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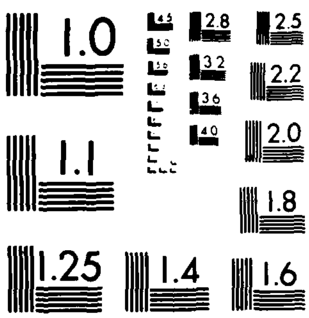
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Non-Contact, Non-Destructive Airport Pavement Profile, Texture and Deflection Measurements

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Final Report

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16. Abstract

A non-contact, non-destructive method is described that allows the user to measure pavement texture and loaded and unloaded profiles from a moving vehicle.

The device uses laser distance-measuring gages. The gages are arranged such that their readings can be interpreted to give the loaded and unloaded pavement profiles and a measure of its texture. Four gages are mounted on a rigid beam that, in turn, is mounted on the side of a load vehicle. The gages read the distance to the pavement. Three of the gages are located outside the range of influence of the load wheel, and hence the pavement below these gages is undeflected. One of the gages is adjacent to the load wheel to measure the induced deflection. An algorithm is presented that relates all measurements to a common datum.

The three gages yield readings that are interpreted to give the profile (do the surveying). The gages make so many readings and so quickly, that the standard deviation of the readings, taken over a short time period, gives a measure of the texture.

A prototype device was constructed and tested. The results were -

1. Pavement profiles were calculated using the new system. These compare favorably, though not completely, with the transit surveys.
2. Standard deviations were recorded. These readings were taken over concrete, asphalt and porous friction surface pavements. Differences were noted between the textures of concrete (smooth) and asphalt (rough) pavements. No correlation between this measure and standard measures was made.
3. The deflections caused by prototype loads were measured and recorded. This was done from the load vehicle, while the vehicle was moving across a pavement at the U. S. Army Corps of Engineers Waterways Experiment Station, in Vicksburg, Mississippi. The scheme for obtaining the resulting deflections is described in detail. An algorithm for accomodating the misalignment of the laser gages on the rigid beam is also presented.

Suggestions are offered for improving the system.

17. Key Words
Airport Maintenance
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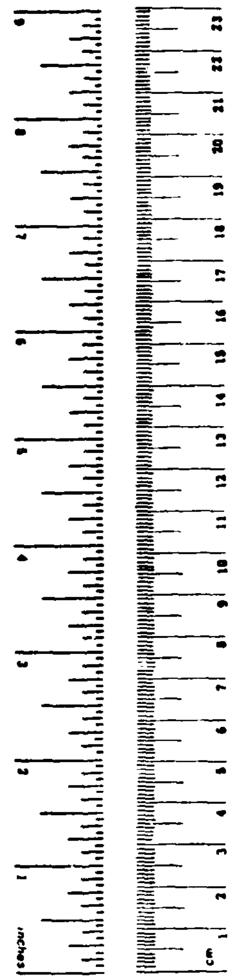
METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

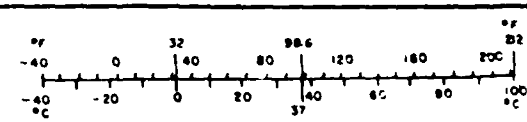
Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



60 mph = 52.1 knots (nautical miles per hour)
60 mph = 88'/sec
1g = 32.2'sec^2

1 mph = .87 knots
1 knot - 1.15 mph

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I. INTRODUCTION

A. Description of the Problem

This study addresses the problem of improving the ability of airport pavement engineers to plan the maintainance of asphalt runways and taxiways. Because of the high cost of closing a runway of an airport, the scheduling of maintenance is very important. This problem is accentuated by the increasing frequency of air travel and of the weight of aircraft. Consequently, any system that will allow maintenance to be predicted and performed before a failure takes place (requiring an unscheduled closing) would be most welcome.

At present, there exist several methods of testing asphalt pavements and of predicting when they will require maintenance. They are discussed in the next section, the "Review of Literature". They all suffer from one or more of the following problems;

1. Being very time consuming (thus expensive),
2. Only being practical to test a very few locations on the pavement,

3) Requiring the destruction of a piece of the pavement in order to get the necessary parameters for predictions.

B. Requirements of the Solution

The solution to the problem described above is to establish a fast, efficient method of predicting pavement performance. The method should be such that large areas of a pavement can be traversed and tested. The method should be quick and easy to implement, so that a minimum of time is required and normal airport operation can be resumed as fast as possible. It would be preferable to have a test that did not require rebuilding a piece of the pavement after the test had been run. Not only is this time consuming, but it creates discontinuities. These discontinuities may limit where this type of test can be run. It would be best if the test could be run day or night, so that testing could be done whenever a lag in traffic occurs.

The use of actual wheel loads is preferred over simulated loadings, as they more accurately portray real conditions and the state of loading under which the pavement will have to perform. Full-scale loadings, using prototype aircraft, would be the most desirable. The load vehicle used should be one that is available when needed, so that testing may be repeated, as desired

To maximize the utility of a method, the equipment should require little or no training to operate so that there will be no great expense incurred in training or hiring personnel. Regular maintenance crews should be able to run the test.

Lastly, the cost of the system should not be prohibitive.

C. Proposed Solution

The proposed solution is shown schematically in Fi e I-1. Shown is a load vehicle (here represented as a truck) carrying the system that will analyze the pavement. The system consists of four laser distance measuring gages attached to a rigid beam which, in turn, is attached to the side of the load vehicle. One gage is adjacent to the load wheel, which is used to measure a deflection created by the load. As the vehicle traverses the pavement, the gages measure the distance to the pavement at intervals specified by the fifth wheel.

In the process of measuring deflections, two other important pavement characteristics are obtained: the undeflected profile and surface texture. The texture measurement is possible because the gages have a resolution smaller than the asperities of the asphalt pavement. The resolution

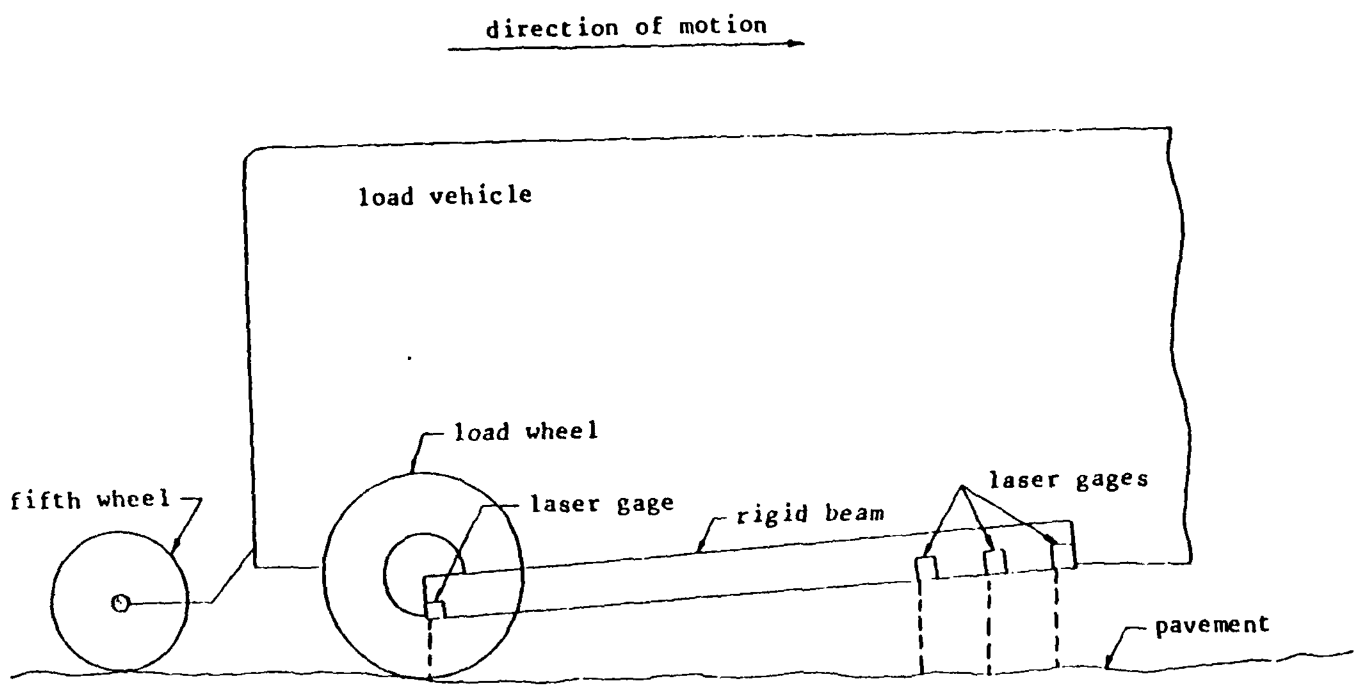


Figure I-1 Components of the system

is enhanced by the fact that a large number of measurements can be obtained in the near vicinity of a point on the pavement. The profile can be used in determining the roughness of the runway.

The proposed system is quick, versatile, requires little mechanical contact with the pavement surface, and uses actual vehicular loads. It allows the operator to test the pavement in a global sense, and at any time of the day. The accompanying electronics , while very sophisticated, are easy to use. With some training, it is expected that regular maintenance personnel could operate it. Almost any vehicle that the beam can be attached to can serve as a load vehicle--trucks, cars, airplanes, fire engines--any vehicle that produces a measurable deflection can be used.

This study encompasses the building and testing of the system shown in Figure I-1.

II. REVIEW OF LITERATURE

A. Introduction

The evaluation of asphalt pavements is a topic of much interest and discussion among highway and airport engineers. The need to assess adequately the condition of pavements, to predict when repair will be necessary and to carry out those repairs in an economical manner is a pressing one, particularly as the frequency of traffic increases.

This review of literature covers methods of asphalt pavement evaluation that have developed over the years. Particularly, objective methods are detailed, although subjective methods exist and are in use. The objective methods can be divided into two categories - those that destroy portions of the pavement in the process of evaluation, and those that do not. Since the thrust of the research done for this report deals with a non-destructive technique, and because it is felt that non-destructive methods will see increasing use in the future, destructive techniques are

Factors that affect pavement performance are considered in this review. Particularly, the effect of weather (seasonal and daily) and changes in material parameters due to construction or pavement history are examined.

Of the several parameters sought in pavement evaluation, four are reviewed in this Section - roughness, surface texture, deflections under wheel loads and modulus of elasticity of the subgrade. Roughness measures changes in the pavement surface elevation that can affect the "rideability" of the pavement. Texture is a measure of the pavement's ability to produce friction. Texture is frequently used to evaluate hydroplaning potential. Deflection, as used in this study, refers to the vertical displacement of the loaded pavement surface from its unloaded position. The modulus of elasticity of the subgrade relates the elastic stress-strain properties of the subgrade. This modulus is used both in design and evaluation of pavements.

B. Subjective and Objective Methods of Pavement Evaluation

1. Subjective Methods

The most common subjective measurement of pavement serviceability is the Present Serviceability Ratio (PSR). This method described by Yoder and Witczak (1975) entails driving over the pavement in question and rating it on a scale of 0 to 5 (very poor to very good). After a number of people have done this, the average of their ratings is taken and declared to be the PSR.

Related to the PSR is the Present Serviceability Index (PSI). The PSI is a number derived from a regression equation relating various pavement qualities (roughness, cracking, area of patching, etc.). It is used to derive results that agree with the PSR. Evaluation of the nature and extent of the parameters of the equation is partially subjective, making this method something less than exact. Nevertheless, both the PSI and PSR play useful roles in current pavement evaluation {Yoder and Witczak (1975)}.

The PSI and PSR methods, being global, have the disadvantage of not being able to pinpoint problem areas. This makes repair more difficult. Another disadvantage of the methods is the fact the that they reflect variability due to human judgment.

No subjective methods were found for evaluating the subgrade, texture or deflection were found.

2. Objective Methods

a. Introduction. Most objective methods have been developed by highway engineers to obtain measures of the strength of the pavement (as a indicator of its remaining life), the rideability and/or the skid resistance. These methods usually involve a mechanical or electrical device that make contact with the pavement and make measurements that reflect the desired quantity. Moreover, many of these devices require that the apparatus be stationary with respect to the pavement at the time of measurement, and thus yield data at only one location per set-up of the apparatus.

Deflection, texture, roughness and subgrade modulus are discussed on the basis of whether the particular test is destructive or non-destructive, contact or non-contact. Whether or not the test is continuous or discrete follows from the description of the device.

b. Destructive Tests - Contact and Non-contact. Destructive tests of asphalt pavements have been practiced for some time. One of the most popular is the California Bearing Ratio (CBR). This test entails pushing a standard cylinder into the base (or subbase or subgrade of a pavement) at a prescribed rate and measuring the resistance required to accomplish this task. This resistance is then correlated with laboratory tests or field performance data {Baker (1975); Bowles (1970)}. The results of the CBR test have been correlated with the modulus of elasticity of the subgrade by the following equation {Asphalt Institute (1973); Yoder and Witczak (1975)} -

$$E = 1500 \text{ CBR}$$

where E = modulus of elasticity (psi)

CBR = California Bearing Ratio

Yoder and Witczak, however, note that "extreme caution should be exercised...when using this relation".

The modulus of elasticity of the subgrade can also be determined from the laboratory testing of a sample. The Asphalt Institute (1978) describes how to determine the "resilient modulus", which is defined as

$$RM = \frac{\sigma_d}{\epsilon_v}$$

where

RM = resilient modulus

σ_d = deviator stress in triaxial cell

ϵ_v = vertical strain of sample

Others have described slightly more subjective ways to determine the modulus. The Asphalt Institute (1973) relates the FAA Soil Classification to the modulus, ranging from an F10 soil with a 5500 psi modulus to an Fa soil with 31,000 psi modulus. Kezdi (1975) gives approximate ranges of the modulus for different soils and conditions. His values range from 50-400 psi for very soft clays to 14,000-28,000 psi for dense sand and gravel.

The plate bearing test is another common destructive test used to evaluate the soil beneath a pavement. It consists of digging a pit large enough to accommodate the plate and loading the plate while measuring the corresponding settlement. Usually the test is run to determine the modulus of subgrade reaction, which is used in the analysis of the pavement system. The general procedure is described by Yoder and Witczak (1975). McLeod (1957) used the plate load test to determine a relation between deflection and settlement.

The modulus of subgrade reaction is defined as

$$k = \frac{\sigma}{\delta}$$

where

k = modulus of subgrade reaction

σ = stress on subgrade

δ = deflection of plate

Often this test is run before the pavement is constructed so that the proper thicknesses of base, subbases and surface courses can be computed.

Vesic and Saxena (1970) studied rigid pavements and the effect of subgrade reaction on the AASHO Road Test pavements. They found that it was very difficult to find a single value of the modulus that would predict deflection, shear stresses, moments and contact pressures at the same time. They noted that the modulus was a function of how the test was run and the size of the plate used. For shallow depth subgrades (i.e. those with bedrock near the surface), they were able to get a single value that satisfied all the statical parameters (deflection, moments, etc.).

Terzaghi, in 1955, also noted that the modulus of subgrade reaction varied with the width of the plate (or footing) resting on the soil. He proposed the following corrections for the modulus of subgrade reaction -

on clay

$$M = (\frac{\sigma}{\delta})(\frac{B}{B'})$$

and on sand

$$M' = M''\frac{(B''+1)^2}{2B''}$$

where M = modulus of subgrade reaction

σ = stress on subgrade caused by a beam of width B

δ = deflection of subgrade caused by a beam of width B

B = width of beam on subgrade

B′ = width of beam to be used in design

B′′ = width of beam used in design

M′ = adjusted modulus of subgrade reaction

M′′ = known modulus of subgrade reaction for one foot wide footing

The above methods were developed primarily for highway use. While they are common tests for design, they are not common tests for pavement evaluation because they are expensive, time consuming and interfere with traffic. Other, more conventional, methods of testing the soil below the pavement exist (these belong to the province of soil mechanics: the interested reader is referred to Terzaghi and Peck (1967)). Most conventional methods of soil testing require a sample and thus are destructive.

As far as could be determined , there are no destructive non-contact methods of pavement evaluation. Thus, this review proceeds to examine non-destructive contact and non-contact methods of deflection, roughness, texture and subgrade modulus measurements.

c. <u>Non-destructive Tests - Contact and Non-contact</u>.

1. Deflection. The deflection of the surface of a pavement under load is probably the most obvious and frequent non- destructive method of evaluating the adequacy of a pavement. Many researchers use deflections to aid in the calculation of remaining life in a pavement. Consequently, many different apparatuses have been developed to measure pavement deflections.

Probably the most widely used (and widely acclaimed) device is the Benkelman beam {Yoder and Witczak (1975)}. This device, which sits on the ground, is a long simple lever with a dial gage placed at one end. The long side of the lever is usually placed between the dual tires of a parked highway truck. As the truck moves away, the rebound of the pavement is measured by the movement of the beam. The number of studies using the beam are too numerous to list. Rather, the reader is referred to the following representative studies - Nichols (1963), Kondner and Krizek (1966), Scrivner and Michalak (1969), Beca, et al. (1974), and Moore, Hanson and Hall (1978).

The advantages of the Benkelman device (which probably account for its popularity) are its ease of use, simplicity of construction and its durability. The disadvantages are the length of time it takes to set up, the fact that only one deflection measurement is made at each site, deflection beneath the tire cannot be measured, and that the rebound of the pavement is measured instead of the deflection caused by a moving wheel load. This last qualification is important because the rebound is often less than the deflection (at least for short measurement times) since the pavement requires time to return to its original position {see Ledbetter (1976), p92; Harr and Ng-A-Qui (1977), p78; Boyer (1972), p136}.

The problem of making only one measurement per set-up has been somewhat circumvented by the LaCroix Deflectograph {(Beca, et al. (1974)}. This device, in essence, is a truck-mounted series of Benkelman beams. As the truck moves forward, one beam measures the deflection of a wheel while another beam is positioned in front of it. After the first beam has made its measurement, it is picked up and moved in front of the other beam and makes another measurement, and so on. This permits a series of points to be measured. The State of California has developed a similar device called the traveling deflectograph {Beca, et al. (1974); Yoder and Witczak (1975); Moore, Hanson and Hall (1978); and Zube (1966)}. This device travels very slowly (about 1/2 mph) and can make measurements at about twenty foot intervals.

Another very popular method of making deflection measurements uses steady-state vibrators. These devices all operate on the same basic principle: a plate is placed on the pavement surface and is excited vertically with an eccentric weight vibrator or by high capacity hydraulic means. Measurements of the surface waves produced are then made by transducers placed on the plate/pavement. Several vibrators are available commercially, notably, the Dynaflect, Shell Vibrator and the Road Rater {(Beca, et al. (1974); Yoder and Witczak (1975); Baker (1975); Public Works (1973)}. Variables that affect the parameters obtained from vibrators are the static weight of the vibrator, the frequency of vibration, the diameter of the plate and the load induced during vibration {(Green and Hall (1975)}. The size of the vibrators range from portable models to the trailer mounted 16-kip Waterways Experiment Station model.

The parameter most commonly determined by vibrators is the elastic modulus of the subsurface soils . This is done by relating the wavelength produced by the vibrator to the velocity of wave propagation. This is then related to the elastic modulus. Comparisons of laboratory and field values show that it is difficult to get agreement between the two {(Moore, Hanson and Hall (1978)}.

Anderson (1976) reports that the State of Utah used the Dynaflect as part of a regular pavement evaluation program. Peterson and Shepherd (1972) used the deflection basin caused by a Dynaflect to determine parameters that indicated which layer beneath the pavement is at fault when excessive deflections are found. He also notes that Dynaflect deflections cannot be related to Benkelman beam measurements.

Poehl and Scrivner (1971) used the Dynaflect to measure changes in deflections with the seasons. This topic is covered in a later part of this review. Lastly, Yang (1977) uses a vibrator that varies the force and frequency applied to the pavement with their frequency sweep vibrator (<u>Engineering News Record</u> (1978); Yang (1977)).

Advantages of the vibrators are that they are (generally) easily transported, and are relatively quick to use. They require somewhat more skill than does the Benkelman beam, and they are considerably more expensive. Because the vibrators do not simulate the actual pavement loading condition that the pavement experiences during its life, the interpretation of the test results is more complicated than, say, a static deflection measurement. Furthermore, the deflection basin created by a vibrator is not the same as that created by an actual wheel load {(Kennedy (1978)}. The difference in shape and magnitude of the vibrator deflection basin adds to the confusion surrounding the interpretation of results from this test. The vibrators also have the disadvantage of measuring only one point on the pavement per set-up (i.e., it's not a continuous measurement). Consequently, interference with traffic is often unavoidable.

It is interesting to note that Ved-os and Barker (1977) used both the Benkelman beam and a vibrator (the Road Rater) on two similar sections of pavement in Kentucky, but were unable to determine why one section failed and the other did not.

Another wave propagation technique is the impulse test {Beca, et al. (1974); Moore, Hanson and Hall (1978)}. This method entails the dropping of a weight onto the pavement and measuring the deflections produced. Measurements are made with velocity or displacement transducers. The property sought is generally the modulus of the subsoils. Bohn, et al. (1972) describe testing with the French Falling Weight Deflectometer. They report finding a good correlation between falling weight deflections and moving wheel deflections. Classen, Valkering and Dimirsch (1976) report good results with their falling weight device. Their elastic parameters and layer thicknesses agree closely with core samples. The impulse test has about the same advantages and disadvantages as the steady-state vibrator.

Measures of permanent deflection are also used to evaluate highway pavements. Particularly, the depth of the ruts made by the tires is used as a measure of the pavement condition. The procedure is to lay a straight-edge across the rut and measure the distance from the straight-edge to the deepest part of the rut. This device is sometimes called a curvature meter (Moore, Hanson and Hall (1978)}. The value of this measure is somewhat questionable, although it is a good measure of the serviceability {(Kondner and Krizek (1966)}. Huang (1971) measured the curvature with a straight-edge twice the radius of the tire print He used this value to derive a curvature equation

Displacement transducers have been used to measure deflection under and near actual wheel loads. Moore, Hanson and Hall (1978) discuss the General Electric Travel Gage, a device embedded in the pavement, anchored at depth, that measured how the surface moved. It was introduced in 1938 but was never used widely. More recently, Boyer and Harr (1972) embedded transducers in airport pavements in order to measure the surface deflection under or near moving wheel loads. Highter and Harr (1975) also used transducers in airport pavements to measure deflections and the shape of the deflection basin. They attached the transducers to rods anchored 17.5 feet below the pavement in order to remove the influence of the wheel loads. Baladi and Harr (1978) used transducers on a rigid beam to measure the deflection basin near wheel loads. This device had the advantage of being able to measure the deflection basin at many locations because the beam was easily transported. Ledbetter (1976) used displacement transducers in airport pavements to measure the responses to maneuvering

In-place transducers have the advantage of being able to measure deflections beneath a wheel - something none of the other devices can do. However, they are time consuming to install and cannot be moved easily once installed. Portable beams with transducers on them can make measurements at different locations but cannot measure beneath the wheel.

There exist a few methods of measuring deflections with non-contact devices. All involve reflected light.

Baker (1957) measured deflections by taking pictures of the pavement before and during loading. An accuracy of 0.0005 inches was achieved. This method, although accurate, is slow and, in the near future, will probably be reserved for research purposes.

Still and Winnett (1975) used lasers and charged coupled devices (similar in operation to a row of photocells) to measure deflection of pavements. The operation of the device was similar to that used by Harr and Ng-A-Qui described below.

Harr and Ng-A-Qui (1977) developed a non-contact device using light emitting diodes and a linear photocell. The light from the diode shined on the pavement and reflected up onto the photocell. As the position of the pavement changed (under load), the position of the light spot on the photocell changed, providing a measure of deflection. A series of these gages was mounted on a rigid portable beam and was used to measure deflections adjacent to moving wheel loads.

The advantage of these methods lies in the fact that they do not affect the pavement when making the measurements. Transducers on a portable beam afford a high degree of flexibility, but do not permit measurements to be made beneath the wheel. Photographic methods also suffer this limitation. Moreover, present photographic methods do not allow continuous measurements.

2. Texture. The surface texture of pavements is of interest to the engineer who desires to evaluate the skid resistance or hydroplaning potential of a pavement.

Surface texture of asphalt pavements is most commonly measured by contact methods. Rose, Hutchinson and Galloway (1973) provide an interesting review of methods that have been used. They cite the following methods -

1) The "patch" method - Rub a given quantity of some substance onto the surface of the road until the substance forms an approximately circular area whose surface is at the height of the projections of the asphalt aggregate. The diameter of the circle is a measure of texture (large diameter implies smooth texture). Materials used include sand, grease and silicone putty.

2) The direct measurement method - This consists of

drawing a feeler needle across the surface and watching its variation in height. Large variation in needle height implies rough texture {see also Moore (1966), and Goodman (1970)}.

3) Miscellaneous methods -

a) Lay a piece of metal foil on the pavement, strike it with a standard rubber mallet and count the number of holes made in the foil. This method has the advantage of finding the sharp points, which are not distinguished by the previous methods.

b) Make a plaster cast of the surface, smear it with paint and measure the percent of area that took paint.

Moore (1966) developed an indirect method for measuring pavement texture. His device, called an outflow meter, works thusly: a Lucite cylinder with a circular rubber gasket around the bottom is pressed down on the pavement and the cylinder is filled with water. The time required for the water to flow out of the cylinder is a measure of the pavement texture. Rough pavements will let the water flow out quickly, while smooth ones take longer because a better seal is made between the gasket and the pavement.

There are some non-contact methods of evaluating the texture of a pavement. Except for one {(Cooper (1974)}, they are strictly research devices. Basically, all depend on the principle of shining light on the pavement and measuring the variation in its reflection.

Rose, Hutchinson and Galloway (1973) note that stereo-photographs are sometimes used to measure texture. Keeping a microscope focused on a sample as it moves slowly past the lens is another method. The movement of the lens' barrel up and down is recorded, providing a measure of texture.

Goodman (1970) used a vertical light shining on the pavement to obtain his measure of texture. He measured the amount of light scattered to both sides of the source to determine the "mean void width". He also measured the image cast by light reflecting off the pavement to get a measure of the drainage depth. The measurements correlated well with those made by a mechanical stylus, although the accuracy was not given. His attempt to mount the device on a moving trailer was met with limited success.

Gee, King and Hegmon (1974) described a preliminary study they did using lasers to measure texture. They measured the change of the dimensions of an ellipse produced on a pavement by a laser as a measure of the texture.

Gee (1978) used polarized light to measure texture. The degree to which the light was depolarized after reflection was his measure of the texture. This system was mounted on a vehicle and driven over test roads to gather data.

Cooper (1974) used lasers and charged coupled devices (CCDs) to measure texture. He shined the light on the pavement so that it reflected onto the CCD. The texture was determined by noting the changes in position of the light on the CCD.

3. Roughness. Pavement roughness is of interest to engineers concerned with the users comfort and safety. Rough pavements make vehicle control difficult and the ride uncomfortable. At present there are two basic methods of measuring roughness - (1) quantifying the change in the pavement profile (either locally or globally) and, (2) measuring vehicle accelerations caused by the changes in profile. Of the two, the former is more common.

Yoder and Witczak (1975) provide a review of some commonly used contact profilometers. The straight-edge profilometer is the most common. It measures the distance to the pavement from a straight-edge supported on both ends by wheels. The accuracy of this device is limited by the wheelbase to the measurement of irregularities shorter than the wheelbase. The "slope profilometer" is an improvement on the common straight-edge in that it measures differences in surface slope from a fixed horizontal datum. Its accuracy is still limited by its wheelbase. The CHLOE profilometer is similar to the slope profilometer except that it lacks the horizontal reference device. The GMR profilometer uses a truck for the straight-edge. An extra wheel is attached under the center of the truck and its movements, monitored by accelerometers and potentiometers, measure the roughness. This is a high speed device, the advantage of which is obvious.

The roughometer varies in concept from the straight-edge devices. It uses a tracking wheel mounted in a heavy trailer frame. Presumably, the inertia of the frame provides the measuring device with a datum against which variations in profile are determined. This is also a relatively high speed device.

The roadmeter {(Yoder et al. (1973)} is different from either of the above described devices. It uses a cable attached to the rear axle of a car to pull on a sliding electrical contact. The contact, counterbalanced by springs, moves in proportion to the amount of relative displacement between the axle and the car body. The statistic derived is a function of the weighted sums of displacements (broken into 1/8 in. intervals). That is,

$$\text{roadmeter statistic} = (1A + 4B + 9C + 16D + \ldots)/64$$

where A = no. of car-axle deviations equal to 1/8 in.

B = no. of car-axle deviations equal to 2/8 in.

C = no. of car-axle deviations equal to 3/8 in.

, etc.

Another contact method, providing roughness measurements, follows from a physical survey of a pavement. This method, though slow, is accurate and is the method that most other methods are checked against. It provides accurate locations of trouble spots and data that are easy to evaluate.

Houbolt (1961) suggests the use of vertical vehicle acceleration as a measure of roughness. The greater the accelerations, the more the passenger discomfort will be. He recommended 0.3 g as the maximum allowable acceleration. Hall and Kapelson (1962), in a similar study, recommend 0.5g as their maximum. This method, while sound conceptually, fails to pinpoint the location of rough spots. Moreover, since the accelerations airplanes experience depend on the history of accelerations during a take-off or landing, it is difficult to evaluate any particular section of a runway.

The Highway Research Board's Special Report No. 95 (1968) describes the philosophy and mechanics of contact roughness measurement and evaluation. Besides contact methods of measuring pavement roughness, there are also non-contact methods.

Dickerson and Mace (1976) describe a device they made that uses lasers to measure distance to the pavement By arranging three of these on a rigid beam towed behind a car, they were able to measure the profile of the pavement over long distances. Their device had the advantage of being able to measure the profile with respect to a datum, making absolute variations of the surface measurable.

Joyce (1975) used an acoustic device to measure the profile of the pavement. He measured the change in wavelength of a signal bounced off the pavement from a moving vehicle. This provided a measure of the distance from a point on the vehicle to the pavement surface.

Both methods have the advantage of being fast and continuous. The data they provide permit the location of trouble spots. They suffer the disadvantages of being expensive and complicated.

4. Modulus of Elasticity of the Subgrade. In Part 1 of this subsection, where deflections were discussed, it was mentioned that these deflections could be used to evaluate the modulus of elasticity of the subgrade. This has been done using vibrators, such as the Shell and Road Rater models. Cunny and Fry (1973) gave a brief description of how the vibrator methodology works.

When the vibrator is placed on the pavement, it sends waves out along the surface. The velocity of these waves can be obtained from

$$v = f\,\lambda$$

where v = velocity

f = frequency of vibration

λ = wavelength

This is approximately equal to the shear wave velocity, V_s. If the density, ρ, of the soil is known, and the compression wave velocity, V_c, is known, one can use

$$G = V_s^2\,\rho \quad , \qquad V_r = V_c / V_s$$

and

$$\nu = \frac{(V_r^2 - 2)}{2\,(V_r^2 - 1)}$$

to get the modulus

$$E = (2)(G)(1+\nu)$$

In the above,

G = shear modulus

ν = Poissons' ratio

E = modulus of subgrade reaction

Cunny and Fry note that the properties thus derived apply best to soils at depths of $\frac{\lambda}{2}$.

Weiss (1977), working with the Waterways Experiment Station vibrator, proposed two methods of determining the modulus. The first, called the "dynamic frequency response spectrum method", models the soil with a mass, spring and dashpot. By using the amplitudes of the waves produced by the vibrator, the properties of the model are determined. It is an iterative process. Once obtained, these properties are used in the Chevron layered elastic computer program to calculate the modulus. The moduli of the pavement and base courses also must be known before the Chevron program can be run. The results of this method do not compare well with the E = 1500 CBR equation. The derived moduli are consistently larger.

The second method Weiss proposed is the dynamic load-deflection curve method. Briefly, this method entails using a non-linear dynamic response theory that predicts surface deflections given a subgrade modulus and pavement moduli. When the measured surface deflections agree with the predicted ones, the correct modulus has been chosen.

The results of this method generally agree with the E = 1500 CBR formula.

Weiss noted that the subgrade modulus is a function of the confining pressure of the soil (and hence, the overburden pressure). Consequently, he went to some length to remove the effect of the weight of the vibrator. Wiseman (1973) noted this same effect when comparing the coefficients of subgrade reaction gained from tests using the Benkelman beam and the Road Rater. The Road Rater produced consistently higher values of the coefficient, which Wiseman attributed to the added confining pressure on the subgrade. He had some success using the Hertz theory of predicting the coefficients of the surface course and the underlying soils.

Witczak (1980) ran vibratory tests on frozen and thawing soils. He noted that the subgrade modulus is heavily dependent on the temperature of the subgrade. However, he found that the subgrade modulus did not have much effect on the maximum deflection measured by a vibrator.

Vaswani (1971) used surface deflections measured by a Dynaflect to predict the modulus of subgrade reaction. He measured the maximum deflection and the deflection profile in front of the maximum deflection, and then used these to compute the "spreadability" - an average deflection of sorts. From his study, he drew up graphs that could be used to approximate the modulus

All of the methods reviewed require contact with the pavement in order to ascertain the desired property. No non-contact methods were reported.

C. Variables Affecting Pavement Performance

This section is intended to examine the variables that affect the measurements described in the last section. The list of possible factors is a long one and is as varied as the human imagination that produces them. Consequently, to be expedient, this review will attempt to cover only the more obvious factors.

Probably the most obvious factor affecting pavement performance is the asphalt concrete itself. Thicker pavements deflect less under a given load than do thinner pavements {(Highter and Harr (1975)}. One would expect that less deflection would mean a longer life for the pavement. If all other variables were held constant, this would probably be the case {(Nichols (1963)}.

Temperature is an important factor in determining when asphalt will show distress under loading. Traxler and Layman (1975) report that the glass transition temperature for some asphalts is not necessarily below 32° F. This is the temperature at which asphalt becomes a brittle material. Kandahl and Wenger (1975) found that the temperature at which asphalt pavement was placed affected its performance. They also noted that high viscosity asphalt pavements (mixed at low temperatures) retained entrained air longer than low viscosity asphalt pavements, since they were compacted more slowly.

Kondner and Krizek (1966) noted that increased temperature leads to increased flexibility of the pavement. Southgate and Deen (1969) also noted that the deflection of an asphalt pavement increases with temperature. They devised a method to adjust the deflection to a standard temperature by noting that the relationship between deflection and the logarithm of temperature was linear. They then scaled the measured deflection by a derived adjustment factor to get the corrected deflection.

Lister (1972) tested asphalt pavements at different temperatures and found a linear variation of deflection for temperatures between 10° C and 30° C, although the rate of change varied with pavement type (Figure II-1).

Peterson and Shepherd (1972), in their study with a Dynaflect, were unable to find any correlation between temperature and deflection. They do, however, provide a good review of the temperature corrections proposed by other organizations. They are listed below -

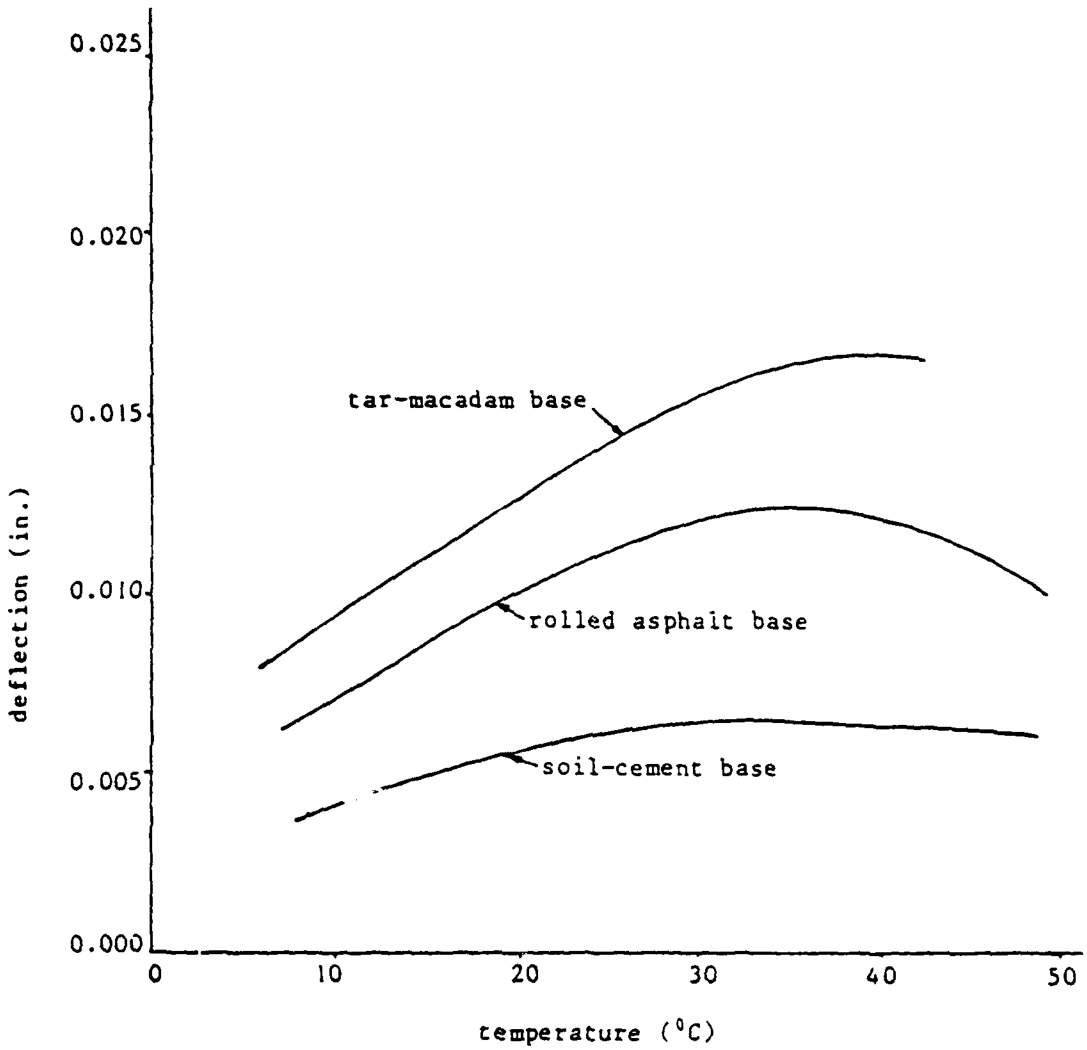


Figure II-1 Deflection vs. temperature (after Lister (1972)).

1) Canadian Good Roads Association - they generalized, saying that the change in deflection was 0.0002 inches for every 10° F,

2) District of Northern Vancouver - uses a linear relation between deflection and temperature,

3) AASHO - above 80° F - no effect of temperature on deflection ; below 80° F - curvilinear effect of temperature on deflection,

4) Transport and Road Research Laboratory - above 86° F - a decrease is noted above this temperature, - below 86° F - deflection increases approximately 7.2% per °F,

5) Colorado - linear relation between temperature and deflection, but different at every site.

The U.S. Army Corps of Engineers (1975) conducted a study using their 16-kip vibrator on asphalt pavements. By testing at different temperatures on different thicknesses of pavements, they were able to establish the correlation shown in their Figure 1 (p75). While they felt this was good for their particular site, they expressed reservations about using it at other sites.

Dorman and Metcalf (1965) studied the effect of temperature on the modulus of the pavement system. They found that the modulus decreased with increasing temperature.

Meyer and Kummer (1969) noted the effect of temperature on the skid resistance of pavements. They broke skid resistance into two components - adhesion and hysteresis. The adhesion component may increase or decrease with temperature, while the hysteresis component only decreases with temperature increases.

Several investigators have found that the season of the year influences pavement properties. Using deflection as a criterion, Kondner and Krizek (1966) found a sinusoidal variation with time. Poehl and Scrivner (1971) also found that deflections varied sinusoidally during the year, with the largest deflections occurring in the springtime. They also noted, as did Peterson and Shepherd (1972), that rainfall increases deflections. Yoder (1962) reported that, among the many factors affecting deflection, climate and temperature are important.

The magnitude of the load applied to a pavement is an important factor to consider. This is why highway departments specify load limits, usually 18 kips per axle (static load). Whittemore (1969) conducted an interesting study on the dynamic load of tires on pavements. Using accelerometers mounted on the axle of a truck, he measured the force applied by the tires to the pavement as the truck moved down the road. He found there was a large variation in the force - up to 5000 pounds. Compared to the design load of 18,000 pounds: this is a large variation!

The last factor to be considered is site dependency. This variable takes into account all the variables that cannot be measured or accounted for directly; particularly, weather history, fluctuations of the groundwater table, construction control (e.g. variation in the materials used, mode of placement, method and degree of compaction, initial water content of the subsoils, locked-in stresses in the pavement and subsoils), animal activity and history of loading. These variables, most of which are difficult to or are impossible to quantify, are very likely to be influential in determining whether a pavement fails or not.

Kondner and Krizek (1966) acknowledged the importance of site dependency. After an exhaustive study of the AASHO Road Test data, in which correlations between PSI and other factors were derived, they concluded that derived relationships are good only at the site where the data were gathered. Extrapolation to other sites would not be likely to be valid.

Yoder (1962) showed that the amount of deflection under a given load varies with the lateral placement of the load on the pavement. Peterson and Shepherd (1972) noted that

Colorado's deflection criteria are different at every site.

Poehl and Scrivner (1971) presented a very good example of site dependency in their study of pavements in Texas. They used a Dynaflect to monitor 1000 foot sections of road in five areas of Texas. Their conclusions were -

1) the odds are 2:1 that the annual mean deflection at the ends of the 1000 foot strip are very different,

2) the odds are 2:1 that the annual mean change in deflection at the ends of the 1000 foot strip are also very different,

3) in a mile of "uniform" pavement, the odds are high that the deflection measured at different points on the same day will vary more than the deflection measured at any one point during a year, and

4) within a 1000 foot strip, the annual percentage change in deflection varied significantly.

Finally, they stated that while the Dynaflect does not measure the same deflection as a static or moving wheel load, it does provide a means of comparing pavements.

Vedros and Barker (1977) presented the results of their study done in Kentucky. They compared two sections of pavement within 51 feet of each other. One had cracked and the other had not. Extensive field and laboratory tests were made to determine the cause. Moisture, CBR, density, cyclic plate tests, deflections, vibratory measurements, and surface profiles were all checked. Gradation, resilient modulus, creep behavior and rutting susceptibility were also determined. They concluded -

> "Data analysis indicates that there were no apparent differences between test pits to explain why the pavement would be cracked at one test pit but not at the other."

They did find, however, that the resilient deformation of the pavement could be predicted by a finite element computer program.

D. Interpretation of Data Obtained from Non-Destructive Tests

1. Texture

Quantitative measures of texture are usually given in terms of skid numbers (SN), rather than absolute measures of the texture. Kummer and Meyer (1967) provide a comprehensive review of skid number determination, detailing the several devices in use and giving correlations between them. Their recommended skid number, 37, as determined by the ASTM E-274 test, falls in the range of values in use in the United States. In the same paper, a correlation (with skid numbers) is given for the aluminum foil texture test mentioned in the previous section. They noted that about 10 holes per square inch are required to gain sufficient skid resistance for medium speed roads.

McCullough and Hankins (1966) studied pavements in Texas with a skid trailer. They recommended that two skid numbers (coefficients of friction) be specified, each measured at a particular speed. For 20 mph and 50 mph, they recommended 0.31 and 0.24, respectively, as minimum values. Pavements that fall below these should be repaired.

Beaton (1971) examined the texture of concrete pavements. He noted that, of the several methods available for "texturing" fresh concrete, the California Highway

Department prefers the broom method. However, no quantitative evaluation was given. Grooving of concrete pavements, implemented to increase drainage and road tire friction, is done in California by 1/8 in. slots on 3/4 in. centers parallel to traffic flow.

Rose and Galloway (1977) studied the effect of depth of

water on skid resistance. After testing various combinations of speed, tires, tire pressures, pavements and water depths, they recommended that the macrotexture of the pavement be greater than 0.04 in. for high speed roads. Moore (1969) suggested that the microtexture of the pavement should be in the range 0.0004 in. to 0.004 in. to insure adequate skid resistance. He noted (in 1969) that there were not any methods to evaluate this.

2. Roughness

The measurement of pavement roughness, as was discussed in section II, B, 2, c, 2, takes many forms. The data obtained from the different devices have their own criteria of acceptability. Because changes in PSI reflect changes in roughness, it is only natural that developed devices should try to correlate with it. Baker (1975) affirmed that this is the case. He noted that regression equations relating the measured variables are used by highway departments to derive the PSI. Because the requirements of each department and the peculiarities of their measuring techniques vary, each department derives its own equation. The Roughometer and the roadmeter are commonly used with regression equations. Roughometer values of 90 in./mile for rigid pavement and 75 in./mile for flexible pavements are sometimes used as construction criteria. The CHLOE profilometer's output, slope variance, is also used in a regression analysis to derive the PSI.

The GRM profilometer, described in Highway Research Board Special Report No. 95 (1968) gives the pavement profile, but not a measure of user acceptability. That must be determined subjectively by the persons conducting the study. The non-contact methods of pavement profile measurement all require a subjective correlation with user acceptability. Neither Joyce (1975) nor Dickerson and Mace (1976) suggested any criteria for the acceptability of pavement roughness.

Houbolt (1961) suggested that a vertical change in profile of more than 0.08 ft per 250 ft is too rough for airplanes. When using a straight-edge to measure roughness, he used

$$\delta < 0.0004 \; L^{\frac{1}{2}}$$

where

δ = deviation from straight-edge (ft)

L = length of straight-edge (ft)

Lastly, he proposed that acceleration experienced by an airplane can be used as a criterion. He suggested that an upper limit of 0.3 g be used. Hall and Kapelson (1962) used 0.5 g. They also noted that, although a particular bump may not cause the maximum acceleration, it may do so when run across in conjunction with previous bumps, since the airplane continues to vibrate after the bump has been passed. Eremin (1962), in a discussion of Houbolt, noted that 0.3 g is less than the design acceleration used in airport pavement construction.

Sonnenberg (1978) used a statistical analysis of airport profiles, filtering out the long wavelengths, to get the standard deviation of the profile. Although he found a range of standard deviations of 3 to 13 mm for the 13 airports examined, he failed to declare what would be considered acceptable.

Walker and Hudson (1978) related roadmeter readings to a serviceability index thus:

$$SI = 5\, e^{\ln\left(\frac{M}{B}\right)^{5}}$$

where

SI = serviceability index

M = roadmeter roughness reading (in./mile)

B = roadmeter instrument coefficient (calibration factor for test vehicle)

Dann and Schultz (1978) in their study of Wisconsin roads with a roadmeter, developed the relationship between roadmeter readings and PSI shown in Figure II-2 . Chong and Phang (1978) carried their roadmeter study further, relating the roadmeter, profilometer, and roughometer to either the PSI or the PPR (Present Performance Rating used by the Canadian Good Roads Association).

3. Deflection

Finding an absolute measurement that will predict when a pavement will fail is difficult. Deflection studies, nevertheless, are often employed to this end. This section reviews some of the criteria put forth in the literature that attempt to define when a pavement will fail.

Highter and Harr (1975) studied distress in airport pavements. By noting the number of airplanes that used a runway, the maximum deflection caused by each and the condition of the pavement, they were able to relate the sum of

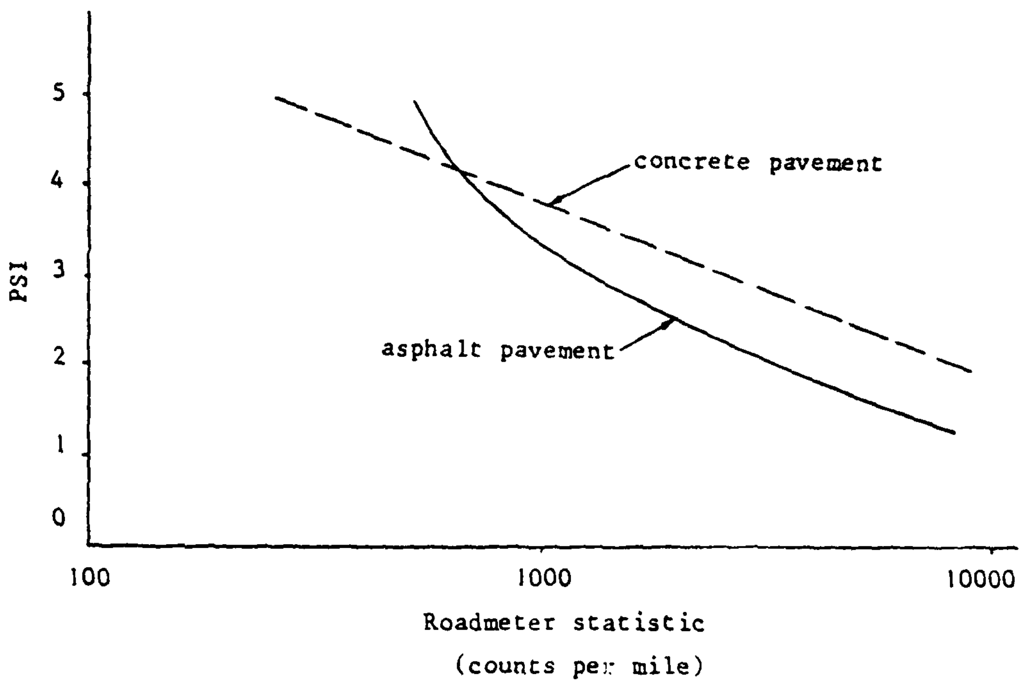


Figure II-2 Pavement evaluation using the Roadmeter statistic (after Dunn and Schultz (1972)).

the deflections the pavement experienced to the PSI. Their hypothesis - that the condition of the pavement could be related to the cumulative peak deflections - was shown to be valid. Typical results are shown in Figure II-3. The three curves represent various combinations of thicknesses of surface courses, bases and subbases.

Huang (1971) proposed that the magnitude of the strain be used as the criterion to determine when asphalt pavements will crack. By measuring the maximum curvature and the deflection caused by a wheel load, he developed a method to calculate the strain. From laboratory investigations, he determined the allowable strain. By comparing the two, it can be seen if the pavement will crack. He noted that the time of year that the measurements are made also affects the results. To predict rutting, the measurements should be made in the summer. To predict cracking, winter measurements should be used.

Lister (1972) found that

$$\text{life} \propto \frac{1}{d^3}$$

where d = deflection of pavement.

He found this by studying the behavior of roads in Great Britain. Sample results are shown in Figure II-4

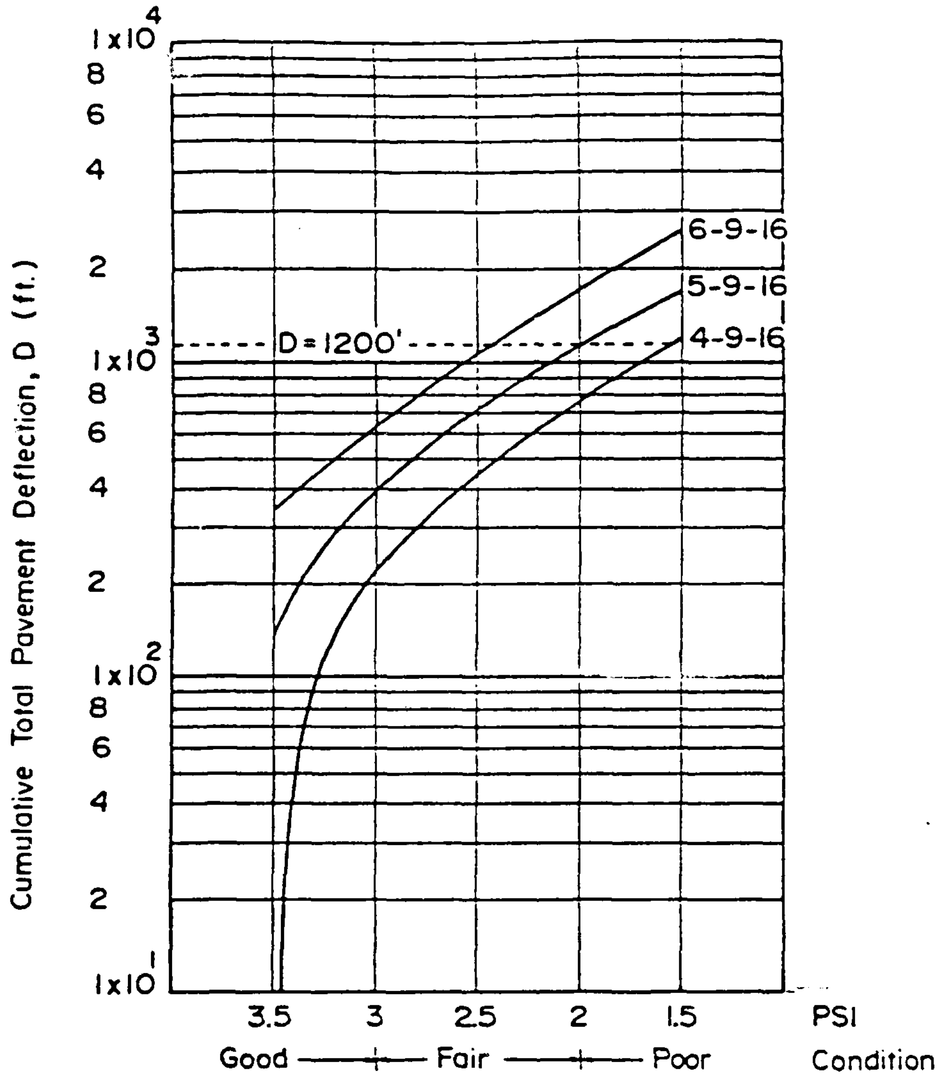


Figure II-3 Cumulative Deflection vs. PSI (after Highter and Harr (1975))

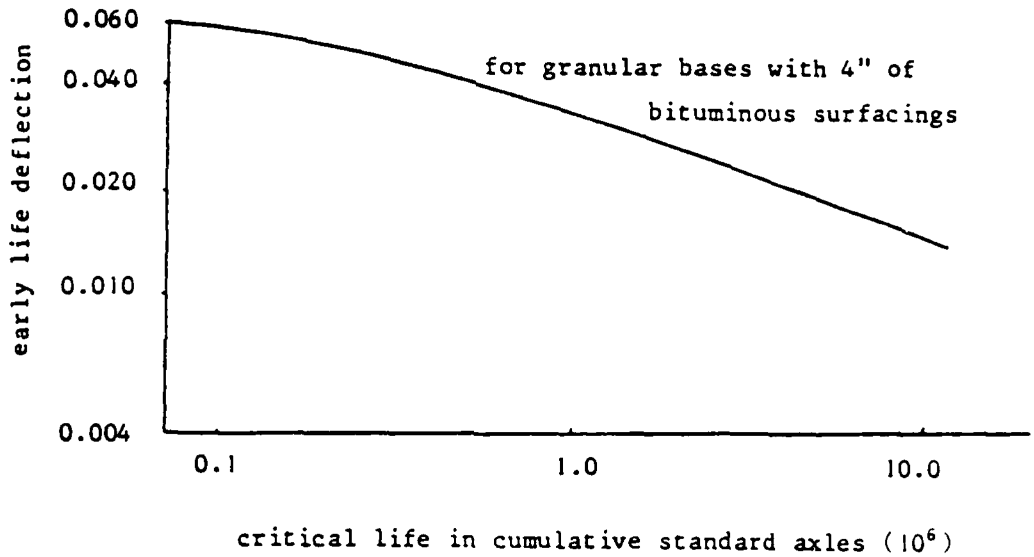
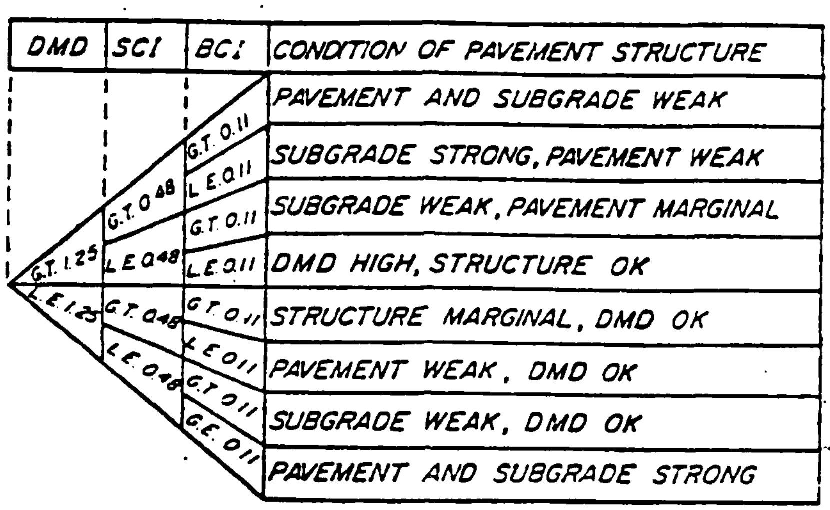


Figure II-4 Summary of relation between life and deflection (after Lister (1972)).

Peterson and Shepherd (1972) used a Dynaflect to determine which layer beneath a pavement needed repair. They defined three parameters - the Dynaflect Maximum Deflection (DMD), the Surface Curvature Index (SCI) and the Base Curvature Index (BCI). The DMD is the maximum deflection measured by the transducer nearest the vibrating wheels (the first sensor). The SCI is the difference between the deflections measured by first and second sensors, and the BCI is the difference between the fourth and fifth sensor deflection. The SCI, a measure of curvature, is used to define the strength of the surface layers. The BCI is used to define the strength of the lower layers. Some examples of how the BCI and SCI are interpreted are shown in Figure II-5. Figure II-6 shows how they evaluate pavements using their parameters. They then developed nomographs to compute overlay thicknesses.

A comprehensive review of deflection analysis methods is presented by Beca, et al. (1974). They give the maximum deflection criterion used by different organizations. These are listed in Table II-1. All measurements were made in the springtime.



KEY

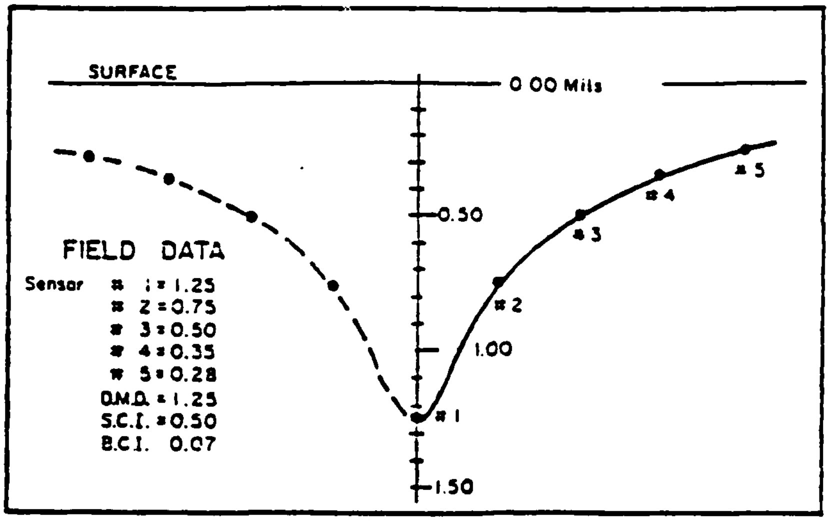
G.T. = greater than

G.E. = greater than or equal to

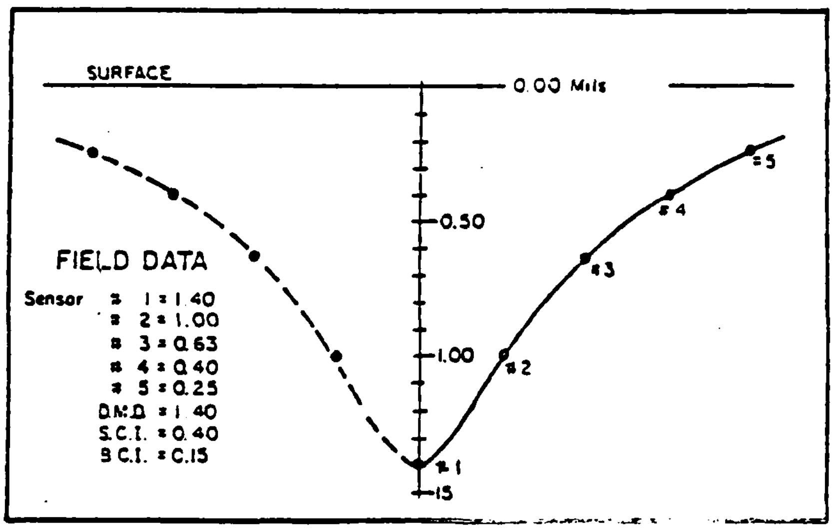
L.T. = less than

L.E. = less than or equal to

Figure II-5 Evaluation using DMD, SCI and BCI (after Peterson and Shepherd (1972))



Subgrade Strong, Pavement Weak



Subgrade Weak, Pavement Marginal

Figure II-6 Evaluation of pavement (after Peterson and Shepherd (1972)).

TABLE II-1

Deflection Criteria

INCHES OF DEFLECTION	AUTHOR
0.05 for 0.5 in. asphalt to 0.018 for 4 in. asphalt	Hveem
0.05	Canadian Good Roads Association
0.036	Virginia Highway Research Council
0.020	Transport and Road Research Laboratory

They noted that curvature is also used as a criterion, although they could not decide if this was a better measure than deflection. They contended that a given deflection cannot be related to a particular degree of distress or loss of serviceability.

Green and Hall (1975) claimed that deflection is not a good indicator of the remaining life of a pavement. They claimed that there is no discernible change in deflection up until failure. They did say, however, that deflection was a good measure of performance. Moore, Hanson and Hall (1978) cited a study by Vaswani in Virginia that showed that the deflection varies over the life of the pavement as shown in Figure II-7. Region I of Figure II-7 represents the densification that takes place after the pavement is placed. The

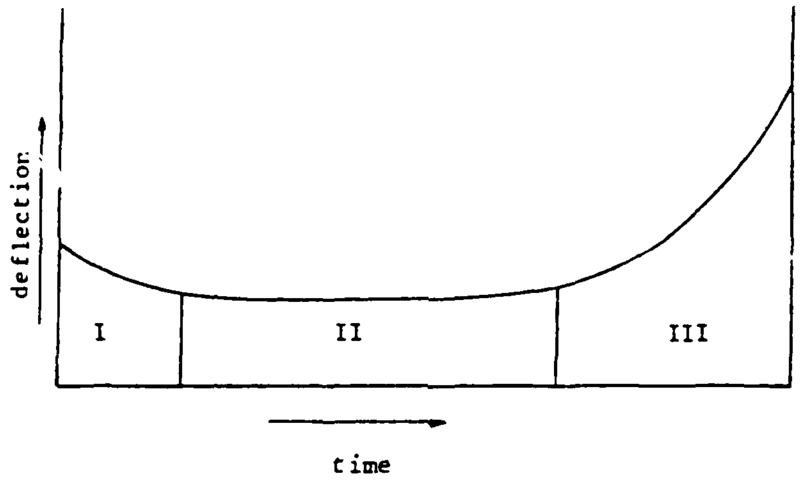


Figure II-7 Deflection vs. time (after Moore, Hanson and Hall (1978)).

deflection then remains constant (region II) until it increases to failure (region III). This shape of figure is called a "bathtub function".

Anderson (1976) used the results of studies by Southgate and Vaswani et al. to evaluate pavements in Utah. Southgate's study developed the method for temperature correction discussed in Section II, C. After correcting the deflections for temperature, Anderson used Vaswani's spreadability concept to get the modulus of the subgrade and the average modulus of the system. They are determined from the chart given in the paper.

Croney (1972) established a rough correlation between PSI and rut depth (permanent deflection). Using a six foot straight-edge laid across the pavement, he found that a rut depth of 10 mm was the most common one in which cracks were found.

4. Modulus of Elasticity of the Subgrade

The modulus of elasticity of the subgrade is used for the design and evaluation of pavements. Methods of obtaining E were reviewed in Section II, B, 2, c, 4. This subsection examines how different investigators use the modulus.

Dorman and Metcalf (1965) used layered system theory to develop design curves for asphalt pavements. They were concerned with the tensile strains on the bottom of an asphalt concrete layer subjected to a wheel load, and the effect of temperature, thickness of the asphalt concrete, and modulus of elasticity of the subgrade on those strains. The design curves they proposed use the expected strains and the thickness of the base to compute the thickness of asphalt concrete required.

Huang (1971) was also interested in the tensile strains at the bottom of asphalt concrete layers. He modeled the pavement in three layers, each having its own modulus. The lowest layer was the subgrade. If the ratios of the moduli, the layer thicknesses, and the "curvature" are known, the tensile strains can be computed. These are then checked against allowable strains to see if the pavement is acceptable, or is in need of repair.

Methods of defining the modulus vary from study to study. Crawford and Katona (1975) discussed different ways to get E from stress-strain plots. Then, having chosen a modulus, they show how it is used in finite element studies of pavement response. A variety of different element types and configurations are considered

Layered elastic theory is sometimes used to analyze pavements, despite the fact that pavements and soils do not behave elastically in all stress ranges. Use of this theory requires a knowledge of the thickness of the layers and their material properties. Weiss (1980) used a pavement vibrator to determine the subgrade modulus and then used it with layered elastic theory to determine the bearing capacity of the pavement. Vaswani (1971) used a Dynaflect to get a measure of the deflection basin he calls "spreadability". With this and the various layer moduli, he developed charts to evaluate the pavement. Yoder and Witczak (1975) note that the modulus of elasticity is used in both the Asphalt Institute and FAA methods of design of airport pavements.

The modulus of subgrade reaction is sometimes used in the evaluation of concrete pavement. Vesic and Saxena (1970) used the subgrade modulus of elasticity in conjunction with the concrete slab properties to derive a formula for the modulus of subgrade reaction. This, in turn, was used to predict the deflections of the slab under load.

This review has shown that there are a great number of ways to test pavements available to the pavement engineer. The divergence of opinions on the subject reflects not only the uncertainty in present methods, but also the need to account for regional factors. This study hopes to provide a method whereby many of these regional factors can be accounted for, through frequent testing.

III. DEVELOPMENT OF THE SYSTEM

A. Introduction

The rapid non-contact measurement of pavement deflections under actual wheel loadings requires a complex state-of-the-art system of electronic components. The system has to be capable of making, recording, and processing large amounts of data, and doing so very quickly. Such a device would not have been possible ten years ago, but, because of recent advances in electronics, it is possible today.

The requirements are that the system make non-contact measurements of the deflected surface of asphalt pavements caused by moving wheel loads. Furthermore, the device is to be transported by the vehicle causing the deflection. Implicit in these requirements are the following details -

1. The device must be sufficiently sensitive to detect deflections on the order of 0.001 inch. This requirement was determined from the magnitude of the deflections recorded in previous studies {(Baladi (1976); Ng-A-Qui (1976)}.

2. The device must be insensitive to changes in the color of the surface.

3. The device must be insensitive to ambient light and sound.

4. The system must be able to provide not only a measure of the pavement condition, but also the location and speed of the vehicle at the time of measurement.

5. The system must be able to record and process the data gathered.

6. The system should be relatively easy to set up and use.

7. The range of the device must be large enough to accommodate the expected vehicle movement plus the pavement deformation.

Most of these criteria were satisfied by the selection of the non-contact distance measuring gages, to be described in section III, C, 1. The main components of the system are the electro-optical distance measuring gages, a rigid beam, a fifth wheel, and the attendant electronics.

The electro-optical distance measuring gages are mounted on a rigid beam which in turn is mounted longitudinally on a load vehicle (see Figure I-1). The gage heads measure the distance from the beam to the pavement in a non-contact way (using lasers). They are the very heart of this system.

In order for the data analysis system to work, the gages cannot move relative to their original alignment. For this reason, they are mounted on a rigid beam.

The data analysis system requires each gage to read the distance from the rigid beam to the pavement surface at the same* horizontal locations. Each succeeding gage must read where the preceding gages have read. A distance measuring device called a "fifth wheel" is used to provide this measure. The speed of the vehicle is determined, indirectly, from the fifth wheel.

The attendant electronics are the power supply, computer, and the electronics for the fifth wheel.

* In the statistical sense

B. Methodology

1. Theory for Profile, Deflection and Texture Measurements

It was desired to measure the deflected profile of the pavement adjacent to the wheel load as well as the undeflected profile. The solutions to these problems go hand in hand. Dickerson and Mace (1976) described an algorithm that was adapted for the present study. Its description follows. The computer program that uses the solution is described and listed in Appendix C.

The algorithm that determines the undeflected profile of the pavement uses five values - three gage measurements and two arbitrary elevations above a datum. These five inputs are then used to calculate a new elevation above the datum while the vehicle moves to a new location. In Figure III-1, the two arbitrary elevations are designated as BB and CC, and the three gage head measurements are A, B, and C. Given these five inputs, the algorithm calculates the elevation, AA, in front of the known elevations. All five inputs are obtained from the undeflected portion of the pavement. AA defines a point on the undeflected profile. For this reason, the front three gages are called the "undeflected profilometer". When elevations are determined in the area influenced by the wheel load, "deflected profile" points are calculated. As any five inputs may be used, (if chosen in a

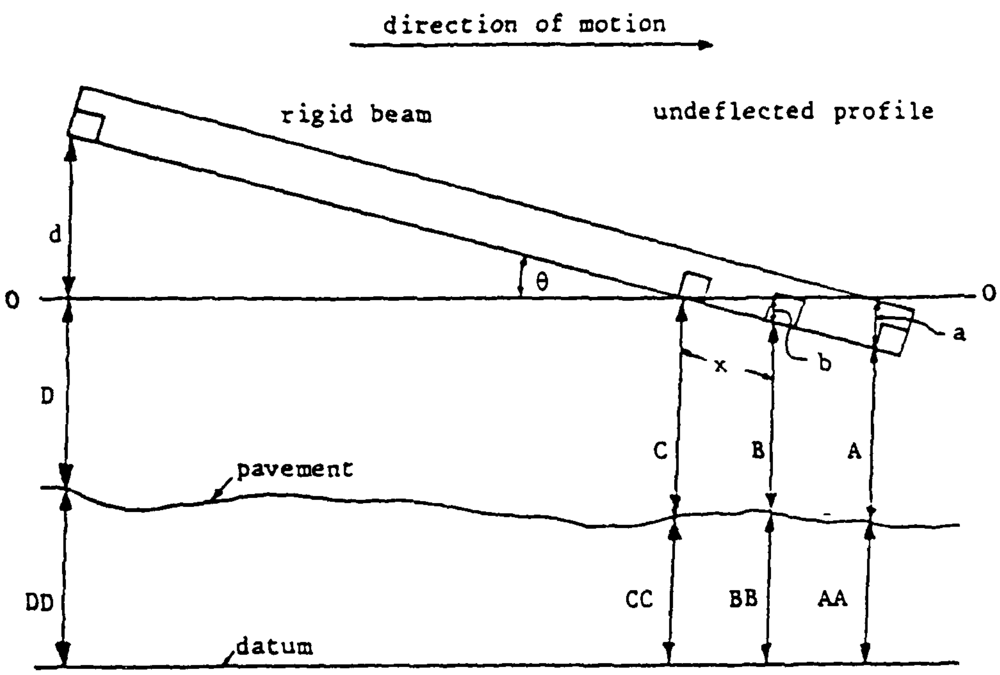


Figure III-1 Schematic of the system. Load wheel not shown (normally at D).

manner consistent with that just described), the elevation can be calculated at gage D, near the load wheel.

The derivation of the algorithm follows from Figure III-1. Here, as above, BB and CC are arbitrarily assigned, and A, B, and C are actual gage readings.

By constructing OO′ parallel to the datum, it follows that

$$C + CC = B + BB + b = A + AA + a. \qquad (1)$$

If the gages are equally spaced on the beam

$$a = 2\ b. \qquad (2)$$

Assuming this, and noting that

$$b = C + CC - B - BB \qquad (3)$$

gives (by substitution)

$$AA = C + CC - A - 2\ (\ C + CC - B - BB\ ), \qquad (4)$$

which is the desired quantity, the new undeflected elevation. AA can be calculated from Eq. (4) as all the quantities on the right side of the equation are known (either measured or assumed). This provides the initial step of the procedure. The process is then continued in the following manner: the gages move forward until gage B is over the previous position of gage A*, and the algorithm is repeated, using the five designated quantities (BB is the previous AA, and CC is the previous BB). A new undeflected profile point is then calculated. Repetition eventually yields the entire undeflected profile at increments corresponding to the gage spacing.

The spacing of the gages on the beam is very important. By mounting all the gage heads at equal intervals along the beam, the gage head readings can be timed so that each reads at the same location as the previous one. Thus, any three gages can be used as a *profilometer*. By placing gage D an integral number of gage spacings from gages A, B, and C, gages B, C, and D can be used as a profilometer. Whereas AA was calculated in a "forward" manner, DD is calculated in a "backward" manner. The five inputs for the latter are B, C, D, BB, and CC. DD is calculated from

$$DD = C + CC - D + (r) (C + CC - B - BB) \tag{5}$$

where r is the ratio of the distance between gages C and D to the distance between gages B and C. When the B-C-D profilometer is used, a deflected profile is calculated,

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* In the statistical sense.

gage D being near the load wheel.

The deflections (relative to the undeflected profile) caused by the load wheel can now be calculated. The undeflected profile was calculated by the A-B-C profilometer. The deflected profile was calculated by the B-C-D profilometer. The fifth wheel assures that all gages read at the same* points on the pavement. So, two profiles are obtained. The difference between the two provides the deflections caused by the load wheel.

Two important pavement parameters con be ascertained from the measurements described above - the profile, and the deflection adjacent to the wheel. Because the gages can make measurements at a very rapid rate (16 kHz), another important pavement characteristic - the pavement texture - can also be determined. The texture can be obtained from the variations in readings in the near vicinity of a point on the pavement. This variation is possible because the laser gages that were used had a light spot size much smaller than the variation in the surface texture, and because the gage resolution is smaller than the surface texture.

Many readings are required over a short distance not only so that the texture can be measured, but also to keep null readings due to "dropout" from entering the profile algorithm. Dropouts occur when the light spot from the gage

---

* In the statistical sense.

is hidden from the view of the photodetector (Figure III-2). In order to keep from losing the data point, the gage head makes many readings over a "short distance", averages them, and considers the average to be the distance from the gage to the pavement. Four inches of the pavement in the line of travel was chosen as the short distance in this study.

Averaging many readings provides a very stable statistical measure of the distance from the gage to the pavement. The large number of readings allows an extra order of magnitude to be added to that accuracy.

Because the resolution of the gages is much smaller than the variation in the surface texture, the variations in the readings over each of the four inch segments of pavement reflect the coarseness of the surface of the pavement at that location. A large variation indicates a coarse surface, while a small variation indicates a smoother one. A useful measure of the variation in the readings is the statistical variance (V) -

$$V = \Sigma_{i=1}^{n} \frac{(x_i - \bar{x})^2}{(n - 1)} \qquad (6)$$

where

x_i = measurement

$\bar{x}$ = mean of n measurements

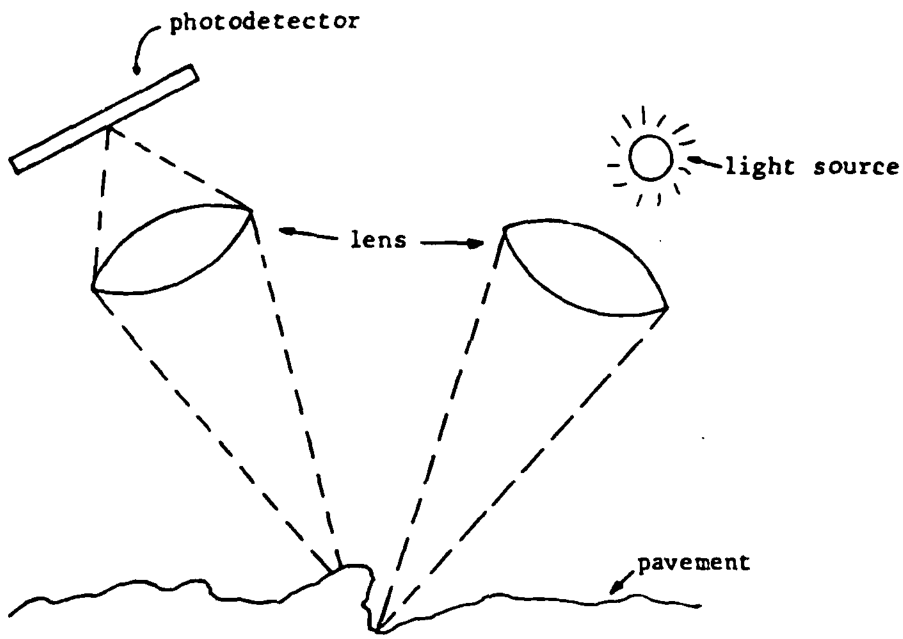

Figure III-2 The dropout case

n = number of measurements

2. Speed and Distance Calculation

The speed and location of the vehicle during a test are recorded with each profile/deflection measurement. By knowing the frequency of the readings (16 kHz), the number of readings (n), and the distance over which the readings were taken (four inches), the speed can be calculated from

$$\text{speed} = (4)(16000)/n \qquad \text{inches/second} \qquad (7)$$

An alternate method also was used to calculate the speed. The time to traverse four inches was measured by a clock in the computer which ran the data collection program. By dividing the this time into four inches, the speed was determined.

Gage readings were made over the four inch distance for every foot of pavement. That is, the gages would read for four inches, skip eight inches, read for another four inches, etc. As the readings are one foot apart, the number of readings gives the distance travelled in feet. Thus, locations are secured.

C. The Equipment

1. The Gage Heads

A review of the literature revealed that there were several non-contact profilometers currently in use. Most of the systems used gages mounted on a rigid beam towed by a vehicle. The gages were electronically connected to and read out on a piece of recording equipment. In order to know where the measurements occurred, a distance meter was connected to the vehicle.

Sound, visible and infrared light gages (using lasers and polarized light sources) have all been tried with some modicum of success. Having seen some prior success with light emitting diodes, for static pavement deflection measurement {(Harr and Ng-A-Qui (1977)}, the use of light sensors was the first course pursued in this study. Several arrangements of lenses, mirrors, and optical detectors were considered, including one particularly promising one that utilized the Scheimflug condition {(Hallert (1979)}. The basic arrangement of the optics for all such schemes is shown of Figure III-3. A light source is reflected from a pavement onto a detector that is calibrated to provide its distance above the point of reflection. Unfortunately, the detectors used (either CCDs or linear photodiodes) were found to be sensitive to the intensity of light. This meant

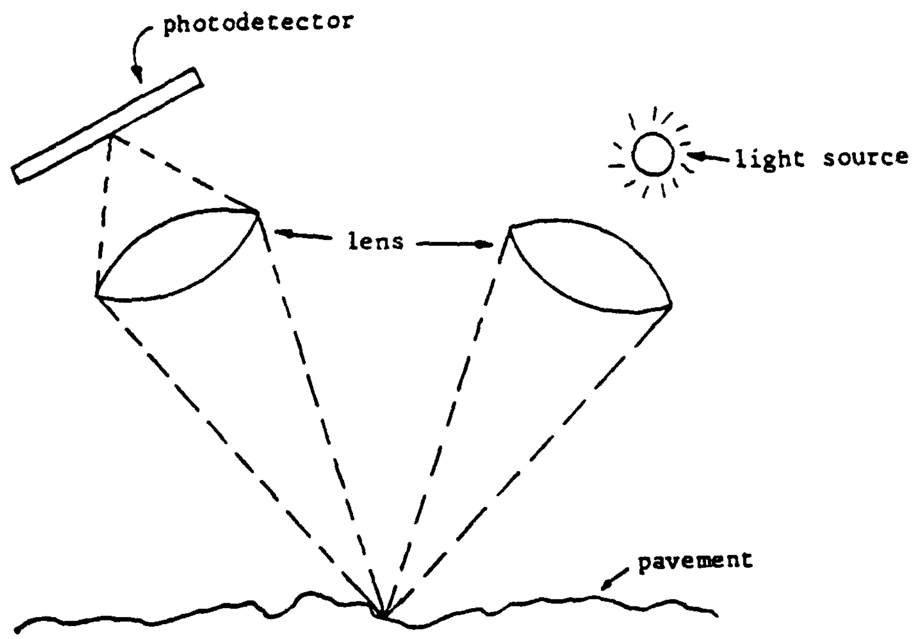

Figure III-3   Arrangement of optics

that readings were sensitive to the color of the pavement and to the intensity of sunlight.

Several commercial companies produce non-contact distance measuring gages. The gage produced by Selective Electronic was chosen for this study. Their gage, the "Optocator", had the required resolution, range and standoff*. In addition, its outputs were compatible with modern computers. Thus, the most important component of the system was secured.

2. The Fifth Wheel

As was noted in the introduction to section III, it was necessary to have the gages read** where the other gages had read. The gages read continuously; however, their readings were sampled only occasionally, as noted above. The sampling rate was controlled by the fifth wheel.

Several methods of timing were considered. First, the use of a shaft encoder on the axle of the load vehicle was contemplated to tell when the required distance had been traversed. This method was discarded because of its inflexibility. The encoder would have to be recalibrated for each vehicle used, causing

* Standoff is the distance from the gage to the center of its measuring range.

** In the statistical sense.

a substantial increase in set-up time when changing vehicles.

Next, long distance laser measuring devices were considered. These devices, commonly used in surveying, are extremely accurate, and have ranges on the order of a mile. These devices were eliminated from consideration because their response time was too slow (0.6 Hz vs. about 7.0 Hz required). Moreover, this method would have required the laser to be coupled with a tracker so it could follow the load vehicle. The tracker would add expense and complication to the system.

Finally, it was decided to use a calibrated wheel of the kind used to measure the performance of four-wheeled vehicles (hence the term "fifth wheel"). "Labeco" manufactured the fifth wheel. A shaft encoder, manufactured by Madison Electric, was attached to the wheel to give a pulse every four inches (for this wheel, 21 pulses per revolution). The power supply for the encoder was made at Purdue University.

An error analysis for the performance fifth wheel is given in Appendix B, 1.

3. The Rigid Beam

For the profile algorithm described in the second part of this section to work, the gages must remain fixed in space relative to one another. As it was the purpose of this study to develop a system that could be used with almost any load vehicle, fixing the gages rigidly onto the load vehicle was ruled out. Attaching the gages to a rigid, portable beam was thought to provide the necessary flexibility.

Considerations in choosing the beam included

1. weight,

2. stiffness,

3. availability, and

4. cost.

Steel and aluminum I-sections were considered. Steel sections are too heavy and difficult to work with. Aluminum sections are available only in one ton lots. Consequently, it was necessary to fabricate a beam. The design was accomplished using the computer program SAP IV {(Bathe, Wilson, and Peterson (1974)} at Purdue University. A truss afforded the best stiffness to weight ratio. A rectangular truss was designed, as it permitted easier gage mounting and afforded some protection for the gages. The truss was fabricated at Purdue University. Figure III-4 shows a picture of the beam.

The length of the beam is of considerable importantance. The beam had to be long enough to mount one gage near the

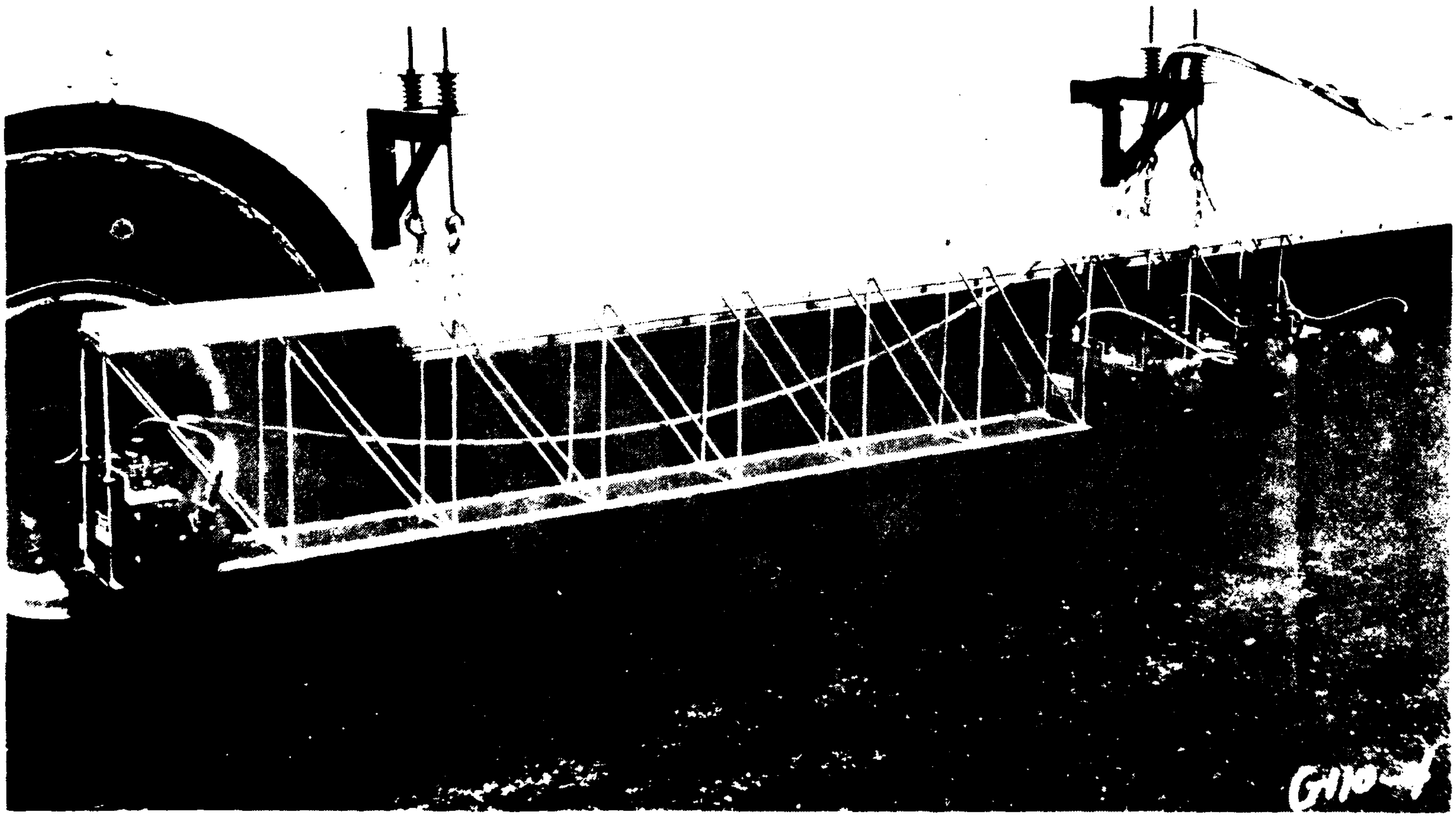

Figure III-4 Rigid beam with laser gages load wheel, and to hold the undeflected profilometer (gages A, B and C) outside the zone of influence of the load wheel. Highter and Harr (1973) and Baladi and Harr(1976) give data that show the deflection basin for flexible pavements rarely extends beyond five feet in front of the load wheel, in the direction of motion. A ten foot beam (nine feet between gages) was chosen.

The beam had to be stiff enough to prevent the gages from moving out of their original relative alignment. The allowable movement was taken to be the resolution of the gages. Any greater movement would not allow one to determine if the pavement had deflected or whether the beam had moved vertically.

4. Data Collection, Storage and Reduction

a. Overview. The data acquisition system collected the data generated by the lasers and the fifth wheel. It consisted of a microcomputer and various peripherals. The computer was triggered by the pulses from the fifth wheel. When the fifth wheel gave the proper pulse, the computer clock started, and the computer began 'looking at' the readings from the lasers. It then averaged the readings from each gage and computed standard deviations for all of them. When the fifth wheel sent the next pulse (at four inches of travel), the computer stopped looking at the readings, stopped looking at the clock, and the data were put in core memory. When the entire desired pavement section had been traversed, the operator flipped a logic switch which told the computer to stop the data gathering program. The program stopped and the data were written onto a floppy disc. The profile/deflection program later uses the data from this disc.

b. The Equipment.

1. Hardware. The electronics for the data collection, storage and reduction system consisted of -

1. a Heath H-11 microcomputer,
2. a Heath H-19 video terminal
3. a Heath H-27 dual floppy disc drive
4. a Texas Instruments TI-810 line printer
5. a Digital Equipment Corporation BA11-NE bus extender, and
6. a 'logic box' with four switches.

The H-11 microcomputer is based on the DEC LSI-11 microprocessor. Consequently, the H-11 uses DEC assembly language. The H-11 is a 16-bit machine. This was required because the Optocators have 16-bit parallel output.

The maximum memory capacity was 56k bytes.

The H-19 video terminal is used to 'talk' to the computer. It uses the RS-232c serial interface, and can display 24 80-character lines.

The H-27 dual floppy disc drive accepts two eight inch discs. It uses a single-side, single density IBM 3740 format. The two discs provide about 500k bytes of storage.

The TI-810 line printer is made by Texas Instruments. It accepts 14-inch paper (132 characters), and uses the RS-232c serial interface. The printing rate is 150 cps.

The BA11-NE bus extender is used to extend the number of parallel input/output (I/O) boards the computer will accept. The parallel I/O boards for the lasers were used in the BA11-NE.

The logic box was used to send one bit signals to the computer. It consisted of a five volt DC transformer and four no-bounce* switches. The switch output was either zero or five volts, depending on the position of the switch. They were used to control the data gathering program.

All of the above equipment used 110-volt 60 Hz AC power. With the exception of the terminal and the logic box, all were approximately the size and weight of a modern electric

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* A no-bounce switch is one whose contacts do not bounce upon closure. Bouncing switches can be made, electronically, to act like no-bounce switches.

typewriter. The bus extender was purchased from Hamilton-Avnet electronics. The logic box was fabricated at Purdue. The remaining equipment was purchased from Heath Corporation.

2. Software. Software is the set of programs that is used to operate a computer. For this study, the term system software will be used to describe that which came with the computer. User software refers to that which was written specifically for this study.

System software included a FORTRAN IV compiler, editor, linker, library functions, assembly language compiler, and a file manager. User software included a data gathering program (GATHER), a data file previewer (LIST), and the data reduction program (CALC). The usefulness of the data file previewer is described in Appendix G.

The system software functions will be described by tracing typical steps in the program creation and execution process. A program is written and modified in the editor. When it is correct, it is compiled by the computer. Then it is linked to the library files by the linker. If no errors are found, the program can be run. Should the program be written in assembly language, the assembly language compiler is substituted for the FORTRAN IV compiler. The file manager is used to view, compress, and copy files.

The data gathering program, GATHER, was written by Mr. Cary Cox of the U. S. Army Corps of Engineers Waterways Experiment Station, Vicksburg, Mississippi. It was written in assembly language so it would be fast enough to keep up with the lasers. When GATHER is run, it asks the operator to name the data to be gathered. After accepting this, GATHER prompts the operator to flip the start switch on the logic box. This being done, GATHER monitors the fifth wheel shaft encoder, the logic box, the line time clock on the computer, and the four laser gages. The fifth wheel encoder gives a pulse every four inches of travel over the pavement. GATHER checks the pulse frequently, and counts the pulses. The beginning of the pulse representing the first four inches of every foot tells GATHER to begin reading, counting and averaging the readings from the lasers. At the same time, it begins counting 1/60-ths of a second on the line time clock. It also begins calculating standard deviations of all four of the lasers. Later, the time is used to calculate speed. While doing this, the computer checks the pulse to see if four inches of pavement have been traversed. When the pulse changes, the four inches have passed, and GATHER puts the four average readings, the number of 1/60-ths of a second, and the four standard deviations into memory. When the operator flips the start logic switch to stop, GATHER puts values of negative one in for all the readings, stores them in memory, and writes the entire data set onto the disc under the name assigned by the operator. The negative ones signal the end of the data to the data reduction program.

After the data are gathered, the operator may wish to preview the data before reducing them. Of interest are the number of readings, the number of zero readings, the standard deviations, and the length of the file. The user program LIST enables the operator to do this examination.

The averaged laser readings are converted to profile and deflection measurements by the user program CALC. CALC reads the data from the file created by GATHER. It then uses all the data to compute two constants - the two out-of-line measurements for gages A and D. (Recall that, for the algorithm to work, the gages must be in a straight line. Gages B and C are used to define a straight line. CALC calculates the deviation of gage A is any time, and that for gage D if the pavement is undeflected (see Appendix E.)) These two constants are then added to their respective calibration equations to correct the "out-of-lineness". CALC then rereads the data, using the algorithm described in section III, B, 1, to obtain the profile and deflections. Then, if the operator desires, plots of the profile vs. distance and deflection vs. distance are produced.

Occasionally, null readings occur. The effect of a null reading on the algorithm depends on when and at which gage it occurs.

There are two ways to create a null reading. First, the pavement may move out of range of the gage. The range of each gage is ± 2.5 inches about the standoff, which is ten inches. The gage then sends a null reading to the computer. Second, the gage may make less than thirty readings in the travelled four inch span. This is interpreted by the program as the gage having gone out of range part way through the four inches. CALC also interprets this as a null. The CALC program is sensitive to both cases.

A special condition occurs when a test is started. The first seven feet of travel (the distance between gages C and D) is a special zone at this time. No deflections are measured there, as the undeflected profile has not been measured in that region. Consequently, if the average reading of gage D is null there, it has no consequence. If gages A, B, or C produce a null (or any combination of nulls) in this zone, CALC ignores past data and begins the algorithm afresh. This happens because the algorithm cannot tolerate gaps in the continuity of the incoming data.

After the first seven feet are traversed, deflections are calculated and the profile continues to be calculated. If gage A produces an average reading that is a null, a deflection is calculated, and the profile is ended. At the next reading, a new profile is begun and six deflections are lost (those between gages C and D). The algorithm begins anew as described in the previous paragraph. If gages B or

C, or both, produce an average reading that is a null, no deflection is calculated, the profile ends, and then begins anew at the next reading. For this case, seven deflections are lost. The CALC program performs all these operations automatically.

The CALC program puts out the following information -

1. the distance travelled,
2. the number of null readings at each gage,
3. the two out-of-line constants,
4. the undeflected profile,
5. the deflections, their mean and standard deviation,
6. a measure of the texture, and
7. plots of the deflected profile or deflections versus distance.

All of the user programs are listed in Appendix C.

IV. RESULTS AND DISCUSSION

A. Profile and Deflection

The developed apparatus, described in Section III, was tested at the Waterways Experiment Station (WES) of the U.S. Army Corps of Engineers in Vicksburg, Mississippi. This was done in December 1981. The first tests were run with the beam mounted on a load cart, simulating one main gear on an F-4 aircraft. The computer was carried in a station wagon which towed an electric generator. These tests uncovered many hardware problems - particularly the need to use no-bounce switches in the logic box. Several bugs in the software were also discovered.

The next tests were run with the beam mounted on the side of a semi-trailer at the Waterways Experiment Station. This was done in January 1982. Gage D (Figure III-1) was adjacent to the rear wheel. The trailer carried the computer and the electric generator. The profile calculated from these tests plunged with distance (although the actual profile was nearly level). The magnitude of the plunge was as great as fifty feet over a one hundred foot horizontal distance. It was exponential - meaning that the amount of plunge increased rapidly with distance traveled. It was obvious that there was a serious problem with the system.

The calculated deflections from these tests were also wholly unrealistic. The weight of the semi-trailer, coupled with the pavement structure, should not have produced deflections greater than about one half inch.

After more testing, and a review of the algorithm, a solution to the plunging profile problem was found. It was discovered that the gages had to be aligned extremely carefully on the rigid beam. Their relative positions on the beam must be known with great precision. A slight error in their alignment causes a large error in the calculated profile. This error, perhaps small at first, accumulates rapidly - each error being added to the previous error. This error manifested itself in causing the measured profile to plunge rapidly.

A source of the noted error will be illustrated by example. Consider the following case - the laser gages lie on a straight line on the rigid beam, the beam moves parallel to a perfectly flat pavement, and the datum is parallel to the pavement. The equation that calculates the next profile point is -

$$AA = C + CC - A - 2 (C + CC - B - BB) \tag{1}$$

This equation was derived in section III, equation (4). For the conditions just stated, equation (1) will calculate a perfectly flat surface. If gage A is out of vertical alignment with respect to gages B and C (Figure III-1) by, say one inch at the first measurement, an error in A of one inch will occur. AA, then, will be too small by one inch. Recall that, in the next iteration, AA will become BB, and the previous BB will become the present CC. So, in the next iteration, A is again one inch too large, and BB is one inch too small. The net error is that after the second measurement, AA will be too small by <u>three</u> inches. The next time, AA will be too small by <u>six</u> inches. The relation between any two consecutive errors is -

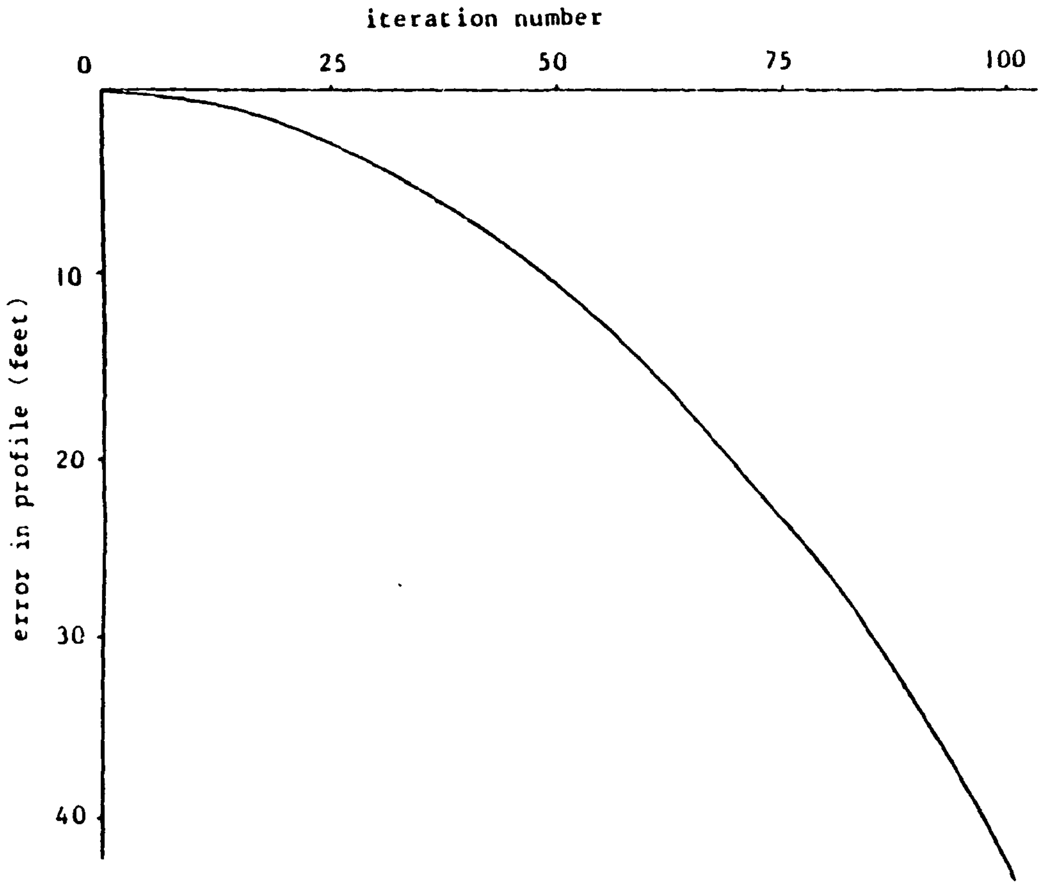

Figure IV-1 Error due to gage A being 0.10" out of line.

the relative vertical positions of the gages on the rigid beam. It did this by using the measurements from the gages themselves, thus having the same accuracy as the entire system. The result of this scheme was to produce the "out-of-line" constants - the deviation from a straight line of any three gages.

In order to get the out-of-line constant for a gage, the beam had to be used where no measurable deflection would occur. At first, the beam was hung from cantilever beams on the F-4 load cart, far away from the zone of influence of the loaded wheel. Unfortunately, the spring mounts used to attach the rigid beam to the vehicle permitted too much lateral movement. Moreover, it was suspected that the gages moved out of their range of reliable measurement during the test. A special lightweight tricycle was then constructed. The beam was attached to its undercarriage in such a way that lateral movements were greatly reduced.

Using the tricycle, new out-of-line constants were calculated for the gages. Once these were obtained, the beam was removed and transferred to the semi-trailer and additional measurements were made. The results from these tests indicated that the calculated profile wandered only slightly from the actual (surveyed) profile.

Figure IV-2 provides the comparison between the transit surveyed profile and three laser beam calculations of the same profile. This and all succeeding transit surveys were made at one foot intervals. The trend of the calculated profiles is the same as that of the surveyed profile. The variance of the endpoints is seen to be only a few inches. Some of the variance can be removed by forcing the endpoints of the laser surveyed profile through the endpoints of the transit survey (recall that BB and CC were arbitrarily chosen initially). This same technique is practiced at the Transport and Road Research Laboratory. The result of this technique is shown in Figure IV-3. The ADJUST program (in Appendix C) was used to do this. The deviations were reduced to less than an inch. However, the deviations themselves still varied. Over a distance of 100 feet, the deviations ranged from positive three tenths inch to negative three tenths inch, which was still considered to be excessive. Testing with a Benkelman beam showed this to be the case. The standard deviation of the deflections was on the order of one tenth inch.

Several extended profile tests were run. Three five hundred foot sections were surveyed with both the present laser system and a transit. All the transit surveys were made on points one foot apart. The results of some of the tests are shown in Figures IV-4 through Figure IV-6. The profiles in these have been adjusted so that the endpoints

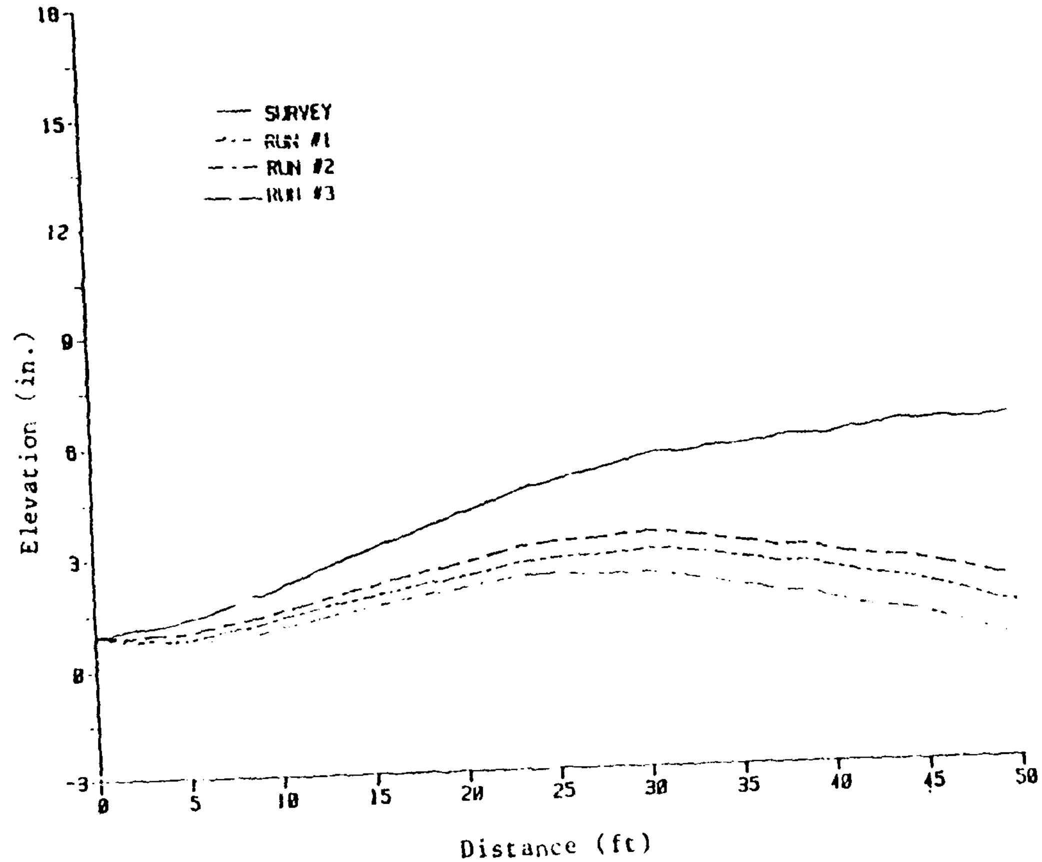

Figure IV-2 Profiles.

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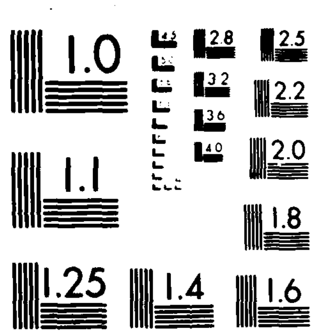

MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS 1963-A

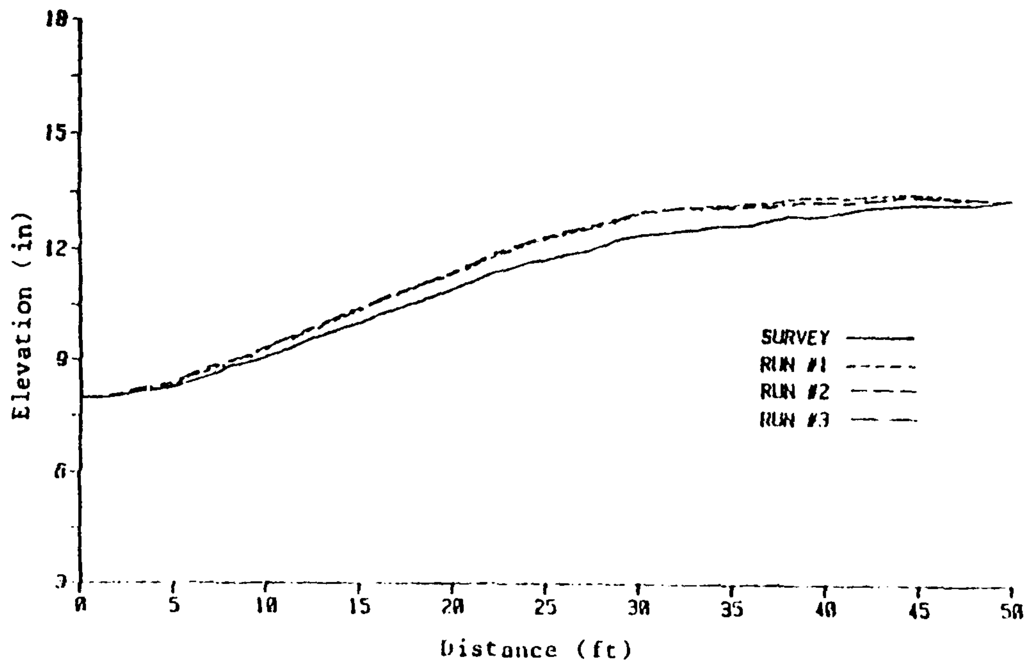

Figure IV-3 Adjusted profiles.

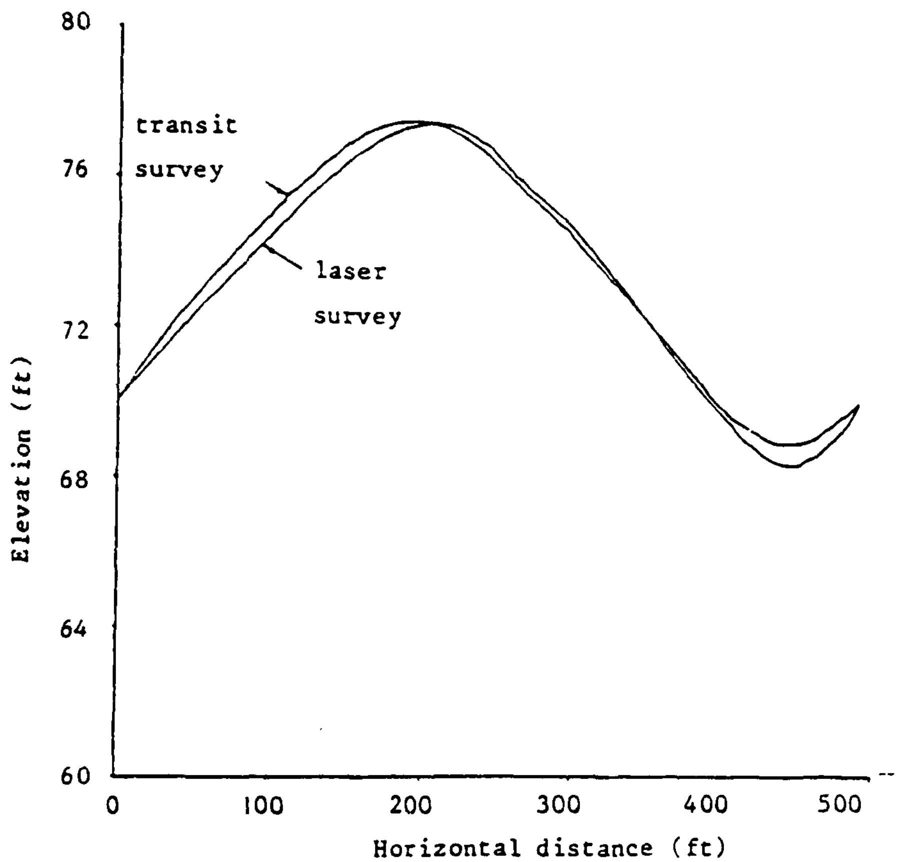

Figure IV-4 Comparison of surveys of a concrete pavement.

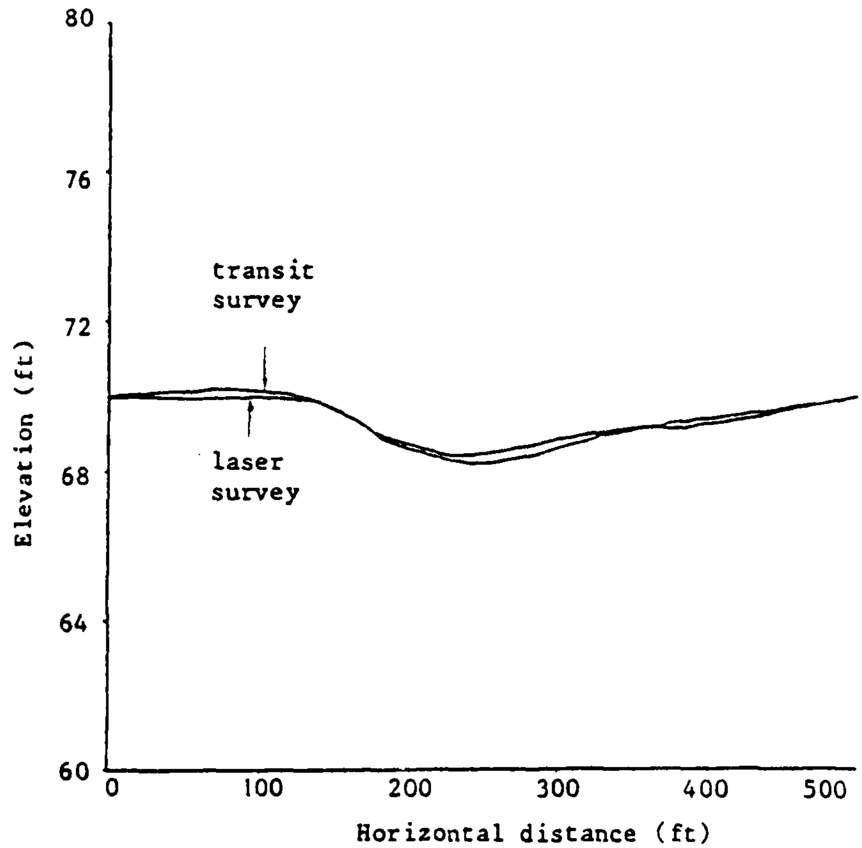

Figure IV-5 Comparison of surveys of an asphalt pavement.

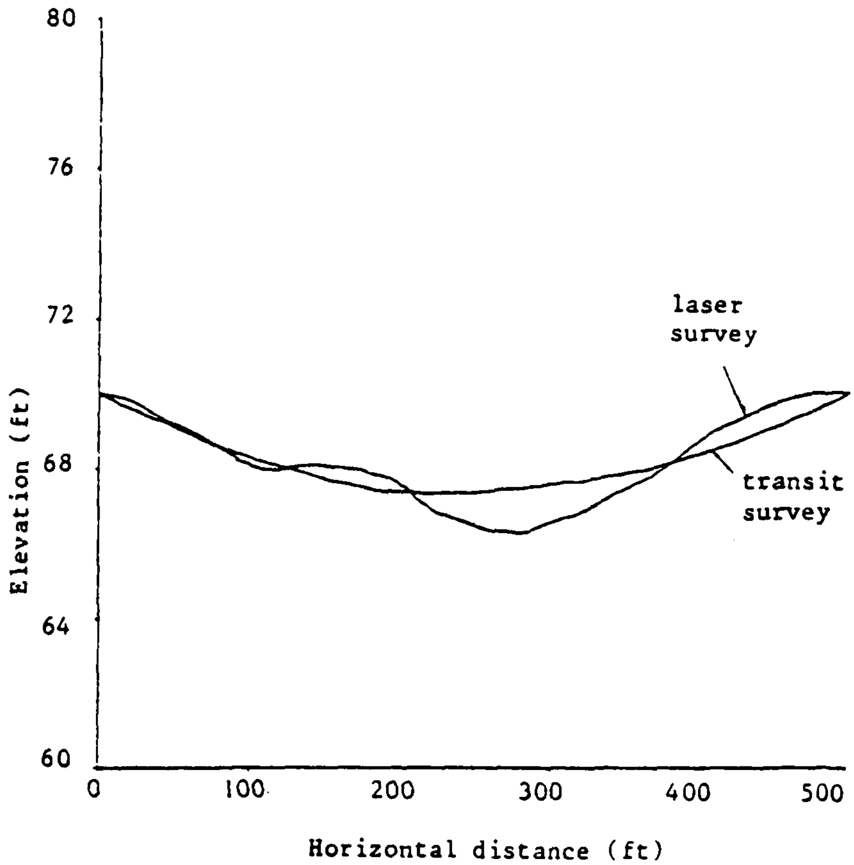

Figure IV-6 Comparison of surveys of porous friction course pavement (out-of-line constant = 0.0267") pass through the same elevation. The maximum deviation of the laser system profile from the transit surveyed profile varied from 0.290 feet to 1.205 feet, over the several profiles.

The search for the reason for the lack of agreement between the transit and laser surveyed profiles continued. The shape of the laser system profile changes radically with small changes in the out-of-line constant. The profiles in Figure IV-4 through Figure IV-6 use an out-of-line constant chosen to minimize the maximum difference between the transit and laser surveys. The constants were chosen to four decimal places. This is one place beyond the accuracy of the laser gages. Closer agreement could have been accomplished if more decimal places had been taken, however, this could not be justified. Figure IV-6 and IV-7 represent the same transit survey. The out-of-line constant in figure IV-7 is 0.0277 inches, while that used in Figure IV-6 is 0.0267 inches. The maximum deviation from the transit profile in Figure IV-6 is 1.205 feet, while the maximum deviation in Figure IV-7 is 5.869 feet.

The raw data from the long profile tests contained inherent errors. Over each five hundred foot length, the laser system recorded about five hundred and ten readings, instead of the expected five hundred and one readings. The standard deviations of the gages, usually between zero and fifty, sometimes jumped an order of magnitude. Both the

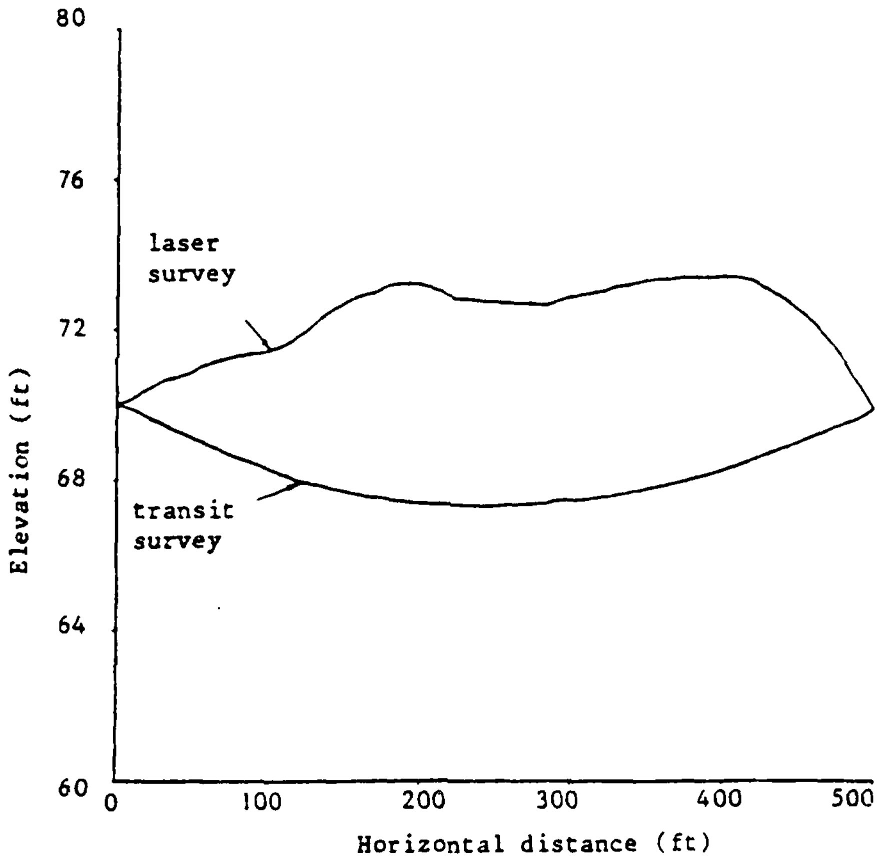

Figure IV-7 Comparison of surveys of a porous friction course pavement (out-of-line constant = 0.0277") extra distance and the large standard deviations were considered indications that the system was still not operating properly.

Testing with the developed system has only just begun and improvements are to be made. Suggestions for these will be addressed below. At this point it should be noted that the main advantage of the system (its ability to do frequent and rapid testing) is worthy of the effort necessary to achieve these ends. As more testing is done, more refinements will come to light. The ability to test pavements frequently and rapidly will provide the pavement engineer with a quantitative measure of the performance of his pavement system.

The system described herein has no built-in redundancy. Some form of redundancy may make it easier to debug the system. The addition of more laser gages or of a device that provides some measure of the tilt of the beam (such as a tiltmeter) will aid in accomplishing this.

The addition of more laser gages to the present sytsem will provide a redundancy. If gages are added between gages C and D (Figure III-1), and these gages are out of the zone of influence of the load wheel, they can be used to calculate the undeflected profile in combination with any other two gages. These additional calculations of the profile could be compared with the first calculation (and with each other) to help determine if the system was working properly. The same method that was used to align gages A, B and C (Figure III-1) could be used to align any additional gages (see Appendix E). If many more gages are added, it may be necessary to lengthen the rigid beam in order to keep the gages out of the zone of influence of the load wheel. Calculating several profiles simultaneously allows the algorithm to "bridge" over gaps in the data. With the present system, if one of the gages goes out of range, the profile skips a point, and then begins anew, relative to a new datum. It should not be expected that the new and old data will be coincident.

If properly placed, the additional gages would also provide better definition of the deflection basin. The deflections at these additional gages could be calculated in a way similiar to that of gage D (Figure III-1). The equation used to calculate the deflection at gage D (equation (5) in Section III) can be changed by modifying "the ratio of the distance between gages B and C" to "the distance between gages C and the additional gage".

A tiltmeter (or any device that measures the tilt of the beam) could also be used to provide a redundancy. The tiltmeter, in conjunction with two laser gages, can be used to calculate the undeflected or deflected profiles. The methodology is detailed in Appendix A. As was the case with additional gages, another calculation of the profile is made. These profiles could then be compared. Adding a tiltmeter to the present system will enable the system to "bridge" lost readings, as does the addition of laser gages. The addition of a tiltmeter would not require the lengthening of the rigid beam. An extremely accurate and responsive tiltmeter would be required.

At present, the laser system uses the first four inches of travel per foot to record data. This was chosen because it was thought that the time required to travel the other eight inches per foot would be needed to do calculations and store the data. However, the present data collection program is fast enough to double the rate previously anticipated. This means that the present system can be used at double its present rate of output. The system can be used to record readings over the first two

- four inch sections of every foot of travel. The last four inches of travel time (so to speak) are sufficient to do the necessary calculations and to store the data. The result is that two profile and two deflection points can be obtained for every foot of travel, instead of the present single profile and one deflection point. Clearly, this is a function of how fast the rigid beam is moving. At the present "creep" speed, the output can be doubled. The upper bound for the speed to do this remains to be found.

Being able to gather pavement deflection data frequently and rapidly yields the advantage of being able to utilize transfer function theory to a high degree to predict pavement performance. Given the deflection caused by one vehicle and the transfer function of the pavement system, the deflections for other anticipated vehicles can be predicted. The transfer functions change with time and season. The laser system allows frequent updating of the transfer function and hence renders it as a valuable tool (Boyer and Harr, 1973).

It should be emphasized that the present system offers the ability to survey a pavement in a global sense. No other device, at the present time, does so. In addition, its speed enables it to be deployed in such a manner as to minimize the interruption of traffic.

B. Texture

As noted in Section III, B, 1, texture measurements were made by recording the standard deviations of the readings each gage made over the short distance.

Table IV-1 shows partial sets of uncalibrated standard deviation data for the different pavements. As expected, the standard deviations for the concrete pavement are smaller than those for the asphalt pavements. This reflects the fact that the concrete pavement is smoother.

TABLE IV-1

Sample values of uncalibrated data

gage			number of readings			standard deviation			time 1/60 sec.
A	B	C	A	B	C	A	B	C	
concrete									
2909	2858	2853	312	312	313	8.	72.	12.	12.
2895	2816	2912.	282	282	282	14.	17.	54	11.
2953.	2832.	2908.	265	265	266	8.	11.	8.	10.
2943	2862.	2895.	246	246	247	17.	11.	6.	10.
2930.	2833.	2912.	248	248	249	17.	19.	7.	10.
2855	2810.	2872.	265	265	266	8.	7.	11.	10.
2870.	2798.	2880.	249	249	249	8.	6.	12.	10.
2875.	2767.	2849.	241	241	242	11.	7.	9.	9.
asphalt									
1973.	1926.	2003.	252	252	252	13.	18.	10.	12.
1996.	1922.	2032.	241	241	241	13.	17.	13.	12.
1990.	1901.	1985.	268	268	268	15.	17.	13.	13.
1947.	1889.	1977.	239	239	239	14.	20.	20.	12.
1997.	1905.	2006.	234	234	234	11.	13.	15.	12.
2041	1947.	2026.	230	231	231	136.	10.	13.	12.
1964.	1962.	2016.	229	229	229	17.	19.	134.	12.
1985	1882	1953.	249	249	249	13.	24.	15.	12.
porous friction surface									
1891.	1797.	2100.	369	376	379	46.	54.	20.	15.
1909.	1888	2082.	282	279	281	31.	47.	23.	11.
1855.	1851.	2013.	236	244	245	34.	36.	40.	9.
1842	1881	2030	217	226	226	30.	36	31.	9.
1871.	1847	2024	206	192	209	40.	39.	200.	8.
1880	1879	2036	189	204	212	23.	44.	34.	8.
1917	1904	2082	212	210	211	26.	36.	143.	9.
1932	1919	2090.	184	172	199	25.	29.	30.	8.

No correlation with standard texture measurements were made. Table IV-1 shows the standard deviations measured over three pavements exhibiting different textures. The concrete pavement was smoother than either of the asphalt pavements. This is demonstrated by the magnitude of the standard deviations listed in Table IV-1. The concrete pavement's standard deviation is less than the asphalt pavement's standard deviation. It is expected that this measure of pavement texture, standard deviation, might be correlated with other standard texture measurements.

C. System Refinement

As was noted above, the following suggestions are offered to refine and improve the developed system.

Some advantage can be had by using a different computer system. The computer, a Heath H-11, is no longer offered by the manufacturer. Buying a "military specification" computer from a well established manufacturer would yield two benefits - reliability and service. A DEC PDP-11 is recommended. The Heath H-27 dual disc drive used a single side, single density format. A Winchester hard/floppy disc drive could collect a lot more information. The Heath operating system editor was difficult to use. A better editor would make the programmers job easier. The TI-810 printer was sufficient, but a printer-plotter would produce better looking plots. A Printronix printer-plotter is recommended.

Replacing the laser gages with Polaroid sonic distance measuring gages warrants further examination. Preliminary tests showed the sonic gages are not affected by winds up to fifty miles per hour. Their resolution was determined to be 0.01 inch. The gages can be made to read as fast as 44 Hz with the addition of a precision clock. It has not been determined if the gages are sensitive to ambient noise, the temperature of the pavement, humidity or air temperature. The replacement of the laser gages with these sonic gages would realize a considerable savings in money (1982). These sonic gages would always measure the shortest distance to the ground, reducing the error described in Appendix B (relating to rotating gages).

The gage readings taken over the four inch distance are averaged and recorded. At present operating speeds, over 1600 readings are averaged. This average is truncated to a four digit integer, the same number of digits that the lasers output. Because a large number of samples is taken, another digit can be accepted. It is felt that this extra digit would improve the accuracy of the system. In lieu of this, the average could be rounded off instead of truncated.

Presently, the system records more readings than it should. That is, in five hundred feet of travel, it records about five hundred and ten readings (instead of five hundred and one). It is felt that slack in the connection between the shaft encoder and the fifth wheel is causing this problem. This slack should be removed. As it is, extra readings might result if the encoder rotates relative to the frame of the fifth wheel

The large standard deviations, noted in section IV, B, might be an indication that the laser gages are defective. At one point in the study, one of the gages failed completely. Before it did so, it gave large standard deviations intermittently and then constantly. It is suggested that the resistor that failed on the failed gage be replaced on the other gages.

V. SUMMARY AND CONCLUSIONS

This study has presented a method whereby the texture and profile of a pavement may be determined from a moving vehicle. The system is relatively portable and requires little contact (a transporting vehicle and a fifth wheel) with the pavement.

The profile algorithm has been derived and refined so that a fair agreement with surveyed profiles has been obtained. Important advances in the algorithm pertaining to the gage alignment have been discovered and reviewed. The profile, which is used in roughness studies, can now be accomplished reasonably quickly, not only in the sense that the test is quick, but also inasmuch as the data reduction is also rapid.

The laser system presented can also measure texture. While the values presented have not been correlated with other methods, the present system allows highway and airport personnel to easily and rapidly detect <u>changes</u> in their texture of the pavements.

A method to measure the deflection caused by a moving vehicle from a moving vehicle has been developed. When perfected, this system will allow the pavement engineer not only to measure deflections, but also to determine the remaining life of a pavement system (based on the deflection). The present study has developed a working prototype. Some refining of the system will result in its improvement.

VI. SUGGESTIONS FOR FURTHER RESEARCH

A method to obtain rapid non-contact measurement of deflections from a moving vehicle was developed in the present study. This section lists various directions that future research could take.

1. Concrete pavements could be tested for pumping potential and groove depth. Pumping requires the movement of the edge of a slab. By starting the undeflected profile just before the edge of the slab, the deflection caused when the load reaches that point can be measured. The procedure might be

   a. move the load vehicle into position
   b. slowly turn the fifth wheel by hand until the first reading is detected, and
   c. move the load vehicle across the slab edge.

   It would be helpful to have a visible indicator of where the first gage was reading. A visible light spot from a HeNe laser could be used. The above described method method would allow the use of the existing program GATHER

To measure groove depth, a new program would have to be written. This one would not calculate a profile. It would monitor the fifth wheel and take readings from the first gage at the signal from the operator. As the gage approached a groove, the operator signals the computer to take readings until the gage has passed the groove. If the beam does not move much vertically during the test, a profile of the groove can be measured. Again, a visible light, indicating the position of the first gage, would be of assistance to the operator.

This test would have to be conducted slowly, to keep the rigid beam from moving vertically. The operator could use a remote switch to trigger the the computer, so he could walk alongside the gage.

2. Running the system transverse to the runways can evaluate rutting. The system can also be adapted to railroad cars to find soft spots in the roadbed. The steel wheels of railroad cars could be used to replace the fifth wheel.

3. Replacing the laser gages with the Polaroid sonic distance measuring gages might be explored. This replacement would realize a considerable savings

in money (1982). In addition, the sonic gages measure the shortest distance to the ground, reducing the error described in Appendix B (relating to rotating gages). With their successful development, a measuring system would be affordable to all engineering organizations interested in pavement performance.

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APPENDIX A

Alternate Theory for Profile, Texture and Deflection Measurement

As an alternative to using three gages for the profilometer, two gages and a tiltmeter can be used (presuming one with sufficient accuracy can be located). A tiltmeter is an electro-mechanical device that measures the angle of a surface with respect to a level datum.

The algorithm for finding the profile is similar to that used with three gages. Consider Figure III-1 again. This time, gages B and C will be used. The inclination of the beam is θ. Initially, B, C, and CC are known. CC was chosen to define the datum - the datum being level and passing through the end of CC, with x known.

$$b = x \sin \theta \tag{1}$$

$$B + b + BB = C + CC \tag{2}$$

so,

$$BB = C + CC - B - b \tag{3}$$

substituting (1) into (3) yields

$$BB = C + CC - B - (x \sin \theta) \tag{4}$$

Again, note that the terms on the right side of the equation are known. Thus, the next pavement profile point is obtained. The beam moves forward, as before, until gage C is over where gage B was, and the process is repeated. The method can be used with gage C and D to get the deflected profile.

The deflection and texture measurements can be calculated in the same manner described in Section III, B, 1.

APPENDIX B

Analysis of the Theory

1. Fifth wheel

An analysis was carried out to see the effect of the fifth wheel slipping on the pavement. If the wheel slips, the succeeding gages would not read where the preceding gages had read. If the vehicle was travelling on a slope, a false elevation would be computed. This was a function of the amount of slippage and the angle of the pavement. Furthermore, it was a cumulative effect; that is, once the wheel slipped, it shifted the elevations at all subsequent points. If it slipped again, this error was added to the previous error for all the points subsequent to that slippage, and so forth. Figure A-1 is a plot of this effect.

Figure A-1 was obtained from the geometry of the system, shown in the upper part of the figure. Here are shown the front three gages of the beam (without the load vehicle) after one iteration. The gages have moved forward one increment (dashed lines) and are making a reading. Normally, they would read directly over where the previous gage had read.

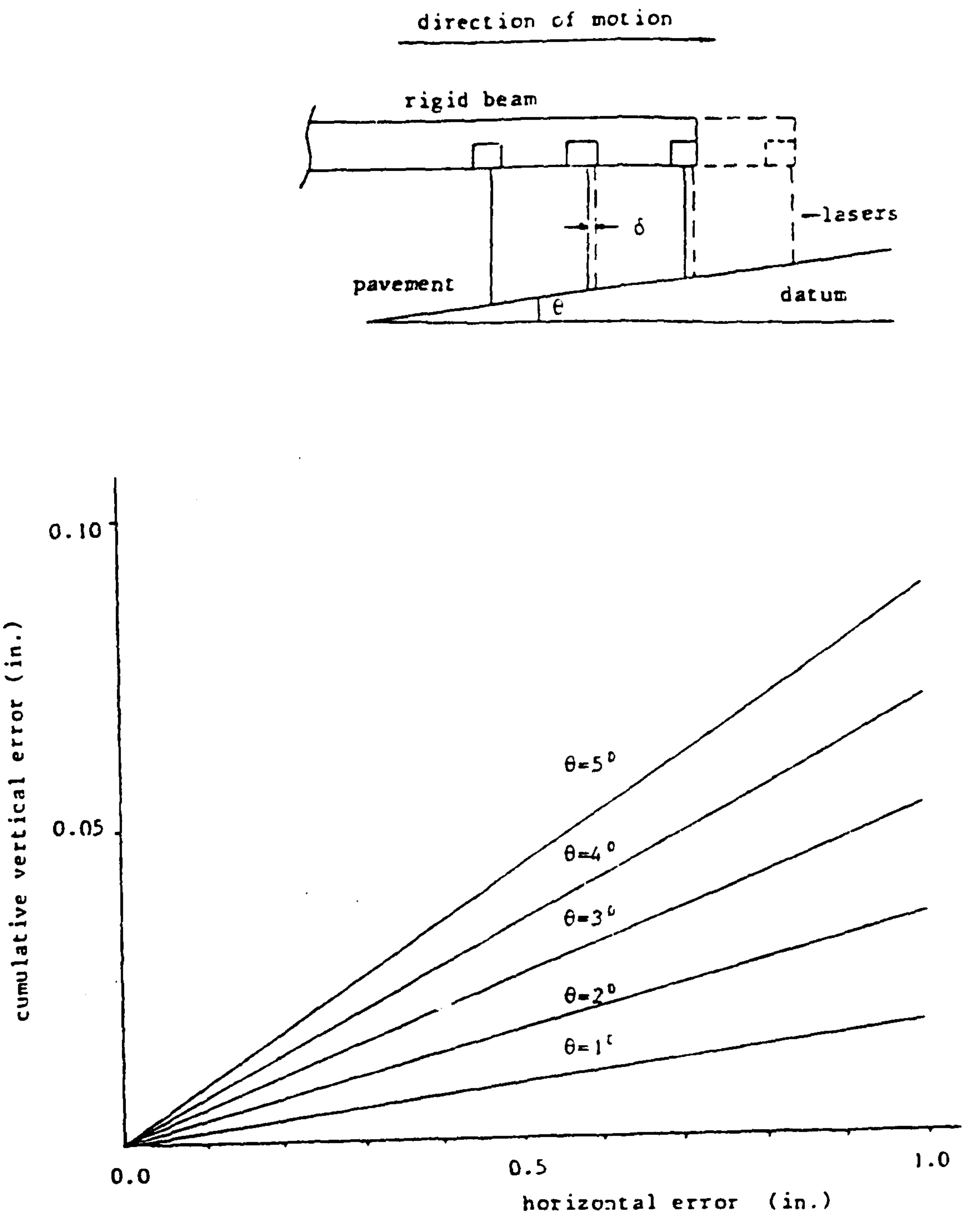


Figure A-1 Effect of fifth wheel slippage

Since the fifth wheel slipped, however, the beam moved more than the standard increment before the computer received the signal from the fifth wheel to take a reading. The horizontal component of the distance slipped is δ. The vertical component is $\delta \tan \theta$. As θ increases the vertical (elevation) error increases. As the amount of slippage increases, the elevation error also increases. This is shown on the plot in Figure A-1. the errors in elevation are cumulative because, in each succeeding iteration, the (incorrect) elevations are used from the previous iteration. When these elevations are larger than they should be, the resulting elevations will be calculated as being larger than they are. Also, the deflections will be calculated at the wrong locations. They will be in error by the amount $\delta \tan \theta$ until the deflection gage reaches the position where the first gage occupied at the time of the slippage.

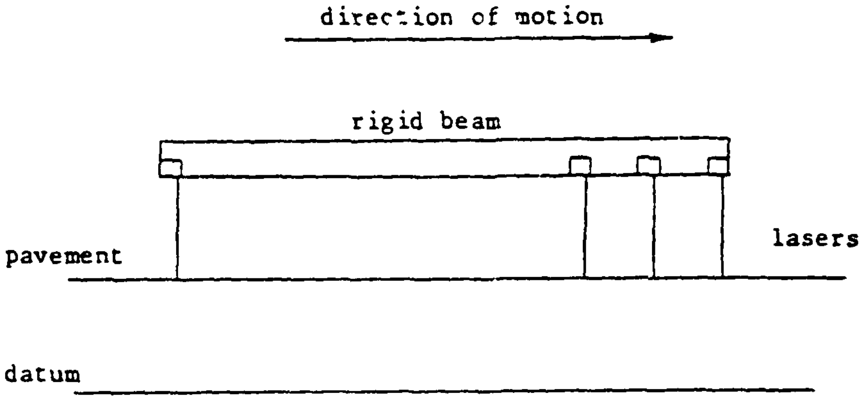
The fifth wheel may go faster than the load vehicle (the opposite of slippage). When this occurs, the exact opposite effect as that of slippage is introduced. Instead of an elevation error being added to the profile, it is subtracted.

Consider the fifth wheel again. Recall that the fifth wheel tells the computer when the succeeding gages are located at a position where the preceding gages had been. If the pavement is level, every foot traversed on the pavement is one foot traversed on the datum. Thus, by counting the number of readings made, one can locate any particular reading in space. If, however, the pavement slopes at an angle θ from the datum (positive or negative), then the fifth wheel does not measure one foot intervals along the datum. Thus, for the horizontal distance to be properly determined, they must be multiplied by cos θ. Theta can easily be determined from any two successive readings. This also assumes the slope of the pavement between the fifth wheel and the other end of the beam is constant - not an unreasonable assumption. If this error is not corrected, the calculated profile will be flatter and longer than it actually is.

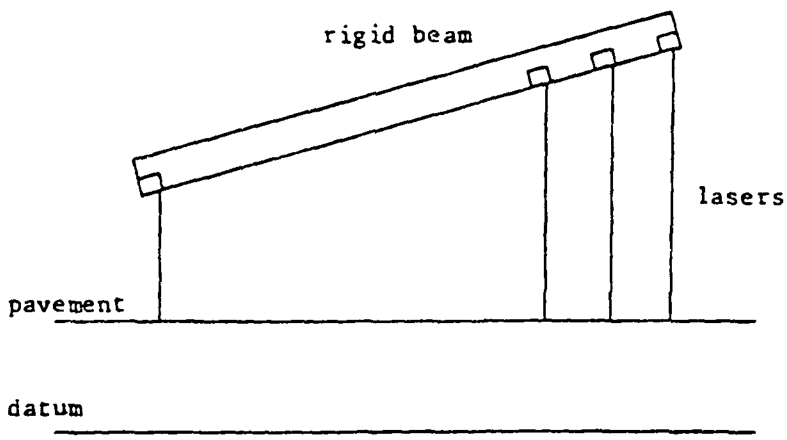
Yet another problem can occur with the fifth wheel. This concerns timing the gages so that each one reads where the preceding gage had read*. Figure A-2a shows the beam and the fifth wheel moving on a surface that is parallel to the datum. Note that the beam and the surface are parallel. As the fifth wheel moves forward one increment, each gage moves up to where the previous gage had been. In Figure A-2b, however, when the beam is not parallel to the surface, one increment moved by the fifth wheel does not place the succeeding gages over where the preceding gage was. How important is this error ?

The size of the error is a function of the slope of the surface, the slope of the beam, and the length of the beam.

* In the statistical sense



a. Theory



b. Practice

Figure A-2 Theory and practice of system usage

Assume the slope is 5 degrees (1 : 11) and the slope of the beam is $5^{\circ} + 2.7^{\circ} = 7.7^{\circ}$. The angle 2.7° was chosen as it is the upper limit the beam can pivot about the end gage before the other end gage goes out of range (that is, 2.5 inches upward for the Optocators). The error that occurs is that the elevation of the pavement (above the datum) is calculated incorrectly. Figure A-3 shows the details of the problem. In this figure, the solid beam is parallel to the slope and measures the pavement profile at B when the fifth wheel has moved one foot up the slope. If the beam had tilted just before the the reading was made, the reading would have occurred at A. the elevation at A would then be computed correctly, but attributed to the horizontal distance B. The difference between these two points, δy, is a function of the slope of the surface and the amount the beam has tipped. For the severe conditions just stated, δy is significant. For a slope of 0.7 degrees (1 : 115) and a beam tilt of 3.4 degrees, δy is 0.002 inches. This is significant, when one considers that deflections are measured in 0.001 inch increments.

The solution to this problem is to keep the beam as parallel as possible to the pavement.

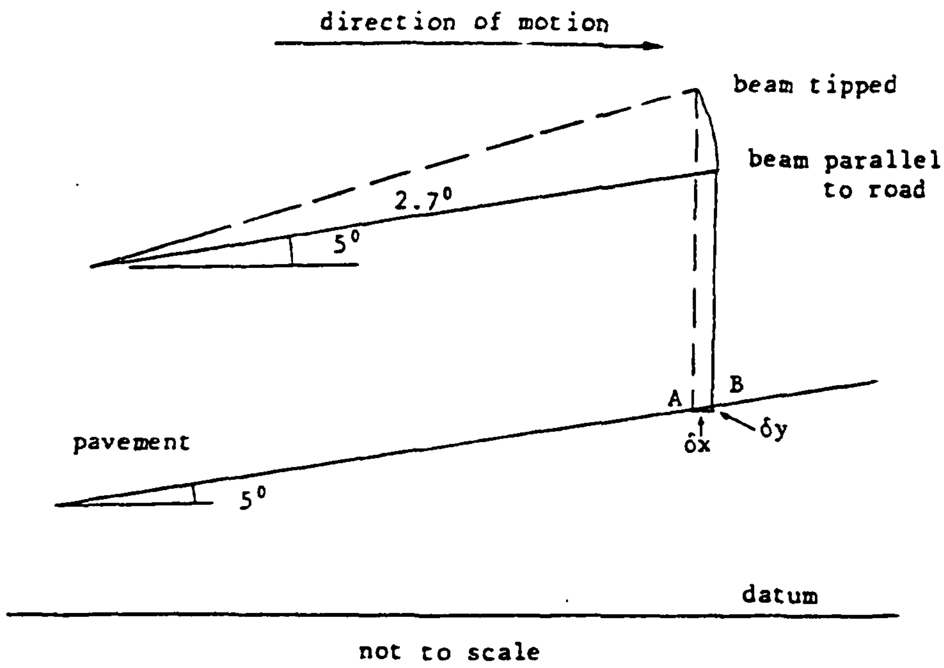


Figure A-3 Effect of beam tilt (gages not shown)

2. Rotating Gages

In the foregoing figures, whenever the beam tipped, the gages continued to make readings perpendicular to the datum. This could only occur if the gages were free to rotate on the beam. If the gages were fixed rigidly to the beam, incorrect data could be generated. A numerical example is given in Figure A-4. This figure shows that a small tilt of the beam over a level pavement produces an error in the horizontal distance measurement.

This is not to say that this error would not occur if the gages were free to rotate on the beam - it would, only the magnitude would be about twenty percent of that of the fixed gage case (see Figure A-5). Thus, from this standpoint, it is more desirable to use pivoting gages.

It is important to note that the gages must pivot <u>in unison</u>; if they do not, their random movements could generate an error larger than that caused by gages fixed to the beam.

Even for readings over a four inch distance on the pavement (instead of single readings), the pivoting gage system is still more desirable. The advantage comes from the fact that one must measure at the same location as the previous gage

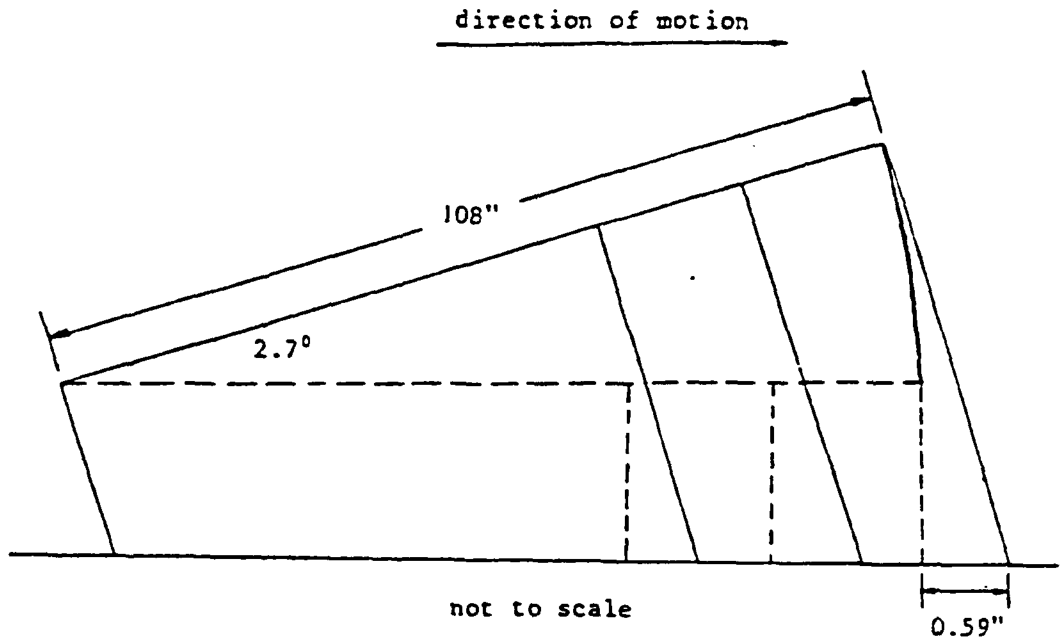


Figure A-4 Horizontal error when gages are fixed rigidly to the beam.

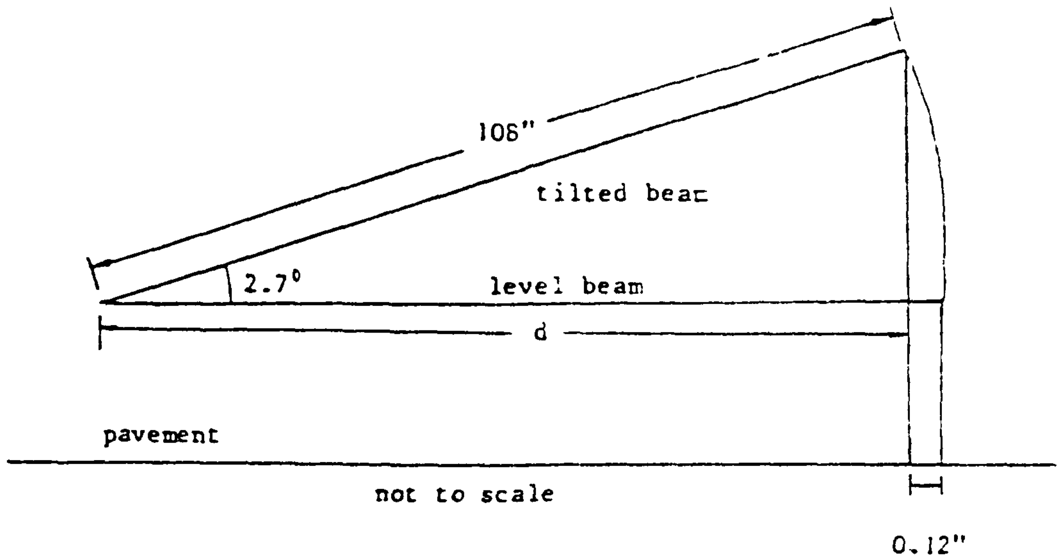


Figure A-5 Horizontal error when gages pivot on the beam.

The horizontal distance error for the floating gage system was absolutely less than that for the fixed gage system. As a percentage of the four inch distance, the floating gage system is closer to the theoretical spacing than the fixed gage system. The closer the gages read where the previous gages had read, the smaller will be the error in the deflection calculation.

If the fixed gage system is used on a slope, with the beam parallel to the slope, the error in the horizontal reading will be the same as in the pivoting gage case. That is, the fifth wheel will not measure distance along the datum unless the cos θ correction is made. Should the beam with fixed gages become oblique to the slope, the distance that the gage laser light spot will be off target will be the same as in the zero slope case. The same problem occurs with approximately the same amplitudes for the pivoting gage case. This problem can be alleviated (though not eliminated) by using the average of readings taken over a short distance, rather than single readings. This averaging was done in this study (section III, B, 1).

The complexity of motion that the beam can go through has only been touched upon in this Appendix. It has examined only one of the many gyrations that the beam can exhibit (the pitch mode). The errors due to roll and yaw remain for future investigators.

APPENDIX C

COMPUTER PROGRAMS

This Appendix lists the data gathering program (GATHER), the data reduction program (CALC), the data preview program (LIST), and the profile adjusting program ADJUST.

GATHER is written in the DEC assembly language. This was done because it had to operate very quickly. It gathered the data from the gages, monitored the fifth wheel, and counted pulses from the line time clock. GATHER writes the data onto the disk in binary.

CALC is written in FORTRAN IV. It reads the data (converted from binary to ASCII by program LIST) and computes the undeflected and deflected profiles and the deflections. Bad data points are noted, as are the standard deviations of the readings made over the four inches of pavements.

LIST is a data previewing program. After the data are gathered, the operator may wish to see if it is good before reducing it. LIST tells the operator how many out-of-range points there are. If there are too many, the operator may wish to drive over that particular stretch of pavement again. LIST is also used to translate the data file into ASCII. In this form, the data is compatible with most any computer.

ADJUST adjusts the endpoints of the profile to user specified elevations. The effect is to change the datum to a user defined datum. In particular, it is useful to adjust the datum to be horizontal.

Program GATHER, used to collect the data.

```
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
C       DATA ACQUISITION PROGRAM FOR DAVE ELTON OF PURDUE
C
C                " GATHER YE DATA WHILE YE MAY "
C
C
C       LOGICAL VALUES RECEIVED FROM LASER SUBROUTINE
C       (WHEEL, THREE SWITCHES, & TIME-OUT-ERROR)
C
C
C       LOGIC=1=TRUE    LOGIC=0=FALSE
C
C
        BYTE SPACE
        DATA SPACE/1H /
        BYTE IYES
        BYTE IANS
        DATA IYES/1HY/
        BYTE NAMEF(80)
        DIMENSION JTIM2(2)
        DIMENSION IBUF2(8192),IBUF3(8191),IBUF4(8190),IBUF5(8189),
     &IBUF6(8188),IBUF7(8187),IBUF8(8186),IBUF9(8195),IBUF10(8194),
     &IBUF11(8183),IBUF12(8182),IBUF13(8181),IBUF14(8180)
        DIMENSION IBUF(8193)
        DIMENSION JTIM(2)
        INTEGER TURN,SD,SB,SC,SD2
        EQUIVALENCE (IBUF(14),IBUF14(1),IBUF13(2))
        EQUIVALENCE (IBUF(12),IBUF12(1),IBUF11(2),IBUF10(3),
     &IBUF9(4),IBUF8(5),IBUF7(6),IBUF6(7),IBUF5(8),IBUF4(9),
     &IBUF3(10),IBUF2(10))
C
C       DT=1./SAMP RATE OF LASERS)
C
        DATA DT/.0005/
C
C       DT IS SET FOR 2000 HZ
C
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
C       GET FILE NAME
C       OPEN FILE &
C       WRITE REC
C
C
1       TYPE 8877
8877    FORMAT (' ENTER 6 CHARACTER NAME: ',$)
        ACCEPT 8876,NC,(NAMEF(I),I=1,NC)
8876    FORMAT (Q,80A1)
        CALL IRAD50(6,NAMEF,XNAME)
```

```
          CALL NAMEIT(XNAME)
          CALL OPEN
          N=1
          IR=1
          TURN=1
          IWHEEL=1
          IWH=1
          TYPE 7010
7010      FORMAT (' SHALL I TAKE THE WHEEL PULSES FROM SWITCH? ',$)
          ACCEPT 7011, IANS
7011      FORMAT (A1)
          IF(IANS.NE.IYES) GO TO 7111
          IWH=5
          IWHEEL=16
7111      TYPE 1005
C
C         START DATA ACQUISITION
C
C
1005      FORMAT (' TURN ON START SWITCH TO START DATA ACQUISITION')
C
C
66        IF(ISW(2).NE.1) GO TO 66
8         IF((ISW(IWH).EQ.1).AND.(ISW(2).NE.0)) GO TO 8
          IF(ISW(2).EQ.0) GO TO 1720
10        IF((ISW(IWH).EQ.0).AND.(ISW(2).NE.0)) GO TO 10
          IF(ISW(2).EQ.0) GO TO 1720
          GO TO 9
1720      TYPE 1721
1721      FORMAT (' YOU HIT STOP BEFORE YOU STARTED???????')
          CALL EXIT
C
C
9         CALL GTIM(JTIM2)
          CALL CLASS(LA2,LA1,KA,LB2,LB1,KB,
      &LC2,LC1,KC,LD2,LD1,KD,
      &ISD3,ISD2,ISD1,ISDB3,ISDB2,ISDB1,
      &ISDC3,ISDC2,ISDC1,ISDD3,ISDD2,ISDD1,IWHEEL)
          CALL GTIM(JTIM)
          SUMA=CONV(LA2,LA1)
          SUMB=CONV(LB2,LB1)
          SUMC=CONV(LC2,LC1)
          SUMD=CONV(LD2,LD1)
          IAVGA=0
          IAVGB=0
          IAVGC=0
          IAVGD=0
          IF(KA.NE.0) IAVGA=SUMA/FLOAT(KA)
          IF(KB.NE.0) IAVGB=SUMB/FLOAT(KB)
          IF(KC.NE.0) IAVGC=SUMC/FLOAT(KC)
          IF(KD.NE.0) IAVGD=SUMD/FLOAT(KD)
          SSA=FIXSD(ISD1,ISD2,ISD3)
          SSB=FIXSD(ISDB1,ISDB2,ISDB3)
```

```
      SSC=FIXSD(ISDC1,ISDC2,ISDC3)
      SSD=FIXSD(ISDD1,ISDD2,ISDD3)
      SA=0
      SB=0
      SC=0
      SD=0
4777  FORMAT (' TESTQ=',F13.4/)
      IF(KD.NE.0) SD=SQRT((SSD-(SUMD*SUMD)/FLOAT(KD))/FLOAT(KD))
      IF(KB.NE.0) SB=SQRT((SSB-(SUMB*SUMB)/FLOAT(KB))/FLOAT(KB))
      IF(KC.NE.0) SC=SQRT((SSC-(SUMC*SUMC)/FLOAT(KC))/FLOAT(KC))
      IF(KA.NE.0) SA=SQRT((SSA-(SUMA*SUMA)/FLOAT(KA))/FLOAT(KA))
9995  IF(ISW(4).NE.1) GO TO 333
      IBUF(N)=IAVGA
      IBUF2(N)=IAVGB
      IBUF3(N)=IAVGC
      IBUF4(N)=IAVGD
      IBUF5(N)=KA
      IBUF6(N)=KB
      IBUF7(N)=KC
      IBUF8(N)=KD
      IBUF9(N)=SA
      IBUF10(N)=SB
      IBUF11(N)=SC
      IBUF12(N)=SD
      IBUF13(N)=JTIM2(2)
      IBUF14(N)=JTIM(2)
      N=N+16
333   IF(ISW(3).EQ.1) TYPE 1112, TURN, IAVGA,IAVGB,IAVGC,IAVGD,KA,
     & KB,KC,KD
33    IF((ISW(IWH).EQ.1).AND.(ISW(2).NE.0)) GO TO 33
      IF(ISW(2).EQ.0) GO TO 1717
34    IF((ISW(IWH).EQ.0).AND.(ISW(2).NE.0)) GO TO 34
      IF(ISW(2).EQ.0) GO TO 1717
      IF(ISW(4).EQ.0) GO TO 43
1112  FORMAT (' ',I4,X,8I6)
      IF(N.GE.8192) CALL WRITE(IBUF,IR)
43    IF((ISW(IWH).EQ.1).AND.(ISW(2).NE.0)) GO TO 43
      IF(ISW(2).EQ.0) GO TO 1717
44    IF((ISW(IWH).EQ.0).AND.(ISW(2).NE.0)) GO TO 44
      IF(ISW(2).EQ.0) GO TO 1717
C
      TURN=TURN+1
      IF(N.LT.8192) GO TO 9
      N=1
      IR=IR+32
      GO TO 9
C
C
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
C
C         NOT START
```

```
C       TYPE EXIT
C
C
1717    TYPE 1007,TURN
1007    FORMAT (' END OF TEST AFTER ',I6,' FEET'//)
        IF(ISW(4).EQ.0) GO TO 1
        DO 1562 I=1,12
1562    IBUF(N+I-1)=-1
        CALL WRITE(IBUF,IR)
        CALL WAIT
        CALL CLOSEX
        GO TO 1
        END
C
C
C
        FUNCTION FIXSD(ISD1,ISD2,ISD3)
        XX=ISD1
        YY=ISD2
        ZZ=ISD3
        IF(XX.LT.0.) XX=65536.+XX
        IF(YY.LT.0.) YY=65536.+YY
        IF(ZZ.LT.0.) ZZ=65536.+ZZ
        FIXSD=XX+65536.*(YY+65536.*ZZ)
        IF(FIXSD.LT 0.) TYPE 12 , ISD1,ISD2,ISD3,FIXSD
 12     FORMAT(2X,'***********************',/,2X,
     &    'ISD1-3, FIXSD = ',3I5,X,G12.6)
        RETURN
        END
C
C
C
        FUNCTION CONV(I2,I1)
        Y=I1
        IF(Y.LT.0.) Y=65536.+Y
        CONV=65536.*FLOAT(I2)+Y
       IF(CONV.LT.0.) TYPE 12, I2,I1,CONV
 12     FORMAT(/,X,'*&*&*&*&*&*&*&*&*&*&*&*&*',
     &   /,2X,'I2,I2, CONV = ',2I7,X,G16.3)
        RETURN
        END
```

Program CLASSY, a subroutine to GATHER.

```
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
;
;
;        CALL CLASS(LA2,LA1,KA,LB2,LB1,KB,LC2,LC1,KC,
;      & LD2,LD1,DK,LSDA3,LSDA2,LSDA1,LSDB3,LSDB2,LSDB1,
;      & LSDC3,LSDC2,LSDC1,LSDD3,LSDD2,LSDD1,IWH)
;
;
;        I=ISW(LSWITCH)
;
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
;
;
        .ENABL AMA
        .GLOBL  CLASS,ISW
;
;                DEFINE SYMBOLS AND REGISTERS
;
AR=177550
BR=177540
CR=177530
DR=177520
ER=177510
Z=%0
Z2=%1
MASK=%2
R=%5
PC=%7
START=2
;
;                START LASERS AT ENTRY POINT "CLASSY"
;
CLASS:  INC      AR
        INC      BR
        INC      CR
        INC      DR
        MOV      #2,ER
;
;                CLEAR SAMPLE COUNT
;
        CLR      KA
        CLR      KB
        CLR      KC
        CLR      KD
;
;                CLEAR AVG REGISTERS
;
        CLR      SUM1A
        CLR      SUM2A
        CLR      SUM1B
        CLR      SUM2B
        CLR      SUM1C
```

```
        CLR     SUM2C
        CLR     SUM1D
        CLR     SUM2D
;
;               CLEAR RMS REGISTERX
;
        CLR     SS1A
        CLR     SS2A
        CLR     SS3A
        CLR     SS1B
        CLR     SS2B
        CLR     SS3B
        CLR     SS1C
        CLR     SS2C
        CLR     SS3C
        CLR     SS1D
        CLR     SS2D
        CLR     SS3D
;
;               SET WHEEL SWITCH BIT
;
        MOV     @62(R),WH
;
;       CLEAR THE HALF CYCLE DETECTOR & SET MASK
;
        CLR     HALF
        MOV     #100007,MASK
;
;   LASER "A" ACQUISITION, AVG, & RMS CALCULATIONS
;
A:      TSTB    AR        ;IS LASER "A" READY
        BPL     B         ;NO - SO GO GET LASER "B"
        CMP     KA,#32767.
        BEQ     B
        MOV     AR+2,Z    ;YES-GET DATA FORM PARALLEL CARD
        INC     AR        ;RESTART LASER
        BIC     MASK,Z    ;CLEAR UNWANTED BITS
        ROR     Z         ; (THESS CAN BE DELETED-
        ROR     Z         ;   IF CABLE IS REWIRED SO THE
        ROR     Z         ;     DATA IS RIGHT JUSTIFIED)
        ADD     Z,SUM1A   ;ADD DATA TO SUM
        ADC     SUM2A
        MOV     Z,TMP
        MUL     TMP,Z
        ADD     Z2,SS1A   ;ADD    SQUARE TO RMS SUM
        ADC     SS2A
        ADD     Z,SS2A
        ADC     SS3A
        INC     KA        ;INC THE SAMPLE COUNT
;
;               LASER "B"
;
B       TSTB    BR
```

```
        BPL     C
        CMP     KB,#32767.
        BEQ     C
        MOV     BR+2,Z
        INC     BR
        BIC     MASK,Z
        ROR     Z
        ROR     Z
        ROR     Z
        ADD     Z,SUM1B
        ADC     SUM2B
        MOV     Z,TMP
        MUL     TMP,Z
        ADD     Z2,SS1B
        ADC     SS2B
        ADD     Z,SS2B
        ADC     SS3B
        INC     KB
;
;               LASER "C"
;
C:      TSTB    CR
        BPL     D
        CMP     KC,#32767.
        BEQ     D
        MOV     CR+2,Z
        INC     CR
        BIC     MASK,Z
        ROR     Z
        ROR     Z
        ROR     Z
        ADD     Z,SUM1C
        ADC     SUM2C
        MOV     Z,TMP
        MUL     TMP,Z
        ADD     Z2,SS1C
        ADC     SS2C
        ADD     Z,SS2C
        ADC     SS3C
        INC     KC
;
;               LASER "D"
;
D:      TSTB    DR
        BPL     E
        CMP     KD,#32767.
        BEQ     E
        MOV     DR+2,Z
        INC     DR
        BIC     MASK,Z
        ROR     Z
        ROR     Z
        ROR     Z
```

```
          ADD     Z,SUM1D
          ADC     SUM2D
          MOV     Z,TMP
          MUL     TMP,Z
          ADD     Z2,SS1D
          ADC     SS2D
          ADD     Z,SS2D
          ADC     SS3D
          INC     KD
;
;                 READ AND PROCESS THE SWITCHES
;
E:        MOV     ER+2,Z
          BIT     #START,Z          ;IS START SWITCH STILL SET?
          BEQ     EXIT     ;NO - GO EXIT
          TST     HALF     ;YES-ARE WE IN FIRST HALF OF CYCLE
          BNE     SNDHLF   ;NO-GO TO SECOND HALF
          BIT     WH,Z     ;YES - ARE WE NOW IN FIRST HALF OF CYCLE?
          BNE     GOTOA    ;NO-GO ACQUIRE MORE DATA
          MOV     #1,HALF  ;YES-SET SECOND HALF FLAG
GOTOA:    JMP     A        ;     AND GO ACQUIRE MORE DATA.
SNDHLF:   BIT     WH,Z     ;SECOND HALF - ARE WE NOW IN FIRST HALF?
          BEQ     GOTOA    ;NO-GO ACQUIRE MORE DATA
;
;                 EXIT WITH ARGUMENTS
;
EXIT:     TST     (R)+
          MOV     SUM2A,@(R)+
          MOV     SUM1A,@(R)+
          MOV     KA,@(R)+
          MOV     SUM2B,@(R)+
          MOV     SUM1B,@(R)+
          MOV     KB,@(R)+
          MOV     SUM2C,@(R)+
          MOV     SUM1C,@(R)+
          MOV     KC,@(R)+
          MOV     SUM2D,@(R)+
          MOV     SUM1D,@(R)+
          MOV     KD,@(R)+
          MOV     SS3A,@(R)+
          MOV     SS2A,@(R)+
          MOV     SS1A,@(R)+
          MOV     SS3B,@(R)+
          MOV     SS2B,@(R)+
          MOV     SS1B,@(R)+
          MOV     SS3C,@(R)+
          MOV     SS2C,@(R)+
          MOV     SS1C,@(R)+
          MOV     SS3D,@(R)+
          MOV     SS2D,@(R)+
          MOV     SS1D,@(R)+
;
          RTS     PC
```

```
;
;                         DATA
;
WH:       .WORD   0
KA:       .WORD   0
KB:       .WORD   0
KC:       .WORD   0
KD:       .WORD   0
SUM1A:    .WORD   0
SUM2A:    .WORD   0
SUM1B:    .WORD   0
SUM2B:    .WORD   0
SUM1C:    .WORD   0
SUM2C:    .WORD   0
SUM1D:    .WORD   0
SUM2D:    .WORD   0
SS1A:     .WORD   0
SS2A:     .WORD   0
SS3A:     .WORD   0
SS1B:     .WORD   0
SS2B:     .WORD   0
SS3B:     .WORD   0
SS1C:     .WORD   0
SS2C:     .WORD   0
SS3C:     .WORD   0
SS1D:     .WORD   0
SS2D:     .WORD   0
SS3D:     .WORD   0
HALF:     .WORD   0
TMP:      .WORD   0
;
;;;;;;;;;;;;;;;;;;;;;
;    FUNCTION SUBROUTINE TO READ
;     ANY BIT OF SWITCH CARD
;
;
ISW:      MOV     #2,ER     ;START SAMPLING
          MOV     #1,Z      ;ROTATE ONE BIT TO TEST LOCATION
          MOV     @2(R),R
          CLR     Z2
          DEC     R
          ASHC    R,Z
          BIT     Z,ER+2    ;TEST IF THIS BIT IS SET IN CARD
          BEQ     NOTSET    ;NO - GO EXIT WITH ZERO
          INC     Z2        ;YES - GO EXIT WITH ONE
NOTSET:   RTS     PC        ;EXIT - SUBROUTINE "ISW"
          .END
          .ENABL  AMA
          .GLOBL  ISW
```

```
ER=177510
Z=%1
R=%5
Z2=%0
PC=%7
```

Program DISK.MAC, a subroutine to GATHER.

```
;
;        DISK READ WRITE SUBROUTINES
;
;
         .MCALL   .LOOKUP,.FETCH
         .MCALL   .READW,.WAIT,.WRITE,.LOCK,.ENTER,.CLOSE
         .GLOBL   OPENO
         .GLOBL   NAMEIT
         .GLOBL   OPEN,CLOSEX,READ,WRITE,WAIT,IER
         .ENABL   AMA
;
R0=%0
R1=%1
R2=%2
R3=%3
R4=%4
R5=%5
PC=%7
OPEN:    .LOCK
         .FETCH   #CORSPC,#NAME
         CLR      FIRST
         MOV      #AREA,%5
         MOV      #1,%4
         .ENTER   R5,R4,#NAME,#-1
         BCS      ERR
         MOV      #1,E
         RTS      PC
ERR:     CLR      E
         RTS PC
NAMEIT:  MOV      2(R5),R1
         MOV      (R1)+,NAME+2
         MOV      (R1),NAME+4
         RTS      PC
;
;
NAME:    .RAD50   /DK /
         .RAD50   /DAT/
         .RAD50   /A  /
         .RAD50   /DAT/
AREA:    .BLKW    10
;
;
IER:     MOV      E,R0
         RTS      PC
;
;
CLOSEX:           MOV      #1,R4
         .CLOSE   R4
         RTS      PC
,
,
,
```

```
OPENO:   .LOCK
         .FETCH   #CORSPC,#NAME
         CLR      FIRST
         MOV      #AREA,R5
         MOV      #1,R4
         .LOOKUP  R5,R4,#NAME
         BCS      ERO
         MOV      #1,E
         RTS      PC
ERO:     CLR      E
         RTS      PC
E.       .WORD    1
;
;
;
READ:    MOV      2(R5),R4
         MOV      @4(R5),R1
         MOV      #1,R3
         MOV      #AREA,R2
         .READW   R2,R3,R4,#8192.,R1
         BCS      RDERR
         MOV      #1,E
         RTS      PC
RDERR:   CLR      E
         RTS      PC
FIRST:   .WORD    0
;
;
;
WRITE:   MOV      2(R5),R4
         MOV      @4(R5),R1
         MOV      #1,R3
         MOV      #AREA,R2
FIR:     .WRITE   R2,R3,R4,#8192.,R1
         BCS      WTERR
         MOV      #1,FIRST
         MOV      #1,E
         RTS      PC
WTERR:   CLR      E
         RTS      PC
;
;
WAIT:    MOV      #1,R3
         .WAIT    R3
         BCS      WAER
         MOV      #1,E
         RTS      PC
WAER:    CLR      E
         RTS      PC
CORSPC:  .BLKW    400
         .END
```

Program LIST, used to preview the data.

```
C  THIS IS LIST.FOR.  IT TAKES
C     A DATA FILE CREATED BY GATHER.FOR AND RE-WRITES
C     IT AS AN ASCII CODE FILE, EITHER ON DISK,
C     PRINTER OR SCREEN.  SEE PROGRAM FOR THE
C     ORDER THE DATA IS PRESENTED.
C        N=NUMBER OF READINGS
C        S=STD DEV OF ONE OF THE GAGES OVER FOUR INCHES
C
         DIMENSION IBUFF(8193)
         BYTE NAMEF(80),NAME2(80)
         BYTE ITT,IAA,ILL,IDD
         DATA ITT,ILL,IDD/1HT,1HL,1HD/
 1       BOZO=0.
         TYPE 5555
 5555    FORMAT(/,X,' LISTING ON TT, LP OR DISK? (T,L OR D) ',$)
         ACCEPT 55, IAA
 55      FORMAT(A1)
         IF(IAA.NE.IDD) GO TO 22
         TYPE 20
 20      FORMAT(/,2X,' OUTPUT FILENAME ? ',$)
         ACCEPT 21, NOC,(NAME2(J),J=1,NOC)
 21      FORMAT(Q,80A1)
         NAME2(NOC+1)=0
         CALL ASSIGN(11,NAME2,NOC,'NEW')
 22      CONTINUE
 23      FORMAT(/,2X,' DATA FILE   ',20A1,/)
        I=17
         DO 10 II=1,32767
         IF(II.GT.1) BOZO=1
        CALL READC(A,B,C,D,NA,NB,NC,ND,SD1,SD2,SD3,SD4,IS,IE,I)
         DT=FLOAT(IE-IS)
         IDT=IE-IS
         ISD1=IFIX(SD1)
         ISD2=IFIX(SD2)
         ISD3=IFIX(SD3)
         ISD4=IFIX(SD4)
         IA=IFIX(A)
         IB=IFIX(B)
         IC=IFIX(C)
         ID=IFIX(D)
         IF(A.LT.0) GO TO 11
        IF(IAA.EQ.IDD) WRITE(11,60) IA,IB,IC,ID,NA,NB,NC,ND,ISD1,
      &    ISD2,ISD3,ISD4,IDT
         IF(IAA.EQ.ITT) TYPE 1000,II,IA,IB,IC,ID,NA,NB,NC,ND,ISD1,
      &       ISD2,ISD3,ISD4,IDT
         IF(IAA.EQ.ILL) PRINT 1000,II,IA,IB,IC,ID,NA,NB,NC,ND,ISD1,
      &     ISD2,ISD3,ISD4,IDT
 10      CONTINUE
 11      IF(IAA.EQ.IDD) CALL CLOSE(11)
 1000     FORMAT(X,13I5,X,I4)
 60      FORMAT(X,13I5)
```

```
      GO TO 1
      END
C
C     SUBROUTINE READC(A,B,C,D,NA,NB,NC,NC,SD1,SD2,SD3,SD4,IS,
C                         IE,I)
C
C             A,B,C,D = LASERS A,B,C,D
C             NA,NB,NC,ND = NO. OF SAMPLES
C             SD1,SD2,SD3,SD4 = STANDARD DEVIATIONS
C             IS = TIME TICKS PEAD BEFORE CLASS
C             IE = TIME TICKS READ AFTER CLASS
      SUBROUTINE READC(A,B,C,D,NA,NB,NC,ND,SD1,SD2,SD3,SD4,
     & ISTART,IEND,I)
      COMMON /RMECOM/IBUF(16,512)
      DATA IOPEN/0/
      DATA LR/-1/
      BYTE NAME(20)
C
      IF(IOPEN.EQ.1) GO TO 1
      IOPEN=1
      WRITE(5,2)
 2    FORMAT(/,3X,'RAW DATA FILE NAME ...  ',$)
      ACCEPT 5,NOC,(NAME(IZZ),IZZ=1,NOC)
      NAME(NOC+1)=0
 5    FORMAT(Q,20A1)
      CALL ASSIGN(1,NAME,NOC,'OLD')
      DEFINE FILE 1 (1000,8192,U,IV)
      WRITE(6,4) (NAME(ITT),ITT=1,NOC)
 4    FORMAT(/,3X,'DATA FILE NAME:  ',80A1)
      WRITE(5,3)
 3    FORMAT(/,3X,'ROARRRRR!!!  CHOMP CHOMP CHOMP',$)
      I=17
 1    IR=((I-1)/512)+1
      IF(IR.EQ.LR) GO TO 30
      READ(1'IR,END=1717) ((IBUF(MZ,LZ),MZ=1,16),LZ=1,512)
      LR=IR
 30   INDX=MOD(I,512)
      IF(INDX.EQ.0) INDX=512
      A=IBUF(1,INDX)
      B=IBUF(2,INDX)
      C=IBUF(3,INDX)
      D=IBUF(4,INDX)
      NA=IBUF(5,INDX)
      NB=IBUF(6,INDX)
      NC=IBUF(7,INDX)
      ND=IBUF(8,INDX)
      SD1=IBUF(9,INDX)
      SD2=IBUF(10,INDX)
      SD3=IBUF(11,INDX)
      SD4=IBUF(12,INDX)
      ISTART=IBUF(13,INDX)
      IEND=IBUF(14,INDX)
      I=I+1
```

```
      IF(A.NE.-1) RETURN
1717  CONTINUE
      RETURN
      END
```

Program CALC, used to reduce the data.

```
c   this is CALC.FOR.   It uses another way. The terror of the hwy.
C         data ab,bc,cd/11.974,12.149,83.75/
          data ab,bc,cd/12.04,12.,84./
          data ascl,dscl,dflt/1.0,1.0,5h*****/
          byte name(30),cue2,YES,NO,prcue,PP,PD
          data YES,NO,key/1hY,1hN,0/
          dimension bb(20),cc(20),dd(20),b(20),c(20),fctra(20),
     &      d(20),aascmn(20),aascmx(20),dmin(20),dmax(20)
     &     ,grad(20),inum(20),aastrt(20),elev1(20),elev2(20),
     &      aascal(20),pr(20),defdif(20),
     &      aaend(20),pltct(20)
          integer fa,fb,fc,fd,to,consec,deflct,reset,cue3
          common /plt/iplt,pmin,dmin
          common a(20),aa(20),defl(20)
          cue2=NO
          cue3=0
          write(5,92)
 92       format(///,3x,'10 - 4 good buddy !! Ready to run CALC ?',
     &       3x,$)
          accept 73,zdz
          write(5,93)
 93       format(/,3x,'Will you want an extended printout?',2x,$)
          accept 73, prcue
          do 122 izi=1,20
          pltct(izi)=0.0
          aastrt(izi)=0.
          aaend(izi)=0.
 122      continue
          if(cue2.eq.NO) go to 85
 78       write(5,68)
          jj=17
 68       format(/,3x,'Type in full name of profile plot file...  '
     &      ,$)
           call assign(8,,-1,'new','CC')
          write(5,69)
 69       format(/,3x,'Type in full name of defl. plot file...',
     $       $)
           call assign(9,,-1,'new','CC')
   85     continue
          xn=(ab+bc)/bc
          if(cue2.eq.NO) write(6,43)
 43       format(1h1,///,45x,'***** PURDUE - WATERWAYS LASER SYSTEM',
     &      ' *****',//)
c   initializations
          ictt=0
          incre=0
          if(cue2.eq.NO) afctra=0.0
          if(cue2.eq.NO) afctrd=0.0
          sa=0.
          sb=0.0
```

```
      sc=0.0
      sd=0.0
      dsb=0.
      dsc=0.
      dsd=0.
      nfa=0
      nfb=0
      nfc=0
      nfd=0
      nnfa=0
      nnfb=0
      nnfc=0
      nnfd=0
      inn=00
      inni=0
      jj=17
      avalid=0.
      dvalid=0.
      if(cue2.eq.YES) go to 63
 1    format(/,2x,' Total number of invalid readings is = ',
     $      5(i4,x),/)
 8    format(/,2x,' No. of data pts. is = ',i7)
 22    format(/,3x,'start/end = ',$)
 21    format(f20.5)
 20    format(/,2x,' start/end = ',2(i10,x),/)
      jj=17
      call redcal(z,z,z,z,z,z,z,z,z,z,z,z,n,n,n,n,z,z,z,z,jj)
c
c   scheme for getting out-of-line constants (delta a,d)
c
      jj=17
      write(6,94)
 94    format(/,3x,'Bad A, B, and C gage readings as follows - ',
     &     /,5x,'location',6x,'gages',/,
     &     8x,'ft.',8x,'A B C',/)
      do 23 innn=1,32575
      call redcal(ax,bx,cx,dx,ascl,dscl,afctra,afctrd,
     &  az,bz,cz,dz,na,nb,nc,nd,stda,stdb,stdc,stdd,jj)
      if(az.lt.0.) go to 34
       call check(az,bz,cz,dz,na,nb,nc,nd,fa,fb,fc,fd)
      nnfa=nnfa+fa
      nnfb=nnfb+fb
      nnfc=nnfc+fc
      nnfd=nnfd+fd
      inn=inn+1
     if(fa.eq.1.or.fb.eq.1.or.fc.eq.1) write(6,95)innn,fa,fb,fc
 95    format(7x,i3,t19,3i2)
      if(fa.eq.1.or.fb.eq.i.or.fc.eq.1) go to 90
      sa=sa+ax
      sb=sb+bx
      sc=sc+cx
      avalid=avalid+1
    afctra=(sa/avalid)-((sc/avalid)-((bc+ab)/bc)*((sc-sb)/avalid))
```

```
90      if(fb.eq.1.or.fc.eq.1.or.fc.eq.1) go to 91
        dsb=dsb+bx
        dsc=dsc+cx
        dsd=dsd+dx
        dvalid=dvalid+1.
      ofctrd=(dsd/dvalid)-((dsc/dvalid)+(cd/bc)*((dsc-dsb)/dvalid))
91      continue
23     continue
 34    incre=nnfa+nnfb+nnfc+nnfd
       jj=17
        write(5,1) nnfa,nnfb,nnfc,nnfd,incre
        write(6,1) nnfa,nnfb,nnfc,nnfd,incre
        write(6,8) inn
        write(5,8) inn
        write(5,22)
        accept 21, rist
        write(5,22)
        accept 21, riend
        ist=ifix(rist)
        iend=ifix(riend)
        write(6,20) ist,iend
        write(5,20) ist,iend
        write(6,96)
96      format(/,3x,'Bad readings between start and end are - ',/,
     &   5x,'location',6x,'gages',/,
     &   8x,'ft ',8x,'A B C',/)
        if(fa.eq.1.or.fb.eq.1.or.fc.eq.1) write(6,95)izz,fa,fb,fc
        do 11 izz=ist,iend
        call readc(az,bz,cz,dz,na,nb,nc,nd,stda,stdb,stdc,stdd,
     &     iistar,iiend,jj)
        call check(az,bz,cz,dz,na,nb,nc,nd,fa,fb,fc,fd)
        if(fa.eq.1.or.fb.eq.1.or.fc.eq.1) write(6,95)izz,fa,fb,fc
        if(az.lt.0.) go to 9
        nfa=nfa+fa
        nfb=nfb+fb
        nfc=nfc+fc
        nfd=nfd+fd
11      continue
9       ictt=nfa+nfb+nfc+nfd
         jj=17
25     format(/,3x,'Gage spacing ab,bc and cd  = ',3(f10.5,x),/)
50      format(2x,i5,x,8(f10.5,x))
        write(5,39) ofctra,ofctrd,nfa,nfb,nfc,
     &      nfd,ictt
        write(6,39) ofctra,ofctrd,nfa,nfb,nfc,
     &      nfd,ictt
39      format(/,2x,' Calculated delta a,d = ',2(f10.6,x),
     &      //,3x,'There were  ',x,5(i6,x),'invalid readings',/,
     &     4x,'in between the start and end.',/)
        write(5,42)
        accept 41, afctra
        write(5,40)
        accept 41, afctrd
```

```
 42       format(/,2x,' input fctra please...   ',$)
 41       format(f10.6)
 40       format(/,2x,' input fctrd please...   ',$)
          write(6,38) afctra, afctrd
 38       format(3x, 'Input delta a,d = ',2(f10.6,x))
           write(6,25) ab,bc,cd
c      establish the arbitrary distances from gages
63          cc(1)=1.
          bb(2)=1.
          deflct=0
          sumdef=0.0
          ssdef=0.0
          iplt=0
          i=1
c   ***************************
c    AHEM! now do the first seven points, for which the
c         deflections at gage d cannot be calculated.
c   ***************************
          jj=17
          if(cue2.eq.YES) ibbi=ist
          if(cue2.eq.NO) write(6,54)
 54       format(///,13('=========='))
          if(cue2.eq.NO) write(6,53)
 53       format(//,t3,'FT.',t12,'AA',t20,'BB',t29,'CC',
     &     t38,'DD',t47,'DEFL',t56,'THETA',t65,'STD A',
     &     t74,'STD B',t83,'STD C',t92,'STD D',t102,'FLAGS',//)
        call advnce(rist)
  31        iplt=iplt+1
          if(cue2.eq.YES.and.cue3.eq.0) write(5,81)
 81       format(//,3x,'Input starting elevation in feet...'$)
          if(cue2.eq.YES.and.cue3.eq.0) accept 82, elev1(iplt)
 82       format(f10.5)
          if(cue2.eq.YES.and.cue3.eq.0) write(5,83)
 83       format(//,3x,'Input ending elevation in feet...',$)
          if(cue2.eq.YES.and.cue3.eq.0) accept 82, elev2(iplt)
          if(cue2.eq.YES.and.cue3.eq.0) elev1(iplt)=elev1(iplt)*12.
          if(cue2.eq.YES.and.cue3.eq.0) elev2(iplt)=elev2(iplt)*12.
          if(cue3.eq.1) call axis(aascmx(iplt),aascmn(iplt),
     &        iplt,pr(iplt),8,'PROFILE - ENLARGED                ',
     &     elev1(iplt),elev2(iplt),1)
          if(cue3.eq.1) call axis(dmax(iplt),dmin(iplt),iplt,
     &     defdif(iplt),9,'DEFLECTIONS - ENLARGED             ',
     &     elev1(iplt),elev2(iplt),2)
          if(cue3.eq.1) go to 71
          dmax(iplt)=-1e36
          dmin(iplt)=1e36
          aascmx(iplt)=-1e36
          aascmn(iplt)=1e36
 71         do 3 ibbi=ist,32573
          if(ibbi.gt.iend) go to 44
          if(cue2.eq.NO) pltct(iplt)=pltct(iplt)+1.
          xn=(ab+bc)/bc
          call nedcal(a(i+2),b(i+1),c(i),dxx,ascl,dscl,afctra,
```

```
     &     afctrd,az,bz,cz,dz,na,nb,nc,nd,stda,stdb,stdc,stdd,
          if(az.lt.0.) go to 44
          call check(az,bz,cz,dz,na,nb,nc,nd,fa,fb,fc,fd)
          if(fa.eq.0.and.fb.eq.0.and.fc.eq.0) go to 32
           if(cue2.eq.NO) write(6,26) ibbi,fa,fb,fc,fd
 26      format(2x,i4,x,'reset',t100,4i3)
          if(cue2.eq.NO) write(5,101)ibbi,fa,fb,fc
 101      format(/,3x,'Bad data point at location ',i4,3x,4i2)
          ist=ibbi+1
          bb(2)=1.
          cc(1)=1.
          if(ist.gt.iend.and.i.gt.1) aaend(iplt)=aa(i+2)
         i=1
          if (ist.gt.iend) go to 46
          if(cue2.eq.YES.and.cue3.eq.1) key=1
          if(key.eq.1) go to 100
          go to 31
 32      continue
c the order the algorithm requires the data is   a b c      d.
c   a,b and c are the profilometer, and d is the deflection pt.
c  First, note that the gage spacing will affect
c      the algorithm. Gage spacing factor is xn.
c  Now to calculate the profile point.
          theta=atan((c(i)+cc(i)-b(i+1)-bb(i+1))/bc)
c          theta=0.
          aa(i+2)=c(i)*cos(theta)+cc(i)-a(i+2)*cos(theta)-xn*
     &      (c(i)*cos(theta)+cc(i)-b(i+1)*cos(theta)-bb(i+1))
         if(cue2.eq.NO.and.i.eq.1) aastrt(iplt)=aa(i+2)
          if(cue2.eq.YES) call scale(elev1(iplt),elev2(iplt),
     &     aastrt(iplt),aaend(iplt),pltct(iplt),aa(i+2),
     &     aascal(i+2),i)
        if(cue2.eq.YES.and.cue3.eq.0) aascmx(iplt)=amax1(aascmx(iplt),
     &   aascal(i+2))
        if(cue2.eq.YES.and.cue3.eq.0) aascmn(iplt)=amin1(aascmn(iplt),
     &   aascal(i+2))
 64     if(cue3.eq.1) call ppt(aascal(i+2),ibbi,aascmn(iplt),pr(iplt),
     &      8,1.)
 17       continue
          if(prcue.eq.YES.and.
     &    cue2.eq.NO) write(6,35) ibbi, aa(i+2),bb(i+1),cc(i),theta,
     &    stda,stdb,stdc,stdd,fa,fb,fc,fd
   35     format(2x,i4,x,3(f8.3,x),9x,9x,5(f8.3,x),t100,4i2)
c    reset
            cc(i+1)=bb(i+1)
            bb(i+2)=aa(i+2)
          if(ibbi.eq.iend.and.cue2.eq.NO) aaend(iplt)=aa(i+2)
            if(i.eq.7) go to 30
            i=i+1
   3      continue
c       *****************************************
c        now to do points 8 to infinity.......     and beyond !!.
c       *****************************************
   30     i=8
```

```fortran
ibbi=ibbi+1
iict=7
if(ibbi.gt.iend) go to 46
do 10 ii=ibbi,iend
iict=iict+1
if(cue2.eq.NO) pltct(iplt)=pltct(iplt)+1.
xn=(ab+bc)/bc
c     note that ii indicates where gage c is.
call redcal(a(i+2),b(i+1),c(i),d(i-7),ascl,dscl,afctra,
&     afctrd,az,bz,cz,dz,na,nb,nc,nd,stda,stdb,stdc,stdd,jj)
if(az.lt.0.) go to 46
call check(az,bz,cz,dz,na,nb,nc,nd,fa,fb,fc,fd)
if(fa.eq.0.and.fb.eq.0.and.fc.eq.0) go to 28
if(fa.eq.1.or.fb.eq.1.or.fc.eq.1) write(6,104) ii,fa,fb,fc,fd
if(fa.eq.1.or.fb.eq.1.or.fc.eq.1) go to 27
104   format(2x,i4,x,'reset2',t100,4i3)
c   Emergency reset (for bad data points
27    ist=ii+1
if(cue.eq.NO) aaend(iplt)=aa(i+2)
if(ist.gt.iend) go to 46
i=1
cc(i)=1.
bb(i+1)=1.
if(cue2.eq.YES.and.cue3.eq.1) key=1
if(key.eq.1) go to 102
go to 31
28    continue
theta=atan((c(i)+cc(i)-b(i+1)-bb(i+1))/bc)
c     theta=0.
aa(i+2)=c(i)*cos(theta)+cc(i)-a(i+2)*cos(theta)-xn*
&     (c(i)*cos(theta)+cc(i)-b(i+1)*cos(theta)-bb(i+1))
if(cue2.eq.YES) call scale(elev1(iplt),elev2(iplt),
&   aastrt(iplt),aaend(iplt),pltct(iplt),aa(i+2),
&   aascal(i+2),iict)
if(cue2.eq.NO.and.ii.eq.iend) aaend(iplt)=aa(i+2)
if(fa.eq.0.and.fb.eq.0.and.fc.eq.0.and.fd.eq.1) go to 84
29    dd(i-7)=c(i)*cos(theta)+cc(i)-d(i-7)*cos(theta)+(cd/bc)*

&      (c(i)*cos(theta)+cc(i)-b(i+1)*cos(theta)-bb(i+1))
defl(i-7)=cc(i-7)-dd(i-7)
deflct=deflct+1
sumdef=sumdef+defl(i-7)
ssdef=ssdef+(defl(i-7)**2)
84    if(cue2.eq.NO.and.ii.eq.iend) aaend(iplt)=aa(i+2)
18    continue
if(cue2.eq.YES) go to 13
if(fa.eq.0.and.fb.eq.0.and.fc.eq.0.and.fd.eq.1.
&   and.prcue.eq.YES)
&   write(6,36) ii,aa(i+2),bb(i+1),cc(i),dflt,dflt,theta,
&     stda,stdb,stdc,stdd,fa,fb,fc,fd
36    format(2x,i4,x,3(f8.3,x),2(4x,a5),5(f8.3,x),2x,4i2)
if(fa.eq.0.and.fb.eq.0.and.fc.eq.0.and.fd.eq.1)
&     go to 13
```

```
          if(cue2.eq.YES) go to 13
          if(prcue.eq.YES)
       &    write(6,16) ii,aa(i+2),bb(i+1),cc(i),dd(i-7),defl(i-7),
       &    theta,stda,stdb,stdc,stdd,fa,fb,fc,fd
  16       format(2x,i4,x,10(f8.3,x),t100,4i2)
  13       continue
          if(cue2.eq.NO.and.cue3.eq.0) go to 66
          if(cue2.eq.YES.and.cue3.eq.1) go to 66
          aascmn(iplt)=amin1(aascmn(iplt),aascal(i+2))
          aascmx(iplt)=amax1(aascmx(iplt),aascal(i+2))
          dmin(iplt)=amin1(dmin(iplt),defl(i-7))
          dmax(iplt)=amax1(dmax(iplt),defl(i-7))
 66      if(cue3.eq.1)call ppt(aascal(i+2),ii,aascmn(iplt),pr(iplt),8,
       &    1.)
          if(cue3.eq.1) call ppt(defl(i-7),ii,dmin(iplt),
       &    defdif(iplt),9,0.)
c   reset cc(1) - cc(8) for next iteration
            cc(1)=cc(2)
            cc(2)=cc(3)
            cc(3)=cc(4)
            cc(4)=cc(5)
            cc(5)=cc(6)
            cc(6)=cc(7)
            cc(7)=cc(8)
            cc(8)=bb(i+1)
            bb(i+1)=aa(i+2)
            if(ii.eq.iend) go to 46
  10        continue
 44       if(cue2.eq.NO) write(5,45)
          if(cue2.eq.NO) write(6,45)
 45       format(//,3x,'You ran out of points before 7 were read!!')
          go to 48
 46       if(cue2.eq.NO) write(5,47)
          if(cue2.eq.NO) write(6,47)
 47       format(//3x,'You ran out of data points. End of data set.')
 48       continue
          if(deflct.lt.1) go to 89
        stddef=sqrt((1./(deflct-1))*(ssdef-((sumdef**2)/(deflct))))
          avgdef=sumdef/deflct
 89       if(cue2.eq.NO) write(6,37) sumdef,deflct,avgdef,stddef
          if(cue2.eq.NO) write(5,37) sumdef,deflct,avgdef,stddef
 37       format(/,3x,'The sum of defl. is = ',g16.3,2x,'divided by',
       & 2x,i5,2x,'is = ',f10.3,2x,'  std. dev. of defl. = ',f10.3,/)
          jj=17
          if(cue2.eq.YES.and.cue3.eq.0) go to 87
          if(cue2.eq.YES.and cue3 eq 1) go to 74
          write(5,72)
 72       format(/,3x,'Do you want plots?  ',$)
          accept 73, cue2
 73       format(a1)
          if(cue2 eq YES and cue3 eq.0) go to 78
          if(cue2 eq NO) go to 75
 100      write(5,103)(i-1),aascal(i+2)
```

```
      go to 74
102   write(5,103) (ii-1),aascal(i+2)
103   format(//,3x,'**** You hit a bad data point while'
     & ' writing on the disc. The plot up to this point has been'
     & ,/,
     & ' saved. To get the rest of the plot, run CALC again'
     &  ' starting at the next point. The last point plotted'
     & ,/,' was ',i5,x,'The last scaled'
     &  ' elevation was ',f10.5,//)
74    write(6,88)
      write(5,88)
88    format(//,33x,' WHEW !!!!  Done with all those plots!   ')
      do 123 i=8,9
      call close(i)
123   continue
87    if(cue3.eq.1) go to 75
      cue3=1
      go to 85
75    call close(7)
c   bozo printer scheme (empty printer buffer)
62    i23=19
      write(6,59) i23
59    format(a1)
      i21=17
      write(6,59) i21
      stop
      end
C
      SUBROUTINE REDCAL(A,B,C,D,ASCL,DSCL,AFCTRA,AFCTRD,
     &     AZ,BZ,CZ,DZ,NA,NB,NC,ND,STDA,STDB,STDC,STDD,JJ)
C  READS DATA AND CALIBRATES IT. VALUE= (DIST. TO MEASURING
C   RANGE + REGRESSION EQ. )  + BEAM ALIGNMENT CONST.
      INTEGER TO
      CALL READC(AZ,BZ,CZ,DZ,NA,NB,NC,ND,STDA,STDB,STDC,STDD,
     &   ISS,IENND,JJ)
      IF(AZ.LT.0) GO TO 174
      CONST=.000032/.0254
      DX=DZ*CONST
      CX=CZ*CONST
      BX=BZ*CONST
      AX=AZ*CONST
C  FOR GAGE 203
      STDB=0.001261*STDB
      B=13.695-.001261*BZ
C  FOR GAGE 269
      STDC=0.001261*STDC
      C=13.652-0.001261*CZ
C  FOR GAGE 270
      STDA=STDA*0.001261
      A=13.935-0.001261*AZ - AFCTRA
C  FOR GAGE 271
      STDD=STDD*0.001261
      D=13.903-0.001261*DZ - AFCTRD
```

```
 174    RETURN
        END
C
C
        SUBROUTINE ADVNCE(RIST)
C  ADVANCES TO THE DESIRED STARTING POINT IN THE DATA SET
        IST=IFIX(RIST)
        IF(IST.EQ.1) GO TO 2
        DO 1 I=1,(IST-1)
        CALL READC(A,B,C,D,NA,NB,NC,ND,STDA,STDB STDC,STDD,ISS,
     &     IND,JJ)
 1      CONTINUE
 2      RETURN
        END
C
C
        SUBROUTINE CHECK(AZ,BZ,CZ,DZ,NA,NB,NC,ND,FA,FB,FC,FD)
C  CHECKS FOR INVALID DAT POINTS
        INTEGER FA,FB,FC,FD
        FA=0
        FB=0
        FC=0
        FD=0
        IF(AZ.EQ.0.OR.NA.LT.30) FA=1
        IF(BZ.EQ.0.OR.NB.LT.30) FB=1
        IF(CZ.EQ.0.OR.NC.LT.30) FC=1
        IF(DZ.EQ.0.OR.ND.LT.30) FD=1
        RETURN
        END
C
C       SUBROUTINE READC(A,B,C,D,NA,NB,NC,NC,SD1,SD2,SD3,SD4,IS,
C                                IE,I)
C
C                A,B,C,D = LASERS A,B,C,D
C                NA,NB,NC,ND = NO.  OF SAMPLES
C                SD1,SD2,SD3,SD4 = STANDARD DEVIATIONS
C                IS = TIME TICKS READ BEFORE CLASS
C                IE = TIME TICKS READ AFTER CLASS
        SUBROUTINE READC(A,B,C,D,NA,NB,NC,ND,SD1,SD2,SD3,SD4,
     & ISTART,IEND,I)
        BYTE NAME(20),ZZZ
        COMMON /RMECOM/IBUF(16,512)
        DATA IOPEN/0/
        DATA LR/-1/
C
        IF(IOPEN.EQ.1) GO TO 1
        IOPEN=1
        WRITE(5,2)
 2      FORMAT(/,3X,'RAW DATA FILE NAME ...   ',$)
        ACCEPT 5,NOC,(NAME(IZZ),IZZ=1,NOC)
        NAME(NOC+1)=0
 5      FORMAT(Q,20A1)
        CALL ASSIGN(7,NAME,NOC,'OLD')
```

```
      DEFINE FILE 7 (1000,8192,U,IV)
      WRITE(6,4) (NAME(ITT),ITT=1,NOC)
 4    FORMAT(/,3X,'DATA FILE NAME:  ',80A1)
      WRITE(5,3)
 3    FORMAT(/,3X,'ROARRRRR!!!  CHOMP CHOMP CHOMP')
      I=17
1     IR=((I-1)/512)+1
      IF(IR.EQ.LR) GO TO 30
      READ(7'IR,END=1717) ((IBUF(MZ,LZ),MZ=1,16),LZ=1,512)
      LR=IR
30    INDX=MOD(I,512)
      IF(INDX.EQ.0) INDX=512
      A=IBUF(1,INDX)
      B=IBUF(2,INDX)
      C=IBUF(3,INDX)
      D=IBUF(4,INDX)
      NA=IBUF(5,INDX)
      NB=IBUF(6,INDX)
      NC=IBUF(7,INDX)
      ND=IBUF(8,INDX)
      SD1=IBUF(9,INDX)
      SD2=IBUF(10,INDX)
      SD3=IBUF(11,INDX)
      SD4=IBUF(12,INDX)
      ISTART=IBUF(13,INDX)
      IEND=IBUF(14,INDX)
      I=I+1
      IF(A.NE.-1) RETURN
 1717 A=-1.
      RETURN
      END
C
C
C HERE ARE THE PLOT ROUTINES
C
      SUBROUTINE AXIS(PMAX,PMIN,IPLT,PR,IU,ID,ELEV1,ELEV2,IX)
      BYTE ID(1)
      EELEV1=ELEV1/12.
      EELEV2=ELEV2/12.
      RANGE=PMAX-PMIN
      PR=1.
      IF(RANGE.GT..005) PR=.01
      IF(RANGE.GT..01) PR=.02
      IF(RANGE.GT..02) PR=.05
      IF(RANGE.GT..05) PR=.1
      IF(RANGE.GT..1) PR=.5
      IF(RANGE.GT..5) PR=1.
      IF(RANGE.GT.1) PR=2.
      IF(RANGE.GT.2) PR=5.
      IF(RANGE.GT.5) PR=10.
      IF(RANGE.GT.10) PR=50.
      IF(RANGE.GT.50) PR=100.
      IF(RANGE.GT.100) PR=250
```

```
      IF(RANGE.GT.250) PR=500.
      IF(RANGE.GT.500) PR=700.
      IF(RANGE.GT.700) PR=1000.
      IF(RANGE.GT.1000) PR=1500.
      IF(RANGE.GT.1500) PR=2000.
      IF(RANGE.GT.2000) PR=2500.
      PPMIN=PMIN/12.
      PPR=PR/12.
     IF(IX.EQ.1)WRITE(8,1)(ID(IY),IY=1,25),IPLT,EELEV1,
   &  EELEV2,PPR,PPMIN,(PPR+PPMIN)
 1    FORMAT(1H1,///,60X,25A1,3X,'#',I4,/,
   & 5X,'START ELEV.  = ',F10.3,' FT.',/,5X,'END ELEV.    = ',
   &  F10.3,' FT.',
   &   70X,'RANGE = ',F8.3,X,'FT.',//,
   &   13X,' MIN.  ',F8.3,83X,' MAX.  ',F8.3,//)
    IF(IX.EQ.2)WRITE(9,4)(ID(IY),IY=1,25),IPLT,PR,PMIN,(PR+PMIN)
 4    FORMAT(1H1,///,60X,25A1,3X,'#',I4,/,T102,'RANGE = ',
   &  F8.3,X,'IN.',//,14X,'MIN.  ',F8.3,' IN.',
   &  78X,'MAX.  ',F8.3,X,'IN.',//)
      WRITE(IU,3)
 3   FORMAT(8X,'VALUE',8X,'DIST.',/,
   &   4X,'IN.',7X,'FT.',T23,'FT.',
   &   T27,'!',10(9X,'!'))
      WRITE(IU,2)
 2    FORMAT(T27,10('0123456789'),'0')
      RETURN
      END
C
      SUBROUTINE PPT(C,II,XMIN,PR,IU,X)
      BYTE PCHAR(100),STAR,PD,PP,PLOT
      DATA STAR/1H*/
      FACTOR=100./PR
      C12=C/12.
      CC=C-XMIN
      NUM=FACTOR*CC+1
      IF(NUM.GT.100) NUM=100
      IF(NUM.LT.1) NUM=1
      DO 1 M=1,100
 1    PCHAR(M)=STAR
       WRITE(IU,2) C,C12,II,(PCHAR(N),N=1,NUM)
 2    FORMAT(X,2(F9.3,X),I4,'#',102A1)
      RETURN
      END
C  THIS IS THE SCALE ROUTINE (SCALES
C     THE AA'S TO USER INPUT ENDPOINTS)
      SUBROUTINE SCALE(ELEV1,ELEV2,AASTRT,AAEND,PLTCT,AA,
   &   SCALAA,N)
      FN=FLOAT(N)
    SCALAA=AA+(FN-1.)*(((ELEV2-AAEND)-(ELEV1-AASTRT))/(PLTCT-1.))
   &     +(ELEV1-AASTRT)
      RETURN
      END
```

Program ADJUST, used to adjust the endpoints of the profile.

```
35736,ouh.
pfiles(get,hngrsur)
pfiles(get,hngr02c)
mnf(t)
pfiles(put,compare)
#eor
        program adjust(input,output,hngrsur,hngr02c,compare,
     &   tape5=input,tape6=output,tape7=hngrsur,tape8=hngr02c,
     &   tape9=compare)
        real las(600),laser,lasstrt,newsur(600),lasend,lasct,
     &    newl(600)
c
c converts the laser file to feet, and adjusts both to 70'
c   endpoints
c
        elev1=70.
        elev2=70.
        is=0
        il=0
c survey endpts
        do 1 ii=1,2222
        is=is+1
        survey=zsurvey
        read(7,33,end=3) i ,  zsurvey
33       format(i5,f10.5)
        if(ii.eq.1) surst=zsurvey
2       format(i5,g20.5)
 1      continue
 3      surend=survey
c laser endpoints
        do 4 iii=1,2222
        il=il+1
        laser=zlaser
        read(8,2, end=5) i,zlaser
        if(iii.eq.1) lasstrt=zlaser
 4      continue
 5      continue
        lasend=laser
        rewind 7
        rewind 8
c adjust and store
        lasct=float(il-1)
        surct=float(is-1)
        llasct=ifix(lasct)
        isurct=ifix(surct)
        do 6 i=1,llasct
        read(8,2,end=7) ii,laser
        laser=laser/12.
        x1=elev1-(lasstrt/12.)
        x2=elev2-(lasend/12.)
```

```
      grad=(x2-x1)/(lasct-1.)
      newl(i)=laser+grad*(i-1) + x1
 6    continue
 7    do 8 i=1,isurct
      read(7,2,end=9) iii,survey
      x1=elev1-surst
      x2=elev2-surend
      grad=(x2-x1)/(surct-1.)
      newsur(i)=survey+grad*(i-1) + x1
 8    continue
 9    continue
      write(6,12) lasstrt,lasend,surst,surend,isurct,llasct
 12   format(//,5x,'starts end= ',4(f10.5,x),x,2i10)
      max=max0(isurct,llasct)
      do 10 iz=1,max
      dif=newsur(iz)-newl(iz)
      write(6,11) iz,newsur(iz),newl(iz),dif
      write(9,11) iz,newsur(iz),newl(iz),dif
 11   format(i5,3(f10.5,x))
 10   continue
      stop
      end
#eor
```

APPENDIX D

System Usage

1. Technical

This section explains briefly how to set up and how to use the system.

The following steps describe how to set up the system -

1. Mount the laser gages in the rigid beam so that all the laser beams lie in a plane, and are parallel,
2. attach the rigid beam to the load vehicle with the spring loaded supports,
3. attach the fifth wheel to the load vehicle,
4. make all electrical connections, and
4. drive over the test pavement.

Better equipment operation will result if -

1. "The operator reads all the manuals on all parts of the equipment, and observes the manufacturers directions",

2. the disk drive is not subjected to shock loads (this may cause the format to change, making all previously made disks unreadable), and

3. the equipment is at a steady state temperature before operation.

2. Philosophical

This system was intended to measure longitudinal profile, deflection at a point, and texture. If the rigid beam was removed from the load vehicle and cantilevered normal to the direction of travel, a definition of the lateral deflection basin can be obtained when the load vehicle is driven past the beam.

If the system is run laterally across a pavement, the profile will reflect the rut depth.

APPENDIX E

Gage Alignment Scheme

In order for the algorithm described in Section III, B, 1 to work, one of the following must hold -

1. The gages must not move relative to one another, and their relative positions must be known, or

2. the gages can move relative to one another, and the movement is known.

The first condition was used in this study. The following scheme was used to get the relative positions of the gages.

Referring to Figure III-1, let "i" be one step in the direction of motion. Note that -

$$AA_i = BB_{i+1} = CC_{i+2} \tag{1}$$

Also note

$$\Sigma_{i=1}^{n-2} AA_i = \Sigma_{i=2}^{n-1} BB_i = \Sigma_{i=3}^{n} CC_i \tag{2}$$

For large numbers of readings (large n), equation (2) can be approximated by

$$\Sigma_{i=1}^{n} AA_i = \Sigma_{i=1}^{n} BB_i = \Sigma_{i=1}^{n} CC_i \tag{3}$$

If n is not large enough, an error may result. This is examined later.

Note that, at any time, the endpoints of A + AA, B + BB, and C + CC define two straight lines (the datum and the rigid beam). Therefore, the endpoints of

$$\Sigma_{i=1}^{n} (A_i + AA_i) \text{ , } \Sigma_{i=1}^{n} (B_i + BB_i) \text{ and } \Sigma_{i=1}^{n} (C_i + CC_i) \tag{4}$$

also form two straight lines.

Because of (3), it follows that

$$\Sigma_{i=1}^{n} (A_i + AA_i) - \Sigma_{i=1}^{n} (AA_i) \tag{5}$$

$$\Sigma_{i=1}^{n} (B_i + BB_i) - \Sigma_{i=1}^{n} (BB_i) \tag{6}$$

$$\Sigma_{i=1}^{n} (C_i + CC_i) - \Sigma_{i=1}^{n} (CC_i) \tag{7}$$

form a straight line.

Rewriting (4), (5), and (6) and dividing by n gives

$$\frac{\Sigma_{i=1}^{n} A_i}{n}, \quad \frac{\Sigma_{i=1}^{n} B_i}{n}, \quad \frac{\Sigma_{i=1}^{n} C_i}{n}, \tag{8}$$

whose endpoints also form straight lines.

When a test is run, the beam alignment constant can be determined if the averages at (8) are known.

The endpoints of the averages should represent two straight lines. If they do not, the difference between one average and the straight lines formed by the other averages is the amount that that gage is out of line with the other two gages. That difference (the out-of-line constant) should be added to the calibration equation for that gage (the effect is to remove a constant offset from that gage).

This method can be extended to the D gage, if the pavement is not deflected. In the testing program, a lightweight tricycle was used for this purpose. It carried the beam without significantly loading the pavement. The tricycle was pulled by hand.

The out-of-line constants are determined automatically by the computer program CALC.

As mentioned previously, equation (3) is not strictly correct. While equation (3) is true for large n, it is rendered invalid by special conditions at the start and end of the test. An examination of Figure III-1 shows that A is never where C is at the start. Neither is C ever where A is at the end. Thus, a more proper representation of equation (3) is

$$\Sigma_{i=1}^{n-2} AA_i = \Sigma_{i=2}^{n-1} BB_i = \Sigma_{i=3}^{n} CC_i \qquad (2)$$

This leaves the beginning and ending terms out. Those terms are

$$CC_1 , CC_2 , BB_1 , BB_n , AA_{n-1} , \text{and } AA_n \qquad (9)$$

If the out-of-line constant is calculated using equation (2) instead of equation (3), no error is introduced. The error introduced by using equation (2) is

$$\text{error} = \frac{1}{n} (2B9 - A9 - C9) \qquad (10)$$

where

error = error in the gage A out-of-line constant

$A9 = AA_{n-1} + AA_n$

$B9 = BB_1 + BB_n$

$$C9 = CC_1 + CC_2$$

n = number of iterations

If the sum of the AA terms (A9) equals the sum of the BB terms (B9), and either equal the sum of the CC terms (C9), no error occurs in the calculation of the out-of-line constant.. If one of the sums just mentioned is different from the other two, an error will occur. This error is a function of how great the difference is, and how large n is. If the difference(s) is small, and n is large, the error will be small.

APPENDIX F

List of Equipment Suppliers

The following firms either manufactured or supplied equipment for this research. Only major equipment is listed.

1. The computer. The computer was purchased from Heath Corporation, Benton Harbor, Michigan. All the peripherals, except the bus extender, were also purchased from Heath.

2. The bus extender. The bus extender, manufactured by Digital Equipment Corporation (Maynard, Massachusetts), was purchased from Hamilton-Avnet (Culver City, California).

3. The laser gages. The laser gages, called Optocators, were manufactured and sold by Selective Electronic, Valdese, North Carolina.

4. The fifth wheel. The fifth wheel was manufactured and sold by Labeco, Mooresville, Indiana.

The following equipment appeared in the section VI, Suggestions for Further Research.

1. A printer-plotter. The Printronix printer-plotter is manufactured and sold by Printronix, Irvine, California.

2. Sonic gages. The Polaroid sonic gages are manufactured and sold by Polaroid Corporation, Cambridge, Massachusetts.

APPENDIX G

Data File Previewer

This appendix describes what the data file previewing program LIST does, and why it is useful to use it.

LIST converts the raw binary data to ASCII format data. At the users request, it will list the data on either the terminal, the printer or the disc.

The raw data consists of five parts -

1. The station number, in feet,

2. the average of the n readings taken by each gage over the four inch distance,

3. the number of readings, n, taken in by each gage over the four inch distance,

4. the standard deviation of the n readings for each gage, and

5. the time the readings started and ended, accurate to one-sixtieth of a second.

The advantage of looking at the raw data before calibrating and reducing it with CALC, is that it can be done quickly. The operator can tell almost immediately if the pavement needs to be tested again. By examining the uncalibrated readings, the operator can see where the gages were out of range for the entire four inches (the averages are zero). If there are too many of these, the operator may wish to run the test again. Zeroes may indicate areas that require closer examination (potholes, etc.).

The number of readings is useful. If the number of readings is small, it could mean that a pothole was driven over. If the number of readings is different for each gage, and the average readings are similiar, it means that the pavement has small "holes" in it, where drop-out readings occur. Porous friction surface pavements display this behavior.

If the averages, the numbers of readings, and standard deviations all compare well with their respective counterparts, the pavement is a typical one - realtively flat, with no "holes".

This system has no outward indicators that it is working properly. By using LIST, the operator can find out quickly if the system has failed.

Table IV-1 is some raw data from a porous friction surface

D

FI

6-