65-3391

3742-5-F

FEASIBILITY STUDY OF A PAVEMENT-DEFLECTION MEASUREMENT SYSTEM

W. H. LAWRENCE
I. J. SATTINGER
L. H. THOMAS

November 1960

Special Projects Group
Institute of Science and Technology
THE UNIVERSITY OF MICHIGAN
Ann Arbor, Michigan

MICHIGAN STATE HIGHWAY DEPARTMENT
Highway Planning Survey Work Program HPS-1 (25)
Michigan Pavement Performance Study
Project No. 03088.

CONTENTS

FIGURES

TABLES

FEASIBILITY STUDY OF A PAVEMENT-DEFLECTION MEASUREMENT SYSTEM

1
INTRODUCTION

This feasibility study has been carried on for the Michigan State Highway Department, Highway Planning Survey Work Program HPS-1 (25), as one of the tasks of the Michigan Pavement Study Project (Project Number 03088). The objective of the Michigan Pavement Performance Study is to measure and evaluate pavement performance on existing roads under actual service conditions and to correlate the data gathered with Michigan standards of design and construction. More specifically, as the means of accomplishing the objective, the study is focused on the recording and analysis of pavement profiles and changes in the pavement surface. This project is under the supervision of the Office of Testing and Research, Michigan State Highway Department, and the direction of William S. Housel, Professor of Civil Engineering and Research Consultant. The feasibility study was conducted at the request of the Michigan Pavement Performance Study Project by the Special Projects Group of the Institute of Science and Technology.

One measure of the adequacy of a pavement, presently being given much attention, is the deflection of that pavement under present legal axle loads or those which may be contemplated in the future. The specific task undertaken by the Special Projects Group was the preliminary design and cost estimate of a highly accurate truck-mounted profilometer capable of recording a continuous load-deflection profile somewhat similar to the unloaded pavement profiles now being recorded. The immediate purposes of this task were to determine the feasibility of constructing this equipment in such a way to insure, insofar as possible, that the planned equipment would accomplish its basic objective, and to determine the probable cost of such equipment.

As a basis for this preliminary design study, it was assumed that pavement deflections of interest would have a magnitude of .050 inch or less. Hence, it would be desirable to measure such deflections with total system errors not exceeding .005 inch. Measurements along the inner wheel path and the outer wheel path are desired. It is preferable but not absolutely necessary that these measurements be continuous rather than intermittent. The speed of the measuring vehicle along the highway should be a maximum consistent with the necessary test accuracy. A pavement-roughness measuring system, similar to that being used on the existing pavement-evaluation vehicle of the Michigan State Highway Department, should also be included in the new measurement system. The pavement-roughness measurement devices may be distinct from the pavement-deflection measurement devices, but they should be situated to permit direct alignment of the roughness measurements at a given position with the deflection measurements at the same position without excessive data processing. The maximum axle load to be used for the deflection measurements would be 50,000 pounds. The total over-all length of the measurement vehicle should be minimized, and provision should be made in the vehicle design for reasonable maneuverability.

Some general suggestions are made in Section 2 for improvements of present methods of measuring pavement roughness. The main emphasis of this study, however, has been placed on the problem of pavement-deflection measurement. In Section 3, an instrumentation vehicle is described which is capable of making continuous measurements of pavement deflection under load. The electrical and mechanical design features of this system are presented in some detail, and an estimate is given of the cost and time required to develop such an instrumentation system. As an alternative to this system, an instrumentation vehicle which would make pavement-deflection measurements at discrete intervals along the pavement rather than continuously is described in Section 4. Although this method is not capable of the speed of advance and continuity of measurement of the system described in Section 3, it has the advantages of substantially lower cost and higher measurement accuracy. It is believed that these advantages outweigh any disadvantages of the system; hence, the intermittent-measurement system is recommended for implementation.

2
PAVEMENT-ROUGHNESS MEASUREMENT METHODS

The basic method of obtaining graphical recordings of pavement roughness being used in the present Michigan pavement evaluation vehicle is generally satisfactory and may therefore be used in the new system. However, some design changes which will result in increased over-all accuracy and reproducibility of data should be adopted. In particular, it is desirable to make the reference beam used for the measurements structurally independent of the load-bearing members. Also, the profile-reference and sensing-wheel assemblies can be modified to reduce the effects of lateral forces on the deflection transducers and to improve performance at higher speeds. Modifications of commercially available graphical recording systems can be obtained which will provide increased frequency response with greater convenience of operation and adjustment.

Some alternative methods of pavement roughness measurement were also studied briefly. These methods, which are described in Appendix B, differ from the present method in that they would provide roughness recordings with less distortion in the short-wavelength components of the elevation profile.

3
INSTRUMENTATION SYSTEM for CONTINUOUS PAVEMENT-DEFLECTION MEASUREMENT

A general description of the equipment and techniques proposed for a pavement-deflection measurement system capable of continuous measurement is presented in this section. Additional system design details are contained in the appendix. Many of the particular design details described here should be considered as tentative and subject to change after more thorough study.

3.1. MECHANICAL CONFIGURATION

The mechanical configuration of the proposed measurement system is shown in Figure 1. The system consists of two vehicles:

(1) A tractor-truck which carries an instrumentation compartment and the necessary auxiliary power supplies.

(2) A full trailer which incorporates the road roughness and deflection-measurement components.

In operation, measurements are made as the trailer is towed by the tractor at a nominal rate of 5 mph. This speed might be reduced, if required by the road condition or the desired accuracy of measurement.

The tractor consists of a conventional truck chassis with a wheel base of about 20 feet. The instrumentation compartment of the truck contains all of the provisions necessary for the operation of the measurement system and for recording both the roughness and deflection data.

The measurement trailer is of special design having an over-all length of about 70 feet and a maximum load capacity of 50,000 pounds over the rear load axle. The nominal load over the rear load axle due to the structure of the trailer is 18,000 pounds. The maximum load would be obtained by adding solid or liquid ballast. A tandem rear axle would have a steering capability for increased maneuverability when the trailer is not operating in the measurement mode. The rear-axle suspension would be designed to permit retraction of the steering axle and extension of the load axle while operating in the measurement mode. A single front steering axle would be controlled by a tongue connecting the tractor and the trailer. The incorporation of front and rear steering will permit the trailer to be moved backward as well as forward.

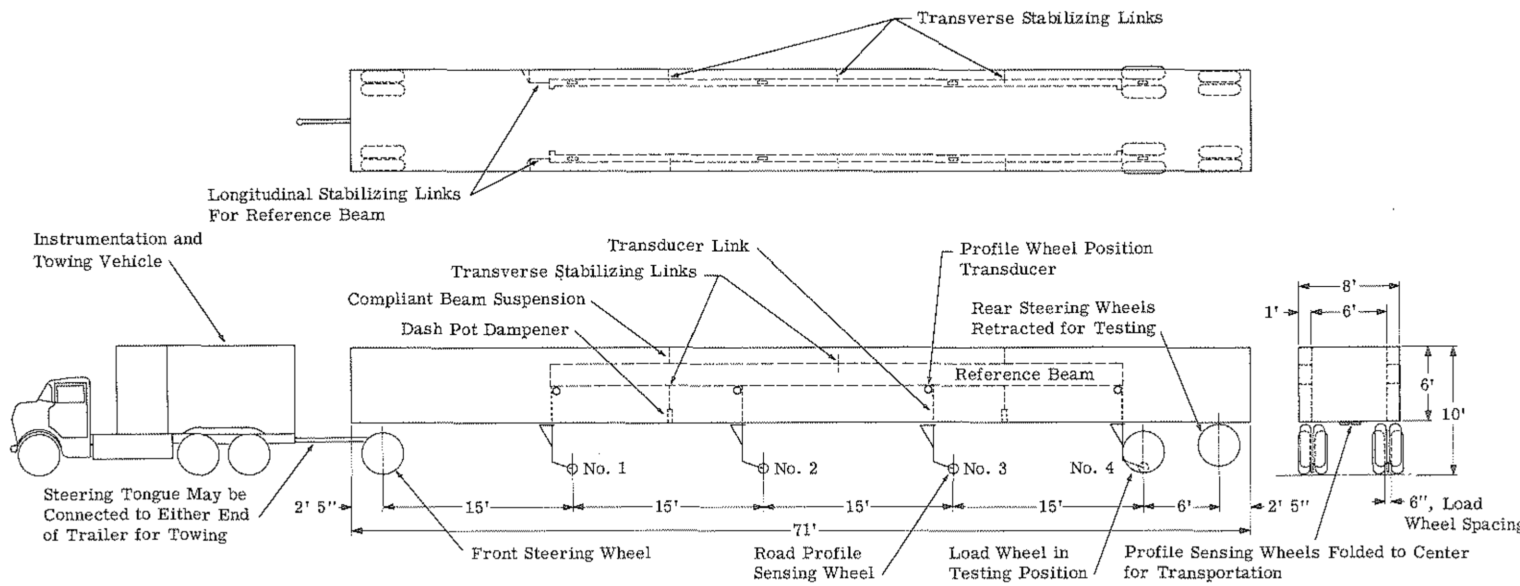

FIGURE 1. INSTRUMENTATION VEHICLE FOR CONTINUOUS ROAD-DEFLECTION MEASUREMENT

3.2. MEASUREMENT SYSTEM

The deflection measurements will be accomplished by means of a reference beam and four sensing-wheel assemblies in each wheel path. The reference beam is 45 feet long and adjacent sensing wheels are spaced at 15-foot intervals. An accurate transducer, described in Section 3.3, is used to measure the vertical position of each sensing wheel with respect to the reference beam. The construction of the reference beam and its mounting on the trailer are such as to make it relatively insensitive to undesirable forces acting on the sensing wheels and the load-carrying wheels of the trailer.

As the trailer is pulled along the pavement, measurements of the vertical position of the sensing wheels are recorded at constant time intervals, corresponding to about one inch of horizontal travel at a velocity of 5 mph. Sensing wheel No. 4 is situated between dual tires on the load axle near the rear of the trailer. These tires apply a vertical load to the pavement as a result of a load mounted in the trailer directly above the axle.

The deflection of the pavement at a given point is determined by two separate measurements. In order to determine the deflection of point C in Figure 2, the first measurement is made with the trailer in the position shown in the figure. The elevation of point C is determined with respect to a reference line passing through points A and B. The second measurement is made when the trailer has moved ahead 15 feet. At this instant, sensing wheels No. 2, 3, and 4 have taken the positions originally occupied by sensing wheels No. 1, 2, and 3, respectively. A second measurement is now made of the elevation of point C with respect to the line joining points A and B. During this second measurement, the total axle load of the rear wheels is being applied at point C because the load wheels coincide with sensing wheel No. 4. In the data-reduction process, the deflection of point C due to the load can then be deter-

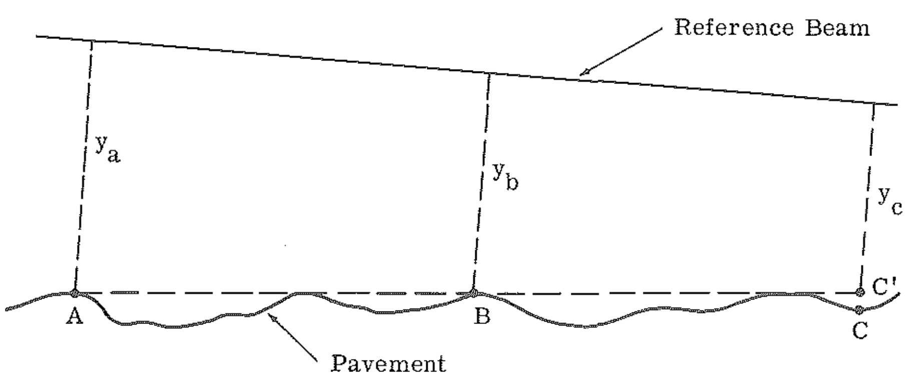

FIGURE 2. MEASUREMENT GEOMETRY

mined by subtracting its loaded elevation from its unloaded elevation. Although the above discussion has referred only to the measurement of point C, the system would be mechanized in such a way that the continuous measurements made at all four reference wheels would be used to compute a continuous curve of pavement deflection.

The computation involved in measuring pavement deflection is based on the diagram of Figure 2. The extension of the line through points A and B intersects the axis of the third transducer at C'. The distance CC' is given by

$$\Delta y_c = y_c - 2y_b + y_a$$

The pavement deflection, D, is determined by subtracting Δy_c, measured at time t_2, from Δy_c, measured at time t_1. Thus, taking into account the specific wheels located at points A, B, and C at the two instants of measurement:

$$D = y_4(t_1) - 2y_3(t_1) + y_2(t_1) - y_3(t_2) + 2y_2(t_2) - y_1(t_2)$$

The measurement technique just described is conducive to high accuracy since the two measurements of pavement deflection at a given point are made with respect to the same reference points on the pavement, and these reference points are located so that their elevation is not affected by the trailer wheel loading. It should also be noted that the position of the reference beam does not need to be the same for the two measurements for a given point. Variations in the position of the reference beam between these two instants of measurement are accounted for by the equation just derived. The method of measurement has the further advantage that the over-all length of the trailer required for the measurement is a minimum.

3.3 DATA-PROCESSING SYSTEM

The system just described has two basic requirements which distinguish it from the existing pavement-roughness measurement system. First, considerably greater accuracy will be required, and second, the time delay which occurs between the initial and final measurements necessitates the temporary storage of the initial measurements before computing the difference. Because of these requirements, all of the raw profile data will be measured, recorded, and processed in digital form, and the final steps in data reduction will be performed by a digital computer. The use of digital computation methods has the additional advantage that it permits great flexibility in analyzing the data. The proposed digital recording method does have the disadvantage that partial or approximate results cannot be readily obtained in the field.

Figure 3 shows a block diagram of the data-acquisition system. The position transducers associated with the sensing wheels are of the digital encoding type. The transducer consists of

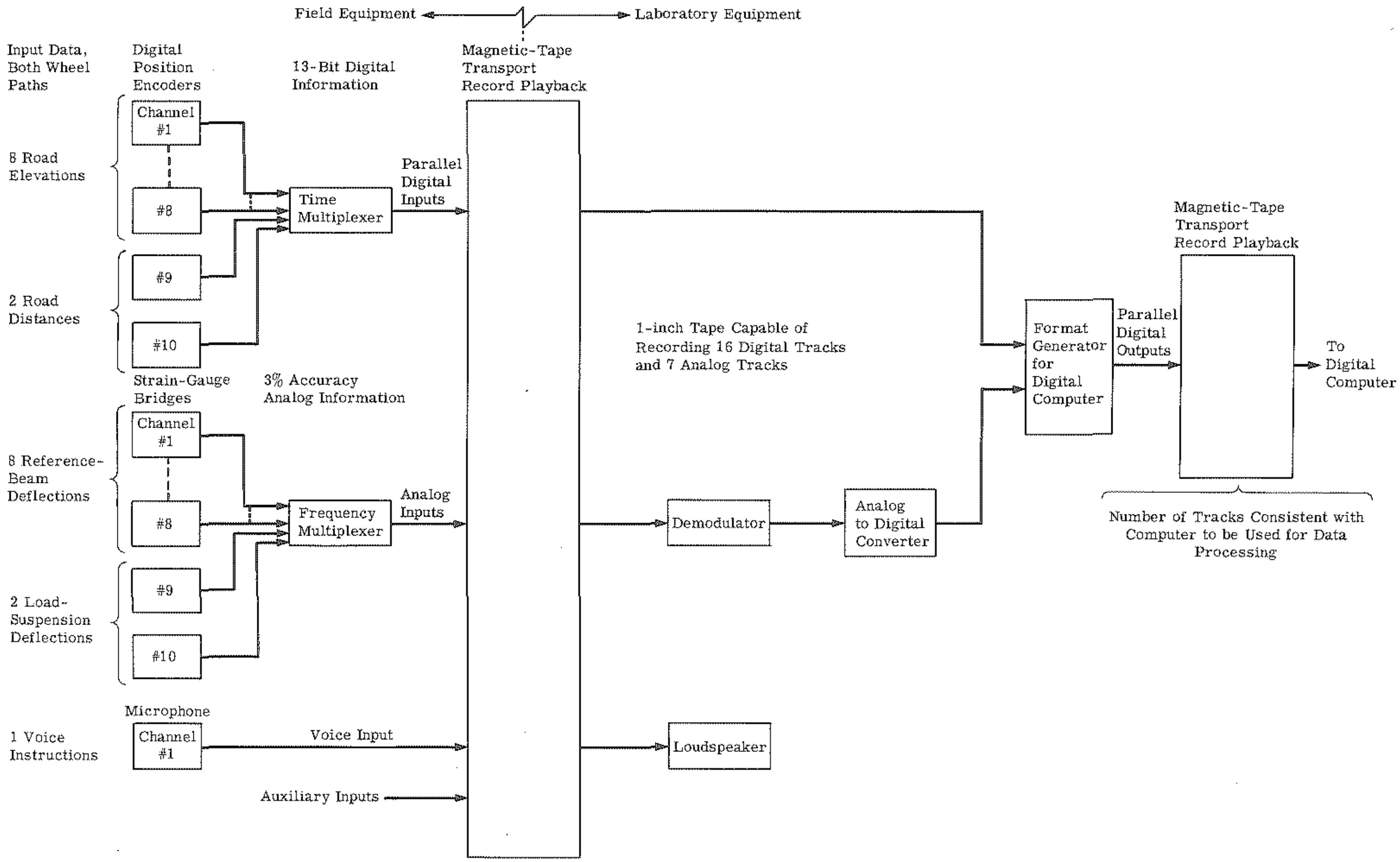

FIGURE 3. BLOCK DIAGRAM OF DATA-ACQUISITION AND RECORDING SYSTEM

a standard photoelectric shaft-position encoder. It is attached to the sensing wheel by a mechanism which converts rectilinear motion to rotary motion. The transducer can measure to an accuracy of 13 bits (i.e., binary digits) corresponding to a resolution of one part in 8092, or .001 inch in a total travel of about 8 inches, which is well within the required system accuracy.

The outputs of transducers for the measurement of sensing-wheel position, longitudinal vehicle motion, and strain-gauge measurements of the reference-beam deflection are fed to a multichannel magnetic-tape recorder, mounted in the instrumentation compartment of the truck. Auxiliary inputs are also shown for road crack locations or other information that may be useful in evaluating the results. The magnetic tape containing the measured data is to be returned to the laboratory, where the same tape-transport mechanism may be used for playback. The reproduced data is then converted to a format suitable for introduction into a general-purpose digital computer. A special program will be prepared to be inserted in the computer along with the field data, so as to obtain the reduced information on pavement deflection in suitable form. This can be provided either in tabular form or as a graphical plot. More detail on the method of recording and interpreting the transducer outputs is given in Appendix A.

Any of various current types of commercial digital computer may be used to process the data. The choice of a particular computer, and the decision whether to lease computer time or purchase outright will depend on the anticipated work load and other economic factors which are beyond the scope of this report. Therefore, the computer is not considered as part of the measurement system proper, although it will be necessary to coordinate some aspects of the data-logging system with the particular computer to be used.

3.4. SYSTEM ACCURACY

It is not possible to give a firm estimate of the accuracy of the proposed system. However, some concept of the sources of error and their probable magnitudes can be presented.

In designing the system, the objective will be to keep each source of error to .001-inch maximum. If this can be achieved, it is believed that an over-all accuracy of .010 inch in the measurement of pavement deflection can be obtained, and that it may be possible to keep this error within .005 inch. The basis for this statement is that a number of errors tend to add together in a statistical manner. For example, if there were a total of 25 independent sources of error, each source having a standard deviation of .001 inch, then the standard deviation of the total error would be $.001\sqrt{25}$ or .005 inch. Since there are four sensing wheels in each wheel path, this corresponds to about six independent sources of error per sensing-wheel assembly.

Errors may be introduced into the pavement-deflection measurements by both electrical and mechanical means. As indicated previously, the use of a digital transducer and of digital data-processing techniques avoids the possibility of introducing any electrical error into the system once the measurement has been converted into digital form by the transducer. However, each digital transducer will have a round-off error not exceeding $\pm 1/2$ binary digit out of 13, corresponding to $\pm .0005$ inch.

Errors which can be introduced into the measurement by mechanical means consist of several types. Errors may be introduced by the assembly which converts the reference-wheel position to transducer rotation. Runout of the sensing wheels will also introduce error. Errors of this type can be minimized by careful attention to the mechanical design of these mechanisms, for example, by the use of sufficient material to maintain necessary rigidity, and by the use of methods of avoiding backlash in the conversion from linear to rotary motion.

Errors may be caused if the elevations of the surface sensed at points A and B are not identical for the initial and final measurements associated with point C. This could occur if the total distance traveled between measurements was not exactly 15 feet; hence accurate horizontal-distance measurement is required. It could also occur if the wheels did not follow exactly the same wheel path.

Pitching motion of the trailer bed could cause a longitudinal displacement of the unloaded and loaded measurement reference points, but this effect is not expected to be appreciable. Lateral displacements of the respective reference points could be caused by misalignment of the sensing and steering wheels or by components of motion not parallel to a line through the sensing wheels, as when turning. If this type of error proves to be serious, it can be minimized by processing the data not for measurements at a point, but for measurements averaged over an interval of 1 foot of vehicle travel. In effect, this would result in determining the elevation not at a single point but over a longitudinal distance of 1 foot. Any tendency of the sensing wheels to bounce due to surface roughness would also introduce errors. The sensing-wheel assembly must therefore be designed to keep the wheel in continuous, uniform contact with the pavement.

Deformation of the reference beam will generally appear in the result as an error. Static deflections of the reference beam due to its own weight can be compensated for or taken into account by means of calibrating procedures, as can quasi-static deflections due to temperature effects. The effect of distortions of the trailer body can be practically eliminated by using a two-point pivoted suspension for the reference beam. However, the effect of dynamic forces transmitted to the moving trailer from the road and hence to the reference beam via its suspension system can cause transient or periodic deformation of the reference beam. The magnitude of errors due to dynamic forces will be a function of the road roughness and the velocity of the measurement trailer, a rough surface requiring a relatively low velocity to maintain a given accuracy. For a given road condition and vehicle velocity, the effect of dynamic forces on the reference beam will depend primarily on the relationship between the natural resonance frequencies of the various structural components and suspension systems. For example, the bounce resonance frequency of the trailer mass in combination with its suspension system will ordinarily occur at about 1 cps. At a velocity of 5 mph, this frequency corresponds to a wavelength of 7.5 feet in the pavement. If the suspension system damping is 20% of the critical value, a sine wave in the pavement with a period of 7.5 feet and an amplitude of 0.1 inch will result in about .001 inch of dynamic deflection of a simply supported reference beam, assuming its own natural resonance is well above 1 cps. This deflection can be reduced by supporting the reference beam at intermediate points rather than at its ends. It can also be minimized by using a beam design which has sufficient moment of inertia and beam depth to keep beam deflection to low values. If these precautions are not sufficient to maintain measurement errors within acceptable limits, it is also possible to improve accuracy by measuring and compensating for the deflection of the beam which cannot be eliminated. This can be done by attaching a small number of strain gauges at points along the length of the beam. The outputs of these strain gauges, if properly interpreted, may be used to indicate beam deflection at various positions along the beam. These values of deflection can be used to correct the wheel-position measurements previously described, so as to minimize or eliminate error due to beam deflection.

3.5 INITIAL TEST PROGRAM

As indicated in Section 3.4, the accuracy obtainable with the proposed system is limited primarily by mechanical errors. These errors are, for the most part, associated with the design of the reference system, consisting of the reference beam and sensing wheels. Since a complete determination of system accuracy cannot be specified in advance, it is suggested that a first step in the proposed system development should be the construction and test of the reference system. This assembly would be designed and constructed in accordance with the preliminary design discussed in this report. Instead of incorporating the assembly into a complete pavement-evaluation vehicle containing all instrumentation, it would be possible to evaluate the system accuracy by a temporary test setup. This would consist of supporting the reference beam by means of its springs and damping devices on a long rigid beam, which would be carried on two vehicles.

The accuracy of this system could be established by a series of relatively simple tests in which data would be collected for insertion into the deflection equation of Section 3.2. Instead of performing this test to determine pavement deflection under load, it would be performed by making two sets of measurements on the undeflected pavement. The resulting value of the measured deflection D should therefore be zero. Consequently, any deviation of the calculated value from zero would give a direct indication of system errors.

The preliminary test program proposed here would thus confirm the estimated accuracy of the proposed system at a fraction of the cost of constructing the complete system. If satisfactory, the reference-system assembly could be retained and used in the final system. If not, the experience gained would be valuable in optimizing the final system design. Estimates of the cost of this initial test program are included in Section 3.6.

3.6. ESTIMATES OF PROGRAM COST AND TIME

On the basis of the preliminary design of a pavement-evaluation system as covered in this report, an estimate has been made of the cost and time required to design, construct, and test such a system. The actual cost will, of course, depend on the organization performing the work. For purposes of this cost estimate, rates representative of the University's salary and overhead structure for research programs sponsored by the Michigan State Highway Department have been used.

Table I contains a cost analysis for the complete system, including both pavement-roughness and pavement-deflection measurement equipment. The cost is shown separately for each of the three phases of the project. Table II provides information on the materials and equipment required for the project. Every effort has been made to arrive at a realistic estimate which accurately reflects the difficulties to be faced in meeting the accuracy requirements for the system. In addition to the costs which are fairly predictable, an item of $18,000 has been included in Table I to cover unforeseen contingencies.

This estimate has been based on the assumption that the preliminary test phase would be substantially completed before construction of the final system was initiated. Under these conditions, the total time required to complete the project would be 24 months. If the preliminary test phase were eliminated, the program for the remaining phases could be modified in such a way as to reduce the total time required to complete the project to perhaps 21 months. A small saving of perhaps $10,000 in the total cost might also result. This approach is not recommended, however, since it would require a commitment for the total estimated cost of the system at the initiation of the program and eliminate the possibility of optimizing the system design on the basis of early test information.

TABLE I. COST ANALYSIS FOR CONTINUOUS-MEASUREMENT SYSTEM

	Phase I Preliminary Test (9 Months)		Phase II System Construction (9 Months)		Phase III System Test (6 Months)		Total (24 Months)	
	Man-Months	Est. Cost	Man-Months	Est. Cost	Man-Months	Est. Cost	Man-Months	Est. Cost
Salaries and Wages								
Engineers and Supervisors	20	$20,000	18	$ 18,000	10	$10,000	48	$ 48,000
Technicians, Secretaries, and Shop Service	20	13,000	10	6,500	7	4,500	37	24,050
Total Salaries and Wages (Including Employee Fringe Benefits)		$33,000		$ 24,500		$14,550		$ 72,050
Overhead (15% of Salaries and Wages)		4,950		3,675		2,175		10,800
Purchases								
Outside Service (Telephone, TWX, Freight, Guard Service, etc.)		200		200		100		500
Report Materials and Supplies		---		---		500		500
Miscellaneous Supplies and Expense		200		200		100		500
Mechanical and Electrical Materials and Equipment		13,000		40,500		3,000		56,500
Total Purchases		13,400		40,900		3,700		58,000
Subcontracting		---		138,000		---		138,000
Travel		400		500		250		1,150
Computer Rental		---		---		2,000		2,000
Contingencies		3,250		12,425		2,325		18,000
Estimated Total Cost		$55,000		$220,000		$25,000		$300,000

TABLE II. ESTIMATED MATERIAL AND EQUIPMENT REQUIREMENTS

Mechanical System	
Truck, complete with instrumentation compartment	$ 7,000
Trailer	50,000
Auxiliary power system (electrical, hydraulic, and pneumatic)	4,500
Reference assembly materials	3,000
Preliminary test vehicle	5,000
Instrumentation System	
Roughness-measurement transducers	1,000
Roughness-measurement recorders	5,000
Deflection-measurement transducers	24,000
Deflection-measurement data-conversion system	88,000
Special test equipment	5,000
Miscellaneous (cables, connectors, racks, etc.)	2,000
Total	$ 194,500

4
INSTRUMENTATION SYSTEM for INTERMITTENT PAVEMENT-DEFLECTION MEASUREMENT

This section describes a pavement-deflection measurement system which makes intermittent rather than continuous measurements. The basic requirements on which this alternative system is based are similar to those described in Section 1. The system configuration proposed here is based only on a preliminary study. It is possible that further analysis would result in an improved configuration; for example, one having a reduced over-all length.

4.1. MECHANICAL AND ELECTRICAL DESIGN

The general configuration of the truck-trailer combination used with this system is shown in Figure 4. The truck provides motive power, carries the electric and hydraulic power systems, and contains an instrumentation compartment for the recording equipment. The trailer carries a deflection-measurement assembly and has means for intermittently applying load to

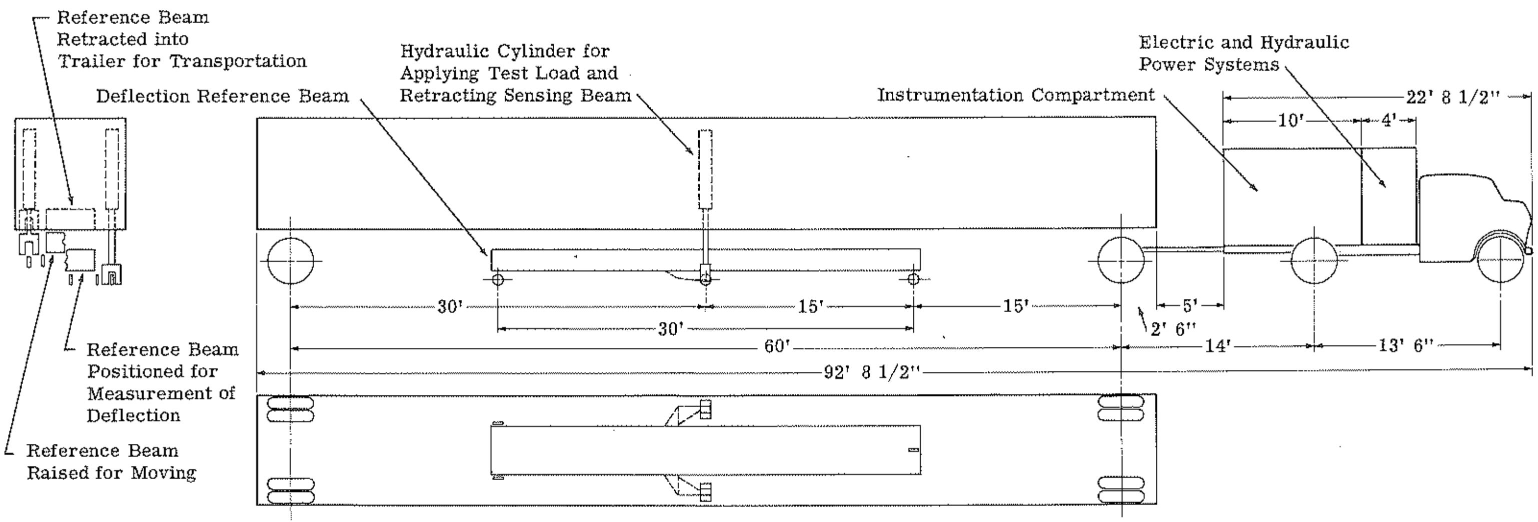

FIGURE 4. INSTRUMENTATION VEHICLE FOR INTERMITTENT ROAD-DEFLECTION MEASUREMENT

the pavement at the point of deflection measurement. The deflection-measurement assembly uses a beam rigidly supported on wheels, one at the front and two at the rear, which make positive three-point contact with the pavement. The reference beam carries two sensing wheels located at the mid-point of the beam, one in each wheel path. Each sensing wheel has an attached transducer to measure its deflection with respect to the beam. When traveling to or from the measurement area, the measurement assembly can be raised off the pavement and carried inside the trailer.

During the measurement process the vehicle is stopped. A measurement is first made of sensing-wheel deflection while the pavement is unloaded. A second measurement is then made with the load applied by means of the hydraulic cylinder within the trailer. The pavement deflection for the applied load is then the difference between the initial and final readings.

Since the pavement deflection is determined by means of a single transducer and since the beam against which the deflection is referenced does not move during the measurement process, it is believed that very high measurement accuracy of pavement deflection can be obtained. The only limiation is the accuracy of the transducer and its recording system, and it is believed that these can be kept within .002 inch.

The load application device shown in Figure 4 consists of a U-shaped load plate which straddles the sensing wheel. (An alternative load application device would consist of a set of dual wheels in each wheel path. This would complicate the mechanical design of the load application system to some extent, but would ensure a realistic representation of actual loading conditions.) The total load of 50,000 pounds for the two wheel paths is applied and removed by means of the extension and retraction of two hydraulic cylinders mounted within the trailer. Since the hydraulic cylinders are located at the mid-point of the trailer, practically the entire weight of the trailer is available to serve as this load. Ballast would be required to make up any difference between the trailer weight and the required axle load. Control of the magnitude of loading could be accomplished by controlling hydraulic pressure either to some nominal value or by means of a strain-gauge measurement of transmitted force.

One of several relatively simple methods can be used to record the deflection measurement. It can be recorded graphically or can be converted to numerical form and printed out or punched on paper tape. Longitudinal distance along the highway should also be recorded at the same time.

A single measuring sequence consists of the following steps:

(1) Make no-load measurement
(2) Apply load
(3) Make loaded measurement
(4) Retract load and simultaneously move to new location

It is believed that a complete measurement, including the move to a new location, could be accomplished in about 5 seconds. If measurements were made at 2-foot intervals, this would correspond to a forward motion of 24 fps. Consideration should be given, however, to the question of the required density of measurements. If the pavement-deflection measurements are required merely as a matter of general information concerning pavement characteristics, a relatively small number of samples, if properly selected, can give an accurate picture of such characteristics. It should therefore be possible to determine such characteristics by a sampling technique rather than by a continuous series of closely spaced measurements. Thus, measurements at intervals of 10 feet or greater might give suitable information for most purposes. Since the interval of movement between measurements is not fixed, it is also possible to obtain closely spaced measurements where desired, for example, at faults or special subgrade conditions. Thus the inherent speed limitation of the intermittent measurement method described here could be minimized by proper sampling and interpretation techniques.

4.2 ESTIMATES OF PROGRAM COST

The estimated cost of developing and constructing the system described in this report is given in Table III. This cost analysis should be considered as only a rough estimate but can be

TABLE III. COST ANALYSIS FOR INTERMITTENT-MEASUREMENT SYSTEM

Salaries and Wages	Man-Months	Estimated Cost
Engineers and Supervisors	30	$ 30,000
Technicians, Secretaries, and Shop Service	30	20,000
Total Salaries and Wages (Including Employee Fringe Benefits)		50,000
Overhead (15% of Salaries and Wages)		7,500
Purchases		
Outside Service (Telephone, TWX, Freight, Guard Service, etc.)		300
Report Materials and Supplies		500
Miscellaneous Supplies and Expense		400
Mechanical and Electrical Materials and Equipment		78,500
Total Purchases		79,700
Travel		800
Contingencies		12,000
Estimated Total Cost		$ 150,000

used for preliminary consideration. It should be noted that the cost estimate assumes that both pavement roughness and pavement deflection are to be measured. If it is decided that pavement-roughness measurement is to be excluded, the estimates contained in Table III could be reduced somewhat, perhaps by $10,000.

Appendix A
DESIGN DETAILS of CONTINUOUS DEFLECTION-MEASUREMENT SYSTEM

A.1. MECHANICAL DESIGN

Figure 5 shows a preliminary design of the sensing-wheel assembly. The construction and operation of all sensing-wheel mechanisms is identical. The sensing wheel carries a solid rubber tire with a maximum runout of .001 inch. Spring loading (not shown) may be required to keep the sensing wheel in constant contact with the ground. A nutcracker arm is attached to the measuring assembly in such a way as to constrain the assembly to move in a direction which remains aligned with that of the vehicle. The mounting of the wheels is such that tracking forces are not transmitted to the reference beam. The wheel is attached to the transducer (not shown), which is mounted on the reference beam. The connection is by means of a tube, which is free to move vertically within a sleeve, being guided inside this sleeve by ball bushings. The total range of vertical motion is 8 inches. The backlash of the system is to be limited to a .001-inch maximum.

The upper end of the tube is attached to the transducer by means of a steel ribbon. This ribbon is maintained at a constant tension by means of a neg'ator spring which is part of the transducer assembly. As the wheel rises, the ribbon winds around a drum attached to the transducer shaft. The diameter of the drum is such that 8 inches of wheel motion produces a complete revolution of the transducer.

A separate reference beam is used for each wheel path. Each beam has an over-all length of 45 feet and is built up of a plate and angles in the form of an I-beam, 18 inches in depth (see Figure 1). Attachments for vertical support from the trailer are provided at two intermediate points along the beam. Each support consists of a spring in parallel with a hydraulic damping device. Additional attachments are made to the trailer to provide lateral and longitudinal stability.

The large rigidity-to-mass ratio (EI/M) of the beam gives it a low static deflection and a high fundamental frequency (15 cps minimum). The beam is constructed of either aluminum or manganese copper in order to provide effective damping of vibration. It is designed for minimum cross-coupling between transverse vibrational modes, especially horizontal to vertical, and has vertical symmetry in its transverse cross section to eliminate cross-coupling from the vertical to the torsional vibration modes.

In the measurement mode, the trailing road arm which supports the measuring wheel is rigidly seated on the vertical tube by a preloaded spring arrangement. For traveling, the force

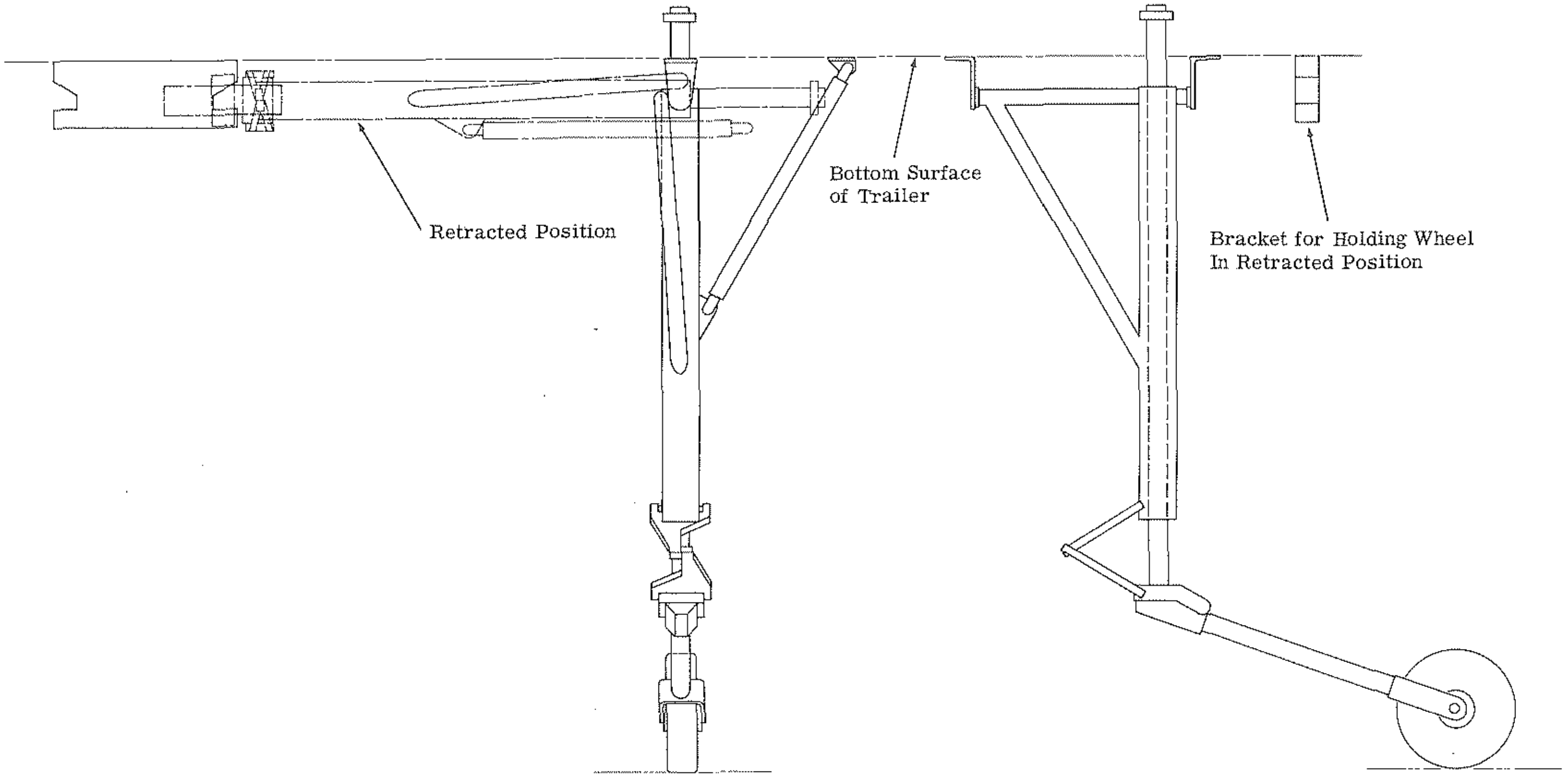

FIGURE 5. SENSING-WHEEL MOUNTING LAYOUT FOR DEFLECTION-MEASUREMENT VEHICLE

applied by the preloaded spring may be overcome by an upward force of 35 pounds at the wheel, permitting the road arm to be partially folded upward, to give a clearance of 1 foot to the road. Arrangement is also made to remove a link between the wheel assembly and the trailer so that the wheel assembly may be retracted into a horizontal position under the trailer. With the wheels raised for traveling, there is a minimum road clearance of 4 feet at the center of the vehicle. The ratio of road clearance to wheel base corresponds approximately to that of a modern automobile.

In order to provide sufficient maneuverability of the vehicle, the trailer is designed for both front and rear steering, with a capability of being transported in either direction. It is not practical to steer the load application wheels; therefore, an extra axle is located behind the load application wheels, as shown in Figure 1. During measurement periods, this set of rear wheels is lifted off the pavement; however, during travel between measurement areas the load application wheels would be raised and the rear end of the vehicle would ride on the rear axle.

A.2. DATA-PROCESSING SYSTEM

In order to compute pavement deflection, it is necessary to measure and record the following outputs (see Figure 3). Eight transducers are used to measure elevations of the pavement with respect to the reference beam. Two transducers are required to continuously measure distance along the pavement. To permit compensation for the deflection of the reference beam would require the use of strain gauges attached to the reference beam. Additional strain gauges would be used in the system, if it is necessary to maintain a record of load applied to the pavement. These applications might require as many as 10 channels of recording for strain-gauge measurements, the strain-gauge channels requiring an accuracy of 3.0%. A channel would be required to record a clock signal to an accuracy of .01%, and one additional channel would be useful to permit voice recording of instructions.

The measured data are recorded on 1-inch tape by means of a magnetic-tape recording system, such as the Ampex AR200 field recorder. There is provision for recording 16 channels of digital data and 7 channels of analog data. The tape is run at a speed of 3.75 ips with a tape packing density of 240 bits per inch, corresponding to a recording rate of 900 bits per second for each channel. The pavement elevation transducers have a resolution of one part in 8192, corresponding to a 13-bit character in reflected binary code. The output of each transducer is recorded in parallel, using 13 digital channels of the magnetic-tape recorder. Each of the 8 transducers will be recorded on one data frame, the frame being repeated continuously at intervals of 1/90 second. The two channels of distance data are also sampled once in each frame and recorded in the same 13 digital channels of the tape recorder. Since it is possible to record

90 frames per second, with each frame representing a maximum of 1 inch traveled along the pavement, a standard 2500-foot reel of tape would be sufficient to record 12 miles of road data if a velocity of 5 mph were continuously maintained. The strain-gauge inputs are recorded on a single channel, by the use of frequency multiplexing.

The laboratory installation of data-processing equipment for this application converts the magnetic-tape-recorded data to a form suitable for insertion into a digital computer. The magnetic-tape recorder also serves as a reproducer to play back the field data. The digital data representing pavement elevation and vehicle travel are converted to a format which is compatible with the particular digital computer to be used. This format requires that the reflected binary code be converted to binary-coded-decimal data and that the data be organized into computer words or blocks of words appropriate to the computer used. The resulting modified data are again recorded on magnetic tape and are introduced into the computer to be used in the same manner as a reel of tape generated directly by the computer.

The clock and synchronizing signals recorded on other channels of the primary tape are used in the format-conversion process. One channel of the recorder would be assigned to record synchronizing signals to indicate the beginning of each frame. The strain-gauge inputs are reproduced by the laboratory tape reproducer in analog form. It is necessary to convert the analog data to digital form by means of a multiplexing and analog-to-digital conversion system. The resulting digital data can then be introduced onto the computer magnetic tape along with the pavement-elevation and vehicle-distance data.

Once the data have been inserted into the computer in a known sequence and format, a special program of computer instructions is used to process the data. These instructions result in performing the computation described in Section 3.2. The computed pavement-deflection data are then stored in the computer memory, each data point representing the pavement deflection at constant increments of longitudinal distance along the pavement. The final results of this computation process will be to produce a tabular printed record of pavement deflection or a graphic plot.

Additional types of information may also be obtained during the computation process by the use of appropriate sets of instructions. For example, it would be possible to obtain summary data of pavement deflection in terms of average values, peak values, and so on. It would also be possible to obtain such summary data in terms of various independent variables, such as the age of the pavement, type of construction, type of subgrade, and pavement contractor.

Appendix B
ALTERNATIVE METHODS of PAVEMENT ROUGHNESS MEASUREMENT

An important criterion to be used in judging the condition of a highway pavement is the quality of the ride that will be experienced in automotive vehicles passing over the surface. This ride cannot easily be measured directly, but can be determined if highway-roughness data are obtained in a form which can be used to compute or predict riding comfort. This can best be accomplished by means of a measuring technique which produces data in the form of an elevation profile for each wheel path of the road.

If data were available in this form, and if typical characteristics of a vehicle suspension system were assumed, they could be used to compute the motion of the vehicle body riding over a particular section of pavement at a given speed. Computing techniques for accomplishing this, based on the simulation of vehicle motion by means of analog computing techniques, have been developed in recent years and are therefore ready for direct application to this problem (References 1, 2, and 3). Alternative computing methods based on frequency analysis are also available. These alternative methods have the advantage of being simpler to apply and capable of providing data on particular road sections in summary form.

If such measurement techniques and data-reduction methods were put into practice, they would thus provide highway design and maintenance engineers with valuable information in a form directly related to the criterion of ride characteristics. The information would also be valuable to the vehicle designer, since it would provide him with an extensive fund of information concerning the characteristics of highway pavements for which vehicles must be designed.

The method of pavement-roughness measurement presently being used in the Michigan pavement-evaluation vehicle gives a general indication of roughness but does not provide the information exactly in the form of an elevation profile. A system for measurement of cross-country terrain which operates on a principle similar to that of the AASHO (American Association of State Highway Officials) system is being developed for the Ordnance Tank-Automotive Command by the Institute of Science and Technology (Reference 4). In this system, the measurement of profile is accomplished by means of a technique which continuously determines ground slope with respect to a gyro used as a vertical reference. The measuring assembly consists of a frame on which are mounted two sensing wheels with a 12-inch wheel base. A series of measurements at 12-inch intervals of the slope of the reference frame with respect to the vertical are obtained from the gyro readings. The output of the gyro is thus the quantity $\frac{dy}{dx}$. The reduced data consist of a plot of points on the profile spaced 12 inches apart.

The difficulty of the problem of using this technique for pavement measurement may be understood from the following analysis. The feasibility of any method of pavement-profile measurement primarily depends on the accuracy attainable with the system. In order to give some indication of the accuracy required, we may consider a pavement profile with a wavelength of 88 feet and a peak-to-peak amplitude of 0.2 feet (2.4 inches). (The roughness index of this profile corresponds to 144 inches per mile.) A vehicle travelling over this pavement at 60 mph would experience a forced vibration of 1cps. If the suspension system were underdamped, the bounce motion of the body would be amplified to some extent. The resulting ride would correspond approximately to the recommended limit for comfort as given in curves published by the SAE (Reference 5). For this road, the slope varies sinusoidally between +7.2 and -7.2 mrad (milliradian). Thus, a gyro which could accurately record this profile should have a sensitivity high enough to detect values only 1/10 as much, that is, 0.7 mrad. The slope for pavement roughness at a wavelength of 8.8 feet corresponding to the recommended limit for comfort would be about 1 mrad rather than 7. Thus, extremely high accuracy is required of the measurement system if it is to be capable of detecting pavement roughness appreciably less than that set by the limits of passenger comfort.

A possible alternative method of measuring pavement roughness may have the accuracy required for determining fine detail in pavement profile, but it is deficient in determining a profile accurately over large distances. The proposed measurement technique for determining highway profile is shown schematically in Figure 6. The technique is basically similar to that used in the Michigan State Highway Department pavement evaluation vehicle, but the measured data are processed differently. It consists of using three sensing wheels which travel on the surface of the pavement. Measurements are made continuously by the transducer of the vertical

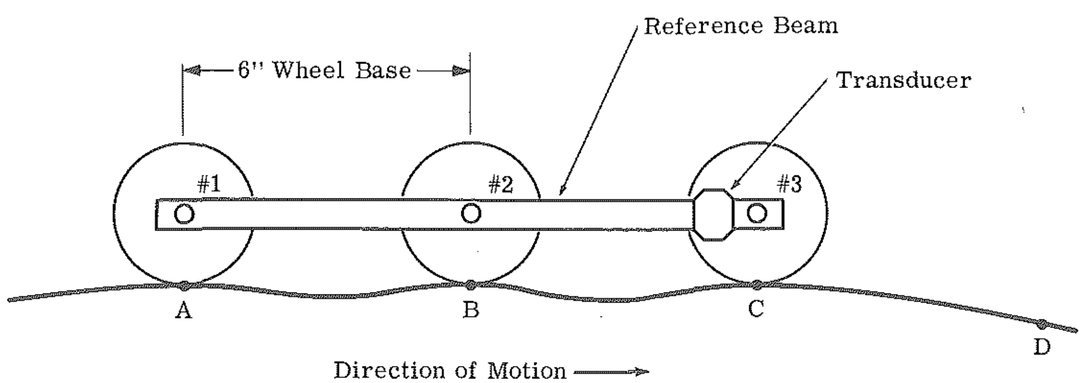

FIGURE 6. ROUGHNESS MEASUREMENT SYSTEM

position of sensing wheel No. 3 with respect to the reference beam supported by and rigidly attached to sensing wheels No. 1 and 2. The output of the transducer associated with the sensing wheel is then used to compute the road profile. If the elevation of points A and B are already known, it is possible from this measurement to determine the elevation of point C. As the wheels move forward, wheels No. 1 and 2 will reach points B and C, respectively. At this instant, the measurement process is repeated to determine the elevation of point D. A continuous repetition of this extrapolation process is thus capable of indicating the profile in terms of a series of points separated from each other at a distance equal to the wheel base of the measuring system. The three-wheel measuring system essentially measures the change in slope of the profile at points 6 inches apart. The transducer output is thus proportional to the second derivative of the elevation.

A system having wheels spaced at 6-inch intervals and having a measurement accuracy of .001 inch can detect slope changes of .001 inch in 6 inches or 0.2 mrad. Sensitivity of this order of magnitude would probably be acceptable for measurement of fine detail of pavement roughness. However, the sensitivity limit of .001 inch per measurement may permit a buildup of error over a series of measurements, even though the error is random. It is therefore desirable to supplement the three-wheel measurement technique with some other technique having better long-term accuracy. Thus, the gyro measurement method and the three-wheel measurement method might be combined in such a way that the three-wheel data are modified to correspond over long distances with the gyro data. Another means of improving the long-range accuracy would be to apply corrections to the measurements made by the three-wheel system to cause the computed profile to pass through known elevations of the pavement at intervals of several hundred feet.

An alternative approach to profile measurement would be to use a three-wheel system in which a wheel base of perhaps 15 feet is used. (This is equivalent to the measurement wheel base of the present Michigan pavement evaluation vehicle.) It can be shown that the buildup of roughness due to random transducer error would then be negligible. However, profile data with such 15-foot resolution would be inadequate for showing the fine detail of the pavement which is important in determining pavement condition. Consequently, it would be necessary to use data not only at 15-foot intervals, but at intermediate points spaced at 6 or 12 inches. This could be done by a series of measurements involving 15-foot extrapolations, each series displaced by 6 or 12 inches from the adjacent one. Over long distances, the random errors of each string of extrapolations would cause it to depart in elevation from adjacent strings. It is believed, however, that such discrepancies could be eliminated by some type of data smoothing.

The pavement-roughness measurement methods described in this appendix have not yet been investigated in sufficient detail to establish definitely their feasibility or cost. However, they are presented here to permit preliminary consideration of their potential usefulness in pavement evaluation.

REFERENCES

1. I. J. Sattinger and E. B. Therkelsen, Simulation of Military Vehicle Suspension Systems, paper presented at the National Simulation Conference of the IRE Professional group on Electronic Computers, Dallas, Texas, 19 January 1956 (UNCLASSIFIED).

2. I. J. Sattinger and D. F. Smith, Computer Simulation of Vehicle Motion in Three Dimensions, Report Number 2901-10-T, Willow Run Laboratories, The University of Michigan, Ann Arbor, Michigan, May 1960 (UNCLASSIFIED).

3. S. Sternick, D. T. Stimel, and I. J. Sattinger, Human Reaction to Military-Vehicle Ride, Report Number 2889-17-F, Institute of Science and Technology, The University of Michigan, Ann Arbor, Michigan, January 1961 (UNCLASSIFIED).

4. I. J. Sattinger and S. Sternick, An Instrumentation System for the Measurement of Terrain Geometry, paper to be presented at 1st International Conference on the Mechanics of Soil-Vehicle Systems, Turin, Italy, 12-16 June 1961 (UNCLASSIFIED).

6. "Ride and Vibration Data," SAE Publication, SP-6, June 1950.

Div. 11/4

Institute of Science and Technology, U. of Michigan, Ann Arbor
FEASIBILITY STUDY OF A PAVEMENT-DEFLECTION MEASUREMENT SYSTEM by W. H. Lawrence, I. J. Sattinger, and L. H. Thomas. Nov. 60. 25 p. incl. illus., tables.
(Report no. 3742-5-F)
(Michigan Pavement Performance Study Project No. 03088)
Unclassified report

Two proposed instrumentation vehicles for accurately measuring the deflection of highway pavements when subjected to large axle loads are described in this report. One of the vehicles would be capable of making continuous measurements of pavement deflection under load. The other vehicle would make measurements at discrete intervals along the pavement. Although the second vehicle system would not be capable of the speed of advance and continuity of measurement of the first, the second system is nevertheless recommended for implementation because of its substantially lower cost and higher measurement accuracy.

(over)

UNCLASSIFIED

I. Lawrence, W. H., Sattinger I. J., Thomas, L. H.
II. Michigan State Highway Department
III. Michigan Pavement Performance Study Project No. 03088

UNCLASSIFIED

Div. 11/4

Institute of Science and Technology, U. of Michigan, Ann Arbor
FEASIBILITY STUDY OF A PAVEMENT-DEFLECTION MEASUREMENT SYSTEM by W. H. Lawrence, I. J. Sattinger, and L. H. Thomas. Nov. 60. 25 p. incl. illus., tables.
(Report no. 3742-5-F)
(Michigan Pavement Performance Study Project No. 03088)
Unclassified report

Two proposed instrumentation vehicles for accurately measuring the deflection of highway pavements when subjected to large axle loads are described in this report. One of the vehicles would be capable of making continuous measurements of pavement deflection under load. The other vehicle would make measurements at discrete intervals along the pavement. Although the second vehicle system would not be capable of the speed of advance and continuity of measurement of the first, the second system is nevertheless recommended for implementation because of its substantially lower cost and higher measurement accuracy.

(over)

UNCLASSIFIED

I. Lawrence, W. H., Sattinger I. J., Thomas, L. H.
II. Michigan State Highway Department
III. Michigan Pavement Performance Study Project No. 03088

UNCLASSIFIED

Div. 11/4

Institute of Science and Technology, U. of Michigan, Ann Arbor
FEASIBILITY STUDY OF A PAVEMENT-DEFLECTION MEASUREMENT SYSTEM by W. H. Lawrence, I. J. Sattinger, and L. H. Thomas. Nov. 60. 25 p. incl. illus., tables.
(Report no. 3742-5-F)
(Michigan Pavement Performance Study Project No. 03088)
Unclassified report

Two proposed instrumentation vehicles for accurately measuring the deflection of highway pavements when subjected to large axle loads are described in this report. One of the vehicles would be capable of making continuous measurements of pavement deflection under load. The other vehicle would make measurements at discrete intervals along the pavement. Although the second vehicle system would not be capable of the speed of advance and continuity of measurement of the first, the second system is nevertheless recommended for implementation because of its substantially lower cost and higher measurement accuracy.

(over)

UNCLASSIFIED

I. Lawrence, W. H., Sattinger I. J., Thomas, L. H.
II. Michigan State Highway Department
III. Michigan Pavement Performance Study Project No. 03088

UNCLASSIFIED

Div. 11/4

Institute of Science and Technology, U. of Michigan, Ann Arbor
FEASIBILITY STUDY OF A PAVEMENT-DEFLECTION MEASUREMENT SYSTEM by W. H. Lawrence, I. J. Sattinger, and L. H. Thomas. Nov. 60. 25 p. incl. illus., tables.
(Report no. 3742-5-F)
(Michigan Pavement Performance Study Project No. 03088)
Unclassified report

Two proposed instrumentation vehicles for accurately measuring the deflection of highway pavements when subjected to large axle loads are described in this report. One of the vehicles would be capable of making continuous measurements of pavement deflection under load. The other vehicle would make measurements at discrete intervals along the pavement. Although the second vehicle system would not be capable of the speed of advance and continuity of measurement of the first, the second system is nevertheless recommended for implementation because of its substantially lower cost and higher measurement accuracy.

(over)

UNCLASSIFIED

I. Lawrence, W. H., Sattinger I. J., Thomas, L. H.
II. Michigan State Highway Department
III. Michigan Pavement Performance Study Project No. 03088

UNCLASSIFIED

UNCLASSIFIED

DESCRIPTORS

Vehicle instruments
Pavements
Deflection

UNCLASSIFIED

UNCLASSIFIED

DESCRIPTORS

Vehicle instruments
Pavements
Deflection

UNCLASSIFIED

UNCLASSIFIED

DESCRIPTORS

Vehicle instruments
Pavements
Deflection

UNCLASSIFIED

UNCLASSIFIED

DESCRIPTORS

Vehicle instruments
Pavements
Deflection

UNCLASSIFIED

Div. 11/4

Institute of Science and Technology, U. of Michigan, Ann Arbor
FEASIBILITY STUDY OF A PAVEMENT-DEFLECTION MEASUREMENT SYSTEM by W. H. Lawrence, I. J. Sattinger, and L. H. Thomas. Nov. 60. 25 p. incl. illus., tables.
(Report no. 3742-5-F)
(Michigan Pavement Performance Study Project No. 03088)
Unclassified report

Two proposed instrumentation vehicles for accurately measuring the deflection of highway pavements when subjected to large axle loads are described in this report. One of the vehicles would be capable of making continuous measurements of pavement deflection under load. The other vehicle would make measurements at discrete intervals along the pavement. Although the second vehicle system would not be capable of the speed of advance and continuity of measurement of the first, the second system is nevertheless recommended for implementation because of its substantially lower cost and higher measurement accuracy.

(over)

UNCLASSIFIED

I. Lawrence, W. H., Sattinger I. J., Thomas, L. H.
II. Michigan State Highway Department
III. Michigan Pavement Performance Study Project No. 03088

UNCLASSIFIED

Div. 11/4

Institute of Science and Technology, U. of Michigan, Ann Arbor
FEASIBILITY STUDY OF A PAVEMENT-DEFLECTION MEASUREMENT SYSTEM by W. H. Lawrence, I. J. Sattinger, and L. H. Thomas. Nov. 60. 25 p. incl. illus., tables.
(Report no. 3742-5-F)
(Michigan Pavement Performance Study Project No. 03088)
Unclassified report

Two proposed instrumentation vehicles for accurately measuring the deflection of highway pavements when subjected to large axle loads are described in this report. One of the vehicles would be capable of making continuous measurements of pavement deflection under load. The other vehicle would make measurements at discrete intervals along the pavement. Although the second vehicle system would not be capable of the speed of advance and continuity of measurement of the first, the second system is nevertheless recommended for implementation because of its substantially lower cost and higher measurement accuracy.

(over)

UNCLASSIFIED

I. Lawrence, W. H., Sattinger I. J., Thomas, L. H.
II. Michigan State Highway Department
III. Michigan Pavement Performance Study Project No. 03088

UNCLASSIFIED

Div. 11/4

Institute of Science and Technology, U. of Michigan, Ann Arbor
FEASIBILITY STUDY OF A PAVEMENT-DEFLECTION MEASUREMENT SYSTEM by W. H. Lawrence, I. J. Sattinger, and L. H. Thomas. Nov. 60. 25 p. incl. illus., tables.
(Report no. 3742-5-F)
(Michigan Pavement Performance Study Project No. 03088)
Unclassified report

Two proposed instrumentation vehicles for accurately measuring the deflection of highway pavements when subjected to large axle loads are described in this report. One of the vehicles would be capable of making continuous measurements of pavement deflection under load. The other vehicle would make measurements at discrete intervals along the pavement. Although the second vehicle system would not be capable of the speed of advance and continuity of measurement of the first, the second system is nevertheless recommended for implementation because of its substantially lower cost and higher measurement accuracy.

(over)

UNCLASSIFIED

I. Lawrence, W. H., Sattinger I. J., Thomas, L. H.
II. Michigan State Highway Department
III. Michigan Pavement Performance Study Project No. 03088

UNCLASSIFIED

Div. 11/4

Institute of Science and Technology, U. of Michigan, Ann Arbor
FEASIBILITY STUDY OF A PAVEMENT-DEFLECTION MEASUREMENT SYSTEM by W. H. Lawrence, I. J. Sattinger, and L. H. Thomas. Nov. 60. 25 p. incl. illus., tables.
(Report no. 3742-5-F)
(Michigan Pavement Performance Study Project No. 03088)
Unclassified report

Two proposed instrumentation vehicles for accurately measuring the deflection of highway pavements when subjected to large axle loads are described in this report. One of the vehicles would be capable of making continuous measurements of pavement deflection under load. The other vehicle would make measurements at discrete intervals along the pavement. Although the second vehicle system would not be capable of the speed of advance and continuity of measurement of the first, the second system is nevertheless recommended for implementation because of its substantially lower cost and higher measurement accuracy.

(over)

UNCLASSIFIED

I. Lawrence, W. H., Sattinger I. J., Thomas, L. H.
II. Michigan State Highway Department
III. Michigan Pavement Performance Study Project No. 03088

UNCLASSIFIED

UNCLASSIFIED

DESCRIPTORS

Vehicle instruments
Pavements
Deflection

UNCLASSIFIED

UNCLASSIFIED

DESCRIPTORS

Vehicle instruments
Pavements
Deflection

UNCLASSIFIED

UNCLASSIFIED

DESCRIPTORS

Vehicle instruments
Pavements
Deflection

UNCLASSIFIED

UNCLASSIFIED

DESCRIPTORS

Vehicle instruments
Pavements
Deflection

UNCLASSIFIED