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16. Abstract

A Self-Calibrating Road Roughness Device known as the Walker Roughness Device (WRD) or SIometer has been under study and evaluation by the Department for the last several years. This device looks promising as a tool to collect road roughness for the Pavement Evaluation System. There is a very definite need for an automated data collection system for road roughness to eliminate some of the cost for this operation. This project was initiated to upgrade the WRD and develop procedures so it can be used for collecting serviceability index roughness measurements for the state. This report describes the procedures for correlating the WRD with the SDP and using the WRD for roughness measurements.

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THE WALKER ROUGHNESS DEVICE

FOR ROUGHNESS MEASUREMENTS

by

Roger S. Walker
Luat Tan Phung

The University of Texas at Arlington

Research Report 479-1F

Upgrade of Self-Calibrating

Road Roughness Device

Research Project 8-10-86-479

conducted for

Texas State Department of Highways
and Public Transportation

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

July 1987

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PREFACE

This project report presents results of Research Project 8-10-86-479, "Upgrade of Self-Calibrating Road Roughness Device." This one year project was initiated to prepare the Self-Calibrating Road Roughness Device, known as the Walker Roughness Device (WRD) or SIometer, for roughness measurement usage in the State.

This project effort was not possible without the close cooperation of State Department personnel, Curtis Goss, Jim Wyatt, and Randy Beck. The assistance of graduate students, Suhas Pai and Steve Schuchman, should also be acknowledged.

Roger S. Walker
Luat Tan Phung

July 1987

ABSTRACT

A Self-Calibrating Road Roughness Device known as the Walker Roughness Device (WRD) or SIometer has been under study and evaluation by the Department for the last several years. This device looks promising as a tool to collect road roughness for the Pavement Evaluation System. There is a very definite need for an automated data collection system for road roughness to eliminate some of the cost for this operation. This project was initiated to upgrade the WRD and develop procedures so it can be used for collecting serviceability index roughness measurements for the state. This report describes the procedures for correlating the WRD with the SDP and using the WRD for roughness measurements.

KEY WORDS: Surface Dynamics Profilometer (SDP), SIometer, Walker Roughness Device (WRD), Present Serviceability Index (PSI), Road Profile.

SUMMARY

This report describes the methods and procedures for usage of the Self-Calibrating Road Roughness Device known as the Walker Roughness Device (WRD), or SIometer. The report presents results of Research Project 8-10-86-479, "Upgrade of Self-Calibrating Road Roughness Device." This one year project was initiated to prepare the WRD, for roughness measurement usage in the State. The device is ready for implementation in the state for obtaining serviceability index roughness measurements.

Correlation procedures between the WRD and the Surface Dynamics Profilometer (SDP) was developed, as well as user interface to the portable Zenith PC, for data recording. The data collected on the PC can be easily entered in the Pavement Evaluation System used by the State. A voice system was developed for ease in user interface to the WRD. Extensive data runs have been and are continuing to be made with the WRD to determine its capability for data measurements.

IMPLEMENTATION STATEMENT

The immediate effect of obtaining a low cost road roughness measuring device which does not require extensive calibration procedures will permit many districts within the state to easily obtain roughness measurements. Because of its costs and ease of operation (designed for one man operations), much of these measurements can be obtained by the various districts. The recording media for roughness measurements can be either in digital readout form, hard copy, and/or cassette for later computer analysis. The results from this project will improve the current roughness measuring collection procedures used in the Department.

This device will provide the Department a better, less expensive, and safer means of measuring pavement roughness and will provide automated procedures for entering such measurements into the Pavement Evaluation System.

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CHAPTER 1

INTRODUCTION

Background

For years engineers have searched for low cost roughness and/or profile measuring instruments. The Mays Ride Meter (MRM) has been found to be an effective inexpensive device for measuring ride quality and thus indirectly road roughness. However, MRM measurements are dependent upon all factors which effect the mass and suspension system of the vehicle used with the MRM. In addition, continual calibration means are needed.

The Surface Dynamics Profilometer (SDP) provides fairly accurate measurements of highway profile from which roughness statistics can be computed. Previous work by the Department and the Center for Transportation Research at The University of Texas at Austin resulted in the development of calibration procedures for the MRM using the SDP. The SDP, however, is not without its faults. First, it is a very expensive device and furthermore, it is very expensive to operate. Few state highway departments, for instance, have purchased such a device even though roughness measurements are usually desired by these agencies. Many departments have purchased MRM or similar devices, but as noted adequate calibration procedures are necessary. Such procedures are often difficult to accomplish.

A new method of measuring profile and roughness data was developed by Roger S. Walker. This method was investigated at the University of Texas at Arlington during a study funded by the Department, Study No. 8-10-80-279. For this method a statistical model of the vehicle is obtained from vertical accelerations of the vehicle. These measurements are used to establish the parameters of the model during a dynamic calibration process. Once these parameters are identified, the vehicle is "calibrated." The vehicle is then driven over various roads and the resulting accelerations measured. The difference between the predicted and actual measurements are used to predict the road characteristics. These characteristics, one of which is the first derivative of road profile, are then used to correlate to SI.

This method was implemented in a non real-time mode using microprocessor based equipment. The method was found to produce roughness measurements closely related to similar ones produced by the MRM and the SDP as illustrated in Figure 1.1.

According to the theory, the method should be able to be used to obtain a roughness measurement irrespective of the vehicle the device is mounted in, as the vehicle's influence to the process is identified and discarded. However, in an experiment involving three car classes there was found to be statistical significance between car classes. Although the experiment did not have enough vehicles within each class for a complete statistical experiment design, the results were consistent with earlier findings, which indicated differences between car classes, but little differences within classes. The results of this study is provided in Report 279-1.

Subsequently, a second study was initiated at McCelland Engineers of Houston, Texas, where Walker was working after leaving the University for a short period. In this study a real-time version of the process was implemented [HAN85]. The real-time version, however, proved to have significant hardware or construction problems. First, in order to handle the real-time computing requirements, several single board computers were used. The result was a unit requiring too much electrical current for practical field applications. The second problem was in the construction methods. The unit did not work well with the vibrations and other harsh environments required of the measuring vehicle. Consequently, sometimes the device gave good results, and sometimes it did not. Most of the times the measurements were bad, hardware problems were found. Other times it became too cumbersome to try and track down the problems. This unit was used in Research Project 3-8-83-354, "Updated Pavement Ride Quality Evaluation," conducted for the Department at the Center for Transportation Research at the University of Texas at Austin. In this study, it was reported that poor correlation was found between the panel of pavement raters and the predicted serviceability index of the unit. Some of this bad correlation was probably due to the above mentioned problems. However, most of the poor results was probably due to using the wrong independent variable in the correlation. The SI value from the SIometer was used instead of a statistic from the predicted profile of the SIometer. That is, it would be equivalent to correlating the SI from the Mays Ride Meter which was calibrated to one of the old SDP results instead of the inches per mile displacement of the MRM.

Walker subsequently developed improvements to the measurement process and designed a system based on newer microprocessor technology, CMOS components, and parallel

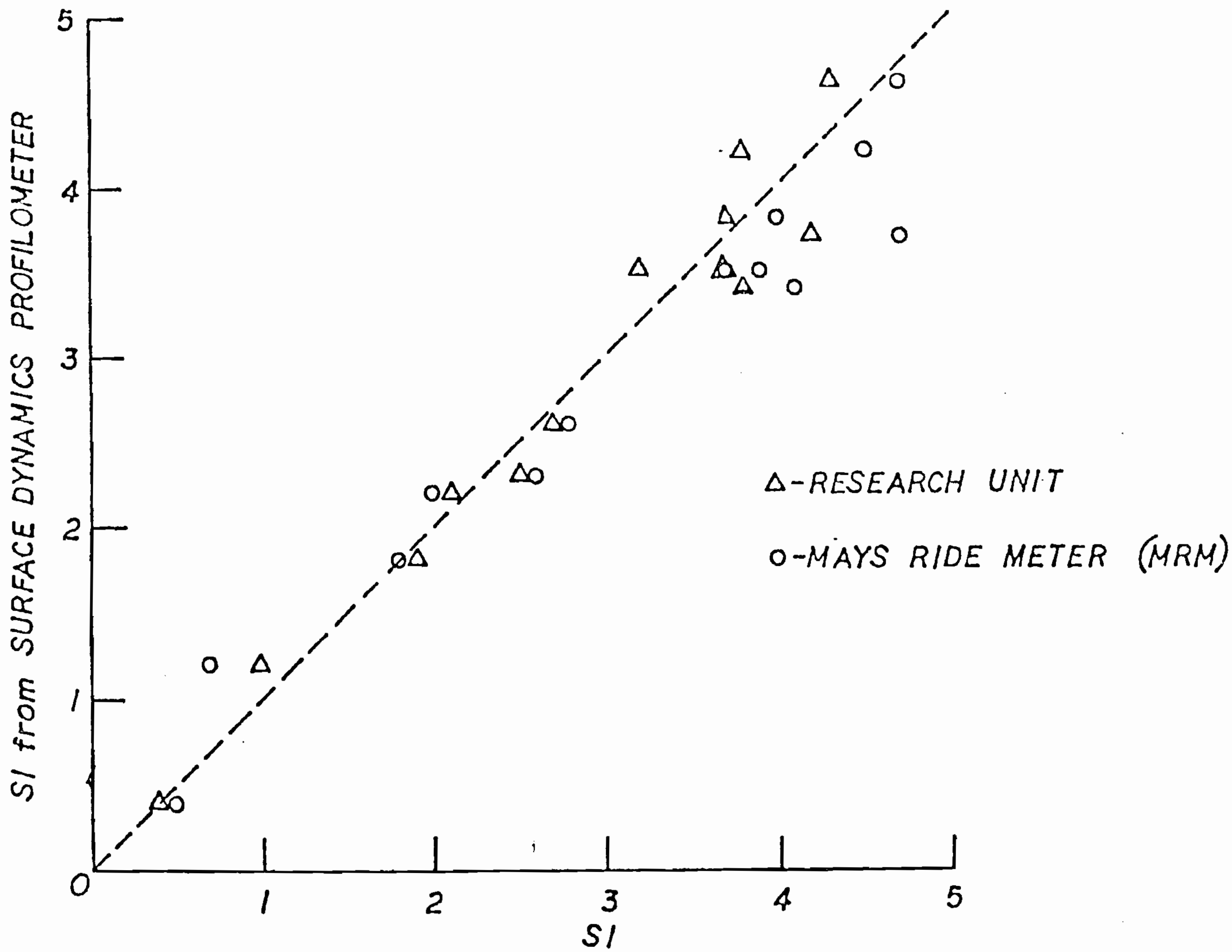


Figure 1.1. MRM, WPD (Research Unit) vs SDP

processing architecture. This updated system would still provide real-time measurements but at much less electrical current and size requirements. The rights of these new improvements were then given to Micro-sher Inc. for future implementation. He then rejoined the faculty at the University of Texas at Arlington. Walker has continued investigations which will specifically be addressed as indicated in the problem statement.

Considerable advancement in microprocessor technology has occurred in the last few years which makes real-time processing with the WRD practical. For example, the number of P.C. boards has been changed from around ten boards in the McCelland unit to one, the electrical current requirements from over 20 amps to less than two, and the time for the self calibration from approximately three and one half minutes to about ten seconds.

Research Plan and Report Scope

The initial objectives of the research study were:

Develop new curve fitting procedures to obtain a better correlation between the WRD and the Surface Dynamics Profilometer.

Refine the design of the measuring process to the point that the system would be a one man operation. This includes human factor considerations in providing a user friendly and intelligent instrument with voice synthesis to eliminate the demand for visual monitoring during operation (operating safety improvements), and improve the data storage system for providing SI inputs into the Pavement Evaluation System.

Develop maintenance procedures for Department personnel for maintaining field operations of the equipment.

Purchase necessary equipment and develop procedures for SI correlation process. The equipment will be used for the current WRD, as well as, for all future units for Pavement Evaluation System data collection procedures.

Determine the sensitivity of the measuring process to speed variations, and based on these studies investigate the feasibility for operator and/or adaptive speed correction features.

Of these initial objectives all but the last listed were completed. Initial studies into developing speed independent measurements, however, were performed, and hardware requirements for such adjustments were included in the current versions of the WRD. These studies are continuing in the current project, 8-10-87-394, "Field Implementation of Non-Contact Profiling and Road Roughness Equipment."

The following two chapters provides details on an expert system designed to provide correlation procedures for the SDP and WRD.

Chapter 4 discusses uses of a well correlated model between the SDP and WRD. This model has been successfully used during the past year for SI measurements. The model has been used in two different car classes with good results. Data runs using this model are discussed in the Chapter.

A program designed for one man operations using the WRD and the Zenith PC was developed. Voice output was added for operational ease. This program, which is described in the Appendix, is currently being used by the Department for roughness measurements.

As indicated, extensive data runs using the WRD were performed during the year. The data collection was performed by D-10 personnel, and various operational and maintenance procedures have been developed. These will be further documented in the field implementation project as additional experience is gained using this equipment.

CHAPTER 2

WRD - SDP CORRELATION

Introduction

Pavement roughness information can be obtained from road profile. This can be done by computing various statistical values from the profile that are related to pavement roughness. The WRD obtains an estimated road profile from which such statistics can be computed. The roughness statistics collected from this device are then correlated and transformed to suitable ride quality measurements. This correlation or modeling involves a number of parameters and variables. An expect system will be designed to guide the appropriate highway design and maintenance personnel through the statistical process of developing such correlations.

Research in artificial intelligence (AI) has contributed significantly to the development of expert systems. These systems are usually computer programs and procedures into which the knowledge of a human expert is encoded and manipulated to emulate man's approach in solving the problem.

Statistical expert systems require increasing research activity because they are different from general expert systems in several aspects. They must be able to provide interactive graphics because graphical representation of data is an important feature in statistical analysis. They must be either interfaced with existent statistical software packages or equipped with special software to perform extensive numerical computation. Current AI languages and expert system development tools normally lack the necessary speed and software in accomplishing these two requirements. Also of importance (in contrast to conventional statistical computer programs), statistical expert systems should be able to offer guidance, interpretation, and instruction to the user [GAL85].

This research involves the development of an expert system that simulates the procedures performed by a statistician in correlation analysis of road profile measurements. The tasks the program executes include selection of a suitable filter, detection of bad data, check for validity in applying regression analysis, and performing piece-wise linear regression to build the table for use by the WRD. The program provides suggestions during the modeling process but does not take control from the user. The user maintains control and may override the program's suggestions.

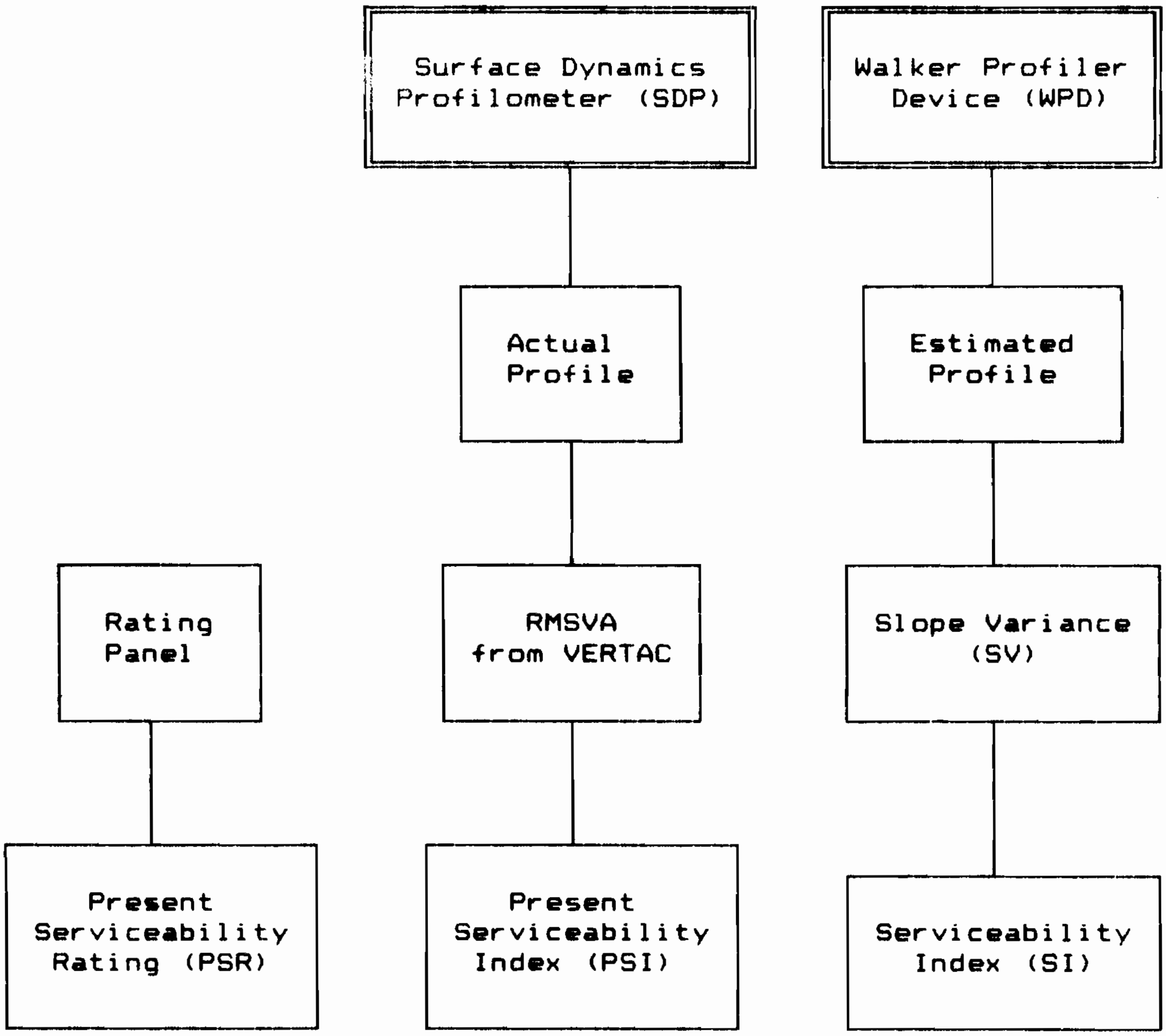
Road Roughness

The Texas State Department of Highways and Public Transportation (TSDHPT) has been working on the problem of determining pavement rehabilitation and maintenance schedules for a number of years. Road or pavement roughness is one of several important variables used in these procedures. Road roughness has been shown to relate directly to safety, ride quality, serviceability, and driving cost. Therefore many means have been explored to accurately and objectively measure road roughness.

A system for road roughness measurement basically consists of two parts: (1) the sensors and hardware used to collect profile or other data which can be used to characterize a pavement, and (2) the methodology used to analyze this data. The analysis process typically correlates the statistics from the profile data and present serviceability ratings to compute a serviceability index, or an indicator of the road roughness. This is illustrated in Figure 2.1.

One instrument that is used to collect profile data is the Surface Dynamics Profilometer. In a study conducted by the TSDHPT [ROB70], a rating panel consisting of "typical" highway users was formed to evaluate the road quality of various pavements types (smooth, rough, etc.). The panel's subjective opinion for each road section was recorded as present serviceability rating (PSR), a value ranging from zero to five, where a value of zero indicates an almost impassible road and a value of five indicates a perfect pavement. Correlation analysis of statistical data from profile measurements and PSR produces a mathematical function (present serviceability index--PSI), which is used to predict the PSR for pavements within the described limits. The report on this study concluded that "the profilometer data can be used to predict PSR values as accurately as the rater, but more conveniently," and less subjectively, by using the PSI equation.

Even though the profilometer produces accurate measurements, it is rather expensive to obtain and operate. An



PSI accurately describes PSR

Task: Correlation analysis of PSI and SV to predict SI

Figure 2.1. Overall Interconnection Describing the Road Roughness Measurement Process

alternative device is the WRD, which also produces profile data but is less expensive and easier to operate. The data obtained from this device provides an estimated profile. From these measurements the slope variance (SV), which is defined as the variation of the slopes of a road profile, is then calculated. The WRD employs this value, which is correlated to PSI, to determine the serviceability index (SI) of the road. A table (obtained from correlation analysis) relating slope variances to corresponding SI values is used to determine SI. The goal of the WRD is to provide an SI value for a given pavement that closely matches the PSI value predicted by the profilometer.

Figure 2.2 provides the overall interconnection of the devices and methods for evaluating road roughness.

The methodology used by the WRD to predict road profile includes the dynamic development of a statistical model of the vehicle in which it is installed. The model assumes linearity in the vehicles' suspension and tire system. Since the suspension and tire system is not linear and this non-linearity differs in a vehicle's wheel base and weight, adjustments are required by classifying the vehicles into groups with similar suspension and tire system characteristics. Depending on the class of cars it is installed in, the WRD will refer to the appropriate look-up table to produce the correct SI values.

To obtain the necessary measurements for correlation analysis the following steps are performed [WAL82].

(1) A set of representative road sections is established. The sections should be of varying roughness so that the values of their expected SI spread throughout the possible range from zero to five.

(2) The Surface Dynamics Profilometer is run to determine PSI for each road section. (Or corresponding PSR can be determined from an appropriately selected rating panel).

(3) Replication runs with the WRD are then made for each section to obtain slope variance values SV (along with other road profile statistics).

The data from step 2 and 3 are inputs to the expert system by which the desired table is obtained.

The usual operation of the WRD consists of essentially three steps. The first step is to perform a dynamic calibration of the vehicle. The second step is to calculate the profile for each reading from the accelerometer. The profile

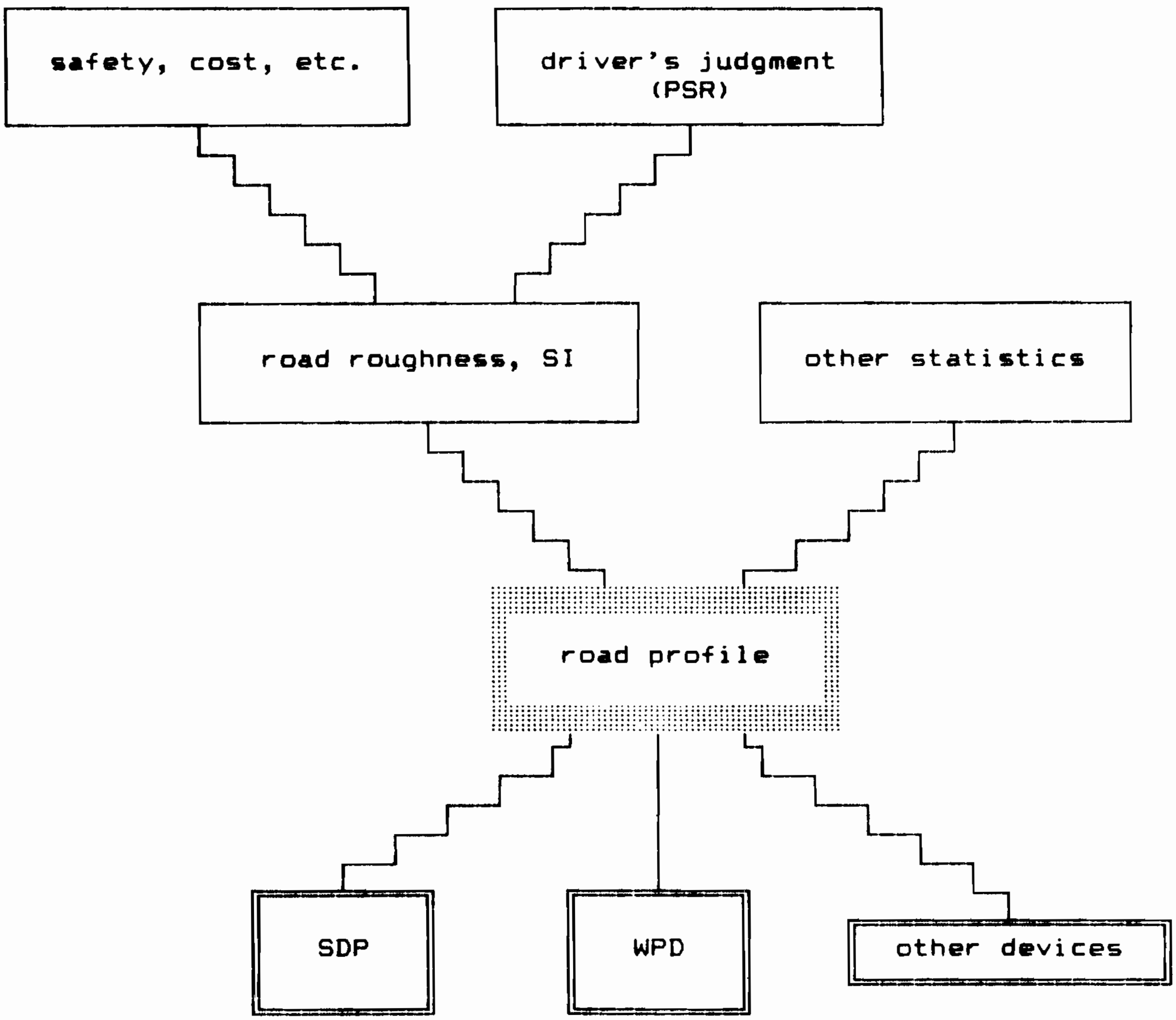


Figure 2.2. Relationship among Elements Affecting Road Evaluation

is used to calculate SV for a section. The third step then involves looking up the table to produce the SI for that particular section.

Following is a description of the the Surface Dynamics Profilometer and the Walker Roughness Device. Statistical concepts that are employed in the correlation procedure will then be introduced. The discussion forms the necessary knowledge for the expert system for performing this correlation.

Surface Dynamics Profilometer

The Surface Dynamics Profilometer was originally designed by General Motors and built by K. J. Law Engineers in 1967. The device has as primary sensors, two accelerometers and two linear potentiometers. The potentiometers are connected to road-following wheels. The accelerometers determine the amount and direction of vertical acceleration undergone by the vehicle while the potentiometers and wheels measure the displacement between the vehicle body and the road surface. A profile measurement is calculated by summing the double integral of the accelerometer signal and the displacement signal from the potentiometer [SPA64]. Recently, two non-contact laser probes were obtained and used to replace the potentiometer/road-following wheel combination.

The SDP measures profile data with considerable accuracy and consistency and is independent of the vehicle suspension [MCK82]. It has been used as a standard reference device for performance evaluation of less accurate and expensive road roughness measurement devices, such as the Mays Ride Meter and the WRD.

The principle statistic currently used by the TSDHPT in analyzing profile data from the SDP is root-mean-square vertical acceleration (RMSVA). This statistic is fully discussed in [MCK82]. RMSVA is the basis for the mathematical model to compute present serviceability index for a section of a road. The implementation of this model is a program called VERTAC (VERTical ACceleration). Initially this program could only be run on a large mainframe computer system. A version of VERTAC has been recently developed on the PC and is used with the SDP [WAL87].

Walker Roughness Device

The Walker Roughness Device (WRD) is a self-calibrating road roughness unit. It was originally known as the SIometer, as it computes and displays serviceability index, or SI.

The WRD consists of three components: (1) a sensor unit, (2) a main control module, and (3) a lap-top computer for storing the results (Figure 2.3). Each of these components is briefly discussed below.

The accelerometer (Figure 2.4), a part of the sensor unit, is housed in a small case which is weighted down and mounted vertically inside the trunk of the vehicle. Similar to the SDP's, the accelerometer measures the vertical acceleration of the vehicle. The signal from the accelerometer is transmitted to the main control module where it is digitized and processed. There is also an optional signal from the speedometer to keep track of the speed at which the vehicle is operating. Vertical acceleration in conjunction with vehicle speed inputs are then used to predict road profile.

The main control module contains two Motorola 68000 microprocessors working in parallel; one performs input/output operations and the other performs numerical computations. Additional hardware includes an analog-to-digital converter, power supply, ROM and RAM chips, ports, and miscellaneous circuitry. The program for analysis of the profile is stored in ROM in this module. The WRD is portable and can be installed in a vehicle within minutes.

The data storage component is a portable Zenith personal computer with two floppy drives. A communication program WRD-PC provides interface between the control module and the PC. This program operates primarily in two modes: (1) terminal mode for debugging purpose, and (2) real-time mode for data collection. Additionally a voice unit, which is made up of a speech synthesizer,is connected to the Zenith and controlled by WRD-PC. It informs the operator of the status of the real-time operation using a series of preprogramed English words. This eases the work of the operator, who is also the driver of the vehicle. Further information on the program WRD-PC can be found in the Appendix.

The WRD, however, is not without faults. Its major disadvantage is that it is not entirely independent of the vehicle suspension system. Most of the vehicle's characteristics are accounted for by a dynamic calibration process used at the start of the operation of the WRD (hence the name "self-calibrating" for the device). This procedure involves using a statistical process to model the vehicle suspension system characteristics. The estimated profile is then computed with these characteristics removed. Previous studies found that there is no significant difference among cars within a class, but there exists a statistical difference between cars from different classes [WAL82]. Further action must be taken to remove this difference.

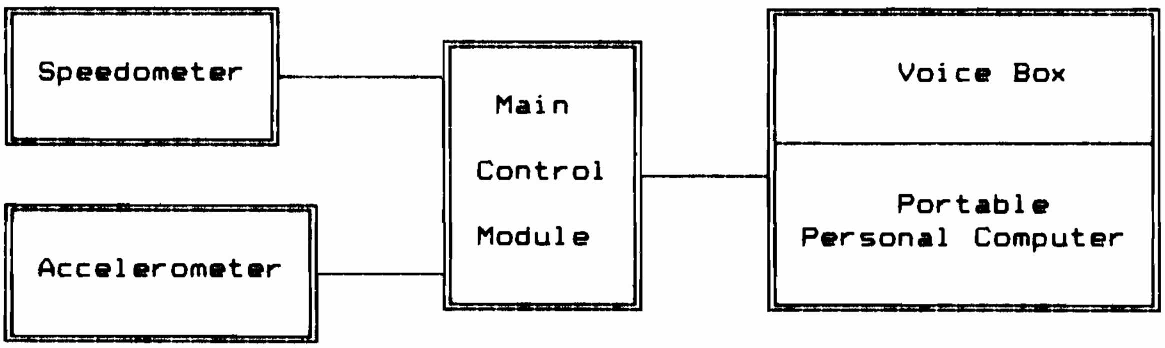


Figure 2.3. Three Components of the Walker Profiler Device: Sensors, Control, and Storage

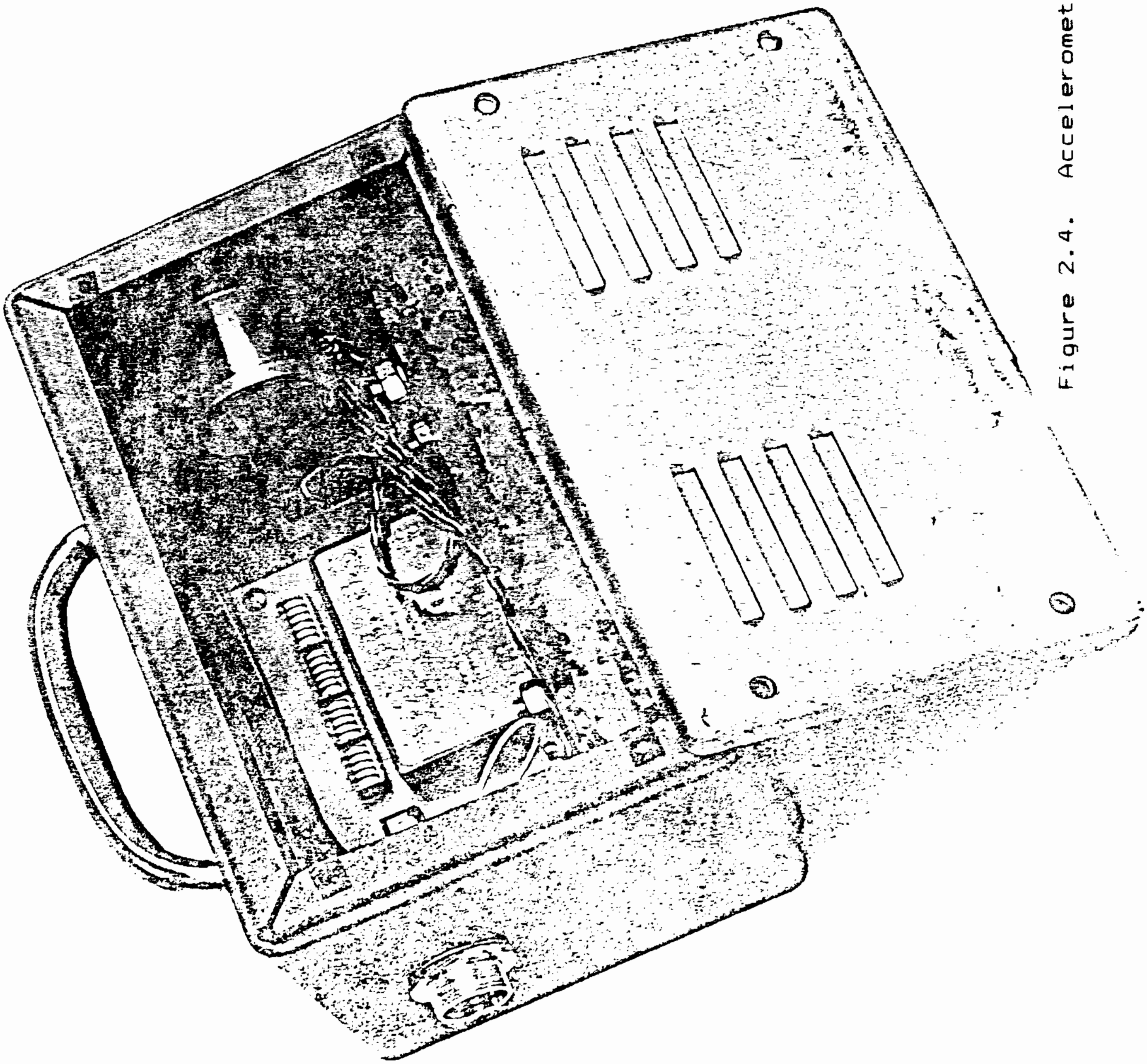


Figure 2.4. Accelerometer Sensor

As previously described, the WRD first calculates the slope variance from the estimated profile and then retrieves the SI value from the correlation table. Because of the above weakness, the device cannot use a single table to predict the SI value for all vehicle classes. Instead a table must be supplied for some vehicle classes. The WRD, in addition to performing self calibration, references the appropriate table to get the desired result.

The WRD predicts SI by means of the slope variance statistic, which is closely related to the first derivative of a pavement profile. Slope variance has been found correlated to road roughness [WAL82]. Mathematical foundation for this statistic is discussed in this reference.

Statistical Concepts

This section reviews fundamental concepts of statistics. Correlation analysis requires minimal understanding of these concepts. Further details can be found in most books in statistics and regression analysis (e.g., [NET83]). Additionally expert system development encourages the use of rules of thumb from experienced experts who are familiar with the problem.

An analysis unit (AU) is defined as the set of data that is necessary for analysis, namely a set of X and Y values. That is,

$$(WSV_i, PSI_i),\ i = 1, ..., n$$

where n is the number of data points (Figure 2.5). The problem in this study applies linear regression analysis involving one independent variable and one dependent variable. The model to be developed is of first-order, i.e. it is linear in the parameters B_0 and B_1 and the independent variable X, as follows:

$$Y_i = B_0 + B_1 X_i + \varepsilon_i$$

In this research, a regression function is obtained with the coefficients computed from suitable observed (collected) values SV_i and PSI_i, i=1,...,n. This function is then used to predict serviceability index given a slope variance value.

An outlier is an extreme observation that may be valid or invalid. If it is valid, an outlier may convey significant information, e.g. the applied model is inadequate. An outlier

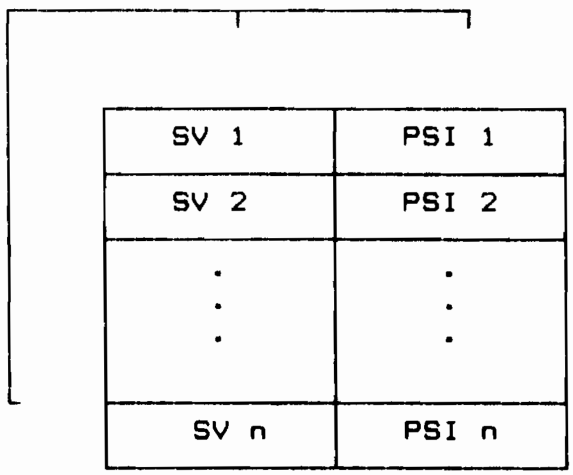


Figure 2.5. An Analysis Unit

may be invalid due to a mistake or other extraneous effect, as in recording or calculating the data, or equipment malfunctioning.

Outliers have been a subject of extensive study in statistics. Many methods have been developed to evaluate outliers. An important tool for detection of outliers is graphic analysis of residuals. A residual is the difference between the observed value and the fitted value.

An outlier should never be discarded automatically by a computer program. Human attention should be called upon and an investigation be performed to check for validity of the data.

A coefficient of determination r^2 is frequently used to describe the linear association between two variables. Sometimes the regression of Y on X follows a particular linear relation in some range of X, but follows a different linear regression elsewhere. The relationship between SV and PSI may follow this pattern. The final model consists of one or more pieces which are non-overlapping in the X direction. Each piece is modeled according to the method of least-squares linear regression. A number of special cases regarding the use of piece-wise regression must be handled by the program.

Two consecutive pieces can be either continuous or discontinuous, as shown in Figure 2.6. In a simple case, two pieces are continuous when the X coordinate of the point of intersection lies between the two pieces; otherwise they are discontinuous. In the final model, two discontinuous consecutive pieces may be connected by creating a third piece between them. In Figure 2.7, the slope of the pieces are of opposite sign. A warning message may be given to the user when such a situation is attempted. Figure 2.8 depicts how the final model may be completed by connecting the pieces together. This model consists of four pieces and can be expressed mathematically as follows:

$$\hat{Y} = 5 + m_1 X_1 + m_2(X_1 - P_2)X_2 + m_3(X_1 - P_3)X_3 + m_4(X_1 - P_4)X_4$$

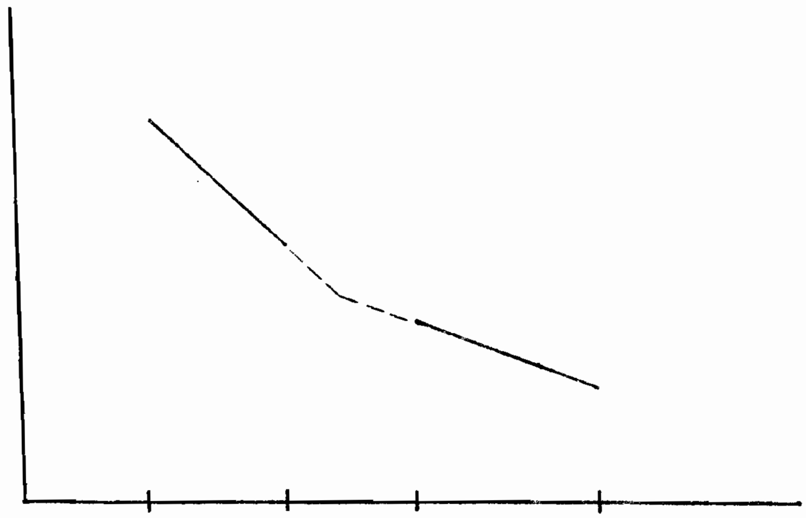
where:

m_i is the slope of piece i, i=1,...,4,

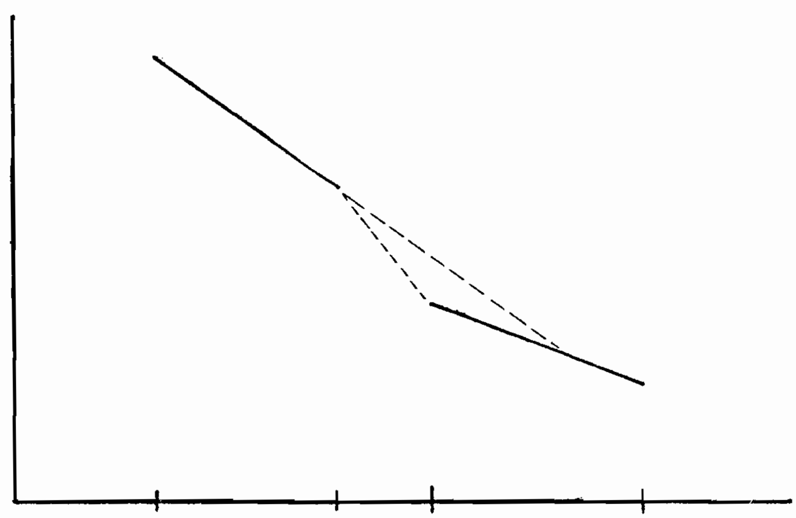
X_1 is the independent variable,

X_i = 1 if $X_1 > P_i$, 0 otherwise, for i=2,3,4,

P_i is the X-coordinate of the point of intersection between pieces i-1 and i, i=2,3,4.



(a)



(b)

Figure 2.6. Consecutive Pieces in Linear Regression: (a) Continuous (b) Discontinuous

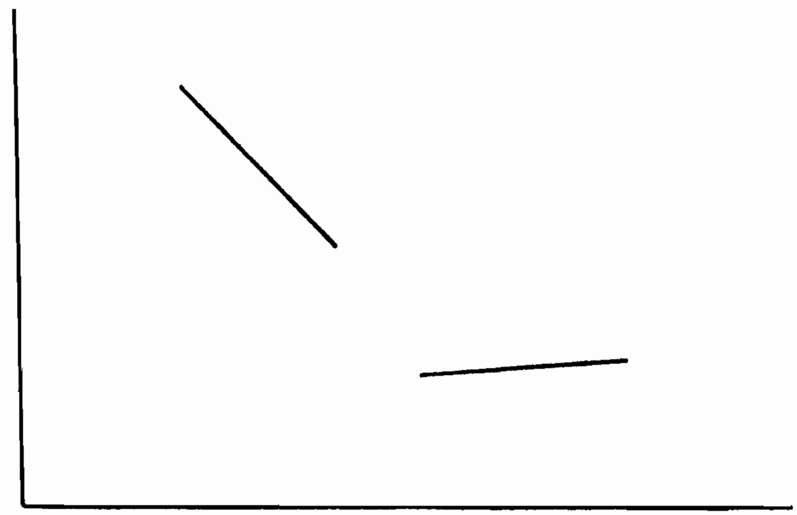


Figure 2.7. Two Pieces with Opposite Slopes

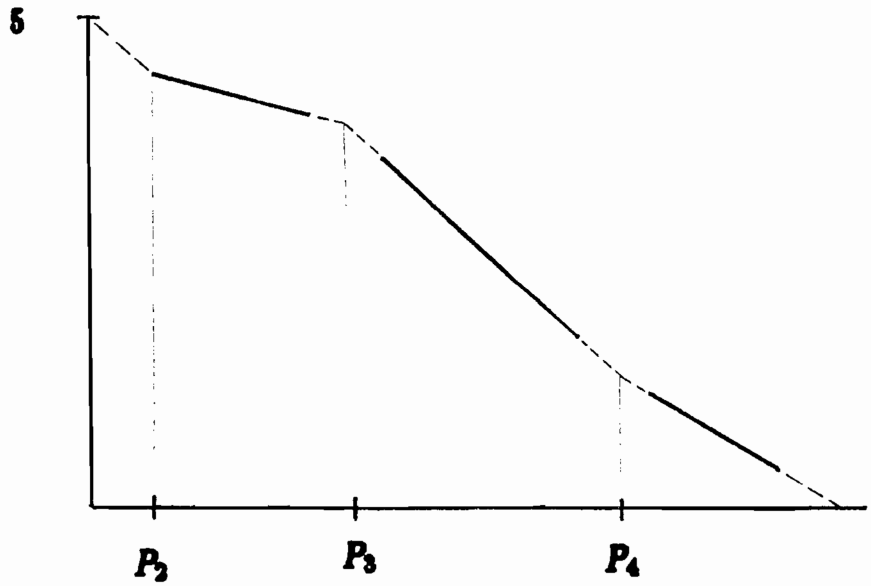


Figure 2.8. Connecting the Pieces

Correlation Procedure

Both devices, the SDP and the WRD, will be run on each of n selected road sections. Using the estimated profile from the WRD, a set of SV will be computed for each of the f filter values used in the modeling process. The filter is used to remove the long wave length or hills, where each model has a different filter cut off frequency. The SDP computes a PSI for each section.

Quite frequently two variables do not possess a linear relationship, or homogeneous variances in the random variables. In this case a transformation function must be applied to either or both variables in order to find a linear relationship between them before proceeding with linear regression analysis. A list of available transformation equations are as follows:

1. $SV' = 1 / \log SV$
2. $SV' = \log SV$
3. $SV' = \ln SV$
4. $SV' = \log (\log SV)$
5. $SV' = \sqrt{SV}$
6. $SV' = 1 / SV$

The goal is to obtain from transformation an AU on which it is valid to apply linear regression. One may begin by breaking the problem into two parts: selecting a filter value, and modeling the selected set of SV with the PSI. Experience has shown that the relationship between SV and PSI is non-linear. If a transformation is performed it must be validated. If data for a section is bad, it should be removed from consideration. Checking for bad data may be done by the method of outlier detection. A basis for filter selection is to analyze the data that provides the highest coefficient of determination between SV and PSI. To continue with linear regression, the validity of the selected SV and PSI data must be checked by performing tests for significance of regression and lack of fit. The final analysis may break the linear regression line into pieces (piece-wise linear regression). The results then must be transformed into the table format. This table will be stored in ROM and referenced by the WRD when the device is installed in the vehicle under test.

The above procedure will be further explored in the next chapter which guides the user through the process encoding the procedure into the expert system.

CHAPTER 3

IMPLEMENTATION

SDP-WRD is implemented for two types of users: (1) those who simply want to get results and are willing to accept suggestions from the program, and (2) those who are curious as to how a solution is selected as such, and why certain tasks must be performed during the correlation process.

Implementation of SDP-WRD requires:

1. Graphic environment - essential for data analysis
2. Numerical computing capability - necessary for computations of statistical concepts
3. Flexibility of statistical strategy - at least at the design stage
5. Efficiency in execution time - a requirement since typical users are not patient enough to wait a long time to get results
6. Using available computer, language, and support software

Explanation Facility

The statistical strategy to carry out the correlation analysis is represented using the tree structure. The feature nodes at the leaves of the tree represent the lowest-level sub-strategies dealing with graphics and computations. Because the tasks that they perform are not general enough, these nodes must be implemented individually as procedures within SDP-WRD. Other nodes can be classified as high-level sub-strategies which are structured similar to frame-based representations.

Three basic questions are expected to be asked by the user of the expert system: what, how, and why. Some typical such questions include:

. What is the filter used for?

. How is it that the data for this section is bad?

. Why is the lack-of-fit test being performed?

Specifically, at many points in the program the user may query the system and the system will respond with the information which is relevant at that time. Responses may involve looking up a small dictionary of terms related to the problem (definition of "filter"), explanation of a statistical method (detection of outliers) or test (to satisfy model assumption).

Explanation facilities permit communications with the user during the session. Unless the user is quite familiar with the problem domain, "what" answers can provide the bridge in helping the user understand the problem more fully, especially with the use of special terminology in a particular context of the problem. Answers to "how" and "why" can be inferred from the statistical strategy through the current frame of high-level sub-strategies or the implemented procedures of low-level sub-strategies as presented above.

Development Environment

Because SDP-WRD is developed as an application of an expert system, AI resources are considered in designing the possible development environment. One constraint is that the program be developed on a popular microcomputer, such as the widely-available IBM-PC. A LISP machine (TI-Explorer), although accessible, is immediately precluded because of its limited availability for use. Languages and support software are carefully considered. AI languages such as LISP and PROLOG provide dynamic manipulation of knowledge structures and are particularly good for symbolic processing but normally perform poorly in numerical processing. SCHEME, a LISP language on the Texas Instruments Professional Computer, offers a limited graphic environment and slow processing speed. Not every application can utilize an AI language for its development phase. Some of the recent expert systems were written in C (or rewritten in C after their pilot phase) to achieve efficient speed. Error handling is another consideration; messages like "unbound variable" or "array out of bound" are meaningless to the users. SDP-WRD was developed in Turbo Pascal which provides many desirable features for the system, including efficient numerical processing, especially with the math co-processor, and graphic capability using Graphix Toolbox. Errors can be well customized for a given situation so the program can create a more friendly environment for the user.

Report

At the end of each session, a report is written to record the activities performed, including inputs from the user. A plot of the final model is an important product from the program. Included in the report are the model's parameters, such as slope, y-intercept, the number of pieces, range of each piece, etc. Ultimately the user is interested in the model in the form of a table that can easily be copied to a ROM chip. Other statistical values are also printed, such as standard deviation, variance, coefficient of correlation, etc. Interpretation is given to explain meanings of these values and how their use affects the results.

User Interface

In normal operation the physical screen consists of three windows as shown in Figure 3.1. The plot concerning the analysis unit being considered is displayed in the top left window. Various kinds of scatter plots and the residual plot are used. An interactive plot allows the user to observe the dynamic modeling process of piece-wise linear regression; the model changes are graphically illustrated to the user. The top right window shows the statistical information about the plot; the information shown depends on the kind of plot being displayed. The bottom window is where conversations between SDP-WRD and the user take place. In this window the user can be informed of the status of the process, instructed on how to proceed, or provided with commands for more control of the process if desired. In addition many pop-up windows of various sizes supply the user with additional information, including

- list of filters and coefficients of corresponding AUs
- list of input data values
- an error or warning message when an invalid condition occurs
- current working environment, detailing what has been done and what remains to be done
- etc.

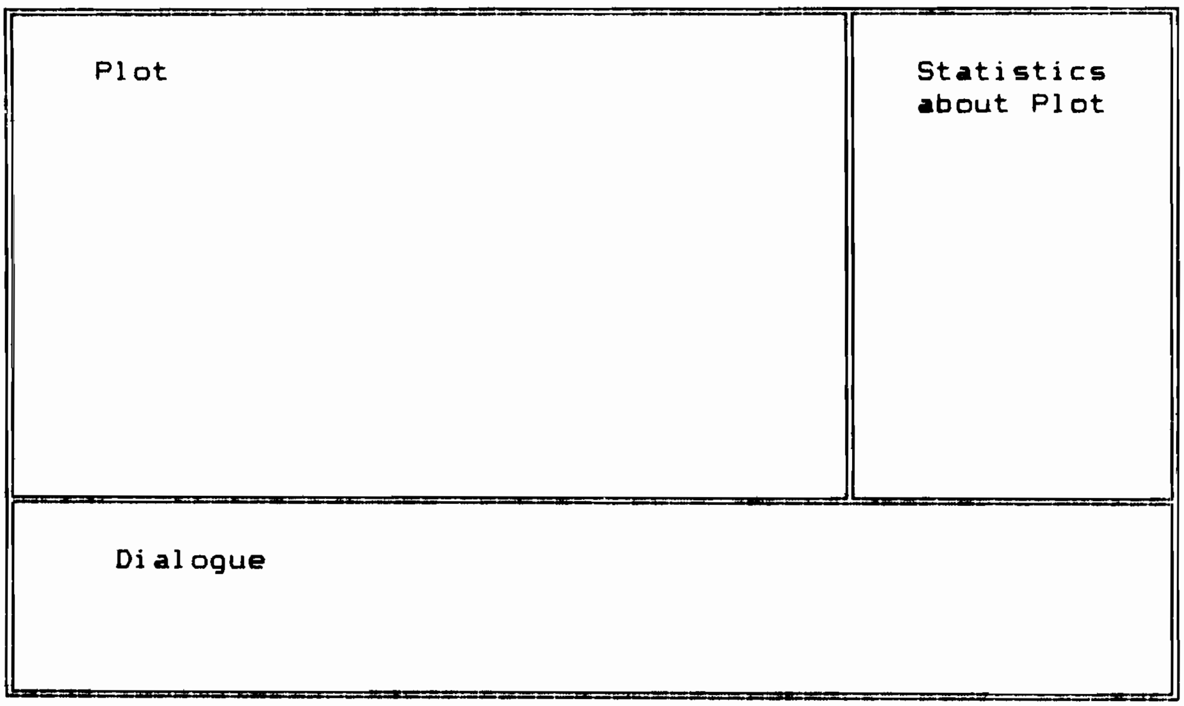


Figure 3.1. Typical Screen in SDP-WPD

A typical user may elect to start the program in automatic mode and have no further interaction with the program until it completes its processing and produces a correlation table. Alternatively, the user may start the program in normal mode in which the user has full control of the correlation process.

CHAPTER 4

WRD STUDIES

This chapter provides a description of studies conducted to determine the usefulness of the Walker Roughness Device for roughness measurements. More extensive usage of this device is currently in progress and will be reported in the profiling implementation project mentioned in Chapter 1.

Statistical Modeling Procedures

As previously discussed, the WRD determines the characteristics of the vehicle it is installed by an AR or ARMA process. (The development of the concepts used in this procedure are described in the references and will not be included in this report.) Although earlier studies considered ARMA processes, none of the ARMA models were found to be superior to the current AR procedure used. The ARMA models have the advantage of less real-time computations, however, have the disadvantages of difficult computational procedures in determining the model coefficients. Both methods have the problems of determining an adequate model. Because of earlier problems in model stability, several other statistical methods were investigated. Lattice filters provide some of the better methods currently used since they result in generation of orthogonal coefficients. Such methods have the advantage of determining how much each new term adds to the correctness of the model. Specifically Burg's Lattice method has this feature. Variations of both direct and lattice methods using Burgs methods were investigated. Several of these methods were compared to the current AR procedure, however they did not result in any significant improvements.

It is believed that many of the problems experienced with earlier versions of the unit was because of hardware. In the next section several plots are given illustrating the use of the WRD for collecting SI measurements.

WRD Data Collection

The WRD has been used this past year to determine its practicality as a roughness measurement instrument. Figure 4.1 illustrates the correlation of slope variance values obtained from the predicted profile from the WRD to PSI computed from profile obtained from the SDP over the same road sections. As noted an R-squared of 0.924 was obtained. The data runs for this correlation was performed in October of 1985.

The correlation is not to be confused with the calibration procedure used with the Mays Ride Meter. The MRM is calibrated perhaps as much as several times a year, where the inches of displacement per mile is correlated to PSI in a similar manner as done in the WRD correlation procedures. The WRD on the other hand is calibrated only once per car class or classes. The WRD is then dynamically calibrated each time the unit is used. As discussed earlier, this calibration takes only a few seconds, where the vehicle the WRD is installed is driven over a road with a PSI of a value within the range of 2.5 to 3.5. The WRD for the correlation shown in Figure 4.1 was installed in a 1983 Ford LTD.

Figure 4.2 illustrates data runs of the SDP with the WRD. The WRD was installed in the same car as the original correlation, however, the data runs shown were done in June and July of the following year. The SI values shown for both the SDP and the WRD is the average of three runs.

Figure 4.3 provides a comparison between the SDP and the WRD when the WRD was installed in a 1986 Celebrity. The data runs were made in July and August of 1986. The same correlation model derived from the data runs in the LTD during October of 1985 were used. Figure 4.4 provides a plot of two data runs with the SDP along with the Celebrity and LTD. Thus the dynamic calibration process appears to work well for both of the two car classes.

The estimated profile from the WRD is currently being investigated. It is being used directly by the SDP-PSI VERTAC program with good results. The WRD appears to provide close estimates of road profile to that generated by the SDP for wavelengths of two feet and greater. More in these studies will be given in the report on the implementation project mentioned in Chapter 1.

Because of these and other positive results the Department has begun to use the WRD for SI measurements in the State.

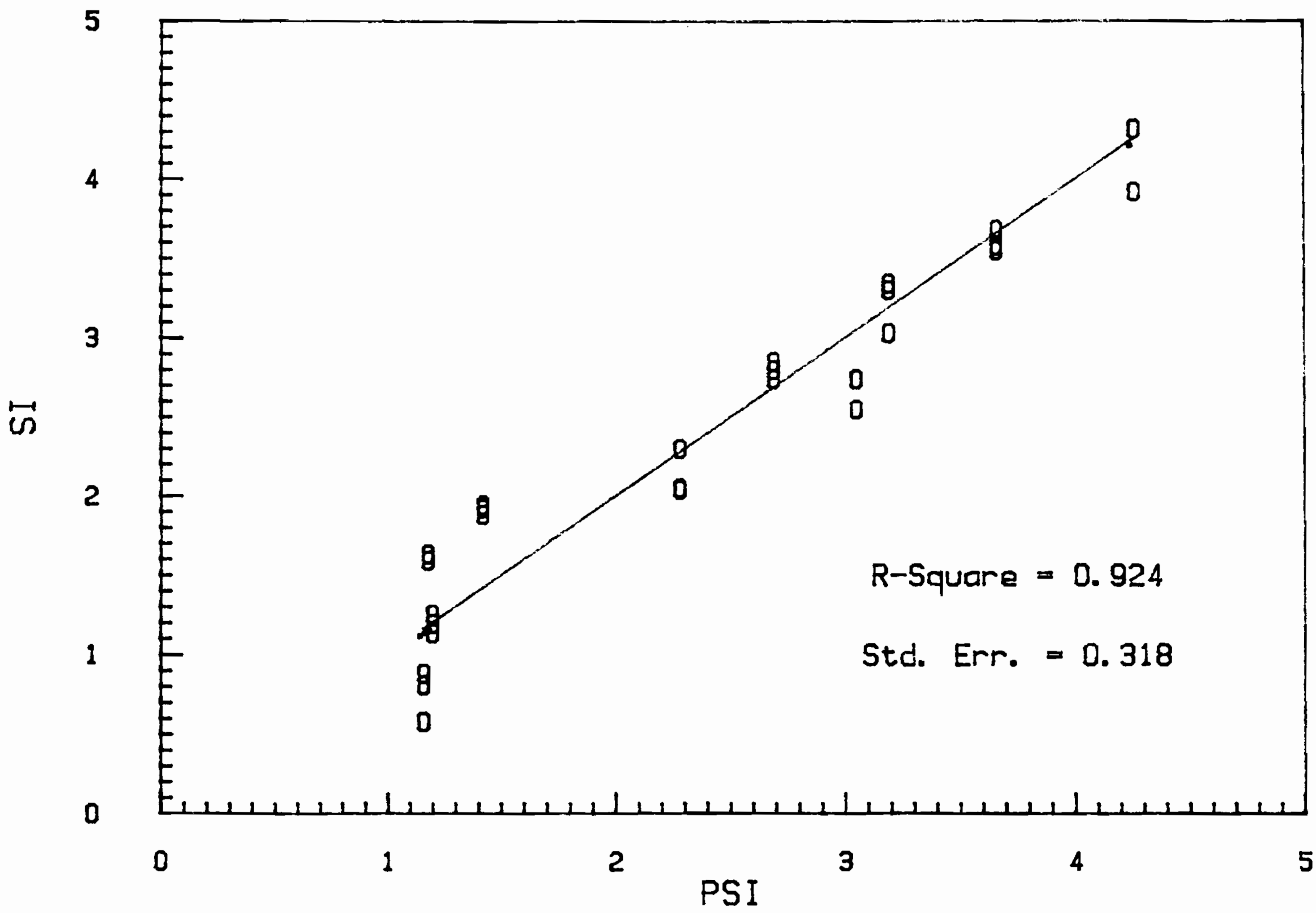


Figure 4.1. WPD - SDP Correlation

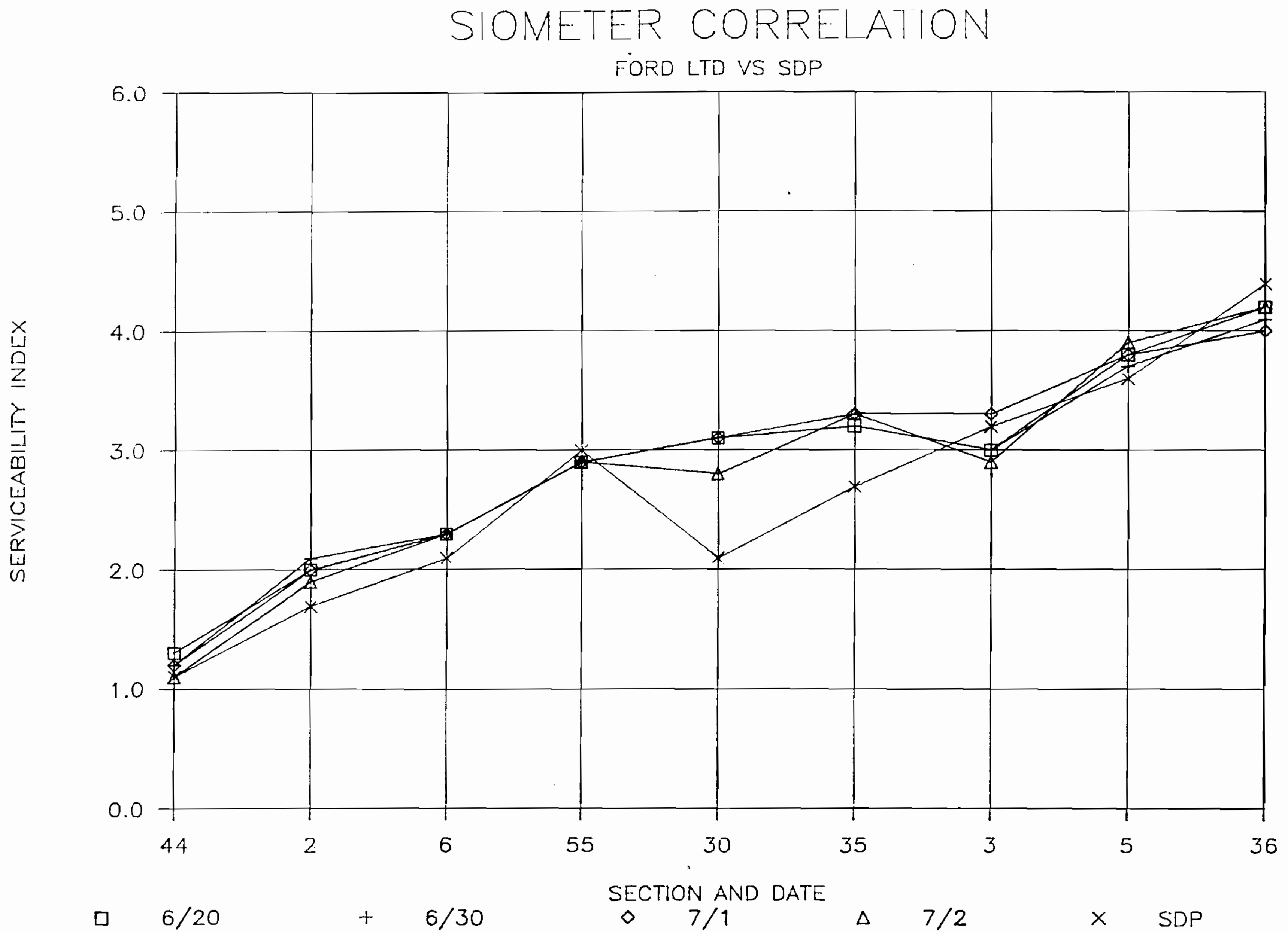


Figure 4.2. WPD vs SDP - Ford LTD

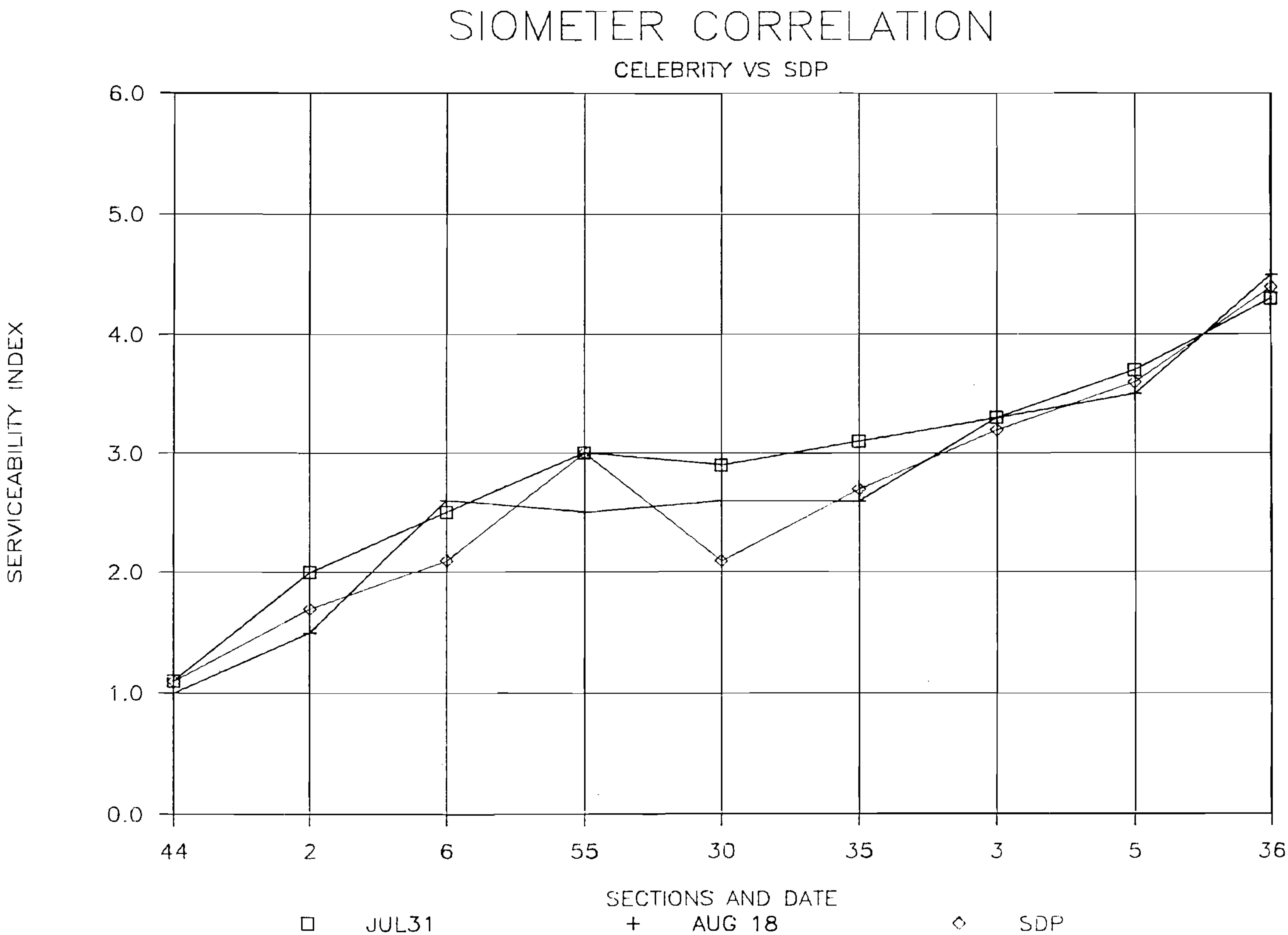


Figure 4.3. WPD vs SDP - Celebrity

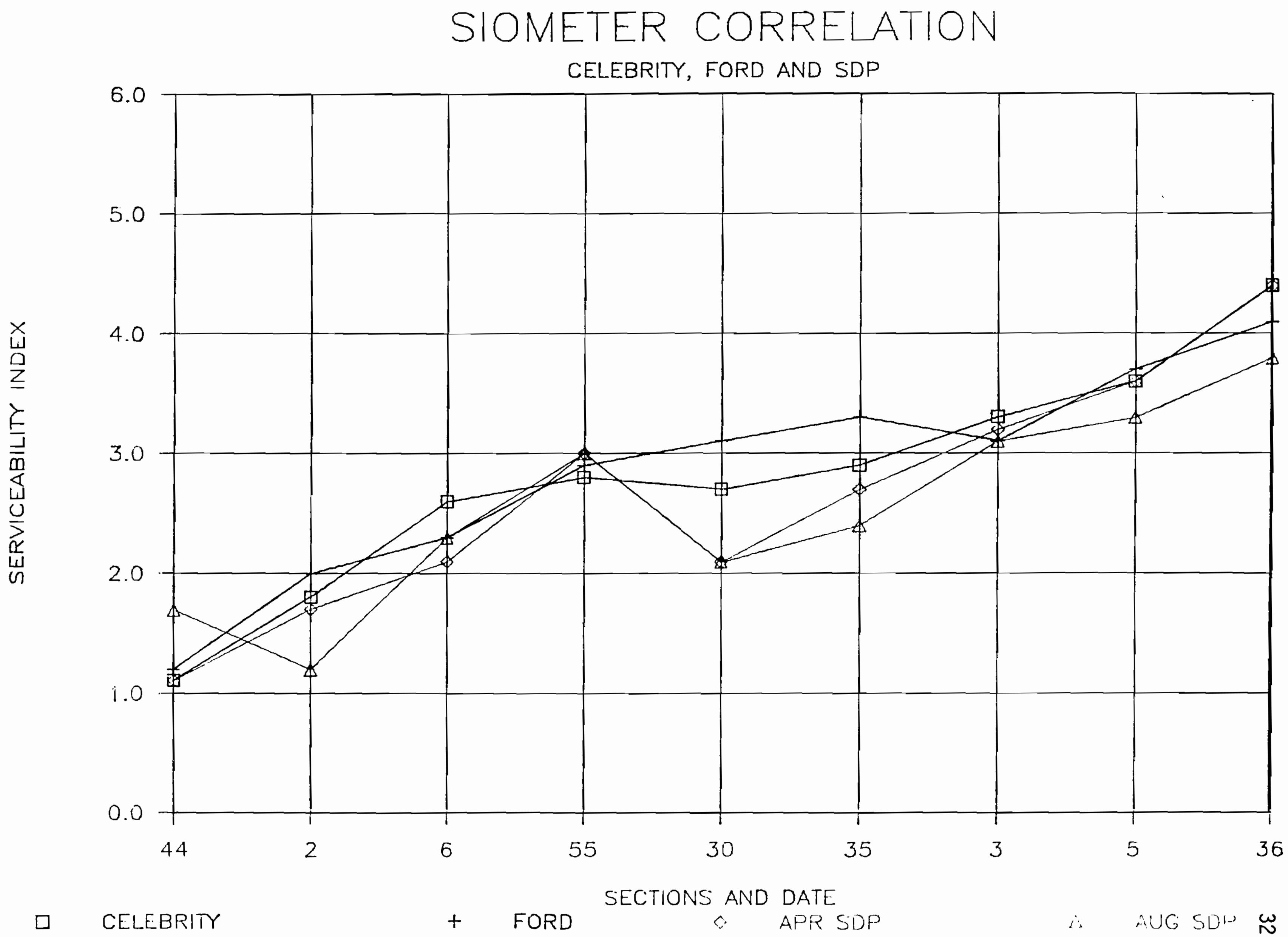


Figure 4.4. WPD vs SDP - Ford LTD and Celebrity

CHAPTER 5

SUMMARY

This report describes results of research intended to develop procedures for making the Walker Roughness Device a usable instrument for obtaining roughness information for the State. To this end the project was a success. The WRD is ready and is currently being used in the State for collecting serviceability index data. It has been found to provide a stable roughness measurement which correlates well with the SDP. In the project the following accomplishments were obtained:

A stable model relating SI from the WRD to PSI obtained from the SDP for two car classes was developed. Software and hardware to permit one man operations of the WRD has been developed. A program was developed for the Zenith PC which provided an interface between the WRD and the user. Speed, roughness and distance measurements are sent to the PC from the WRD for storage. This data may then be easily entered into the Pavement Evaluation System.

The WRD has been used for data collection and is currently being used for providing roughness information.

An expert system was developed for the procedures of providing a correlation analysis between PSI from the SDP and slope variance from the WRD. The program includes many features that are desirable in determining new models between different car classes with the WRD and the SDP. Preliminary tests indicate it is a working tool that provides reasonable models for the Walker Roughness Device.

APPENDIX

WRD-PC Interface Program

WRD-PC is a communication program interfacing the Walker Roughness Device with a portable personal computer (Zenith 171). Its purpose is twofold: (1) to store data obtained from the WRD, and (2) to assist the operator in using the device.

The WRD is installed in a vehicle and operated by the driver. A voice box can be connected to the PC to ease the work of the operator. From the main menu, the operator can

1. create a header file

2. enter real-time (collect) mode

3. enter terminal (debug) mode

A header contains information about a continuous segment of road whose roughness is being evaluated. A segment contains multiple sections; each section is two tenths of a mile long. The WRD produces an SI (along with other information, such as speed and profile) for each section. Header information includes highway name, beginning mile post, operator, date, etc. During a session the operator may wish to run a number of segments of road. A collection of headers

for these road segments can be stored in a file. The first selection from the main menu allows the operator to create such a header file.

```
                   Segment  (Number of sections)

             /        1     (5) |---|---|---|---|---|
            /
           /          2     (2) |---|---|
          /
Session  <            3     (4) |---|---|---|---|
          \
           \                     . . .
            \
             \        s     (7) |---|---|---|---|---|---|---|
```

To collect the data, the operator enters the real-time mode. A header must be provided, either from a header file or as being specified interactively. The collected data can be saved onto the floppy diskette in one of the disk drives of the PC.

By entering the terminal mode the user can execute commands of the monitor which is resident on the control module of the WRD. These commands are useful to the designer/developer of the device primarily during the development and testing phase. The operator normally does not need to utilize this mode. Therefore, this option is available but not visible to the operator.

WRD-PC is written in GWBASIC and uses a program diskette and a data diskette for processing. By default the program diskette is inserted in drive A and the data diskette in drive B of the PC.

The program diskette contains the system (bootable) and the following files:

- AUTOEXEC.BAT allows the computer to automatically start the interface program when the computer is turned on or re-booted

- BASICA.COM
- BASICA.EXE BASIC interpreter (GWBASIC)

- WRD-PC.BAS source code of WRD-PC

A data diskette is used to store collected data as well as header information.

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