PAVEMENT DEFLECTION MEASUREMENT-DYNAMIC

- A Feasibility Study -

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FINAL REPORT

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Electrical Engineering Section

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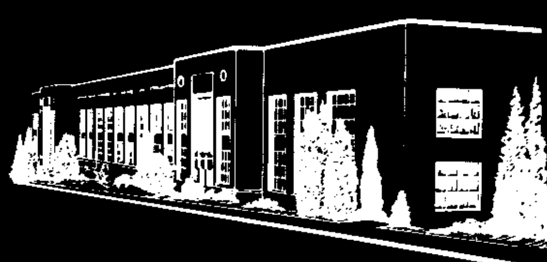
Highway Research Section



WASHINGTON STATE UNIVERSITY
COLLEGE OF ENGINEERING
RESEARCH DIVISION

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Pullman, Washington
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ABSTRACT

The objective of this study was to determine the feasibility of developing a device or technique to provide rapid measurement of parameters indicative of roadway condition or structural capacity.

Currently existing equipment is inadequate for making meaningful measurements with speed and convenience. Consequently, a new system called "impulse testing" has been proposed and its concepts proved in this study. This system incorporates new techniques of non-destructive testing, and is adaptable to mechanization for automatic operation. The system is based on the deflection of the pavement under impulse loading, and also on the energy propagation characteristics of the pavement. These two parameters are combined to formulate a quantity which is called the impulse index and which has a high degree of correlation with the structural properties of the pavement.

CHAPTER I

INTRODUCTION AND SUMMARY

The determination of the present load bearing capacity and the life expectancy of highway pavements is an important factor in managing and maintaining highway systems. Presently used measurement techniques have been found to be inadequate in reliability, in economy and in practicality on very busy roads. Our effort was therefore aimed primarily at an examination of the parameters which are relevant to pavement strength, and at developing a technique which would allow the measurement of sufficient parameters to adequately evaluate pavement structural condition. Another consideration was to make such measurements in a short enough time to permit a vehicle carrying the system to maintain reasonable speed.

In Chapter II of this report the currently existing equipment in common use for various road tests are arranged according to the parameters measured. Comments on the significance of each of these parameters are then presented.

In the process of examining the relevant pavement parameters, a number of novel schemes were conceived for possible development. These schemes are presented and briefly evaluated in Chapter III along with comments. One of these schemes called "impulse testing" was selected for further investigation. The resulting system and results of tests on various pavements are described in Chapters IV and V. The system produces a number which we designate the "impulse index" and which has a high degree of correlation with the structural condition of the pavement. Test results are presented along with some data taken using a Benkelman Beam and a Dynaflect. Other known factors about the pavements tested are also presented to facilitate adequate evaluation of the test results.

Finally, it is concluded that the described system is workable and will yield data of a quality superior to that obtained by present techniques, and the speed of measurement makes possible operation from a moving vehicle with automatic data acquisition.

Summary of Impulse Index Method

The Impulse Index is a measure of the dynamic response of a pavement to a disturbance such as a hammer blow. The magnitude of the vibration produced, together with the attenuation of the signal with distance are quantities which are used to calculate the Impulse Index. A brief description of the system is presented here, with a more detailed presentation appearing in Chapters IV and V.

Two transducers, such as accelerometers, are positioned on the surface of the pavement separated by a known distance. Eighteen inches was found to be a satisfactory distance for a wide variety of types of pavements. An impulse, such as a hammer blow of controlled energy, is delivered to the pavement very close to one of the transducers. The electrical output signal from each transducer is rectified and integrated. Identifying the resulting quantity from the transducer nearest the hammer as R_0 and the value from the transducer eighteen inches away from the hammer as R_{18}, the Impulse Index is calculated by the relation

$$\text{Impulse Index} = \frac{(R_0)^2}{R_{18}}$$

CHAPTER II

DESCRIPTION OF PRESENTLY AVAILABLE OPERATING EQUIPMENT AND SIGNIFICANCE OF THE PARAMETERS MEASURED

Parameters which are currently being measured to evaluate pavements include:

1) Roughness or texture

2) Profile or slope

3) Static or nearly static deflections under load

4) Vibrations under dynamic loads

5) Visual evaluation

The various equipment and techniques which have been developed for monitoring these parameters are familiar to most people involved in highway evaluation work and so will not be described in detail here. A listing with references is presented on the following pages. Comments are also provided on the significance of the parameter which the equipment measures relative to the objective of this study.

Devices Which Monitor Roughness or Texture

1) Texas Texture Meter - NCHRP Report #7

2) ML-350 Pavement Skid Tester, Soiltest, Inc. - "INPUTS" published by Brush Instrument Company Division of Clevite Corporation, Vol. 5, No. 1, July, 1969.

The roughness or texture of a road is a significant parameter, particularly because of its relationship to safety and the ability to maintain traction. It is a surface parameter however and has little relationship to the load carrying capacity of the road. For this reason, devices which measure this parameter are not adequate for fulfilling the objectives of this study. If it is desirable to monitor skid resistance of a pavement at the same time as tests are being conducted on pavement strength it would be quite reasonable to add a skid resistance monitor to the equipment that is proposed at the conclusion of this report. The output of the skid resistance monitor could be recorded along with the impulse index and the location data.

Devices Which Monitor Profile or Slope

1) AASHO Slope Profilometer - NCHRP Report #7

2) CHLOE Profilometer - NCHRP Report #7

3) Kentucky Accelerometer - NCHRP Report #7

4) University of Michigan Profilometer - NCHRP Report #7

5) General Motors Device - NCHRP Report #7

6) GMR Road Profilometer - General Motors Research Publication GMR 452

7) Purdue Tire Pressure Measurement Device - NCHRP Report #7

8) Bureau of Public Roads Roughometer - NCHRP Report #7

9) California Profilograph

This equipment is designed to supply information on an important aspect of highways as it affects driver comfort and safety. The surface contours which they measure may also give a clue to conditions beneath the surface as well. However, measurement of the surface contours only may give a deceptive impression. If the material of the road base deteriorates, it is only a matter of time until the surface shows the effect; however, it also happens that a surface can become uneven without significant deterioration of the road base. In this case, the maintenance requirement would be different than in the case of a road whose base had deteriorated. A means of differentiating between the two conditions is necessary. It is for this reason that the impulse testing method is proposed. Impulse testing as presented in Chapters IV and V of this report yields information on the deterioration of the pavement before it has reached the point where it is visible from the surface. It is recommended that profile information be recorded along with the impulse index and the location data in order to detect such areas as may require surface condition correction only. Additional comments will be found in Conclusions of Chapter VI.

Devices Which Monitor Static or Nearly Static Deflections

1) Benkelman Beam - HRB Bulletin 114

2) California Traveling Deflectometer - HRB Bulletin 129

3) Lacroix Deflectographe - Ann Arbor Conference 1967

These devices all operate on the premise that the deflection and recovery of the pavement under a large and nearly static load is indicative of load carrying capacity. This approach to pavement evaluation has received some widespread acceptance. Some of the problems associated with the use of these systems are listed below.

1) A truck moving at high speed presents a transient or dynamic load on the pavement rather than a static load as is used in this equipment. Information obtained from a static measurement is not always indicative of dynamic performance.

2) Measurements from these systems are subject to wide variations due to temperature and hysteresis.

3) The measurements are slow and consequently expensive, requiring heavy equipment, flagmen, and causing disruption of traffic with its consequent hazards.

Impulse testing as presented in Chapters IV and V of this report makes a dynamic rather than a static measurement, can be made to proceed at a much faster rate thereby greatly reducing the traffic hazard, and does not require heavy trucks.

Also it is suspected that impulse testing would be less sensitive than other methods to variations due to temperature because the periods of most of the frequencies in the impulse are much shorter than the time constant of static pavement deflection for ordinary pavements on even the warmest of days. As a result, the variation in the time constant from temperature changes would not have a primary effect.

Devices Which Monitor Vibrations Under Dynamic Load

1) Lane-Wells Dynaflect - NCHRP Report 59

2) Road Rater - Foundation Mechanics Inc.

3) Cornell Direct Deflection Transducer - NCHRP Report 21

4) Shell Vibrator System - NCHRP Report 59

The loads utilized in the Dynaflect and the Road Rater, while dynamic, are single frequency and therefore are subject to resonance and anti-resonance phenomena. These systems are in various stages of acceptance and do give useful information. Information acquired over a spectrum of frequencies would be much more complete. The Shell system does use a spectrum of frequencies, but the quantity that it measures is sonic wave velocity and this has not been widely accepted as being particularly indicative of load carrying capacity.

The Cornell Direct Deflection Transducer was used to measure pavement deflection under impact, but the system was not developed far enough. Cornell reports a correlation between the height of the first large peak deflection as measured on an oscillograph and the pavement condition.

The Cornell tests were limited in extent and our testing of their method on a greater number of roads of known condition showed that the information available in the first large peak is not sufficient and can provide erroneous evaluations. None of these systems has been developed to the point that data can be acquired with the vehicle in motion.

The impulse testing system described in Chapters IV and V of this report successfully overcomes all these disadvantages.

Visual Evaluation Methods

1) "Present Performance Rating" (PPR) - A Guide to the Structural Design of Flexible and Rigid Pavements in Canada; Canadian Good Roads Association.
2) "Present Serviceability Rating" (PSR) - HRB Special Report 61E
3) "Present Serviceability Index" (PSI) - HRB Special Report 61E
4) "A Pavement Condition Rating System and Its Use," by R.V. Le Clerc and T.R. Marshall, Washington State Highway Commission, Washington State Highway Department Visual Condition Rating System, Olympia, Washington.

Consistent results from rating teams requires that the members be carefully selected and trained. In addition, if the rating system depends either wholly or in part on subjective judgment, many problems arise. Such problems as psychology, level of experience, bias, conscious or unconscious pressure and response to environment may be lessened by careful personnel selection and training. The value of results from subjective judgment or visual ratings is a direct function of the methodology used.

Current rating systems certainly have demonstrable use. However, automatic and meaningful objective measurements would be preferable.

CHAPTER III

COMPILATION AND BRIEF DESCRIPTION OF GENERATED IDEAS FOR ATTACKING THE PROBLEM

Several approaches for solving this problem were studied, resulting in a number of novel schemes being generated and offered for possible consideration. Some of these ideas are for improved equipment to measure the same parameters that are now being measured by presently existing equipment. Other ideas are based on entirely new principles and monitor different parameters. Several of the more promising ideas are briefly described in this chapter.

The systems described in this chapter were evaluated on the basis of their potential for producing data which would be an indicator of roadway condition or structural capacity, the potential for automating the system and making tests with the vehicle in motion at reasonable speed, and estimating the amount of development required.

Impulse testing presented a number of important advantages over other approaches and presently used methods. It was selected for further investigation and refinement after preliminary tests proved to be encouraging. Chapters IV and V of this report are devoted to a more detailed description of this system, and the results of the field tests.

Part 1 - Rolling Benkelman Beam (Figure III-1)

A modification of a Benkelman Beam with the three contact points of the beam supported on lightly loaded wheels and placed between the dual wheels of a loaded truck provides the potential for acquiring deflection data while the vehicle is in motion. When the deflection of the center wheel is instrumented with an appropriate transducer such as a linear potentiometer or Linear Variable Differential Transformer (LVDT), a voltage proportional to the deflection can be measured while the truck is in motion. A low pass filter would remove the road irregularities by averaging. The resulting average voltage would be proportional to the average deflection of the road under load. The wheels are small enough that the equipment can fit between the dual wheels of the truck. The dual wheels may have to be separated by a small amount to accommodate the width of the device.

Advantages: Highway people are familiar with Benkelman Beam data.

Automatic collection of such data would be achieved.

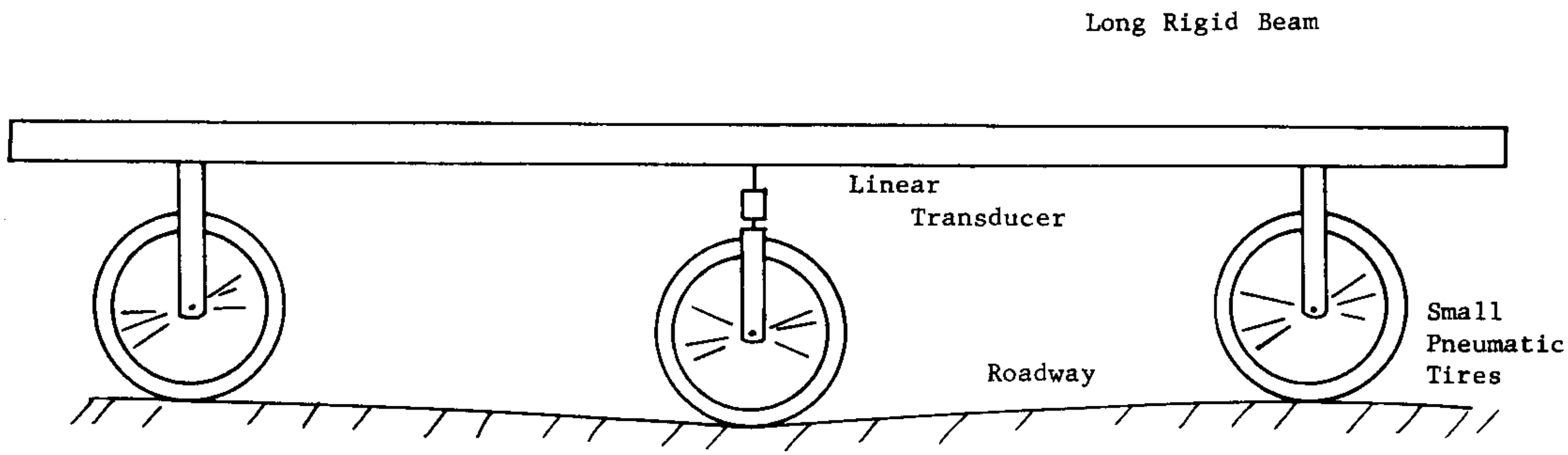
The device would measure the dynamic deflection of the pavement.

It may get results which are of more significance than the conventional Benkelman Beam because of the dynamic characteristics. Data averaged over some length of road would be obtainable.

Disadvantages: It may take so much time for the pavement to deflect that the truck may not be able to go very fast and still get results comparable to the conventional Benkelman Beam.

It may not be possible to design a suspension capable of performing satisfactorily at the desired road speed.

ROLLING BENKELMAN BEAM



Unit To Be Placed Between
Loaded Dual Wheels

FIGURE III-1

Part 2 - Deflection Measurements from a Stable Platform (Figure III-2)

On a loaded truck, mount a precision electronically controlled stabilized platform from which distance to the pavement surface can be measured by echo return detection or laser beam interferometer methods.

By measuring the vertical distance from the stable platform to the pavement surface at a point ahead of the wheel, under or nearly under the wheel, and behind the wheel, the amount of deflection caused by the load can be calculated. The data would be taken with the truck in motion and the required calculations performed on a computer (probably also mounted in the truck). This is similar to the Benkelman Beam but a dynamic pavement deflection measurement is performed at road travel speeds.

Advantages: This method would permit the automatic collection of dynamic deflection data.

Disadvantages: The performance specifications of the stable platform and the measuring devices are quite rigorous. Therefore, initial cost may be prohibitive. Averaging techniques must be used to eliminate effects of road grade or surface irregularities.

DEFLECTION MEASUREMENTS
FROM A STABLE PLATFORM

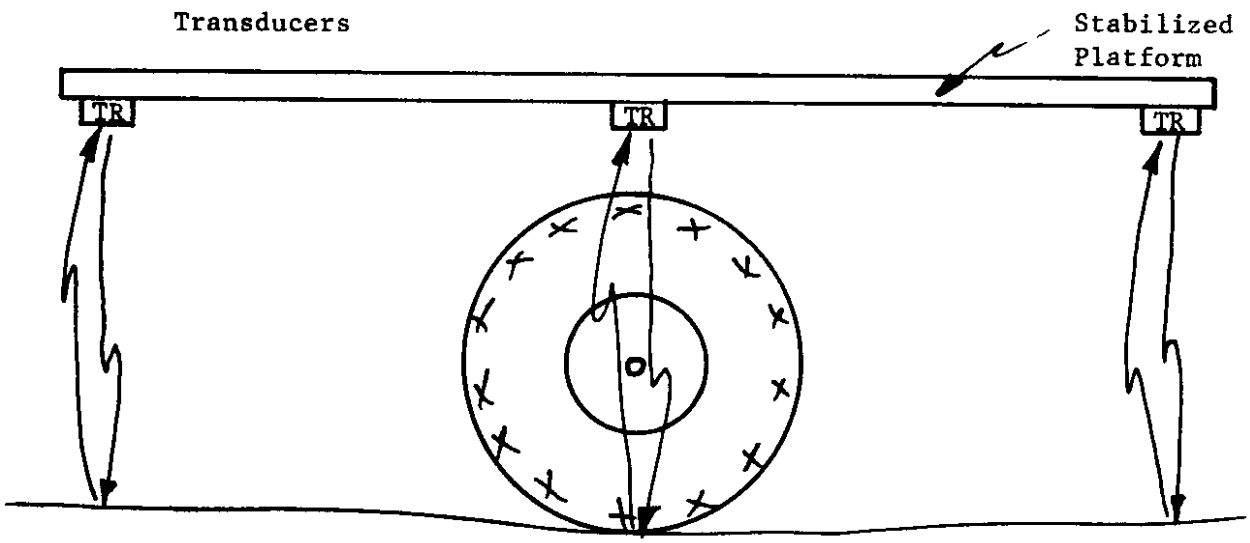


FIGURE III-2

Part 3 - Complex Response Function

A great deal of information can be obtained about many physical systems by producing a plot of amplitude and phase vs. frequency of the dynamic system response to a known driving function. Such a plot of the transfer function of a highway could be produced by either of the systems described below.

Transfer Function Concept (Figure III-3):

A vibrator capable of vibrating at several frequencies covering a frequency range of interest is placed on the highway. A transducer is located a specified distance from the vibrator. The output of the transducer together with the reference signal from the vibrator can be used to acquire phase and amplitude information from which the desired plot can be constructed. The poles and zeroes of the transfer function can also be determined and located on the complex s-plane, from which can be determined the resonant frequencies, the damping ratios and the damping constants for the various pairs of the complex poles. These parameters could be correlated with known highway conditions and potentially with theoretical studies of the performance of highway materials.

Impedance Concept:

Related to the previous idea is one involving the same type of plot but for the pavement mechanical impedance rather than the transfer function. The device would consist of a vibrator and transducers to record the force of the vibrator as well as the deflection of the pavement at the point of application of force. The ratio of the force to deflection is the mechanical impedance. Measurements taken for a range of frequencies would permit the construction of a similar type plot from which can be determined the poles and xeroes of the impedance function and correlations with roadway conditions can be made.

Advantages: More reliable information than has been available might result.

Note: Special Committee No. 3, Department of Traffic and Operations, HRB Circular No.86 dated November 1968 recommends investigation of the Complex Function of Frequency as related to mechanical impedance.

Advantages: Facilitates detailed spot testing for pavement study and research on sample pavements.

Disadvantages: The correlations would have to be obtained on sample pavements of known characteristics, as there is presently no way that theoretical studies can exactly relate these plots to specific pavement construction. The time involved in performing this test would preclude the mobility that is desired for logging highway condition.

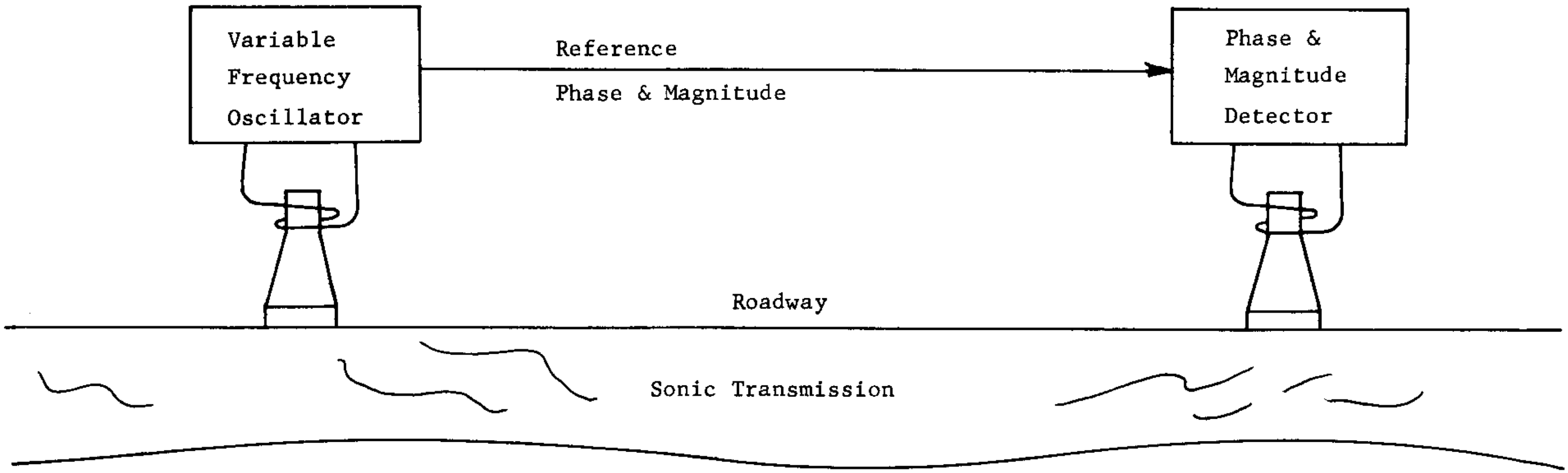

Variable
Frequency
Oscillator
Reference
Phase & Magnitude
Phase &
Magnitude
Detector
Roadway
Sonic Transmission

FIGURE III-3

Part 4 - Sonar Fracture Seeker

Information of the interior of opaque materials can frequently be obtained by transmitting sound waves through the material and examining the echo return. Discontinuities such as fractures and voids in a pavement would be detectable from the echo return pattern. A device of this type would be similar in principal to the SONAR systems used on submarines for navigation and on commercial fishing boats for finding fish. Recently a similar device has been developed for measuring the thickness of the material buildup of artery walls in human beings.

Advantages: This type of device would almost certainly be successful for locating cracks and voids.

Note: This type of device would be particularly useful for monitoring the integrity of large critical structures such as dams and bridges. A log could be kept of the SONAR return and any change in the pattern would indicate a change in the structure.

Disadvantages: The interpretation of the data would logically be done by means of a Plan Position Indicator (PPI) similar to a radar display. Interpreting the picture on a PPI can be done by a human being, but attempts to automate this have not been very successful. This system does not appear to be readily adaptable to mobility on pavement.

Part 5 - Shadowgram/Hologram Approach

The discovery of shadowgram/hologram techniques (EDN May 15, 1969) giving promise of three dimensional x-ray type examination of ordinary opaque materials presents an interesting approach to examination of pavements. If this method is developed, as it well might be in the future, voids and fractures in the pavement should become detectable.

This technique, while interesting at this time, is currently much too undeveloped and would require a long and costly development program.

Part 6 - Impulse Testing

Several systems of pavement evaluation have utilized analysis of steady state single frequency vibration response. Several distinct advantages can be gained by using a wideband analysis of vibrational response to a shock wave or an impulse. Signal theory tells us that an impulse contains all frequencies, therefore if an impulse is used to excite the pavement, more information is obtainable from the vibrational response than is obtainable if a steady state single frequency of excitation is employed. An additional advantage of using an impulse to excite the pavement is that the time required to perform the measurement is greatly reduced over that inherently required for a steady state sinusoidal excitation. This suggests the possibility of performing these tests from a vehicle which is in motion. A vehicle traveling at 30 mph or 44 feet per second could lay down the instrumentation at the front of the vehicle nominally 20 feet long and pick it up at the back of the vehicle almost one-half second later. If the entire measurement can be performed in less than this amount of time, it is then worth investigating the feasibility of developing this type of device for operation at highway speeds.

Advantages: Information from steady state sinusoidal vibrational analysis appears to be related to pavement quality. An impulse excitation would be an improvement by facilitating the acquisition of more information in much less time.

Disadvantages: Highway tests would have to be conducted to verify the relationship of the measured values to pavement quality.

CHAPTER IV

IMPULSE TESTING INVESTIGATION AND RESEARCH RESULTS

After considering the proposed possible approaches to the problem it was decided that the one which held the most promise is "Impulse Testing" described in Part 6 of Chapter III. This method would require only reasonable development and appeared to have a high degree of potential for yielding meaningful data with good road speed capability. Similar non-destructive testing devices used in other fields have extracted parameters from the unrestrained vibration of a specimen following impact from which the strength is determined with a high degree of reliability. (Proceedings of the Second Symposium on Non-Destructive Testing of Wood, April 1965, CERD, Washington State University). HRB Record #86 urges further study of the complex impedance, and a study of the vibrations following impact will yield related information. In another report (NCHRP #21) Cornell reports correlation between certain vibration parameters and pavement condition. There is a clear indication that the propogation of stress waves through the pavement tests the ability of the pavement to transmit energy from one pavement component to the next. Different types of pavements may have different characteristics, but if the cohesiveness of the pavement system is disrupted, the response will be changed.

The manner of instrumenting impulse testing applicable to pavements is to impact the surface of the pavement with a hammer blow of controlled energy. Appropriate transducers, such as accelerometers, are positioned at controlled distances from the point of impact and the resulting transducer outputs are used to calculate a quantity which will be referred to in this report as the

"Impulse Index." The calculations used to compute this index will be explained later in the chapter.

Linearity tests were conducted to determine whether the size of the hammer blow would affect the quality of the data. (See Figure IV-5). Additional tests on the attenuation of the vibration as it propagated through the pavement were conducted to establish the significance of the propagation characteristics as a measure of pavement condition. (See Figures IV-6, 7, 8 and 9).

The tests verified that the loss of energy as the signal propagates is an important pavement parameter.

This is to be expected because the sonic propagation characteristics of a medium are a function of the shear, tensile, and elastic properties of the medium. For explanation purposes, consider a steel beam, strong in shear and tensile strength and having good elastic properties. If a point on the beam is struck the energy is coupled to adjacent points on the beam which vibrate and the signal propagates with little attenuation. This would be analogous to the behavior of a solid road.

A not-so-solid road with poor qualities of shear and tensile strength and elasticity could be considered to be analogous to a layer of poorly consolidated material. If one point on such a layer is struck, the lack of coupling to adjacent points precludes the propagation of the energy to those adjacent points, hence the signal attenuates rapidly with distance.

In addition a given force on the strong beam would cause a smaller deflection at that point than the same force on a point of the poorly consolidated material. Tests were designed to verify the theoretical behavior on actual roads and the results are shown to correlate well with pavement condition.

The Transducer

In order to conduct the desired tests on this system, a suitable transducer was required. Because the natural frequency of vibration of the pavements is relatively low, a transducer capable of monitoring these low frequencies was necessary. A strong output signal is also necessary in order to maintain a high signal to noise ratio under field conditions. Various commercial transducers were examined to determine their applicability for this project, but none were found to yield the characteristics which were required. In general the magnitude of the outputs was found to be very low, and the low frequency response was poor. After consultation with the Vibrations Laboratory of the College of Engineering Research Division and the Washington State University Physics Department, a transducer was fabricated that met the necessary special requirements much more satisfactorily. The basic principal of the device utilizes the piezoelectric effect of a lead-zirconium-titanate crystal in an accelerometer configuration. A photograph of the transducer as it evolved after a few alterations appears in Figure IV-1 with a cross section diagram shown in Figure IV-2. The first model worked for a time but the crystal eventually cracked due to stresses caused by clamps that held the crystal in place and because of the load distribution. These problems appear to be eliminated in the present configuration. This transducer has a very high output voltage with excellent low frequency response characteristics. It has performed well in collecting data for the various field tests.

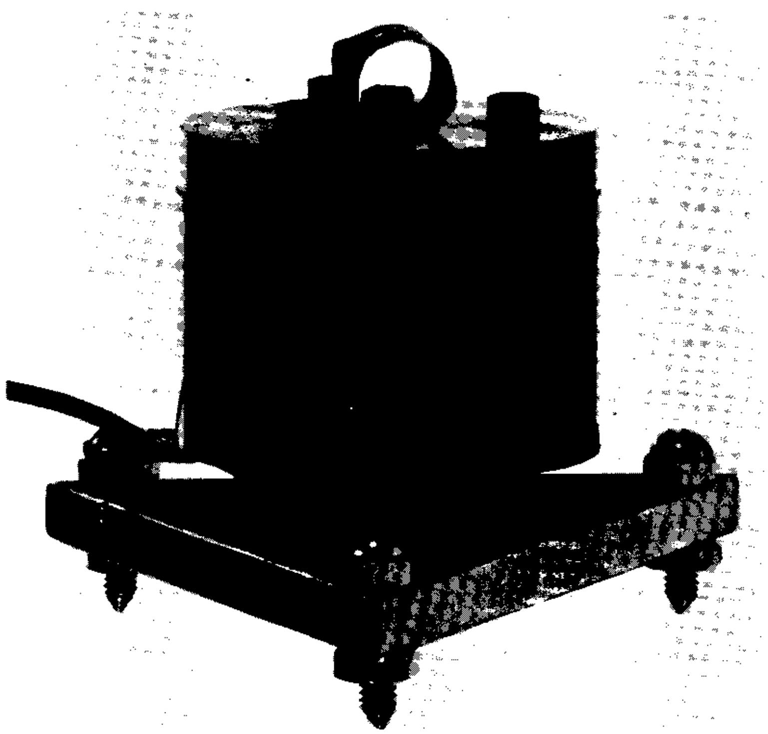
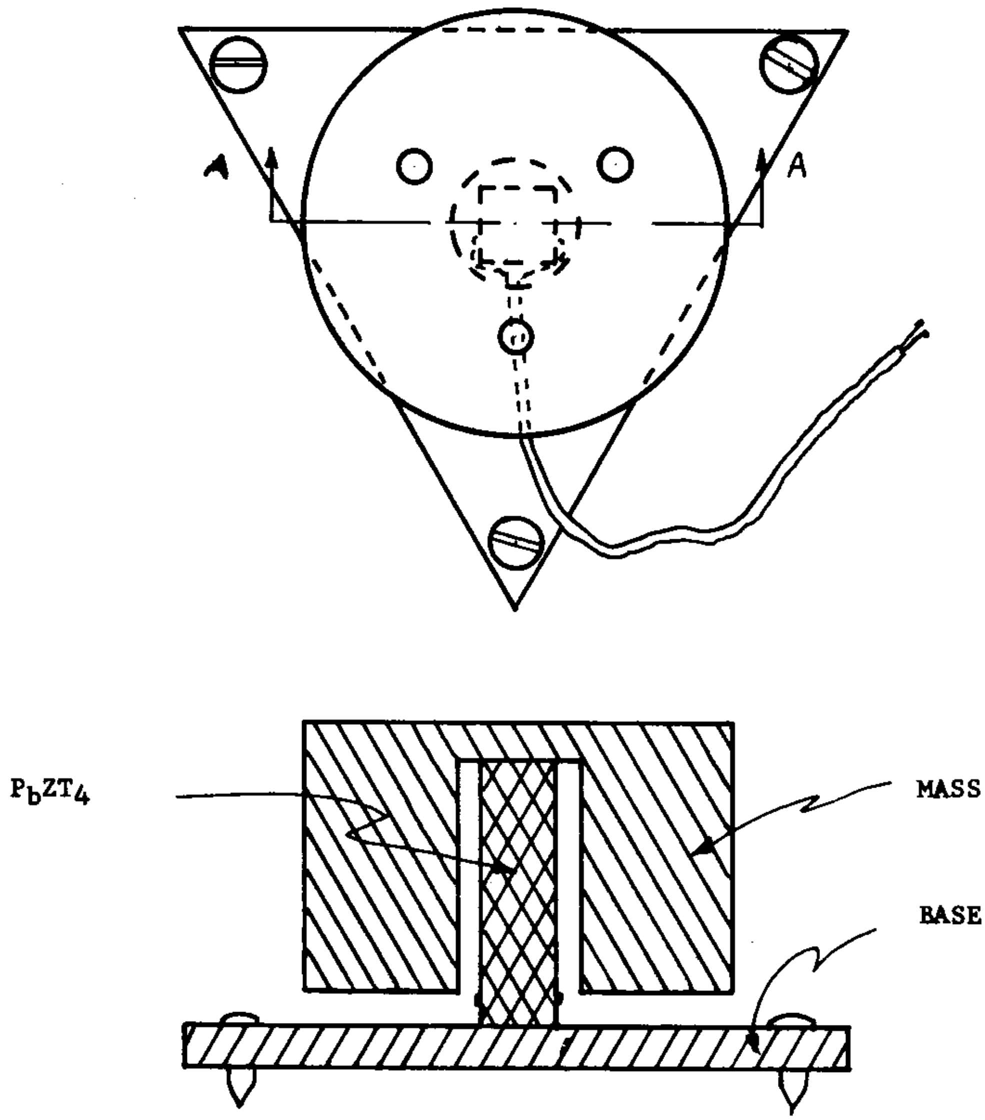


FIGURE IV-1

Lead-Zirconium-Titanate Piezoelectric Accelerometer

PIEZOELECTRIC ACCELEROMETER



Section A-A

FIGURE IV-2

FIGURE IV-3

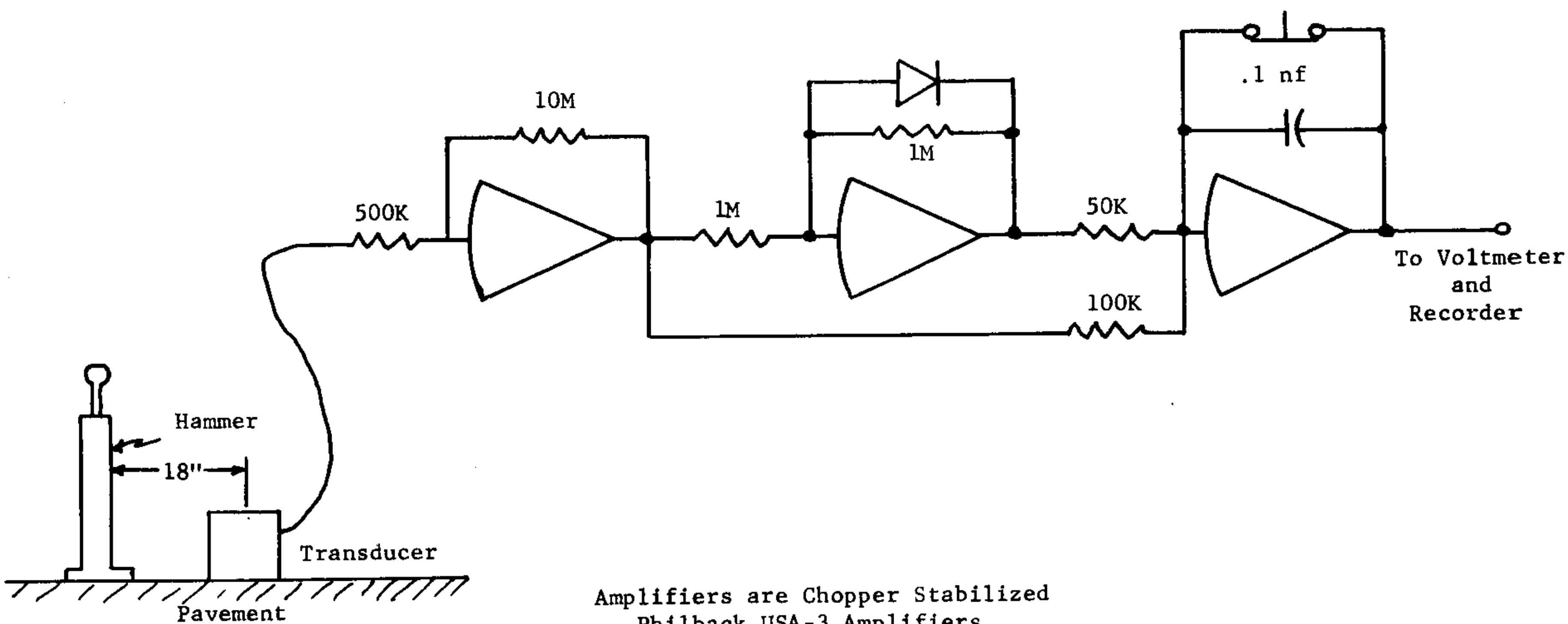
Accelerometer shown with the computing equipment used to process the signals. The equipment shown here is off-the-shelf vacuum tube general purpose laboratory equipment. Solid State equipment specially built for the purpose used here would be much more compact. Output devices other than the strip chart recorder shown here could be utilized.

First Field Tests

The first set of road tests were designed to determine if satisfactory linearity existed in the pavement and transducer system. The tests were conducted on several pavements in order to provide additional information on the adequacy of determining pavement condition using only one transducer. The output of the transducer was processed in two ways and compared in order to evaluate the two processing methods. One method consisted of putting the accelerometer output into a magnitude circuit and then integrating. This process produces the integral of the magnitude of the acceleration. The second method consisted of putting the output of the accelerometer into a magnitude circuit and then into a peak detector. This process produces an output proportional to the largest peak of the accelerometer output.

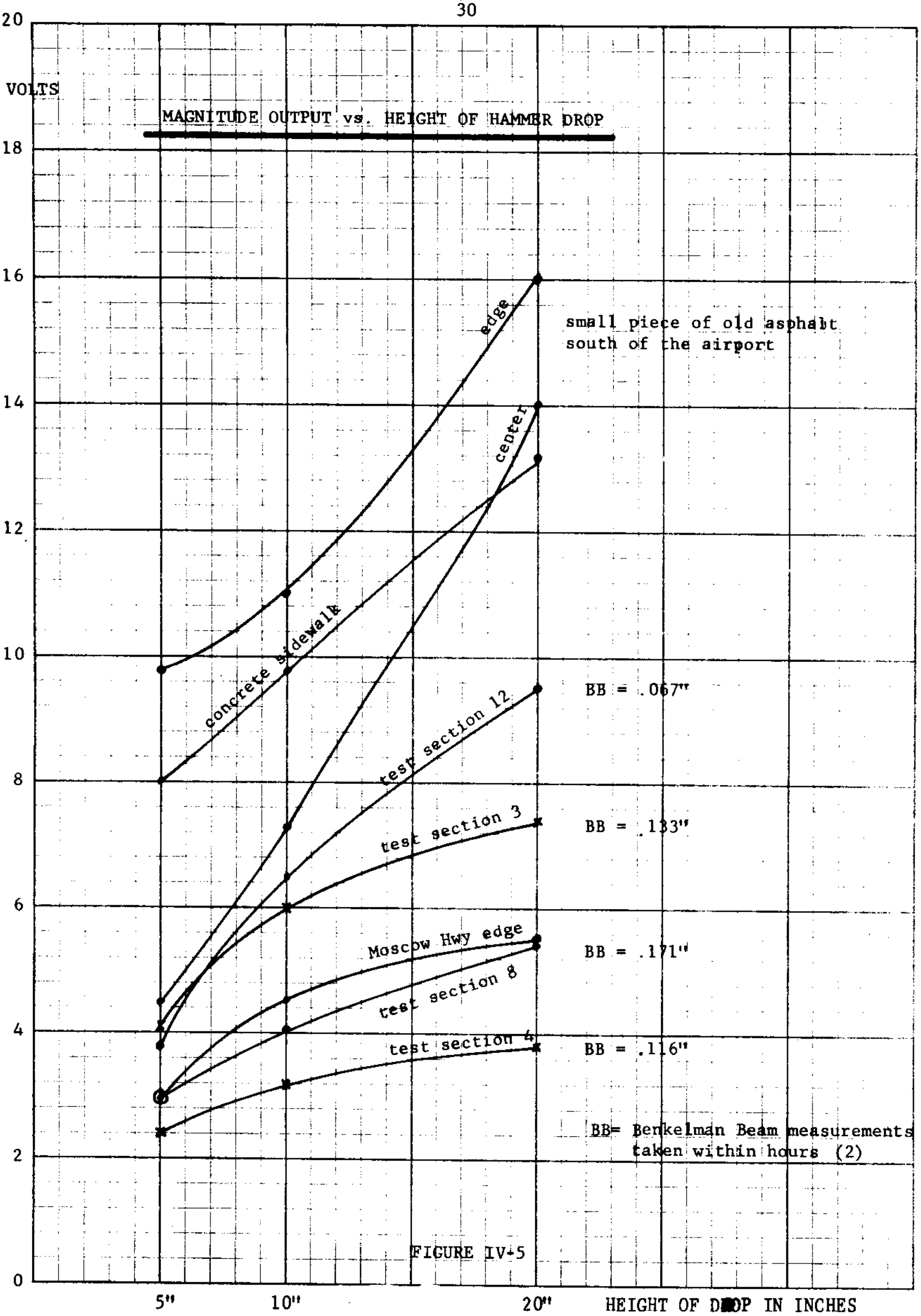
Results of many tests of these two processes indicated that either method could be used to provide equally valuable data, but the integral of the magnitude proved to be somewhat easier to instrument, produced better signal to noise ratios and better repeatability. Consequently, in the work reported subsequently in this report, the integral of the magnitude of the transducer output is the indication used. Figure IV-4 is a schematic of the signal processing used.

The test sites that were used for this set of tests were chosen to provide a broad range of pavement conditions in a convenient manner. The results of tests on each of the sites is shown graphically in Figure IV-5. The concrete sidewalk was selected because it was just outside the laboratory window and was convenient for an operational check of the equipment before putting it in the vehicle. The Moscow Highway (S.R. 270) is the main state highway leaving Pullman to the east and was resurfaced with an overlay of asphalt about 1966.



Amplifiers are Chopper Stabilized
Philback USA-3 Amplifiers

FIGURE IV-4



VOLTS
MAGNITUDE OUTPUT vs. HEIGHT OF HAMMER DROP
20
18
16
14
12
10
8
6
4
2
0
edge
center
small piece of old asphalt south of the airport
concrete sidewalk
test section 12
BB = .067"
test section 3
BB = .133"
Moscow Hwy edge
test section 8
BB = .171"
test section 4
BB = .116"
BB= Benkelman Beam measurements taken within hours (2)
5"
10"
20"
HEIGHT OF DROP IN INCHES

FIGURE IV-5

It is generally smooth and shows only an occasional small crack. The "small piece of old asphalt south of the Pullman-Moscow Airport" is an old unmaintained remnant of a road which is severely broken up. In addition to these, the Highway Research Section of Washington State University operates a highway test ring which has several sections of pavement and a frame which can roll loaded truck wheels over it for accelerated pavement life tests. Four of these sections were used for the tests and they are identified by the numbers 3, 4, 8 and 12.

Analysis of the Test Results

The tests were conducted by placing the accelerometer on the pavement and dropping a length of iron pipe on the pavement at a point 18" away from the accelerometer. The output of the system is the integral of the magnitude of the accelerometer signal. Results of the tests are shown graphically in Figure IV-5. The vertical axis is the output of the integrator in volts, and the horizontal axis is the height through which the pipe was dropped. It can be observed that the curves are well behaved functions and in general inflect in the correct direction consistent with the square root relationship between velocity and energy indicating satisfactory linearity of the system. The small piece of old asphalt did not behave as well, probably because the signal being very large could very well have produced saturation in the amplifiers.

It can be seen from these curves that some degree of correlation exists between the vertical distance in Figure IV-5 and the condition of the pavement, a large vertical distance indicating a poor pavement and a small vertical distance indicating a better pavement. The poorest pavement was the old piece of asphalt and it came out to be the highest on the graph. The concrete sidewalk was next. The Moscow Highway is relatively low on the graph with the test ring sections intermingled.

In addition, Benkelman Beam measurements were made on the test ring sections and the results are recorded also on Figure IV-5. It can be seen that the position of the curves on the graph does not correspond very well with the Benkelman Beam data, indicating that more information is required than simply measuring the integral of the magnitude of the acceleration after impact. Such a method appears capable of differentiating only extreme cases of good and poor roads.

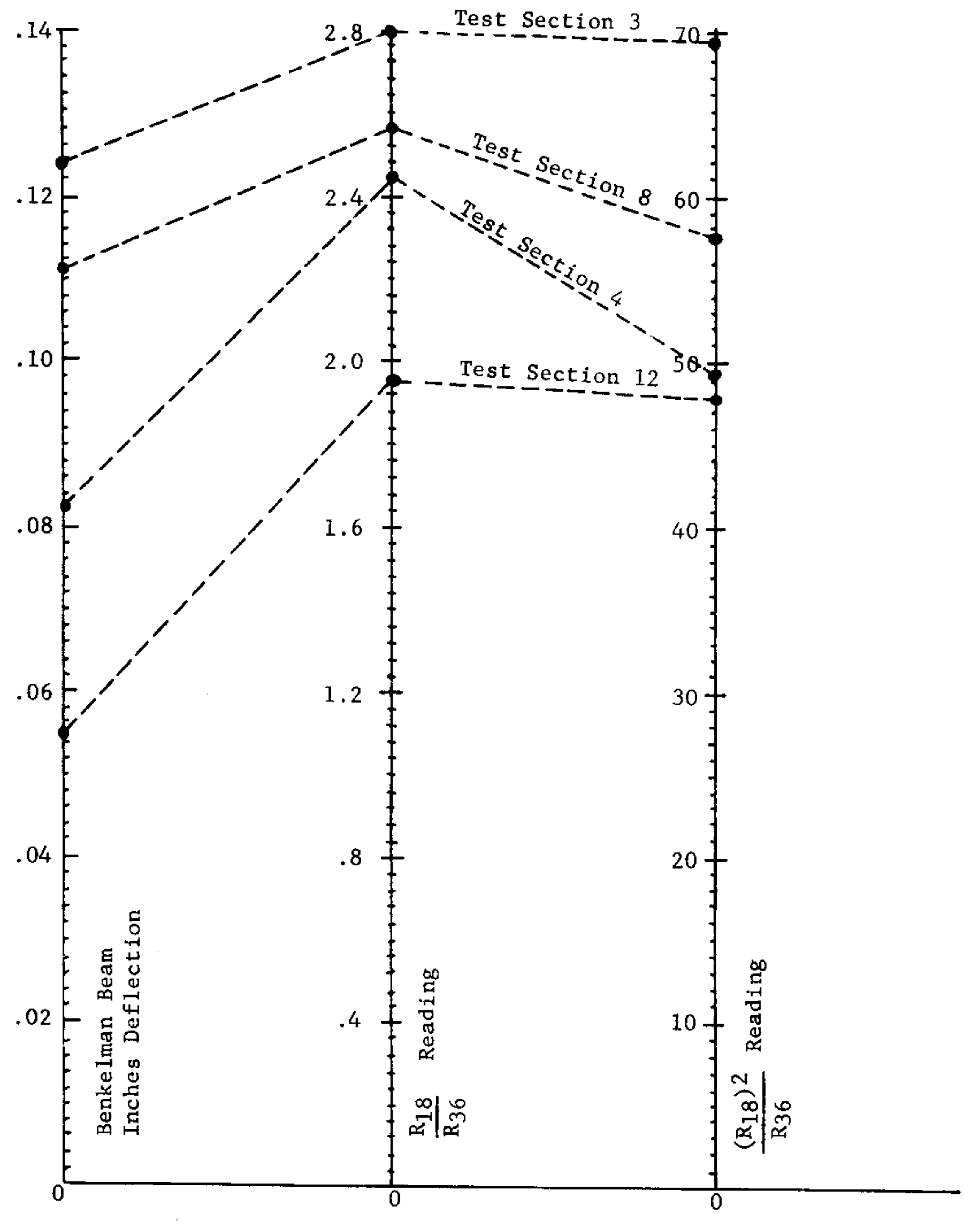
Attenuation Tests

Additional tests were then conducted to determine the effectiveness of using the attenuation of the signal as it propagates through the pavement as a measure of pavement condition. These tests were conducted by placing the accelerometer 18" from the impact point and taking a reading and then moving the accelerometer to 36" from the impact point and taking a second reading.

The reading at 18" divided by the reading at 36" gives a result which is identified as $\frac{R_{18}}{R_{36}}$ and which is displayed graphically in Figure IV-6. Also displayed in Figure IV-6 is a set of values identified as $\frac{(R_{18})^2}{R_{36}}$. This is the value obtained by multiplying the $\frac{R_{18}}{R_{36}}$ ratio by the (18") reading. This value takes into account the attenuation of the signal as it propagates, as well as the amplitude of the acceleration at the 18" point. In Figure IV-6, dashed lines connect the data taken with the Benkelman Beam with the $\frac{R_{18}}{R_{36}}$ and also with the $\frac{(R_{18})^2}{R_{36}}$ for the four sections of the test ring on which it was convenient to take Benkelman Beam data.

In this figure, the $\frac{R_{18}}{R_{36}}$ ratio correlates better with the Benkelman Beam data than does the $\frac{(R_{18})^2}{R_{36}}$ value.

However, examination of the amplitude data of Figure IV-5 in addition to visual observation makes it appear unlikely that Section 12 is as much better than the rest of the sections as the Benkelman Beam makes it appear. On theoretical grounds it was strongly suspected at this point that the formula involving both the amplitude and the attenuation was the superior formula. A modification of this formula described in the next paragraph was used to process the data acquired during the final road tests.



Test Section 3
Test Section 8
Test Section 4
Test Section 12
.14
.12
.10
.08
.06
.04
.02
0
2.8
2.4
2.0
1.6
1.2
.8
.4
0
70
60
50
40
30
20
10
0
Benkelman Beam
Inches Deflection
R18/R36 Reading
(R18)²/R36 Reading

FIGURE IV-6

Final Road Test

During efforts to further test the validity of the procedures which had been developed, some disconcerting anomolies occurred in the results obtained at other test sites. While some results appeared quite reasonable, occasionally a pavement which visual observation indicated to be inferior would yield a test value which would be disturbingly low. Recalling that a low value should mean a good pavement, confidence in the credibility of the test value as an absolute indicator was less than desired. This phenomena was investigated, the reason for it discovered and steps were taken to correct the problem. The low value problem would be observed in pavements determined to be poor by other considerations and the reason for the low value was discovered to be that in these poor pavements the attenuation of the signal was so great in the first 18" of distance that the first accelerometer received a deceptively small signal. The net result was a deceptively low value which would normally indicate a good pavement. To correct this, one of the accelerometers should be placed as near to the impact point as is physically possible. Tests on an appropriately poor road indicated that distances of up to 6" did not seriously deteriorate the resulting value. In the subsequent tests a value of about 3" was used as being the smallest practical distance. A second reading was then taken with the transducer located 18" from the impact point and a third reading at 36".

The test sites selected for this final field test were the various highways leading out of Pullman. In addition to the Moscow Highway mentioned in earlier tests, two points on the Palouse Highway (S.R. 27) were used and three points on the Colton Highway (U.S. 195). The Palouse Highway is a seal coat type of pavement in good condition and not subject to heavy traffic.

The Colton Highway has relatively heavy traffic and was tested in three places where the pavement was in markedly different condition. Photographs of the places tested are included in this section.

At each place where tests were conducted, measurements were made in the outside wheel track and also in the center of the lane or the center of the road. The lane center was used for the fairly busy Moscow and Colton Highways, but for the Palouse Highway the road center was used because it is a fairly narrow road. Results of these tests are displayed in two distinct ways. Figures IV-7, 8 and 9 show the three transducer readings obtained by impulse testing compared to the five transducer readings obtained from a Dynaflect at approximately the same locations. These locations are identified as "Moscow Highway," "Mile Post 19" of the Colton Highway and "New Road .45 mi. S of Colton." Because of the configuration of the Dynaflect, the readings were taken somewhat toward the lane center from the outside wheel track and were not repeated at the wheel track and lane center as were the impulse tests. The data is displayed in the conventional Dynaflect manner except that the scale of the Dynaflect readings is adjusted by a factor of 10 to make an easier comparison with the results of the impulse tests. It should be observed that the raw data from the Dynaflect compares quite well with the raw data from the impulse tests.

A more impressive display of the impulse test data is shown in Figure IV-10 which displays the Impulse Index for each location. The Impulse Index is obtained by utilizing the data from only two of the three transducers. Identifying the data from the transducer nearest to the hammer as R_0 and the data from the transducer located 18" from the hammer as R_{18} the Impulse

Index is computed by multiplying the ration of these two readings by R_0. This is mathematically identical to

$$\text{Impulse Index} = \frac{(R_0)^2}{R_{18}}$$

In Figure IV-10 the left hand bar of each pair is the result from the outside wheel track and the right hand bar is the result from the lane or road center. Note that the tests at both points on the Palouse Highway, on the Moscow Highway, and at Mile Post 19 on the Colton Highway all show very clearly a higher index for the wheel track demonstrating the deterioration of the wheel track.

"Colton Begin 35" and "New Road .45 mi. S of Colton" show a different relative effect. In the case of the "Colton Begin 35" test, the road is quite patched in that area as can be seen from Figures IV-11 and 12. In addition, Figure IV-12 very clearly shows the depression in the road. The impulse index obtained for this test site then does seem very reasonable, considering the obvious condition of the pavement.

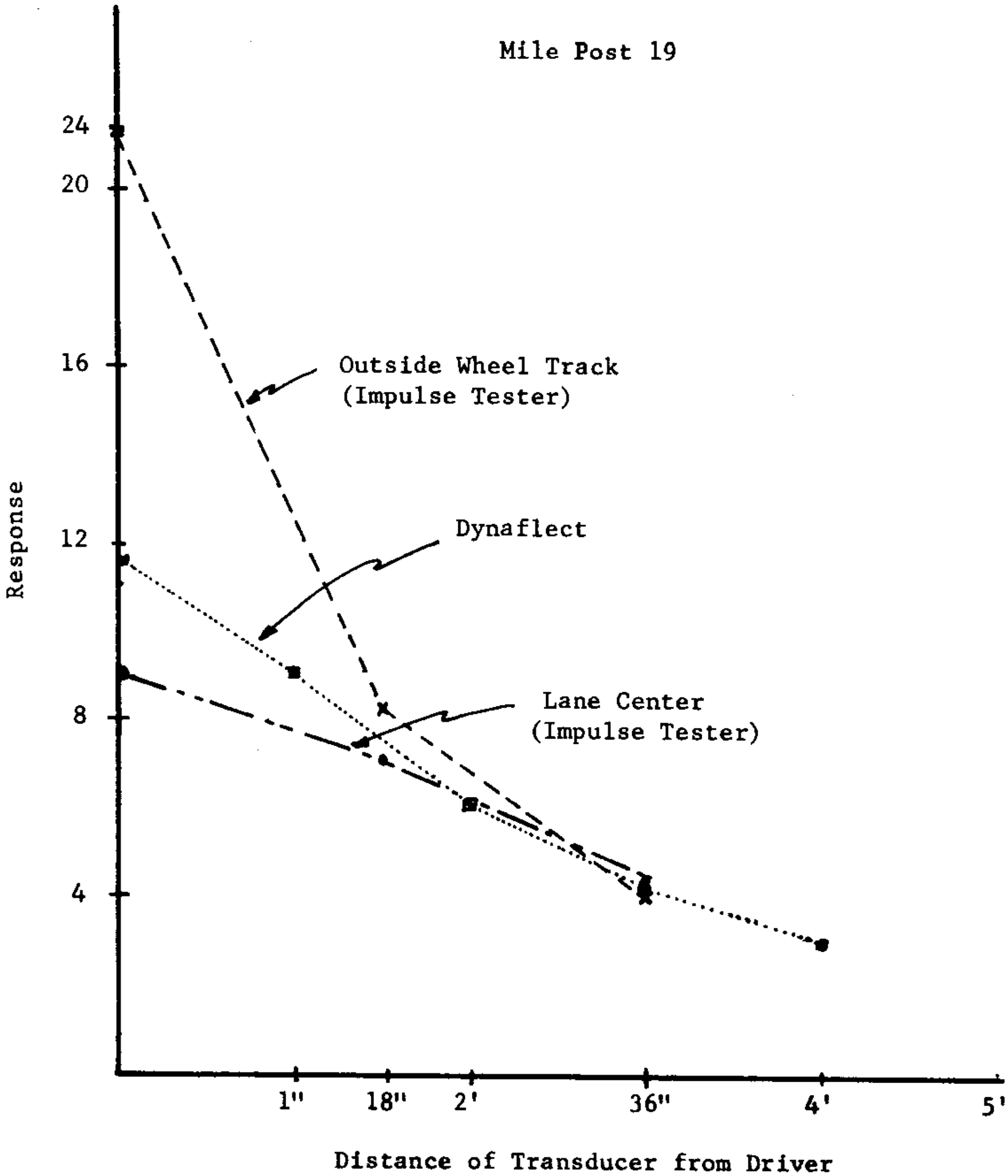
The graphs for the "New Road .45 mi. S of Colton" should be interpreted with reference to Figure IV-13. Notice that the centerline has not been painted on the pavement. Naturally then the wheel tracks do not show any deterioration on this newly constructed pavement section.

The data from "Mile Post 19" is especially interesting. This pavement is not new but reference to Figure IV-14 shows it to appear to be in good condition. However, the test data indicates deterioration under the wheel track has taken place even though it is not visible at the surface. Further down the road, there are many exterior signs of deterioration.

Conclusion

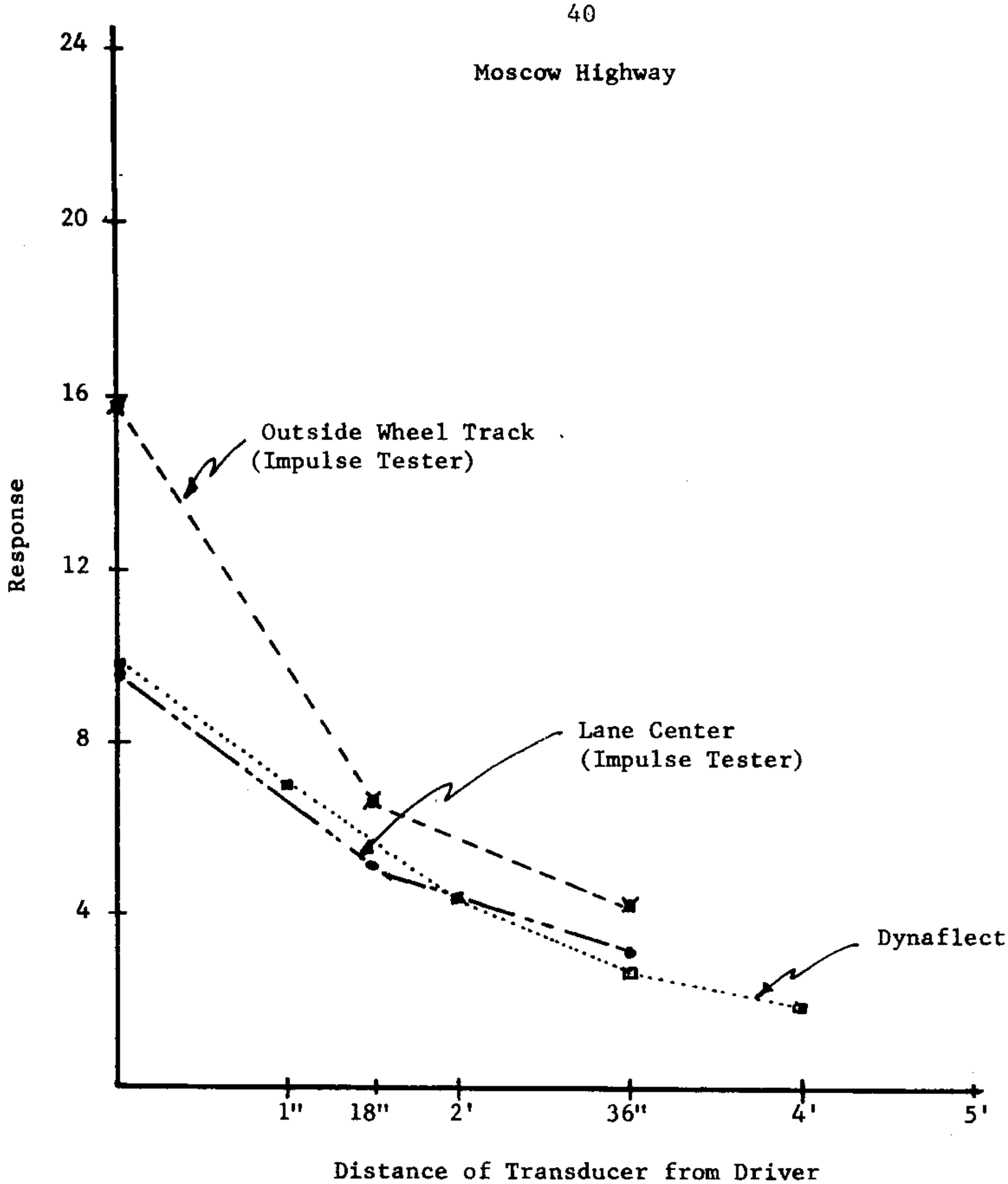
The data presented in this chapter gives substantial evidence of the usefulness of the "Impulse Index" as an indicator of pavement strength. The "Impulse Index" is obtained by placing an accelerometer on the pavement as near as practicable to a point to be impacted, and a second accelerometer at some distance, such as 18" from the impact point. The impact is produced by dropping a hammer on the pavement at the impact point. The integral of the magnitude of the outputs of the accelerometers is then computed electronically. Referring to the integral of the magnitude of the accelerometer nearest to the impact point as R_0 and the integral of the magnitude of the accelerometer placed at 18" from the impact point as R_{18}, the "Impulse Index" is computed using the relation

$$\text{Impulse Index} = \frac{(R_0)^2}{R_{18}} = \frac{(\text{Signal Magnitude at Source})^2}{(\text{Signal Magnitude at Specified Distances})}$$



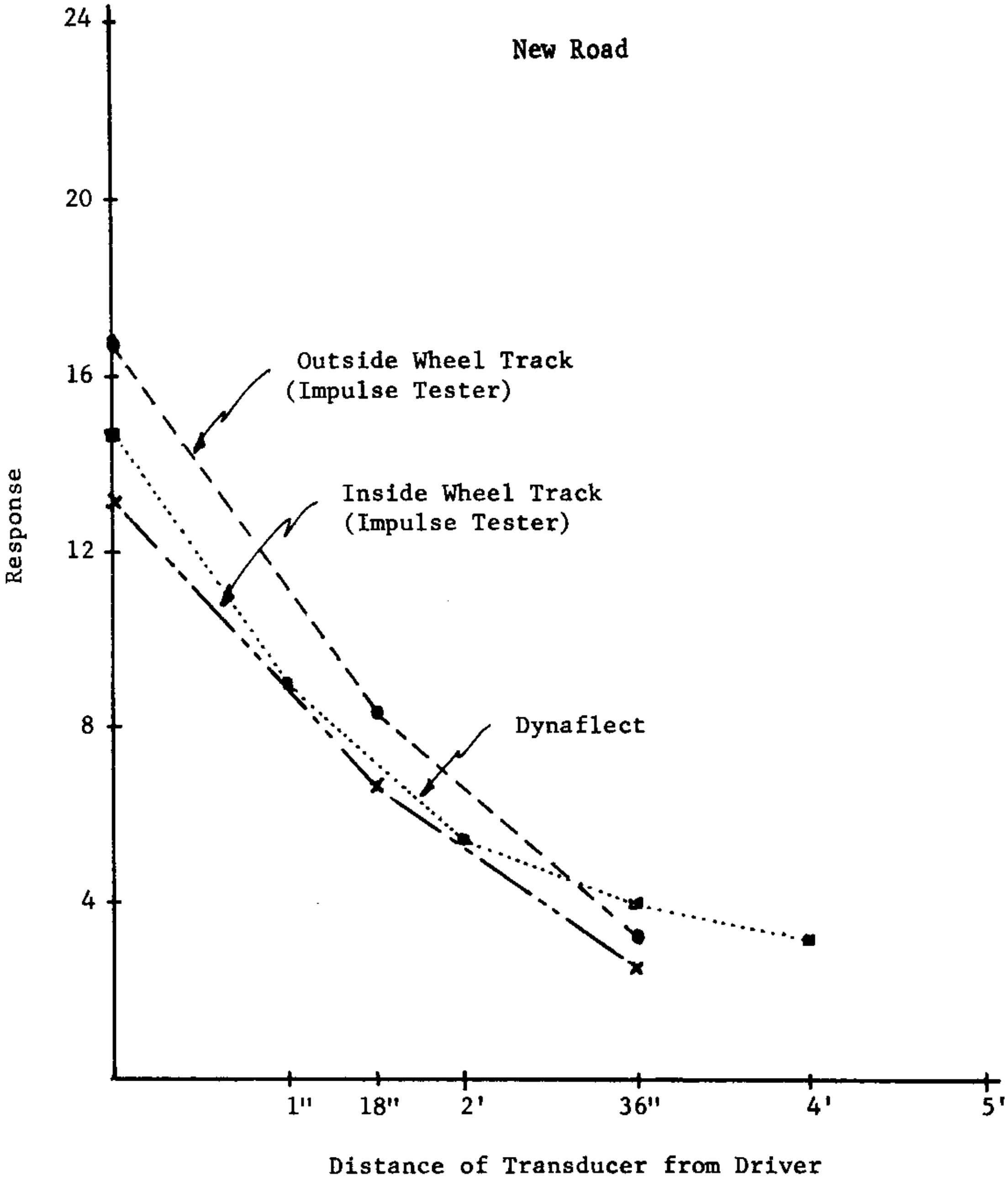
Comparison of data from the transducer of the impulse tester compared to the data from the transducers of the Dynaflect. To facilitate comparison, the Dynaflect readings were scaled up by a factor of 10.

FIGURE IV-7



Comparison of data from the transducer of the impulse tester compared to the data from the transducers of the Dynaflect. To facilitate comparison, the Dynaflect readings were scaled up by a factor of 10.

FIGURE IV-8



Comparison of Data from the transducer of the impulse tester compared to the data from the transducers of the Dynaflect. To facilitate comparison, the Dynaflect readings were scaled up by a factor of 10.

FIGURE IV-9

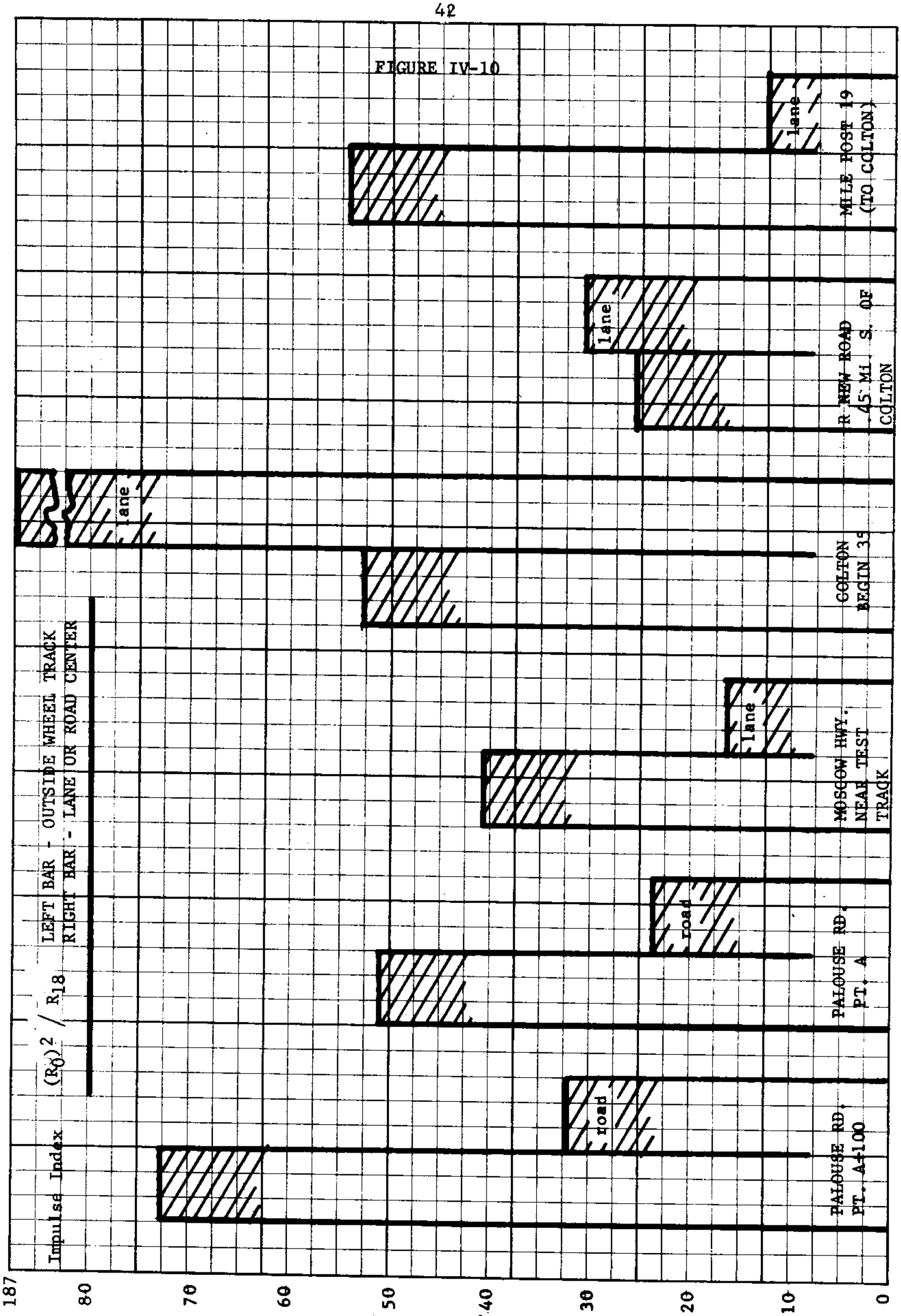


FIGURE IV-10
Impulse Index
$(R_0)^2 / R_{18}$
LEFT BAR - OUTSIDE WHEEL TRACK
RIGHT BAR - LANE OR ROAD CENTER
187
80
70
60
50
40
30
20
10
0
road
road
lane
lane
lane
lane
PALOUSE RD. PT. A+100
PALOUSE RD. PT. A
MOSCOW HWY. NEAR TEST TRACK
COLTON BEGIN 35
R NEW ROAD .45 Mi S. OF COLTON
MILE POST 19 (TO COLTON)

FIGURE IV-11

Photograph of the pavement at "Colton Begin 35" test site. Notice the patches visible in the photograph.

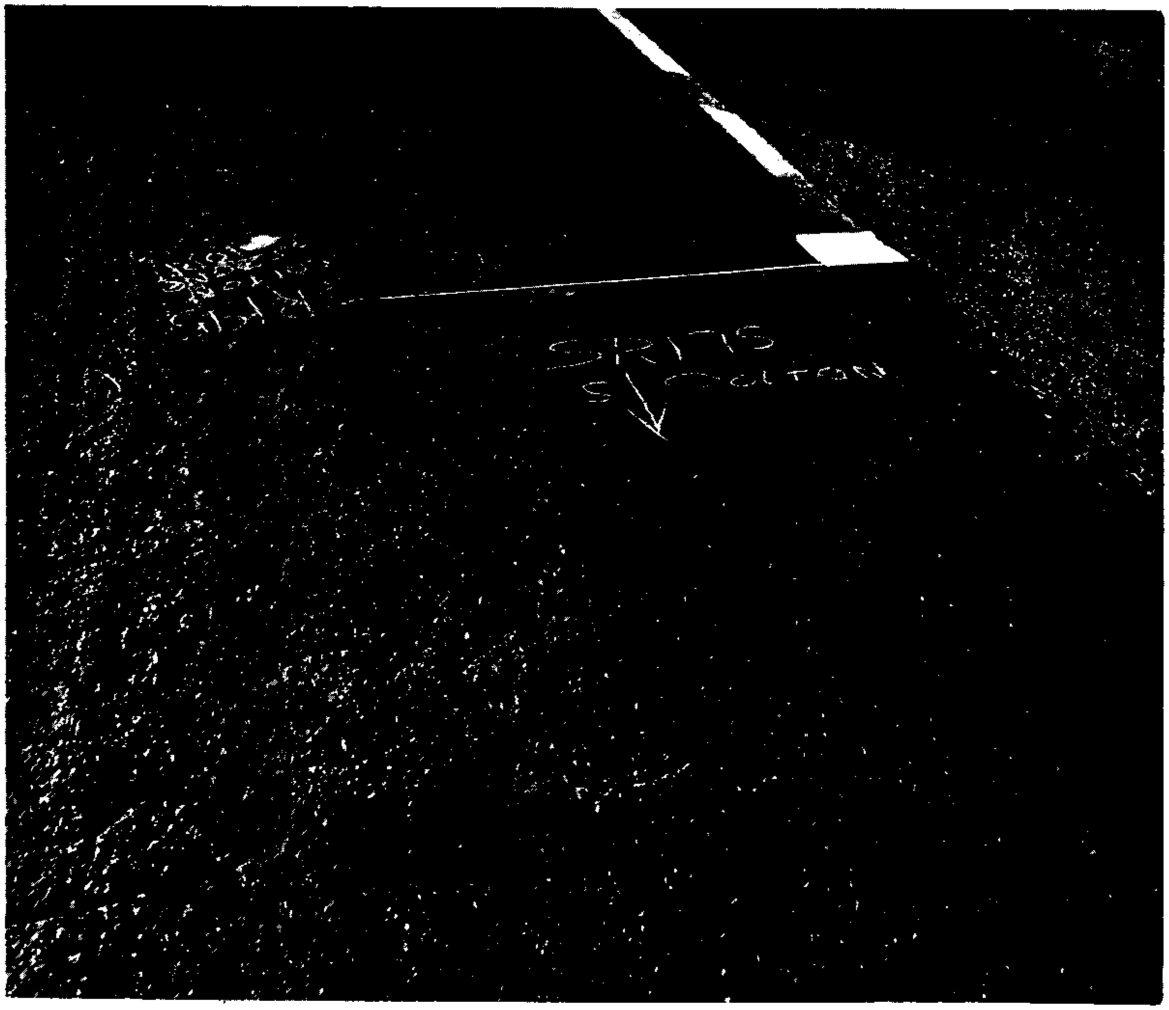


FIGURE IV-12

Notice the depression in the pavement at this point in the near vicinity of the "Colton Begin 35" test site.

FIGURE IV-13

Newly constructed asphalt pavement at "New Road .45 mi. S of Colton" site.

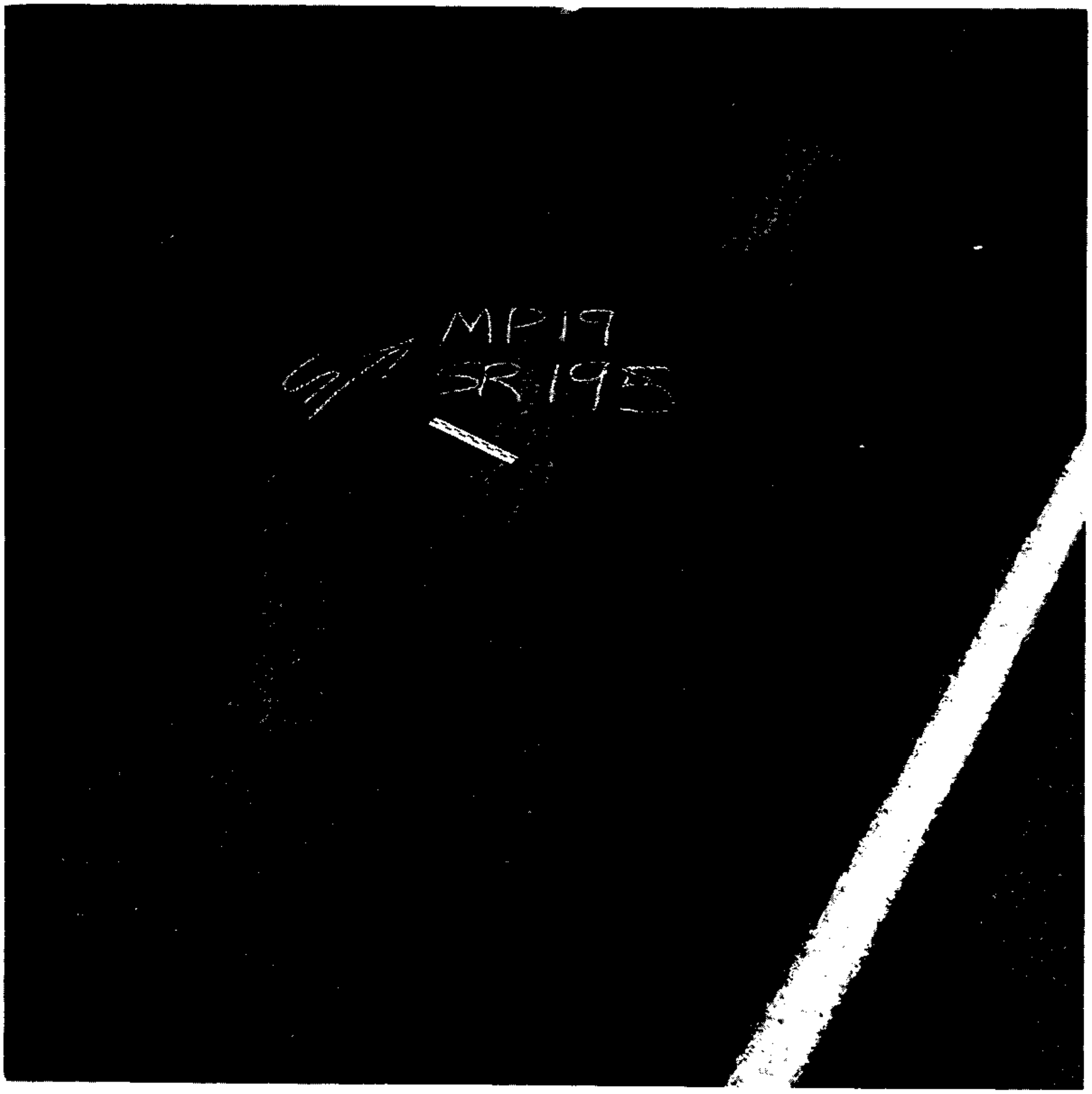


FIGURE IV-14

"Mile Post 19" test site.

CHAPTER V

MECHANICAL ASPECTS

The previous chapter describes the basic concepts of a system which appears feasible to acquire data related to pavement strength and details results obtained at various points on several highways. If a mechanism can be designed which will place the transducers on the roadway, impact the roadway, pick them up again and advance down the road, the system can make nearly continuous evaluation along a highway. The system can be made entirely automatic except for the driver of the vehicle. It is a certainty that such a mechanism can be built. The question is, how fast can it travel down the road and still collect usable data? If we assume that the vehicle is basically a passenger car or light van roughly 20 feet long, we can compute the time it would take for the vehicle to advance its own length. Using a presumed speed of 30 mph, it would require almost 500 milliseconds for the vehicle to advance its own length. The actual reading of the data required only about 50 milliseconds, leaving 450 milliseconds for the picking up, setting down, and settling operation. The actual settling time required is a function of the mechanical design, and has not yet been determined.

A mechanism for performing this operation has been conceived, but will require detailed design and development.

Referring to Figure V-1, the mechanism has spools of about four-inch diameter mounted on axles at the front and the rear of the vehicle and off to one side. Alternatively, it can be constructed on a trailer and towed. A belt is stretched over the spools and driven at a speed synchronized with the vehicle speed so that the lower half of the belt is stationary with respect to the road. A carriage is mounted on the belt with a loose pin so that as the belt travels around the spools, the carriage is carried around the oval but does not rotate about its own axis. Counterbalancing would minimize the whipping motion of the carriage. No signal slip rings would be necessary in this configuration. The two required transducers are suspended from the carriage by webbing and spaced the required distance apart. As the belt rotates around the front spool, the carriage is lowered close to the ground so that the transducers are set on the road and their webbing becomes slack. The vehicle advances but the point on the belt holding the carriage remains fixed with respect to the ground. As the vehicle advances far enough, the point on the belt holding the carriage is lifted up around over the rear spool and carried to the front of the vehicle where it is once more lowered around the front spool. The impact device is mounted on the vehicle or in the carriage and produces an impact at such time as the transducers are in the proper place and settled.

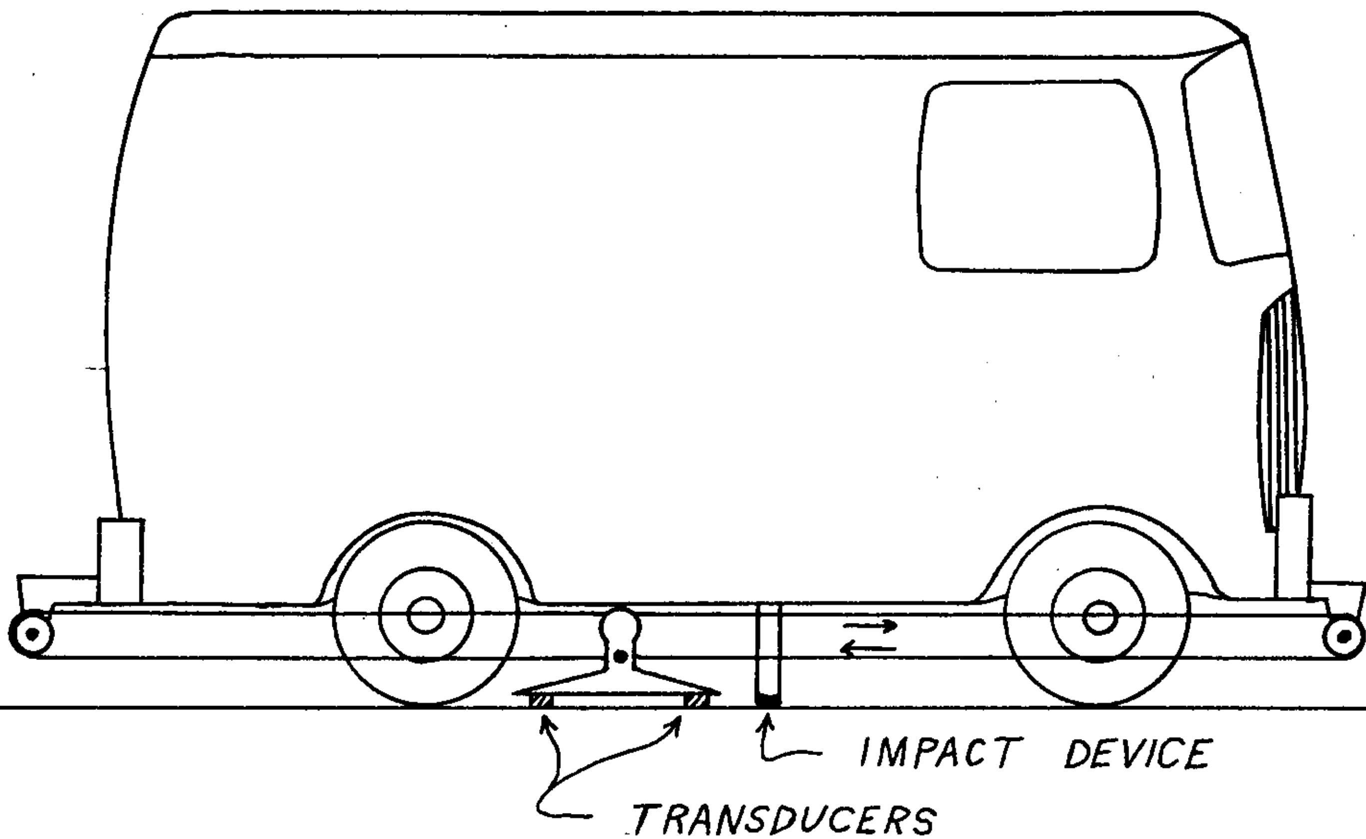


Figure V-1

CHAPTER VI

CONCLUSIONS AND RECOMMENDATIONS

Chapters three and four have described a system concept useful for logging data related to pavement strength at speeds in excess of any other known device for making measurements of comparable quality. In fact, even if a start-stop system were used, more readings can be taken in less time and more ground covered than with any other device so far developed.

The signal processing equipment which was utilized for these tests was of the "off the shelf" variety and is shown in Figure IV-3. Note that because it was available off the shelf at the University it is vacuum tube type and much larger than would be required for a specially constructed package. It is also larger because it has more capability than is needed here. Even so, it obviously easily fits into most any vehicle and the total power requirement was less than 500 watts. Specially packaged equipment would require much less power. However, an addition which we did not have but which should be in the final system, would be automatic recording equipment. It is suggested that the output of the impulse index be recorded automatically on either magnetic tape or printed out along with mileage marker data. In addition, it might be desirable to perform some auxilliary calculations such as averaging the values over some distance such as a half mile, and also recording maximums.

Making these extra calculations and recording them along with individual values would generate data in a very convenient and usable form. The data would be adequate and meaningful with concurrent minimization of extraneous data.

It should be noted that the device described herein produces data related to pavement strength, but does not measure the riding qualities of the pavement. It is recommended that one of the many profilometer type devices be utilized and incorporated in this same vehicle and the data recorded in the same format. Such an instrument would give additional information which would not otherwise be obtainable. It is conceivable that a road could have a sound structure but yet have poor riding qualities, in which case a relatively thin overlay could make a lot of difference. If the riding qualities as indicated by the profilometer are poor and the strength is also poor, the problem is obviously more serious.

Utilizing automatic equipment of the type described in this report would facilitate logging the condition of the entire highway system on a regular basis. Repeated loggings would facilitate the discovery of any significant change with time and give additional information useful for managing a system of highways and anticipating maintenance requirements.

Development of this equipment and construction of a prototype is a feasible project within the capability of current technology.