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16. Abstract

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A SELF CALIBRATING ROUGHNESS MEASURING PROCESS

By

Roger S. Walker

RESEARCH REPORT 279-1

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Research Report Number 279-1

Development and Evaluation of a Low Cost
Profilometer and Roughness Measuring Unit

Study No. 3-10-80-279

conducted for

The Texas Department of Highways and Public Transportation

in cooperation with the
U. S. Department of Transportation
Federal Highway Administration

August 1982

The contents of this report reflect the views of the author, who is responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Federal Highway Administration. This report does not constitute a standard, specification, or regulation.

PREFACE

This project report presents results of Research Project 3-10-80-279, "Development and Evaluation of a Low Cost Profilometer and Roughness Measuring Unit." A new method for predicting road profile from simple accelerometer measurements was developed by the author. This project was initiated to investigate the usefulness of the method for obtaining roughness measurements. Two roughness measuring units which implement the method were developed and evaluated in this project.

The assistance of John Nixon, Ken Hankins, and Curtis Goss of the Department of Highways and Public Transportation is especially appreciated. The assistance of project personnel Larry Oliver should also be acknowledged.

Roger S. Walker

August 1982

ABSTRACT

This report describes a new method to obtain road profile estimates and the use of these estimates for obtaining serviceability index measurements. Two units were constructed implementing this method. The method takes into account the characteristics of the vehicle in which the measuring unit is installed. The units are in field test by the Department of Highways and Public Transportation. Initial evaluation of the method and data from the units are discussed.

KEY WORDS: SIometer, Surface Dynamics Profilometer, Mays Ride Meter, serviceability index, autoregressive process, road roughness, road profile.

SUMMARY

For many years engineers have been interested in instruments for measuring road roughness. As the many miles of interstate and other highways begin to deteriorate, this interest has increased. A new method for obtaining road profile estimates was developed by Roger S. Walker. This method is easily implemented with an accelerometer and a microcomputer that can be mounted in most vehicles. The method identifies the characteristics of the vehicle in which the accelerometer is installed from the vertical acceleration measurements, and then corrects for these characteristics to yield an estimate of road profile. From this profile a roughness statistic is computed, related to serviceability index, and then displayed. The process and an evaluation of the process is discussed in the report.

IMPLEMENTATION STATEMENT

A new process for measuring pavement roughness yielding serviceability index directly has been developed. Two roughness measuring units implementing this process were built and are in use in field tests by the Department of Highways and Public Transportation. The units identify and account for the characteristics of a particular vehicle class, thereby minimizing the extensive calibration procedures required by the Mays Ride Meter.

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CHAPTER 1. INTRODUCTION

For a number of years engineers have been interested in instruments that can provide objective roughness measurements of highway pavements. As the many miles of interstate and other highways begin to deteriorate, this interest has increased. Such instruments are needed by highway engineers and other maintenance personnel to aid in determining when to perform various maintenance policies.

Roughness Measuring Units

A number of various roughness measuring devices have been developed and marketed; however, each usually has some undesirable characteristics. At one end of the spectrum of roughness-measuring instruments is the Mays Ride Meter (MRM). The MRM has been found to be a simple, inexpensive but very effective instrument for measuring ride quality and thus, indirectly, road roughness. However, MRM measurements are dependent upon all factors which affect the mass and suspension system of the vehicle used with the MRM. For instance, tire pressure, the weight of the vehicle's passengers and/or equipment, etc., can all affect the roughness measurements. The suspension system of similar vehicles can result in different roughness measurements with the MRM. To minimize these effects, MRM devices are often installed in specially constructed trailers and towed over the roads to be measured. The trailers are designed to be as similar to one another as possible. Calibration and various control procedures are then developed and used for maintaining accurate measurements.

At the other end of the spectrum of roughness measuring instruments is the Surface Dynamics Profilometer (SDP). This device provides fairly accurate measurements of highway profile from which roughness statistics can be computed. The SDP, however, is not without its faults. The device is very expensive to purchase and to operate. Few state highway departments, for instance, have purchased such a device even though roughness measurements are usually desired by these agencies. Although the SDP seems to provide accurate profile measurements, experiments to compare repeatability between two or more SDP's are not frequently conducted. The high cost of this instrument makes such tests difficult. Some type of standard unit, however, is needed for calibrating the other less expensive devices, and the SDP has been used in some cases for this function.

The Texas State Department of Highways and Public Transportation has been using calibration and control procedures for the MRM using roughness measurements obtained from the SDP as the calibration standard. For the calibration process, a set of roads or sections of varying roughness are measured by the MRM. The profile of the same sections is then measured by the SDP. From the measured profile a serviceability index (SI) is computed, providing a single quantitative roughness number for each section. The MRM roughness numbers are then regressed on the SI obtained via the SDP correlating the MRM and SDP. A set of tables is derived in the process, and with these tables MRM measurements are correlated to a predicted SDP SI measurement. Standard statistical control procedures are used to ensure the continued calibration of the MRM to the SDP. The MRM is periodically recalibrated as necessary. Although this method has been satisfactory, it is expensive, time consuming, and not without problems.

A New Measurement Process

This report is concerned with describing another process for measuring road or pavement roughness. Two prototype units for the Department of Highways and Public Transportation were constructed which use this method. The investigation of these units for roughness measurements is discussed. This new method was developed by Roger S. Walker. It was then investigated by simulating a vehicle's response (quarter car) to various profile inputs. The profile used was from random data and actual values obtained from the SDP. The vehicle's response was next used in the measurement process to predict the original profile inputs. The resulting predicted profile compared favorably to both the simulated and actual profile.

The process is described in detail in the next chapter. Briefly, however, the process involves the use of three principal components: an accelerometer, a micro or mini computer and recording units, and a program that implements the process. The process involves mounting the accelerometer vertically in a vehicle or in a trailer towed by a vehicle. Vertical acceleration in conjunction with vehicle speed inputs is then used to predict road profile. The micro or mini computer performs the prediction computations. The computations directly provide an estimate of the profile with the vehicle suspension system's characteristics removed.

In order to remove vehicle characteristics, a dynamic calibration procedure is initially performed. This procedure involves obtaining acceleration measurements for the "typical" class of road to be measured. The micro or mini computer then performs computations that provide a statistical identification of the vehicle's suspension system characteristics. The effects of the vehicle's suspension system characteristics on various road profile frequency components are thus identified and used to obtain an autoregressive model of the vehicle. The calibration procedures involve determining what the coefficients are in this autoregressive process. Once these coefficients have been obtained, the measurement process involves discarding the predictable components or the components due to the vehicle's suspension characteristics resulting in an estimate of road profile.

The process will be described in detail in Chapter 2. Chapter 3 describes an evaluation of the method using the prototype units constructed for the Department of Highways and Public Transportation. Field tests seem to indicate that the self calibrating process can account for vehicle characteristics of similar vehicle classes, e.g., small cars, large cars, etc.

CHAPTER 2. THEORY OF OPERATION

Introduction

The process used for measuring road or pavement roughness involves essentially three procedures. First, the predominant frequencies of the vehicle's suspension system characteristics are identified during a dynamic calibration process. Next, a prediction of the road or pavement profile is obtained with these characteristics removed. Finally, a road roughness statistic is computed and used to correlate this statistic to a pavement servicability index. Three primary components are required for the measuring process - an accelerometer, a computer and recording equipment, and the program for implementing the process. The accelerometer is mounted vertically in a vehicle or in a trailer towed by a vehicle. Vertical accelerations in conjunction with vehicle speed inputs are then used to predict road profile.

A micro or mini computer performs the prediction computations. In addition, these computations also directly provide acceleration, slope, and profile variance with the vehicle suspension system's characteristics removed. To remove these characteristics, a calibration procedure is first performed. This procedure involves obtaining acceleration measurements for the "typical" class of road to be measured. The micro or mini computer then performs computations that provide an identification of the vehicle's suspension system characteristics. That is, the effects of the vehicle's suspension system characteristics from various road profile frequency components are identified. When these characteristics are identified, the vehicle can be modeled as an autoregressive process. The calibration procedures involve determining what the coefficients are in this process. Once these coefficients have been obtained, the predictable components or the components due to the vehicle's suspension characteristics can be discarded, resulting in an estimate of the true profile.

This autoregressive process is mathematically described in equation (2.1) below.

$$A(t) = \sum_{i=1}^{m} A(t-i)\theta_i + E(t) \qquad (2.1)$$

Where:

$A(t)$ is the measured acceleration at the t^{th} instant of time

θ_i, $i = 1, m$ are the autoregressive coefficients

Thus:

$$P(t) = \iint E(t) = \iint [A(t) - \sum_{i=1}^{m} \theta_i A(t-i)] \qquad (2.2)$$

The random term E is the acceleration after the vehicle's system characteristics have been removed. The estimate of road profile, P(t) is then obtained by the double integration of this term.

Since the predicted road profile provides a rather large set of profile estimates (depending on the sampling rate), a single statistic is often desired to estimate pavement roughness. Much research has occurred trying to determine one or more such statistics. For this project the variance of the profile and its first and second derivations were all examined. Each of these statistics was then compared with different road-roughness classes. The variance of the first derivative of the road profile estimates was found to provide the best of the three for distinguishing between road roughness classes. One other statistic not tried but that could possibly also work well is the third derivative of the profile. This statistic is usually referred to as "jerk," or the change in vertical acceleration, and has been investigated by groups interested in rail roughness.

The first derivative of the pavement profile is closely related to the slope variance statistic. Slope variance has been found closely correlated to road roughness (Ref. 1).

The Texas State Department of Highways and Public Transportation has been using servicability index (SI) as measured by the Surface Dynamics Profilometer (SDP - see Ref. 2) as the principal roughness statistic. This number is obtained by a mathematical model that relates the power in road profile frequency components to rider ratings. The following equation was found to correlate the variance of the first derivative of the estimated road profile to SI as predicted by the SDP.

$$SI = 5e^{-(\alpha V[P'])^{\beta}} \qquad (2.3)$$

Where:

α, β = regression coefficients

SI = servicability index predicted by the SDP or PSR (Ref. 2)

$V[P']$ = the variance, $V[\,]$ of the first derivative of the profile, P

The α and β regression coefficients are obtained by making measurements with the SIometer (the name given to the instrument which implements this new process), obtaining the variance of the first derivative of the road profile estimates. These values are than used in conjunction with the SDP SI readings in a first order linear regression. A log transformation is used to obtain the linear relationship. Additionally, a digital high pass filter is used to filter out the long wave lengths associated with hills, etc.

The Measuring Process

In this section the mathematics involved in the roughness measurement process is described. This unique method uses an autoregressive (AR) process for describing the vehicle characteristics. A dynamic self-calibration procedure is used to identify the parameters of the autoregressive process.

The acceleration values sampled at equal distance intervals constitute a time series or collection of observations taken sequentially in time. Since the sequence of observations is taken only at selected distance intervals, the time series is said to be discrete even though the actual acceleration values constitute a continuous time series process.

The acceleration value at the t^{th} instant of time will be represented by the variable $A(t)$. The collection of acceleration values will be denoted as the process

$$\{A(t)\ ;\ t \varepsilon T\},$$

and is said to be an autoregressive process (discrete) of order m if

$$A(t) = \sum_{i=1}^{m} \theta_i A(t-i) + E(t). \qquad (2.4)$$

The process E(t) consists of a sequence of uncorrelated random variables (a white noise process) and may be regarded as a "series of shocks" that drive the system (See Ref. 3). We will assume that the process A(t) will be stationary and have a mean, μ, of zero.

To estimate the parameters of a linear autoregressive process from a set of observed samples, A(t), two procedures are required. First, we must decide the order, m, of the process and then, once m is determined, estimate the parameter θ_i (Ref. 4).

Although there are a number of considerations to be given in solving for the parameter $\hat{\theta}_i$ or θ_i estimates, and which are discussed in Ref.'s 3 and 4, we will use the maximum likelihood procedure for such estimates. From Ref. 4 it is shown that the maximum likelihood estimate (mle) equations may be approximated by

$$C_{xx}(i) = \hat{\theta}_1 C_{xx}(i-1) + \hat{\theta}_2 C_{xx}(i-2) + \ldots + \hat{\theta}_m C_{xx}(i-m) \qquad (2.5)$$

Where $i = 1, \ldots m$

C_{xx} = the autocovariance function

Additionally, the residual sum of squares may be approximated as

$$S(\hat{\theta}_1, \ldots \hat{\theta}_m) = (N-m) \{C_{xx}(0) - \hat{\theta}_1 C_{xx}(1) - \ldots - \hat{\theta}_m C_{xx}(m)\} \qquad (2.6)$$

Since $\hat{\theta}_i$ estimates can be obtained from (2.5) we must now determine the order m of the process. From (2.6) an approximate estimate of the residual variance may be obtained as

$$S_z^2(m) = \frac{1}{N - 2m - 1} S(\hat{\theta}_1, \ldots \hat{\theta}_m) \qquad (2.7)$$

One simple method suggested in Ref. (4) to determine the order would be to examine the residual variance of the AR model. This estimate should be inflated by those terms not yet added. This method indicates that the correct number should exist by finding the minimum points of the variance function with respect to m or solving for values of m for which

$$\frac{\partial S\ (m)}{\partial m} = 0 \qquad (2.8)$$

From (2.8) we find that a necessary condition for the appropriate number of terms m would be when

$$C_{xx}(0) - \hat{\theta}_1 C_{xx}(1) - \ldots - \hat{\theta}_m C_{xx}(m) = 0 \qquad (2.9)$$

This same result was validated in a somewhat different fashion in Ref. (5). The sufficient condition for the appropriate number of terms is more difficult to establish. As it turns out, it has been observed that equation (2.9) is satisfied a number of times as m increases and at periods corresponding to multiples of the half wave length of the predominant frequencies of the linear process which is being modeled. Additional methods for order determination are described in Ref. 6.

The References 3 and 4 as well as numerous other publications on AR processes should be consulted for more detailed discussions and characteristics of AR processes. Next, we will review some important constraints regarding the modeling process we are assuming for the vehicle model and profile.

<u>Model Assumptions</u>

The AR process we are using to model a vehicle has specific requirements. We must assume (1) that the vehicle system is linear, (2) that the second derivative of the road profile is random and uncorrelated, and (3) in the process of determining the order, m, of the AR process, that a sufficient condition has occurred. Each of these constaints will be separately considered.

The vehicle is not linear; however, vehicles are often modeled as a linear system for a specific operating range. The more non-linear the vehicle, obviously the more biased the estimates become.

The road profile is correlated. The smaller the wave lengths considered, generally the more uncorrelated the profile becomes. Pavement texture, for instance, is often treated as being uncorrelated. Some have suggested that the first derivative might not be as correlated. This is evidenced from attempts to model runway elevation profiles and some types of highway profiles for selected frequency ranges with linear relationships of power and the various frequency components. If this could be modeled as a linear function, then the first derivative of power spectrum functions would be a constant for a specific range, thus indicating uncorrelated noise.

The first derivative almost being random doesn't suggest that the second is more so. Both assumptions, a linear system and uncorrelated random second derivatives of road profile data, are obviously violated. However, it has been found in this research effort that such violations are for the most part small compared to overall errors for the measurement process. There are obviously cases where some violations can cause problems.

The last assumption concerns determining the order of the process. As noted Eq.(2.9) has been found to be true for many values of m. When modeling the vehicle we have found that there are two predominant wave lengths associated with the suspension system (about one hertz) and the wheel (about 10 hertz). Furthermore, power spectral studies have revealed that the most predominant frequencies are those associated with the wheel (Ref. 7). Since, as noted earlier, Eq.(2.9) will be true for half wave multiples of these frequencies, it would seem appropriate to select a point containing at least one full multiple of the most predominant wave length.

In the course of this research effort, as will be discussed later, it was found that vehicles with similar suspension system characteristics could be distinguished by using only enough terms to satisfy Eq. (2.9) and still contain a full multiple of the tire wavelength.

Thus, to summarize, all of the above conditions are somewhat violated. The question becomes how much. From results obtained during this research effort and from further tests conducted by the Department of Highways and Public Transportation, the measurement method and vehicle identification procedure appear to work well for similar vehicle classes. For dissimilar classes the order m should probably be increased to include more of the 1 hz vehicle body frequency.

The Roughness Measuring Units

During the project two separate roughness measuring units (referred to as SIometers) were developed. Unit I was the first unit constructed and has features for firmware and equipment debugging and parameter variations.

The second device, Unit II, has no debugging features and has a fixed set of parameters. Unit II was designed for a specific operation and thus is much easier to operate than Unit I.

The Unit I device has three primary modules, the accelerometer module, the computer module, and the control module. The primary functions are depicted in Fig. 2-1. The accelerometer module (Fig. 2-2) contains three components: an accelerometer, low pass filter, and a DC-DC converter. The Servo Accelerometer (Columbia Research Laboratories, Inc., Model SA-107-R Range ± 2G), is used to obtain vertical accelerations. The signal from the accelerometer is sent back to the computer module where it is digitized and then processed. An active low pass filter (programmable -.5 to 512 hertz) is used to ensure the sampling theorem is not violated. The DC-DC converter provides the proper voltage level to the accelerometer. The accelerometer module is housed in a small case which is weighted down so that it can be placed in the trunk of the vehicle used for measurements. Because of its design (See Fig. 2-2) it can be quickly placed in position and does not have to be physically attached or restrained to the trunk when measuring in most conventional vehicle types.

The computer module (Fig. 2-3) performs all measurement computations and controls the general operations of the unit. It contains three primary components: an Intel SBC 8030 board, an accessory board, and the power circuitry. The Intel SBC 8030 board contains an Intel 8085 microprocessor, 16K bytes of volatile semiconductor random access memory (RAM), 4K bytes of semiconductor program or read only memory (ROM), input/output (I/O) and other supporting circuits. The accessory board is a specially designed component that contains a 12 bit analog-to-digital converter, a fast math IC (AMD 9511) and supporting circuitry. The A-D converter samples the accelerometer readings at equal distance intervals (as directed from the CPU). The fast math IC performs all floating point and other mathematical operations. The power supply component converts the 12-15 volt supplied by the battery in the vehicle to 5 volts and isolated ± 12 volt supplies as required by the electrical components.

The console module (Fig. 2-4) is used by the operator for entering the various system parameters and for directing the measuring process. This

FIG. 2-1

SIometer Components

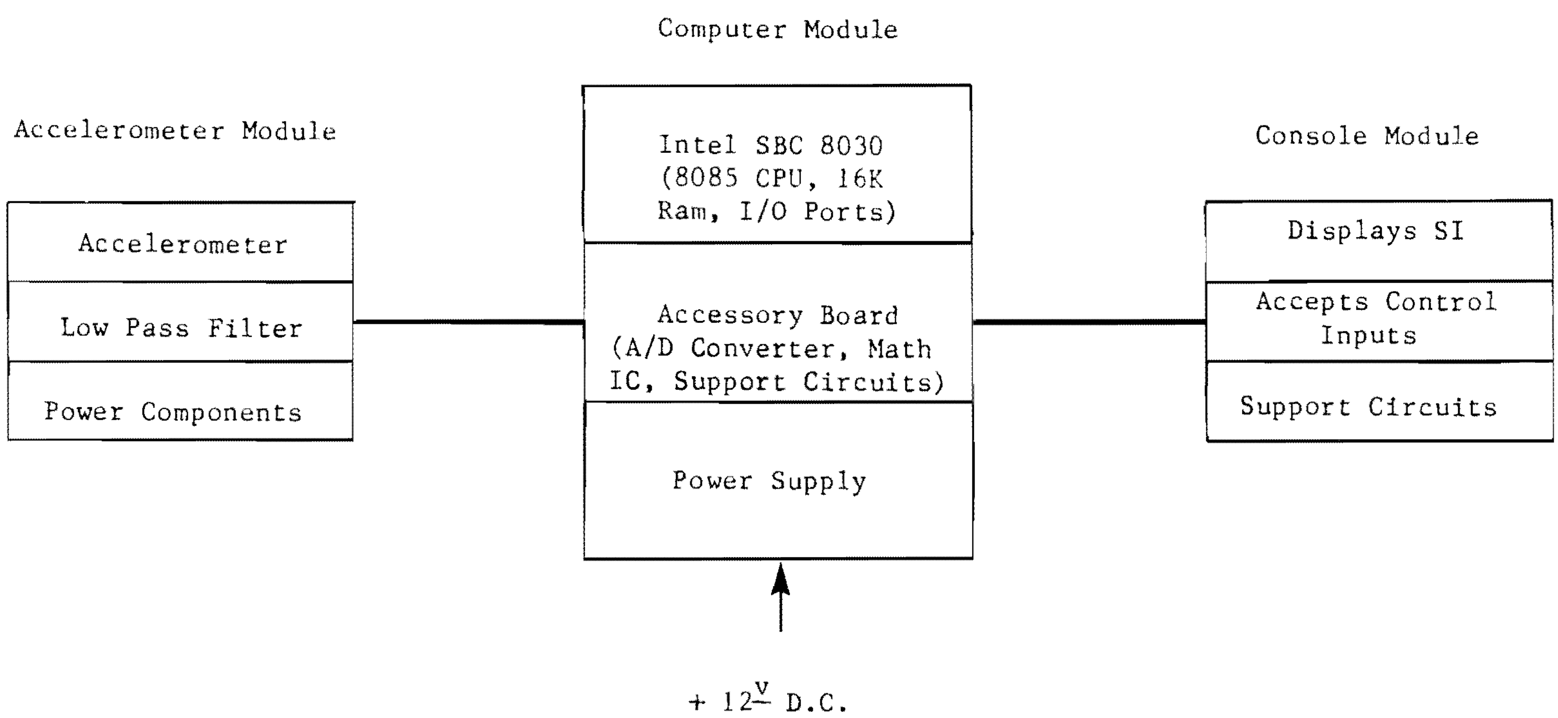

Fig. 2-2

ACCELEROMETER MODULE

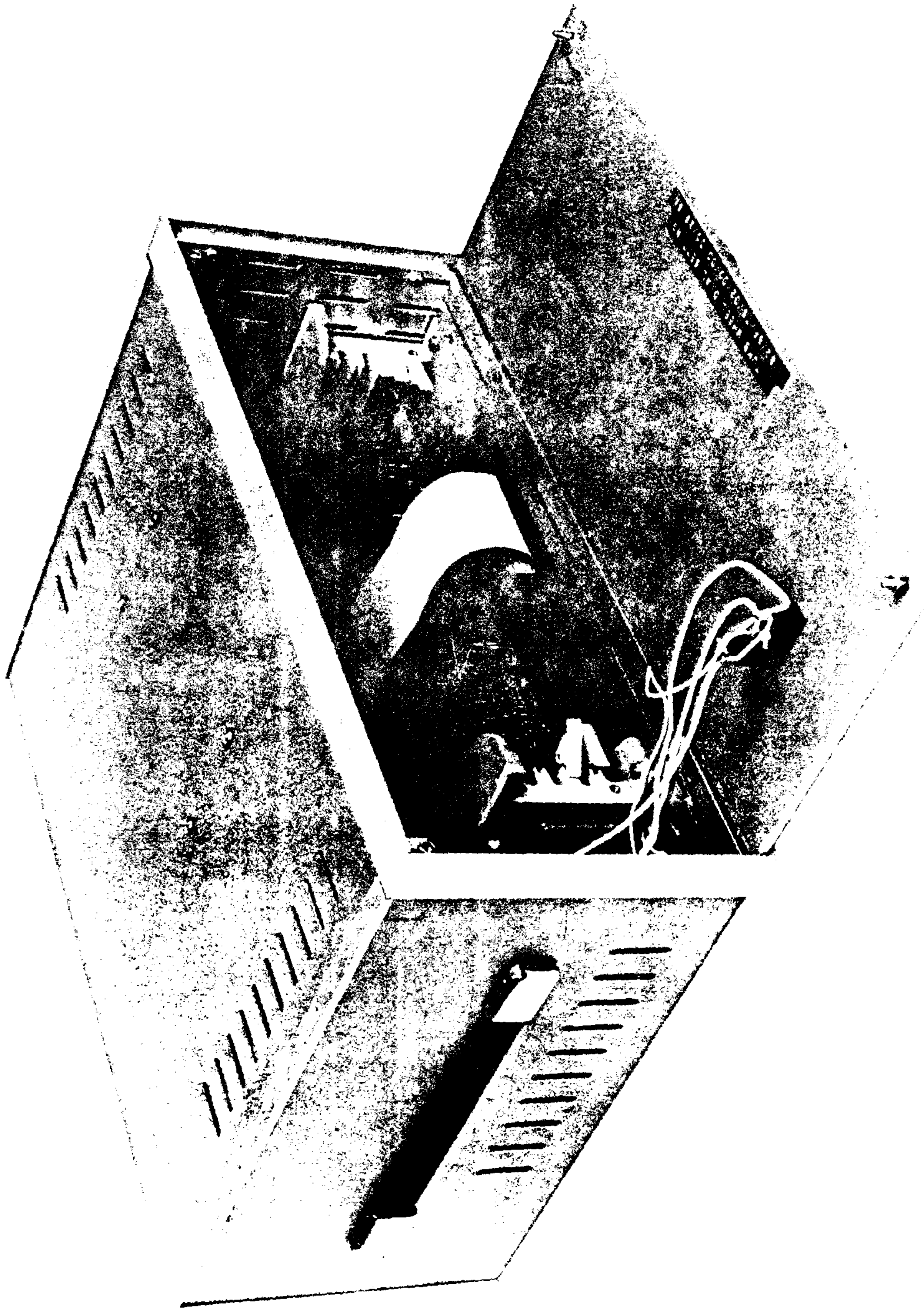

Fig. 2-3

COMPUTER MODULE

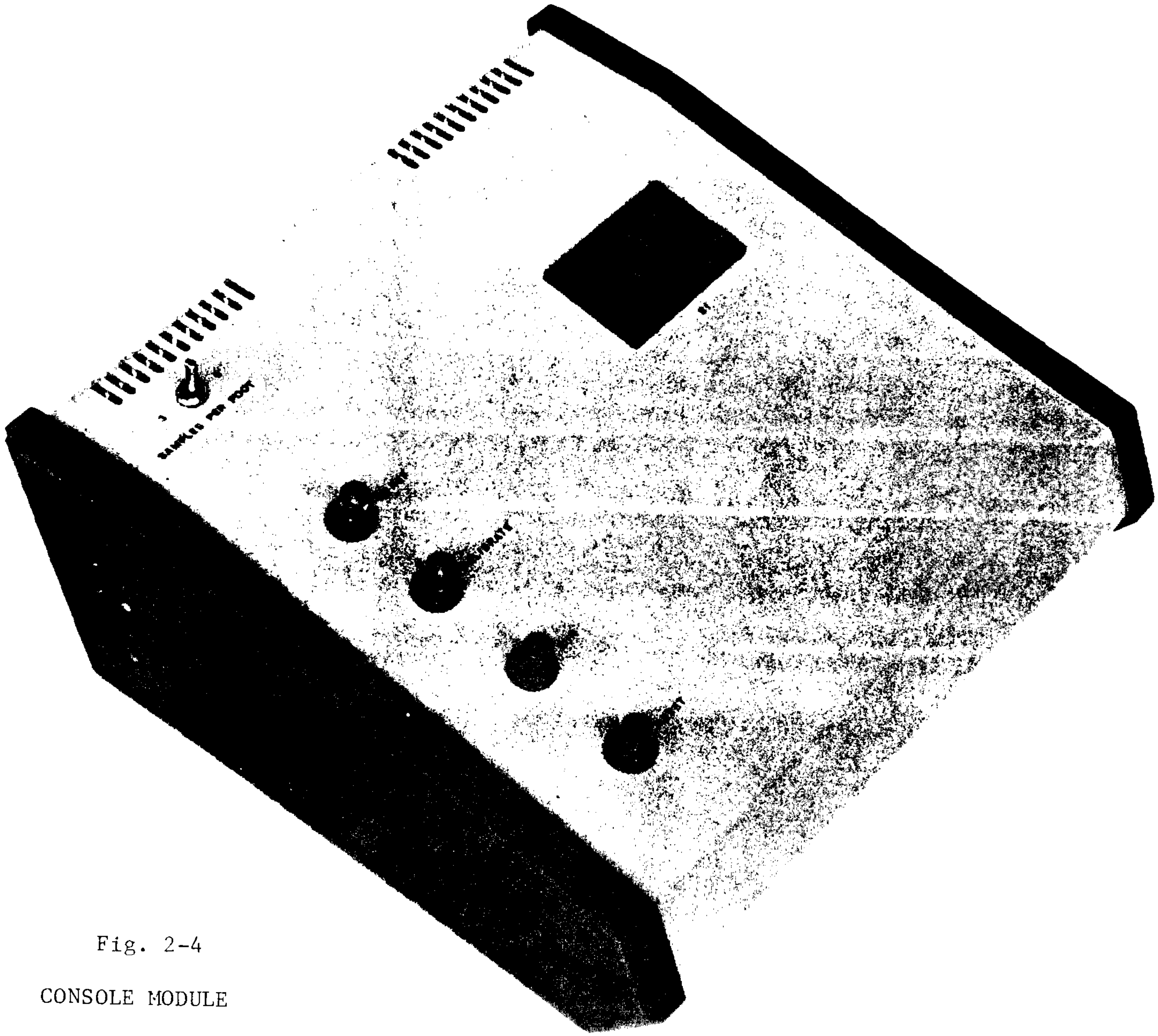

Fig. 2-4

CONSOLE MODULE

module and the firmware in the computer module are the principal differences between Units I and II. The Unit I console module permits varying the roughness measuring speed, the sampling interval, the number of sampling points (the distance of the section to be measured), and the minimum number of coefficients permitted in the autoregressive process.

The second unit is much easier to operate; however, it does not permit the many options available on the first unit. Unit II will operate with only two commands, which are initiated by two push button switches. To calibrate, the calibrate switch is depressed. To measure data, the run switch is depressed. This unit was set for an operating speed of 50 mph, a sampling interval of 3 samples per foot, and a 1000-foot measurement section. After an SI has been calculated for a 1000-foot section, it is displayed on LCD displays.

The Measuring Procedure

The measuring procedure consists of essentially three steps. The first step involves relating or correlating servicability index (SI) to the variance of the first derivative of road profile estimates [P']. The second step is performing a dynamic calibration of the vehicle. The third step is actually computing first the profile variance, and then computing the corresponding SI as determined from the first step.

Correlating SI. The modeling of SI to the variance of the first derivative of road profile, V[P'], is obtained by a standard linear regression. For this procedure a set of representative 1000 foot road sections is established and its corresponding SI or PSR determined. SI can be determined via the surface dynamics profilometer. PSR can be determined from an appropriately selected rating panel. Replication runs with the SIometer are then made for each section. This unit provides both an unscaled estimate of V[P'] and an SI based on the current α and β settings. These variance readings are read in hexadecimal AMD 9511 floating point notation and must therefore be converted to decimal numbers. After all readings have been obtained, a linear regression analysis is performed to determine the α and β coefficients for the following model:

$$SI = 5e^{-(\alpha V[P'])^{\beta}} \qquad (2.10)$$

A linear regression of the form,

$$Y = Ax + B \qquad (2.11)$$

may be performed following the transformations:

$$Y = \ln(\ln 5 - \ln SI)$$

$$\beta = A \qquad (2.12)$$

$$X = \ln(V[P'])$$

$$B = \beta \ln\alpha$$

Once the α and β parameters have been determined, they are entered into the computer module of both Units I and II via a set of thumb wheel switches. This first procedure need only be performed once. After an appropriate α and β have been found and entered, all future roughness readings from both units will be expressed in terms of SI as computed from the variable V[P'] in equation (2.10). Typically this process will only be done once for each vehicle class unless a new rating panel, or other PSR index has been structured.

Dynamic Calibration. The second procedure of the process involves a determination of the characteristics of the vehicle in which the measurements are to be made. That is, the estimates of the parameters θ_i of the vehicle's autoregressive model are determined. Once these are determined, the measurements of SI may proceed. The calibration process need not be performed again unless the power is turned off, in which case the parameters are lost, or the vehicle's characteristics significantly change (e.g., an additional rider is added, etc.). The parameters are stored in volatile semiconductor memory.

The calibration process involves making a calibration run over a pavement with an SI in the range of 2.0 to 4.0. The pavement should cause enough vibrations to the vehicle so that the periodic or repeatable characteristics of the vehicle can be determined. The calibration section should be about 900 feet and traveled at the intended SI measurement speed. It should be fairly straight for accelerometer stability. Extreme characteristics that might result in the vehicle operating in its extreme nonlinear ranges should be avoided.

The computer will collect 2900 samples corresponding to equal distance intervals and then begin the process of determining the order m of the process and the $\hat{\theta}_i$ parameters as specified by equations (2.5) and (2.9).

The order m in which equation (2.9) is solved is determined. As previously discussed, this solution can occur for numerous values. Hence the solution associated with the first one full wavelength of the tire frequency, about 10 hertz, is selected. A better model might likely be that which includes terms for the 1 hertz frequency of the vehicle's suspension system. Although this would better help distinguish between car suspension system vehicle types, it causes a significant increase in the computation time (an approximate factor of 10). Since computation time is already at a premium for this measurement procedure, the 10 hertz frequency was chosen as a compromise. The parameters of the model for 10 hertz will be affected by the 1 hertz signal, thus providing good identification of tire characteristics and usually adequate identification of vehicle characteristics. Nevertheless, there are some car classes which would need either the additional points or a new set of α and β coefficients.

Measuring SI. Once the set of m coefficients has been computed, the device is ready to compute SI. The computation of SI involves running the vehicle over a 1000 foot road section at the calibration speed (50 mph). The unit will collect 3000 points* corresponding to acceleration readings sampled every 4 inches. The SIometer operator will be notified when the 1000 foot section has been traveled at which time the device begins to process the acceleration readings. Each reading is processed according to equation (2.2). A recursive form of Simpsons' three-eighths integration rule is used for obtaining $\int E(t)$. The sum and sum of squares are accumulated for computing the variance after the 3000 points have been processed.

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* The sampling settings, speed, etc., may be easily varied with Unit 1. The 50 mph and 3 samples per foot setting were selected from current Mays Ride Meter operations and with consideration given to memory and computational speed constraints.

After ${}^{f}E(3000)$ has been computed the variance V[P'] is obtained and equation (2.3) solved to display SI. Unit I displays V[P'] in an unscaled form in addition to SI. Both Unit I and Unit II compute SI based on the α and β values selected on the thumb wheel switches inside the computer module.

CHAPTER 3. DATA COLLECTION AND ANALYSIS

During this project several experiments were conducted to validate the roughness measuring theory and to determine the system operating parameters and characteristics. These experiments are discussed in this chapter.

Initial Investigations

Prior to this research project, the measuring process described in Chapter 2 was investigated by two experiments. The evaluation was not extensive but was designed to provide a cursory test of the theory when applied to actual road profile data. In the first experiment an analytical model of a simple second order linear damped system was excited by road profile data obtained from the Surface Dynamics Profilometer. Acceleration measurements from the model were then used as inputs to the autoregressive procedures of Chapter 2. The resulting profile was compared to the original road profile data.

In the second experiment, acceleration measurements were recorded in a vehicle traveling over a road section at 20 mph. The recorded data was digitized and used as inputs to the autoregressive process. The resulting estimated profile was then compared to rod and level measurements of the road section.

Simulation of Second Order Linear Damped Spring-Mass System. As discussed above, a second order linear damped spring-mass system (Fig. 3-1) was used for a quarter car simulator. The differential equations for this system are given below. The subscripts B and W are used for the vehicle body and wheel configurations, respectively.

$$-K_W(X_W - P) - K_B(X_W - X_B) - C_W(\dot{X}_W - \dot{P}) - C_B(\dot{X}_W - \dot{X}_B) = M_W\ddot{X}_W \tag{3.1}$$

$$-K_B(X_B - X_W) - C_B(\dot{X}_B - \dot{X}_W) = M_B\ddot{X}_B \tag{3.2}$$

This system of equations was excited by the road profile, P, which was obtained from the Surface Dynamics Profilometer.

Profile samples were taken every 0.0169 feet. The following parameter values were used for the model:

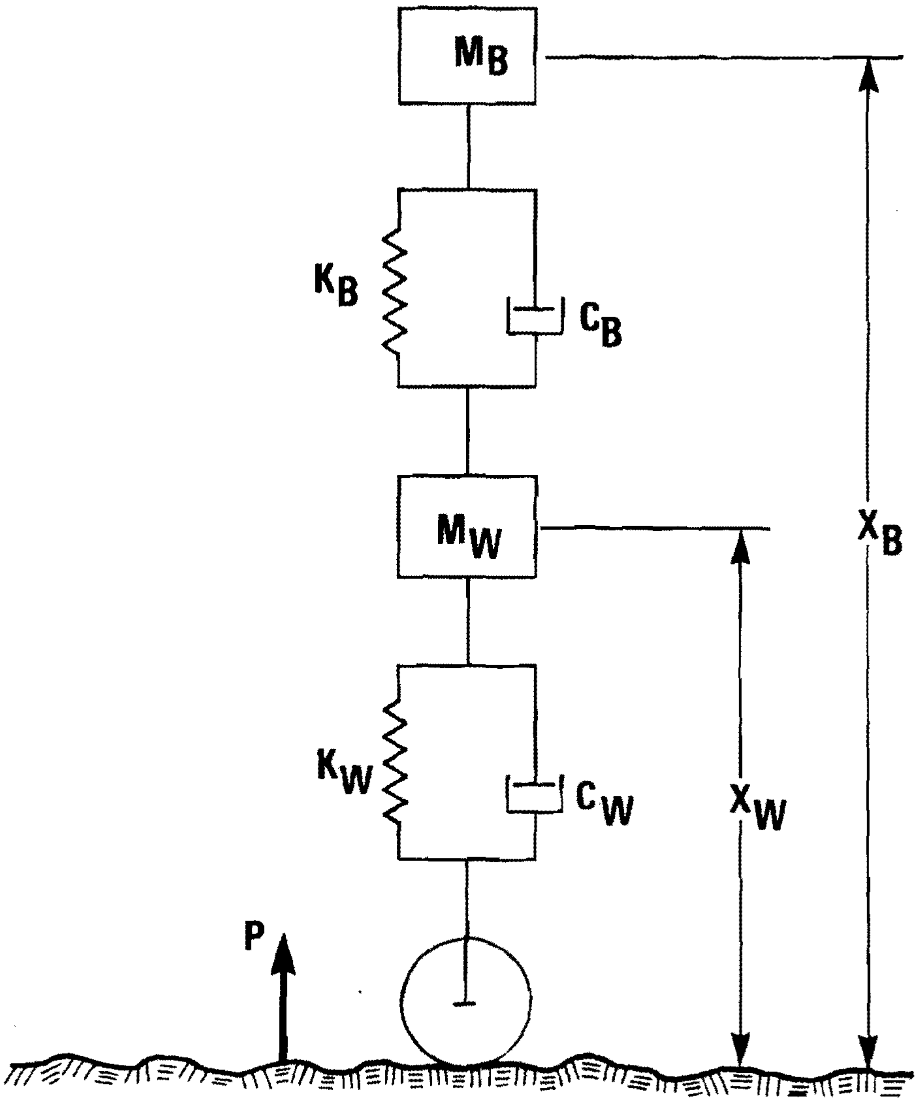


Fig. 3-1 —SECOND ORDER LINEAR DAMPED SYSTEM

$K_W = 11800$ lbf/ft

$C_W = 11$ lbf sec/ft

$M_W = 1.72$ lbf sec^2/ft

$K_B = 1788$ lbf/ft

$C_B = 95$ lbf sec/ft

$M_B = 7.22$ lbf sec^2/ft

A standard Runge-Kutta method was used to solve the differential equations yielding the acceleration $\ddot{X}_B$. The acceleration values were next used to determine the autoregressive parameters, $\hat{\theta}_i$ (Eq. 2-1), and then the predicted profile P(t). Fig. 3-2 illustrates the simulation experiment. Figure 3-3 provides the plot of the actual profile (obtained with the SDP) and the predicted profile computed using the autoregressive model.

Predicting Road Profile - A Preliminary Study. The second simple experiment involved obtaining acceleration measurements from an accelerometer mounted in a vehicle. These measurements were used to obtain a predicted profile to compare with rod and level measurements.

A half mile of rod and level measurements were taken on Kelly-Elliot Road (South of IH-20) in Arlington, Texas. Measurements were obtained every 10 feet along the center of this road. A Servo accelerometer (Columbia Research Laboratories, ± 10g) was mounted in the trunk of a 1975 Volvo and vertical acceleration samples were taken every foot for 2400 feet. These values were digitized and recorded. The recorded values were transferred to a digital computer. The acceleration measurements were used to determine the autoregressive parameters and the predicted profile.

The road section recorded sloped downward the first 900 feet to about 27 feet below the initial measurement. It then went back up for the next 400 feet. The predicted values closely followed the actual profile measuring 26.5 feet down compared to the 27-foot measurement. The predicted values continued to follow the actual profile for the next 400 feet. After that the predicted and actual values were not closely related. Since actual measurements were taken every ten feet, profile within this increment could not be compared. The predicted values appeared somewhat smoother than they

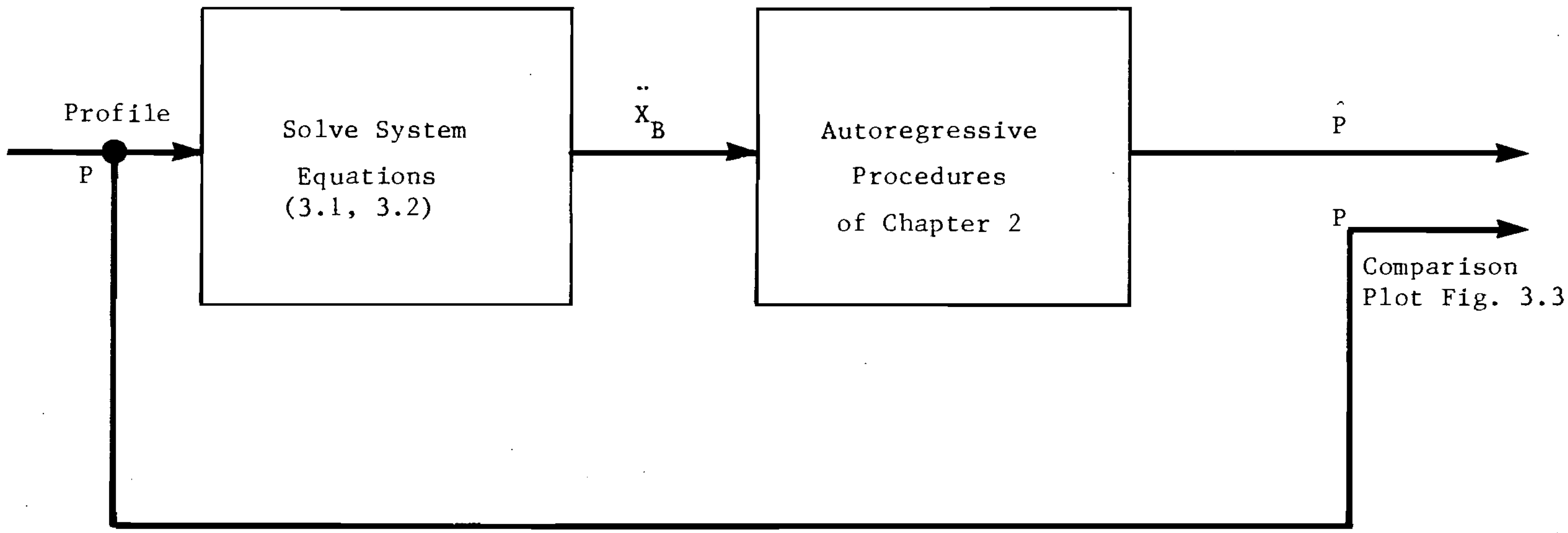
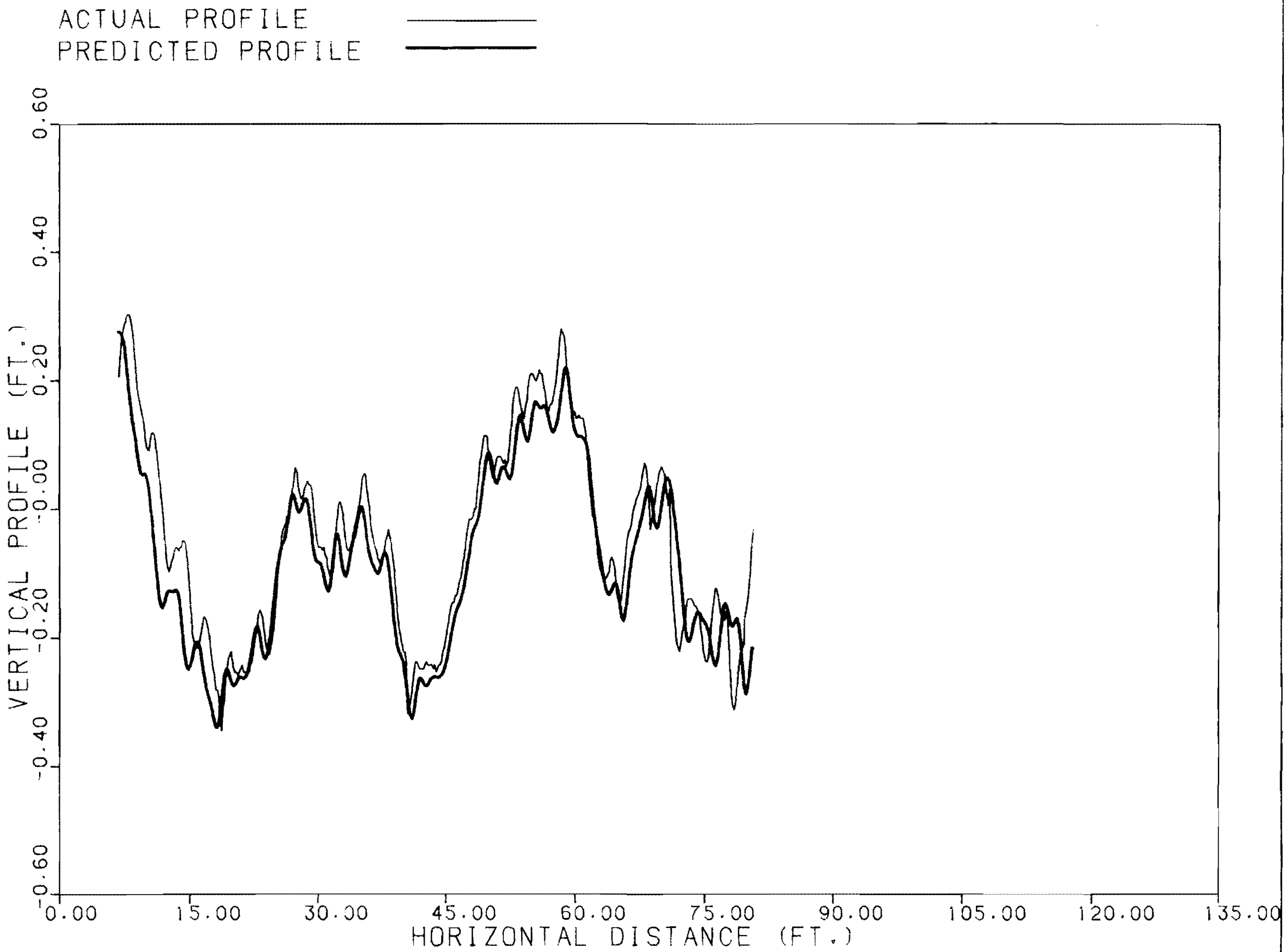


FIG. 3.2

Simulation Experiment



ACTUAL PROFILE
PREDICTED PROFILE
VERTICAL PROFILE (FT.)
0.60
0.40
0.20
-0.00
-0.20
-0.40
-0.60
0.00
15.00
30.00
45.00
60.00
75.00
90.00
105.00
120.00
135.00
HORIZONTAL DISTANCE (FT.)

probably should have been within the 10-foot intervals. Thus, two problems were considered. First, the resolution within the ten-foot intervals and then, the failure to track the actual profile after 1300 feet. These discrepancies could have occurred because of one or more of the following reasons:

(1) The accelerometer did not provide sufficient resolution (± 10g range as opposed to ± 2g range used in current units).

(2) Accelerometer drift occurred and the errors accumulated.

(3) The resolution used (one foot samples) was insufficient. Actually, only two foot resolution could be expected because of the low pass filter to account for the sampling theorem.

(4) The method does not provide a continuous accurate profile prediction for very long wave lengths (this is true for the SDP). This is related to item 2.

(5) The vehicle speed was held constant using normal driving methods and the errors (sampling was based on this speed) accumulated.

Because of accelerometer drift mentioned in item 2 there will be some limit to long wave lengths. However, the difference between the actual and predicted profile at 900 feet (.5 foot) was encouraging as the analog version of the SDP had previously been unable to measure wavelengths of this magnitude.

It was from the results of these two experiments that funds were sought for more extensive investigations of this method.

<u>Multiple Vehicle Roughness Comparisons - Preliminary Study</u>

Initial research efforts were directed toward developing an easy to use roughness measuring device which would not require the extensive calibration procedures used by the Mays Ride Meter. The process described in Chapter 2 statistically models the vehicle in which the accelerometer is mounted. A roughness statistic is then obtained which partially removes the vehicle's characteristics. Thus a "self-calibrating" roughness measuring procedure was first investigated.

To test this roughness measuring concept, acceleration measurements were taken over four sections using three vehicle types traveling at 50 mph. The acceleration values were digitized, recorded and brought back to the laboratory. Table 3-1 provides the results of the measuring process. The α and β coefficients for the SI values were obtained from a previous experiment using a Datsun 280 Z, estimating the actual PSR and performing the regression described in Chapter 2. From the results depicted in Table 3.1 and after the Unit I roughness device had been constructed, it was decided to make data runs over the Austin test sections used for the Mays Ride Meter calibration procedures.

MRM - SDP - Research Unit Comparisons

Construction of the Unit I research device was completed in early 1980. This device provided the capability of measuring the unscaled variance of the first derivative of the road profile, computing SI given the α and β coefficients, and recording the acceleration data. Tests were made on the same test sections in Austin that are used for calibrating the MRM. Using the same test sections would provide a way of comparing both the SDP and MRM with the Unit I research device as well as a means of computing a more realistic α and β for SI computations.

The accelerometer was mounted in the MRM trailer and multiple runs were made over 12 sections. Readings were taken from both the MRM and the Unit I research device. The roughness readings were then used in the regression procedures described in Chapter 2. The SI values computed from these readings were compared with those obtained by the SDP and the MRM. Fig. 3-4 provides a comparison between the three units. Fig. 3-5 compares just the MRM and the research unit (Unit I).

The resulting α and β coefficients obtained from the regression were set in the research unit. The unit was taken to the Fort Worth district office for comparison runs between the Mays Meter used by that office. The accelerometer was installed in both the trailer and the vehicle pulling the trailer. Extensive runs were not made because of noise problems in the electrical system. However, comparison runs with the accelerometer mounted in the vehicle yielded consistently higher readings than with the accelerometer mounted in the trailer.

Several additional attempts were made to verify these results. All measurements, however, seemed to indicate a difference when the accele-

Table 3-1

Comparison Runs Between Vehicle Types

Section	Ford Pinto Wagon	Volvo	Datsun (280 Z)
1	3.5	3.5	3.5
	3.5	3.4	3.5
2	4.4	4.5	4.4
	4.6	4.5	4.4
3	4.5	4.3	4.4
	4.5	4.3	4.4
4	3.3	3.2	3.2
	3.3	3.2	3.3

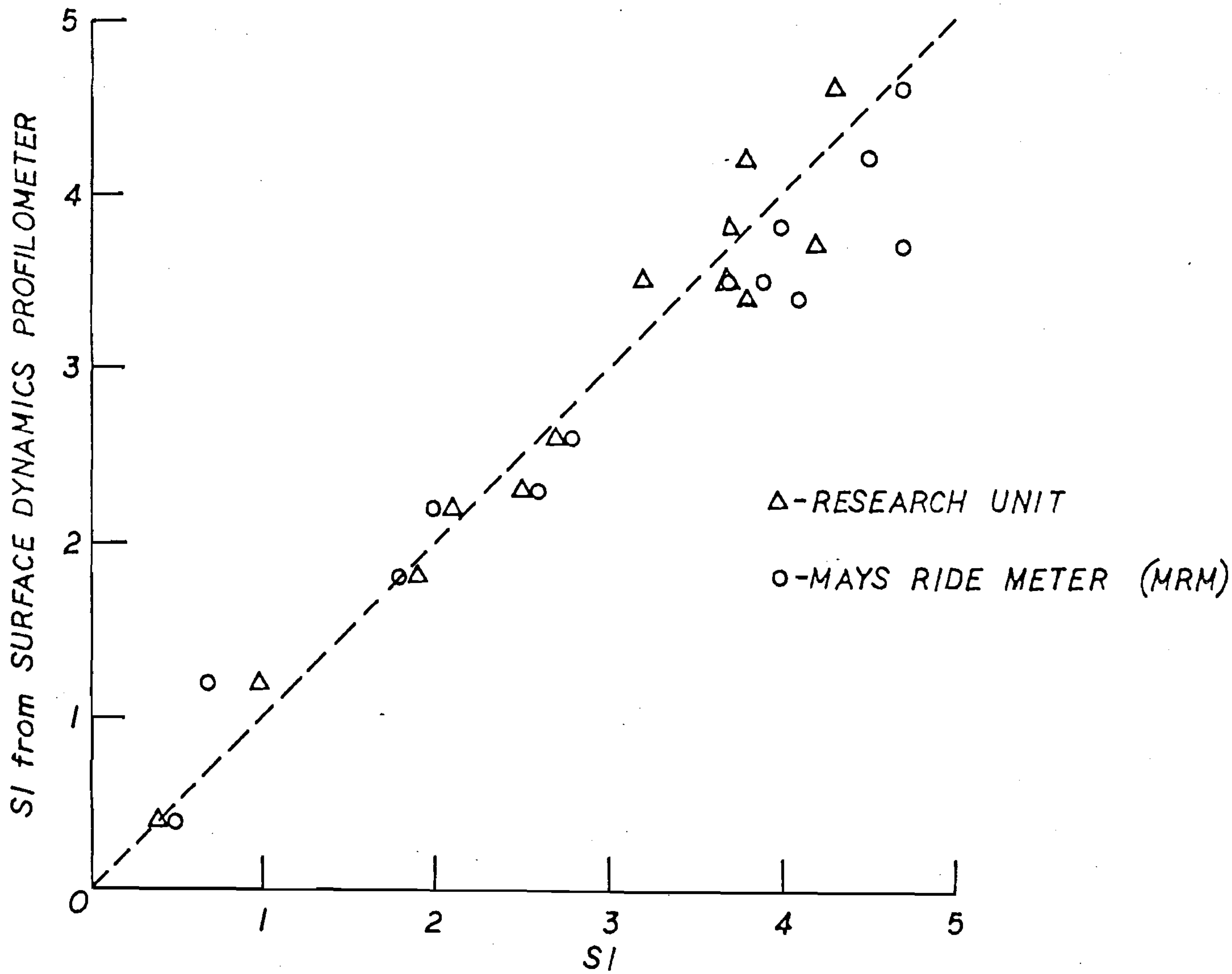


FIG. 3.4

SDP - MRM - SIometer Comparisons

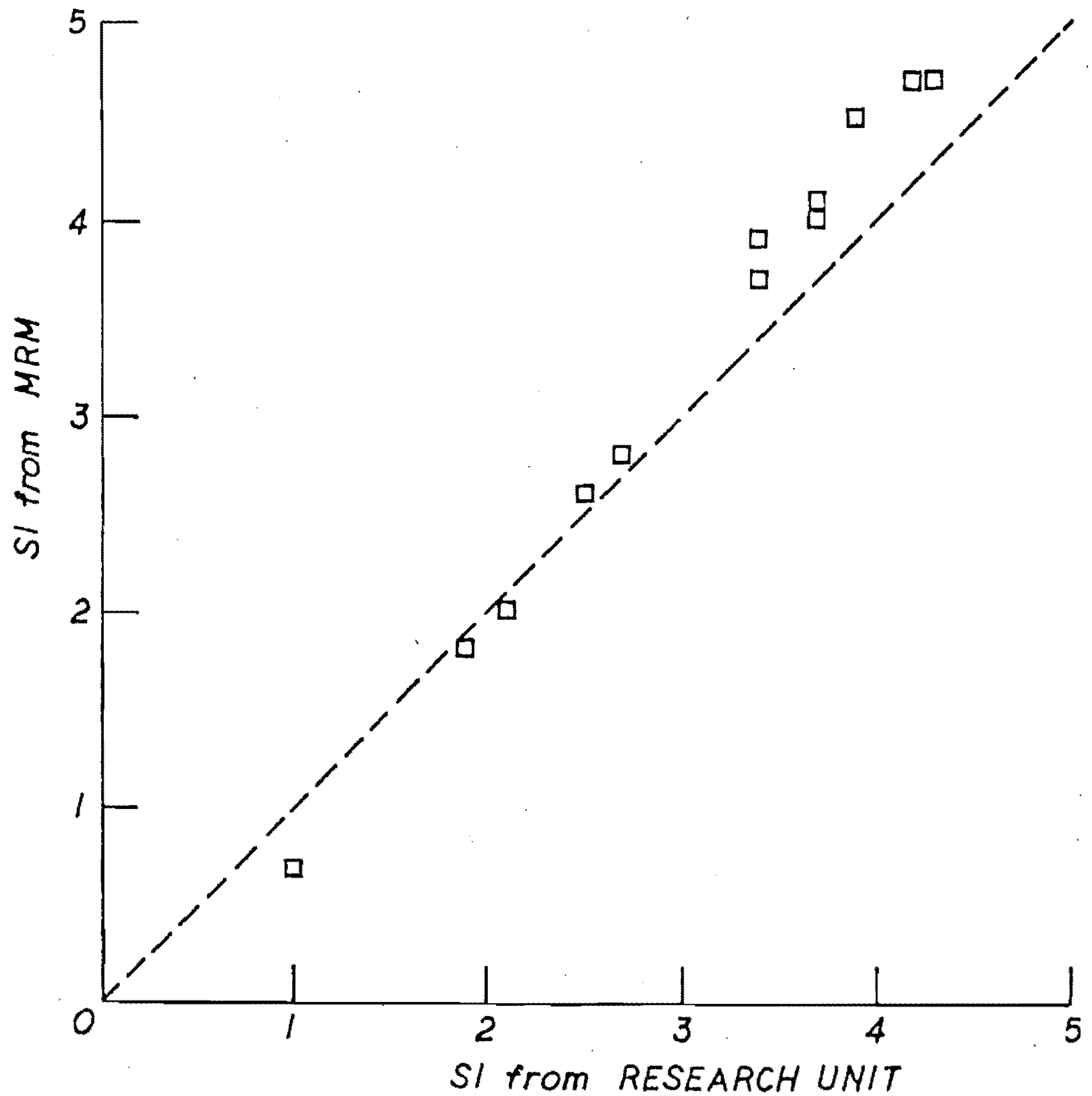


FIG. 3.5

MRM vs. SIometer

rometer was mounted in the trailer and when it was mounted in the vehicle. As discussed in Chapter 2, the order of the autoregressive process should perhaps have been increased to better account for the suspension system.

Initially, however, there was not a great deal of concern expressed over these differences, since:

(1) A major advantage of the new procedure was that it did not need the trailer and previous results indicated little difference in vehicle types; and

(2) The computation time for computing SI directly increases as the order of the process increases.

Later, however, it will be shown that differences were also noted in vehicles of various classes, e.g., large vs. small vehicle types. Although it has yet to be proven it appears that many of these differences can be accounted for by increasing the order of the measuring process as described in Chapter 2.

Since the α and β coefficients determined from the Austin tests were based on the accelerometer being mounted in the trailer an adequate SI model was still not available. Consequently, another experiment was designed to find such a model and to make further investigations into differences in vehicle types.

Tests for Vehicle Differences

As noted, differences were observed in roughness values between the trailer and car; thus, it was decided to further investigate differences between vehicle types. Eleven test sections were selected in the Arlington area. The sections were first run by the Fort Worth district's Mays Meter. Three cars were selected from UTA staff personnel (1979 Oldsmobile Cutlass, 1978 Ford T-Bird, and 1978 Pontiac Grand Prix) and acceleration data recorded. Two runs were made with each vehicle type. An analysis of variance was then made on the log transformation* of the unscaled values of the

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* The log transformation was used because of the differences in variances of replication runs between smooth and rough pavements. That is, replication runs of smooth pavements typically have less variance than those with rough pavements.

variance of the first derivative of the profile. Table 3-2 provides the analysis of variance performed.

As noted, no significant differences were detected between the three vehicle types. Next, the 1975 Datsun 280-Z used in the previous work was run over the test sections. In all sections, a statistically significant lower value was recorded for the Datsun. The tires of this vehicle had been replaced, however, and were somewhat out of round. Two additional vehicles were obtained for the test, a 1980 Granada and a 1980 Volarie. Although there was no significant difference between these two vehicles there was a statistical difference between these two new vehicles and the original three vehicles. Table 3-3 provides the analysis of variance for all six vehicle types.

Because several weeks had elapsed between the time the second set of vehicles and the first set of vehicles were run, a short test was conducted using the 1979 Cutlass. Test results were similar to the first time the data was taken using this car. Table 3-4 provides the cell means used in the AOV. It was decided that:

(1) There are some car classes where differences can exist using the procedure of primarily identifying the 10 hz signal.

(2) There could have been problems in the data collection voltages. It was later determined that the power supply was more sensitive than expected to voltage ranges of the vehicle's batteries. A noticeable difference was observed between battery voltages of just under 12V and those over 13V. One run each of the Granada and Volarie were lost due to voltage problems. The last two vehicles were rented and were no longer available so voltages or additional runs could not be obtained.

It is more likely that there are differences between some vehicle class types. Since the order of the autoregressive process was selected primarily to account for the 10 hz tire characteristics it should probably be increased as discussed in Chapter 2. This, however, would affect processing time.

Table 3-2

Analysis of Variance
(Cutlass, T-Bird, Grand Prix)

Source	df	SS	MS	F
Vehicles	2	0.017	0.008	.44+
Sections	10	70.067	7.007	389.3 **
Interaction	20	0.647	0.032	1.8
Replication	33	0.593	0.018	

+ $F_{99\%,2,33} \cong 5.39$ - thus not significant

** Significant as expected

Table 3-3

Analysis of Variance
(All Vehicles)

Source	df	SS	MS	F
Vehicles	5	4.661	0.932	43.825
Sections	10	133.578	13.358	627.968
Interactions	50	2.147	0.043	2.019
Replication	64	1.361	0.021	

Table 3-4

Cell Means
Log of V[P'] Readings (Unscaled)
(Used in AOV)

Section										
1	2	3	4	5	6	7	8	9	10	11
13.26	11.07	13.52	10.36	11.13	12.55	11.64	13.10	12.10	10.89	11.34

Vehicle					
Cutlass	T-Bird	Pontiac	Granada	Volarie	Datsun
11.71	11.74	11.74	11.97	12.04	12.21

Section	Vehicle					
	Cutlass	T-Bird	Pontiac	Granada	Volarie	Datsun
1	13.05	12.98	13.20	13.28	13.42	13.64
2	11.05	10.91	10.88	11.10	11.33	11.18
3	13.24	13.28	13.54	13.85	13.51	13.85
4	9.93	9.94	10.25	10.45	10.55	11.01
5	11.08	10.93	11.06	11.01	11.20	11.51
6	12.33	12.42	12.23	12.72	12.71	12.88
7	11.49	11.57	11.64	11.77	11.49	11.89
8	12.94	13.05	12.89	13.34	13.17	13.22
9	11.84	12.08	11.69	12.27	12.49	12.25
10	10.74	10.85	10.59	10.71	11.16	11.23
11	11.12	11.16	11.19	11.52	11.39	11.66

As noted there were no significant differences between the Granada and Volarie On further examinations, the Granada and Volarie are small cars compared to the Pontiac, Oldsmobile and Ford T-Bird. The Datsun 280-Z is a sports car.

SI Model Computation

The α and β coefficients computed from the Austin tests were based on the accelerometer mounted in the trailer. Since there was a difference observed between the vehicle and trailer mounted accelerometer, it was decided to use the data from the eleven sections of the above experiment to develop a better SI model. Additionally, as discussed in Chapter 2, a high pass filter is necessary when using the variance of the first derivative of the profile as the primary measuring statistic. That is, a relatively smooth road going up a hill can in general give a rougher reading than a flat road of similar roughness characteristics. Consequently, the high pass filter is used to attenuate these frequencies. The problem is to determine the proper filter characteristics. Twenty different regressions were run on 20 different filter combinations using all six vehicles. Even though statistical differences were detected in the roughness statistics as discussed above, all six vehicles were selected for obtaining an average for all vehicle types. The model with the best multiple R and least standard error was selected. The α and β coefficients for this model were found to be 0.529423×10^{-5} and 0.588642, respectively. The correlation coefficient (R^2) was 0.932 with a standard error of 0.24. The SI readings for the experiment are given in Table 3-5. The two research units were provided to the highway department with the α and β values set accordingly.

The SI model determined from the above experiment still seemed to measure roads somewhat low. The Fort Worth Mays Meter was used to obtain the SI's for the dependent variable in the regression. This unit appeared to give relatively low values for these sections. It was later sent back to Austin for recalibration.

Additional Measuring Procedure Verifications

At the termination of the project, the two measuring devices were provided to the Highway Department. A new set of tests were conducted by D-10

Table 3-5

SI Readings

Section	Cutlass	T-Bird	Pontiac	Granada	Volarie	Datsun
	Vehicle					
1	.9 .9	1.0 1.0	.8 .8	.7 .7	.7 .6	.4 .5
2	2.9 3.0	3.1 3.0	3.2 3.1	2.9 2.9	2.3 3.0	3.0 2.7
3	0.8 0.7	0.7 0.8	0.5 0.6	0.3 -*	0.5 0.6	0.3 0.3
4	3.8 3.8	4.0 3.6	3.5 3.7	3.5 3.4	3.1 3.6	3.1 2.9
5	2.9 2.9	3.1 3.0	2.9 2.9	3.0 3.0	2.8 2.8	2.5 2.5
6	1.7 1.6	1.5 1.6	1.6 1.9	1.2 1.3	1.2 1.3	1.2 1.0
7	2.5 2.5	2.3 2.6	2.3 2.4	2.2 2.3	2.6 2.4	2.1 2.2
8	1.1 1.0	0.8 1.0	1.1 1.0	0.6 0.7	0.9 0.8	0.8 0.7
9	2.3 2.0	1.9 2.0	2.4 2.3	1.9 1.5	1.5 1.4	1.8 1.7
10	3.3 3.2	3.4 2.9	3.4 3.3	3.3 -*	2.8 2.9	2.8 2.8
11	2.9 2.9	3.0 2.7	2.8 2.9	2.6 2.4	2.6 2.7	3.3 2.4

* Data loss due to voltage problems.

of the Department. First tests were conducted to develop a model based on the Austin test sections and thus the SI's computed by the Surface Dynamics Profilometer. Next, field tests of the measuring devices were done with this new model.

Once the α and β coefficients were computed the field tests described in Exhibit 3-1 were conducted. Exhibit 3-2 provides the results of these tests (Ref. 7). These tests were conducted independently by the Department after the termination of this project and are included in this report for reference purposes only.

Exhibit 3-1

WORK PLAN FOR FIELD TESTING SIOMETER

I. Check Repeatability

A. Calibrate Siometer, record calibration number and temperature.
B. Obtain 10 repeat runs on same section with average SI value.
C. Prepare INFO. showing average and standard deviation (range).

II. Check Daily Variance

A. Calibrate SIometer, record calibration number and temperature.
B. Obtain 3 repeat runs on 2 separate sections with high and low SI value, record temperature for each section.
C. Repeat A and B at regular intervals over one day's time.
D. Prepare plots.

III. Prove Correlation (Alpha α & Beta β) Remains Same Once Established

A. Calibrate SIometer, record calibration number and temperature.
B. Run SIometer, SDP, and MRM on calibration sections at periodic intervals and compare changes if any.
C. Prepare plots to compare data scatter of each unit.

IV. Check Calibration

A. Obtain 5 repeat runs on 5 separate sections (full range of SI values) using 4 vehicle combinations, calibrating each time vehicle is changed.

1. Auto only - 29-171-D
2. Truck only - 29-4012-B
3. Auto with trailer - 29-186-E & 29-9867-A
4. Auto only - 29-186-E

B. Obtain 2 repeat runs on 3 separate sections changing vehicle condition, calibrating each time condition is changed.

1. Normal weight - Added weight
2. Normal tire pressure - Reduced tire pressure
3. All tires balanced - One or more out of balance by adding weights to rim.

Exhibit 3-2

SIOMETER EXPERIMENT RESULTS

Repeatability

General Range = 0.2 to 0.3 SI

Standard Deviation = 0.06 SI

Temperature

Little effect if any.

Day to Day Variance

General Range = 0.3 to 0.5 SI

Standard Deviation = 0.22 SI

Self Calibration

Simulated self-calibration indicates the self calibration feature works for sedan class vehicles. Little effect noted when varying tire balance or tire pressure. Slight variance noted when changing overall vehicle weight. Slight variance noted when changing unit from sedan vehicle to vehicle with stiffer suspension. This indicates the SIometer calibrates for tire effects (say 10 Hz area) better than for suspension changes. This variance is probably significant when compared to repeatability but not significant when compared to changes occurring "day to day." Suggest sedan vehicles be used and vehicle weight be maintained at a relatively constant level (no greater weight variance than ± 160 lbs).

Prove Correlation

Only one run made. This is insufficient data for analysis.

CHAPTER 4. CONCLUSIONS AND RECOMMENDATIONS

The following conclusions are summarized from this research effort:

. A new method has been developed for predicting road profile from vertical acceleration data.

. A method for computing serviceability index directly from this predicted profile has been developed.

. A device (referred to as SIometer) has been constructed which uses these methods.

. The method developed appears to adequately identify the vehicle's characteristics for specific vehicle classes during a dynamic calibration procedure.

Following are recommendations for future studies:

. Extensive field tests of the SIometer should be conducted to establish operational errors.

. The method developed should be further investigated to determine if different vehicle classes can be adequately identified.

. Predicted profile errors should be identified and the accuracy of the method for obtaining such measurements determined.

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