vehicle, and the pavement roughness are involved. Hutchinson (3) has described the problems associated with analyzing the subjective experience of highway users and deriving an absolute measure of pavement 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 responses of vehicles; and (c) a quantitative knowledge of the response of humans to motion.

This report is primarily concerned with the first factor but considers the others since the information required concerning roughness is dependent on the response of passengers and vehicles to the resulting motion. Consideration of roughness models emphasizes one important aspect of this study, the need to develop a method of measuring "true profile," meaning the faithful reproduction of the undulation of the pavement with respect to frequency, amplitude, slope and curvature at all points. No really good method for making such profiles exists and without one the progress in solving the overall problem will continue to be slow.

The second important aspect of the problem is more pragmatic. Based on data (1, 4, 7) which show that several different roughness parameters are highly correlated with riding comfort, the need for a better device for measuring present serviceability is apparent. In particular, an accurate device which travels at high speed is required.

The term "true profile" then can refer to an elevation profile, a slope profile or an acceleration profile. Any one of these is a "true profile" in a sense if it is a true representation of the factor it attempts to measure. It should be noted that most people are referring to an elevation profile when they refer to the "true profile." From our point of view, however, an instrument capable of reproducing any of these profiles faithfully could prove to be satisfactory. The desirability of a particular method depends on the purpose for which the data are to be used.

### Speed Aspects

It should be emphasized that the requirement to travel at high speed is inherent in this study. It is extremely important that the equipment be capable of traveling at least 30 mph, and speeds of 45 to 60 mph are definitely preferable, since they are closer to the current operating speeds on our freeways and would result in the least danger for personnel handling the equipment.

## PAVEMENT ROUGHNESS

The term "pavement roughness" is defined for this report as the distortion of the pavement surface which contributes to an undesirable or uncomfortable ride. In previous studies Hudson and Scrivner (2) have shown that variations in the surface less than ½-inch in length do not materially affect the riding quality and have been termed texture in lieu of roughness. The evaluation of this relationship between pavement roughness and passenger discomfort cannot be made until more is known about true profile, vehicle dynamics, and human response. For purposes of this report, however, the foregoing definition will suffice.

### Roughness Parameters

Four roughness factors are of general concern to highway engineers: (a) area roughness of the roadway, (b) transverse variations in profile, (c) longitudinal variations in profile, and (d) horizontal alignment of the roadway. In other words, any function of the 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 or discomfort of the passenger. Previous study has shown that longitudinal roughness is probably the major contributing factor to undesirable vehicle forces (1), and 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 component to the vehicle is considered to be the least offensive and one which is normally handled by following good highway alignment practice. Whereas the total road roughness is certainly of importance because of normal variations in transverse vehicle placement, it is generally conceded that 70 percent of the vehicles travel in a well-defined wheelpath with their right wheels located 2½ to 3½ ft from the right-hand lane line. From this information we are tempted to conclude that measurements of longitudinal profile in the two respective wheelpaths, 6 ft apart, might provide the best sampling of roadway surface roughness. Furthermore, a comparison between the two wheelpaths can provide some measurement of the cross slope or transverse variations which are also important.

Data from existing instruments have not been totally adequate for evaluating even a longitudinal line profile of the roadway. However, if more proficient equipment could be developed, it should be merely a matter of duplicating the equipment to provide the comparison between the two wheelpaths. On the basis of these assumptions, immediate attention is directed to the development of adequate transducers and data processing equipment for recording a single line profile. This confines the problem to two distinct phases: (a) developing adequate transducers for measuring the roadway profile, and (b) developing adequate recording and data processing equipment capable of speedy and accurate data analysis to provide the necessary summary information.

## True Profile

In the past a great deal of effort has gone into measurements of pavement profiles. Cursory examination of the problem indicates that the profile is probably not the factor of major importance to the driver or passenger. Since there is no force associated with elevation or with velocity, the height of the passenger above sea level, i.e., his elevation, is of no great importance to him within normal ranges, nor is his vertical velocity or rate of change of elevation important. However, his vertical acceleration or rate of change of velocity (second derivative of elevation) becomes very important to him since it has a force associated with it which exerts desirable or undesirable pressures on his body and its components.

Other studies have shown that some passengers find undesirable characteristics to be associated with certain frequencies. The exact size and relationship of the effects remain to be studied.

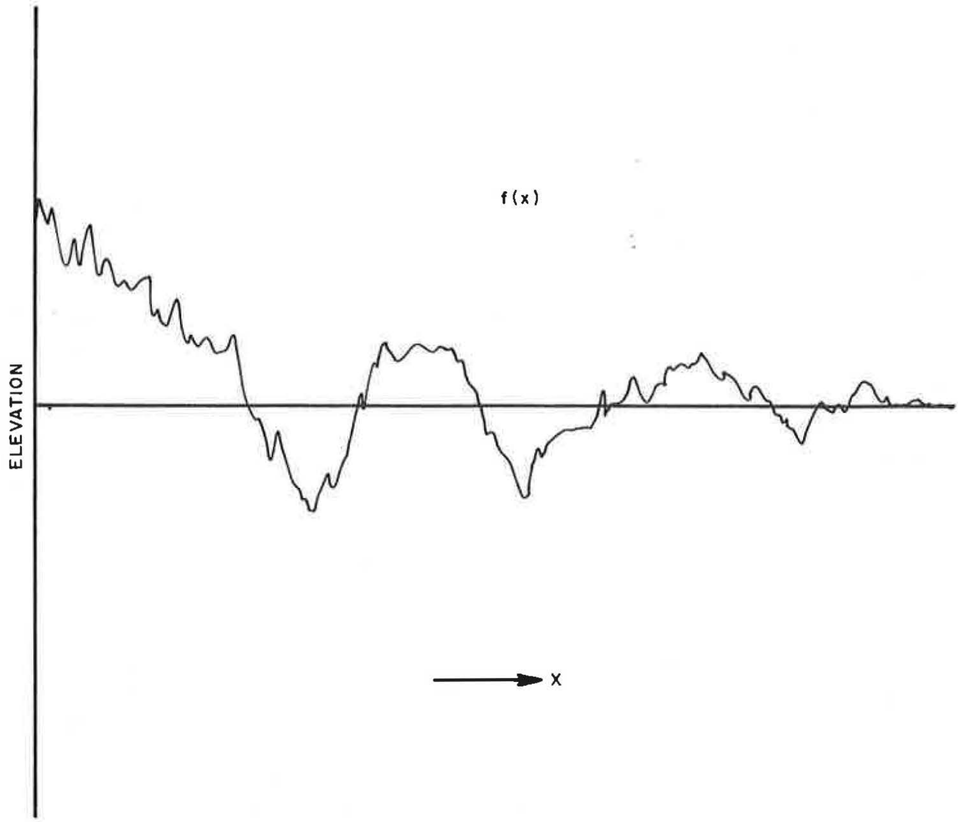


Figure 1. Plot of a random function.

In this regard, the characteristics of a typical random function (Fig. 1) are of interest. To define this function, in this instance an elevation profile, we are interested in (a) wavelength, (b) frequency, (c) surface slope, and (d) amplitude (elevation). On the other hand, some researchers record slope and plot a so-called slope profile, as was done on the AASHO Road Test with the AASHO slope profilometer (1). Finally, it is possible to record an acceleration profile by recording the analog trace output of a vertical accelerometer as done by the Kentucky Department of Highways (6).

A discussion of the various components of an elevation profile will be useful at this time, it being understood, however, that the recording of an elevation profile may not in the final analysis be of most interest. In order to consider this profile, the extremes covered in a roadway are of interest as is some estimate of the accuracy felt to be desirable because less accuracy than specified in the following will undoubtedly suffice if some sort of economic balance can be struck. These calculations describe the extremes of the parameters which have previously been measured in attempts to define this profile.

The parameters can be summarized as follows: wavelengths of interest—0.1 ft minimum, 500 ft maximum; frequency at 60 mph—range 0.17 cps to 1100 cps at 40 mph—0.1 cps to 700 cps; slope—dy/dx or dy/dt = ±18 deg. If a physical set of slope wheels with a finite wheelbase of 6 to 9 in. were used, it is probable that an angle of approximately ±10 deg or 0.166 radian would be all that could be obtained. This would be adequate to do the job.

Amplitudes of interest will depend on ability to measure wavelengths. For short-wavelength roughness, maximum amplitudes of ±6 in. will be desirable; however, for wavelengths up to 250 ft, amplitudes of 24 to 36 in. will be desirable. It is impractical to measure such amplitudes directly on an elevation profile and some compromise is therefore necessary in such cases. A General Motors Profilometer, for example, attenuates the signal based on frequency and wavelength to keep it on an analog chart.

## Accuracy

Accuracy is important in addition to the limitations suggested for measuring these parameters. This accuracy is improved by increased resolution in transducers and recording equipment. The values of resolution suggested below should be adequate for evaluating pavement roughness.

Amplitude or Elevation—Accuracy for amplitude or vertical displacement of 0.010 in. is desirable. This corresponds to 0.001 radian for a 9-in. wheelbase. Using a linear motion transducer covering a range of ±2 in. this requires a resolution of 400 units or 0.01 in.

Slope—For slope measurements a resolution of the total range into 100 units should be quite adequate.

Distance—The ability of any piece of equipment to measure distance accurately will decrease with speed. It is highly desirable, however, to be able to measure distance to the nearest ½ ft at 50 mph. It should be noted that all of the factors discussed herein are relative. The maximums or mimimums may not occur together. For example, a 6-in. deflection or elevation change is not of interest associated with a 2-in. wavelength.

## PROFILOMETER EQUIPMENT

Equipment capable of measuring pavement profiles at high speeds can be divided into two general categories. The first produces a summary statistic highly correlated with the present serviceability index of highway pavements. The second category is more sophisticated and consists of equipment capable of measuring a "true profile" of the pavement surface. With proper data recording and processing equipment, the second category of profilometer can also be used to provide the summary statistic. Visual analog profiles, however, are not satisfactory for this purpose.

A survey of existing equipment discloses three devices which purport to evaluate pavement profile at high speeds. These are (a) the Bureau of Public Roads Rough-

ometer, (b) the Kentucky Accelerometer, and (c) the GMR Road Profilometer. Other equipment currently used in the United States must be eliminated from this comparison because of speed characteristics. These include the AASHO Profilometer, the CHLOE Profilometer, and the Michigan-California Profilograph.

An evaluation of the measuring techniques used in the last three instruments indicates that it is not possible to use their principles at high speeds because of the mechanical problem of holding the recording wheel on the pavement. The Roughometer was also eliminated from consideration because its speed, while somewhat higher than most other equipment, is still not satisfactory for operation on modern highways. In addition, the ability of the Roughometer to measure serviceability of highway pavements consistently over a reasonable period of time is suspect because of temperature and moisture-associated variations which were observed at the AASHO Road Test (8) and which have been noted by the State of Illinois (9) with its equipment.

Two new pieces of equipment offer some possibility of development within the next two years. These are (a) a gyro-stabilized profilometer which uses a "true horizontal reference" and (b) a summary profiler being developed by Lane-Wells Corporation, Houston, Texas. The gyro-stabilized device offers possibilities of measuring true profile, while the Lane-Wells device is primarily intended as a device for measuring present serviceability index (PSI).

This then gives four types of equipment for primary consideration. Two of these offer possibilities of measuring true profile. The other equipment would be primarily useful for measuring PSI.

Devices for Measuring True Profile

Gyro-Stabilized Profilometer—Since 1961 the Texas Highway Department and the Center for Highway Research of The University of Texas have been discussing the development of gyro-stabilized profilometers with various manufacturers of gyroscopes. Particular interest has been shown by Sperry Gyroscope Corporation and by

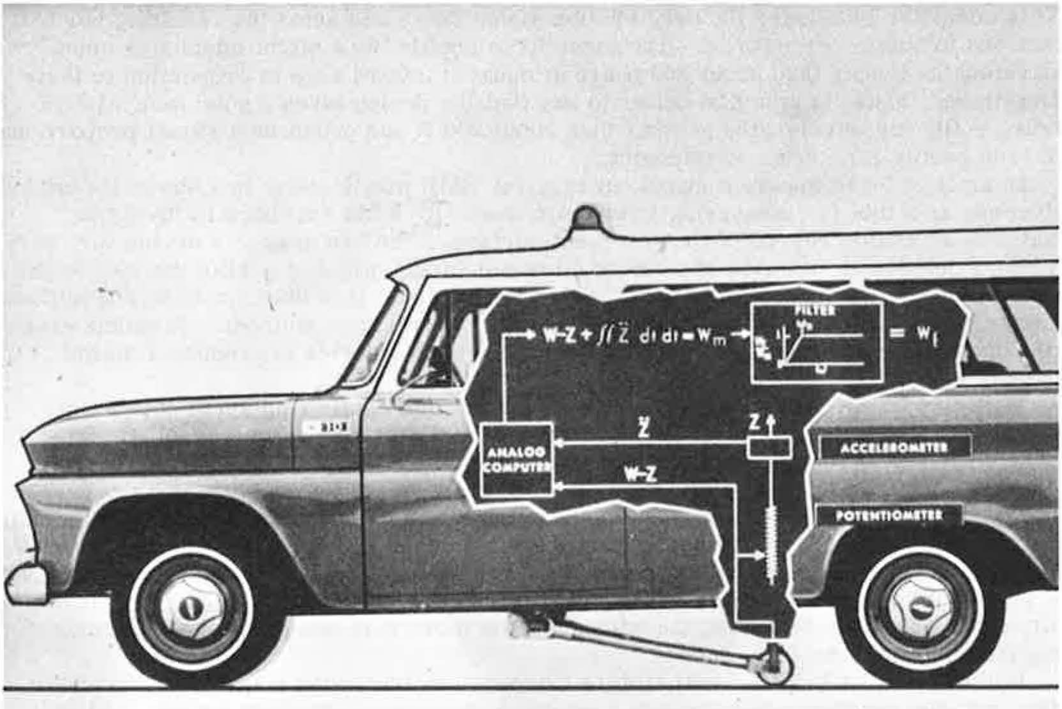


Figure 2. GMR road profilometer.

Minneapolis-Honeywell Corporation. The latter company at one time proposed to build for the Texas Highway Department a device stabilized by a single vertical gyro. However, experience at the AASHO Road Test has shown that a vertical gyro will not provide an accurate reference for measurement of profiles at high speeds. Large errors are introduced into the profile by precession of the gyro due to accelerations imparted by rough roads at high speeds. Further pursuit of this subject with commercial firms indicated that no stabilized platforms of the required accuracy were available at a cost of less than $100,000. A gyro-stabilized platform consists of three gyros mounted with their principal axes arranged orthogonally to each other to provide three-dimensional stability against rotation. Such a platform can be used as a very accurate indication of true horizontal. It appears that development costs for such a device would be approximately $100,000 if borne by an agency such as the Texas Highway Department or the Bureau of Public Roads.

Continued investigation into this subject, however, indicates that such a platform is being developed by a firm of physicists, LaCoste and Romberg, manufacturers of gravity meters, in Austin, Texas. They propose to use the platform as a base from which to measure very accurately small differences in the earth's magnetism or gravity. These differences are used to indicate ore deposits of various kinds. As soon as this platform is sufficiently operable, it will be tested as a possible road roughness profilometer.

GMR Road Profilometer—The only existing profilometer which appears capable of measuring true profile accurately is a device developed by the General Motors Research Laboratory, at Warren, Michigan (5). The device is small, compact, and relatively inexpensive (Fig. 2). The road wheel is mounted on a trailing arm underneath the measuring vehicle and is held in contact with the ground with a 300-lb spring force. The truck mass and truck suspension form a mechanical filter between the road and the accelerometer. The relative motion of a location on the vehicle body and the road wheel is measured with a potentiometer. The accelerometer is mounted on the vehicle body above the road-following wheel at a point where the potentiometer fastens to the body. Figure 3 is a diagram of these components. The signals from the accelerometer and the potentiometer are input into an analog computer which is carried in the vehicle. This computer integrates the acceleration signal twice and sums the resulting vertical motions to obtain true profile. The term "true profile" is a slight misnomer since wavelengths longer than about 200 ft are attenuated toward zero in proportion to their amplitude. Thus, it would be better to say that the device gives a good indication of true profile for wavelengths shorter than about 200 ft and produces a signal proportional to true profile for longer wavelengths.

In spite of these apparent shortcomings, the GMR profilometer has shown its effectiveness as a tool for measuring road roughness. Its main drawback is its output, which is an analog record of the pavement surface. The use of such a device for, say, 4 hours per day at 50 miles an hour could result in 200 miles of profile per day or the equivalent of 1000 road miles of profile per work week. It is uneconomical and almost humanly impossible to read such quantities of data with hand methods. It seems essential that electronic data processing be coupled with this device to produce a digital output.

With this in mind several efforts have been made to obtain equipment capable of converting the analog output of the GMR device to digital form. Two excellent proposals have been received. A summary of each proposal is included in the Appendix. These proposals were developed after several conferences between the Project Director and personnel from interested firms and, while not complete in all details, they should provide a good basis for estimating data processing needs and costs. In both cases it appears that the purchase price of such equipment is approximately $40,000 to $50,000. A large portion of this cost, however, can be saved by renting part of the equipment on a per-mile basis, or by using the equipment for more than one purpose, thus amortizing the cost more rapidly.

In the spring of 1966 General Motors Corporation announced plans to market their device to the general public through a licensed equipment manufacturer, K. J. Law Engineering Company, Detroit, Michigan. The device will be known as the Surface

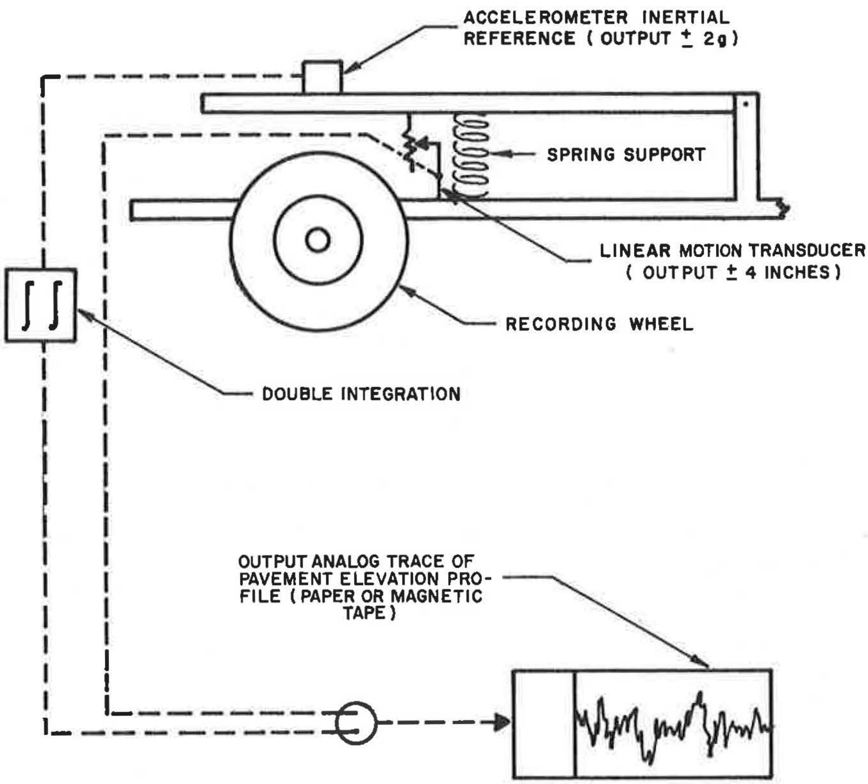


Figure 3. Schematic of GMR road profilometer.

Dynamics Road Profilometer. Unfortunately, the Center for Highway Research has not been able to obtain the use of a GMR device for evaluation. This has caused a delay in gaining information necessary to complete this project. A model of the new equipment was to be delivered to the Texas Highway Department early in 1967.

The Michigan Highway Department obtained a GMR profilometer from General Motors in 1964. A recent visit indicates that they now have the device working well. They have compared runs with the General Motors model and obtained excellent results. At the present time they use a simple vertical motion counter to summarize their data. They are working on development of power spectral techniques.

The many unknowns involved in this problem make it very difficult to establish accurate cost estimates, and, for that reason, no detailed cost breakdown is presented here. The best available information, however, indicates that a two-track GMR profilometer complete with towing vehicle will cost approximately \$50,000. Data processing equipment will cost from \$30,000 to \$50,000, so that the total equipment package may cost approximately \$80,000 to \$100,000.

## Statistical Profilometers

In addition to a "true profile," an instrument capable of measuring roughness and summarizing it in the field is needed by highway departments for use in determining present serviceability index.

Evaluation of this problem has uncovered two types of equipment of potential usefulness for obtaining statistical summaries of pavement profiles, thus providing PSI in the field without the need for digital computers. One of these, the Kentucky Accelerometer, is presently in use in Kentucky and could be purchased and put into operation by others within six months. The other device is one being developed by the Lane-Wells Corporation.

The Kentucky Accelerometer—The Kentucky Department of Highways has available plans and specifications for accelerometer profile equipment which the Department developed. The equipment is not available commercially as yet. The parts and pieces for manufacturing such a device can be purchased for approximately $2,000. In addition the use of a standard automobile costing approximately $2,500 is required.

The Kentucky equipment has several distinct advantages but also several disadvantages. Data from the NCHRP study conducted at Purdue (7) indicate that the Kentucky device can measure PSI just as accurately as the CHLOE profilometer. Furthermore, it operates at speeds of 40-50 mph and therefore qualifies as a high-speed device. Finally, the equipment is already in existence and can be purchased without the delay of commercial developments.

The disadvantages of the equipment cannot, however, be neglected. As presently used by Kentucky the device involves the measurement of accelerations on a human body riding in a standard automobile. Cursory studies published by Kentucky indicate the effect of variations in the physical build of the subject and of the automobile is relatively minor. These factors do affect the profile to some extent; but the most important effect, as might be expected, is the quality of the automobile being used. A compact or "stripped, low-price car" gives relatively rough profiles when compared with those obtained from higher priced, luxury automobiles.

Lane-Wells Equipment—During recent years the Lane-Wells Corporation, a wholly owned subsidiary of Dresser Industries, has applied its technical knowledge to the improvement of equipment used in highway engineering. Their best-known developments include the nuclear road logger and a device for measuring deflections under dynamic load called a "Dynaflect." They have budgeted some $25,000 for the development of a prototype high-speed summarizing profilometer capable of providing PSI in the field without the requirement for digital computers. The pressure of other work, however, has delayed the development of this prototype.

## DATA PROCESSING AND ANALYSIS

An adequate physical description of pavement roughness is very complicated due to its multidimensional nature. Simplifications are required to describe roughness in terms meaningful to most engineers. The forces and movements to which the highway user is subjected by this pavement roughness are also very complex. As with many natural phenomena, man's efforts to describe pavement roughness and its effects have lead to empirical correlations, in this case between certain easily defined roughness parameters and the subjective rating of the riding quality of the pavement by the highway user. Such ratings have been termed present serviceability rating (PSR), and the resulting correlation based on certain measurable parameters, present serviceability index (PSI) (1).

The PSI concept has been very useful in recent years but the problem is by no means solved. Statistical evaluation of pavement ratings (1, 4, 7) indicates correlation coefficients for various roughness measurements to be in the range of 60 to 90 percent. Most of these correlations involve rather elementary use of longitudinal profile information. Better measurements should lead to better correlations. Continued study of human response to external stimuli and of roadway roughness parameters should lead to better ways of measuring pavement roughness and thus to better ways of characterizing the subjective serviceability rating of the highway user.

Most of the factors used in previous correlation work have been rather simple statistics, such as the summation of the deviations of the deflection profile from some mean value (Bureau of Public Roads Roughometer and the Michigan Profilograph). Other statistics include (a) the summation of the area under a continuous analog plot of vertical accelerations and (b) variance of slope measurements taken by a slope profilometer. In every case the development of these statistics has been governed by available economical data handling techniques.

Other more sophisticated data processing techniques have been developed. Coupled with the advent of better data recording equipment, these will undoubtedly make the use of the more sophisticated methods meaningful and desirable.

Two such useful data processing techniques are the harmonic analysis and the power spectral density analysis. In general, a harmonic analysis is useful for evaluating periodic or repetitive wave patterns. The power spectral density function on the other hand is most suitable for characterizing random functions. In one case the validity of the analysis depends on the assumption of periodicity; in the other on randomness.

Unfortunately, highway roughness is neither completely random nor especially periodic although periodic wave patterns often develop under repetitive traffic. Examples of periodic patterns include 15-ft joint spacing in concrete and washboarding associated with some classes of weaker flexible pavements. On the other hand, many pavements, particularly flexible pavements and continuously reinforced pavements, show no such periodic pattern.

Although the harmonic and power spectral analyses are rather complex, a practical method of performing them has been developed. Some of the best work available to date has been accomplished by Hutchinson (3). Other significant work has been done by Quinn (10). A complete discussion of these two methods does not seem to be appropriate here since only their use in analysis, evaluation, and correlation of ratings can provide an understanding of their suitability as pavement parameters.

Many other possible methods of analysis present themselves, such as an evaluation of body accelerations and the analysis of slope variance, as done at the AASHO Road Test. In such analyses, it is probable that some measure of frequency and wavelength should be considered along with amplitude.

The two types of profilometers of interest to the highway engineer have been discussed. One is the true profilometer, capable of giving rather exact reproduction of the pavement surface, and the other is the statistical summary profilometer, which coordinates data processing equipment in the field and produces a summary statistic which is correlated with riding quality. The development of the true profile equipment will facilitate research into the problem of correlating various roughness parameters with riding quality. The high-speed statistical profilometer is badly needed to provide highway engineers and researchers with rapid, efficient means of evaluating pavement serviceability in the field.

The equipment required for processing and analyzing data is even more diverse than the possible methods of recording the data because the output from each measuring method can be processed in many ways. In most instances it is desirable to discreetly sample a continuous analog output. Such a technique would be useful in sampling the output of the Kentucky accelerometer equipment and the GMR profilometer output. The proposals received describe equipment capable of performing this task and producing the output in a form compatible with high-speed digital computational equipment.

Equipment suitable for performing summary calculations and data processing in the field is highly dependent on the transducer and recording equipment. Many such techniques have been employed. These vary from the simple one-way clutch "integrater" used on the Bureau of Public Roads Roughometer, through the solenium electrochemical integrater used by the Kentucky device, to the compact special purpose digital computer developed and utilized with the CHLOE profilometer.

In summary, the data processing requirements can be stated as follows:

1. True profile information must be easily digitized for machine computations to be useful.
2. Summarizing-statistical profilometers should be equipped to do routine processing analysis in the field, but under certain circumstances digital output which can be processed by digital computers overnight could also be used very successfully.

## SUMMARY AND RECOMMENDATIONS

It is not possible nor desirable to make an exhaustive study of existing roughness equipment on a limited budget. Such a survey would require several studies the size of the NCHRP Study at Purdue (7). Furthermore, the instrument which should be evaluated, a GMR-type profiler coupled with automatic digital data processing equipment, does not exist. However, all other available information has been evaluated.

Consideration of all data now available indicates that the GMR profiler should be adapted for use by highway engineers. It is high-speed, far more accurate than other equipment available, and compact and efficient in operation. With the addition of proper digital data processing equipment the GMR device can serve not only as a basic tool for evaluating roadway profile parameters and their relationship to riding quality and ultimately to specifications for finished roadway surfaces, but can also serve as a summary profiler for evaluating serviceability (PSI) for pavements as desired by highway engineers and designers throughout the nation. Such a device would greatly facilitate the observation of selected experimental sections.

## ACKNOWLEDGMENTS

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# *Appendix*

## PROPOSAL FOR A ROAD-PROFILE DATA ACQUISITION AND PROCESSING SYSTEM

### FOREWORD

This proposal is submitted in response to a letter request-for-proposal dated February 26, 1965, from the Center for Highway Research, The University of Texas, Austin, Texas.

A Road Profile Data Acquisition and Processing System comprised of two subsystems is proposed. One subsystem consists of equipment to be installed in a truck, which is to be used in conjunction with a General Motors Corporation Road Profilometer to obtain and record road profile data in analog form. The other subsystem is an analog-to-digital tape conversion system to be installed in the laboratory, which converts the data on the analog tape to digital form. The digital tape produced by this subsystem contains the data in a format suitable for processing by the Control Data Corporation (CDC) Model 1604 Digital Computer presently installed at the Center.

### SUMMARY

It is proposed to furnish and install a Road Profile Data Acquisition and Processing System designed for use with a General Motors Corportation Road Profilometer. The

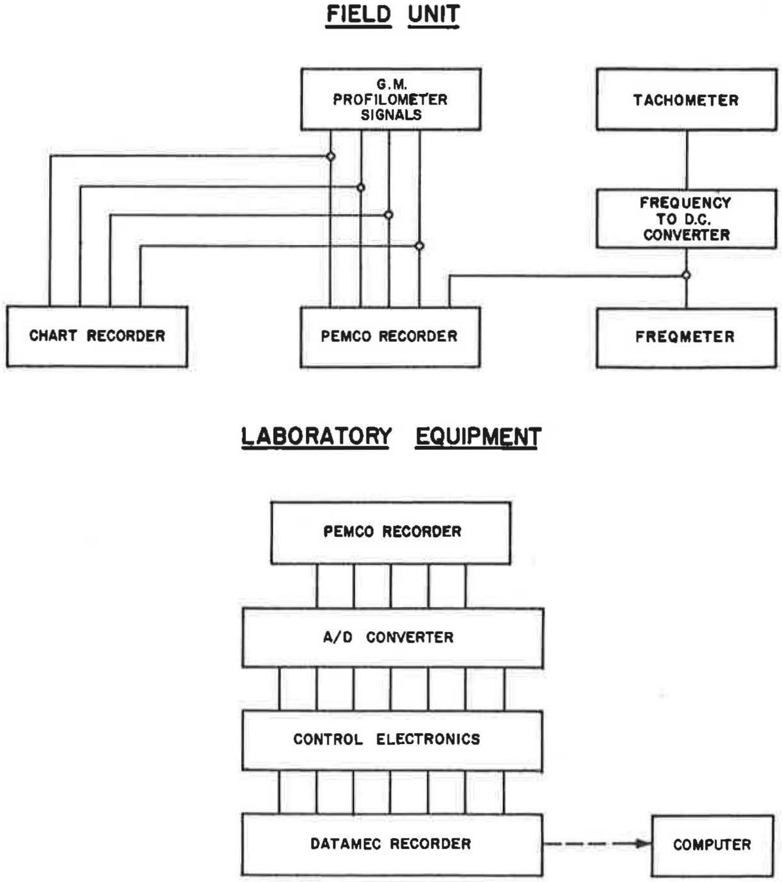


Figure A1. Proposal for a road profile data acquisition and processing system.

proposed equipment can record and process data from a vehicle containing two road profile transducer systems.

The proposed system is composed of two major assemblies; one is used for the acquisition of data, and the other for the conversion of the acquired data to a form suitable for processing by a digital computer. The data acquisition components are to be installed in a truck furnished by the customer. They supply reference data that augments the data obtained with the Road Profilometer. A portable, analog magnetic-tape recorder records the Road Profilometer and reference data as analog signals, and is used in the laboratory to play back the data into the conversion system. The analog-to-digital conversion components are to be installed in an equipment enclosure furnished by the contractor. This assembly converts the analog data to digital form on a computer-compatible tape.

The PEMCO Scientific Data Recorder used to record the data has a 1000-foot capacity, giving a recording duration of 26 minutes and, therefore, a recording distance of 26 miles when the truck is operated at the maximum acquisition speed of 60 mph. The accuracy of data conversion is 0.5 percent and the linear resolution is one inch when data is acquired at 60 mph.

A Thermal Writing Recorder is recommended as optional equipment for visually checking the analog data in the field. This chart recorder is not included in the contract price since it is not essential to system operation.

The price of the proposed system is $41,230. The Thermal Writing Chart Recorder can be furnished for an additional cost of $4,500. An inverter which will permit the Chart Recorder to operate from the truck's 12 volt battery is available at a price of $3000. The installation of the equipment in the truck will be performed by the contractor on a time and material basis. The contractor will guarantee freedom from defects in workmanship and materials for one year, exclusive of major assemblies of other than the contractor's manufacture. Delivery will be made within 120 days after receipt of a purchase order.

## PROPOSED MODIFICATION OF GMR ROAD PROFILOMETER TO FACILITATE AUTOMATIC DATA REDUCTION

A cost study has been made at the request of the Center for Highway Research to determine the approximate cost of a system to convert the output of the GMR Road Profilometer to a form easily acceptable by a computer. Two different cost estimates are shown below, one for leasing the equipment on an hourly basis and the other constructing a complete data conversion system. The cost shown below is not a firm quote, but is of the approximate value.

A block diagram of the proposed system is attached showing the recording system for the field equipment and the data conversion equipment. The analog data representing the road profile will be recorded on a portable FM magnetic tape recorder. Also the distance markers and voice will be recorded simultaneously on two channels of the recorder. A photocell pickup would have to be added to the GMR Profilometer to give better distance resolution. A tone generator could also be supplied to enable the operator to mark an event on the voice channel by simply pushing a button.

The same recorder could be used in the data conversion equipment for playback purposes. The analog profile data would by digitized by an analog to digital converter and sampled by the distance markers. These markers would probably be spaced every three (3) inches., After the profile data is digitized, it will be stored on digital magnetic tape in the form easily handled by available computers. Also a typewriter keyboard will be necessary to add header information on the magnetic tape and control the operation of the whole system. A breakdown of the costs follows.

I. Portable Equipment

| | |
|---|---|
| Parts | $19,890 |
| Labor | 1,500 |
| | $21,390 |

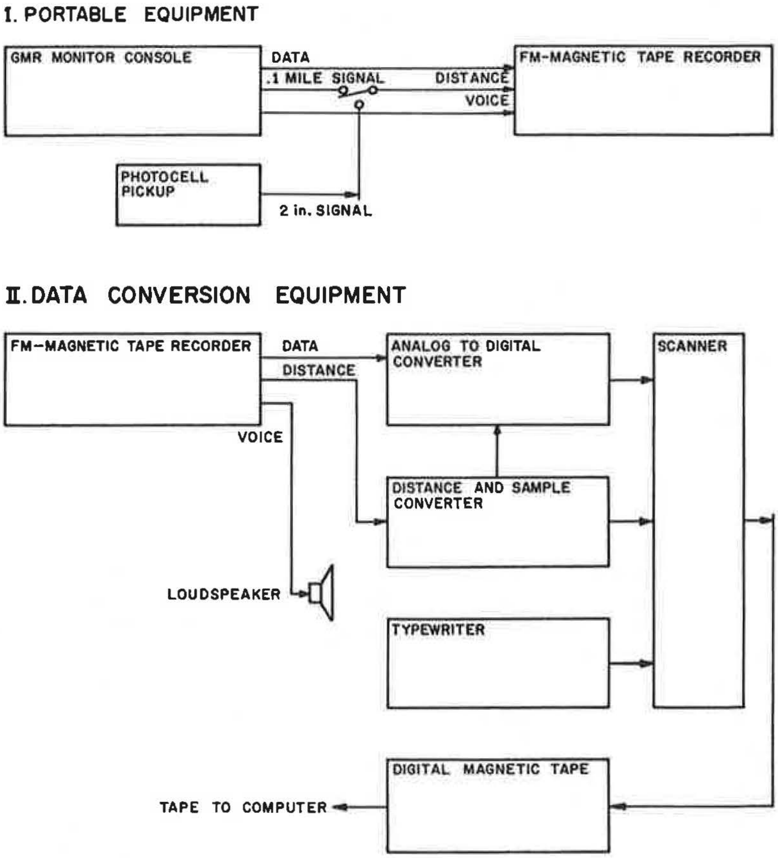


Figure A2. Proposed modification of GMR Road Profilometer to facilitate automatic data reduction.

| | |
|---|---|
| II. Data Conversion Equipment | |
| Parts | \$27, 330 |
| Labor | 4, 500 |
| | \$31, 830 |
| III. Total Cost | |
| Portable Equipment | \$21, 390 |
| Data Conversion Equipment | 31, 830 |
| | \$53, 220 |

The other alternative of reducing the profile data is to record the data as before and lease time on existing equipment. This equipment can be leased locally at a rate of approximately \$150.00 per hour. The analog data can be played back eight times faster than recorded. This would then cost \$18.75 per hour of data. The cost of the portable equipment above would remain the same and the \$31, 830 would not be required. If the \$31, 830 was applied to lease the equipment and data were recorded at 25 miles per hour, approximately 42, 300 miles of data could be converted.

The most economical method of converting the profile data will depend on the number of miles of data recorded and the maximum number of GMR Road Profilometers being serviced.

## *Discussion*

PAUL MILLIMAN, Supervisor, Instrumentation and Data Systems, Research Laboratory Division, Michigan Department of State Highways (Presented by E. A. Finney, Director, Research Laboratory Division, Michigan Department of State Highways)—Mr. Hudson has excellently summarized the field of highway profilometry, with emphasis on current systems—especially the system developed by General Motors Research. This brief supplemental discussion is in support of his comments relative to the GMR profilometer, and results from work performed with Michigan's GMR-type profilometer.

In 1962, the Michigan Department of State Highways teamed up with the General Motors Technical Center to determine the accuracy, reliability, and applicability of the GM rapid travel road profilometer to routine highway testing of road surfaces. This work, conducted in cooperation with the Bureau of Public Roads, had three principal objectives.

The first was to determine whether profiles reported by the GMR device were true profiles, using the term "true" in the same sense as Mr. Hudson, namely survey or elevation profile (of limited wavelength, of course). This was accomplished in the following manner:

1. The first step was to investigate the system's ability to reproduce dimensions and shapes of known pavement surface irregularities, and effects of various speeds on this ability. This was done by fabricating three steel obstacles, securing them to a pavement surface, and then profiling them at various speeds. The three shapes used were a semicircle, a triangle, and a rectangle, all of 1-in. amplitude. Shapes and dimensions reported by the profilometer were excellent at low speed (about 10 mph). Predictably, at higher speeds the large amplitude of these artificial bumps tended to throw the follower wheel away from the surface.
2. For the second verification method, nine test sections were selected, each representing a different construction method. They included six 1000-ft pavement sections and three bridge decks and approaches. On each of these test sections, elevations were taken with a precise level and target, at 1- to 5-ft intervals. Machine profiles were taken simultaneously with these elevation or "true" profiles. The results of this work were excellent. The machine profiles, taken at speeds up to 40 mph, duplicated the survey profiles for all practical purposes. After study of the data it was concluded that in those locations where the two profiles did exhibit minor differences, it was simply a matter of a continuous profile (machine) vs one made up of a series of connected straight lines (survey).

The second objective was to determine the correlation, if any, between the GMR profilometer and BPR-type roughometers, and between the profilometer and CHLOE-type slope variance devices. Successful correlation would allow replacement of both of these types of instruments with a superior device while not invalidating the massive body of important pavement data which they have accumulated over the years. In addition, it would permit determination of pavement serviceability indices with the profilometer.

Since both the roughometer and CHLOE produce a single accumulated numerical result for any surface measurement, it was necessary that a method be devised to digitize machine profiles prior to any correlation tests. Therefore, an electronic digitizer was designed and constructed. The output of this accumulator is the numerical sum, in inches, of all positive excursions of the profile being digitized.

Simultaneous runs were performed on 22 sections of flexible, overlay, and rigid pavement with the profilometer, Michigan's BPR-type roughometer, and a slope variance instrument furnished and operated by the Bureau.

Correlations resulting from these tests were all excellent and readily usable. They demonstrate that adoption of the new profilometer will not disrupt or invalidate pavement roughness histories and that pavement serviceability indices can be readily obtained.

The third and final objective was to determine whether the system was of such a nature and ruggedness as to be capable of the type of extensive, continuous use to which it would be subjected in highway work. It was decided that the only practical way to determine the durability and reliability of the system was to put it into service and see how it performed.

Before and after completion of the accuracy and correlation work, thousands of miles were logged with the system. It has been used on many projects, including bridge finishing studies, evaluation of blowup repair methods, performance of insulated flexible pavement, 24-hr observation of pavement slab action, joint spacing studies, continuously reinforced pavement evaluation, progress of joints constructed without load-transfer dowels, initial roughness surveys of new pavement projects (to be supplemented with 5-year measurements), as well as other miscellaneous applications.

Throughout all of this work, the system has performed admirably. The only malfunctions of any consequence to date have been in the system's magnetic tape recorder. These malfunctions, which were minor, have been isolated and corrected. The reliability and durability of the system have been demonstrated to be excellent—exceeding expectations.

Despite its complexity and the need for skilled operating personnel, the GMR Profilometer should ultimately prove to be of great value to highway engineers. In particular, it promises to be of great assistance to researchers studying over-the-road vehicle dynamics, and interactions of road and vehicle. It is being used for such purposes in a current research project in Michigan.

It is a device of great potential.