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FACTORS AFFECTING THE ACCURACY OF ROAD PROFILERS MEASUREMENTS

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by

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Preface

This study describes a study conducted at the University of Wyoming to evaluate the various factors affecting the accuracy of Road Profilers measurements. Highway agencies across the U.S. use Road Profilers to measure roughness and rut-depth characteristics of pavements. These measurements are utilized by the Federal Highway Administration to assess the health of the national pavement network. Therefore, consistency in measurements among states is essential. This research was conducted to examine the different factors that affect consistency of roughness and rut-depth measurements. These factors included: errors caused by differences in equipment being used, human operators, and environmental conditions. In addition, the study involved comparing results from four commonly used rut-depth measurement techniques.

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EXECUTIVE SUMMARY

The main objective of this study was to evaluate several factors affecting the accuracy of Road Profilers measurements. These factors included: errors caused by differences in equipment being used, human operators, and environmental conditions. A secondary objective was to compare rut-depth measurements with the following most commonly used techniques: five-sensor road profilers, three-sensor road profilers, straightedge, and the theoretical water capacity of ruts. This research study was performed in three phases. The sections below present important results and conclusions for each phase.

PHASE I: CONSISTENCY OF ROAD PROFILERS MEASUREMENTS

To evaluate the consistency of roughness and rut-depth measurements, eleven South Dakota type Road Profilers and four pavement types were included in the analysis. A total of eight test sections were selected representing a wide range of roughness and rut-depth variations experienced nationwide. IRI and rut-depth data were then collected by running the participating Road Profilers three times on all test sections. Data analysis was then carried out using regular statistical tools and the major findings are presented herein:

1. Roughness and rut-depth measurements obtained with any single system seem to be repeatable.

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2. Roughness and rut-depth measurements obtained with all systems were statistically different in most cases.

3. Regression analysis resulted in very strong linear relationships among systems

PHASE II: EFFECT OF ENVIRONMENTAL AND HUMAN FACTORS ON PAVEMENT LONGITUDINAL PROFILE MEASUREMENTS

This phase concentrated on examining the effects of operator and environmental conditions on the repeatability of longitudinal pavement profile measurements. This examination consisted of collecting IRI and rut-depth data by three operators on 36 test sections in addition to monitoring a single test section for various environmental conditions. The following important conclusions were derived after performing the statistical analysis:

1. Roughness measurements obtained by three operators were statistically equal in most cases. On the other hand, rut-depth measurements obtained by different operators were statistically different in 20 percent of the cases.

2. Regression analysis yielded a fairly good linear relationship between IRI and two environmental factors, indicating that pavement roughness does fluctuate due to changes in environmental conditions.

PHASE III: COMPARISON OF RUT-DEPTH MEASUREMENTS OBTAINED WITH FOUR DIFFERENT TECHNIQUES

The third and final phase of the study involved comparing the following four rut-depth measuring techniques: three-sensor road profilers, five-sensor road profilers, straightedge, and theoretical water capacity of ruts. The design of experiment consisted of selecting profiles of different shapes and then extracting rut measurements from them. The statistical analysis resulted in following important conclusions:

1. Five-sensor and three-sensor Road Profilers do produce statistically different rut measurements. Similarly, straightedge and theoretical water capacity of ruts produced statistically different results.

2. Regression analysis yielded strong non-linear relationships among the four techniques when all profiles were analyzed.

3. The correlation between measurements from three-sensor and five-sensor profiles resulted in high R^2 irrespective of transverse profile shape. Correlations between high speed techniques and manual techniques, however, were influenced by the profile shape.

CHAPTER 1

INTRODUCTION

by

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BACKGROUND

Highway agencies use roughness and rut-depth measurements to monitor the condition and performance of their pavement networks. The existing conditions of pavements, measured by roughness, determine the distribution of available funds for highway allocation such as providing routine maintenance or reconstruction of pavement sections. In addition, roughness measurements are often employed as the dependent factor or relative to the evaluation of new or modified pavements, pavement maintenance, materials, or construction techniques.

During the last few decades, roughness response devices were the primary instruments to measure pavement roughness. Results from these devices were known to be affected seriously by the condition of shock absorbers, wear and pressure of tires, and vehicles. These uncertainties greatly reduced the level of confidence in the data and demanded that consideration be given to the development of a more accurate and positive apparatus.

In the early 1980's the South Dakota Department of Transportation (SDDOT) developed and built a highway profiling and rut-depth measurement system. This equipment, referred to as a Road Profiler, operates at highway speeds and measures pavement profile only in the left wheel path. Pavement profile can be then converted to any computerized roughness statistic. Over the years, quantifying roughness from pavement profiles proved to be much more accurate and reliable than depending on the point response of a vehicle.

The SDDOT shared the Road Profiler technology with several other highway agencies. The demand for road profilers has become so great that they are now built commercially. Today, eight states have duplicated the road profiler in-house and about two dozen others have purchased commercially manufactured systems. The following two reasons are behind the fast spread of this technology:

a. The Federal Highway Administration (FHWA) requirement that pavement roughness measurements be reported in International Roughness Index (IRI) units [18].

b. The relatively low cost of road profilers when compared with other available technologies.

The increased interest in the use of Road Profiler for roughness measurements brought all the states that possessed this equipment together, leading to the formation of the South Dakota Road Profiler User's Group (SDRPUG) in 1989. All group members meet annually to share system improvement information, and attempt to meet federal requirements for calibration of class-II profiling devices.

PROBLEM STATEMENT AND OBJECTIVES

When looking at the accuracy of Road Profilers, most agencies are mainly concerned with hardware precision rather than the errors caused by differences in the equipment being used, human operators, or environmental conditions. The main objective of this research project is to determine the effect of these factors on the accuracy and repeatability of roughness and rut-depth measurements. A secondary objective is to examine the relationships among the following four commonly used rut-depth measuring techniques: five-sensor road profilers, three-sensor road profilers, straightedge, and the theoretical water capacity of ruts. To accomplish the above objectives, extensive data were collected, analyzed, and then conclusions were drawn. It is believed that the findings of this major study will provide a better understanding of various factors that affect the accuracy of roughness and rut-depth measurements obtained by road profilers.

SCOPE OF RESEARCH AND REPORT ORGANIZATION

This research project was performed in three separate phases as shown in Figure 1.1. The first phase involved analyzing IRI and rut-depth measurements collected during the third Annual South Dakota Road Profiler User's Group (SDRPUG) Meeting in Minnesota in 1991. The data collected by various Road Profilers were reduced and analyzed statistically. The findings of this phase are presented in Chapter III.

The second phase aimed at examining the major environmental and human factors affecting the repeatability of pavement longitudinal profile measurements. To examine the effect of different combinations of environmental factors, a test section was monitored and tested repeatedly in the 1991 testing season. To investigate the effect of the operator, data were collected on several sections having varying levels of roughness and rut-depths. The entire data collected were then statistically analyzed and conclusions were drawn. The findings of this phase are provided in Chapter IV. The third phase of the study concentrated

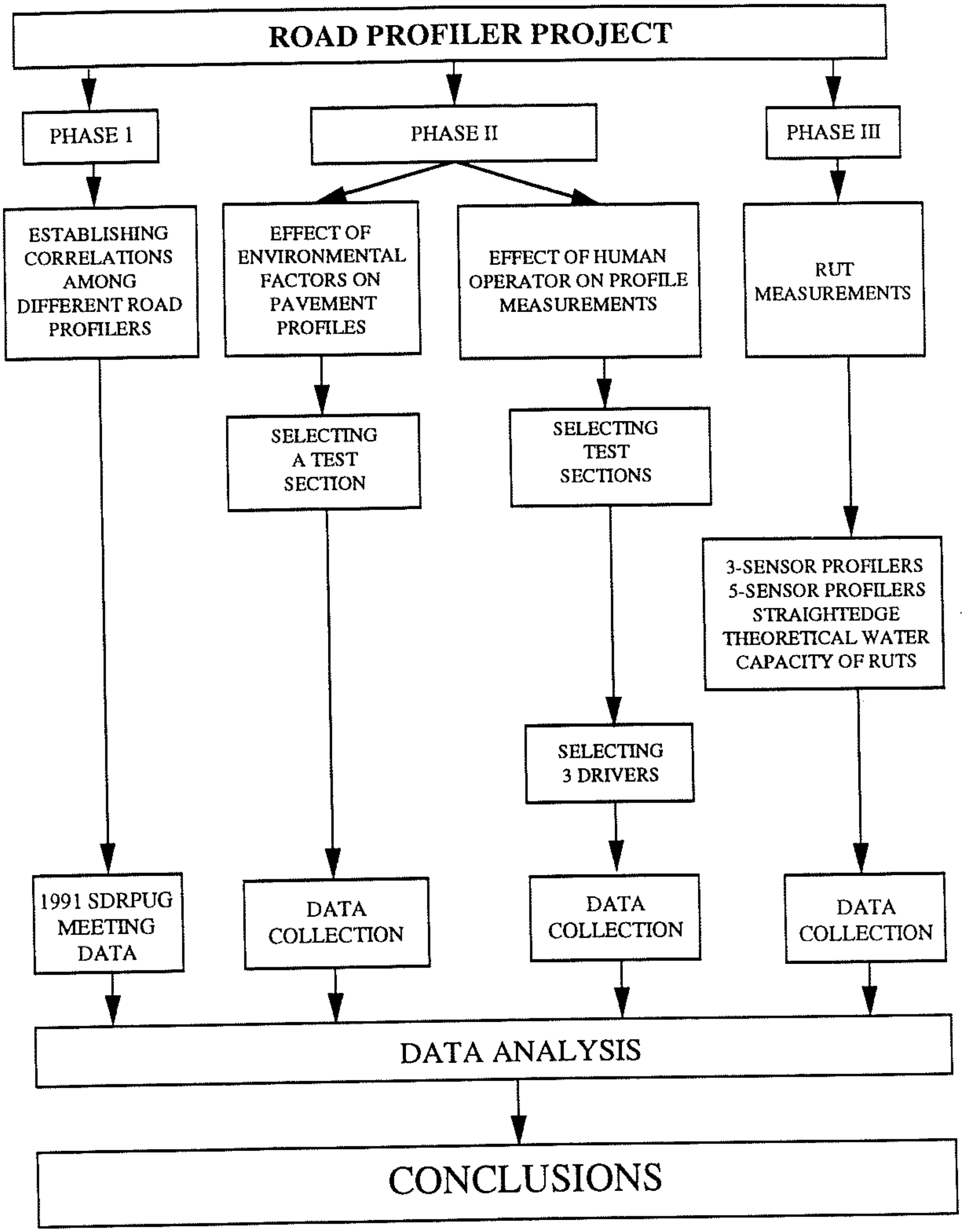


FIGURE 1.1. Overall Design of Experiment

on comparing rut-depth measurements obtained with four different techniques. These techniques were: five-sensor road profilers, three-sensor road profilers, four-foot long straightedge, and the theoretical water capacity of ruts. The study consisted of selecting transverse profiles of varying shapes, extracting rut measurements by four methods, and conducting statistical analysis. This analysis resulted in several regression models correlating rut-depth measurements collected with all four techniques. Findings of this phase are provided in Chapter V. Finally, a summary of the entire research, conclusions, and recommendations for future research are presented in Chapter VI.

CHAPTER 2

LITERATURE REVIEW

The concern about roughness of pavement surfaces precedes the development of motorized vehicles. Pavement engineers have always been concerned with providing pavements of acceptable serviceability. The serviceability of a highway segment, which is largely a function of pavement roughness, is a widely used criterion for deciding when pavements are in need of rehabilitation [Emmanuel at al. 1990]. In early days, a simple straightedge was used as the sole indicator of pavement roughness. But even before the turn of the century, efforts were directed at developing improved devices for roughness measurement. From 1900 to near mid-century, numerous devices of varying complexity were invented. These were primarily mechanical devices with elaborate multi-wheeled support systems. Advances in several technological areas have now been applied to roughness-measuring equipment, resulting in the incorporation of electric circuitry, electronics, ultrasonics, lasers, and computerization [NCHRP 1990, NCHRP 1986]. This chapter discusses roughness, rut-depth, and various causes associated with them. In addition, it also discusses in detail the evolution and description of various types of rut-depth and roughness measuring instruments.

PAVEMENT ROUGHNESS

Road roughness can be defined as "the deviations of a pavement surface from a true planar surface with characteristic dimensions that affect vehicle dynamics, ride quality, dynamic pavement loads, and pavement drainage" [Wambold et al. 1981]. In other words, roughness can be described as vertical surface undulations that affect vehicle operating costs and the riding quality of that pavement as perceived by the user [Ksaibati et al. 1993]. Pavement longitudinal roughness is an important data component in any pavement performance evaluation. Pavement roughness is best characterized by pavement profile since various research results have shown that the primary factor affecting the rating of pavements is longitudinal distortion. These longitudinal disturbances of various frequencies and amplitudes can set up oscillations in a vehicle traveling over pavement surface [Rogers et al. 1991]. Likewise, transverse distortions can cause discomfort to passengers [Yoder & Witczak 1975]. Roughness measurements for in any state, therefore, plays a key role in future construction and maintenance decisions.

Roughness Measurements

Highway design speeds, which have increased steadily with the development of the automobiles, demand that long and flowing ribbons of pavement be maintained in a very smooth condition so that the traveling public will be served adequately [Hudson 1967]. Yearly roughness surveys are conducted on all highway segments which are particularly useful in monitoring rapidly deteriorating pavements [Pavement Profile Measurement Seminar 1988]. Measurement of pavement roughness, therefore, has become a subject of concern to most highway engineers, including designers and maintenance personnel. Pavement roughness is measured for several reasons, a few of which can be stated from

1. To measure acceptability for newly constructed pavements.
2. To assist the maintenance engineer and the highway administrator in determination of optimum maintenance programs.
3. To aid in the establishment of priority for major maintenance, reconstruction, and relocation projects.
4. To furnish information needed for sufficiency ratings and need studies. This involves a comprehensive study of pavement systems within a given area.
5. To assist in determination of the load carrying capacity of the pavement as to both volume of traffic and loads.
6. To aid the design engineer in determination of the degree of success with which his design has met the design criteria and help him learn causes for failure.
7. To serve as the basis for new concepts and designs.

The following sections explain parameters used to express roughness of a pavement.

International Roughness Index (IRI)

IRI is a standardized measurement of roughness which can be defined as an objective measure of roughness of a pavement section and is used to rate the severity of roughness experienced by a vehicle traveling on the road. It is the only existing roughness index that has been demonstrated to be reproducible with a wide variety of equipment, including single- and two-track profiling systems, rod and level, and RTRRMs [Sayers 1990]. IRI is generally reported in metric units of millimeters/meter or meters/kilometers [U.S. Dept. of Transportation 1989]. The IRI was originally developed for The World Bank, based on a continuation reported in metric units of millimeters/meter or meters/kilometers [U.S. Dept. of Transportation 1989]. The IRI was originally developed for The World Bank, based on a continuation of research that was begun in an NCHRP project [Sayers et al., Gillespie 1980]. The computation of IRI is often done by numerically simulating the response of generic vehicle-with standard mass, spring constants, and damping constants-to the profile. To simplify the computation, only one corner of the vehicle is considered, leading to the term "quarter-car simulation" [U.S. Dept. of Transportation 1989].

Present Serviceability Index (PSI)

PSI is a commonly used objective measure of serviceability a road provides to its users. It is based upon the concept of correlating user opinions with measurements of road roughness, cracking, patching, and rutting [Yoder & Witczak 1975]. This index is formulated by rating a series of pavements by a group of individuals on a 5-point scale. A rating of 5 indicates a perfect pavement (one that conceivably does not exist) whereas a rating of 0 is an exceedingly poor pavement.

ROUGHNESS MEASURING DEVICES

Road roughness in the United States is measured primarily by two types of equipments: equipments that measure a vehicle's response to roughness, or response-type road roughness meters (RTRRMs), and equipments that measure road profiles, or profiling devices [Pong & Wambold 1992]. Table 2.1 summarizes various equipment available for measuring longitudinal roughness. The section below discusses few of these pavement

TABLE 2.1. List of Roughness Measuring Devices

Device	Operating Principal	Source
Straightedge	Actual variation in road profile	-
Rolling Straightedge	Actual variation in road profile	-
Mays Ride Meter	Response Type	Rainhart Co., Texas
Model 690D Profilometer	Inertial Profilometer	K. J. Law Engineers
Model 8300 A	Inertial Profilometer	K. J. Law Engineers
Cox-meter/PCA mater	Response Type	James Cox Co.
PURD/ARAN	Housing Mounted Accelerometer	HPI - Ontario, Canada
Swedish Laser RST	Multipurpose Device (Accelerometer and laser sensors)	Novak, Dempsey and Assoc., IL
FHWA PSM	Noncontact sensors	Earthtech, Inc. Baltimore, MD
Rainhart Profilograph	Multiple wheel profilograph	Rainhart Co, TX
California Profilograph	Multiple wheel profilograph	California
A P L	True profiling	LCPC, Paris, France
South Dakota Road Profiler	Profilometer principle	South Dakota DOT
RODRECON (1 in 3)	Accelerometer and laser sensor	PASCO, Japan

roughness-measuring equipments in detail, including the basic types as well as variations that have evolved in certain models [Hudson & Uddin 1987].

Straightedge

The straightedge is usually 8 to 16 feet long and is made of wood or metal. A wire or string stretched out from the ends of a bow shaped form is sometimes used. When it is placed on a pavement surface, variation in distance from the bottom of the straightedge to the pavement surface are readily observed and measurements of these variations can be made. The principle of the straightedge is used in a variety of construction applications. At one time it was undoubtedly the only tool to evaluate pavement roughness. This tool is very labor intensive for large projects; thus most application are limited to the evaluation of localized areas. Although straightedge is useful in defining local surface aberrations, accuracy diminishes as the wavelength of the bump increases beyond about one-half the length of the straightedge [NCHRP 1990, NCHRP 1986].

Rolling Straightedge

A rolling straightedge is merely a straightedge with a wheel (or wheels) under each end. Located at its midpoint is third wheel, which also rides on pavement surface. This wheel is linked to some form of indicator that shows deviation from the plane of the rolling straightedge. These devices have proved to be somewhat impractical for general use because of their slow speed of operation and their inability to provide adequate definition of pavement roughness [NCHRP 1990].

Profilographs

Road profilographs are low-speed devices (hand-pushed at walking speed) designed to measure the roughness of road surfaces [Kulakowski & Lin 1991]. They are used primarily to measure the roughness of new or newly surfaced pavements before they are open for traffic. Profilographs consist of a rigid beam or frame with a system of support wheels that serve to establish a datum from which deviation can be evaluated. They are somewhat more sophisticated than the rolling straightedge because they create an analog record of surface deviations. A "profile" is located at the midpoint of the unit and is attached to a strip chart recorder in order that variation in the vertical movement of the profile wheel from the established datum can be recorded. Profilographs come in several different designs. The two most commonly used profilographs are the Rainhart Profilograph and the California Profilograph [Kulakowski & Lin 1991]. Both devices use a long, rigid member or main truss supported through minor trusses by 12 wheels. The supporting wheels provide a reference platform for the measuring wheel located at the center of the main truss. As the profilograph is pushed along the pavement, the vertical motion of the measuring wheel is recorded by a tracing pen on a strip chart recorder to provide the measurement of surface profile. Both the Rainhart and the California profilographs have the appealing features of being able to be used on concrete pavement surfaces a few hours after placement. The main disadvantage of profilographs is the slow speed at which they operate and the time required in evaluating the chart to determine profile index. A brief description of Rainhart and California profilographs is provided below.

Rainhart Profilograph

The rainhart profilograph was developed by the Rainhart Co. in conjunction with the Texas Highway Department in 1967. Their studies served to establish the parameters under which the device was designed and constructed. These include: twelve averaging wheels, 24.75-foot length, and averaging wheels spaced 27 inches apart. The 12 wheel are arranged in four groups of three. Each of the 12 wheels has its own longitudinal path, spaced at 4-inch interval [NCHRP 1990].

California Profilograph

California's first profilograph, developed in 1940s, was a multiple-wheel unit on a 10-foot frame. Later on, it was concluded that an improved profilograph should have a longer frame, and a 25-foot length was arbitrarily selected. The 25-foot dimension applies to the straightedge or beam length of the profilograph. Early models had an articulated wheel system that was 7 feet long and centered under each end point of the beam, making the overall length of the unit as about 32 feet. Each wheel system consisted of a total of six wheels, four on the right side and two on the left. In 1983, a simplified wheel system with a single axle and two wheel was substituted [NCHRP 1990].

RESPONSE-TYPE ROAD-ROUGHNESS-MEASURING SYSTEMS (RTRRMS)

Response-type equipment records the dynamic response of mechanical systems traveling on the road at some predetermined constant speed [NCHRP 1986]. Accordingly a relative measure of roughness is obtained that depends on the mechanical system and the speed of travel [Epps & Monismith 1986]. The primary advantages of RTRRMS are [NCHRP 1990]:

1. Initial and operating costs are low. Data is collected at high speeds (usually 50 mph); thus a considerable length of pavement can be evaluated in a relatively short period of time.
2. Reasonably accurate and reproducible roughness data can be collected if the device is properly calibrated and maintained.

On the other hand, the limitations of RTRRMS are as follows:

1. The characteristics of the mechanical systems and the speed of travel affect measurements.
2. Response-type road-roughness-measuring systems measure a dynamic effect of roughness but do not define pavement profile features.
3. They must frequently be calibrated through a range of operating speeds, against sections of known profile ranging from very smooth to rough to provide accurate and repeatable data. The costs of calibration can be quite high.
4. The vehicles in which RTRRMS are installed contribute to many sources of potential variation, including rear suspension damping, tire non-uniformities, vehicle weight changes, and windage effects.
5. Because of variations of the different mechanical systems, comparability of data among users is difficult. Numerous pieces of response-type equipment have been developed; only the more widely used types are discussed herein.

Bureau of Public Roads (BPR) Roughometer

This device was first introduced in 1925 and was recognized as being the best "high-speed" smoothness device available at the time. The BPR Roughometer is a single-wheel trailer that measures the unidirectional vertical movements of a damped leaf-spring wheel by a mechanical integrator as the trailer is towed along the roadway (data is expressed in inches per mile). Because of the slow response of the electromechanical counter, measurements are usually made at 20 mph (32 km/h). Modifications have been made to the device to improve data acquisition capabilities and to permit operations at higher speeds; however, basic operational characteristics of the unit alter at higher speeds [NCHRP 1990, Chong & Phang 1973, Ahlborn & Moyer 1956, Quinn & Smeyak 1972].

Road Meters

Road meters comprise a widely used type of response equipment. These meters measure the vertical movements of the rear axle of an automobile relative to the vehicle frame [Epps & Monismith 1986]. In the United States, commonly used types are the Portland Cement Association (PCA) Roadmeter and the Mays Ride Meter.

Portland Cement Association (PCA) Roadmeter

This roadmeter was developed by Brokaw of PCA in 1965 "to provide a rapid, simple, and inexpensive way of measuring road roughness, the principle ingredient of the present serviceability index (PSI) established as a result of the AASHO Road Test [Brokaw 1973]." The device measures the number and the amplitude of vertical deviations between a "standard" automobile and the center of the rear-axle type housing. The deviations are recorded in 1/8-inch increments up to a maximum excursion of $\pm$ 1½ inches from the neutral position. The advantage of using PCA meter is that tests are made by the automobile driver without the need for traffic protection or extra personnel, and at a speed of 50 mph or more if required by the traffic stream [Brokaw 1967]. PCA Road Meters have been used primarily in connection with pavement-rating systems and to a limited degree as a part of smoothness specifications.

Mays Ride Meter

The Mays Ride Meter was developed by an employee of the Texas Highway Department. Like the PCA Road Meter, the Mays meter is driven by movement of the rear-axle housing with respect to the body of the vehicle. The unit can be mounted in either a standard sedan or a trailer and can be operated at highway speeds, usually at 50 mph standard operating speed.

Although all road meters measure a dynamic effect of roughness, this type of measurement does not define the profile of roughness. Some wavelengths will be attenuated and others amplified, depending on the mechanical system [Wambold et al. 1981]. However, roadmeters are useful for rapid evaluation to predict the user's response to the ride quality. If more detailed information on the actual profile is required, then it is necessary to use another form of equipment capable of measuring profiles.

Inertial Profilometers

Underlying the efforts that have been invested in the development of the various pieces of road-roughness-measuring equipment, there has existed a recognition of the need for a high speed profiling system that would yield a "true" portrayal of pavement surface characteristics. Such devices have come to be known as "inertial profilometers" or "inertial road profiling systems." Response type measurements are not reproducible over time while profile measurements are repeatable. There have been cases where a response type device has shown that a pavement has been getting better over time. Profile measurements, on the other hand, are reproducible and have credibility over response type [Pavement Profile Measurement Seminar 1988]. In practice, the range and resolution of such systems are limited to a minor degree. However, within the wavelength and amplitude limitations of the systems, a profile measurement may be called "absolute". In other words, it does not require comparison to any other system but requires only calibration of its own sensors and associated electronics, together with proper functioning of its computer hardware and software.

Modern inertial road profiling systems require four basic subsystems:

1. Accelerometers for determination of the height of the vehicle relative to an inertial reference frame (the vehicle or trailer).
2. Height sensors for measurements of the instantaneous riding height of the vehicle relative to a location on the road below the sensor.
3. Distance or speed sensor for measurement of the position of vehicle along the length of the road (odometer).

4. Computer hardware and software for computation of road profiles from the above sensor inputs.

The sections below describe a few commonly used inertial profilometers.

GMR Profilometer

General Motors Corporation Research (GMR) Laboratories developed the first modern roadway profiling equipment, the GMR profilometer, in 1960s [NCHRP 1985]. It used two spring-loaded, road following wheels, instrumented with linear potentiometer to measure relative displacements between the vehicle frame and the road surface. The equipment was mounted in a panel truck and could be operated at 97 km/h (60 mph). It had the ability to record pavement features covering a broad range of wavelengths. GMR Profilometer was originally developed for the purpose of measuring, recording, and bringing a replica of a pavement surface profile into the laboratory for use in computerized vehicle suspension simulations. Its development was made possible by the availability of high-quality force balance accelerometers as well as high-quality analog computer components, including the integrators used in profile computation [NCHRP 1990]. The accelerometers, which are mounted on the frame over each of the follower wheels, measure the vehicle frame motion by double integration of the signal. The frame motion is then added to the relative displacement motion to yield two voltage signals, which in theory are the road profiles of wheelpaths [Spangler & Kelly].

K.J. Law Inertial Profilometers

The first commercial profilometer built by K. J. Law Engineers, Inc. was manufactured in 1966 for the Texas Highway Department and operated by the Center for Highway Research at the University of Texas [Hudson 1967]. By 1976, two more states and Brazil had acquired Law Profilometers. These units were manufactured using essentially the same state-of-the-art technology as the GMR Profilometers. Availability of new technology, recognition of earlier weaknesses that should be corrected, and a growing national interest in pavement-roughness problems led to the development of the Model 690 Surface Dynamics Profilometer in 1969. Improvements have continued, resulting in the current model 690 DNC (digital noncontact). It measures and computes the longitudinal profile of pavement through the creation of an inertial reference by using accelerometers placed on the body of the measuring vehicles. Relative displacement between the accelerometer and the pavement surface is measured with a noncontact light beam-measuring system mounted with the accelerometers on the vehicle body. The profile is computed in each wheelpath as a function of the distance traveled [NCHRP 1990].

PRORUT-FHWA System

The University of Michigan Transportation Research Institute was contracted by the FHWA to design and build a profiling and rut-depth measuring system. Consequently, a system that uses the IBM PC microcomputer was designed. With the exception of a signal conditioning unit, the system is constructed from commercial components. The software controls the measurement of road profile and rut-depth, the viewing of data, and daily checks of hardware integrity [NCHRP 1990, Gillespie et al. 1987].

The Swedish Laser Road Tester (RST)

This is a road-surveying system developed by the Swedish National Road Administration. The equipment has the capability to measure roughness, rut-depth, cracking, and macrotexture. It is not sold, but engineering services are available through a U.S. firm that is the marketing representative for the device [NCHRP 1990].

Model 8300A Pavement Roughness Surveyor

This is also a noncontact pavement-roughness-measuring system developed by the K. J. Law Engineers, Inc. The device uses an ultrasonic probe and an accelerometer to measure roadway roughness [NCHRP 1990, Hudson 1967].

French Longitudinal Profile Analyzer (APL)

APL was developed by the French Road Research Laboratory in 1968. It is a contact-type profilometer consisting of a single-wheel trailer unit pulled by a towing vehicle at constant speed. It has been used primarily for project-level construction control and acceptance roughness measurements [NCHRP 1990, Carmichael 1987].

South Dakota Road Profiler

In the early 1980s, the South Dakota Department of Transportation (SDDOT) designed and developed a sophisticated, less expensive, more reliable and accurate system than roughness meters, called Road Profiler. This system had the ability to collect profile and rut-depth data at highway speeds. It consists of a host vehicle (usually a van) equipped with electronic instrumentation and data processing hardware and software. The front bumper houses an accelerometer and three ultrasonic sensors. The linear accelerometer measures the vehicle's vertical accelerations while the ultrasonic sensors measure the vertical distance between the bumper and pavement. A laptop keyboard is also provided which allows the operator to enter the commands and to identify highways, locations and descriptions. Information collected is processed by a DEC or IBM computer in real time [U.S. Dept. of Transportation 1989, DuBose 1991].

CHAPTER SUMMARY

This chapter described in detail the various parameters used and instruments developed over the years to measure the pavement roughness and rut-depths. Specifically, principles and procedures involved in various roughness and rut-depth measuring methods, and their significance in assessing pavement quality have been discussed in detail.

CHAPTER 3

CONSISTENCY OF ROAD PROFILERS MEASUREMENTS

INTRODUCTION

After the development of the South Dakota Road Profiler, several highway agencies duplicated the system in house. Due to the great demand of Road Profilers, several manufacturers also started marketing commercial versions of the South Dakota Road Profilers. These Road Profilers are being used by the State Highway Agencies (SHA) to collect roughness and rut-depth data. Subsequently, the Federal Highway Administration (FHWA) utilizes these data in assessing the overall health of the national pavement network. Since Road Profilers currently in use are built by different commercial manufacturers, it was deemed necessary to ascertain if all systems produce comparable roughness and rut-depth measurements. Therefore, analysis was carried out on roughness and rut-depth data collected by eleven different Road Profilers during the third annual meeting of the South Dakota Road Profiler User's Group (SDRPUG).

This chapter describes in detail the complete design of experiment, data collection, and the statistical analysis used to establish correlation among the eleven South Dakota Road Profilers participated in the experiment.

DESIGN OF EXPERIMENT

One major objective of the Minnesota experiment was to run the participating road profilers on several pavement test sections and then conduct statistical analysis on the collected IRI and rut-depth measurements. Figure 3.1 shows the data gathering and analysis strategies for this experiment. Pavement sites used in this study were selected to represent the range of surface types encountered in Minnesota. These pavement types were: Concrete, Bituminous, Bituminous over concrete, and Concrete/bituminous over concrete. All test sections were two-tenth of a mile long, and were selected to represent wide ranges of roughness and rut-depths of pavements in Minnesota. The test sections were conveniently located around the St. Paul area, Minnesota. Table 3.1 shows the locations and pavement types of the selected eight test sections.

TABLE 3.1. Test Section Types and Locations

TEST SECTION NO.	PAVEMENT TYPE	LOCATION
1	CONCRETE	I-94 EAST
2	CONCRETE	I-94 WEST
3	BITUMINOUS	CO-10 WEST
4	BITUMINOUS	CO-10 EAST
5	BITUMINOUS OVER CONCRETE	IS-694 NORTH
6	BITUMINOUS OVER CONCRETE	IS-694 SOUTH
7	CONC/BOC	MN-5 EAST
8	CONC/BOC	MN-5 WEST

Of the total eleven road participating profilers, seven were DEC (Digital Equipment Corporation) based and four were IBM based. It should be mentioned here that the original South Dakota Road Profiler is DEC based while the IBM based road profilers are

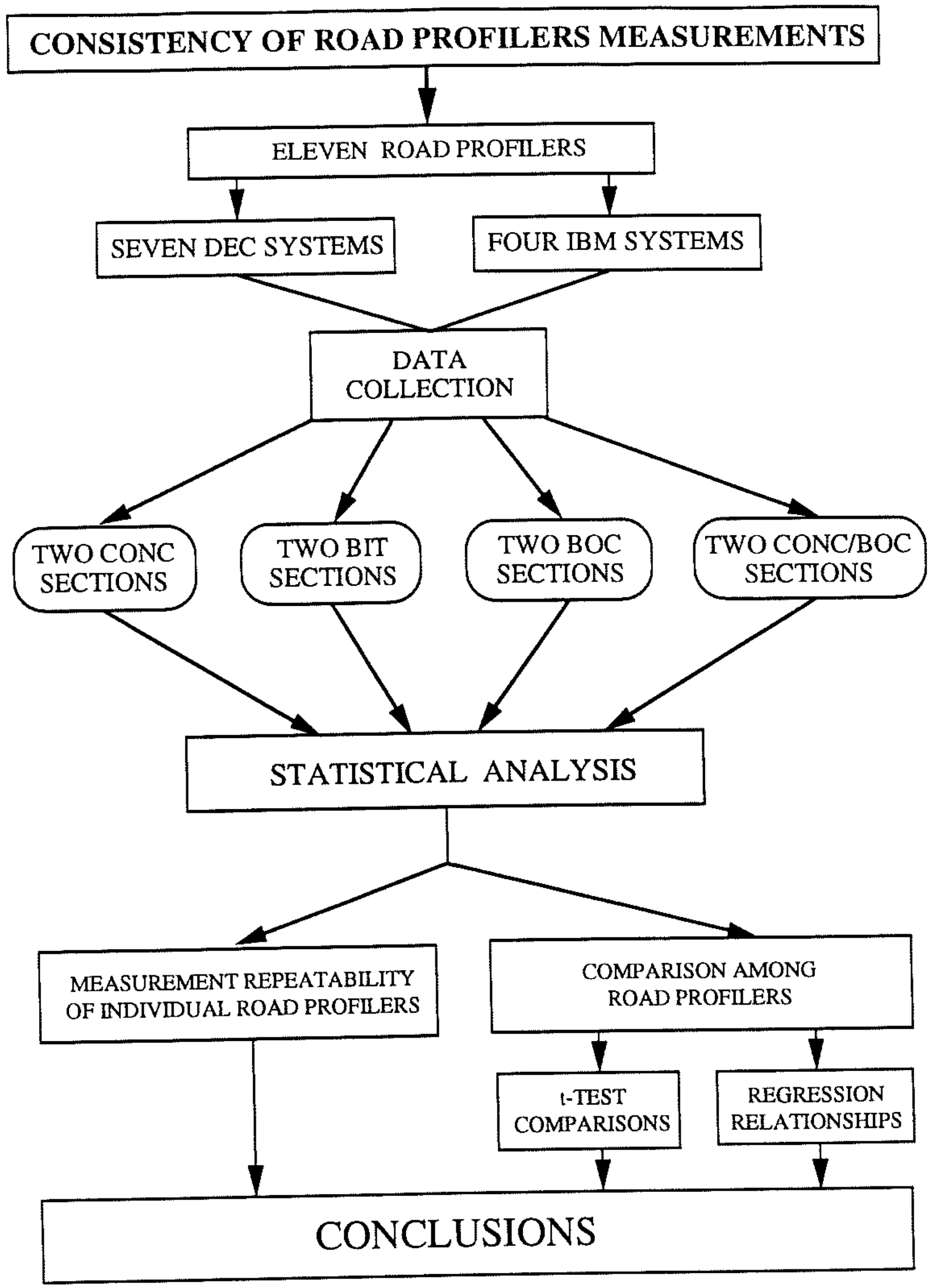


FIGURE 3.1. Data Gathering and Analysis Strategies

commercially manufactured with slight hardware and software modifications. Table 3.2 below provides a list of the participating road profilers and their types.

TABLE 3.2. Road Profilers which Participated in the Minnesota Experiment

ROAD PROFILER NUMBER	STATE	TYPE
1	Wyoming (WY)	DEC
2	Nebraska (NE)	DEC
3	Minnesota (MN)	DEC
4	Wisconsin (WI)	DEC
5	Illinois (IL)	DEC
6	North Dakota (ND)	DEC
7	South Dakota (SD)	DEC
8	Iowa (IA)	IBM
9	Alabama (AL)	IBM
10	Montana (MT)	IBM
11	Idaho (ID)	IBM

DATA COLLECTION AND ANALYSIS

On the second day of the Minnesota RPUG meeting, all road profilers' operators were given detailed information about the locations of test sections. Data were then collected by all eleven road profilers at the same time. The collected data included pavement roughness expressed in International Roughness Index (IRI) and rut-depth measurements. Each road profiler was run three times on each test section. In total, each road profiler made 24 runs.

All collected data were later summarized in a computerized data base and prepared for analysis. This analysis utilized available statistical tools at the University of Wyoming. Tables 3.3 and 3.4 summarize in tabular forms the collected roughness and rut-depth data respectively. The following sections outline in detail the analysis procedures used to: examine the repeatability of individual Road Profilers, compare among all devices, and evaluate the effect of pavement type on measurement repeatability.

Measurements Repeatability of Individual Road Profilers

The objective of this analysis was to determine the repeatability of IRI and rut-depth measurements collected by individual South Dakota Road Profilers. The data were collected by all Road Profilers and each Profiler was run three times on each test section. Roughness and rut-depth measurements from all three runs were then averaged and the standard deviations were calculated. Tables 3.3 and 3.4 summarize these averages and standard deviations of IRI and rut-depth measurements for all Road Profilers on all test sections. It is clear from these tables that the standard deviations were extremely low which indicates that the overall repeatability of both IRI and rut-depth measurements for all road profilers is very good.

Comparisons Among Road Profilers

The objective of this analysis was to determine if the roughness and rut-depth measurements obtained with eleven South Dakota Road Profilers are comparable. Roughness and rut-depth measurements obtained from all eleven road profilers were first examined visually without conducting any analysis. This preliminary examination indicated some

TABLE 3.3. IRI Data Collected at the Minnesota Experiment

CONC	MN	SD	IA	AL	ND	MT	ID	WY	NE	WI	IL
Test #1 IS 94 (EB)											
Run 1	1.26	1.36	1.20	1.19	1.21	1.14	1.11	1.28	1.37	1.26	1.34
Run 2	1.27	1.42	1.18	1.18	1.19	1.14	1.10	1.37	1.49	1.31	1.37
Run 3	1.26	1.45	1.19	1.18	1.22	1.08	1.13	1.38	1.35	1.25	1.35
Average	1.26	1.41	1.19	1.18	1.21	1.12	1.11	1.34	1.40	1.27	1.35
Std. Deviation	0.01	0.05	0.01	0.01	0.02	0.03	0.02	0.06	0.08	0.03	0.02
CONC	MN	SD	IA	AL	ND	MT	ID	WY	NE	WI	IL
Test #2 IS 94 (WB)											
Run 1	1.50	1.56	1.40	1.46	1.38	1.31	1.53	1.51	1.53	1.38	1.45
Run 2	1.44	1.64	1.42	1.46	1.39	1.26	1.53	1.60	1.45	1.37	1.47
Run 3	1.49	1.59	1.41	1.43	1.39	1.27	1.38	1.53	1.46	1.37	1.49
Average	1.48	1.60	1.41	1.45	1.39	1.28	1.48	1.55	1.48	1.37	1.47
Std. Deviation	0.03	0.04	0.01	0.02	0.01	0.03	0.09	0.05	0.04	0.01	0.02
BIT	MN	SD	IA	AL	ND	MT	ID	WY	NE	WI	IL
Test #3 CO 10 (WB)											
Run 1	4.47	4.38	4.30	4.43	4.53	3.88	4.21	4.58	4.23	4.51	4.53
Run 2	4.56	4.31	4.27	4.54	4.36	3.93	4.24	4.51	4.44	4.46	4.43
Run 3	4.54	4.28	4.34	4.32	4.41	3.97	4.24	4.48	4.43	4.53	4.38
Average	4.52	4.32	4.30	4.43	4.43	3.93	4.23	4.52	4.37	4.50	4.45
Std. Deviation	0.05	0.05	0.04	0.11	0.09	0.05	0.02	0.05	0.12	0.04	0.08
BIT	MN	SD	IA	AL	ND	MT	ID	WY	NE	WI	IL
Test #4 CO 10 (EB)											
Run 1	4.53	4.42	4.39	4.48	4.52	3.73	4.18	4.70	4.47	4.45	4.43
Run 2	4.81	4.27	4.36	4.25	4.55	3.72	4.14	4.54	4.51	4.56	4.44
Run 3	5.13	4.27	4.39	4.21	4.54	3.74	4.05	4.54	4.51	4.40	4.45
Average	4.82	4.32	4.38	4.31	4.54	3.73	4.12	4.59	4.50	4.47	4.44
Std. Deviation	0.3	0.09	0.02	0.15	0.02	0.01	0.07	0.09	0.02	0.08	0.01
BOC	MN	SD	IA	AL	ND	MT	ID	WY	NE	WI	IL
Test #5 IS 694 (NB)											
Run 1	1.07	1.10	0.99	0.95	1.25	0.86	0.87	1.03	1.03	0.99	1.05
Run 2	1.09	0.98	0.99	0.89	1.19	0.86	0.91	1.03	1.06	1.02	1.09
Run 3	1.07	1.04	0.99	0.93	1.03	0.85	0.89	1.01	1.05	1.01	1.14
Average	1.08	1.04	0.99	0.92	1.16	0.86	0.89	1.02	1.05	1.01	1.09
Std. Deviation	0.01	0.06	0	0.03	0.11	0.01	0.02	0.01	0.02	0.02	0.05

TABLE 3.3. Continued. . .

BOC	MN	SD	IA	AL	ND	MT	ID	WY	NE	WI	IL
TEST #6 IS 694 (SB)											
Run 1	1.16	1.08	1.00	0.88	0.97	0.87	0.90	1.05	1.07	1.05	1.09
Run 2	1.11	1.04	1.00	0.87	0.95	0.85	0.89	1.07	1.15	1.08	1.07
Run 3	1.04	1.03	1.02	0.88	0.95	0.88	0.85	1.10	1.13	1.07	1.07
Average	1.10	1.05	1.01	0.88	0.96	0.87	0.88	1.07	1.12	1.07	1.08
Std. Deviation	0.06	0.03	0.01	0.01	0.01	0.02	0.03	0.03	0.04	0.02	0.01
CONC/BOC	MN	SD	IA	AL	ND	MT	ID	WY	NE	WI	IL
TEST #7 MN 5 (EB)											
Run 1	2.23	2.63	1.99	2.08	2.07	1.84	1.95	2.10	2.23	2.16	2.28
Run 2	2.22	2.55	1.96	2.08	2.09	1.86	1.98	2.20	2.25	2.02	2.26
Run 3	2.24	2.53	2.03	2.01	2.11	1.84	1.98	2.19	2.23	2.15	2.29
Average	2.23	2.57	1.99	2.06	2.09	1.85	1.97	2.16	2.24	2.11	2.28
Std. Deviation	0.01	0.05	0.04	0.04	0.02	0.01	0.02	0.06	0.01	0.08	0.02
CONC/BOC	MN	SD	IA	AL	ND	MT	ID	WY	NE	WI	IL
TEST #8 MN 5 (WB)											
Run 1	2.15	2.16	1.92	2.07	2.03	1.72	2.02	2.30	2.11	2.04	2.19
Run 2	2.27	2.12	1.95	1.98	2.06	1.74	2.04	2.37	2.11	2.06	2.18
Run 3	2.19	2.16	1.97	2.09	2.02	1.73	2.00	2.33	2.09	2.03	2.15
Average	2.20	2.15	1.95	2.05	2.04	1.73	2.02	2.33	2.10	2.04	2.17
Std. Deviation	0.06	0.02	0.03	0.06	0.02	0.01	0.02	0.04	0.01	0.02	0.02

MN: Minnesota
SD: South Dakota
IA: Iowa
AL: Alabama
ND: North Dakota
MT: Montana
ID: Idaho
WY: Wyoming
NE: Nebraska
WI: Wisconsin
IL: Illinois

TABLE 3.4. Rut-Depth Data Collected at the Minnesota Experiment

BIT	MN	SD	ND	WY	NE	WI	IL	IA	AL	MT	ID
Test #1 CO 10 (WB)											
Run 1	0.64	0.54	0.67	0.65	0.58	0.63	0.63	0.72	0.65	0.58	0.59
Run 2	0.64	0.49	0.71	0.64	0.60	0.64	0.60	0.70	0.66	0.58	0.58
Run 3	0.63	0.49	0.66	0.64	0.60	0.65	0.61	0.72	0.66	0.60	0.56
Average	0.63	0.51	0.68	0.64	0.59	0.64	0.61	0.71	0.66	0.59	0.58
Std. Deviation	0.01	0.03	0.03	0.01	0.01	0.01	0.02	0.01	0.01	0.01	0.02
BIT	MN	SD	ND	WY	NE	WI	IL	IA	AL	MT	ID
Test #2 CO 10 (EB)											
Run 1	0.53	0.43	0.62	0.59	0.50	0.51	0.55	0.61	0.57	0.43	0.48
Run 2	0.55	0.41	0.64	0.58	0.49	0.52	0.54	0.62	0.53	0.43	0.48
Run 3	0.55	0.36	0.63	0.58	0.47	0.51	0.54	0.61	0.54	0.42	0.44
Average	0.54	0.40	0.63	0.58	0.49	0.51	0.54	0.61	0.55	0.43	0.47
Std. Deviation	0.01	0.04	0.01	0.01	0.02	0.01	0.01	0.01	0.02	0.01	0.02
BOC	MN	SD	ND	WY	NE	WI	IL	IA	AL	MT	ID
Test #3 IS 694 (NB)											
Run 1	0.11	0.05	0.17	0.16	0.05	0.11	0.12	0.11	0.09	0.01	0.01
Run 2	0.11	0.02	0.17	0.16	0.05	0.11	0.12	0.11	0.09	0.02	0.00
Run 3	0.12	0.02	0.17	0.17	0.05	0.12	0.12	0.12	0.10	0.02	0.00
Average	0.11	0.03	0.17	0.16	0.05	0.11	0.12	0.11	0.09	0.02	0.00
Std. Deviation	0.01	0.02	0	0.01	0	0.01	0	0.01	0.01	0.01	0.01
BOC	MN	SD	ND	WY	NE	WI	IL	IA	AL	MT	ID
Test #4 S 694 (SB)											
Run 1	0.09	0.02	0.12	0.11	0.03	0.07	0.06	0.08	0.05	0.00	0.00
Run 2	0.08	0.01	0.13	0.12	0.03	0.08	0.06	0.08	0.05	0.00	0.00
Run 3	0.09	0.03	0.13	0.12	0.03	0.08	0.06	0.08	0.05	0.00	0.00
Average	0.09	0.02	0.13	0.12	0.03	0.08	0.06	0.08	0.05	0.00	0.00
Std. Deviation	0.01	0.01	0.01	0.01	0	0.01	0	0	0	0	0

MN: Minnesota
SD: South Dakota
IA: Iowa
AL: Alabama
ND: North Dakota
MT: Montana
ID: Idaho
WY: Wyoming
NE: Nebraska
WI: Wisconsin
IL: Illinois

variations in the results from different road profilers. As an example, Table 3.3 shows that the mean roughness of test section # 1 is 1.41 when measured with the South Dakota Road Profiler and 1.11 when measured with the Idaho Road Profiler. Therefore, it was necessary to determine the statistical significance of these differences. The two-sample t-test was utilized in the comparison among the means. Basically, IRI and rut-depth measurements from any two Road Profilers were compared to see if they were statistically equal. A 95% confidence level was used in the whole analysis to be within practical limits and the following assumptions were made in order to conduct the t-test:

1. The population samples are small.
2. Both populations are normal with $\sigma_1 = \sigma_2 = \sigma$ and the design is completely randomized.

The t_o value was calculated with the following equation:

$$t_o = \frac{(\overline{Y}_1 - \overline{Y}_2)}{S_p\sqrt{\frac{1}{n_1} + \frac{1}{n_2}}} \qquad \text{(Eqn. 3.1)}$$

where:

where:	$\overline{Y}_1$ and $\overline{Y}_2$	=	sample means
	n_1 and n_2	=	sample sizes
	S_p	=	estimate of the common variance $\sigma_1^2 = \sigma_2^2 = \sigma^2$.

The common variance S_p was computed with the following equation:

$$S_p^2 = \frac{(n_1-1)\,\sigma_1^2 + (n_2-1)\,\sigma_2^2}{n_1+n_2-2} \qquad \text{(Eqn. 3.2)}$$

Where: σ_1^2 and σ_2^2 = two individual sample variances.

In the analysis of IRI and rut-depth data, the above described two-sample t-test was used. Means of IRI and rut-depths for all three runs on each test section were calculated and compared with each other. The test statistic t_o was then determined by using Equation 3.1, and finally its absolute value was compared with $t_{\alpha/2,\, n1+n2-2}=2.776$ (for $\alpha=0.05$ and degrees of freedom=4 since $n_1=n_2=3$). If $ABS(t_o) > t_{\alpha/2,\, n1+n2-2}$, it would be concluded that the two means are statistically different. A large number of two-by-two comparisons were made. By two-by-two, it is meant that measurements obtained by two Road Profilers were compared at a time. As an example, roughness measurements from each Road Profiler were compared with the measurements from ten other road profilers on eight test sections which would result in 80 possible comparisons. The results from all of these comparisons are summarized in Tables 3.5 and 3.6 for roughness and rut-depth measurements respectively. It is clear from examining these Tables that Road Profilers produced equal IRI measurements in 35.5 percent of the cases and equal rut-depth measurements in only 25.7 percent of the cases. These extremely low percentages are alarming since all systems are similar in design.

In addition to above described t-test, a two-way analysis of variance (ANOVA) was performed to confirm that all the Road Profilers were producing statistically different IRI and rut-depth measurements. The following model was used for the two factor fixed effect ANOVA:

TABLE 3.5. Results from IRI Comparisons

SYSTEM	SECTION	POSSIBLE COMPAR'ON	EQUAL COM-PAR'ON	% EQUAL COMPAR'ON
MN	CONC	20	8	40
	BIT	20	13	65
	BOC	20	10	50
	CONC/BOC	20	5	25
	All Sections	80	36	45
SD	CONC	20	5	25
	BIT	20	9	45
	BOC	20	10	50
	CONC/BOC	20	3	15
	All Sections	80	27	33.8
IA	CONC	20	4	20
	BIT	20	8	40
	BOC	20	5	25
	CONC/BOC	20	4	20
	All Sections	80	21	26.3
AL	CONC	20	6	30
	BIT	20	16	80
	BOC	20	3	15
	CONC/BOC	20	10	50
	All Sections	80	35	43.8
ND	CONC	20	3	15
	BIT	20	13	65
	BOC	20	7	35
	CONC/BOC	20	6	30
	All Sections	80	29	36.3
MT	CONC	20	2	10
	BIT	20	0	0
	BOC	20	3	15
	CONC/BOC	20	0	0
	All Sections	80	5	6.25

TABLE 3.5. Continued. . .

SYSTEM	SECTION	POSSIBLE COMPAR'ON	EQUAL COM-PAR'ON	% EQUAL COMPAR'ON
ID	CONC BIT BOC CONC/BOC	20 20 20 20	10 2 4 5	50 10 20 25
	All Sections	80	21	26.3
WY	CONC BIT BOC CONC/BOC	20 20 20 20	10 10 10 5	50 50 50 25
	All Sections	80	35	43.8
NE	CONC BIT BOC CONC/BOC	20 20 20 20	10 14 9 3	50 70 45 15
	All Sections	80	36	45
WI	CONC BIT BOC CONC/BOC	20 20 20 20	4 14 8 9	20 70 40 45
	All Sections	80	35	43.8
IL	CONC BIT BOC CONC/BOC	20 20 20 20	8 11 9 3	40 55 45 15
	All Sections	80	31	38.8
All Systems	CONC BIT BOC CONC/BOC	220 220 220 220	70 110 78 53	31.8 50 35.5 24.1
	All Sections	880	311	35.3

TABLE 3.6. Results from Rut-Depth Comparisons

SYSTEM	SECTION	POSSIBLE COMPAR'ON	EQUAL COMPAR'ON	% EQUAL COMPAR'ON
MN	BIT BOC	20 20	6 7	30 35
	Both BIT & BOC	40	13	32.5
SD	BIT BOC	20 20	2 7	10 35
	Both BIT & BOC	40	9	22.5
IA	BIT BOC	20 15	2 5	10 33.3
	Both BIT & BOC	35	7	20
AL	BIT BOC	20 15	10 2	50 13.3
	Both BIT & BOC	35	12	34.3
ND	BIT BOC	20 19	6 2	30 10.5
	Both BIT & BOC	39	8	20.5
MT	BIT BOC	20 15	7 4	35 26.7
	Both BIT & BOC	35	11	31.4
ID	BIT BOC	20 15	7 3	35 20
	Both BIT & BOC	35	10	28.6
WY	BIT BOC	20 20	4 2	20 10
	Both BIT & BOC	40	6	15

TABLE 3.6. Continued. . .

SYSTEM	SECTION	POSSIBLE COMPAR'ON	EQUAL COMPAR'ON	% EQUAL COMPAR'ON
NE	BIT BOC	20 15	4 3	20 20
	Both BIT & BOC	35	7	20
WI	BIT BOC	20 20	6 7	30 35
	Both BIT & BOC	40	13	32.5
IL	BIT BOC	20 14	6 3	30 21.4
	Both BIT & BOC	34	9	26.6
All Systems	BIT BOC	220 188	60 45	27.3 24
	Both BIT & BOC	408	105	25.7

$$y_{ijk}=\mu+(\alpha_i)^T+(\alpha_j)^P+(\alpha_{ij})^{TS}+\epsilon_{ijk} \qquad \text{(Eqn. 3.3)}$$

Where:

y_{ijk}	=	(ijk)th observation
μ	=	parameter common to all treatments called the overall mean
$(\alpha_i)^T$	=	*ith* treatment effect i.e. effect due to test sections
$(\alpha_j)^P$	=	*jth* treatment effect i.e. effect due to Road Profilers
$(\alpha_{ij})^{TP}$	=	*ijth* treatment effect i.e. effect due to interaction between test section and Road Profilers effect
ϵ_{ijk}	=	random error

The following test of hypothesis was formulated for the above described ANOVA model:

$$H_o:\sigma^2{}_P=\frac{1}{j-1}\sum_{j=1}^{J}(\alpha^P{}_j)^2=0$$

$$H_1:\sigma^2{}_P\neq 0$$

where: α_P^2 = is the variance due to difference in Road Profilers

H_o would be rejected if $F_o > F_{\alpha,\, a-1,\, N-a}$, where a-1 and N-a are the degrees of freedom for treatments and error respectively. The ANOVA analysis was performed on both IRI and rut-depth data. Tables 3.7 and 3.8 show the analysis of variance for IRI and rut-depth data respectively. It is clear from the F ratios that there are significant differences among IRI and rut-depth measurements collected by different Road Profilers.

In order to find the reasons behind the differences in measurements from the eleven Road Profilers, an additional statistical analysis was conducted. This analysis aimed

TABLE 3.7. Analysis of Variance for IRI Data

SOURCE	DF	SS	MS	F	$F_{\nu 1, \nu 2}$
Test	7	454.14	64.877		
Profiler	10	3.748	0.37484	118.67	1.83
Test & Profiler	70	2.4226	0.03461	10.95	1.30
Error	176	0.5559	0.00316		
Total	263	460.87	1.7523		

TABLE 3.8. Analysis of Variance for Rut-Depth Data

SOURCE	DF	SS	MS	F	$F_{\nu 1, \nu 2}$
Test	3	8.3788	2.7929		
Profiler	10	0.35333	0.03533	248.08	2.7
Test & Profiler	30	0.05549	0.00185	12.987	1.6
Error	88	0.01253	0.00014		
Total	131	8.8002	0.06717		

at determining if there are any regression relationships among IRI and rut-depth data collected with different Road Profilers. A regular regression approach was used to establish these relationships, and the following basic regression model (i.e. simple linear parameters) was used in the analysis:

$$Y_i = \beta_o + \beta_1 X_i \qquad \text{(Eqn. 3.4)}$$

Where: Y_i = Mean of IRI or rut-depth for three runs by one

		profiler
X_i	=	Mean of IRI or rut-depth by another road profiler
β_0 and β_1	=	regression constants

Tables 3.9 and 3.10 summarize the regression equations for IRI and rut-depth measurements respectively. These regression equations yield very high R-square (100% in some cases) which indicate almost perfect agreements among systems. Sample plots of the raw data used in the regression analysis are shown in Figures 3.2 and 3.3.

The t-test results can be now explained based on the results from regression analysis. Although all participating road profilers are similar in design, they should be calibrated against each other before making any attempts for comparisons. Unfortunately, the South Dakota type road profilers are used by different highway agencies to create a national roughness data base without calibration. This national data base can be used to compare roughness measurements within any individual state. However, roughness measurement comparison for sections in different states will not be accurate without calibration.

Effect of Pavement Type on Repeatability of Measurements

The objective of this analysis is to determine if the pavement type influences the repeatability of Road Profilers measurements. As mentioned earlier, the following four types of pavements were included in the experiment: concrete, bituminous, bituminous over concrete, and concrete over bituminous over concrete. As shown in Table 3.5, the percentages of good IRI comparisons were 50 percent and 31.8 percent on bituminous and concrete sections respectively. These percentages may lead someone to believe that measurements on

TABLE 3.9. IRI Calibration Equations

SYSTEMS		REGRESSION EQUATION	R-SQUARE(%)
MN	SD	$IRI_{MN} = -0.229 + 1.11\ IRI_{SD}$	98.2
MN	IA	$IRI_{MN} = 0.0218 + 1.08\ IRI_{IA}$	99.7
MN	AL	$IRI_{MN} = 0.0734 + 1.05\ IRI_{AL}$	99.3
MN	ND	$IRI_{MN} = 0.0214 + 1.04\ IRI_{ND}$	99.7
MN	MT	$IRI_{MN} = -0.015 + 1.23\ IRI_{MT}$	99.0
MN	ID	$IRI_{MN} = 0.029 + 1.11\ IRI_{ID}$	99.1
MN	WY	$IRI_{MN} = -0.0687 + 1.04\ IRI_{WY}$	99.6
MN	NE	$IRI_{MN} = -0.133 + 1.08\ IRI_{NE}$	99.7
MN	WI	$IRI_{MN} = 0.0185 + 1.04\ IRI_{WI}$	99.6
MN	IL	$IRI_{MN} = -0.126 + 1.07\ IRI_{IL}$	99.6
SD	IA	$IRI_{SD} = 0.262 + 0.95\ IRI_{IA}$	98.1
SD	AL	$IRI_{SD} = 0.295 + 0.932\ IRI_{AL}$	98.7
SD	ND	$IRI_{SD} = 0.262 + 0.918\ IRI_{ND}$	97.9
SD	MT	$IRI_{SD} = 0.215 + 1.09\ IRI_{MT}$	98.7
SD	ID	$IRI_{SD} = 0.257 + 0.982\ IRI_{ID}$	98.5
SD	WY	$IRI_{SD} = 0.177 + 0.917\ IRI_{WY}$	98.3
SD	NE	$IRI_{SD} = 0.115 + 0.96\ IRI_{NE}$	98.9
SD	WI	$IRI_{SD} = 0.254 + 0.921\ IRI_{WI}$	98.3
SD	IL	$IRI_{SD} = 0.117 + 0.956\ IRI_{IL}$	99.1
IA	AL	$IRI_{IA} = 0.0465 + 0.975\ IRI_{AL}$	99.6
IA	ND	$IRI_{IA} = 0.0012 + 0.966\ IRI_{ND}$	99.8
IA	MT	$IRI_{IA} = -0.0381 + 1.14\ IRI_{MT}$	99.6
IA	ID	$IRI_{IA} = 0.0056 + 1.03\ IRI_{ID}$	99.5
IA	WY	$IRI_{IA} = -0.082 + 0.962\ IRI_{WY}$	99.6
IA	NE	$IRI_{IA} = -0.142 + 1.01\ IRI_{NE}$	99.8
IA	WI	$IRI_{IA} = -0.004 + 0.967\ IRI_{WI}$	99.9
IA	IL	$IRI_{IA} = -0.136 + 0.999\ IRI_{IL}$	99.6

TABLE 3.9. Continued. . .

SYSTEMS		REGRESSION EQUATION	R-SQUARE(%)
AL	ND	$IRI_{AL} = -0.0385 + 0.987\ IRI_{ND}$	99.4
AL	MT	$IRI_{AL} = -0.085 + 1.17\ IRI_{MT}$	99.8
AL	ID	$IRI_{AL} = -0.0429 + 1.06\ IRI_{ID}$	99.9
AL	WY	$IRI_{AL} = 0.129 + 0.985\ IRI_{WY}$	99.7
AL	NE	$IRI_{AL} = -0.186 + 1.03\ IRI_{NE}$	99.5
AL	WI	$IRI_{AL} = -0.045 + 0.989\ IRI_{WI}$	99.6
AL	IL	$IRI_{AL} = -0.184 + 1.02\ IRI_{IL}$	99.8
ND	MT	$IRI_{ND} = -0.0349 + 1.18\ IRI_{MT}$	99.3
ND	ID	$IRI_{ND} = 0.0105 + 1.06\ IRI_{ID}$	99.2
ND	WY	$IRI_{ND} = -0.08 + 0.994\ IRI_{WY}$	99.3
ND	NE	$IRI_{ND} = -0.143 + 1.04\ IRI_{NE}$	99.5
ND	WI	$IRI_{ND} = -0.0003 + 0.999\ IRI_{WI}$	99.7
ND	IL	$IRI_{ND} = -0.138 + 1.03\ IRI_{IL}$	99.6
MT	ID	$IRI_{MT} = 0.0405 + 0.899\ IRI_{ID}$	99.6
MT	WY	$IRI_{MT} = -0.0317 + 0.893\ IRI_{WY}$	99.3
MT	NE	$IRI_{MT} = -0.0844 + 0.877\ IRI_{NE}$	99.5
MT	WI	$IRI_{MT} = 0.035 + 0.844\ IRI_{WI}$	99.8
MT	IL	$IRI_{MT} = -0.0821 + 0.873\ IRI_{IL}$	99.7
ID	WY	$IRI_{ID} = -0.0804 + 0.933\ IRI_{WY}$	99.7
ID	NE	$IRI_{ID} = -0.132 + 0.972\ IRI_{NE}$	99.3
ID	WI	$IRI_{ID} = 0.0015 + 0.935\ IRI_{WI}$	99.4
ID	IL	$IRI_{ID} = -0.13 + 0.968\ IRI_{IL}$	99.5
WY	NE	$IRI_{WY} = -0.055 + 1.04\ IRI_{NE}$	99.6
WY	WI	$IRI_{WY} = 0.0896 + 1.0\ IRI_{WI}$	99.5
WY	IL	$IRI_{WY} = -0.0512 + 1.04\ IRI_{IL}$	99.6
NE	WI	$IRI_{NE} = 0.141 + 0.961\ IRI_{WI}$	99.8
NE	IL	$IRI_{NE} = 0.0063 + 0.993\ IRI_{IL}$	99.8
WI	IL	$IRI_{WI} = -0.137 + 1.03\ IRI_{IL}$	99.8

TABLE 3.10. Rut-Depth Calibration Equations

SYSTEMS		REGRESSION EQUATION	R-SQUARE(%)
MN	SD	$RUT_{MN} = 0.0685 + 1.32\ RUT_{SD}$	97.2
MN	ND	$RUT_{MN} = -0.045 + 0.963\ RUT_{ND}$	99.6
MN	WY	$RUT_{MN} = -\ 0.0452 + 1.03\ RUT_{WY}$	99.7
MN	NE	$RUT_{MN} = 0.0616 + 0.969\ RUT_{NE}$	100.0
MN	WI	$RUT_{MN} = 0.008 + 0.999\ RUT_{WI}$	99.6
MN	IL	$RUT_{MN} = 0.0107 + 0.998\ RUT_{IL}$	99.6
MN	IA	$RUT_{MN} = 0.0123 + 0.986\ RUT_{IA}$	94.6
MN	AL	$RUT_{MN} = 0.0319 + 1.05\ RUT_{AL}$	94.9
MN	MT	$RUT_{MN} = 0.0955 + 0.95\ RUT_{MT}$	99.2
MN	ID	$RUT_{MN} = 0.101 + 0.922\ RUT_{ID}$	99.9
SD	ND	$RUT_{SD} = -0.0806 + 0.716\ RUT_{ND}$	98.7
SD	WY	$RUT_{SD} = -0.0797 + 0.766\ RUT_{WY}$	98.2
SD	NE	$RUT_{SD} = 0.0011 + 0.712\ RUT_{NE}$	96.8
SD	WI	$RUT_{SD} = -0.036 + 0.727\ RUT_{WI}$	94.8
SD	IL	$RUT_{SD} = -0.038 + 0.738\ RUT_{IL}$	97.6
SD	IA	$RUT_{SD} = -0.0453 + 0.755\ RUT_{IA}$	99.5
SD	AL	$RUT_{SD} = -0.03 + 0.805\ RUT_{AL}$	99.5
SD	MT	$RUT_{SD} = 0.0286 + 0.688\ RUT_{MT}$	93.3
SD	ID	$RUT_{SD} = 0.03 + 0.676\ RUT_{ID}$	96.6
ND	WY	$RUT_{ND} = 0.0004 + 1.07\ RUT_{WY}$	100.0
ND	NE	$RUT_{ND} = 0.112 + 1.0\ RUT_{NE}$	99.4
ND	WI	$RUT_{ND} = 0.0578 + 1.03\ RUT_{WI}$	98.6
ND	IL	$RUT_{ND} = 0.0583 + 1.04\ RUT_{IL}$	99.8
ND	IA	$RUT_{ND} = 0.0561 + 1.03\ RUT_{IA}$	97.0
ND	AL	$RUT_{ND} = 0.0776 + 1.1\ RUT_{AL}$	97.3
ND	MT	$RUT_{ND} = 0.149 + 0.977\ RUT_{MT}$	97.6
ND	ID	$RUT_{ND} = 0.153 + 0.951\ RUT_{ID}$	99.1

TABLE 3.10. Continued. . .

SYSTEMS		REGRESSION EQUATION	R-SQUARE(%)
WY	NE	$RUT_{WY} = 0.104 + 0.934\ RUT_{NE}$	99.6
WY	WI	$RUT_{WY} = 0.0529 + 0.962\ RUT_{WI}$	99.0
WY	IL	$RUT_{WY} = 0.0539 + 0.966\ RUT_{IL}$	99.9
WY	IA	$RUT_{WY} = 0.0532 + 0.961\ RUT_{IA}$	96.3
WY	AL	$RUT_{WY} = 0.0722 + 1.03\ RUT_{AL}$	96.7
WY	MT	$RUT_{WY} = 0.138 + 0.913\ RUT_{MT}$	98.2
WY	ID	$RUT_{WY} = 0.142 + 0.888\ RUT_{ID}$	99.3
NE	WI	$RUT_{NE} = -0.0555 + 1.03\ RUT_{WI}$	99.7
NE	IL	$RUT_{NE} = -0.0524 + 1.03\ RUT_{IL}$	99.5
NE	IA	$RUT_{NE} = -0.05 + 1.02\ RUT_{IA}$	94.2
NE	AL	$RUT_{NE} = -0.0299 + 1.08\ RUT_{AL}$	94.5
NE	MT	$RUT_{NE} = 0.0347 + 0.982\ RUT_{MT}$	99.3
NE	ID	$RUT_{NE} = 0.0402 + 0.951\ RUT_{ID}$	99.9
WI	IL	$RUT_{WI} = 0.0042 + 0.995\ RUT_{IL}$	99.1
WI	IA	$RUT_{WI} = 0.0101 + 0.970\ RUT_{IA}$	91.7
WI	AL	$RUT_{WI} = 0.0291 + 1.04\ RUT_{AL}$	92.2
WI	MT	$RUT_{WI} = 0.0872 + 0.953\ RUT_{MT}$	99.9
WI	ID	$RUT_{WI} = 0.0935 + 0.92\ RUT_{ID}$	99.6
IL	IA	$RUT_{IL} = 0.0004 + 0.991\ RUT_{IA}$	95.7
IL	AL	$RUT_{IL} = 0.0199 + 1.06\ RUT_{AL}$	96.2
IL	MT	$RUT_{IL} = 0.0866 + 0.946\ RUT_{MT}$	99.2
IL	ID	$RUT_{IL} = 0.0916 + 0.918\ RUT_{ID}$	99.0
IA	AL	$RUT_{IA} = 0.0204 + 1.07\ RUT_{AL}$	100.0
IA	MT	$RUT_{IA} = 0.103 + 0.892\ RUT_{MT}$	89.8
IA	ID	$RUT_{IA} = 0.104 + 0.881\ RUT_{ID}$	93.7
AL	MT	$RUT_{AL} = 0.0769 + 0.839\ RUT_{MT}$	90.2
AL	ID	$RUT_{AL} = 0.0779 + 0.827\ RUT_{ID}$	93.9
MT	ID	$RUT_{MT} = 0.0072 + 0.963\ RUT_{ID}$	99.4

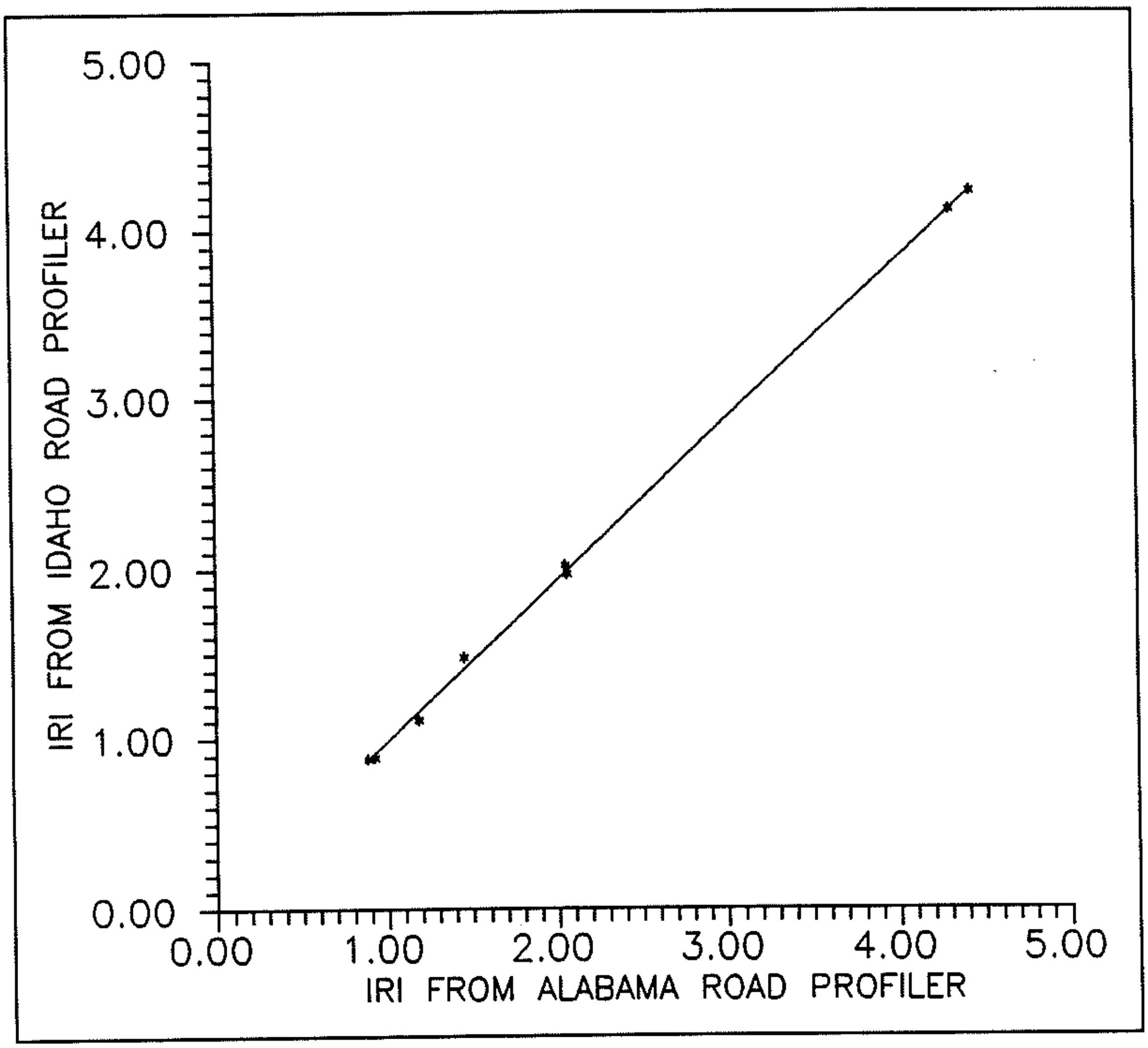


FIGURE 3.2. IRI Correlation between Idaho and Alabama Road Profilers (R-sq. 99.9%)

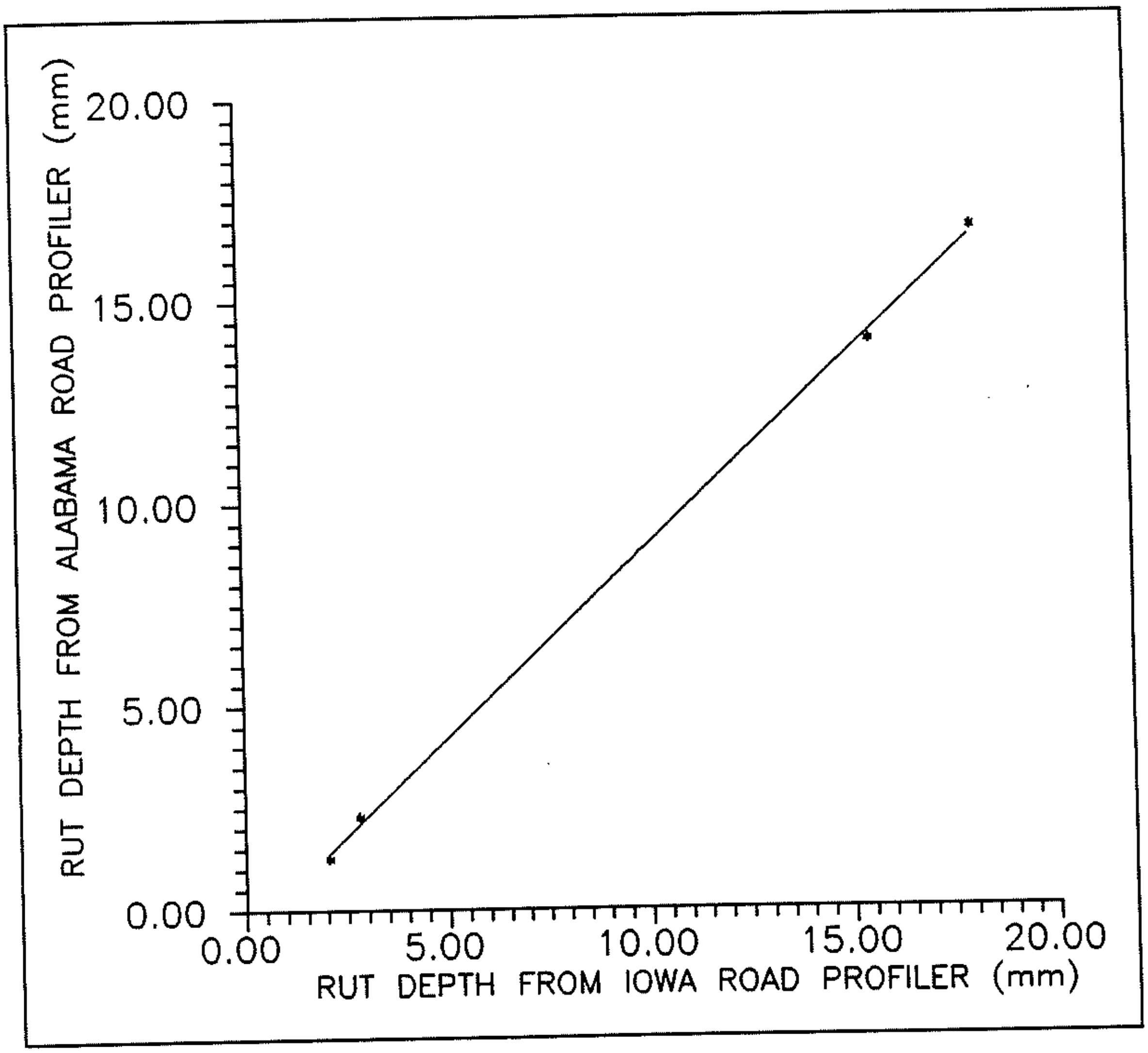


FIGURE 3.3. Rut-Depth Correlation between Iowa and Alabama Road Profilers (R-Sq. 100.0%)

bituminous surfaces are more repeatable than measurements on concrete sections. But since all bituminous sections were rough and all concrete sections were smooth, the factor roughness level should be taken into consideration. In other words, the encountered differences could be due to the effect of roughness level rather than pavement type. In this experiment, the selected sections did not reflect all roughness ranges. Therefore, no conclusive conclusions could be obtained with regard to the effect of pavement type on the repeatability of measurements.

CHAPTER SUMMARY

This chapter concentrated on evaluating the repeatability and consistency of roughness and rut-depth measurements collected by eleven South Dakota Road Profilers on four different pavement types. All data were collected during the third annual meeting of SDRPUG in 1991. Statistical analysis was then performed on IRI and rut-depth measurements to determine their repeatability and consistency. Also, regression analysis was utilized in establishing correlations among different Road Profilers.

CHAPTER 4

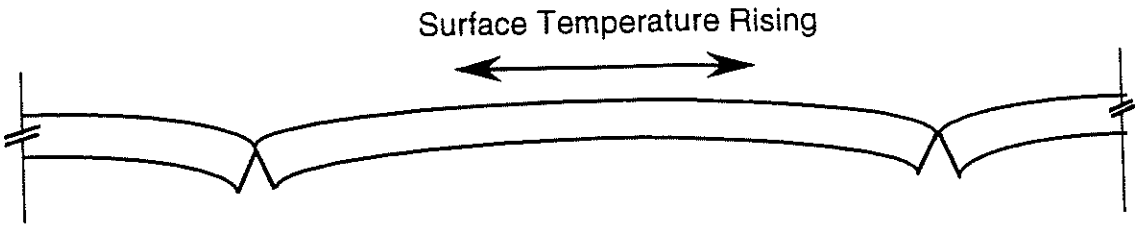
EFFECT OF ENVIRONMENTAL AND HUMAN FACTORS ON PAVEMENT LONGITUDINAL PROFILE MEASUREMENTS

INTRODUCTION

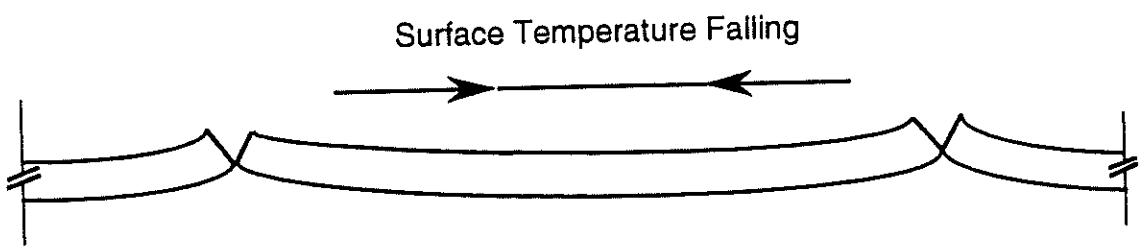
When an agency is considering the purchase of a profilometer, factors related to hardware accuracy are normally considered. Other important factors such as the effect of human operator on measurement repeatability or the effect of fluctuations in environmental factors on changing road profiles are seldom taken into account.

Operators' ability and experience can be one of the major factors contributing to the inaccuracy of the collected roughness data. The human profilometer operator has a limited ability to concentrate on the job of profiling. The ability to concentrate is somewhat time-dependent. The operator will probably do a better job testing short control sections, where the required attention span is short, than longer inventory sections. Also, every operator has a particular style of driving and reaction to particular situations. For example, if an operator is familiar with the profile of the section being tested, he or she may tend to avoid driving over rough spots by deliberately swerving to the left or the right. This type of behavior will result in inaccuracies in measuring longitudinal road profiles. Thus, the very fact that a human is required to operate the profiling equipment may limit the accuracy and repeatability of the profilometer data.

Variations in environmental conditions can also have a significant impact on pavement longitudinal profiles. Road profile characteristics can change significantly due to the daily cycle of heating and cooling, seasonal cycles of heating and cooling, and wetting and drying. As an example, excess rain fall will change the moisture conditions in the subgrade and the pavement layers. Variation in water content may cause shrinkage or swelling of subgrade soils contributing to change in the profile pattern of a pavement. Also, wide variations in temperature may cause the profile of a concrete pavement to change. During the day, the top of the pavement slab heats under the sun light while the bottom of the slab remains relatively cooler. The maximum difference in temperature between the top and bottom of the pavement slab may occur sometime after noon. This may cause the slab to warp or bend downward, developing stresses [See Figure 4.1.a]. Late in the evening, there may be reversal of warping stresses because of the heat transfer from top to bottom, making top surface colder than the bottom surface [See Figure 4.1.b]. One of the studies conducted by Scofield, Larry A. et al. revealed that roughness of a pavement increased by 7 percent for the morning and by 9 percent for the afternoon readings [32]. Seasonal variation in temperature may also contribute to the change in road profile of concrete sections. During summer, as the mean temperature of the slab increases, the concrete pavement expands. As the slab tends to expand, compressive stress is developed at its bottom. Similarly, during winter the slab contracts causing tensile stresses at the bottom [33, 34]. If the profile of a road changes from day to day and season to season, it raises the question about the value of acquiring highly accurate and repeatable profilometer data.



a. **Surface Temperature is Higher than Temperature at Bottom**



b. **Surface Temperature is Lower than Temperature at Bottom**

FIGURE 4.1. Temperature Effects on Concrete Slabs

DESIGN OF EXPERIMENT

A detailed plan was prepared to determine the effect of human factors and environmental variations on the accuracy of pavement longitudinal profile measurements. This testing plan involved the creation of two data bases. The first data set was used to examine the effect of human operators on the accuracy of profile measurements, while the second data set was used to determine the magnitude of changes in pavement profiles (roughness) due to changes in environmental factors. Figure 4.2 shows the data collection and analysis strategies for this experiment. The Wyoming Road Profiler was utilized to measure the roughness of all test sections included in the experiment.

In order to examine the effect of human operator on the repeatability of road profiler measurements, 36 sections were included in the experiment. Twenty-seven pavements were flexible and 9 pavements were rigid. The sections were selected to represent all possible ranges of roughness and rut-depth values. These ranges were:

$0 \leq$ IRI ≤ 2.0 (mm/m) - Low IRI

2.0 (mm/m) $<$ IRI ≤ 3.0 (mm/m) - Medium IRI

3.0 (mm/m) $<$ IRI - High IRI

$0 \leq$ Rut-Depth ≤ 2.54 mm (0.1 in) - Low Rut-Depth

$2.54 <$ Rut-Depth ≤ 6.35 mm (0.25 in) - Medium Rut-Depth

6.35 mm (0.25 in) $<$ Rut-Depth - High Rut-Depth

The test sections were conveniently located on I-25, SR-96, and SR-211 in the Southeastern corner of Wyoming. Table 4.1 shows the testing matrix for this experiment. Three operators were selected to operate the road profiler including the regular operator who

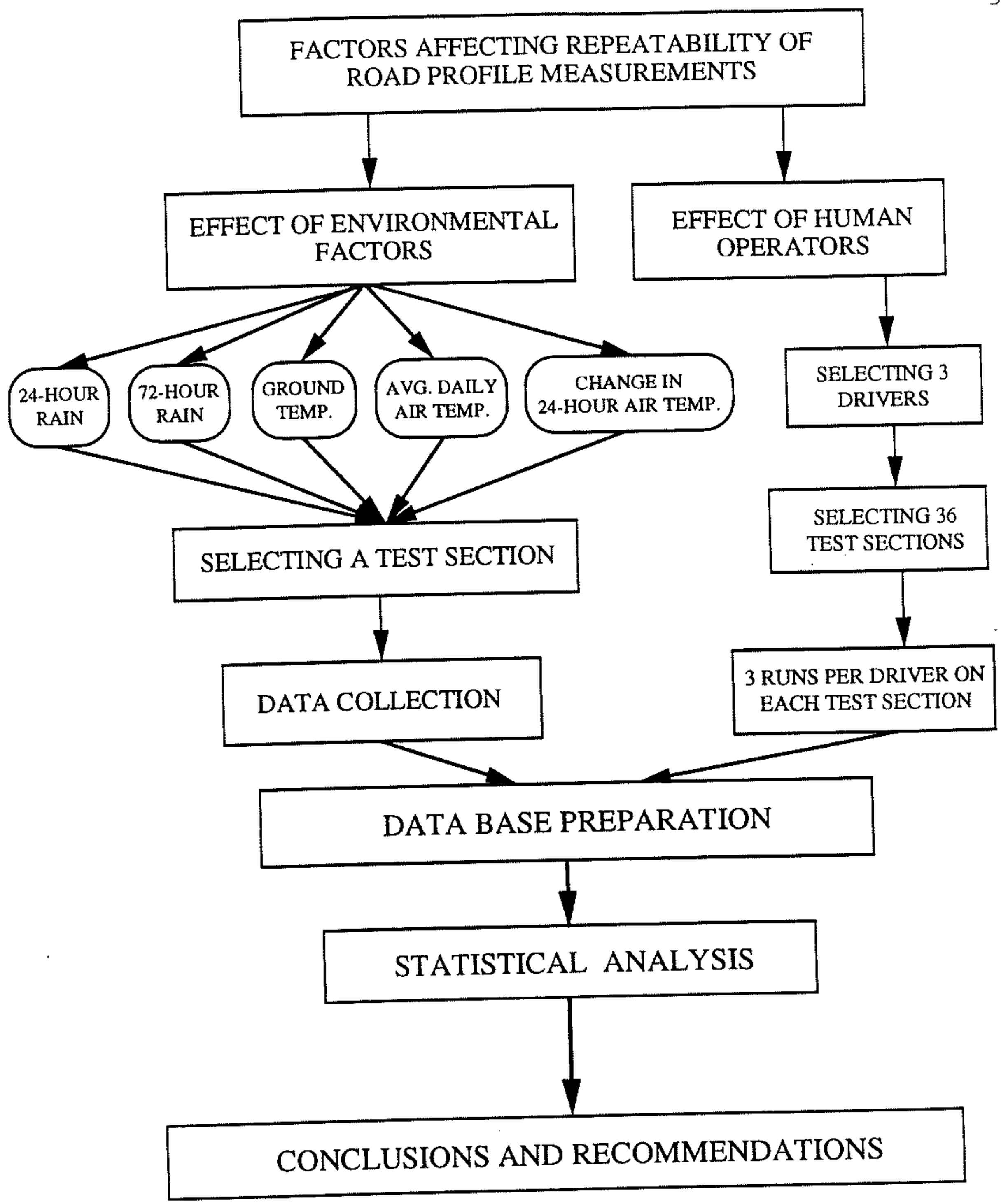


FIGURE 4.2. Data Collection and Analysis Strategies

TABLE 4.1. Locations of Test Sections Used to Evaluate the Operators' Effect on Roughness Measurement Accuracy.

Road Profiler Project		Pavement Type											
		Flexible									Rigid		
		Performance Index									Performance Index		
		IRI									IRI		
		Low			Medium			High			L	M	H
		Rut			Rut			Rut					
		L	M	H	L	M	H	L	M	H			
Sections	1	25N MP 5.0	25N MP 6.2	25N MP 18.0	25N MP 9.7	25N MP 14.9	25N MP 14.3	211 MP 39.0	25N MP 15.1	96W MP 2.1	25N MP 11.3	25N MP 11.0	25S MP 9.5
	2	25N MP 4.1	25N MP 6.5	25N MP 18.3	25N MP 9.2	25N MP 16.3	25N MP 14.6	211 MP 40.2	25N MP 15.9	96W MP 1.7	25N MP 11.5	25N MP 12.4	25S MP 10.3
	3	25N MP 9.4	25N MP 7.0	25N MP 18.6	25N MP 4.0	25N MP 28.3	W96 MP 1.0	211 MP 40.9	25N MP 16.1	96W MP 0.1	25N MP 11.7	25N MP 12.9	25S MP 12.1

Where: L, M, and H stand for Low, Medium, and High rut-depth levels.

normally conducts the routine inventory testing for the Wyoming Transportation Department. The other two operators had no prior experience in driving the road profiler. Each operator drove the road profiler three times on each test section. The operators were not told the exact locations of test sections. Instead, they were asked to cover long test segments on different highways. This was done to simulate regular field operating conditions when the operators are collecting routine data for inventory purposes.

After the data on all sections were collected, IRI and rut-depth measurements for 0.32 km (0.2 mile) long test sections were extracted from the long segments. The means, standard deviations, and coefficients of variations of IRI and rut-depth observations were then calculated. Tables 4.2, 4.3, and 4.4 summarize these values for flexible and rigid test sections.

In order to examine the effect of environmental factors on pavement longitudinal profiles, one test section was monitored in 1991 for three consecutive months. This test section is located on a 3.9 km (2.4 miles) long stretch of I-25 between MilePosts 13.8 and 16.2. The wearing surface of test section consisted of a 22.86 cm (9 inches) jointed un-reinforced portland cement concrete underlain by 15.24 cm (6 inches) of crushed gravel. Roughness data was collected on the test section under different combinations of environmental conditions. These environmental conditions were:

(1) 24-Hour Rainfalls (millimeters)

(2) 72-Hour Rainfall (millimeters)

(3) Ground Temperature at bottom of the slab (°C)

(4) Average Daily Air Temperature (°C)

TABLE 4.2. Means and Standard Deviations of IRI Values for Flexible Test Sections

			Low IRI								
			Rut								
			Low			Medium			High		
			Sections								
			1	2	3	1	2	3	1	2	3
Drivers	1	Avg.	2.27	1.52	1.39	1.50	1.63	1.69	1.97	2.09	1.51
		S.D.	0.27	0.11	0.13	0.17	0.14	0.13	0.05	0.15	0.09
		C.V.	11.89	7.24	9.35	11.33	8.59	7.69	2.54	7.18	5.96
	2	Avg.	2.08	1.44	1.74	1.51	1.61	1.54	1.68	2.08	1.21
		S.D.	0.16	0.07	0.30	0.05	0.16	0.14	0.06	0.11	0.05
		C.V.	7.69	4.86	17.24	3.31	9.94	9.09	3.57	5.29	4.13
	3	Avg.	2.24	1.45	1.53	1.69	1.87	1.74	1.84	2.05	1.36
		S.D.	0.12	0.10	0.18	0.08	0.15	0.12	0.11	0.15	0.06
		C.V.	5.36	6.90	11.76	4.73	8.02	6.90	5.98	7.32	4.41

Avg: Average of IRI Values from Three Runs
S.D: Standard Deviation
C.V: Coefficient of Variation = S.D./Avg.

TABLE 4.2. Continued. . .

			Medium IRI								
			Rut								
			Low			Medium			High		
			Sections								
			1	2	3	1	2	3	1	2	3
Drivers	1	Avg.	1.83	2.14	2.37	2.42	2.96	3.02	2.79	2.54	3.40
		S.D.	0.16	0.09	0.03	0.18	0.20	0.31	0.24	0.10	0.24
		C.V.	8.74	4.21	1.27	7.44	6.76	10.26	8.60	3.94	7.06
	2	Avg.	2.00	2.57	2.30	2.47	2.84	2.89	2.80	2.53	3.98
		S.D.	0.07	0.29	0.10	0.12	0.28	0.14	0.10	0.05	0.40
		C.V.	3.50	11.28	4.35	4.86	9.86	4.84	3.57	1.98	10.05
	3	Avg.	1.91	2.56	2.21	2.46	2.97	2.77	2.91	2.65	3.71
		S.D.	0.02	0.32	0.10	0.04	0.22	0.12	0.19	0.10	0.30
		C.V.	1.05	12.50	4.52	1.63	7.41	4.33	6.53	3.77	8.09

TABLE 4.2. Continued. . .

			High IRI								
			Rut								
			Low			Medium			High		
			Sections								
			1	2	3	1	2	3	1	2	3
Drivers	1	Avg.	4.11	3.59	3.45	3.05	3.64	3.84	2.85	2.24	2.54
		S.D.	0.05	0.19	0.08	0.12	0.40	0.17	0.07	0.23	0.31
		C.V.	1.22	5.29	2.32	3.93	10.99	4.43	2.46	10.27	12.20
	2	Avg.	4.37	3.83	3.49	3.06	3.77	3.76	3.55	4.66	4.26
		S.D.	0.26	0.16	0.17	0.08	0.29	0.20	0.12	0.70	0.22
		C.V.	5.95	4.18	4.87	2.61	7.69	5.32	3.38	15.02	5.16
	3	Avg.	4.30	3.79	3.54	3.12	3.90	3.90	3.63	4.34	4.34
		S.D.	0.11	0.22	0.10	0.15	0.04	0.18	0.16	0.10	0.04
		C.V.	2.56	5.80	2.82	4.81	1.03	4.62	4.41	2.30	0.92

TABLE 4.3. Means and Standard Deviations of IRI Values for Rigid Test Sections

			Low IRI			Medium IRI			High IRI		
			Section			Section			Section		
			1	2	3	1	2	3	1	2	3
Drivers	1	Avg.	2.12	1.86	1.81	2.08	2.34	2.42	2.33	2.80	3.10
		S.D.	0.09	0.08	0.11	0.12	0.13	0.16	0.04	0.21	0.01
		C.V.	4.25	4.30	6.08	5.77	5.56	6.61	1.72	7.50	0.32
	2	Avg.	2.31	2.06	1.99	2.24	2.37	2.50	2.44	2.83	3.30
		S.D.	0.10	0.28	0.21	0.10	0.07	0.06	0.17	0.16	0.06
		C.V.	4.33	13.59	10.55	4.46	2.95	2.40	6.97	5.65	1.82
	3	Avg	2.26	1.90	1.79	2.06	2.20	2.55	2.26	3.00	3.26
		S.D.	0.17	0.06	0.03	0.10	0.08	0.09	0.10	0.43	0.11
		C.V.	7.52	3.16	1.68	4.85	3.64	3.53	4.42	14.33	3.37

Avg: Average of IRI Values from Three Runs
S.D: Standard Deviation
C.V: Coefficient of Variation = S.D./Avg.

TABLE 4.4. Means and Standard Deviations of Rut-Depth Values for Flexible Test Sections

			Low IRI								
			Rut								
			Low			Medium			High		
			Sections								
			1	2	3	1	2	3	1	2	3
Drivers	1	Avg.	0.10	0.10	0.08	0.15	0.13	0.10	0.33	0.46	0.52
		S.D.	0.04	0.01	0.01	0.06	0.04	0.06	0.11	0.02	0.03
		C.V.	40.00	10.00	12.50	40.00	30.77	60.00	33.33	4.35	5.77
	2	Avg.	0.13	0.11	0.09	0.11	0.13	0.07	0.40	0.47	0.49
		S.D.	0.05	0.01	0.00	0.02	0.05	0.04	0.06	0.02	0.07
		C.V.	38.46	9.09	0.00	18.18	38.46	57.14	15.00	4.26	14.29
	3	Avg.	0.09	0.07	0.09	0.19	0.21	0.17	0.39	0.45	0.52
		S.D.	0.07	0.02	0.00	0.01	0.02	0.02	0.06	0.02	0.02
		C.V.	77.78	28.57	0.00	5.26	9.52	11.76	15.38	4.44	3.85

Avg: Average Rut Depth from Three Runs
S.D: Standard Deviation
C.V: Coefficient of Variation = S.D./Avg.

TABLE 4.4. Continued. . .

			Medium IRI								
			Rut								
			Low			Medium			High		
			Sections								
			1	2	3	1	2	3	1	2	3
Drivers	1	Avg.	0.11	0.06	0.08	0.23	0.19	0.32	0.23	0.25	0.63
		S.D.	0.03	0.01	0.01	0.02	0.03	0.03	0.05	0.05	0.02
		C.V.	27.27	16.67	12.50	8.70	15.79	9.38	21.74	20.00	3.17
	2	Avg.	0.11	0.08	0.08	0.25	0.23	0.21	0.24	0.26	0.65
		S.D.	0.01	0.00	0.01	0.01	0.03	0.03	0.01	0.03	0.01
		C.V.	9.09	0.00	12.50	4.00	13.04	14.29	4.17	11.54	1.54
	3	Avg.	0.12	0.07	0.05	0.24	0.27	0.28	0.28	0.29	0.61
		S.D.	0.01	0.01	0.02	0.01	0.01	0.01	0.03	0.00	0.02
		C.V.	8.33	14.29	40.00	4.17	3.70	3.57	10.71	0.00	3.28

TABLE 4.4. Continued. . .

			High IRI								
			Rut								
			Low			Medium			High		
			Sections								
			1	2	3	1	2	3	1	2	3
Drivers	1	Avg.	0.08	0.18	0.19	0.17	0.14	0.17	0.41	0.44	0.40
		S.D.	0.01	0.01	0.02	0.03	0.03	0.03	0.03	0.04	0.02
		C.V.	12.50	5.56	10.53	17.65	21.43	17.65	7.32	9.09	5.00
	2	Avg.	0.15	0.16	0.20	0.19	0.15	0.15	0.35	0.43	0.38
		S.D.	0.03	0.01	0.01	0.02	0.04	0.03	0.05	0.01	0.02
		C.V.	20.00	6.25	5.00	10.53	26.67	20.00	14.29	2.33	5.26
	3	Avg.	0.12	0.17	0.17	0.20	0.20	0.21	0.55	0.48	0.42
		S.D.	0.02	0.01	0.02	0.01	0.01	0.03	0.02	0.01	0.04
		C.V.	16.67	5.88	11.76	5.00	5.00	14.29	3.64	2.08	9.52

(5) Change in 24-Hour Air temperature (°C)

Table 4.5 summarizes all roughness and environmental data collected on the test section.

DATA ANALYSIS

All collected data were reduced and compiled in computer files. Data analysis was later conducted by using regular statistical tools. The main objectives of the analysis were to:

1. investigate the repeatability of roughness and rut-depth measurements obtained by each operator,
2. compare the results obtained from three operators, and
3. investigate the effect of environmental factors on pavement roughness.

Measurements Repeatability by Each Operator

The objective of this analysis was to determine if roughness and rut-depth measurements obtained by individual operators were repeatable. To accomplish this objective, IRI and rut-depth data collected by three test operators on all 36 test sections were analyzed. The averages, standard deviations, and coefficients of variation were then calculated for IRI and rut-depth data on all test sections (See Tables 4.2, 4.3, and 4.4). The IRI coefficients of variation ranged from <u>0.32 to 14.33</u> on concrete sections and from <u>0.92 to 17.74</u> on bituminous sections. These coefficients of variation indicate acceptable variability of IRI measurements. In other words, IRI measurements obtained by any operator were repeatable.

Table 4.5. Data Collected for IRI and Other Environmental Factors

Test No.	IRI (mm/m)	Ground Temperature (°C)	Average Daily Air Temperature (°C)	Change in 24-Hour Air Temperature (°C)	Total 24-Hour Rain (mm)	Total 72-Hour Rain (mm)	Change in Air vs Ground Temperature (°C)
1	2.76	13	13	+2.8	0.00	2.03	0.6
2	2.75	12	13	0	0.00	3.64	1.1
3	3.04	15	11	-2.2	18.54	73.15	3.9
4	2.76	14	15	-1.7	0.00	5.33	0.6
5	2.72	20	19	+1.1	0.00	0.51	1.1
6	2.70	21	22	+3.9	0.00	1.27	1.1
7	2.75	22	21	+0.6	2.30	15.55	1.1
8	2.68	21	16	-1.1	0.00	0.00	5.0
9	2.71	22	21	-0.6	3.30	3.81	0.6
10	2.81	24	22	+1.7	0.00	4.06	2.2
11	2.69	16	21	+2.2	0.00	4.06	5.0
12	2.77	20	22	+1.1	0.00	0.00	1.7

On the other hand, the coefficients of variation for rut-depth measurements ranged from 0 to 77.78 indicating high relative variability for rut-depth measurements.

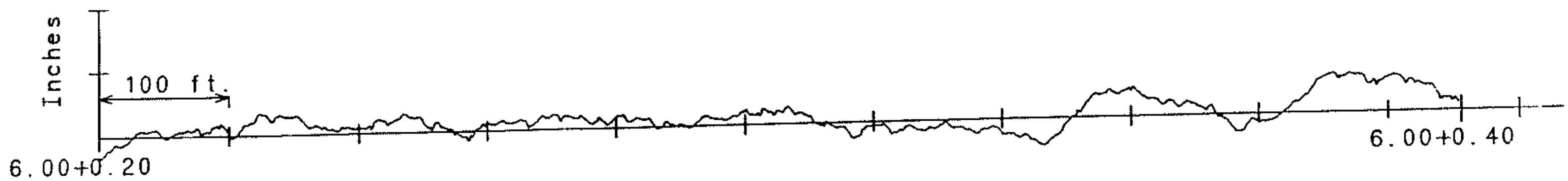
Comparison Among the Three Operators

This analysis was aimed at determining the repeatability of roughness and rut-depth measurements obtained by three different operators. Pavement longitudinal profiles obtained by the three drivers were first plotted and compared visually. Figure 4.3 shows some of these profiles on a selected test section. Since no definite conclusions could be obtained by the visual comparisons, IRI and rut-depth measurements were calculated and averaged for each test section. The two-sample t-test was then used to conduct two-by-two comparisons between the means. Basically, average measurements from any two operators were compared to determine if they were statistically different at 95 percent confidence level.

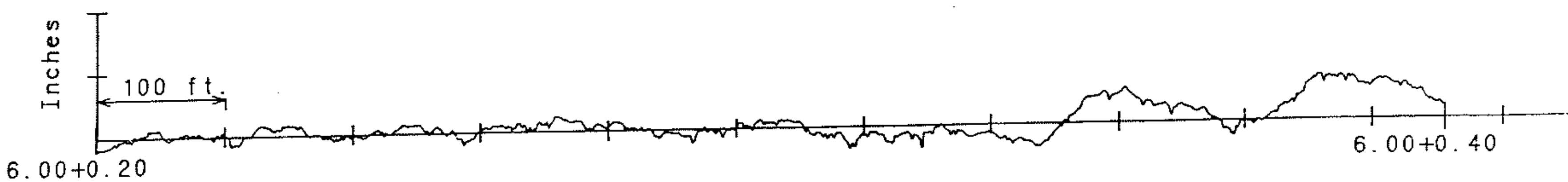
The t-statistic used in the analysis was calculated with the following equation:

$$t=\frac{(\overline{Y_1}-\overline{Y_2})}{S_p\sqrt{\frac{1}{n1}+\frac{1}{n2}}} \qquad \text{(Eqn. 4.1)}$$

Where:	Y_1 and Y_2	=	sample means.
	n_1 and n_2	=	sample sizes = 3 in our case.
	S_p^2	=	estimate of the common variance computed with the following equation:



Driver (2), Run No. 3



Driver (3), Run No. 3

FIGURE 4.3. Profile of the Test Sections Between MilePosts 6.2 and 6.4 for Run No. 3 by Drivers (2) and (3)

$$S_p^2 = \frac{(n1-1)\,\sigma_1^2 + (n2-1)\,\sigma_2^2}{n1+n2-2} \qquad \text{(Eqn. 4.2)}$$

Where: σ_1^2 and σ_2^2 = two individual sample variances.

The calculated t-value was compared with $t_{\alpha/2,\,n1+n2-2} = 2.776$ (for $\alpha = 0.05$ and degrees of freedom = 4). If ABS (t) > $t_{\alpha/2,\,n1+n2-2}$, it would be concluded that the two means are statistically different. Using this two-sample t-test, a large number of two-by-two comparisons were conducted on IRI and rut-depth data. Measurements obtained with each operator were compared with measurements from the other two operators on all 36 test sections. The results of the statistical analysis are summarized in Tables 4.6 and 4.7 for IRI and rut-depth data respectively. Table 4.6 shows how IRI measurements obtained with the three operators were equal in all cases except five. It is interesting to see that three of the five cases were on flexible sections with low roughness levels. On the other hand, Table 4.7 shows how the inequalities among operators were much higher when dealing with rut-depth measurements. In this case, more differences were detected on sections with high roughness level.

Effect of Environmental Factors on Pavement Roughness

All environmental data collected on the concrete test section were analyzed statistically. The main objectives of the analysis were to: first determine which environmental factors cause changes in pavement profiles and second to develop a regression relationship that can predict IRI based on these important factors. The following regression model was initially

Table 4.6. Results from IRI Paired Comparisons.

Road Profiler Project			Pavement Type											
			Flexible									Rigid		
			Performance Index									Performance Index		
			IRI									IRI		
			Low			Medium			High			L	M	H
			Rut			Rut			Rut					
			L	M	H	L	M	H	L	M	H			
Drivers (1) and (2)	Sections	1	E*	E	NE**	E	E	E	E	E	E	E	E	E
		2	E	E	E	E	E	E	E	E	E	E	E	E
		3	E	E	NE	E	E	E	E	E	E	E	E	NE
Drivers (1) and (3)	Sections	1	E	E	E	E	E	E	E	E	E	E	E	E
		2	E	E	E	E	E	E	E	E	E	E	E	E
		3	E	E	E	NE	E	E	E	E	E	E	E	E
Drivers (2) and (3)	Sections	1	E	NE	E	E	E	E	E	E	E	E	E	E
		2	E	E	E	E	E	E	E	E	E	E	E	E
		3	E	E	E	E	E	E	E	E	E	E	E	E

* E: IRI data obtained with respective drivers are statistically equal.
** NE:IRI data obtained with respective drivers are statistically different

Table 4.7. Results from Rut-Depth Paired Comparisons

Road Profiler Project			Pavement Type								
			Flexible								
			Performance Index								
			IRI								
			Low			Medium			High		
			Rut			Rut			Rut		
			L	M	H	L	M	H	L	M	H
Drivers (1) and (2)	Sections	1	E*	E	E	E	E	E	NE	E	E
		2	E	E	E	E	E	E	E	E	E
		3	E	E	E	E	NE	E	E	E	E
Drivers (1) and (3)	Sections	1	E	E	E	E	E	E	NE	E	NE
		2	E	NE**	E	E	NE	E	E	NE	E
		3	E	E	E	E	E	E	E	NE	E
Drivers (2) and (3)	Sections	1	E	NE	E	E	E	E	E	E	NE
		2	NE	E	E	E	E	E	E	E	NE
		3	E	NE	E	E	NE	E	NE	NE	E

used:

$$Y_i=\beta_o+\beta_1X_1+\beta_2X_2+\beta_3X_3+\epsilon_i \qquad \text{(Eqn. 4.3)}$$

Where: Y_i = value of response variable IRI
X_1, X_2, X_3 = independent variables (Environmental factors such as temperature, rain, etc.)
β_0, β_1, β_3 = regression constants.

Based on the above regression model, relationships were established by using the Minitab software package. All factors were linearly correlated with IRI and the resulting R-Squares were examined. Graphs were also drawn to determine the general shape of relationship between each environmental factor and IRI. The relationship between IRI and the variation in air temperature during 24 hours is shown in Figure 4.4. After several trials of linear regression, the following regression model was obtained with R^2 = 84.3%:

$$IRI=2.72+0.00434A+0.00153B \qquad \text{(Eqn. 4.4)}$$

Where: IRI = International Roughness Index
A = 72-hour rainfall prior to testing
B = change in 24-hour air temperature

In addition, in an effort to visualize how much influence these factors have on IRI measurements, Tables 4.8 and 4.9 were prepared. The tables show the predicted IRI values at varying levels of 72-hour rainfall and change in 24-hour air temperature values.

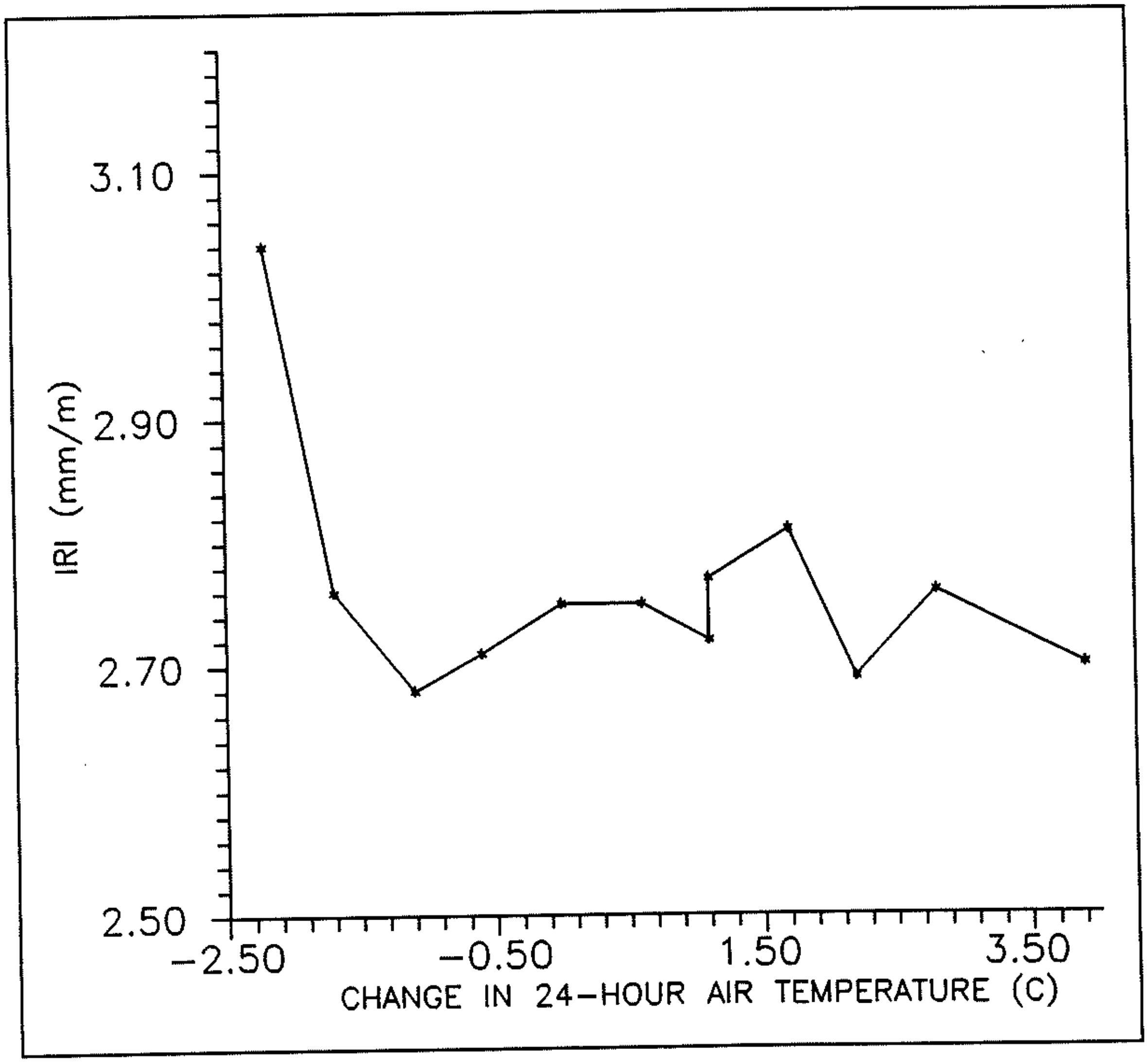


FIGURE 4.4. IRI vs Change in 24-Hour Air Temperature

TABLE 4.8. IRI Variation Due to Change in 72-hour Rainfall

Model: IRI = 2.72 + 0.00434 A + 0.00153 B

where: A = 72-hour Rainfall (mm)

B = Change in 24-hour Air Temperature (°C)

A (mm)	B (°C)	IRI (mm/m)
0	-2.2	2.717
40	-2.2	2.891
70	-2.2	3.021
0	+3.9	2.726
40	+3.9	2.900
70	+3.9	3.030

TABLE 4.9. IRI Variation Due to Change in 24-hour Air Temperature

Model: IRI = 2.72 + 0.00434 A + 0.00153 B

where: A = 72-hour Rainfall (mm)

B = Change in 24-hour Air Temperature (°C)

B (°C)	A (mm)	IRI (mm/m)
-2.2	0	2.717
0.0	0	2.720
3.9	0	2.726
-2.2	70	3.020
0.0	70	3.024
3.9	70	3.030

The regression relationship, therefore, indicates clearly that IRI is influenced by environmental factors. Specifically, the higher the amount of rain falling on the section within 72 hours prior to testing the higher the measured IRI value. Also, the roughness of a concrete section will vary slightly depending on air temperature fluctuation prior to testing. Some other relationships were developed with the factor 24-hour rainfall. However, these relationships produced lower R-square.

CHAPTER SUMMARY

The objective of this chapter was to investigate the effect of human operators on repeatability of IRI and rut-depth measurements. In addition, the effect of varying environmental conditions on roughness measurements was examined. Statistical analysis was performed to determine the operators' effect on accuracy of IRI as well as rut-depth measurements. On the other hand, a regression model was developed characterizing the variation of IRI with respect to two environmental conditions.

CHAPTER V

COMPARISON OF RUT-DEPTH MEASUREMENTS OBTAINED WITH FOUR DIFFERENT TECHNIQUES

INTRODUCTION

Rut-depth and pavement roughness have long been recognized as the primary indicators of pavement performance. Phenomenon of roughness can be attributed to the varying longitudinal profile of a roadway section. Ruts, on the other hand, can be defined as the depressions which occur in the pavement's wheel path as a result of traffic loads. Small amounts of rutting may occur due to the continued densification under traffic after initial compaction during construction. Large amount of rutting, however, occurs due to the overstressed Hot Mix Asphalt (HMA) layer, underlying layers, or the subgrade soil along with significant densification or shear failure. Although rut-depth does not contribute much to the longitudinal roughness of pavement, measurement of rut depths plays an important role in assessing pavement safety. Deep ruts may pond water in the wheel path, hence resulting in possibility of hydroplaning of fast moving vehicles. Ponding of water is a more serious problem in cold climates where freezing of the water may create slick conditions.

Rut-depth of a pavement section can be determined by several techniques. One way would be to use a three-sensor or a five-sensor road profiler. The sensors of these road profilers are normally mounted on the front bumper so that rut-depth can be obtained while measuring roughness. The three-sensor system measures distances between the front bumper and pavement surface in the left wheel path, the right wheel path, and the center of the lane.

Rut-depths obtained with this method basically represent the height of the hump between the extreme two sensors. On the other hand, the five-sensor road profiler has two additional sensors to measure the actual ruts in both wheel paths rather than measuring the hump. Another common technique utilized in measuring rut-depth is by using a straightedge. The straightedge is normally four-foot long and is generally used for rough estimation of rut-depth in the field. Measurements with the straightedge are usually taken in the left and right wheel paths and the average value is then used as rut-depth of the section. Theoretical water capacity of ruts can also be used to measure the severity of pavement rutting. As briefly described earlier, deep ruts can result in collection of water which may act as a safety hazard causing vehicles to hydroplan and producing slick conditions in winter.

Most highway agencies in the U.S. utilize either three-sensor road profilers or five-sensor road profilers in determining the severity of pavement rutting. The collected data is then used locally by individual states to identify sections with potential problems. On the other hand, the data collected by all states is used by the Federal Highway Administration (FHWA) to determine the overall health of the national network. Since different states are using different methods in measuring rut-depth, pavement engineers are faced with the following questions: Do three-sensor and five-sensor systems produce equal results? And how do these high speed methods compare with other manual methods such as the straight-edge and the theoretical water capacity of ruts? The main objective of this chapter, therefore, was to address the above questions and to determine how well the rut measurements obtained with three-sensor road profilers, five-sensor road profilers, straightedge method, and the theoretical water capacity of ruts correlate among each other.

DESIGN OF EXPERIMENT

In order to conduct this experiment, 57 test sections were selected on Interstate-80 in the state of Wyoming. I-80 was selected simply because of its heavy traffic loading. Over 30% of the traffic on I-80 is trucks which resulted in various levels and shapes of rutting. Transverse profiles of all test sections were obtained by the Wyoming Transportation Department (WTD) utilizing a Rainhart Transverse Profilograph. These transverse profiles were first examined visually to identify shapes and rut-depth variations. All profiles were then grouped into three categories since they seemed to vary distinctively in shapes and rut-depth levels. Figures 5.1, 5.2, and 5.3 show representative profiles for categories I, II, and III respectively. After classifying all profiles into three categories, rut-depth measurements were obtained by using four different techniques. A comprehensive computerized data base was then prepared for analysis. Data analysis was conducted first on the whole data base and later on each profile category. This was done to determine the effect of rut-depth shape on the analysis. Figure 5.4 shows the overall design of experiment and analysis strategies for this analysis.

RUT-DEPTH MEASUREMENTS

As mentioned earlier, the following rut measuring techniques were used in the experiment: five-sensor road profiler, three-sensor road profiler, straightedge, and the theoretical water capacity of ruts. Rut-depth measurements for all four methods were extracted from transverse profiles using the same techniques and algorithms utilized in the field. The following section describes in detail how rut-depth measurements were obtained

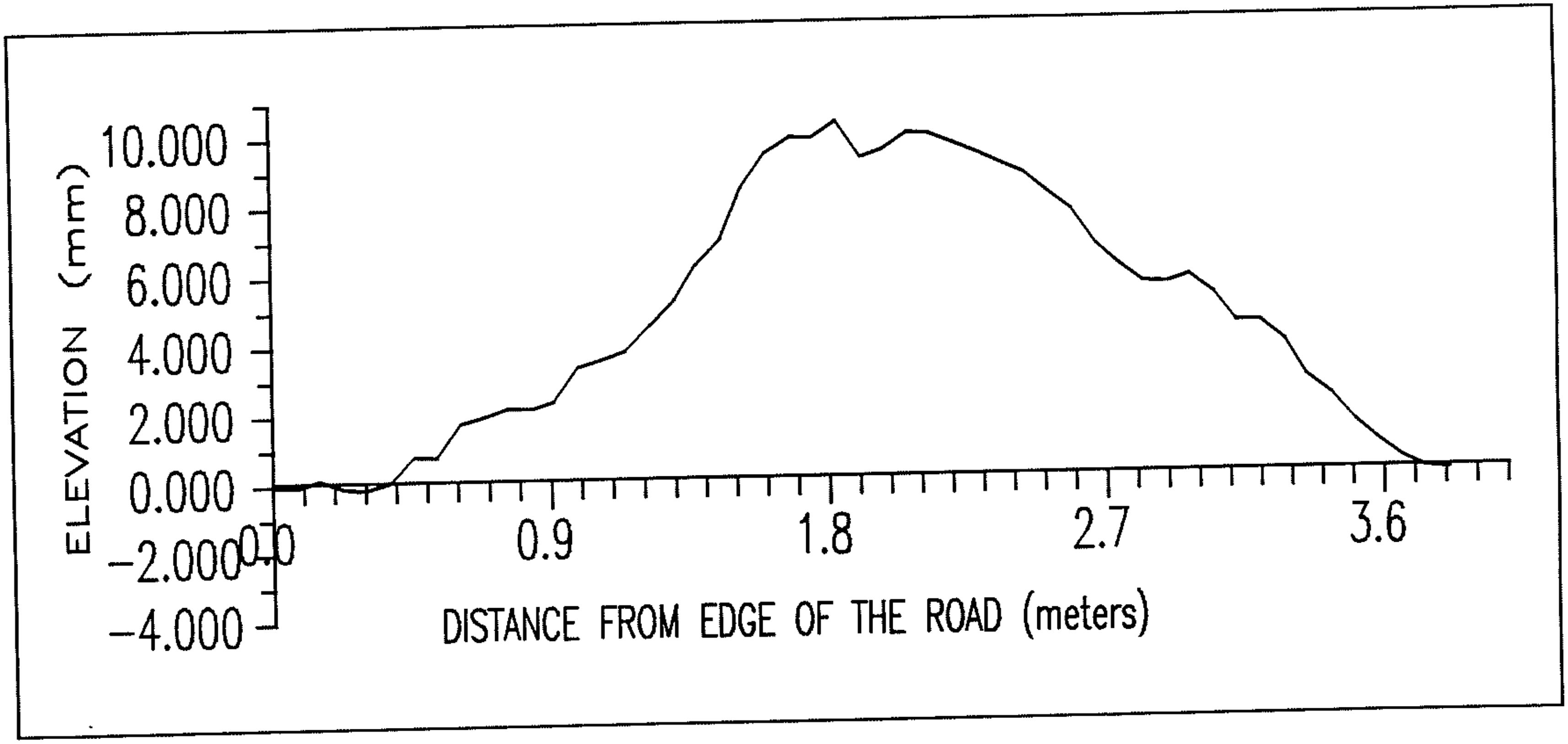


FIGURE 5.1. A Transverse Profile Representing Category I

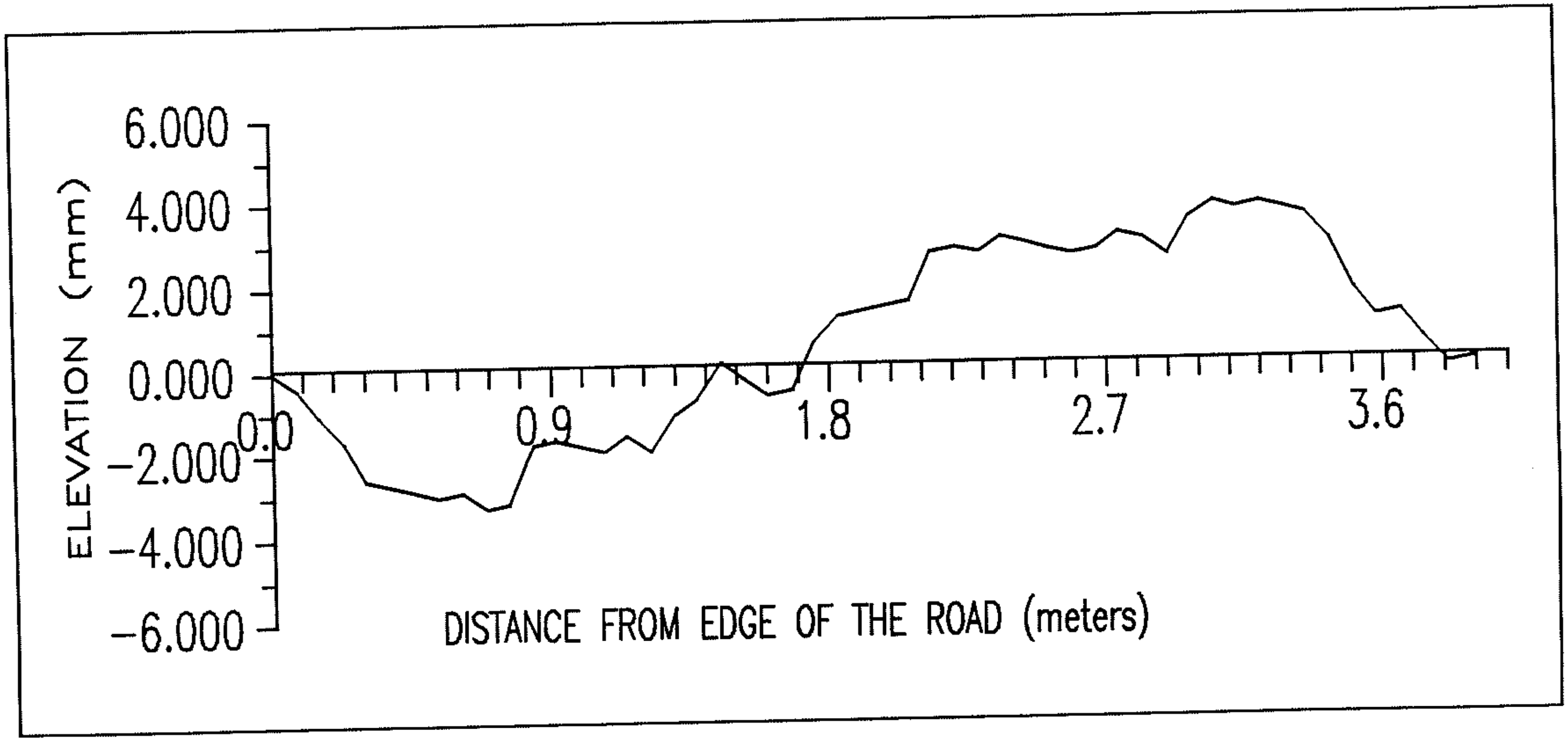


FIGURE 5.2. A Transverse Profile Representing Category II

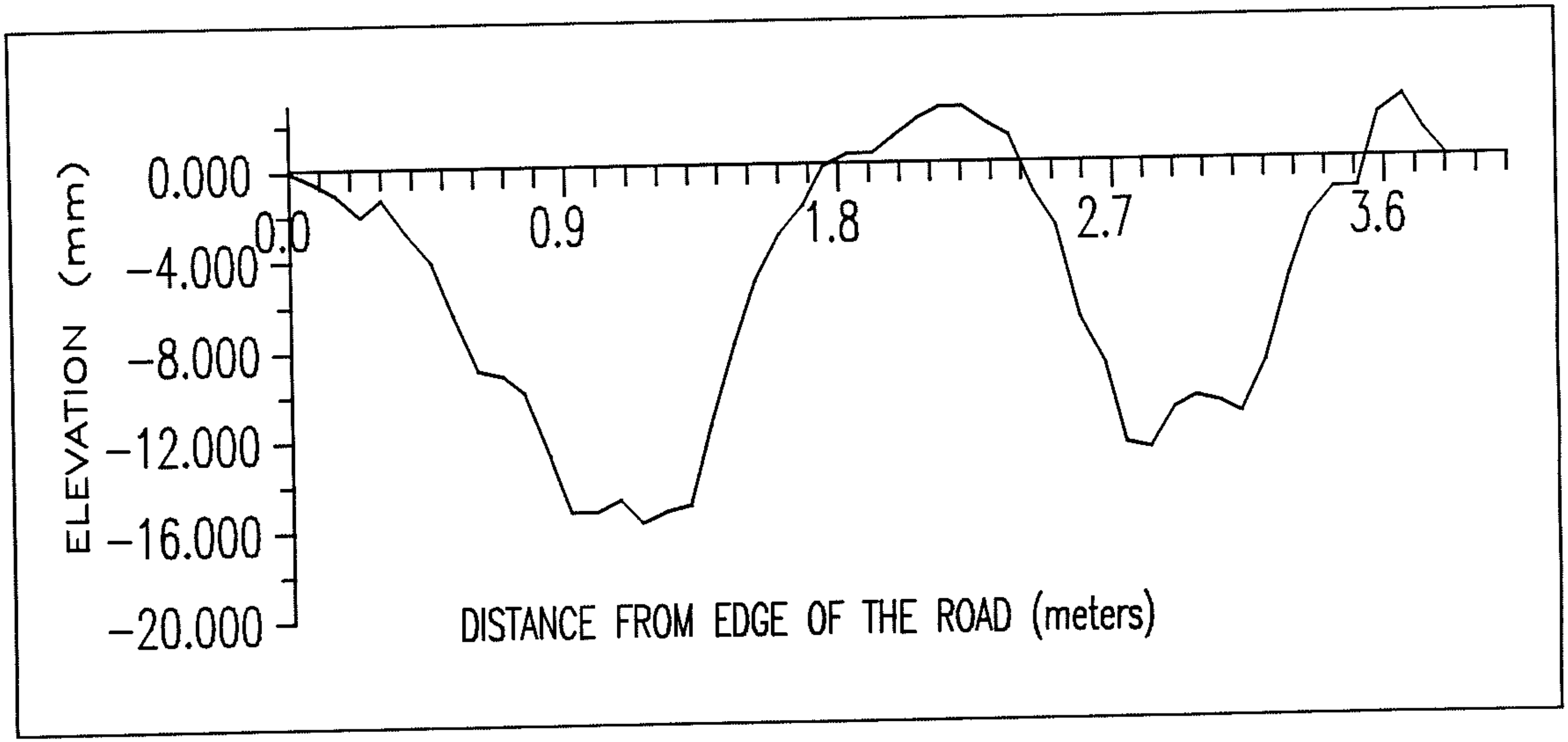


FIGURE 5.3. A Transverse Profile Representing Category III

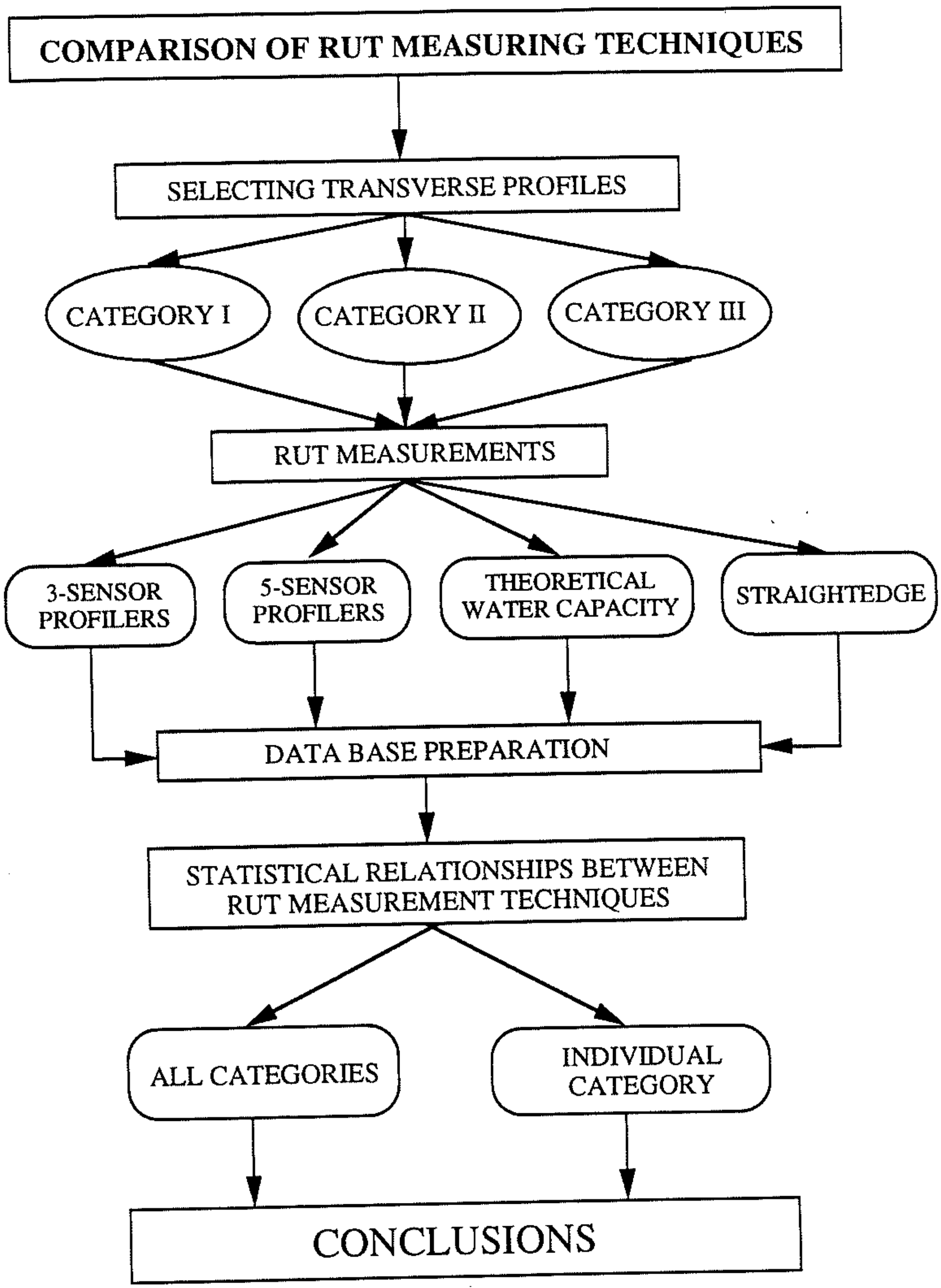


FIGURE 5.4. Data Collection and Analysis Strategies

by each method.

Three-Sensor Road Profilers

Rut measurements were extracted from all transverse profiles assuming the same sensor spacing on three-sensor road profilers. The three sensors were assumed to be mounted at the same level on a 1.88 meters (74-inch) long front-bumper of a road profiler. As shown in Figure 5.5, the sensors were located 81.3 centimeters (32 inches) apart. Vertical elevations were recorded by measuring the distance between each sensor and pavement surface. Rut-depth D was then computed with the following equation:

$$D = (h_1 - 2h_2 + h_3)/2$$

Where: h_1, h_2, and h_3 = the respective distances between the pavement and the left, center, and right sensors.

D represents the hump height between the two wheelpaths and approximates the average rut in the left and right wheel paths. Tables 5.1, 5.2, and 5.3 summarize rut measurements collected with this technique.

Five-Sensor Road Profilers

Rut measurements with five-sensor road profilers were obtained in a similar manner as three-sensor road profilers. Vertical distances between the five sensors and pavement surface were extracted from transverse profiles. The five sensors were assumed to be

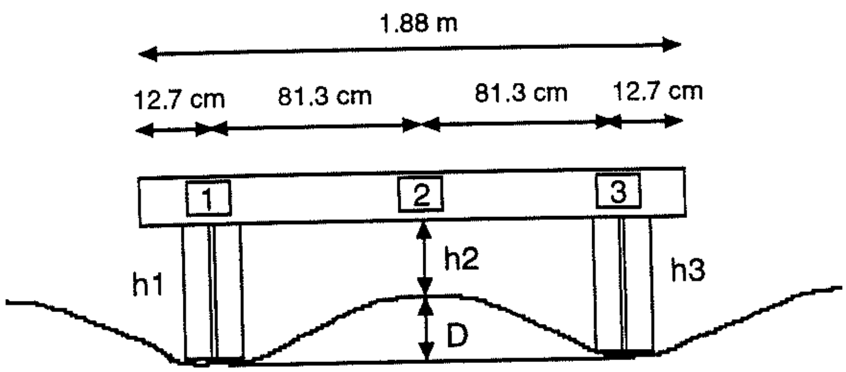


FIGURE 5.5. Sensor Arrangement on Three-Sensor Road Profilers

TABLE 5.1. Rut-Depth Data Collected for Category I Profiles

Profile No.	Rut-Depth with 5 Sensors (cm)	Rut-Depth with 3 Sensors (cm)	Water Capacity (cm)	Rut-Depth by Straightedge (cm)
1	0.152	0.512	0.000	0.076
2	0.078	0.097	0.051	0.151
3	0.000	0.071	0.013	0.112
4	0.062	0.203	0.000	0.070
5	0.030	0.236	0.000	0.107
6	0.089	0.381	0.038	0.038
7	0.071	0.363	0.025	0.112
8	0.006	0.097	0.038	0.057
9	0.195	0.538	0.015	0.157
10	0.171	0.475	0.051	0.178
11	0.000	0.000	0.041	0.142
12	0.166	0.618	0.020	0.216
13	0.157	0.737	0.038	0.254
14	0.243	0.660	0.051	0.210
15	0.175	0.617	0.029	0.216
16	0.117	0.284	0.036	0.272
17	0.083	0.406	0.011	0.079
18	0.005	0.203	0.051	0.191
19	0.000	0.274	0.017	0.067
20	0.127	0.368	0.053	0.147
21	0.144	0.432	0.025	0.168
22	0.130	0.325	0.076	0.273
23	0.275	0.566	0.076	0.235
24	0.219	0.640	0.028	0.235
25	0.000	0.000	0.013	0.267
26	0.064	0.216	0.032	0.239
27	0.139	0.445	0.025	0.178
28	0.264	0.559	0.064	0.241

Table 5.2. Rut-Depth Data Collected for Category II Profiles.

Profile No.	Rut-Depth with 5 Sensors (cm)	Rut-Depth with 3 Sensors (cm)	Water Capacity (cm)	Rut-Depth by Straightedge (cm)
1	0.045	0.102	0.089	0.083
2	0.300	0.475	0.183	0.304
3	0.229	0.457	0.076	0.269
4	0.229	0.400	0.191	0.249
5	0.200	0.432	0.375	0.640
6	0.157	0.312	0.344	0.372
7	0.409	0.695	0.109	0.431
8	0.196	0.297	0.102	0.197
9	0.050	0.081	0.170	0.179
10	0.070	0.070	0.180	0.179
11	0.010	0.147	0.128	0.222

TABLE 5.3. Rut-Depth Data Collected for Category III Profiles.

Profile No.	Rut-Depth with 5 Sensors (cm)	Rut-Depth with 3 Sensors (cm)	Water Capacity (cm)	Rut-Depth by Straightedge (cm)
1	0.267	0.471	0.127	0.232
2	0.180	0.573	0.518	0.542
3	1.069	1.271	1.060	1.270
4	0.000	0.047	0.503	0.588
5	0.261	0.541	0.343	0.489
6	0.320	0.584	0.194	0.436
7	0.184	0.348	0.154	0.348
8	0.772	1.207	1.765	1.905
9	1.603	2.215	1.689	1.594
10	1.187	1.542	1.245	1.353
11	0.984	1.123	1.308	1.289
12	0.613	1.194	1.270	1.435
13	1.123	1.214	1.549	1.359
14	0.894	1.049	2.019	2.057
15	1.078	1.455	1.829	1.880
16	0.792	1.200	1.524	1.657
17	1.105	0.973	1.003	1.232
18	0.709	1.100	1.257	1.257

mounted on a 3.05 m (120-inch) long front-bumper. As shown in Figure 5.6, the spacings between consecutive sensors were 54.61 cm (21.5"), 87.63 cm (34.5"), 87.63 cm (34.5"), and 54.61 cm (21.5"). The left wheelpath rut measurements were taken by the two leftmost and middle sensors while the right wheelpath rut-depths were taken by the two rightmost and middle sensors. The following equations were then used in calculating rut depth:

$$D_L = (h_1 - 2h_2 + h_3)/2$$

$$D_R = (h_3 - 2h_4 + h_5)/2$$

$$D = (D_L + D_R)/2$$

Where:

h_1, h_2, h_3, h_4, and h_5	=	the respective vertical distances between the pavement and five sensors
D_L	=	rut-depth in the left wheelpath
D_R	=	rut-depth in the right wheelpath
D	=	rut-depth of the section.

All rut-depth measurements obtained with this technique are summarized in Tables 5.1, 5.2, and 5.3.

Theoretical Water Capacity of Ruts

Theoretical water capacity of a rut can be simply defined as its potential water ponding capacity. Water capacity can be a critical safety concern if pavement rutting is excessive. In this study, the theoretical water capacity of ruts was obtained by first drawing a horizontal line from the lowest point in left and right ruts in a transverse profile. Rut-

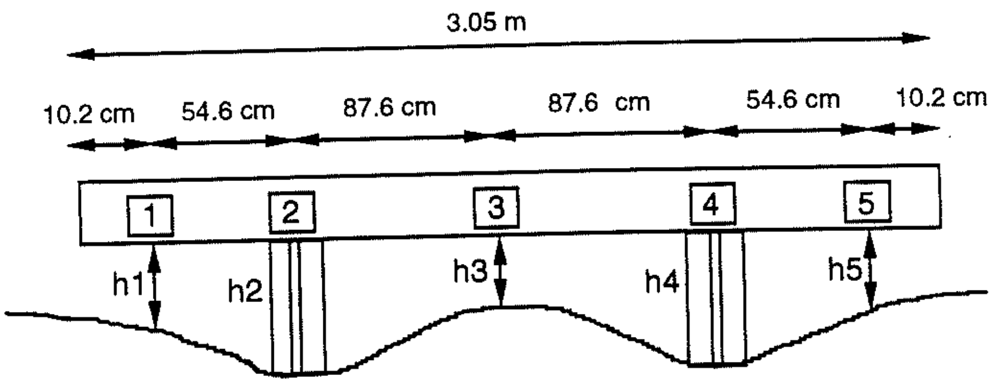


FIGURE 5.6. Sensor Arrangement on Five-Sensor Road Profilers

depth was then determined by measuring the vertical depth below that line (See Figure 5.7). The average of the left and right water capacities was then taken as the theoretical water capacity of the section. Tables 5.1, 5.2, and 5.3 summarize the theoretical water capacity of all test sections.

Straightedge

Rut-depths by this method were determined by using a four-foot long straightedge. Like all previously described methods, rut-depth data was not collected in the field. Instead, a straightedge of proportionate length was placed on the rutted transverse profile and the maximum vertical drop from the straightedge to the pavement was measured (See Figure 5.8). All of these measurements were then summarized in Tables 5.1, 5.2, and 5.3.

DATA ANALYSIS

Prior to conducting any statistical analysis, rut measurements collected by all four methods were examined visually. It was observed that about 93% of rut-depths obtained by three-sensor profilers were larger than those obtained by five-sensor profilers. Similarly, 91% of rut-depth measurements by a straightedge were larger than the theoretical water capacity measurements. To verify these interesting observations, the t-test was performed to determine if the two high speed profilers and two manual rut measuring techniques produced significantly different rut measurements. The t_o statistic was computed with the following equation:

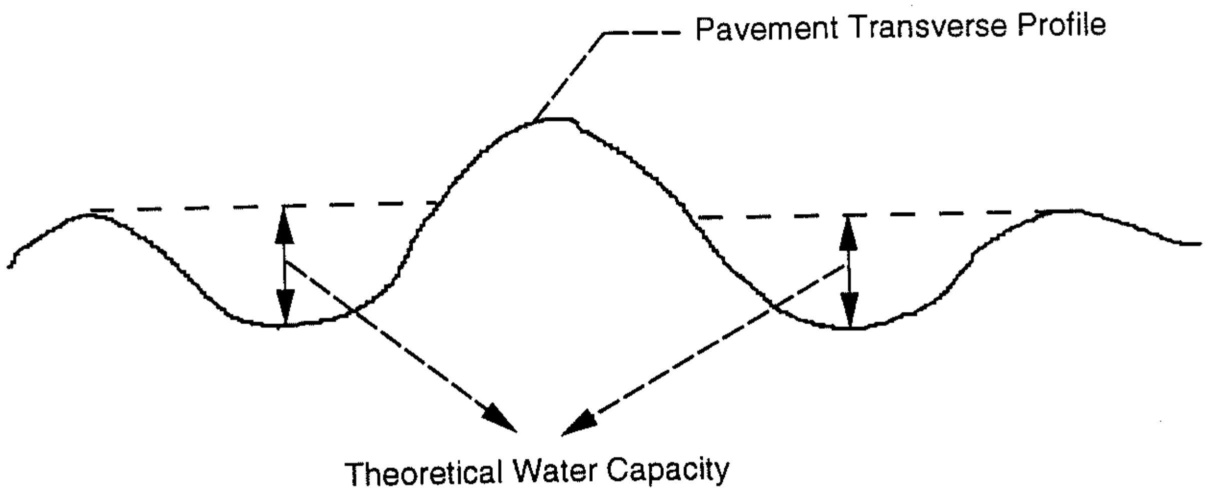


FIGURE 5.7. Determination of the Theoretical Water Capacity of Ruts

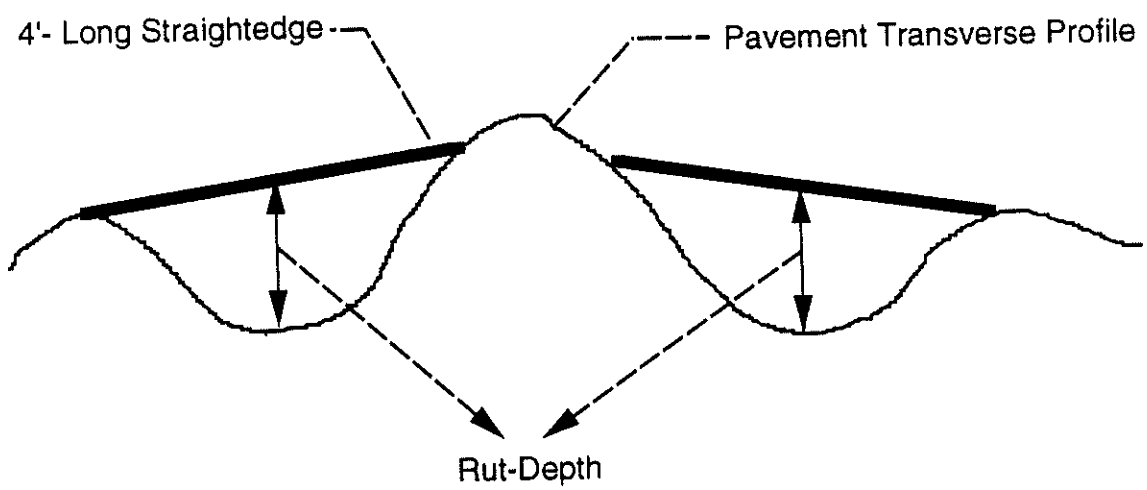


FIGURE 5.8. Rut-Depth Measurement with a 4-Foot long Straightedge

$$t_o = \frac{\overline{d}}{S_d/\sqrt{n}} \qquad \text{(Eqn. 5.1)}$$

Where: $\overline{d}$ = is the sample mean of differences (e.g. between five-sensor and three-sensor rut measurements),
S_d = is the sample standard deviation of the differences,
n = is the number of rut depth observations.

$\overline{d}$ and S_d were computed with the following equations:

$$\overline{d} = \frac{1}{n}\sum_{j=1}^{n} d_j \qquad \text{(Eqn. 5.2)}$$

$$S_d = \sqrt{\frac{\sum_{j=1}^{n}(d_j - \overline{d})^2}{n-1}} \qquad \text{(Eqn. 5.3)}$$

Where: d_j = difference between rut observations obtained with two different techniques.

The t_o value calculated with Equation 5.1 was compared with $t_{\alpha/2,\, n-1}=2.002$ (for $\alpha=0.05$ and n-1=56). If $ABS(t_o) > t_{\alpha/2,\, n-1}$, it was concluded that rut measurements obtained by two techniques were statistically different. As shown in Table 5.4, this analysis indicated that the two high speed profiler systems as well as the two manual techniques produced statistically different rut measurements. Subsequently, relationships among the four rut measuring techniques were developed by using regression analysis. The analysis was first performed on all profiles and then on each individual profile category. In all cases, rut-depths measured

TABLE 5.4. Results of t-test Comparisons

Techniques Compared	t_o	$t_{\alpha/2, n-1}$	Remarks
Three-Sensor Profiler and Five-sensor Profiler	11.59	2.004	Rut Measurements are Statistically different
Theoretical Water Capacity of Ruts and Straightedge	9.28	2.004	Rut Measurements are statistically different

by one method were correlated with rut-depths obtained with another method. The following general linear regression model was first utilized in the analysis:

$$y_i=\beta_0+\beta_1 x_{i1}+\ldots+\beta_j x_{ij}+\epsilon_i \qquad \text{(Eqn. 5.4)}$$

Where:
- y_i = dependent variable (rut-depth by one technique)
- x_{ij} = independent variable (rut-depth by another technique)
- β_j = regression coefficients
- ϵ_i = random error.

The R^2 values obtained by fitting this linear model were relatively low. Therefore, several non-linear models were examined and the following model was found to fit best:

$$y_i=\beta_0+\beta_1 x_i+\beta_2 (x_i)^4 \qquad \text{(Eqn. 5.5)}$$

Where: y_i = dependent variable (rut-depth by one technique)
x_i = independent variable (rut-depth by another technique)
$\beta_0, \beta_1, \beta_2$ = regression coefficients

Table 5.5 shows the models developed and their respective coefficients of determination (R^2) values for all profiles.

TABLE 5.5. Correlation Equations for All Profiles

Rut Equation	R^2
Rut(5) = -0.137 + 0.804 Rut(3) + 0.00131 $Rut^4(3)$	89.0
Rut(5) = 0.072 + 0.745 WC - 0.035 WC^4	81.2
Rut(5) = -0.045 + 0.843 St.edge - 0.043 $St.edge^4$	83.1
Rut(3) = 0.303 + 0.772 (WC) - 0.03 WC^4	70.3
Rut(3) = 0.176 + 0.887 St.edge - 0.04 $St.edge^4$	73.2
WC = -0.124 + 1.01 St.edge + 0.0047 $St.edge^4$	97.6

Where: Rut(5) = rut-depth obtained with 5-sensor profilers (cm)
Rut(3) = rut-depth obtained with 3-sensor profilers (cm)
WC = water capacity of the ruts (cm)
St.edge = rut-depth obtained with Straightedge (cm)

It can be observed that measurements obtained with five-sensor profilers correlated very well with all other three techniques (R^2 in upper to mid 80%). On the other hand, R^2 for the three-sensor profilers were slightly lower (lower 70%). Also, it is interesting to note that theoretical water capacity of ruts and rut measurements by straightedge correlated exceptionally well with R^2 value of 97.6%. A similar analysis was carried out on each profile category. The various models developed are summarized in Tables 5.6 for Categories I, II, and III.

TABLE 5.6. Correlation Equations for Category I, II, and III

Rut Equation	R^2
Category I	
Rut(5) = -0.036 + 0.423 Rut(3) - 0.193 $Rut^4(3)$	77.6
Rut(5) = 0.0754 + 0.79 WC + 2412 WC^4	Very Low
Rut(5) = - 0.028 + 1.08 St.edge - 24.3 $St.edge^4$	26.5
Rut(3) = 0.321 + 1.7 (WC) + 246 WC^4	Very Low
Rut(3) = 0.107 + 2.23 St.edge - 62.4 $St.edge^4$	Very Low
WC = 0.0067 + 0.168 St.edge - 1.25 $St.edge^4$	23.3
Category II	
Rut(5) = - 0.0012 + 0.487 Rut(3) + 0.323 $Rut^4(3)$	92.9
Rut(5) = 0.21 - 0.32 WC + 5.0 WC^4	Very Low
Rut(5) = - 0.105 + 1.19 St.edge - 2.66 $St.edge^4$	55.9
Rut(3) = 0.515 - 1.54 (WC) + 24.5 WC^4	Very Low
Rut(3) = - 0.312 + 1.93 St.edge - 3.96 $St.edge^4$	57.6
WC = 0.089 + 0.256 St.edge + 0.68 $St.edge^4$	50.2
Category III	
Rut(5) = - 0.14 + 0.893 Rut(3) - 0.01 $Rut^4(3)$	87.4
Rut(5) = - 0.004 + 0.846 WC - 0.045 WC^4	66.5
Rut(5) = - 0.226 + 1.05 St.edge - 0.061 $St.edge^4$	70.5
Rut(3) = 0.164 + 0.961 (WC) - 0.049 WC^4	66.9
Rut(3) = - 0.064 + 1.15 St.edge - 0.062 $St.edge^4$	68.8
WC = - 0.181 + 1.1 St.edge - 0.006 $St.edge^4$	97.0

In all three categories, the five-sensor and three-sensor rut measurements correlated well. Other correlation in Categories I and II had low R^2 due the unusual shape of transverse profiles while all Category III models had acceptable R^2. It should be mentioned here that most pavement sections fall under Category III.

The above analysis brings some interesting facts into light. First, the two-high speed profilers and two manual techniques do produce statistically different rut measurements. Also, the two high-speed rut measurement techniques correlate very well with each other irrespective of transverse profile shapes. The degree of correlation among all other rut measurement techniques, however, is dependent on profile shape.

CHAPTER SUMMARY

In this chapter, the following four commonly used rut-depth measuring techniques were evaluated: five-sensor road profilers, three-sensor road profilers, straightedge, and the theoretical water capacity of ruts. The study consisted of selecting 57 transverse profiles of varying shapes, obtaining rut measurements by the four methods, and conducting statistical analysis. Consequently, several regression models were developed correlating all four techniques. This chapter furnishes in detail the data collected and statistical analysis performed to correlate all four rut-depth measuring techniques.

CHAPTER VI

CONCLUSIONS AND RECOMMENDATION

The main objective of this research project was to evaluate several factors affecting the accuracy of Road Profilers measurements. These factors were: variation among duplicate Road Profilers used by various states, human operators, and variations in environmental conditions. A secondary objective was to compare rut-depth measurements obtained with the following most commonly used techniques: three-sensor road profilers, five-sensor road profilers, straightedge, and the theoretical water capacity of ruts. All the objectives of this study were accomplished in three phases: Phase I, Phase II, and Phase III. This chapter provides the detailed conclusions along with some suggested recommendations for each phase of the study.

CONCLUSIONS

The sections below provide detailed conclusions along with a brief summary of all three phases of the research project.

Phase I: Consistency of Road Profilers Measurements

To evaluate the consistency of roughness and rut-depth measurements, eleven South Dakota type Road Profilers and four pavement types were included in the analysis. A total of eight test sections, two sections for each type, were selected representing a wide range of roughness and rut-depth variations experienced nationwide. IRI and rut-depth data were then collected by running the participating Road Profilers three times on all test sections. Subsequently, data analysis was carried out using regular statistical tools and the following conclusions were drawn:

a. Roughness and rut-depth measurements obtained with any single system seem to be repeatable.

b. The t-test results indicate that roughness measurements obtained with all systems were statistically different in 64.5 percent of the cases. On the other hand, rut-depth measurements were statistically different in 74.3 percent of the cases.

c. Analysis of variance also support the conclusions that the Road Profilers do produce statistically different results.

d. The regression analysis yielded very strong linear relationships among systems. R^2 values were in the upper 90's for almost all relationships. These relationships indicate that the systems do correlate among each other.

e. There is no conflict in the findings stated in parts b, c and d. They simply reflect the fact that road profilers should be calibrated prior to conducting any comparisons. Calibration will insure the validity of the comparison.

f. The data collected were not adequate to determine if pavement type influenced the repeatability of measurements of road profilers.

Phase II: Effect of Environmental and Human Factors on Pavement Longitudinal Profile Measurements

In this phase, the effects of operator and environmental conditions on the repeatability of longitudinal pavement profile measurements were examined. This examination consisted of collecting IRI and rut-depth data by three operators on 36 test sections in addition to monitoring a single test section for various environmental conditions. Subsequently, statistical analyses were performed and the following conclusions were drawn:

a. When considering measurements obtained by any single road profiler operator, the coefficient of variation of rut measurements are much higher than the coefficient of variation of roughness measurements. In other words, the roughness measuring capability of a Road Profiler is much better than its rut-depth measuring capability.

b. The t-test results indicate that roughness measurements obtained by the three operators were statistically equal in all but five cases. Three of these five cases were on sections with low roughness level. This indicates that road profiler operators should give more attention when measuring roughness of smooth pavements. On the other hand, rut depth measurements obtained by different operators were statistically different in 20 percent of the cases. More differences were detected on sections with high roughness level where it is harder for the operator to drive in the wheel paths.

c. The regression analysis yielded a fairly good linear relationship between IRI and two environmental factors. R-square for this relationship was almost 85 percent which indicates that pavement roughness does fluctuate due to changes in environmental conditions.

Phase III: Comparison of Rut-Depth Measurements Obtained with Four Different Techniques

The third and final phase of study involved comparing the following four rut-depth measuring techniques: three-sensor road profilers, five-sensor road profilers, straightedge, and the theoretical water capacity of ruts. The overall design of experiment consisted of selecting profiles of different shapes and then extracting rut-measurements from them. The statistical analysis performed resulted in following conclusions:

a. The t-test results indicate that five-sensor and three-sensor profilers do produce statistically different rut-depth measurements. In fact, rut measurements obtained with three-sensor road profilers were higher than measurements obtained with five-sensor road profilers in 93% of the cases included in this experiment.

b. The theoretical water capacity of ruts and stick method also produce statistically different rut measurements. In fact, the extracted data revealed that rut-depth measurements obtained with straightedge were higher than theoretical water capacity measurements in 91% of the cases.

c. Regression analysis yielded strong non-linear relationships among the four techniques when all transverse profiles were analyzed. These relationships indicate that although the four techniques produce different results, they do correlate among each other.

d. The correlation between measurements from three-sensor and five-sensor profilers resulted in high R^2 irrespective of transverse profile shape. Correlations between high-speed techniques and manual techniques, however, were influenced by profile shape.

RECOMMENDATIONS

Based on the results of this research project, the following recommendations are suggested :

1. All states using the South Dakota type Road Profiler should calibrate their devices to insure data consistency. Calibration is necessary since the Highway Agencies all across the U.S. invest a huge amount of resources every year in collecting roughness data. Roughness data from all states are then used by the Federal Highway Administration (FHWA) to determine the level of deterioration for the pavement network nationwide. Calibration could be achieved by establishing regional calibration sites. These calibration sites could then be used in establishing calibration factors which would insure that roughness devices operating across the United States produce comparable results.

In fact, based on the recommendations of this study, the Pennsylvania Department of Transportation (Penn DOT) has already initiated a large-scale research study. This project will involve collecting IRI and rut-depth data by 40-50 Road Profilers on calibration sites located in Pennsylvania, Mississippi, Nevada, and South Dakota. Subsequently, data would be analyzed for measurement repeatability of individual Profilers and comparison among Road Profilers.

2. A more controlled experiment should be conducted to have a better estimate of the effect of environmental variations on roughness measurements. Data should be collected over a longer period of time to accommodate wider environmental variations.

3. Field measurements of rut-depths should be obtained using all four techniques. This would help verify the accuracy of rut-depth correlations developed using extracted data from profiles. Also, it can be ascertained how well the field measurements by all four techniques correlate with the theoretical rut-depth measurements.

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