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16. Abstract

As the complexity of highway engineering increases, information related to pavement condition, vehicle operating cost, ride quality, driving safety, passenger comfort, and newly-constructed road acceptance—all this information needs to be effectively and safely collected and evaluated by instrumentation. For such purposes, comprehensive or multi-function measurement of pavement conditions is providing a more efficient and economical way to complete the measurement process. In 1985, the Texas State Department of Highways and Public Transportation (SDHPT) purchased a multi-functional road quality surveying system, called the Automatic Road Analyzer (ARAN), which measures several roadway conditions simultaneously, including pavement roughness, pavement transverse profile (rutting), and roadway geometrical characteristics. This report evaluates the orientation subsystem and rut depth subsystem of the ARAN unit using field tests and the resulting data. In this evaluation, the principal activities involved the evaluation of the static, dynamic, and operational performance. Static performance tests were conducted separately to test the stability, measurement specifications, and measuring accuracy of the orientation subsystem and rut depth subsystem. The dynamic performance tests of the orientation and rut depth subsystems (conducted with the ARAN unit operating under normal conditions) compare responses of the two subsystems with chosen references. The operational performance tests were conducted to check whether the subsystems are reliable under different operating conditions. A procedure characterizing the transverse profile and rutting was developed in this study. The final output of this procedure is a rutting index.

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by

Jian Lu
Carl Bertrand
W. Ronald Hudson

Research Report 1223-2F

Evaluation and Implementation of the ARAN Unit

Research Project 3-18-89/0-1223

conducted for

Texas State Department of Highways and Public Transportation

in cooperation with the

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CENTER FOR TRANSPORTATION RESEARCH

Bureau of Engineering Research

THE UNIVERSITY OF TEXAS AT AUSTIN

July 1991

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W. Ronald Hudson (Texas No. 16821)
Research Supervisor

PREFACE

This is the final report for Research Project 1223, "Evaluation and Implementation of the ARAN Unit." This research project was conducted by the Center for Transportation Research (CTR), The University of Texas at Austin, and sponsored by the Texas State Department of Highways and Public Transportation. The main objective of the study described in this report was to evaluate and implement the orientation subsystem and rut depth subsystem of the Automatic Road Analyzer (ARAN), based on field tests and data analysis. The evaluation and implementation of the roughness measuring subsystem, which have been described in another CTR research report (RR1223-1), are reviewed as well.

We would like to express our appreciation to the Texas State Department of Highways and Public Transportation (SDHPT) contact representatives for their cooperation in this project study. Special thanks are due to Mr. David Fink for his cooperation and assistance with the research and testing program.

In addition, the authors gratefully acknowledge the technical support provided by CTR staff members. In particular, we wish to thank Mr. Terry Dossey for assistance with this report, and Mr. Bill Moffeit for his assistance with the field tests and data collection.

Jian Lu
Carl Bertrand
W. Ronald Hudson

LIST OF REPORTS

Report number 1223-1, "Evaluation and Implementation of the Roughness Measuring Subsystem of the ARAN Unit" by Jian Lu, Carl Bertrand, and W. Ronald Hudson, covered field tests, roughness statistics report interval, repeatability, correlation analysis, new PSI model development, speed effect analysis, and speed effect cancelling models.

Report number 1223-2F, "Evaluation and Implementation of the Automatic Road Analyzer (ARAN)," by Jian Lu, Carl Bertrand, and W. Ronald Hudson, presents the research results obtained from this study. The four aspects of the report include the static performance tests, the dynamic performance, the operational performance tests, and the development of index characterizing transverse profiles and rutting of pavements.

ABSTRACT

As the complexity of highway engineering increases, information related to pavement condition, vehicle operating cost, ride quality, driving safety, passenger comfort, and newly-constructed road acceptance—all of this information needs to be effectively and safely collected and evaluated by instrumentation. For such purposes, comprehensive or multi-function measurement of pavement conditions is providing a more efficient and economical way to complete the measurement process. In 1985, the Texas State Department of Highways and Public Transportation (SDHPT) purchased a multi-functional road quality surveying system, called the Automatic Road Analyzer (ARAN), which measures several roadway conditions simultaneously, including pavement roughness, pavement transverse profile (rutting), and roadway geometrical characteristics. This report evaluates the orientation subsystem and rut depth subsystem of the ARAN unit using field tests and the resulting data. In this evaluation, the principal activities involved the evaluation of the static, dynamic, and operational performance. Static performance tests were conducted separately to test the stability, measurement specifications, and measuring accuracy of the orientation subsystem and rut depth subsystem. The dynamic performance tests of the orientation and rut depth subsystems (conducted with the ARAN unit operating under normal conditions) compare responses of the two subsystems with chosen references. The operational performance tests were conducted to check whether the subsystems are reliable under different operating conditions. A procedure characterizing the transverse profile and rutting was developed in this study. The final output of this procedure is a rutting index.

Key Words: The Automatic Road Analyzer, Roughness, Orientation, Transverse Profile, Rutting, Rut Depth Index, Roadway Curve, Roadway Slope, Roadway Super Elevation.

SUMMARY

The Automatic Road Analyzer (ARAN) is mainly used to collect data for pavement management and pavement evaluation; in addition, it has proven useful in the routine surveying of pavement conditions. As a comprehensive system, the ARAN should be thoroughly evaluated in order that its full potential might be realized.

This report, then, describes the evaluation and implementation of the orientation and rut depth subsystems of the ARAN unit. The roughness measuring subsystem, which has been described in another CTR research report (RR1223-1), is also reviewed.

In evaluating these subsystems, researchers conducted static performance tests, dynamic performance tests, and operational tests; a procedure quantifying the transverse profiles and rutting of the pavement was developed as well. The results show that while the orientation subsystem and the rut depth subsystem generally satisfy the requirements for routine measurements (including repeatability and accuracy), certain operating conditions need to be specified to obtain reliable data from the two subsystems. Special attention is required in the selection of the report interval for both subsystems; in addition, drift error has been shown to affect the orientation subsystem. Further research examining and developing the potential of the rut depth subsystem is recommended. In particular, special effort is required in developing software capable of characterizing the transverse profiles and rutting index for pavements.

IMPLEMENTATION STATEMENT

The primary purpose of this study was to evaluate the orientation subsystem and the rut depth subsystem of the Automatic Road Analyzer (ARAN) for implementation. The evaluation and implementation of the roughness measuring subsystem, described in another CTR research report (RR1223-1), are reviewed as well. In addition to improving the operation of the ARAN unit in the field, these findings can suggest areas for further research. The proposed models and operational methods should result in more effective and economic application of the orientation and rut depth subsystems of the ARAN unit.

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CHAPTER 1. INTRODUCTION

GENERAL BACKGROUND

The collection of data in support of proper maintenance and rehabilitation decisions is very important at both the project and network levels of a pavement management system (PMS) (Refs 1, 2). Because of the increasing pavement maintenance and rehabilitation needs in Texas, pavement surface measurements relating to roughness, serviceability performance prediction, road safety evaluation, and passenger comfort have become more important in the routine operation of the Pavement Evaluation System (PES). The rapidly increasing and broadening scope of pavement condition surveys shows that data collection conducted at walking speed is unsafe, inefficient, and expensive—especially in urban areas of the state. There is an increasing need for an accurate, multifunctional, and safe automated data acquisition system to be used in pavement surface and safety condition surveys. Such a system must be capable of collecting and processing large amounts of field data in urban areas.

Among the factors which need to be investigated, pavement surface roughness, rutting, and geometric characteristics are the primary concerns (Refs 1 through 12). The AASHO Road Test showed that about 85 percent of the road user's perception of road "serviceability" results from pavement surface roughness. Considerable research has proven that road roughness can be directly related to riding quality, vehicle operating cost, and safety (Refs 3 through 7, 13). Furthermore, the measurement of road roughness can be used as an acceptable criterion for newly constructed or overlaid pavements (Refs 14, 15). Pavement rutting has long been known to affect the performance of flexible pavements, and the presence of rutting can be used as an indication of structural deterioration and road surface deformation (Refs 16 through 18). Moreover, excessive rutting has a direct effect on the safety and comfort of the travelling public (Ref 19), and roadway geometric characteristics, although not directly related to pavement surface conditions, have a direct effect on riding comfort, safety, and drainage (Ref 10).

Instrumentation for evaluating road roughness and rutting has been significantly improved in the past decade. Studies have focused on the development and evaluation of techniques which measure and predict road roughness and rutting (Refs 20 through 25). In the measurement of roadway geometric characteristics, new techniques have begun to be applied (Refs 26, 27). But the development of new techniques to measure roadway geometric characteristics automatically has been relatively slow, compared with techniques for measuring roughness and rutting. It may be that roadway geometric characteristics do not significantly change after construction, and consideration of roadway geometric characteristics is normally based on the design of the roadway. In general, measurement of roughness, rutting, and roadway geometric characteristics can efficiently be supported by combined instruments in the future. The combined measurement of roughness, rutting, geometric characteristics and other related pavement conditions can result in more effective, economic, and safer data acquisition.

To address these problems, the Texas State Department of Highways and Public Transportation (SDHPT) purchased in 1985 a combined measuring system called the Automatic Road Analyzer (ARAN), taking delivery of the unit in January 1987. Capable of being operated at 30 to 50 mph under normal conditions, the ARAN unit is equipped with the following subsystems: (1) roughness measuring subsystem, (2) orientation subsystem, (3) rut depth subsystem, (4) video logging subsystem, and (5) pavement condition rating subsystem. With such an array of subsystems, the ARAN unit is considered a comprehensive pavement surface condition and safety surveying system.

OBJECTIVES

The main objective of this research was to evaluate and implement the roughness measuring subsystem, the orientation subsystem, and the rut depth subsystem of the ARAN unit. The conclusions will be presented for adoption to the Texas SDHPT for their use in future operation of the ARAN unit.

This research was divided into two phases. The first phase, which included the evaluation and implementation of the roughness measuring subsystem, was conducted from August of 1988 through August of 1989. The important results from this study were presented in a CTR research report (Ref 28). The second phase, conducted from August of 1989 through August of 1990, discussed the evaluation and implementation of the orientation subsystem and the rut depth subsystem. This document concentrates on the results of the second phase.

The primary objective of this study was achieved by completing the following supporting tasks:

(1) Reviewing the orientation subsystem and the rut depth subsystem (including their measurement principles);
(2) Determining factorials for the field tests and data collection;
(3) Selecting test sections and developing procedures for field tests and required data collection;
(4) Selecting statistical analysis methods for use in evaluation;
(5) Performing static and dynamic performance tests and data analysis;
(6) Performing operational tests and data analysis;
(7) Developing a procedure quantifying transverse profiles and rutting; and
(8) Making a recommendation for the operations of the orientation subsystem and the rut depth subsystem.

RESEARCH APPROACH

Because evaluation and implementation must be based on field data, the field tests and data collection had priority during this study. Figure 1.1 shows a flowchart of the research approach used. Conceptually, this study can be divided into four parts: (1) static performance tests, (2) dynamic performance tests, (3) operational tests, and (4) development of a procedure quantifying transverse profiles and rutting.

Static Performance Tests

Static performance tests were mainly conducted to examine stability, measurement specifications, and measuring accuracy of the orientation subsystem and the rut depth subsystem. Sometimes measuring equipment shows sharply different characteristics at static and dynamic working states because of vibration, changes in environment, changes in frequency of the input signals, operator's behavior, etc. In addition to dynamic tests, therefore, static tests are necessary to evaluate each measuring system.

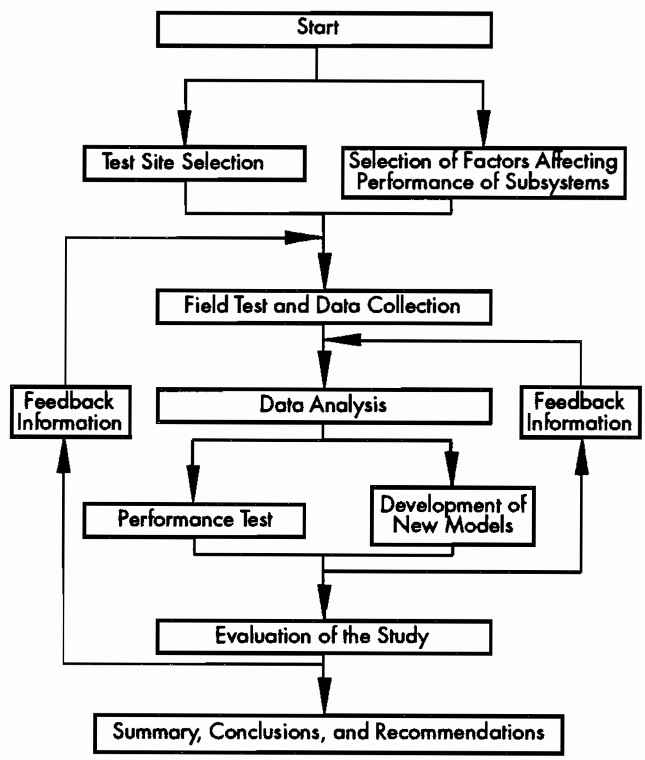


Figure 1.1 Flowchart of the research approach

Dynamic Performance Tests

In the dynamic performance tests of the orientation subsystem and the rut depth subsystem—made while the ARAN unit operated under normal conditions—the outputs or responses of the two subsystems were compared with selected references (e.g., the design plan and the Face Dipstick). The practical plan to test the dynamic performance of the two subsystems involved choosing an existing bridge and road section for testing with known geometric characteristics (curve, slope, and crossfall) and known transverse profiles or rutting.

Operational Performance Tests

The operational tests served to determine if the subsystems were reliable at different operating conditions. In these tests, different operating conditions were applied to the two subsystems, and the outputs of the two subsystems were examined to determine if the results of the different operating conditions were significantly different.

Development of a Procedure Quantifying Transverse Profiles and Rutting

Pavement transverse profile is usually evaluated according to its geometric characteristics. Mathematically, this method can be defined as an evaluation in the space domain. However, pavement transverse profiles in the space domain can be transferred into polynomial variables in the polynomial domain. In this study, a fifth-order polynomial function was used to fit transverse profiles, and the resulting polynomial coefficients were weighted and summed to produce an index correlated to existing serviceability and rut depth indices. Statistically, the amplitudes of the polynomial coefficients can reflect the geometric characteristics of the transverse profiles. Thus, the decomposition of transverse profiles can potentially be used to evaluate transverse profiles and rutting mathematically.

SCOPE AND ORGANIZATION

Chapter 1 gives general background information, the objectives of this study, and the research approach adopted. Chapter 2 describes the ARAN unit and the measurement principles of the roughness measuring subsystem, the orientation subsystem, and the rut depth subsystem. Chapter 3 reviews the first phase in this research and summarizes the evaluation and implementation of the roughness measuring subsystem. The results of the orientation subsystem evaluation are presented in Chapter 4. Chapter 5 presents the results of the evaluation of the rut depth subsystem, while Chapter 6 presents a procedure to quantify pavement transverse profiles and rutting. Finally, Chapter 7 presents the summary, conclusions, and recommendations.

CHAPTER 2. ARAN SUBSYSTEM DESCRIPTION AND MEASUREMENT PRINCIPLES

THE ARAN UNIT

The ARAN unit is a van-mounted system that measures and records a wide variety of roadway condition parameters (Refs 29 through 32). The system is mounted in a 1986 Ford cab and chassis, the roof and side windows of which were raised to provide more space for the equipment, and to enhance operator observation during data collection. Figures 2.1 and 2.2 show a photograph and schematic diagram of the ARAN unit, respectively. As a multi-function system, the ARAN unit is equipped with the following specialized subsystems:

(1) pavement surface roughness measurement,
(2) orientation measurement,
(3) transverse profile and rut depth measurement,
(4) right-of-way and pavement condition video logging, and
(5) pavement condition rating.

Figure 2.3 is a block diagram showing the structure of the subsystems and their interaction. These subsystems are described below.

Roughness Measurement

This subsystem measures the accelerations of the vehicle caused by pavement surface roughness within certain wavelengths. The roughness indices reported—which reflect the surface ride quality—are RMSVA (root mean square vertical acceleration), MAS (mean absolute slope), and TEXTURE. The signal sampled by the subsystem is the response of the vehicle to the pavement surface profiles according to the criteria used to classify roughness measuring instruments. This subsystem is therefore classified as a Class III roughness measuring instrument; that is, a response-type road roughness measuring (RTRRM) instrument (Refs 33, 34).

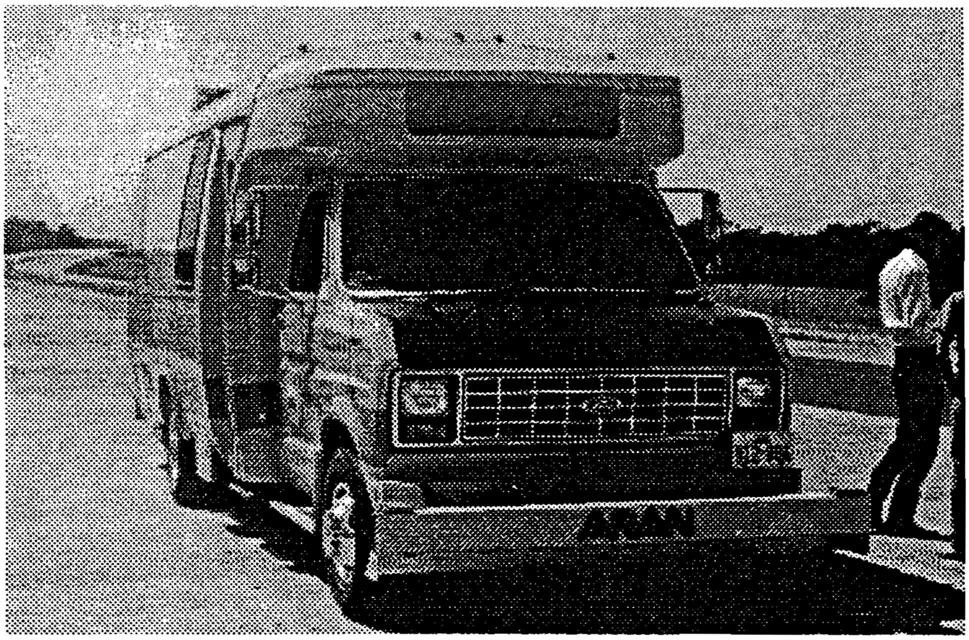


Figure 2.1 Picture of the ARAN unit

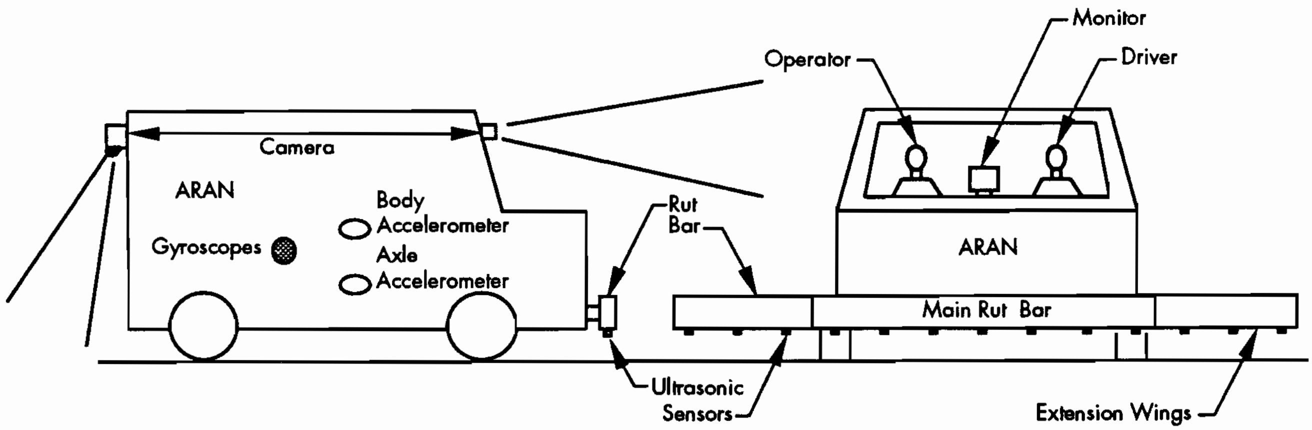


Figure 2.2 Schematic diagram of the ARAN unit

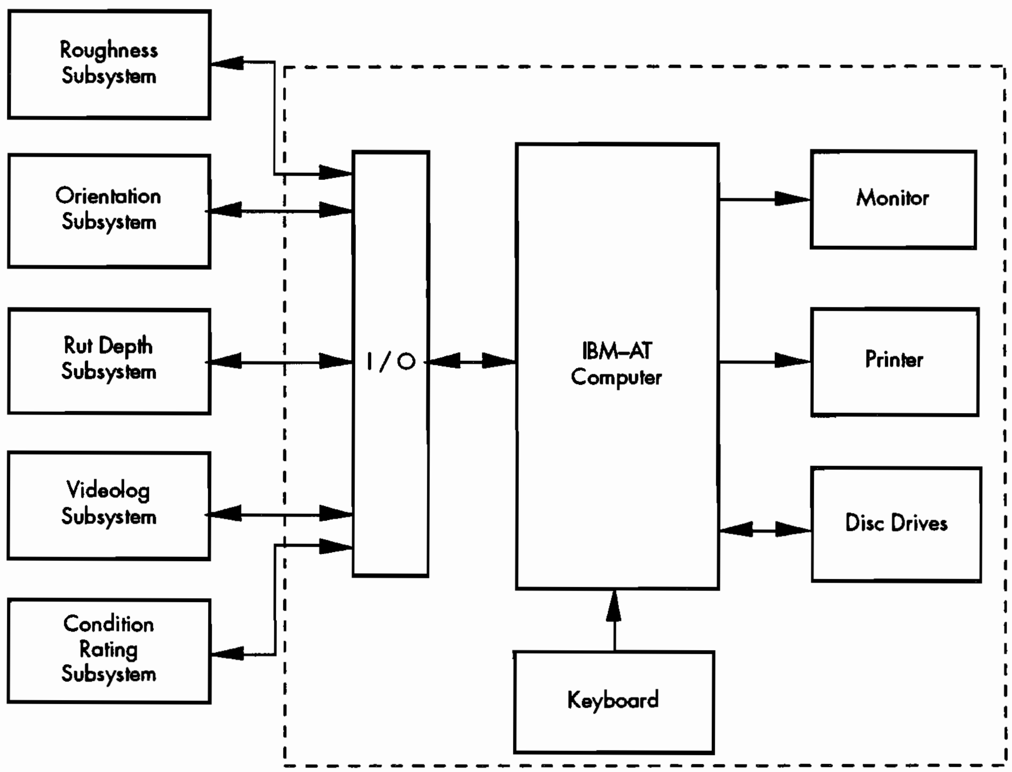


Figure 2.3 System block diagram of the ARAN unit

Orientation Measurement

This subsystem consists of two gyroscopes that produce the outputs HEADING, PITCH, and ROLL. The results obtained from this subsystem can be used to determine direction of travel, radius of curvature, grade, and superelevation of a roadway. Also, in conjunction with the rut depth subsystem, crossfall of the roadway can be obtained.

Transverse Profile and Rut Depth Measurement

This subsystem provides a vehicle-to-road reference measure across the full width of a lane. The results obtained from this subsystem can be used to determine transverse profiles, rut depth, or, in conjunction with the orientation subsystem, road crossfall.

Right-of-Way and Pavement Condition Videologging

The right-of-way view is recorded by a color video camera and a video cassette recorder (VCR). Characteristics of the pavement surface were originally recorded on a separate VCR by a mechanically shuttered black-and-white video camera mounted on the back of the unit aimed at the pavement surface. The pavement camera was replaced in April 1990 with an electronically shuttered, remote head color video camera.

Pavement Rating

This subsystem has two main purposes: to annotate the collected data and to inventory roadway conditions. Annotation means noting data collection anomalies during the operation (e.g., lane changes, railway tracks, construction, and traffic interruption, etc.). Inventory involves recording subjectively the status and condition of roadways (e.g., pavement surface conditions, lane markings, shoulder width, sign post, and bridges, etc.).

ROUGHNESS MEASURING SUBSYSTEM

A block diagram of the roughness measuring subsystem is shown in Figure 2.4. This subsystem is divided into two main parts: the hardware and the software. The hardware consists of axle and body accelerometers (the axle or both selected during the operating set-up procedure), analog signal amplifiers, analog low-pass filters, and a 12-bit analog-to-digital converter, while the software is composed of digital band-pass filters passing wavelengths of 1 to 300 feet, digital high-pass filters passing wavelengths of 2 feet or less, and statistical models generating the reported roughness statistics RMSVA, MAS, and TEXTURE. (NOTE: Texture here is defined according to Highway Products International literature; see earlier report 1223-1.) The normally used roughness statistics generated by the roughness measuring subsystem are described below.

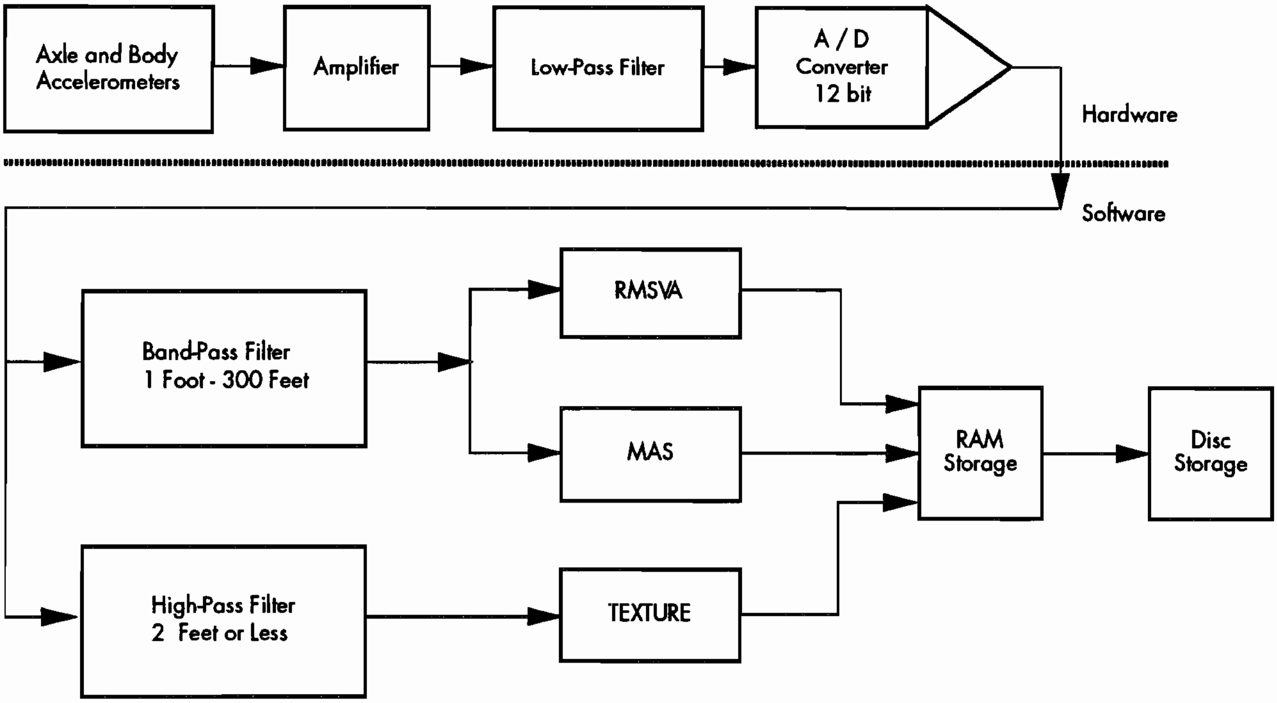


Figure 2.4 Block diagram of the Roughness Measuring Subsystem

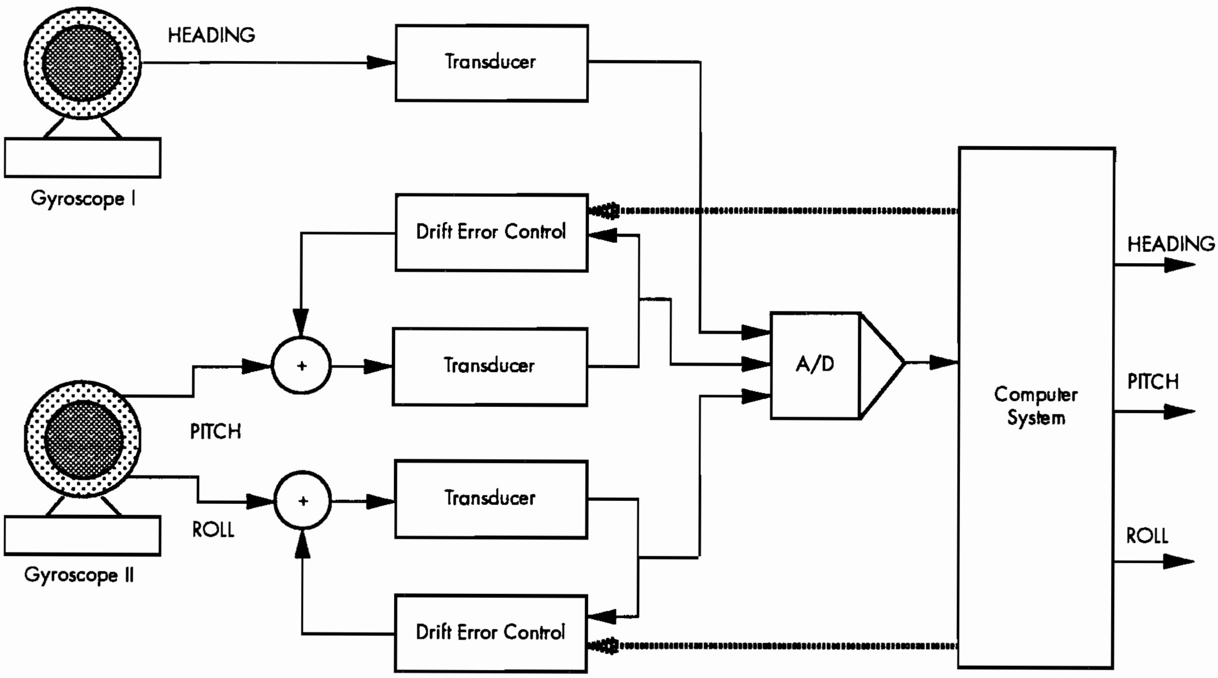


Figure 2.5 Diagram of the ARAN unit Orientation Subsystem

Root Mean Square Vertical Acceleration (RMSVA)

RMSVA is mathematically defined by:

$$RMSVA = \sqrt{\frac{1}{N}\sum_{i=1}^{N}[a(i)]^2} \qquad (2.1)$$

where a(i) is the i^{th} discrete value of filtered acceleration and must be spatially filtered to remove any DC bias. N is the number of samples in a section.

Mean Absolute Slope (MAS)

MAS is the cumulative value of the absolute vertical axle or body displacement divided by the vehicle's travelled distance. Mathematically,

$$MAS = \frac{1}{2N}\left(\frac{T}{L}\right)^2 (\Delta X)\sum_{i=1}^{N}|Z(i)| \qquad (2.2)$$

where

T = elapsed time in seconds in a test station,

L = station length in miles,

ΔX = sample interval of raw acceleration values, and

Z(i) = Z(i-1) + a(i) + a(i-1)

Texture

Once the acceleration signal is processed by an A/D converter, there are two paths that the signal can follow, as shown in Figure 2.4. One path is through the high-pass filter, the other through the band-pass filter. The output of the high-pass filter allows more high-frequency (short wavelength) components of the input signal (acceleration) to pass, eliminating in the process low-frequency signal (long wavelength) components. The high-frequency components of the acceleration signal represent the detailed characteristics of roughness (such as texture and cracks), as their wavelengths are relatively short with respect to the low-frequency components. The output signals of the high-pass filter go through the same mathematical model used to calculate RMSVA, and the resulting statistic is defined as TEXTURE.

Serviceability Index (SI)

The serviceability index of a pavement section is determined by equation (2.3). The original Texas equation used in the ARAN was:

$$SI = 5.6797 - 0.00134\ RMSVA - 0.7553\ MAS \qquad (2.3)$$

where

RMSVA = root mean square vertical acceleration defined by equation 2.1, and
MAS = mean absolute slope defined by equation 2.2.

The index, SI, is not the direct output of the roughness measuring subsystem, but a linear function of RMSVA and MAS.

ORIENTATION SUBSYSTEM

Figure 2.5 shows a block diagram of the orientation subsystem, with signals from two gyroscopes. The first gyroscope produces the measurement HEADING, and the second produces the measurements PITCH and ROLL. These measurements—HEADING, PITCH, and ROLL—are the basic outputs of the subsystem. The measurement HEADING determines road direction (curve) in degrees (0° to 360°), while the measurements PITCH and ROLL determine road grade (slope) and crossfall (superelevation) in percent rise over run. As indicated in Refs 35 and 36, drift error is the basic problem associated with the gyroscopes; accordingly, the PITCH and ROLL gyroscope is equipped with two drift cancelling models, as shown in Figure 2.5, that eliminate the effect of drift error.

Heading

The HEADING gyroscope is used to determine the relative direction in which the ARAN unit is moving. The stored index HEADING can then be processed and analyzed to estimate the radius of curvature and the relative directional orientation of a roadway over which the ARAN unit has traveled.

Pitch

The PITCH measurement determines road grade or slope in percent rise over run. Rise is the distance that the road rises or falls over a separate distance. For example, if a road rises 2

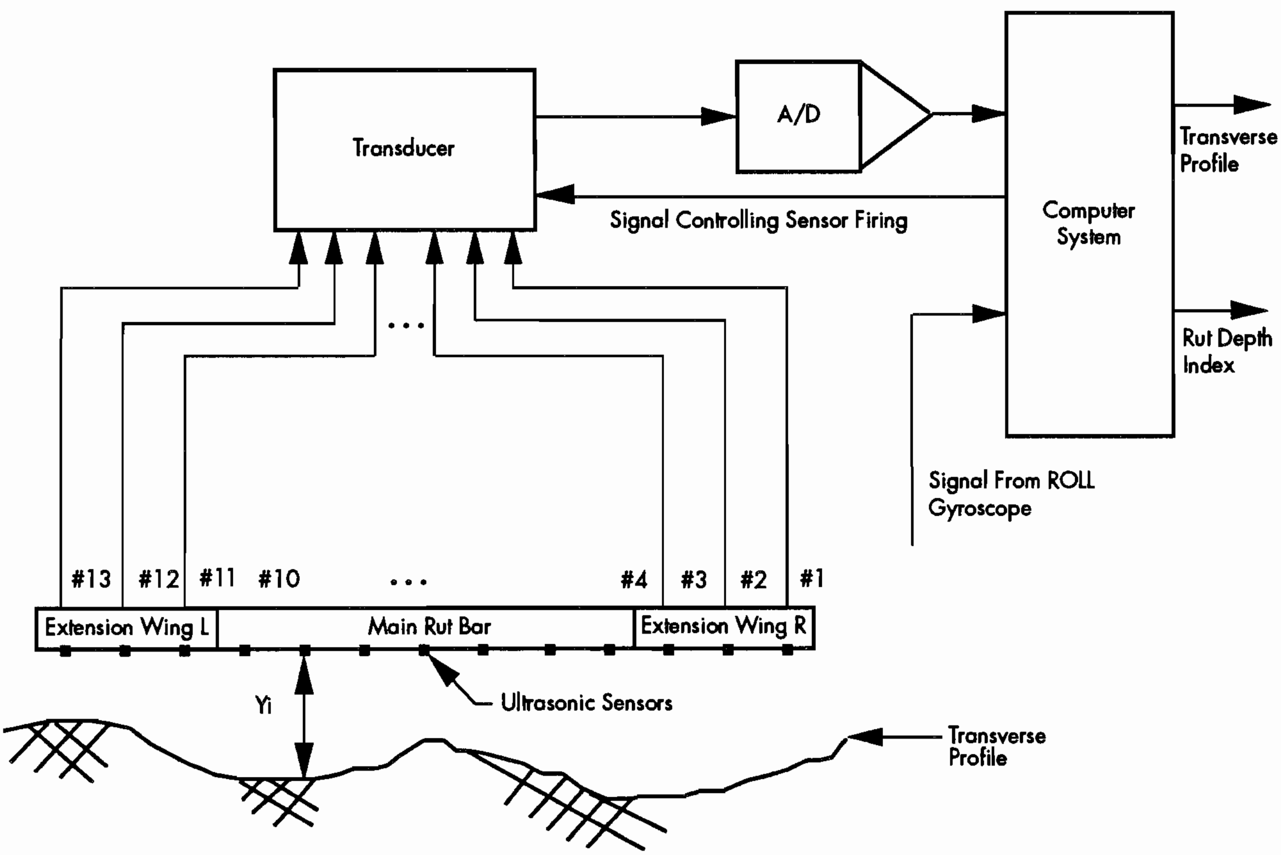


Figure 2.6 Rut depth subsystem diagram

meters in 100 meters, then grade is 2 percent or PITCH = 2.

Roll

The ROLL measurement determines road crossfall—or superelevation—as a percentage. Actually, this measurement can be related to the pavement transverse profiles of a roadway. Roll measurement is used in conjunction with the sonar signals from the ultrasonic sensors mounted on the bottom side of the rut bar to determine the crossfall of the travel lane. The roll gyro is on the same plane as the rut bar so that all sensor readings are adjusted to remove the effect of the vehicle roll through corners.

RUT DEPTH SUBSYSTEM

This subsystem is depicted in Figure 2.6. Each ultrasonic sensor measures the distance between the sensor and pavement surface directly below the sensor. The measured signals from each sensor then go through the measuring path that includes the transducer and A/D converter which digitizes the analog signals. The basic outputs of this subsystem are the pavement transverse profile data. The equipment features two sets of extension wings to cover a 10-foot lane width and a 12-foot lane width, respectively. If the long extension wings are used, as shown in Figure 2.6, sensors #1, #2, and #3 are mounted on the long extension wing R, and sensors #11, #12, and #13 on the long extension wing L. If the short extension wings are used, then sensors #2 and #3 are mounted on the short extension wing R, and sensors #11 and #12 on the short extension wing L.

Pavement Transverse Profile Measurement

Pavement transverse profiles are measured by the rut bar with the ultrasonic sensors. The direct output of each sensor is the distance between the sensor and pavement surface directly below the sensor. Because the distance between two adjacent sensors is 1 foot, the transverse data sampling interval of the transverse profile is, therefore, 1 foot. This set of data can be used to evaluate a rut depth index and a transverse profile. This average rut depth index can be used on a section-by-section basis to compare rut depth.

The mathematical model calculating rut depth or crossfall was not clearly defined. Additionally, a check of the raw rut depth output in early tests revealed very poor repeatability. Based on this information, a decision was made to concentrate the major work on the roughness subsystem. The results of the work performed on the rut depth subsystem are given in Chapters 5 and 6.

CHAPTER 3. THE EVALUATION AND IMPLEMENTATION OF THE ROUGHNESS MEASURING SUBSYSTEM

BACKGROUND

The roughness measuring subsystem is one of the most important of the ARAN unit subsystems. The evaluation and implementation of this subsystem required one year to complete, and the results obtained were initially reported in Ref 28.

Pavement surface roughness measuring systems can be classified into three different categories (Refs 33 and 34). Manually operated instruments are considered Class I instruments that accurately measure short-wavelength profiles of the roads; dynamic direct profiling instruments are considered Class II instruments, employing as they do a variety of methods to produce elevation data from the road surface with good accuracy; and response-type road roughness measuring (RTRRM) systems are considered Class III instruments; these instruments accumulate suspension deflections or acceleration values of the vehicle axle or body from the roadway surface. The roughness measuring subsystem of the ARAN unit is classified as a Class III instrument because the subsystem measures the response of the vehicle axle to the pavement roughness conditions through the measurement of the axle acceleration.

The vertical accelerations of the ARAN unit axle are sampled and processed to produce the roughness indices, Root Mean Square Acceleration (RMSVA), Mean Absolute Slope (MAS), and TEXTURE. The smaller the values of the reported indices, the better the corresponding pavement surface ride quality. The Texas SDHPT is primarily interested in obtaining the Serviceability Index (SI); and as an indirect output of the subsystem, the serviceability index (SI) can be obtained through a linear regression model using the variables RMSVA and MAS.

The main research objectives associated with the roughness measuring subsystem were (1) to check if the operation and the outputs of this subsystem are reliable; (2) to estimate the impacts of the operating conditions on the subsystem; and (3) to develop some useful models which supplement the subsystem and make the subsystem work more effectively. Two major research efforts were conducted in the study, the general subsystem evaluation and new model development. Concerning the general subsystem evaluation, the main activities were in the areas of data report interval effect analysis, repeatability evaluation, correlation analysis, and operational speed effect analysis. For new model development, the main efforts were made to develop (1) models solving the problems found in evaluation, and (2) other models found useful to the ARAN unit.

This chapter summarizes the study relating to the evaluation and implementation of the Roughness Measuring Subsystem in terms of two main aspects: (1) subsystem evaluation, and (2) new model development. Since this study has been reported previously (Ref 28), only a review is given here.

SUBSYSTEM EVALUATION

Several factors were found to affect the accuracy of the roughness measuring subsystem, including operating conditions, driver and operator behavior, vehicle response, pavement conditions, and the applicability of the measurement principles. The important factors and analyses are discussed below.

Data Report Interval

For routine operation of the roughness measuring subsystem, the ARAN operator must first set a specific data report interval. The report interval is defined as follows:

Report Interval: Pavement conditions are sampled by the ARAN unit at every sampling interval, S. At every M sampling intervals, the data collected in the M sampling intervals are processed and stored in the computer. The length L, ($L = S \times M$), is called *report interval*.

Field experience shows that different report intervals selected for the operation produce different outputs of the subsystem. Two major factors contribute to this: (1) The data sampling storing procedures of the computer system, and (2) the non-linearity of the roughness index models, as explained in Ref 28. However, if the impact of the report interval on the subsystem is not statistically significant, it can be neglected, and the operator of the ARAN unit can choose the report interval by considering other factors, such as the memory space of the computer system.

To evaluate the impact, field tests were conducted in the Austin Test Sections (ATS), and a statistical analysis, called One-Way ANOVA (Analysis of Variance) (Ref 37), was applied. The final test results showed that the report interval does not significantly affect RMSVA, MAS, and TEXTURE. In fact, the data sampling interval is a more important factor than the report interval. In this subsystem the data sampling interval is constant regardless of report interval selection.

Test of Repeatability

In the evaluation of a measuring system, repeatability (in addition to accuracy and correlation) is an important subject for investigation—especially as the quality of the roughness measuring subsystem is determined by its repeatability. There are two aspects to repeatability: (1) the systematic repeatability indicating the stability of the hardware system and the accuracy of the subsystem's measurement principle, and (2) the operational repeatability reflecting the driver's and/or the operator's behavior and environmental conditions during the operation of the subsystem.

The researchers were primarily interested in systematic repeatability. But, since it is difficult to distinguish between the systematic and operational repeatability, the combined performance of the two types of repeatabilities was considered in the evaluation of the subsystem. If the subsystem showed good overall repeatability, it was assumed that the systematic repeatability of the roughness measuring subsystem was good.

Field tests were arranged at Austin Test Sections and repeat runs were made to check repeatability. By defining a repeatability index, it was found that the relative repeatability error was less than 5 percent, which was considered good. It should also be mentioned here that repeatability of this subsystem depends not only on the performance and quality of the subsystem, but also on the suspension system of the ARAN unit, which must be kept in good condition to maintain accuracy.

Correlation Analysis

The correlation of a measuring system is one of the most important factors for evaluation—one which must be quantified by the use of a standard instrument as a reference. Since the roughness measuring subsystem is considered to be a Class III instrument, or a response-type road roughness measuring system, the chosen reference should be a Class I or Class II instrument, so as to ensure that the reference is more accurate.

The Texas SDHPT-modified K. J. Law Profilometer (considered by the Texas SDHPT to be the reference instrument for calibration of all its roughness monitoring equipment) is a Class II instrument chosen as the correlation analysis reference. Based upon past field operations, it was assumed that the roughness statistics from this profilometer were reliable (Ref 38).

In order to conduct the correlation analysis for the Roughness Measuring Subsystem, a combination of 29 flexible and rigid pavement sections in Austin were selected. Such a selection of test sites was thought to provide the broadest range of roughness levels, while at the same time allowing runs at test speeds of 50 mph. The smooth sites were needed to ensure that the subsystem had the resolution necessary to measure smooth pavements correctly; the rough sites ensured that the subsystem could handle the large amplitudes generated down rough pavements; and the medium sections allowed data points to be located between the two extremes. The roughness conditions were measured by both the modified K. J. Law Profilometer and the roughness measuring subsystem.

Test results of the correlation analysis indicate that if different testing speeds of the ARAN unit are used, the correlation models between the profilometer and the roughness measuring subsystem should be different. This means that, like other RTRRM devices, the ARAN unit's statistics are speed dependent; that is, the testing speed has a direct impact on the roughness statistics measured and reported by the subsystem. The test results also show that the roughness statistics MAS and SI of the subsystem correlate well with the roughness statistics of the profilometer. But the roughness statistics RMSVA and TEXTURE had relatively poor correlation with the roughness statistics of the profilometer.

Importance of Operational Speed

In a response-type road roughness measuring system, it can be assumed that the roughness statistics of the roughness measuring subsystem are speed-dependent; that is, the reported roughness statistics on the same road surface are different if the operational speed is varied. Conceptually, this effect depends on both the suspension system of the ARAN unit and the pavement surface conditions. It appears that if the pavement surfaces are rough, as speed increases, the passengers in a vehicle would feel more uncomfortable. On the other hand, if the pavement surfaces are smooth, as speed increases, the perception of the passengers to the ride would not change as much. In fact, what the passengers are sensitive to are the amplitudes and frequencies of the pavement surface profiles. The change in speed is equivalent to changing the frequency of the profiles.

In the evaluation of the impact of the operational speed, two alternate methods were used: the reference quarter car simulation (RQCS) (Ref 39) and field testing. The RQCS analysis qualitatively simulated the suspension system of the ARAN unit and predicted the effect of different speeds. As the simulated operational speed of the RQCS changed, the response of the RQCS also changed. As a result of this simulation, the impact of the operational speed was evaluated. Field tests were conducted by operating the subsystem at various speeds to find out how the subsystem responded. Because the subsystem performance also depends on pavement surface conditions, several pavement sections were selected for the field tests. According to the results of RQCS analysis and field tests, the speed-dependence of the roughness statistic was confirmed, and the roughness indices RMSVA and TEXTURE were found to be more sensitive to the operational speed than MAS.

NEW MODEL DEVELOPMENT

The roughness information from the ARAN unit is processed by some models (such as RMSVA, MAS, and TEXTURE) to produce roughness indices. In addition, the manufacturer of the ARAN unit has provided a serviceability index (SI) estimation model for the ARAN unit. Since the first SDHPT-developed SI model has some practical disadvantages, new pavement serviceability index (PSI) models were developed in this study. Speed-effect-cancelling models were also developed using the Austin Test Section data.

New PSI Estimation Models

The original SI equation used with the ARAN was developed by the Texas SDHPT and correlated to the modified K. J. Law Profilometer. The SI equation produced from the roughness measuring subsystem of the ARAN should, it was decided, be capable of directly estimating profilometer SI.

It was also determined that the operational speeds of the ARAN unit significantly affect its roughness statistics output. The equation estimating SI values should be used only for a specific operational speed, since the SI equation does not contain a speed to correct for speed effects.

Because of the factors listed above, new Serviceability Index (SI) equations which exclude TEXTURE were developed. These equations were obtained through linear regression analysis comparing the roughness statistics from the ARAN unit with the output of the modified K. J. Law Profilometer.

Computer programs were developed to implement the new SI estimation equations using FORTRAN and BASIC. The programs model the correlation between the SI from the profilometer and the SI estimate from the roughness measuring subsystem of the ARAN unit.

Speed Effect Cancelling Models

Analysis shows that operational speed does have significant impact on the subsystem; and with respect to this, two basic problems regarding the operation of the ARAN unit are often encountered.

First, in order to correlate the roughness statistics of the subsystem to the roughness statistics of some other roughness measuring system, a standard operational speed is required. But in some cases, such as in a heavily trafficked area or on very rough pavements, the ARAN unit may be incapable of maintaining the required operational speed. According to the results of the operational speed effect analysis, the biased operational speed would result in errors in the roughness outputs.

In an attempt to overcome these difficulties, two different types of speed effect cancelling models were developed in this study (Ref 39). The first model is based on the correlation between the roughness statistics from the modified K. J. Law Profilometer and the ARAN unit. The second speed-effect-cancelling model is based on the relationship between the operational speed and the roughness statistics of the subsystem at different roughness levels of pavement sections. The roughness statistics measured at any operational speed can be referred to the roughness statistics at a standard speed, say 50 mph, by using the second speed-effect-cancelling model. From the standpoint of applicability, the second speed-effect-cancelling model is more useful than the first one because it does not consider external references.

The methodologies adopted in the speed-effect-cancelling models can be applied to other response-type road roughness measuring systems—if they demonstrate good repeatability and if they provide operational speed as an output.

CHAPTER 4. EVALUATION OF THE ORIENTATION SUBSYSTEM

DESCRIPTION OF GYROSCOPE AND EVALUATION ASPECTS

In the gyroscope shown in Fig 4.1, the outer ring A is fixed to a frame, the second ring B is pivoted vertically to the outer ring A, inner ring C is pivoted at right angles in the second ring B, and the ball D is pivoted at right angles in the inner ring C to its pivot in the second ring B. This arrangement gives the ball, rotating on its own axis, the freedom to move in any direction within the sphere; changing the direction of the ball (once it is rotating rapidly) requires great force. If the relative three-dimensional angle increment of the ball relative to the frame is measured, the "attitude" of the ball can be determined.

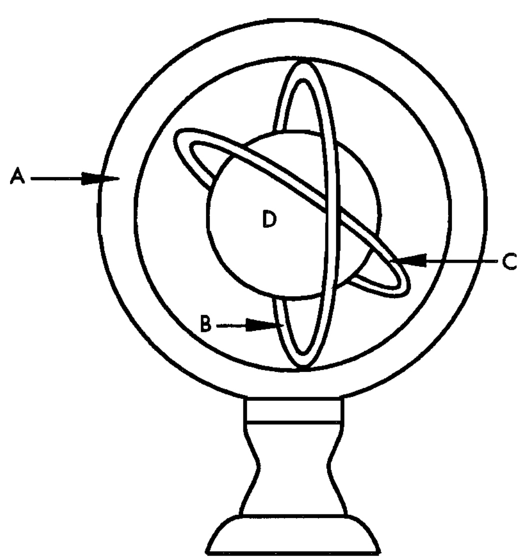


Figure 4.1 Structure of a gyroscope

Concerning the evaluation of the orientation subsystem, the first step was to examine the reliability of the subsystem by conducting drift error and dynamic performance tests. The drift error test, including static and dynamic drift tests, determined the inherent error of the gyroscopes. The dynamic performance test was conducted to determine the measuring accuracy and measurement principle of the subsystem. The second step was to conduct an operational test which examined whether changes in operating conditions significantly affected the measurement outputs. In general, the results from the drift error test, the dynamic performance test, and the operation test can provide information and references for the operation of the subsystem, as well as for subsequent roadway condition evaluations.

DRIFT ERROR TEST

One of the more serious problems associated with the gyroscopes is drift error, which is capable of producing incorrect subsystem readings. Drift error is temperature-sensitive and will, over time, accumulate in one direction (positive or negative). According to Ref 36, drift is defined as the unwarranted deviation of the momentum axis from its reference position. The momentum axis is associated with the rotating or translating mass, and the reference position is fixed or programmed to turn in accordance with some mathematical law. Drift error can be further classified as either fixed drift or random drift.

Fixed gyro drift is due to such unchanging parameters as initial constraint, eccentricity of centers of mass and support, and differences in elastic compliance coefficients. Fixed drift can be corrected or compensated, while random changes cannot. Random drift is due to random or uncertain torques. While fixed drift progresses in one direction (positive or negative), random drift can be either positive or negative.

The combination of fixed drift error and random drift error causes measurement error in the outputs of the orientation subsystem. As a part of the research effort, the measurement error caused by gyroscope drift was evaluated. Two methods were used to test for drift error: static drift error test and dynamic drift error test. In the static test, the outputs of the orientation subsystem were recorded as the gyroscopes were held immobile and in a stable state. The changes in the measured outputs, which should be time-dependent, represents the drift error. In the dynamic test of drift error the ARAN unit was used to collect data several times over a given test section, while environmental conditions and test conditions remained constant. Again, the results were used to determine if the drift error was significant.

Static Drift Error Test

As a part of the tests evaluating the reliability of the orientation subsystem, a static drift error test was conducted on November 3, 1989, at Balcones Research Center in Austin. As designed, the orientation subsystem is supported by two computer programs: the data acquisition and data reduction program, and the calibration program (Ref 32). The operation of the former program needs an interrupt signal from a distance measuring instrument (DMI), generated by the turning wheels. Since the test was made at a static state to keep vibration and environmental interruption at a minimum level, it was decided that the DMI could not be used, and consequently, the program for data acquisition could not be used. The program for calibration automatically samples the data from the gyroscopes without any triggering signal, and, therefore, was used in the test. Since the data sampled by the program could not be automatically recorded by the computer system, the readings were manually recorded.

Test Procedure. The ARAN unit remained parked during testing. Except for vibration from the air conditioning system and generator (providing power for the electrical system), the environmental interruption was kept at a minimum level. The orientation subsystem was operated as if calibrating under normal conditions. The operator monitor was moved toward the passenger side door so that data could be read from outside without disturbing the ARAN unit. The data from the gyroscopes were manually recorded from the monitor at 30-second time intervals, with the test lasting about 65 minutes. Since no movement of the ARAN unit was allowed during this test, any changes in the readings should be a consequence of static drift.

Test Results and Discussions. The test data are presented in Table 4.1. It can be seen from this table that PITCH and ROLL were constant during this test, meaning that there were no static drift errors in PITCH and ROLL. But the static drift error in HEADING was very significant, and the drift rate was not constant, i.e., the drift was nonlinear. Figure 4.2 shows the curve of HEADING vs. time. From the results, the following conclusions can be made:

(1) According to the measurement principle of the orientation subsystem, two identical static drift cancelling models are used to eliminate the static drift errors in PITCH and ROLL; but because HEADING does not have a drift cancelling model, it is reasonable to assume that HEADING would have significant static drift, while PITCH and ROLL would not.

(2) Because the static test is at an ideal operating state (without mechanical vibration or acceleration), the conclusion of no static drift cannot be applied to the dynamic state (operating state). On the other hand, if there is static drift, it can be said that there must be dynamic drift.

(3) In principle, fixed drift is also sensitive to temperature changes, with the sensitivity depending on the quality of the gyroscopes. During this static drift error test, the changes in temperature were not significant, as can be seen in Table 4.1. Therefore, the temperature-sensitivity of the drift could not be determined. However, the air conditioning system of the ARAN unit guarantees a constant temperature environment for the gyroscopes, minimizing the effect of temperature on drift error.

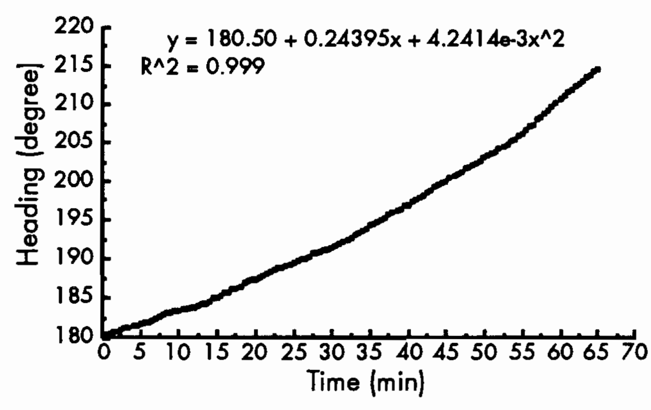


Figure 4.2 Static drift existing in HEADING

Dynamic Drift Error Tests

A gyroscope, in principle, is a mechanical system relatively sensitive to vibration, speed, acceleration, temperature, and other mechanical movements and changes in its environment. It can therefore be assumed that drift, existing in the gyroscopes of the orientation subsystem, would differ at static and dynamic operating states. When a gyroscope is at static state, i.e., the mechanical movement and environment change are kept at minimum levels, the fixed drift error may con-

Table 4.1 Data table of static drift test of the orientation subsystem

Time (min)	Heading (degree)	Pitch (%)	Roll (%)	Temp. (°F)	Time (min)	Heading (degree)	Pitch (%)	Roll (%)	Temp. (°F)
0.0	180.4	1.0	0.8	57.6	17.5	186.3	1.0	0.8	
0.5	180.4	↑	↑		18.0	186.6	↑	↑	
1.0	180.5				18.5	186.8			
1.5	180.7				19.0	187.1			
2.0	180.8				19.5	187.3			
2.5	180.9				20.0	187.5			
3.0	181.1				20.5	187.7			
3.5	181.2				21.0	187.9			
4.0	181.4				21.5	188.1			
4.5	181.5				22.0	188.3			
5.0	181.7				22.5	188.5			
5.5	181.9				23.0	188.7			
6.0	182.0				23.5	188.9			
6.5	182.2				24.0	189.1			
7.0	182.4				24.5	189.3			
7.5	182.6				25.0	189.5			
8.0	182.8				25.5	189.7			
8.5	183.0				26.0	189.9			
9.0	183.1				26.5	190.1			
9.5	183.3				27.0	190.3			
10.0	183.4				27.5	190.6			
10.5	183.5				28.0	190.7			
11.0	183.6				28.5	190.9			
11.5	183.8				29.0	191.1			
12.0	183.9				29.5	191.2			
12.5	184.1				30.0	191.4			60.2
13.0	184.2				30.5	191.6			
13.5	184.4				31.0	191.9			
14.0	184.6				31.5	192.2			
14.5	184.9				32.0	192.4			
15.0	185.1			58.2	32.5	192.7			
15.5	185.3				33.0	193.0			
16.0	185.6				33.5	193.3			
16.5	185.8	↓	↓		34.0	193.6	↓	↓	
17.0	186.1	1.0	0.8		34.5	193.9	1.0	0.8	

Table 4.1 (continued)

Time (min)	Heading (degree)	Pitch (%)	Roll (%)	Temp. (°F)	Time (min)	Heading (degree)	Pitch (%)	Roll (%)	Temp. (°F)
35.0	194.2	1.0	0.8	57.6	52.5	204.5	1.0	0.8	
35.5	194.5	↑	↑		53.0	204.8	↑	↑	
36.0	194.7				53.5	205.2			
36.5	195.0				54.0	205.5			
37.0	195.3				54.5	205.9			
37.5	195.6				55.0	206.3			
38.0	195.9				55.5	206.7			
38.5	196.2				56.0	207.1			
39.0	196.5				56.5	207.5			
39.5	196.8				57.0	208.0			
40.0	197.0				57.5	208.4			
40.5	197.3				58.0	208.9			
41.0	197.6				58.5	209.4			
41.5	197.9				59.0	209.8			
42.0	198.2				59.5	210.3			
42.5	198.5				60.0	210.7			64.8
43.0	198.8				60.5	211.1			
43.5	199.2				61.0	211.6			
44.0	199.5				61.5	212.0			
44.5	199.8				62.0	212.4			
45.0	200.1			62.2	62.5	212.7			
45.5	200.4				63.0	213.1			
46.0	200.7				63.5	213.5			
46.5	201.0				64.0	213.8			
47.0	201.3				64.5	214.2	↓	↓	
47.5	201.6				65.0	214.6	1.0	0.8	
48.0	201.9								
48.5	202.2								
49.0	202.5								
49.5	202.7								
50.0	203.0								
50.5	203.4								
51.0	203.6								
51.5	203.9	↓	↓						
52.0	204.2	1.0	0.8						

stantly increase in a direction (positive or negative) because the working level of the gyroscope is constant. But when the gyroscope is moved or affected by changes in the environment, its working level is correspondingly changed, causing the direction of the fixed drift error to change accordingly. The changing direction of the fixed drift may result in relatively less cumulative drift error with respect to the constant direction of the fixed drift.

Because of this consideration, a dynamic drift error test was proposed to examine how the orientation subsystem is affected by drift error.

Test Procedure. In order to examine the dynamic drift error, repeat runs on given test sections were made at normal operating conditions. Usually, drift error is time-dependent. This time-dependence can be observed from the repeat runs of the orientation subsystem on the given test sections. The Austin Test Sections ATS01 and ATS04 were selected as the test sites. During the test, different operational speeds and report intervals were applied to determine their effect.

Results and Discussion. The direct outputs of the orientation subsystem at each run are a summarized HEADING, a summarized PITCH, and a summarized ROLL. The summarized outputs statistically characterize the conditions of the roadway. Table 4.2a shows the summarized data collected for PITCH and ROLL from Sections ATS01 and ATS04. Summarized HEADING data (Table 4.2b) was collected for the sections at a later date, in order to include time stamp data. The TIME and HEADING data were manually recorded from the monitor at the end of each run. These headings were identical to the ARAN summary data, except in the case of 0.05 or 0.10 mile report intervals, which the ARAN software reports incorrectly. Figures 4.3, 4.4, and 4.5 present the outputs HEADING, PITCH, and ROLL vs. repeat runs, respectively. Since no static drift cancellation mode is provided for the HEADING gyro (unlike the PITCH and ROLL gyro), significant drift with time was observed. Figure 4.3 shows a drift of approximately 0.6 degrees/minute, independent of operational speed. The change in HEADING was caused by drift in the HEADING gyroscope, and not by poor repeatability or choice of report interval and speed, etc. The PITCH data, depicted in Fig 4.4, shows poor repeatability, but trends for both test sections still can be found by curve-fittings, represented by solid lines. The observed trends may be due to dynamic drift errors caused by mechanical movement. Figure 4.5 shows the ROLL data obtained from the repeat runs. As shown in the figure, dynamic drift error is not significant. The following represents some of the conclusions from the test.

(1) Although there is no static drift in PITCH, it does not mean no dynamic drift exists. Poor repeatability makes it difficult to determine the effect of dynamic drift on PITCH, making this function unreliable if the summarized data are used.
(2) The finding that dynamic drift error in ROLL is not significant is related to repeatability, report interval, and operational speed; i.e., the dynamic drift error was confounded by these factors.
(3) The static drift error test indicated that there was no significant static drift error in PITCH and ROLL. But the dynamic drift error test indicated that the dynamic drift error in PITCH may be significant. The dynamic drift error in PITCH might be caused by vibration of the ARAN unit during the test. Vibration could result in deviation of the momentum axis from its reference position and thereby cause dynamic drift error in PITCH.
(4) The impact of operational speed on the orientation subsystem can be determined by the data from the dynamic drift error test which was conducted at speeds of 30, 35, 40, 45, and 50 mph. Figures 4.3 and 4.5 show that HEADING and ROLL are not speed-dependent because no significant changes in HEADING and ROLL were found when the operational speed was changed. Unfortunately, the poor repeatability existing in PITCH, shown in Fig 4.4, makes it difficult to judge the impact of the operational speed on PITCH. But because PITCH and ROLL are generated by the same gyroscope, the speed-independent property of PITCH can be inferred from the impact of the operational speed on ROLL.

DYNAMIC PERFORMANCE TEST

The dynamic performance tests of the orientation subsystems were made at normal operating conditions to compare with given references. Because of the constraints of funding, time, technique, equipment and other related factors, it was impossible to set standard or artificial inputs to the subsystem, even though standard inputs are important to testing and detection. Instead, a case study was made, using an existing bridge as the testing specimen and its design plan data as a reference.

Table 4.2a Summarized data of dynamic drift test at ATS01 and ATS04

Speed (mph)	Report Interval (miles)	Run	ATS01 Pitch (%)	ATS01 Heading (degree)	ATS01 Roll (%)	ATS04 Pitch (%)	ATS04 Heading (degree)	ATS04 Roll (%)
30	.005	1	.1	256.9	-.2	.9	81.7	3.8
		2	.5	257.6	.0	.3	82.3	3.6
		3	.7	258.0	-.1	.1	81.2	3.6
		4	.3	258.6	-.3	.2	82.9	3.7
		5	.5	259.9	-.1	.0	83.9	3.5
	.01	6	.4	259.4	.1	-.4	83.7	3.6
		7	.6	260.4	-.1	.1	87.9	3.5
		8	.5	260.8	.0	-.1	83.5	3.6
		9	.6	261.3	-.1	.0	85.6	3.6
		10	.7	261.9	-.1	.0	85.6	3.7
35	.005	11	.6	262.8	.0	-.2	87.1	3.3
		12	.9	263.4	-.1	-.1	87.9	3.6
		13	.7	263.6	.0	-.3	87.4	3.4
40	.005	14	.2	265.3	-.4	.9	90.6	4.0
		15	.5	266.0	-.1	.2	93.5	3.6
		16	.0	268.4	-.1	-.2	91.8	3.4
		17	.7	268.8	.0	-.3	93.2	3.2
		18	.7	269.5	-.2	.0	93.2	3.5
	.01	19	.1	270.1	-.3	.8	94.2	4.2
		20	.3	270.5	-.1	.0	94.8	3.8
		21	.6	271.1	.2	.0	95.6	3.6
		22	.7	271.6	.2	-.4	95.8	3.5
		23	.9	272.1	.0	-.3	97.6	3.6
45	.005	24	.1	272.8	-.7	.9	97.1	4.3
		25	.3	273.3	-.1	.2	98.3	3.7
		26	.9	273.6	.0	.3	106.2	3.4
50	.005	27	1.4	275.0	.5	-.9	99.2	3.3
		28	1.2	275.5	.2	-1.0	99.1	3.4
		29	1.1	276.1	.0	-.9	100.3	3.7
		30	1.1	276.4	.0	-.4	100.6	3.7
		31	1.1	277.0	-.1	-1.1	101.3	3.9
	.01	32	1.2	277.6	.2	-.6	101.6	3.7
		33	1.3	277.7	.4	-1.5	100.5	3.3
		34	1.4	278.2	.2	-1.0	102.4	3.5
		35	1.1	278.5	.0	-.6	102.8	3.8
		36	1.1	279.0	.3	-1.3	103.3	3.7
	.05	37	.6	358.2	-.1	.5	180.8	3.9
		38	.9	358.9	.1	-.2	181.4	4.1
		39	1.0	359.3	-.1	.1	181.8	4.0
		40	1.6	359.6	-.2	-.4	182.1	3.8
		41	.9	360.2	.0	-.4	182.7	3.8
	.1	42	.0	360.5	.7	.3	180.3	4.2
		43	.7	360.9	.8	-.5	180.9	3.9
		44	.9	361.4	1.0	-1.3	181.0	4.3
		45	1.3	361.6	1.3	-1.7	181.6	3.9
		46	.8	361.9	1.2	-.7	182.0	4.2

Table 4.2b Summarized heading data from ATS01 and ATS04

Time (min)	Heading (degree)	Pitch (%)	Roll (%)	Temp. (°F)	Time (min)	Heading (degree)	Pitch (%)	Roll (%)	Temp. (°F)
35.0	194.2	1.0	0.8	57.6	52.5	204.5	1.0	0.8	
35.5	194.5	↑	↑		53.0	204.8	↑	↑	
36.0	194.7				53.5	205.2			
36.5	195.0				54.0	205.5			
37.0	195.3				54.5	205.9			
37.5	195.6				55.0	206.3			
38.0	195.9				55.5	206.7			
38.5	196.2				56.0	207.1			
39.0	196.5				56.5	207.5			
39.5	196.8				57.0	208.0			
40.0	197.0				57.5	208.4			
40.5	197.3				58.0	208.9			
41.0	197.6				58.5	209.4			
41.5	197.9				59.0	209.8			
42.0	198.2				59.5	210.3			
42.5	198.5				60.0	210.7			64.8
43.0	198.8				60.5	211.1			
43.5	199.2				61.0	211.6			
44.0	199.5				61.5	212.0			
44.5	199.8				62.0	212.4			
45.0	200.1			62.2	62.5	212.7			
45.5	200.4				63.0	213.1			
46.0	200.7				63.5	213.5			
46.5	201.0				64.0	213.8			
47.0	201.3				64.5	214.2	↓	↓	
47.5	201.6				65.0	214.6	1.0	0.8	
48.0	201.9								
48.5	202.2								
49.0	202.5								
49.5	202.7								
50.0	203.0								
50.5	203.4								
51.0	203.6								
51.5	203.9	↓	↓						
52.0	204.2	1.0	0.8						

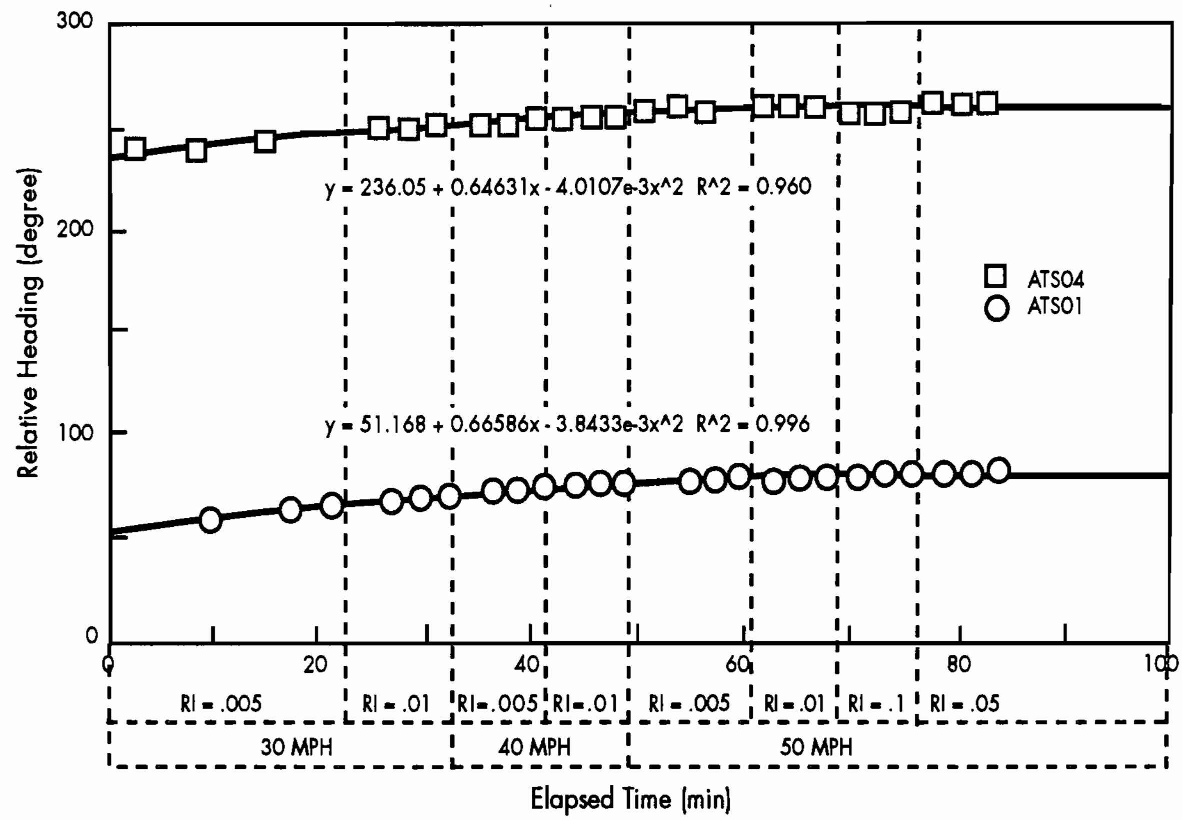


Figure 4.3 HEADING of repeat runs at ATS01 and ATS04

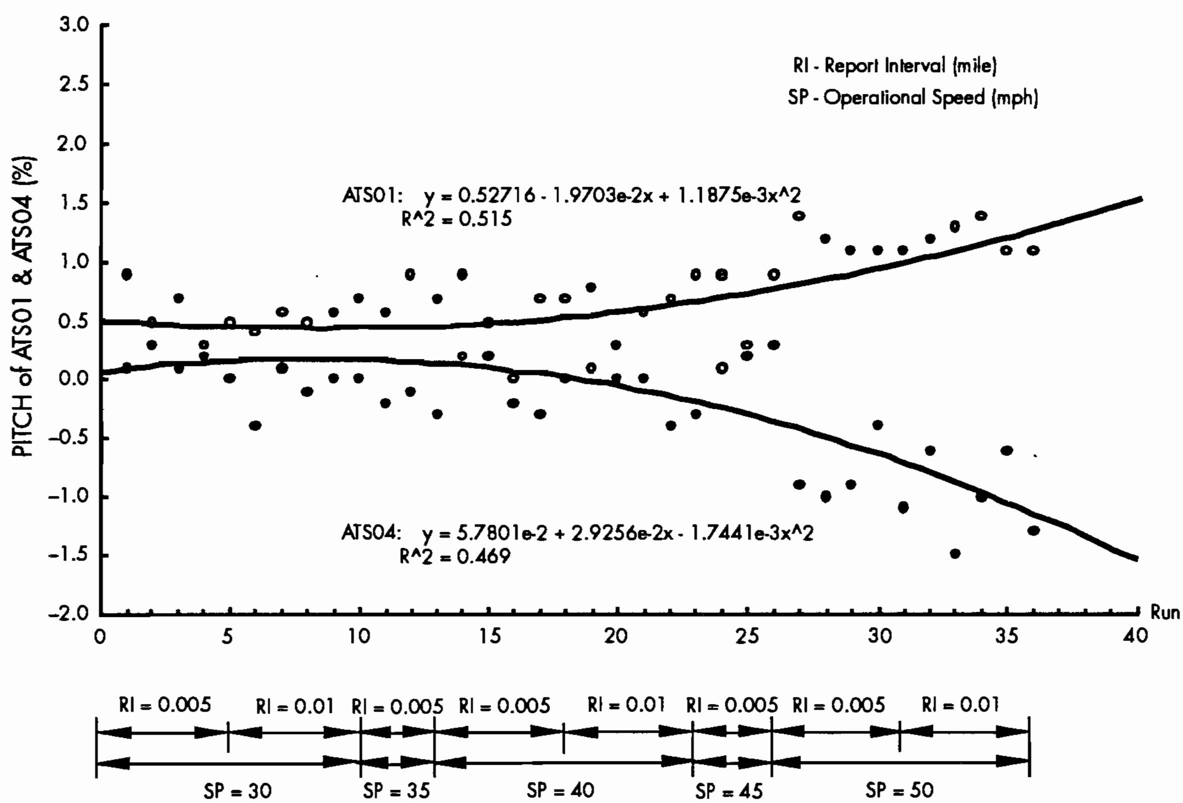


Figure 4.4 PITCH of repeat runs at ATS01 and ATS04

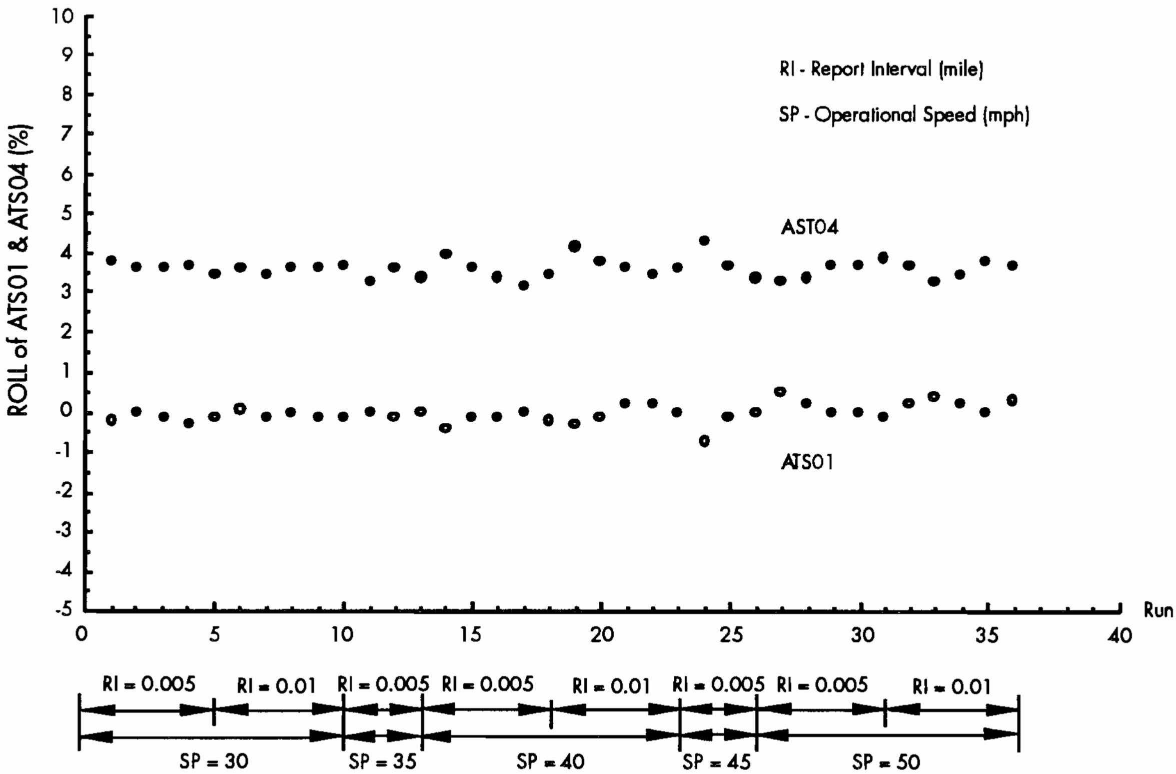


Figure 4.5 ROLL of repeat runs at ATS01 and ATS04

The test was conducted to compare measured HEADING, PITCH, and ROLL with the design plan of a given section. However, because the subsystem only collects relative three-dimensional states (HEADING, PITCH, and ROLL), and because no structure is built precisely to specification, it was not feasible to analyze the measurement errors quantitatively. Instead, the conclusions were based on subjective comparisons between the subsystem data and the design plan.

Test Site Choice

The test was run on Ramp E-N at the MoPac and U.S. 183 interchange in Austin. This site was selected for several reasons: (1) it represents a bridge with significant curve, slope, and superelevation that can be measured by the orientation subsystem (represented by HEADING, PITCH, and ROLL); (2) comparison of the ARAN data could be made with the design plan and measured data provided by the Texas SDHPT; and (3) the bridge deck and associated ramps had not been opened to public traffic, assuring safe operation of the test and minimum disturbance. The test site and stationing are shown in Fig 4.6.

Design Plan Interpretation

The design plan of the test section is shown in Fig 4.7. After detailed discussion, the interpretation of the plan by CTR project personnel was confirmed by the Texas SDHPT staff. The following is the confirmed interpretation of the design plan with respect to curve, slope, and superelevation:

(1) ***Curve***. Before station 321+16.44, the curve is: D=4° 15'
Between stations 321+16.44 and 326+36.93, D=8° 30'
Between stations 326+36.93 and 328+26.93, D=4° 15'
After station 328+26.93, D=0° (D is the degree difference between the ends of the associated span)

(2) ***Slope***. Before station 324+59, the slope is : 1.88 percent
Between stations 324+59 and 330+28.93, the slope is : -3.38 percent
After station 330+28.93, the slope is : -3.44 percent

(3) ***Superelevation***. The superelevation data were provided by the Texas SDHPT, not from

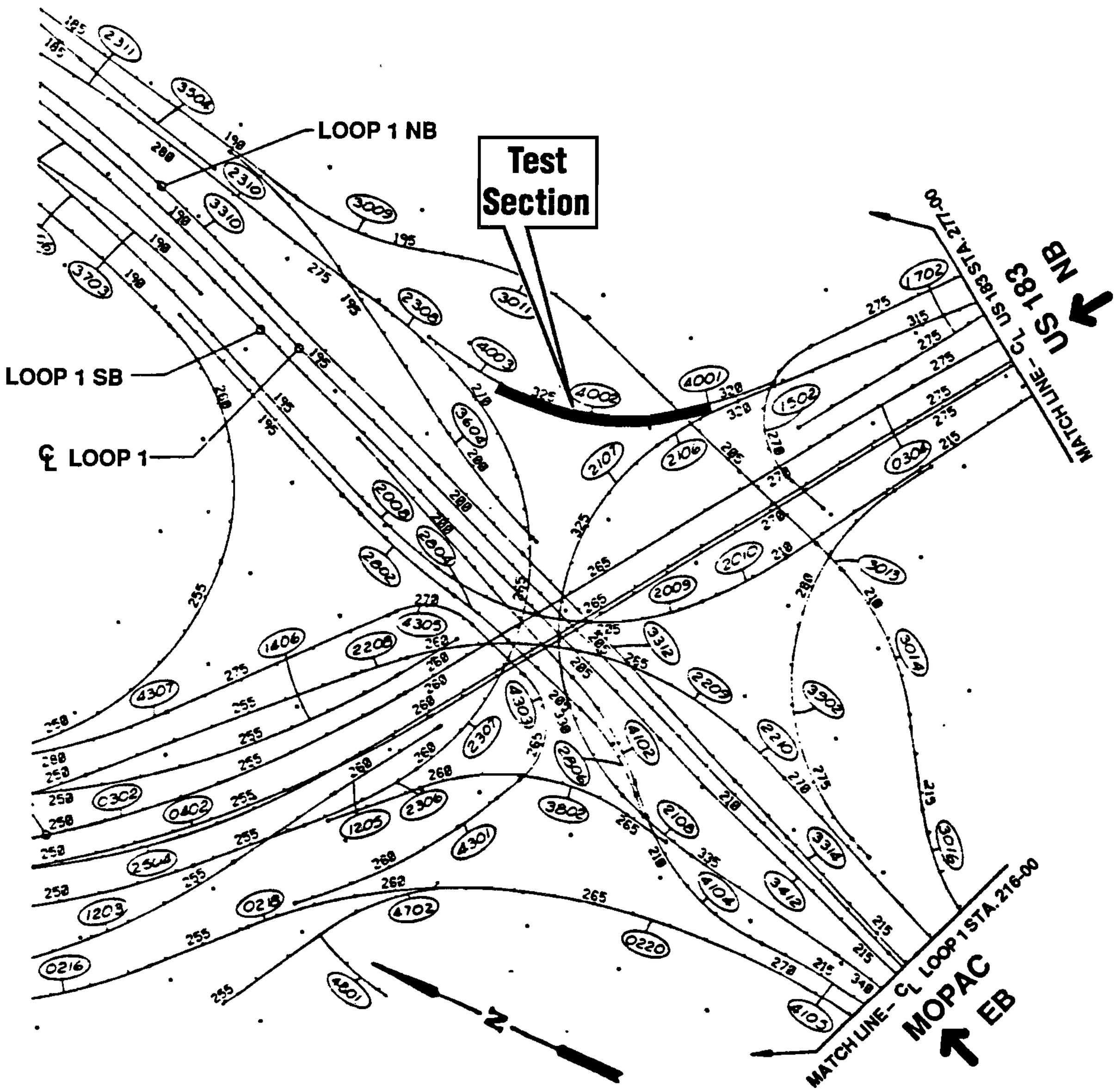


Figure 4.6 Location of the dynamic performance test for the Orientation Subsystem

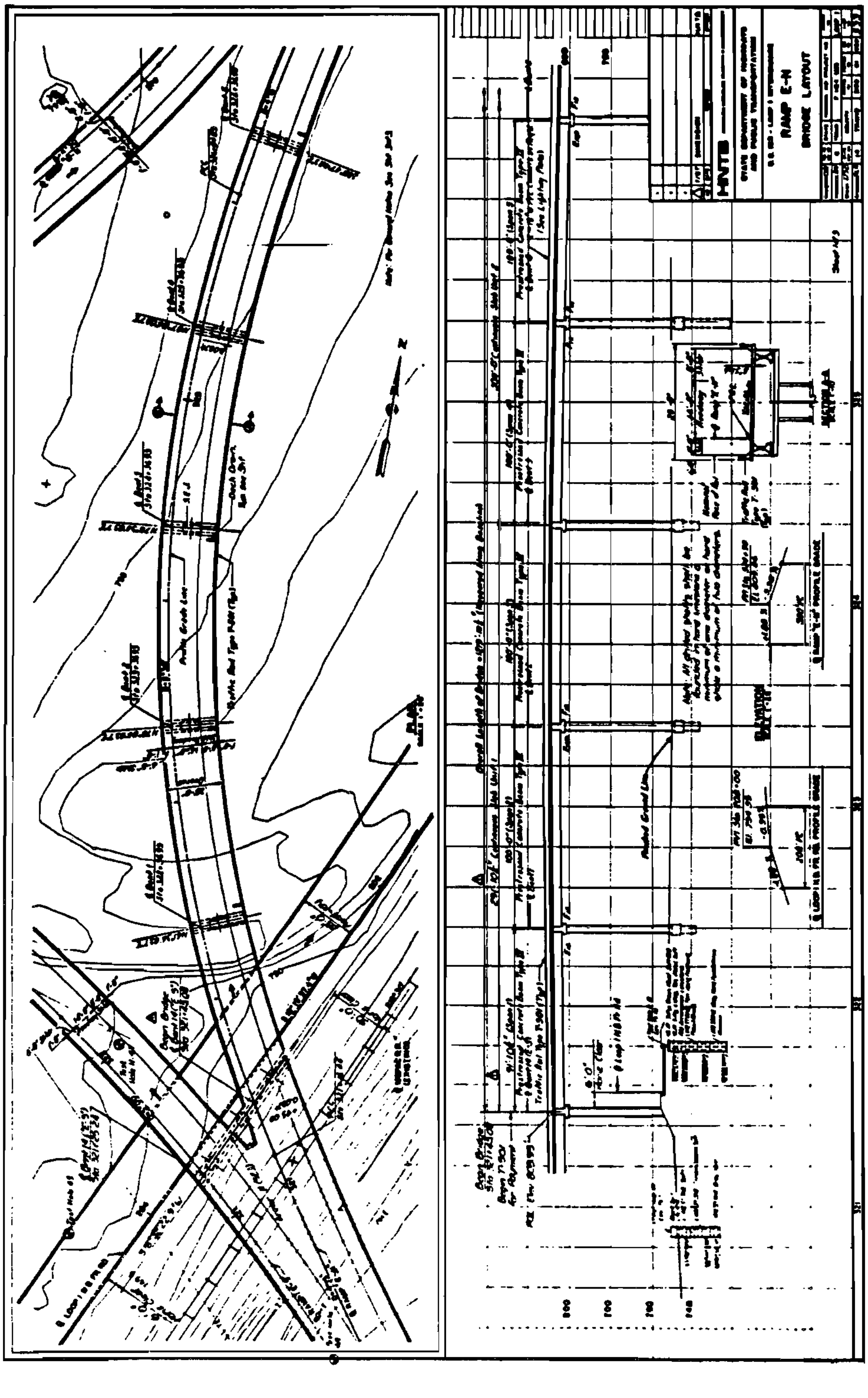


Figure 4.7 Design plan of the test section of the dynamic performance test for the Orientation Subsystem

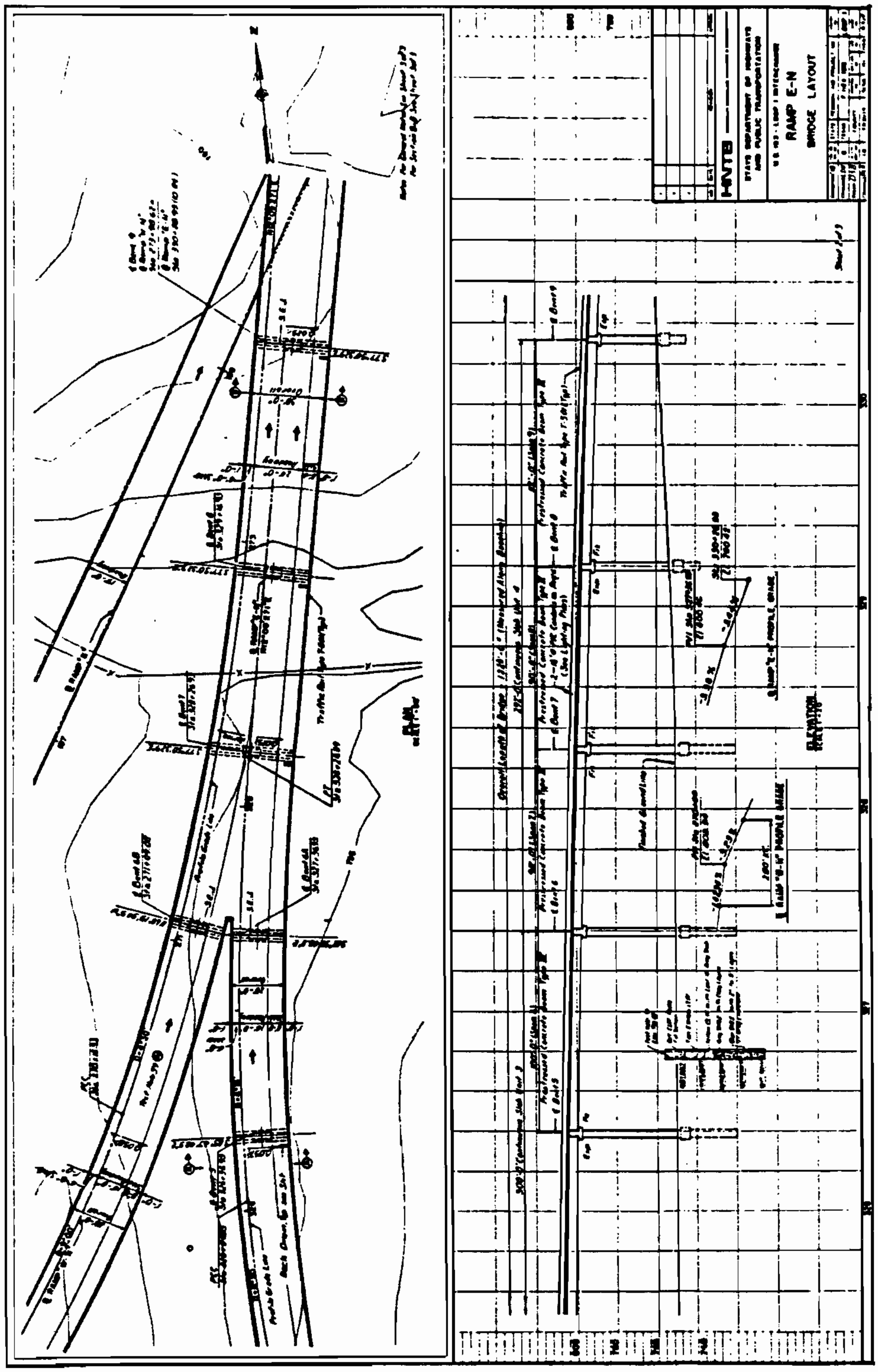


Figure 4.7 (continued)

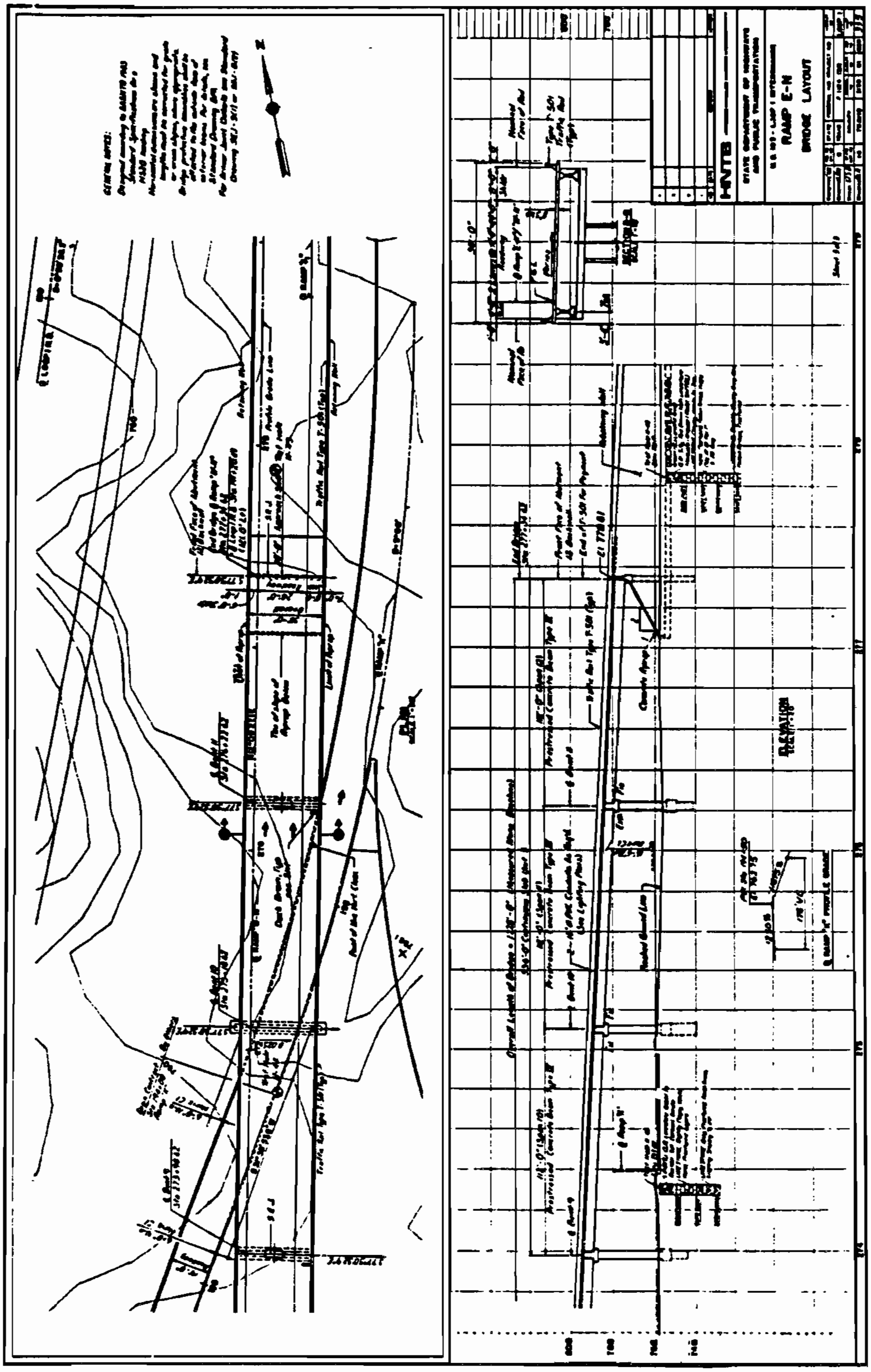


Figure 4.7 (continued)

Table 4.3 Superelevation of the test Section (Ramp E-N of the Bridge at MoPAC and U.S. 183 Interchange)

Distance (ft)	Super Elevation (%)	Distance (ft)	Super Elevation (%)	Distance (ft)	Super Elevation (%)	Distance (ft)	Super Elevation (%)
0.000	2.92	295.264	4.92	590.528	3.62	885.792	2.38
9.227	3.22	304.491	4.92	599.755	3.44	895.019	2.51
18.454	3.47	313.718	4.91	608.982	3.24	904.246	2.64
27.681	3.69	322.945	4.91	618.209	3.25	913.473	2.74
36.908	3.87	332.172	4.91	627.436	3.12		
46.135	4.04	341.399	4.91	636.663	2.95		
55.362	4.20	350.626	4.91	645.89	2.78		
64.589	4.36	359.853	4.91	655.117	2.61		
73.816	4.53	369.08	4.91	664.344	2.42		
83.043	4.72	378.307	4.91	673.571	2.23		
92.27	4.91	387.534	4.91	682.798	2.06		
101.497	4.86	396.761	4.91	692.025	1.89		
110.724	4.91	405.988	4.92	701.252	1.72		
119.951	4.91	415.215	4.92	710.479	1.78		
129.178	4.90	424.442	4.93	719.706	1.84		
138.405	4.90	433.669	4.93	728.933	1.82		
147.632	4.91	442.896	4.93	738.16	1.79		
156.859	4.90	452.123	4.95	747.387	1.76		
166.086	4.91	461.35	4.95	756.614	1.74		
175.313	4.91	470.577	4.95	765.841	1.71		
184.54	4.92	479.804	4.94	775.068	1.68		
193.767	4.92	789.031	4.90	784.295	1.66		
202.994	4.92	498.258	4.85	793.522	1.63		
212.221	4.92	507.485	4.79	802.749	1.60		
221.448	4.91	516.712	4.72	811.976	1.58		
230.675	4.91	525.939	4.63	821.203	1.22		
239.902	4.91	535.166	4.53	830.43	1.40		
249.129	4.90	544.393	4.41	839.657	1.55		
258.356	4.90	553.62	4.27	848.884	1.69		
267.583	4.90	562.847	4.12	858.111	1.87		
276.81	4.91	572.074	3.96	867.338	2.05		
286.037	4.91	581.301	3.79	876.565	2.22		

Table 4.4 Dynamic performance data from the Orientation Subsystem

Station (Mile)	Heading (Degree)	Pitch (%)	Roll (%)	Station (Mile)	Heading (Degree)	Pitch (%)	Roll (%)	Station (Mile)	Heading (Degree)	Pitch (%)	Roll (%)
.002	272.3	1.8		.060	246.2	-0.2		.118	227.1	-2.6	3.2
.004	271.5	1.9	3.8	.062	245.3	-0.2		.120	226.9	-2.9	
.006	270.7	2.6		.064	244.4	-0.4	3.3	.122	226.7	-3.4	
.008	269.9	2.6	4.1	.066	243.5	-1.0		.124	226.4	-3.5	2.8
.010	269.2	2.5		.068	242.7	-1.0	3.6	.126	226.2	-3.3	
.012	268.3	2.3		.070	241.9	-0.7		.128	225.9	-3.5	2.4
.014	267.4	2.4	3.8	.072	241.0	-0.9		.130	225.7	-3.9	
.016	266.5	2.4		.074	240.2	-1.3	3.8	.132	225.5	-3.9	
.018	265.5	2.2	3.9	.076	239.3	-1.5		.134	225.3	-3.6	2.5
.020	264.7	2.1		.078	238.4	-1.3	3.5	.136	225.2	-3.2	
.022	263.9	2.1		.080	237.4	-1.3		.138	225.1	-3.1	2.6
.024	263.2	2.3	4.1	.082	236.6	-1.7		.140	225.1	-3.6	
.026	262.3	2.0		.084	235.7	-2.1	3.6	.142	225.0	-3.9	
.028	261.5	1.7	3.9	.086	234.9	-2.1		.144	225.0	-3.8	3.2
.030	260.5	1.3		.088	234.2	-1.9	4.0	.146	225.0	-3.3	
.032	259.5	1.5		.090	233.6	-1.9		.148	225.0	-3.5	3.1
.034	258.6	1.5	3.6	.092	232.9	-2.2		.150	225.0	-3.2	
.036	257.7	1.3		.094	232.3	-2.4	4.1	.152	225.0	-3.2	
.038	256.8	1.0	4.1	.096	231.7	-2.3		.154	225.0	-3.3	2.9
.040	255.8	0.9		.098	231.1	-2.2	3.7	.156	225.0	-3.3	
.042	254.9	0.9		.100	230.5	-2.3		.158	224.9	-3.6	3.0
.044	254.0	1.1	3.8	.102	230.0	-2.5		.160	224.9	-3.3	
.046	253.1	0.4		.104	229.5	-2.7	3.5	.162	224.9	-3.3	
.048	252.1	0.5	3.8	.106	229.1	-3.0		.164	224.9	-3.3	3.1
.050	251.2	0.5		.108	228.7	-2.9	3.3	.166	224.9	-3.4	
.052	250.2	0.4		.110	228.3	-3.0		.168	224.9	-3.5	3.4
.054	249.2	-0.1	3.4	.112	227.9	-3.2		.170	224.9	-3.3	
.056	248.2	-0.7		.114	227.6	-3.1	3.4	.172	225.0	-3.0	
.058	247.2	-0.8	3.4	.116	227.3	-2.6		.174	225.0	-3.0	3.2

the design shown in Fig 4.7. Table 4.3 shows the superelevation data, and the beginning point for data collection is at station 321+16.44, as shown in Fig 4.7.

Test Results

The ARAN unit was operated at approximately 40 mph with a selected report interval of 0.005 mile in order to obtain good repeatability. During this test, the bridge had not yet been opened to public traffic, though occasionally some working vehicles passed by. Traffic through the test section was controlled by a flagman. The data collected by the subsystem from this test are listed in Table 4.4. The following conclusions were made.

Comparison between Curve and HEADING. A reference direction must be established to compare the measurements of the HEADING gyroscope and the design plan. In this test, the direction degree at the start line is considered to be the reference and is designated as 100 degrees. From Table 4.4, it is known that as the ARAN unit left the start line, HEADING decreased corresponding with a decrease in direction degree. Figure 4.8 shows the test results. From this figure, it can be seen that the two measurements are quite close, indicating the HEADING gyroscope can satisfactorily measure the curve of this bridge. Since the designed curve might differ somewhat from the constructed one, it could be that the curve measured by the HEADING gyroscope is closer to the actual construction.

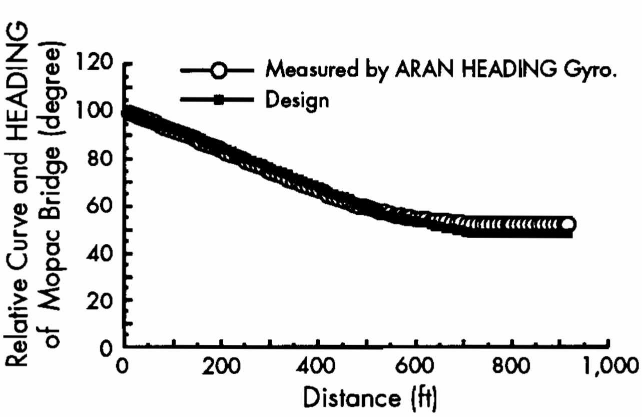


Figure 4.8 Comparison of the relative curve and HEADING of MoPac Bridge

Comparison between Slope and PITCH. An easier way to compare the measured data (PITCH) with the slope from the design plan is to change PITCH and slope to the corresponding relative elevations using equations (4.1) and (4.2). Again, the start line where the elevation is considered to be zero is chosen as the reference.

$$ME_i = \frac{1}{100}\sum_{j=1}^{i} \Delta X\, PITCH_j \quad (i=1,2,..,N) \tag{4.1}$$

$$DE_i = \frac{1}{100}\sum_{j=1}^{i} \Delta X\, SLOPE_j \quad (i=1,2,..,N) \tag{4.2}$$

where

N = number of sampled data points,
ΔX = sampling interval of the subsystem (ΔX = 10.56 feet, or 0.002 miles),
$PITCH_j$ = j^{th} reading of PITCH gyroscope,
$SLOPE_j$ = j^{th} reading of the design slope,
ME_i = i^{th} relative elevation measured by the orientation subsystem, and
DE_i = i^{th} designed relative elevation obtained from the design plan.

Figure 4.9 shows the measured and designed relative elevations; it can be concluded that these two measurements are relatively close (the trends at least being almost the same). However, it can be assumed that the constructed slopes or longitudinal profiles are usually not exactly the same as those designed because of construction procedures and techniques. As with HEADING, the real slope or profile could be closer to those measured by the orientation subsystem.

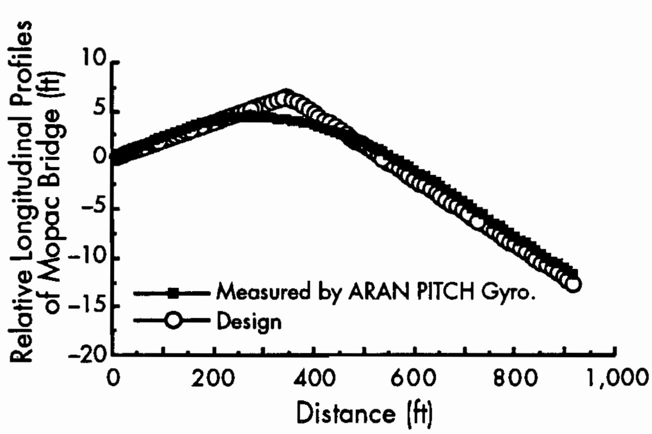


Figure 4.9 Comparison of the relative longitudinal profiles of MoPac Bridge as designed and as measured by the ARAN unit

Comparison Between Superelevation and ROLL. The superelevation sampled at each station is independent of samples at other points. Therefore, absolute data can be used in this test. Figure 4.10 compares the superelevation data from the orientation subsystem to the data provided by the Texas SDHPT. It can be seen from this figure that the difference between the two superelevation curves is significant, but the trends in the two curves are somewhat similar. The difference might be explained as follows: the superelevation data provided by the Texas SDHPT are based on the relative elevation differences of the left and right edges of the bridge, while the superelevations measured by the ARAN unit are taken in the wheelpaths. As a result, the absolute values of the two types of data should be different, but they should have the same changing trends.

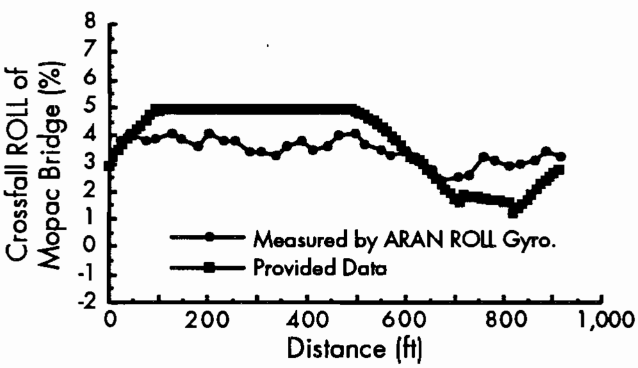


Figure 4.10 Comparison between the superelevation and ROLL of the MoPac Bridge

Curve Layout Measurement by HEADING Gyroscope. The HEADING readings can be used to determine the relative layout of a bridge or roadway, an important geometric characteristic. Again, the start line is considered to be the reference, and the direction of this section at the start line is assumed to be 45°. If a Cartesian coordinate system is adopted, then the projection of the section onto the X and Y axes can be expressed by equations (4.3) and (4.4).

$$V_i = \sum_{j=1}^{i} \Delta X \, Sin \left(HEADING_j \right) \quad (i=1,2,..,N) \qquad (4.3)$$

$$H_i = \sum_{j=1}^{i} \Delta X \, Cos \left(HEADING_j \right) \quad (i=1,2,..,N) \qquad (4.4)$$

where

V_i = the i^{th} projected coordinate of the section at the vertical or y-axis,
H_i = the i^{th} projected coordinate of the section at the horizontal or x-axis,
ΔX = sampling interval of the subsystem (ΔX = 10.56 feet, or 0.002 miles), and
$HEADING_j$= the j^{th} relative readings of HEADING.

Figure 4.11 shows the relative layout of the bridge measured by the orientation subsystem; the measured layout (curve) shows some similarity when compared with the design plan (see Fig 4.7).

The models presented in equations (4.1) through (4.4) are some of the practical applications of the subsystem; if properly implemented as computer programs, these models can be directly applied to the routine measurement of roadway geometric characteristics.

OPERATIONAL TESTS

Before operating the orientation subsystem, a series of operating conditions, such as report interval, speed, and number of repeat runs, etc., need to be properly set by the operator. If the operator does not make these choices wisely, the repeatability of the data may be adversely affected. In order to determine optimum operating conditions, their impacts should be evaluated.

The determination of operating-condition impact on the orientation subsystem was based primarily on field tests and field data. During the evaluation, different sets of operating conditions were applied to determine changes in the collected data for a given test section. The operational tests included tests of repeatability and of report interval and operational speed impacts.

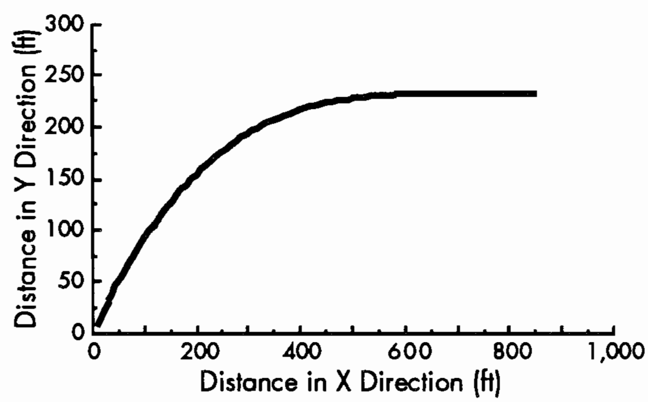


Figure 4.11 Relative layout (curve) of MoPac Bridge as measured by the ARAN unit

Discussions of the Report Interval and the Reported Statistics

Through careful scrutiny of data report lists, it was found that the selected report interval for the operation of the orientation subsystem does not have the same meaning as the report interval for the roughness measuring subsystem and rut depth subsystem. It was found that regardless of the report interval selected, HEADING and PITCH are reported every 0.002 mile; ROLL is reported correctly at every report interval. Also, it was found that the summarized PITCH and ROLL for each section are the mean values of the reported values, while the summarized HEADING is the last value of the reported values.

Another anomaly of the orientation subsystem is that, for a given length of roadway section, the data report length covered by the reported data is not always equal to the length of the section: it depends on the selected report interval. A field test was run to check this observation. The selected test section length was 0.200 miles and the selected report intervals were 0.005, 0.01, 0.05, and 0.1 mile. The following conclusions were obtained from the field test:

(1) HEADING and PITCH: If the selected report interval is less than or equal to 0.01 mile, the data report length is 0.200 miles, the correct section length. If the report interval is 0.05 or 0.1 mile, then the data report length is 0.160 miles or 0.08 miles, respectively. This means that the data report length is shorter than the section length if a report interval 0.05 mile or larger is applied.

(2) ROLL: The report length is always 0.200 miles no matter what the report interval is. This means that the data report length is not affected by the selected report interval.

In summary, when the selected report interval is 0.05 or 0.1 mile, the report lengths of HEADING and PITCH are less than the section length. In this case, the measured data might not be adequate. Therefore, if the Orientation Subsystem is going to be used, it is recommended that the report interval be no greater than 0.01 mile.

Repeatability Test

The operational repeatability of the orientation subsystem is affected by both the measurement principle of the subsystem and the stability of the hardware system. Conclusions regarding the repeatability can be used to determine how many repeat runs are needed to get satisfactory field data. Practical experience has indicated that repeatedly operating a roadway condition measuring system on a given roadway section is necessary to eliminate the deviations caused by unstable working states and driver/operator variability. Concerning the orientation subsystem, stable driving behavior is especially important because the three-dimensional orientation of the ARAN unit is based on the wheelpath of the unit. Repeatability is needed to determine the effects of these variabilities.

Definition of Repeatability Index. A repeatability index, RRMSE (Relative Root Mean Square Error) is defined as follows to characterize the repeatability of the summarized outputs, HEADING, PITCH, and ROLL.

$$RRMSE = \frac{1}{X}\sqrt{\frac{1}{N}\sum_{i=1}^{N}(X_i - X)^2} \qquad (4.5)$$

where

X_i = the summarized reading (HEADING, PITCH, or ROLL) from a given test section at i^{th} run,
X = mean value of X_i, and
N = number of repeat runs.

Conceptually, the smaller the RRMSE, the better the repeatability.

Field Tests and Results. During the field tests conducted for evaluation of repeatability, the ARAN unit was operated at a constant speed of 50 mph. Report intervals of 0.005, 0.01, 0.05, and 0.1 mile were used so that the repeatability at these different report intervals could be evaluated. These tests were conducted on Austin Test Sections ATS01 and ATS04, where five repeat runs (N=5) recording PITCH and ROLL were made on each test section. Three repeat runs for HEADING were made at a later date. Table 4.5 shows the summarized field test data collected from ATS01 and ATS04.

Table 4.6 shows the calculated repeatability index data RRMSE for HEADING, PITCH, and ROLL. According to the concept that smaller RRMSE means better repeatability, the following conclusions can be made:

(1) The variable HEADING shows good repeatability at all selected report intervals. As determined before, whatever the report interval is, HEADING is reported at every 0.002 miles. As long as a constant report interval is set during repeat runs, it has no effect on the

Table 4.5 Field data for repeatability and report interval effect tests

Report Interval (miles)	Run	ATS01 Pitch (%)	ATS01 Heading (degree)	ATS01 Roll (%)	ATS04 Pitch (%)	ATS04 Heading (degree)	ATS04 Roll (%)
.005	1	1.4	275.0	.5	–.9	99.2	3.3
	2	1.2	275.5	.2	–1.0	99.1	3.4
	3	1.1	276.1	.0	–.9	100.3	3.7
	4	1.1	276.4	.0	–.4	100.6	3.7
	5	1.1	277.0	–.1	–1.1	101.3	3.9
.01	1	1.2	277.6	.2	–.6	101.6	3.7
	2	1.3	277.7	.4	–1.5	100.5	3.3
	3	1.4	278.2	.2	–1.0	102.4	3.5
	4	1.1	278.5	.0	–.6	102.8	3.8
	5	1.1	279.0	.3	–1.3	103.3	3.7
.05	1	.6	358.2	–1	.5	180.8	3.9
	2	.9	358.9	.1	–.2	181.4	4.1
	3	1.0	359.3	–.1	.1	181.8	4.0
	4	1.6	359.6	–.2	–.4	182.1	3.8
	5	.9	360.2	.0	–.4	182.7	3.8
.1	1	.0	360.5	.7	.3	180.3	4.2
	2	.7	360.9	.8	–.5	180.9	3.9
	3	.9	361.4	1.0	–1.3	181.0	4.3
	4	1.3	361.6	1.3	–1.7	181.6	3.9
	5	.8	361.9	1.2	–.7	182.0	4.2

Table 4.6 Data of RRMSE for the repeatability test of the orientation subsystem

Run	ATS01 Heading (degree)	ATS01 Pitch (%)	ATS01 Roll (%)	ATS04 Heading (degree)	ATS04 Pitch (%)	ATS04 Roll (%)
0.005	5.899E-3	9.883E-2	1.77951	2.402E-3	0.28100	6.086E-2
0.01	3.689E-3	9.559E-2	0.60302	1.442E-3	0.36332	4.969E-2
0.05	3.267E-3	0.32863	1.69967	3.312E-3	4.28661	2.975E-2
0.1	4.299E-3	0.57078	0.22804	0.946E-3	0.88229	4.082E-2

repeatability of HEADING. It can be understood that the direction (HEADING) of a moving vehicle is not sensitive to its lateral position or wheelpath. Although it is difficult to keep the vehicle on the same wheelpath over different runs, the insensitivity of HEADING to the wheelpath may guarantee a good repeatability.

(2) The outputs PITCH and ROLL show relatively poor repeatability. Since the Austin Test Sections ATS01 and ATS04 had quite poor surface conditions (roughness and rutting) at the time the test was conducted, the relatively poor repeatability may be caused by variability in lateral wheel placement. It is difficult to keep the ARAN (or any other vehicle) running along the same wheelpaths for multiple runs, and this could be a reason for the orientation subsystem to have relatively poor repeatability in PITCH and ROLL.

(3) While the repeatability for PITCH and ROLL on these test sections was rated poor, it will be desirable in a future study to re-examine repeatability on smoother test sections under more controlled conditions.

Test of the Impact of the Report Interval

Report interval is an important factor requiring consideration in the evaluation of the orientation subsystem. Since different report intervals result in data of varying report lengths, the report interval could indirectly affect outputs of the subsystem. And because the repeatability of PITCH and ROLL is relatively poor, statistical methods to evaluate the report interval effect are not recommended. Instead, an evaluation was made graphically. Where the apparent effects were intuitively significant, conclusions were made regarding the results of the report interval effect. The data shown in Table 4.5 were used in the evaluation.

Field Tests and Results

The results are as follows:

(1) ***HEADING.*** Figure 4.12 shows the output HEADING vs. the repeat runs at different report intervals. Except for time-dependent drift, the HEADING remains relatively constant regardless of the report interval selected. However, it should be noted that the data were recorded manually from the ARAN console; if an RI of .05 or .10 is selected, the ARAN will report for only a .16 or .80 mile length, which may not adequately represent the test section, especially if it is curved.

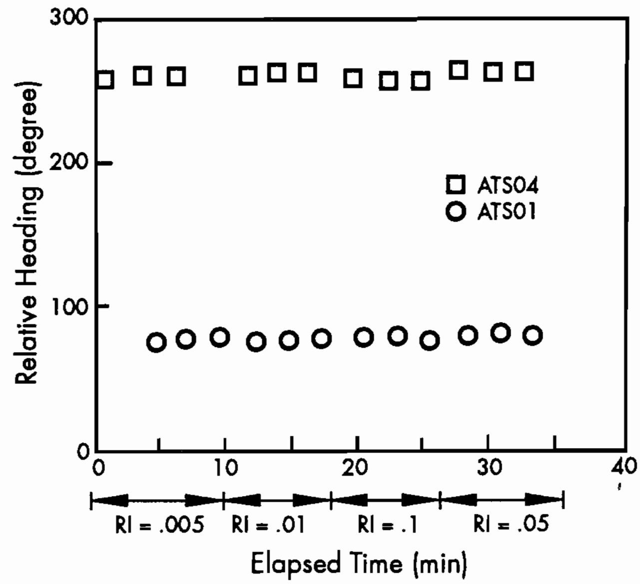


Figure 4.12 Impact of the report interval on HEADING at 50 mph

(2) ***PITCH.*** Figure 4.13 shows the output PITCH vs. repeat runs at different report intervals. As shown, when the report interval is greater than or equal to 0.05 mile, poorer repeatability is found. In addition to the effects of unstable wheelpath and dynamic drift error, another important factor affecting the repeatability of the output could be the report interval. As discussed before, if the report interval of the subsystem is set at 0.05 or 0.1 mile, the data report length should be shorter than the test section length, and information on the rest of the test section is lost.

(3) ***ROLL.*** The output ROLL vs. repeat runs at different report intervals is depicted in Fig 4.14. As the figure illustrates, when the report interval is greater than or equal to 0.1 miles, the repeatability becomes poorer. This might be due to two factors: (1) poor repeatability of ROLL because of the unstable wheelpath; and (2) loss of detail due to large report interval.

SUMMARY

The impact of report interval on the orientation subsystem can be significant due to the fact that different report intervals result in different data report lengths for HEADING and PITCH, and as the report interval becomes larger, more detailed information regarding ROLL is lost. When the report interval is greater than or equal to 0.05 miles, the impact on the outputs is relatively significant. In order to use the orientation subsystem adequately, a report interval of 0.01 mile or less is recommended.

Considerations of the Impact of the Operational Speed

The outputs of the gyroscopes in the orientation subsystem only indicate the attitude or position of the ARAN unit, and, in principle, should not be affected by the operational speed of the vehicle (Ref 36). But over time the drift error could accumulate, resulting in more significant error in the outputs. Therefore, the measurement should be made in as short a time period as possible, using the highest operational speed possible.

The poor repeatability in PITCH and ROLL made evaluation of the operational speed effect difficult. In addition, uncompensated static drift error exists in HEADING, further complicating the testing of the operational speed effect. Because certain conclusions have been made based on the dynamic drift test presented before, no further analysis regarding the impact of the operational speed on the orientation subsystem will be undertaken in this section. It is emphasized here again that the operational speed does not have significant impact on the outputs HEADING, PITCH, and ROLL. But adequate speed, say 50 mph, should be maintained based on such considerations as vibration (caused by high operational speed) and the sampling rate limit of the hardware system.

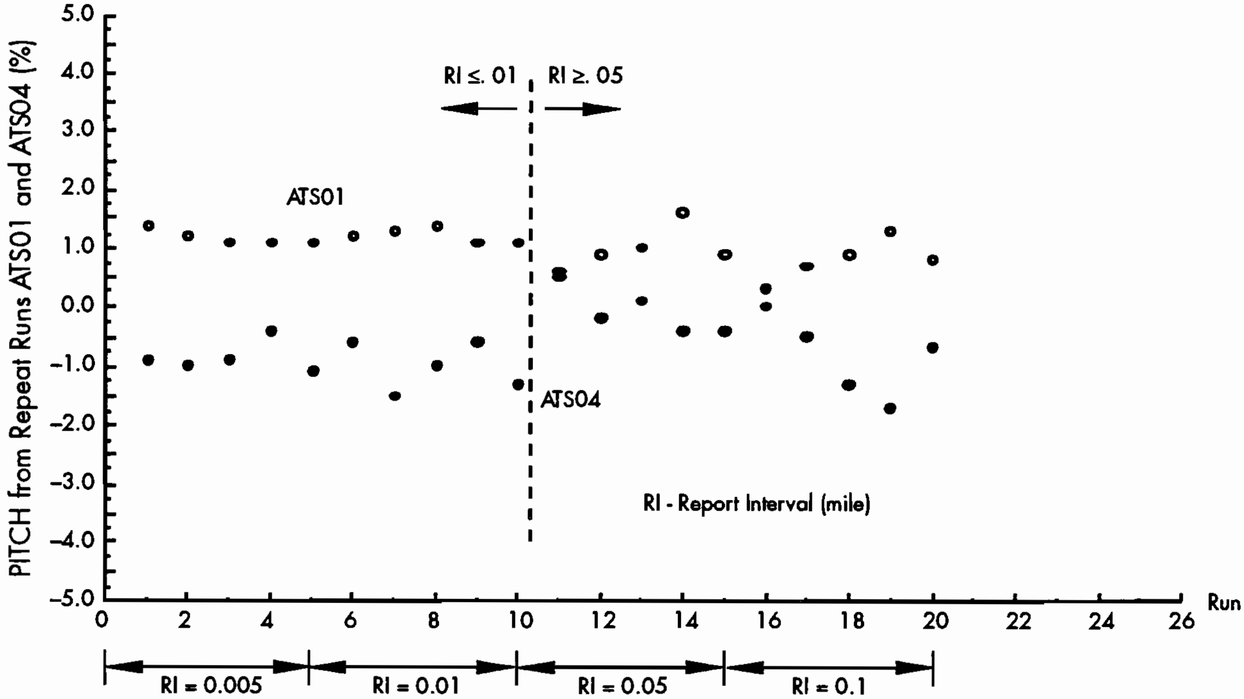


Figure 4.13 Impact of the report interval on PITCH at 50 mph

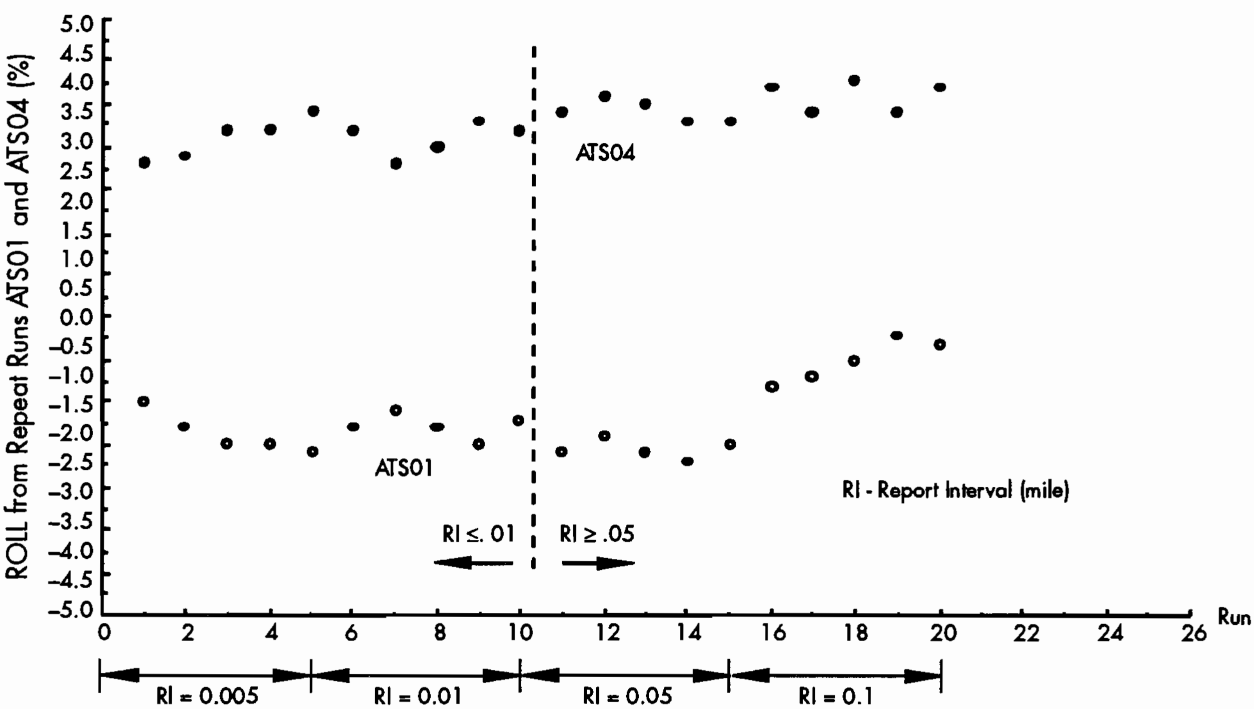


Figure 4.14 Impact of the report interval on ROLL at 50 mph

CHAPTER 5. EVALUATION OF THE RUT DEPTH SUBSYSTEM STATIC PERFORMANCE TEST

BACKGROUND

A static performance test of the rut depth subsystem was conducted to examine the subsystem's inherent quality and characteristics separate from the effects of the operating conditions, operator's behavior, and dynamic responses to certain external factors. The subsystem's static characteristics are the basis of the subsystem's operational performance, and the reliability of the data collected by the subsystem is based on the subsystem's static performance. For example, good static accuracy and resolution are required for small dynamic measurement errors. One of the purposes of the static performance test was to determine the measuring ranges of the subsystem so that an objective reference could be provided for measuring rutting and transverse profile.

The static test was performed on August 31, 1989, at Balcones Research Center (BRC), Austin, Texas. The rut depth subsystem was evaluated in the static mode utilizing diagnostic software that allows the operator to view the separate ultrasonic sensor outputs continuously. The six different types of subtests performed included tests on:

(1) Vibration effects caused by engine and generator;
(2) Linearity for each ultrasonic sensor;
(3) Measurement range;
(4) Sensor spot size;
(5) Resolution; and
(6) Sensor accuracy.

Test of Vibration Effects Caused by Engine and Generator

In its operating state, the ARAN unit's engine and generator provide air conditioning and electrical power to the unit. They may also cause vibration that results in errors in the readings of the ultrasonic sensors used in the rut depth subsystem. The purpose of this test was to determine the magnitude of this effect. Three testing conditions were used in which: (1) both the engine and generator were operating; (2) the generator alone was operating; and (3) both the engine and generator were turned off.

During the test, the readings shown on the screen were continuously monitored and the maximum changes in the readings were recorded by the research staff. The follows results were obtained:

Condition 1: **Both engine and generator running.** Maximum vibration magnitude of the readings was ±1 unit, or ± 0.1 inch.

Condition 2: **Generator running, but engine turned off.** Maximum vibration magnitude of the readings was ±1 unit, or ±0.1 inch.

Condition 3: **Both engine and generator turned off (outside electricity was used).** Maximum vibration magnitude of the readings was, again, ±1 unit, or ± 0.1 inch.

Vibrations from only the engine running were not tested, but these were assumed to be weaker than condition one, and therefore less than ±1 unit or ± 0.1 inch.

From these results it can be concluded that the vibrations caused by the engine and generator in a static condition do not significantly affect the readings of the rut depth sensors.

Linearity Test for Each Ultrasonic Sensor

Linearity is very important in a measuring system such as the rut depth subsystem. The recorded changes in distance between the ultrasonic sensor and the pavement surface directly below the sensor should be linearly or proportionally measured by the subsystem. The linearity not only depends on the quality of the ultrasonic sensors, but also on the measuring path of the subsystem, which includes the transducers, interfaces, etc. However, under normal conditions it is impossible to test the linearity of each specific aspect of the measuring path. Of greater interest, therefore, is the combined linearity of the total hardware.

In this test, a linear ruler was used as a standard reference measurement. The data from the linearity test are shown in Table 5.1 (see page 36), where the linearity of each sensor can be graphically checked. For example, the linear characteristics of the ultrasonic sensors #4 and #9 are shown graphically in Figs 5.1 and 5.2. From these figures, it can be concluded that the linearities of the two sensors are consistent, insofar as the points are distributed along a straight line. The linearities of the other sensors were checked in the same way. Table 5.1 and Figs 5.1 and 5.2 show a y-intercept for each sensor; an explanation for this might be that the standard measurement indicates the distance between the pavement surface and the surface of the sensor. But the sensor surface might not be the reference surface within the equipment software. In this case, if the sensor surface is taken as the reference surface, there should exist an approximately constant difference (y-intercept) between the readings of the subsystem and the readings of the standard measurement (ruler).

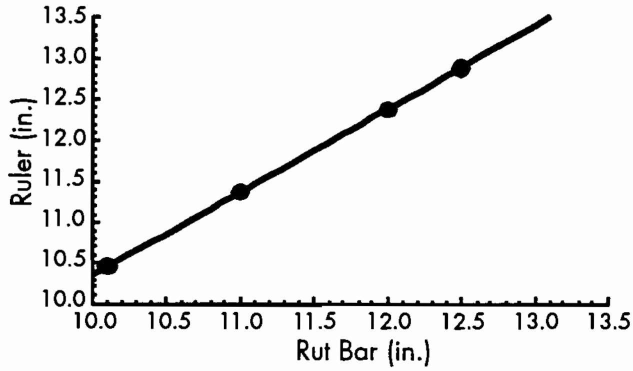


Figure 5.1 Linearity test of sensor #4

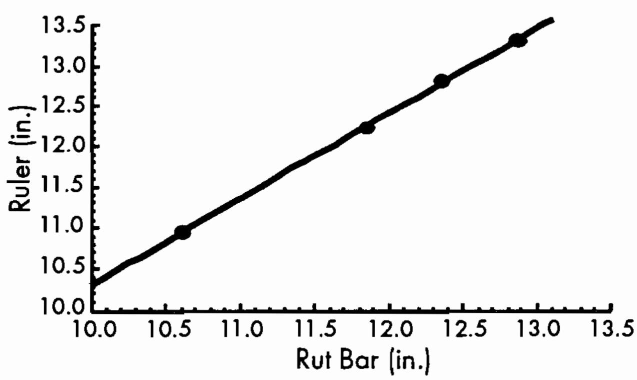


Figure 5.2 Linearity test of sensor #9

Neither the absolute value of each sensor reading nor the constant difference is important for the rut depth or transverse profile output; only the values relative to the reference level are important. Therefore, it is unnecessary to identify the reference surface of each sensor.

Measurement Range Test

This test was relatively simple: The distance between the pavement surface and the sensor face was adjusted until a minimum reading and a maximum reading were found. The test results are as follows:

Minimum reading of the subsystem: 10.0 inches

Maximum reading of the subsystem: 20.0 inches

Consequently, the depth of field (or measurement range) of the sensors is 10.0 inches.

Sensor Spot Size Test

The beam projection area of an ultrasonic sensor on the pavement surface is defined as the sensor spot size. A large spot size would make the rut depth subsystem insensitive to narrow rutting. The sensor spot size, consequently, is important to the operation of the subsystem and to the analysis of the measured data.

Because the sensor face is round, it is reasonable to assume that the sensor spot shape is also round. In this simple test (shown in Fig 5.3 a) (see page 37), a 1-inch thick plate was moved from each of four directions toward the center of the sensor spot. Any change in the reading of the corresponding sensor meant the plate had touched the side of the sensor spot from the direction of the plate movement. Accordingly, a mark was made on the pavement surface at that point. This procedure was repeated for all four directions, and the sensor spot size was then estimated from the pavement markings as shown in Fig 5.3 (b). The diameter of the sensor spot size was estimated to be 3.5 inches, at a distance of 13.5 inches between pavement and sensor surface.

Resolution Test

Many factors affect the static resolution of the rut-depth measuring subsystem. Some of the factors are: (1) sensor resolution; (2) A/D converter resolution; (3) vehicle body vibration; and (4) hardware quality. It is not necessary to evaluate the resolution for each factor—only the summary resolution.

Sensors #4, 7, and 10 were chosen for testing. Thin metal plates (0.0556-inches thick, on average,

Table 5.1 Static test data for linearity and accuracy tests

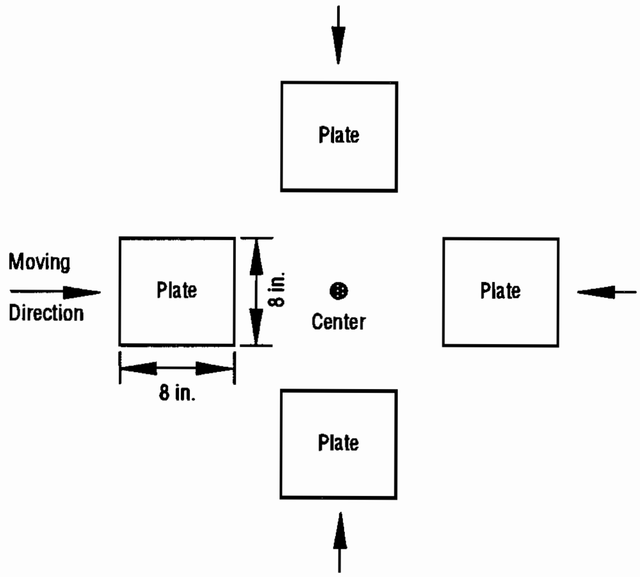
	Sensor #	2	3	4	5	6	7	8	9	10	11	12
1st Reading (in.)	ARAN	12.5	12.4	12.5	12.4	12.4	12.6	12.7	12.8	13.0	13.2	13.3
	Reference	13.06	12.94	12.88	12.88	12.88	13.06	13.13	13.25	13.44	13.56	13.75
	Difference	0.56	0.54	0.38	0.48	0.48	0.46	0.43	0.45	0.44	0.36	0.45
2nd Reading (in.)	ARAN	12.0	11.9	12.0	11.9	11.9	12.1	12.2	12.3	12.6	12.7	12.9
	Reference	12.63	12.44	12.38	12.38	12.38	12.56	12.63	12.75	12.94	13.13	13.31
	Difference	0.63	0.54	0.38	0.48	0.48	0.46	0.43	0.45	0.34	0.41	0.41
3rd Reading (in.)	ARAN	11.1	11.0	11.0	11.0	10.9	10.7	11.7	11.8	12.0	11.7	12.2
	Reference	11.50	11.38	11.38	11.31	11.25	11.06	12.06	12.19	12.31	12.13	12.56
	Difference	0.40	0.38	0.38	0.31	0.35	0.36	0.36	0.39	0.31	0.43	0.36
4th Reading (in.)	ARAN	10.1	10.1	10.1	10.1	10.0	10.2	10.3	10.6	10.1	10.3	11.6
	Reference	10.50	10.38	10.44	10.38	10.38	10.50	10.63	10.94	10.31	10.69	12.06
	Difference	0.40	0.28	0.34	0.28	0.38	0.30	0.33	0.34	0.21	0.39	0.40
Average Difference (in.)		0.50	0.44	0.37	0.39	0.42	0.40	0.39	0.41	0.33	0.40	0.41

as measured by a micrometer with a precision of 1/1000th of an inch) were used to change the distance between the pavement surface and the sensor surface. Before the plates were placed below the sensors, the readings for sensors #4, 7, and 10 were reported as 12.5 inches, 12.6 inches, and 13.0 inches, respectively (at state 1), and 10.7 inches, 10.7 inches, and 11.0 inches, respectively (at state 2). When only one thin metal plate was put below these sensors, the readings did not change. With an additional metal plate, however, all readings changed 1 unit, or 0.1 inch. The total thickness of the two plates was 0.0556 plus 0.0556≈0.112 inches. Therefore, it can be concluded that the static resolution of the subsystem is approximately 0.1 inch.

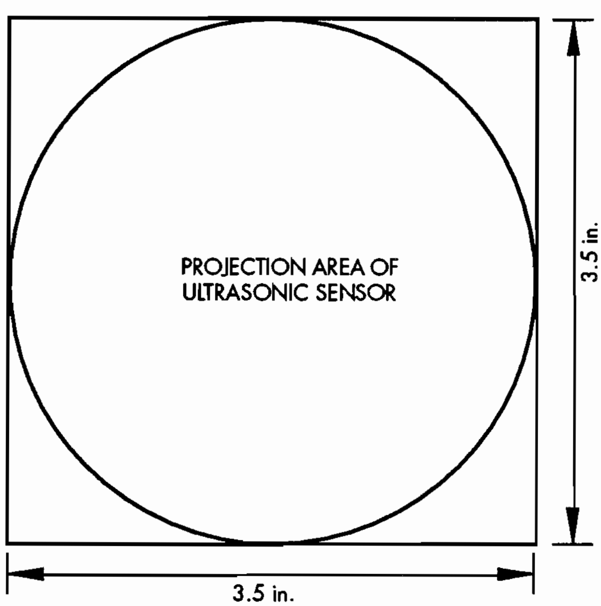
Accuracy Test

Standard measurements were used to determine the measurement accuracy of the individual measuring path. The data measured for the linearity test, shown in Table 5.1, can also be used as an accuracy test. As discussed before, for each sensor there exists a constant difference between the readings of the subsystem and the readings of standard measurement. However, the subsystem only measures the relative transverse profiles, so the constant difference can be neglected. Now the following accuracy index (AI) is defined:

$$AI = Max. \{ \text{Difference at } i^{th} \text{ reading - Average Difference}, \quad i = 1, 2, \dots, 4 \} \qquad (5.1)$$



(a) Sensor spot size test procedure



(b) Approximate sensor spot size

Figure 5.3 Sensor spot size test

By this definition and the data shown in Table 5.1, the accuracy data can be calculated and presented in Table 5.2 (see page 38). From this table, it is known that the maximum accuracy index, AI, is 0.16 inches, and the average accuracy index is 0.08 inches. As presented before, the static resolution of this subsystem is 0.1 inch. Thus, the static accuracy of this subsystem is adequate for the subsystem resolution.

DYNAMIC PERFORMANCE TEST

Background

The dynamic response characteristics of the rut depth subsystem may differ significantly from the static performance of the subsystem for the following reasons:

(1) Under normal operating conditions, pavement surface roughness, rutting, and other distress can cause the ARAN unit's wheels to bounce off the pavement surface, especially at high speeds and/or on rough pavement. The level position of the rut bar might then change from its reference position. This change due to wheel bounce or to the ARAN's rotation is the main source of measurement error for measuring transverse profile or rutting of pavements. The quality and condition of the ARAN's suspension system at any time affects this error. A stable suspension system reduces this error.

(2) Electrically, the frequency bands of the ultrasonic sensors are limited. High frequency signals could be deformed because of the limited band width of the system.

Two methods of dynamic testing could be adopted to evaluate the dynamic characteristics of the subsystem. In one method, an artificial pavement section designed to check the dynamic measurement accuracy is used for the evaluation of a road measuring system (Ref 40). Since the input to the road measuring system is known, it is easy to evaluate the dynamic measurement accuracy by comparing the measured data with the design data of the artificial pavement.

The other method, called comparison testing, requires an additional standard instrument as a reference for the dynamic comparison. It is easy and economical to use this method with respect to the first method, but using this method cannot evaluate the dynamic measurement accuracy unless the standard instrument has a very good dynamic measurement accuracy and, moreover, is officially considered a standard instrument for measurement specifications. In the area of the evaluation of road measuring systems, correlation analysis is based on this kind of method.

Table 5.2 Static accuracy index data of the rut depth subsystem

Sensor #	2	3	4	5	6	7	8	9	10	11	12
Difference at 1st Reading (in.)	0.56	0.54	0.38	0.48	0.48	0.46	0.43	0.45	0.44	0.36	0.45
Difference at 2nd Reading (in.)	0.63	0.54	0.38	0.48	0.48	0.46	0.43	0.45	0.34	0.41	0.41
Difference at 3rd Reading (in.)	0.40	0.38	0.38	0.31	0.35	0.36	0.36	0.39	0.31	0.43	0.36
Difference at 4th Reading (in.)	0.40	0.28	0.34	0.28	0.38	0.30	0.33	0.34	0.21	0.39	0.40
Average Difference (in.)	0.50	0.44	0.37	0.39	0.42	0.40	0.39	0.41	0.33	0.40	0.41
Accuracy Index (AI)	0.13	0.16	0.03	0.11	0.07	0.10	0.06	0.07	0.12	0.06	0.05
Average Accuracy Index (AI = 0.08 in.)											

The two methods discussed above were carefully considered and discussed at several project meetings that included the SDHPT technical coordinator and project research personnel. At first, the method to evaluate the dynamic performance of the subsystem using an artificial pavement was proposed. But because making artificial profiles would be very expensive and time consuming, and because of limited research funds, it was not possible to design a long artificial pavement with known transverse profiles. The comparison test was therefore adopted.

As mentioned before, the comparison test requires a standard instrument as a reference to be compared with the outputs of the rut depth subsystem for a given test section. A 6-foot long straightedge and the Face Dipstick were discussed as possible references, with the Face Dipstick finally selected as the standard instrument for comparison because it has good measurement accuracy and is easy to use in the field (Ref 41).

The Face Dipstick as a Reference

The Face Dipstick, shown in Fig 5.4, includes a sensor which measures the angle between the vertical gravity line and vertical instrument line. Mathematically, this angle is also equal to the angle between the gravity level line and the instrument level line. Since the distance between the two feet of the instrument is known to be 12 inches, the vertical elevation difference between the two feet can be derived from the measured angle. Theoretically, this type of the instrument can measure the pavement surface profiles across the whole wavelength spectrum.

The Dipstick, classified as a Type I instrument according to the classification of road measuring systems, can measure longitudinal and transverse pavement profiles. The direct output of the instrument is the vertical elevation difference between the two feet. The elevation at each point is the summation of the current reading plus the previous vertical elevation. The Face Dipstick has been technically evaluated by the Center for Transportation Research, and its reliability is good (Ref 41). In this comparison test, the Dipstick was used to measure the three-dimensional profile of the test section. An averaged transverse profile was obtained from the three-dimensional profile to compare with the one measured by the rut depth subsystem.

Test Plan and Procedure

ATS25 was chosen as the test section for this comparison because it has significant rutting on the outside wheelpath. In the test plan shown in Fig 5.5, the dashed lines indicate the measurement tracks of the Dipstick. Data from the Dipstick included (1) individual transverse profiles spaced 1 foot apart, which was then used to create a three-dimensional pavement profile, and (2) the mean transverse profile, called summarized transverse profile, from the 300-foot-length test section. The ARAN unit operator started the data acquisition as close to the marked start line as possible. The results were (1) the mean transverse profile

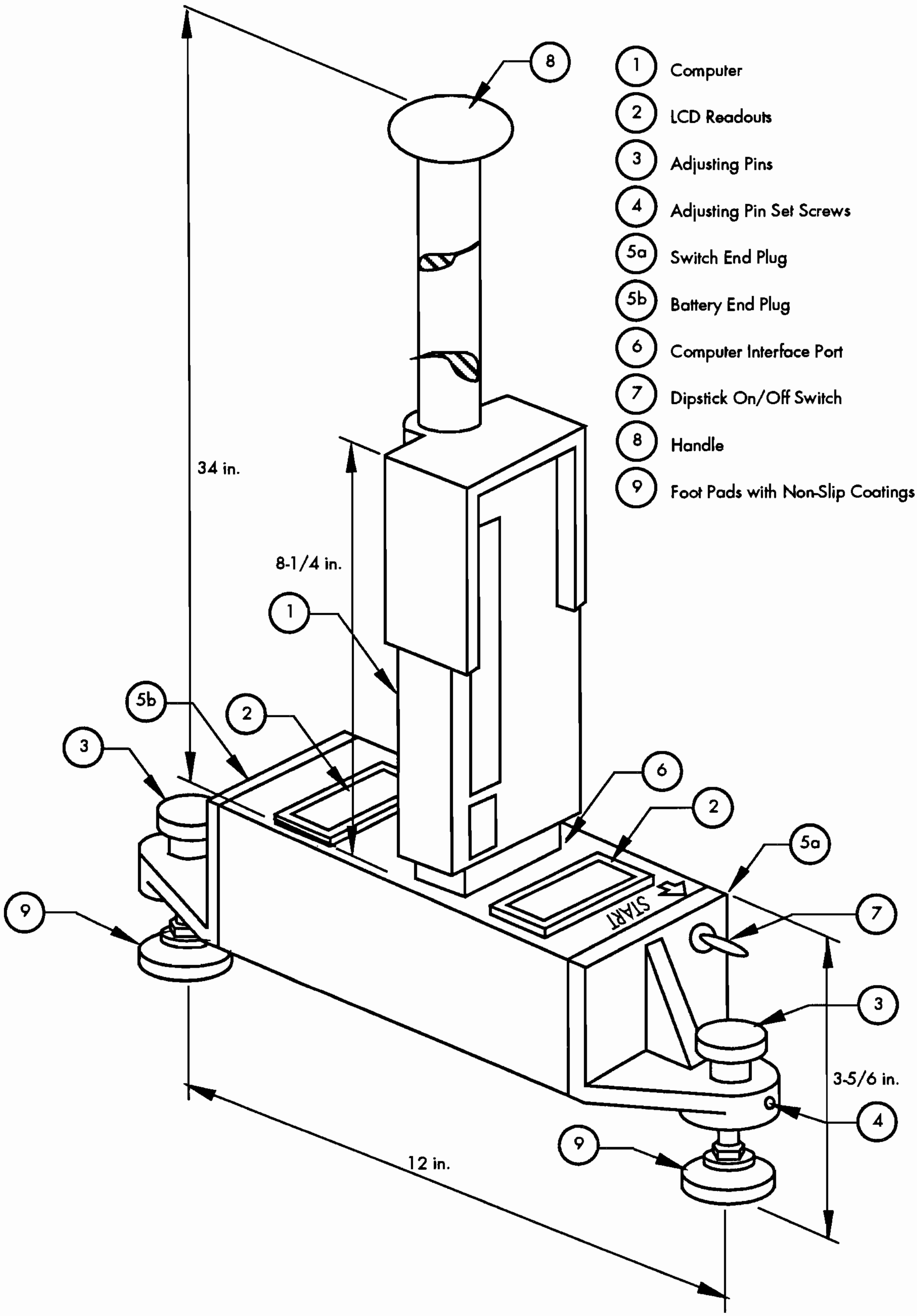


Figure 5.4 Schematic view of the Face Dipstick

(called summarized transverse profile) measured from the 300-foot-length test section at normal operating state, (2) rut depth index data calculated from the summarized transverse profile, and (3) a three-dimensional pavement profile spaced at 1-foot intervals in the transverse and longitudinal directions measured in the diagnostic working state.

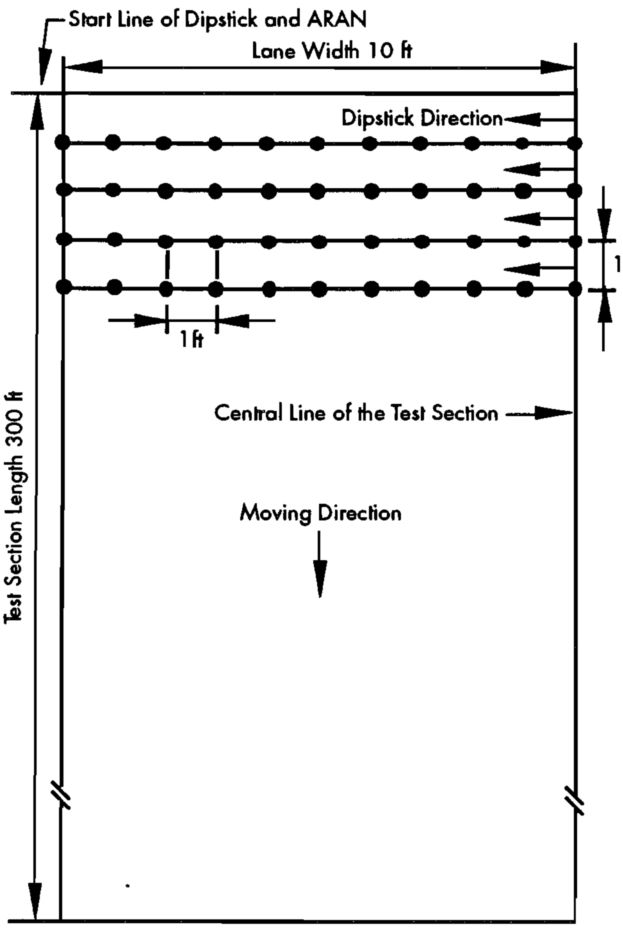


Figure 5.5 Test plan of dynamic performance test of rut depth subsystem

A 100-foot steel tape was used to lay out the center line and the outside edge of the section as shown in Fig 5.5. The entire marking process took four people approximately 3 hours to complete. The inside wheelpath was marked so that the driver would follow the same wheelpath during repeat runs.

Results from the Comparison Between Summarized Transverse Profiles Measured By Face Dipstick and The Rut Depth Subsystem

(1) ***ARAN Data***. Five repeat runs were made at 30 mph with a report interval of 0.005-mile. The direct outputs of the subsystem from the repeated runs were five summarized transverse profiles statistically representing the characteristics of the transverse profiles and rutting of the test section. The five summarized transverse profiles were then averaged to eliminate the deviations in each individual run. Table 5.3 shows the summarized output from the five runs. Each reading shown in the table represents the distance (Y_i) between the associated ultrasonic sensor and the pavement surface directly below the sensor as shown in Fig 5.6. The summarized transverse profile data was transferred into a discrete transverse profile (W_i) using the mean value of the profile as the reference by equation (5.2).

$$W(\text{ARAN})_i = -(Y_i - Y) \qquad (5.2)$$

where

Y_i = the i^{th} reading shown in Table 5.3 (i=0, 1, 2, ..., 10),
Y = the mean value of Y_i (i=0, 1, 2, ..., 10), and
$W(\text{ARAN})_i$ = the i^{th} reading of the discrete transverse profile (i=0, 1, 2, ..., 10).

Table 5.4 shows the discrete transverse profile measured by the rut depth subsystem.

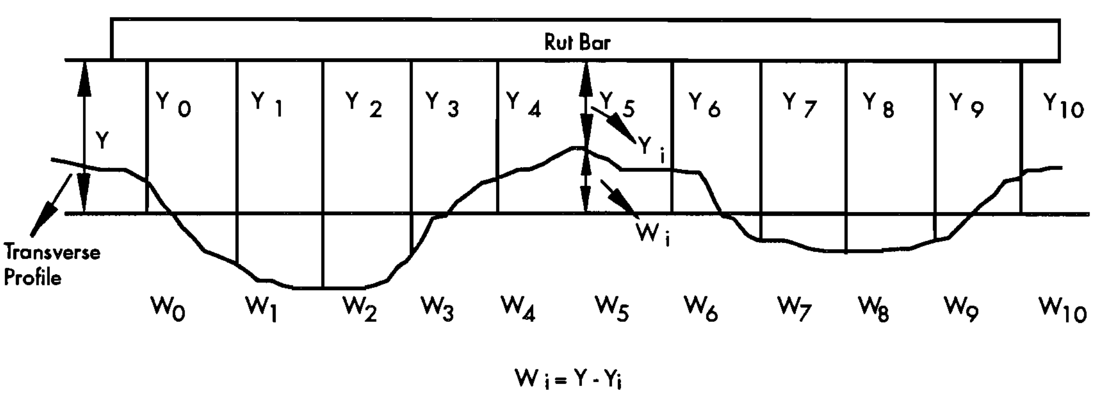


Figure 5.6 Geometric measurement of transverse profile

Table 5.3 **Summarized transverse profile measured by the rut depth subsystem from five repeated runs**

From Inside Wheelpath (Central Line) to Outside Wheelpath											
Distance (ft)	0	1	2	3	4	5	6	7	8	9	10
Readings (in.), Yi	15.18	14.94	14.56	14.26	14.10	13.98	14.04	14.56	14.88	14.80	14.14

Table 5.4 **Discrete transverse profile measured by the rut depth subsystem**

From Inside Wheelpath (Central Line) to Outside Wheelpath											
Distance (ft)	0	1	2	3	4	5	6	7	8	9	10
Readings (in.), Wi	–0.558	–0.313	0.023	0.321	0.452	0.537	0.483	0.005	–0.448	–0.484	–0.017

Table 5.5 **Summarized transverse profile measured by the Face Dipstick from 300 transverse profiles**

From Inside Wheelpath (Central Line) to Outside Wheelpath											
Distance (ft)	0	1	2	3	4	5	6	7	8	9	10
Readings (in.)	0.000	0.071	0.233	0.358	0.316	0.227	0.000	–0.652	–1.279	–1.489	–1.195

(2) ***Face Dipstick Data*** The Face Dipstick was used to measure the 300 transverse profiles constituting a three-dimensional pavement profile or grid along the test section spaced at 1-foot intervals. The profiles were averaged to produce a summarized transverse profile, statistically representing the characteristics of the transverse profiles or rutting on the test section. Table 5.5 shows the summarized transverse profile data.

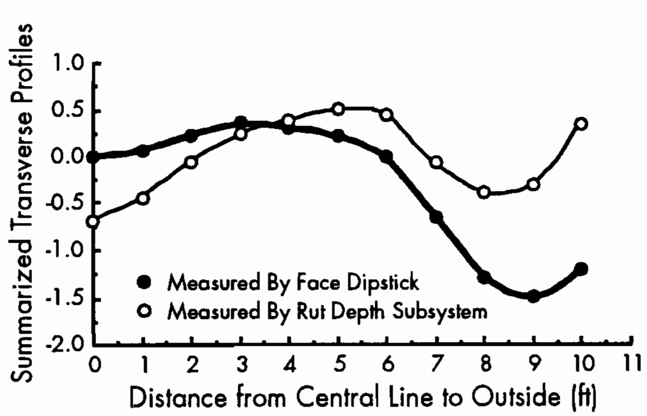


Figure 5.7 **Comparison of summarized transverse profiles measured by Face Dipstick and the rut depth subsystem**

Figure 5.7 shows the comparison between the summarized transverse profiles measured by the dipstick and by the rut depth subsystem. A significant difference between the two curves can be seen in this figure. This is reasonable because the dipstick uses the gravity horizontal level as the reference level, while the rut depth subsystem uses the rut bar as the reference level; the rut bar is not parallel to the gravity horizontal level under normal operational conditions. Correction for the difference can be made by using two first-order functions to fit the two transverse profiles. The resulting functions are used as the reference lines for the two corresponding transverse profiles, and are as follows.

Face Dipstick

$$W'(\text{dipstick})_i = 0.55773 - 0.17357\ i \qquad (5.3)$$

ARAN

$$W'(\text{ARAN})_i = -0.19318 + 3.8727 \times 10^{-2}\ i \qquad (5.4)$$

where $W'(\text{dipstick})_i$ and $W'(\text{ARAN})_i$ are the dependent variables of the curve-fittings for the curves from the dipstick and the rut depth subsystem, respectively, corresponding to the transverse distance variable i (ft). The variable i can also be considered as the sequence of the transverse profile readings. The corrected transverse profiles by the above first-order functions are called relative summarized transverse profiles, and are obtained by equations (5.5) and (5.6).

Face Dipstick

$$W_R(\text{dipstick})_i = W(\text{dipstick})_i - W'(\text{dipstick})_i \quad (i=0, 1, ..., 10) \qquad (5.5)$$

ARAN

$$W_R(\text{ARAN})_i = W(\text{ARAN})_i - W'(\text{ARAN})_i \quad (i=0, 1, ..., 10) \qquad (5.6)$$

where $W_R(\text{dipstick})_i$ = i^{th} point of the relative summarized transverse profile measured by the dipstick, and $W_R(\text{ARAN})_i$ = i^{th} point of the relative summarized transverse profile measured by the rut depth subsystem.

Figure 5.8 shows the first-order function curve fittings. The two stright lines are considered to be the references of correction for the difference. Figure 5.9 shows the comparison of the two relative summarized transverse profiles. It can be seen from these figures that the two profiles measured by the dipstick and the rut depth subsystem are similar. The rut depth subsystem has a statistically reliable dynamic measurement accuracy in this test section.

Evaluation of the Dynamic Performance Based on Two Rut Depth Indices

(1) ***Definition of Rut Depth Index.*** Figure 5.6 shows the geometric measurements of the transverse profile data from each ultrasonic sensor. Referring to that figure, two rut depth indices are defined as follows (NOTE: Researchers did not analyze HPI rut depth index software; the measurement from each sensor of the ARAN unit was used in the following equations to establish the index used):

$$R_1 = \frac{\frac{W_0 - 2W_2 + W_4}{2} + \frac{W_6 - 2W_8 + W_{10}}{2}}{2} \qquad (5.7)$$

and

$$R_2 = W_5 - \frac{W_2 + W_8}{2} \qquad (5.8)$$

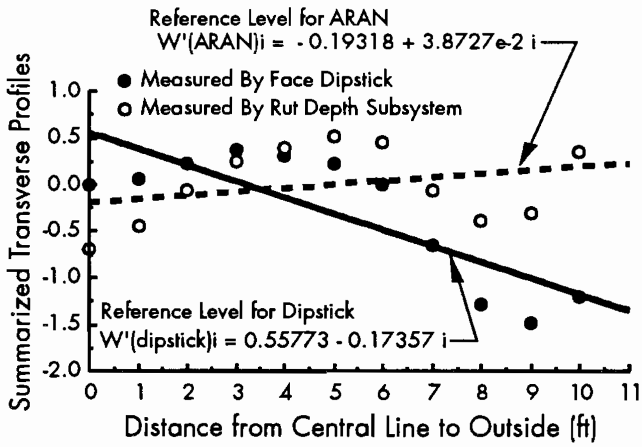


Figure 5.8 First-order curve fittings as reference levels

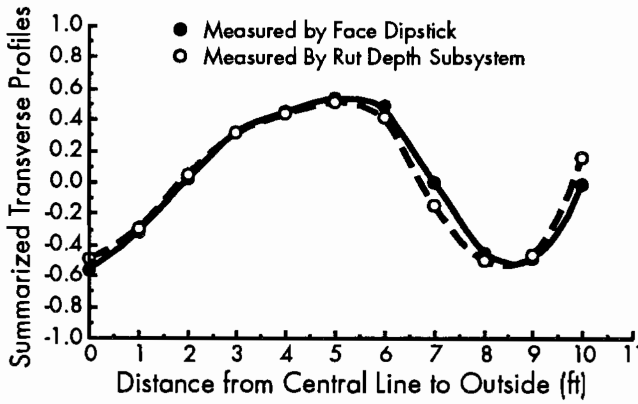


Figure 5.9 Comparison of relative transverse profiles measured by dipstick and the rut depth subsystem

The two indices have certain geometric meanings. R_1 indicates the average depth of left and right wheelpaths, and R_2 represents the difference between the elevation of the central line of the two wheelpaths and the average elevation of the two wheel paths.

(2) ***Evaluation.*** The data from ATS25 were used in the evaluation, with the dipstick serving as the standard reference. In order to obtain a common reference level for both the rut depth subsystem and dipstick, the procedure discussed in the last section to obtain relative transverse profiles was adopted. Table 5.6 presents the rut depth index data from the dynamic performance test. From this table, it can be seen that dynamic measurement accuracy is relatively good if the dipstick is used as the standard reference.

Comparison Between Dipstick and ARAN for Three-dimensional Profile

Two three-dimensional pavement profiles were measured by the dipstick and the rut depth

Table 5.6 Comparison of rut depth predictions by ARAN and dipstick

Rut Depth Index R	ARAN	Dipstick	Absolute Error
R_1 (in.)	.3550	.3033	.0518
R_2 (in.)	.8900	.9360	.0460

subsystem. The longitudinal sampling interval was 1 foot for each method. The minimum report interval or sampling interval of the rut depth subsystem at normal operating conditions is 0.005-mile; in order to sample transverse profiles at 1-foot longitudinal interval, the subsystem had to be operated in the diagnostic state, in which the readings of the ultrasonic sensors can be continuously monitored, but cannot be automatically recorded. It was necessary to stop the ARAN unit at each 1-foot distance interval to record manually the transverse profiles from the monitor. This method of measuring three-dimensional profiles is not practically feasible if no significant improvement of the data sampling software is obtained. However, as a qualitative evaluation or case study, the results from this comparison were useful.

Figure 5.10 (see page 44) shows the two three-dimensional pavement profiles of ATS25 measured by the dipstick and the rut depth subsystem. The elevations of the left edges of the two three-dimensional profiles are forced to a reference level of zero so that the two profiles can be compared.

It can be seen from Fig 5.10 that the two three-dimensional pavement profiles have certain similarities. Although this similarity does not assure the dynamic performance of the subsystem (because the subsystem was operated in the diagnostic state), it does provide some qualitative evaluation of the rut depth subsystem.

OPERATIONAL TEST

The operational test of the rut depth subsystem mainly addresses the subsystem's repeatability and the effect of the report interval and operational speed on the output of this subsystem. Correct understanding and proper selection of these operating conditions are necessary for obtaining reliable pavement condition data. The main objective of the operational performance test was to determine if the outputs of the rut depth subsystem working at different operating conditions (e.g., different report interval and operational speeds) are significantly different. If the outputs at different operating conditions are significantly different, then proper operating conditions should be specified. If they are not, then the selection of operating conditions would be more flexible.

In this evaluation, readings from each individual ultrasonic sensor were examined in terms of repeatability and influence of report interval and operational speed. The operational performance reflected in the readings from the sensors is essential, as the outputs of the rut depth subsystem are based on the readings. The rut depth index, R_1, defined by equation (5.7) was also used to examine operational performance.

REPEATABILITY TEST

Possible Factors Affecting Repeatability

Systematic repeatability may be affected by the following factors:

(1) If the subsystem's electric hardware is relatively sensitive to changes in temperature and humidity, then the outputs of the subsystem collected from different runs on a given road might be different. For example, as the temperature changes, the gains of the signal amplifiers and the frequency pass bands of the ultrasonic sensors might change. And while HPI includes corrections for temperature and humidity, the effectiveness of those corrections is unknown in this test.

(2) The mechanical characteristics (tire pressure, spring constants, etc.) of the suspension system of the ARAN unit are not strictly stable over time. If the differences of these characteristics are significant over time, then subsystem output may be significantly different.

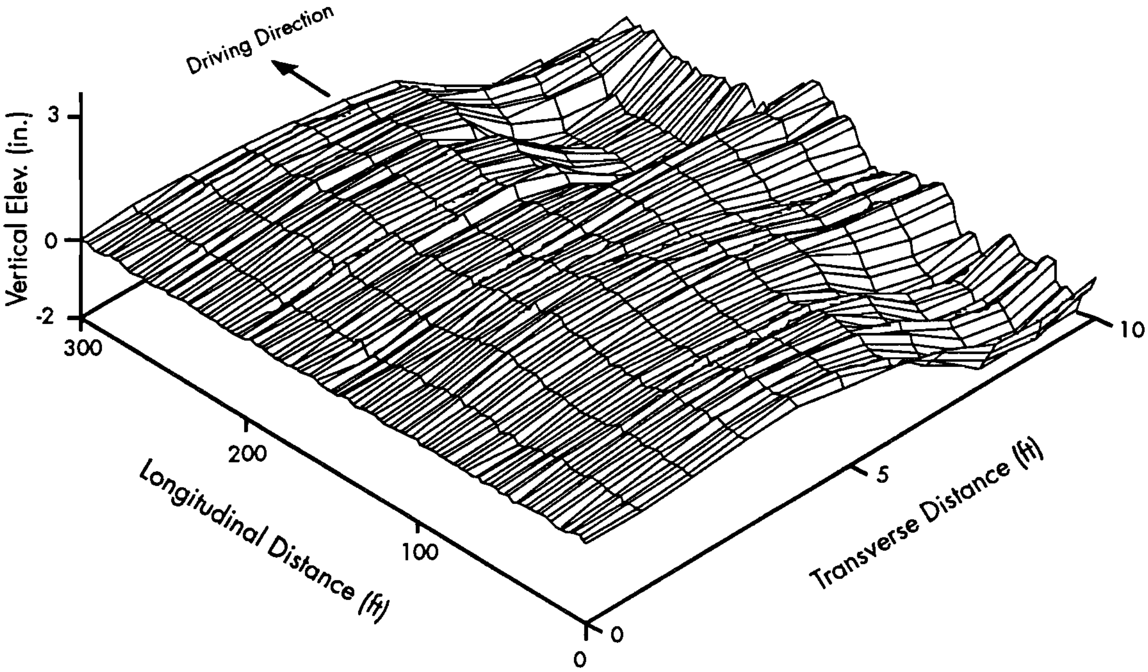
The operational repeatability may be affected by the following factors:

(1) It is impossible for the driver to steer the ARAN unit along the same wheelpath at the same speed on different runs. These differences could result in different outputs from the rut depth subsystem.

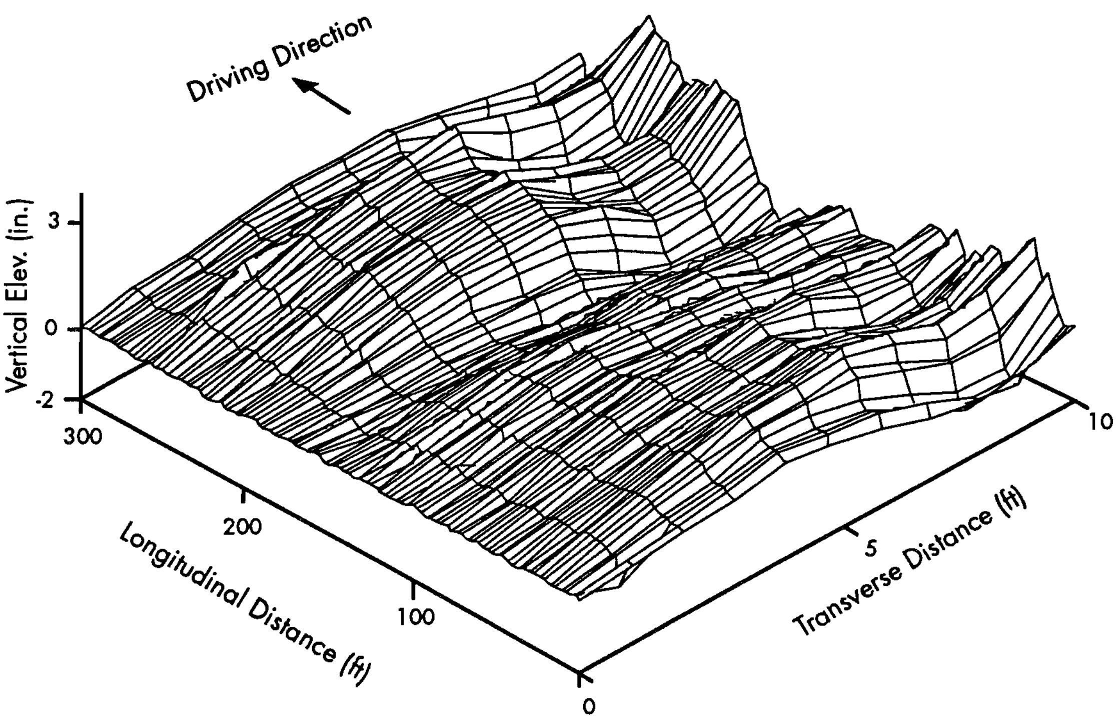
(2) It is impossible for the ARAN operator to sample data starting at the exact same location during repeat runs on the same section. This would result in differences in the outputs.

Field Test and Data Collection

The field test was conducted in June of 1989 at Austin Test Section ATS01. Five repeat runs were made at 50 mph. The chosen report intervals were 0.005, 0.01, 0.05, and 0.1 mile. Table 5.7 shows the summarized transverse profile data from sensor #4 to sensor #9, and Table 5.8 shows the summarized rut depth index data R_1 from ATS01.



(a) Three-dimensional profile measured by dipstick



(b) Three-dimensional profile measured by ARAN

Figure 5.10 Three-dimensional profiles at ATS25

Table 5.7 Transverse profile data (0.1 inch) from ultrasonic sensors measured at 50 mph

Sensor	Run	Report Interval (mile) .005	.01	.05	.1
Sensor #4	1	156	156	160	150
	2	157	157	156	151
	3	156	157	156	155
	4	156	157	155	152
	5	156	157	153	150
Sensor #5	1	154	154	158	148
	2	154	155	154	149
	3	154	154	153	152
	4	154	155	152	150
	5	154	154	151	148
Sensor #6	1	153	152	157	146
	2	153	154	153	147
	3	152	153	151	151
	4	152	154	151	149
	5	152	154	149	147
Sensor #7	1	154	154	157	147
	2	155	155	155	149
	3	154	155	153	151
	4	154	155	153	150
	5	154	156	151	148
Sensor #8	1	156	156	160	150
	2	156	157	157	150
	3	156	156	155	153
	4	156	157	155	152
	5	155	158	153	150
Sensor #9	1	158	158	162	152
	2	158	159	159	151
	3	158	158	156	155
	4	158	159	157	153
	5	158	159	154	151

Table 5.8 Rut depth index R_1 for the repeatability test

		R_1			
Report Interval RI (mile)		RI = 0.005	RI = 0.01	RI = 0.05	RI = 0.1
Run	1	1.009	1.265	0.722	0.177
	2	1.156	0.915	0.354	1.414
	3	1.184	1.262	0.658	1.591
	4	1.194	0.920	0.987	0.530
	5	1.122	1.024	0.948	0.884

TEST PRINCIPLE

The following test principles were used to evaluate the repeatability of the subsystem.

(1) Evaluation Based on Transverse Profile Data. In order to check the repeatability, a repeatability index RMSE (Root Mean Square Error) was defined by equation (5.9).

$$RMSE_j = \sqrt{\frac{1}{n}\sum_{i=1}^{N}\left(Y_{ij} - Y_j\right)^2} \tag{5.9}$$

where

N = the number of run (N=5);

$RMSE_j$ = root mean square error of the readings from sensor #j from repeat runs;

Y_{ij} = the reading (tenths of inches) of the sensor #j at i^{th} run, and

Y_j = mean value of Y_{ij} (i = 1, 2, ..., N).

Conceptually, the smaller the RMSE, the better the repeatability.

(2) Evaluation Based on Rut Depth Data R_1. An index, called relative root mean square error (RRMSE), was defined to check the repeatability of the rut depth subsystem based on the rut depth index R_1:

$$RRMSE = \frac{1}{\bar{R}_1}\sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(R_{1i} - \bar{R}_1\right)^2} \tag{5.10}$$

where

N = the number of run (N=5),

R_{1i} = rut depth index, R_1, at i^{th} run, and

$\bar{R}_1$ = the mean value of R_{1i} (i=1, 2, ..., N).

Test Results

Table 5.9 shows the results of RMSE calculated from transverse profile data. Table 5.10 shows the results of RRSME for the repeatability evaluation using the rut depth data. From Tables 5.9 and 5.10, it can be concluded that the repeatability at report intervals 0.005 and 0.01 mile is much better than that at report intervals 0.05 and 0.1 mile. This can be explained as follows.

According to Ref 32, the report interval of the rut depth subsystem is equal to the data sampling interval. Data sampling theories show that large sampling intervals not only result in detailed information being lost, they also produce poor repeatability. Therefore, the rut depth subsystem shows good repeatability when a small report interval is selected, and poor repeatability when a large report interval is chosen.

Statistical Analysis of the Impacts of the Report Interval

Sampling interval of the rut depth subsystem is equal to the selected data report interval. That is, the subsystem samples the transverse profile data from the ultrasonic sensors at every selected report interval, and all the sampled data are saved in the computer system. When the subsystem is operated, the report interval must be set before the subsystem begins to collect field data. The most frequently used report intervals are 0.005, 0.01, 0.05 and 0.1 mile, as was discussed previously. The smaller the report interval, the more memory space the computer in the ARAN unit needs to store the results, and the more often the operator has to save the results to disk. This situation increases the chance for losses when the computer is saving data. On the other hand, if the report interval is too large, detailed information regarding transverse profile and rutting of the pavement section cannot be viewed in the output listing. The objective of this statistical analysis was to examine the impact of the report interval on subsystem output.

Table 5.9 Analysis results of repeatability

		RMSE					
	Sensor #	4	5	6	7	8	9
Report Interval (mile)	0.005	.4000	.0000	.4899	.4000	.4000	.0000
	0.01	.4000	.4899	.8000	.6325	.7483	.4899
	0.05	2.2804	2.4166	2.7129	2.0396	2.3664	2.7276
	0.1	1.8547	1.4967	1.7889	1.4142	1.2649	1.4967

Table 5.10 Analysis results of repeatability

		RRMSE
Report Interval (mile)	0.005	0.05907
	0.01	0.14562
	0.05	0.31120
	0.1	0.57564

Methodology Used to Conduct the Analysis

The basic principle for testing the effect of the report interval was to run the subsystem at different report intervals and statistically examine the difference in reported output at different report intervals for significance. If the impact of the report interval on the outputs of the subsystem is not significant, report interval can be ignored. In order to test the significance, two different statistical methods were used.

(1) Evaluation Using One-Way Analysis of Variance. One of the best methods for testing for significance is the one-way Analysis of Variance, called one-way ANOVA (Ref 37). Its basic concept can be simply described as follows.

In the statistical test, a statistical hypothesis, Ho, with given significance level a should be proposed. Then, according to a specified model, a statistical value, or F value, needs to be calculated. The statistical test used in the one-way ANOVA is called F-test. Two kinds of degrees of freedom (n_1 and n_2) should be given,

$$n_1 = n-1, \qquad n_2 = n \ (N-1)$$

where N is the number of runs made at each report interval, and n is the number of alternative report intervals. The criterion judging the hypothesis is denoted by $Fa(n_1, n_2)$, where n_1 and n_2 are the two degrees of freedom, and a is the significance level. The criterion, $Fa(n_1, n_2)$, can be checked from an F-distribution table, and if $F < Fa(n_1, n_2)$ then the statistical hypothesis Ho should be accepted; otherwise, Ho should be rejected. In the evaluation by one-way ANOVA, the transverse profile data were used to evaluate the impact of the report interval on the rut depth subsystem.

(2) Evaluation Using t-distribution Hypothesis Test Unlike ANOVA, the t-test compared pairs to determine if the mean value of rut depth from several runs is significantly influenced by report interval. The details about the mathematical derivation of the t-distribution hypothesis test can be found in Ref 37. The results for the test will be presented later.

Field Test and Data Collection

The field test for impact of report interval was conducted in June of 1989 at the Austin Test Section ATS01. Five repeat runs were made for each selected report interval. In order to run worst-case tests, an operational speed of 50 mph was selected, since high speed could result in significant vibration of the ARAN unit.

Test Results

Results regarding the impact of the report interval on the rut depth subsystem are discussed in two aspects.

(1) Evaluation Using One-Way Analysis of Variance. One-way ANOVA was used to test if the report interval had significant impact on the transverse profile data. The hypothesis was defined as:

Ho: Report interval has no significant impact on transverse profile data from the rut depth subsystem. A significance level of a=0.05 (95 percent confidence) was chosen.

Two groups of alternative report intervals were considered in this test. The first group included four report intervals which were 0.005, 0.01, 0.05, and 0.1 mile, and the second group included three alternative report intervals, 0.005, 0.01, and 0.05 mile.

(a) Four Alternative Report Intervals.

The alternative report intervals were 0.005, 0.01, 0.05, and 0.1 mile (n=4) with five runs for each interval (N=5). According to the one-way ANOVA, the F-test degrees of freedom should be

$$n_1 = n-1 = 3 \qquad n_2 = n \times (N-1) = 16$$

If a significance level a = 0.05 is chosen, then the test F value obtained from a F-Distribution table is

$$Fa(n_1, n_2) = 3.24$$

If the calculated F value (from ANOVA) is larger than the test value of 3.24, then the hypothesis Ho should be rejected; otherwise Ho cannot be rejected.

The transverse profile data used for the repeatability test, shown in Table 5.7, can be also used for the evaluation. Table 5.11 shows the results of one-way ANOVA based on the data shown in Table 5.7. According to the results, for every sensor the hypothesis Ho should be rejected.

(b) Three Alternative Report Intervals.

The alternative report intervals were 0.005, 0.01, and 0.05 mile (n=3) with five runs for each interval (N=5). Therefore, the F-test degrees are

$$n_1 = (n-1) = 2 \quad n_2 = n \times (N-1) = 12$$

The significance level is a = 0.05. Then from a F-distribution table, the test F value is

$$Fa(n_1, n_2) = 3.89$$

Table 5.12 shows the results of ANOVA for the three report intervals. Using the table, Ho should be accepted for each sensor, meaning that

Table 5.11 Results of one-way ANOVA for the significance of report interval. Report interval = 0.005, 0.01, 0.05, and 0.1 mile. $F_a (n_1, n_2) = 3.24$

Sensor #	4	5	6	7	8	9
F Value	10.205	10.370	8.003	17.528	14.038	13.212
Ho	$F > F\alpha (n_1, n_2)$ REJECT Ho	$F > F\alpha (n_1, n_2)$ REJECT Ho	$F > F\alpha (n_1, n_2)$ REJECT Ho	$F > F\alpha (n_1, n_2)$ REJECT Ho	$F > F\alpha (n_1, n_2)$ REJECT Ho	$F > F\alpha (n_1, n_2)$ REJECT Ho

Table 5.12 Results of one-way ANOVA for the significance of report interval. Report interval = 0.005, 0.01, and 0.05 mile. $F_a (n_1, n_2) = 3.49$

Sensor #	4	5	6	7	8	9
F Value	.318	.314	.605	.954	.534	.395
Ho	$F > F\alpha (n_1, n_2)$ ACCEPT Ho	$F > F\alpha (n_1, n_2)$ ACCEPT Ho	$F > F\alpha (n_1, n_2)$ ACCEPT Ho	$F > F\alpha (n_1, n_2)$ ACCEPT Ho	$F > F\alpha (n_1, n_2)$ ACCEPT Ho	$F > F\alpha (n_1, n_2)$ ACCEPT Ho

the factor of report interval does not have significant impact on the transverse profile data if only the report intervals 0.005, 0.01, and 0.05 mile are considered.

(2) Evaluation Using t-distribution Hypothesis Test. The t - distribution statistical hypothesis was used to test if the two different report intervals resulted in statistically different rut depth indices. The hypothesis Ho was defined as:

Ho: Two different report intervals result in statistically equivalent rut depth indices, R_1, with a significance level a = 0.05.

Since the rut depth subsystem shows very poor repeatability when the report interval 0.1 mile is used, this evaluation considered only the report intervals 0.005, 0.01, and 0.05 mile. The comparison was conducted for the following pairs of report intervals:

Pair 1: Report Interval 0.005 and 0.01 mile;
Pair 2: Report Interval 0.005 and 0.05 mile; and
Pair 3: Report Interval 0.01 and 0.05 mile.

If the hypothesis Ho is accepted (for each pair of report intervals), then the two report intervals do not have significantly different system impacts.

The data for rut depth index R_1 shown in Table 5.8 were also used for the report interval impact test. Table 5.13 shows the results of the t-distribution statistical hypothesis test. For the rut depth index R_1, it was found that each pair of report intervals is not significantly different because the test shows that Ho for any pair of report intervals should be accepted. The analysis based on the rut depth index (R_1) resulted in the same conclusion as that based on the transverse profile data (though different statistical hypotheses were used).

Effect of Operational Speed

The measurement principle of the rut depth subsystem is simplified if one discounts the ARAN

Table 5.13 The hypothesis tests of the impact of the report interval on the rut depth index R_1

<table>
<tr><th colspan="2"></th><th colspan="3">Report Interval</th></tr>
<tr><th colspan="2"></th><th>0.005 mile</th><th>0.01 mile</th><th>0.05 mile</th></tr>
<tr><th rowspan="3">Report Interval</th><th>0.005 mile</th><td>X</td><td>Accept Ho</td><td>Accept Ho</td></tr>
<tr><th>0.01 mile</th><td>Accept Ho</td><td>X</td><td>Accept Ho</td></tr>
<tr><th>0.05 mile</th><td>Accept Ho</td><td>Accept Ho</td><td>X</td></tr>
</table>

unit's suspension system response to pavement surface conditions and operational speed. In principle, the operational speed factor does not significantly affect the resulting outputs of the rut depth subsystem (since this subsystem only measures the distances between the surface of the ultrasonic sensor and pavement surface directly below the sensor). However, practical experience has indicated that the outputs of the subsystem are somewhat different at different operational speeds. This can be explained as follows:

(1) During the operation of the ARAN unit, vibration caused by pavement surface conditions and the operational speed affect the readings of the ultrasonic sensors, and vibrations become more significant as speed increases and/or pavement conditions become worse.

(2) As the operational speed increases, the time interval between two samplings decreases. Since data processing (including calculation and data storage) has higher priority over data sampling, the faster the ARAN unit runs, the more likely it is for the subsystem to lose important data points. Consequently, the operational speed might affect the outputs of the subsystem.

Research concerning the operational speed impact needs to be conducted so that field data acquisition and data analysis can be accomplished. Conclusions resulting from the research would be valuable for the evaluation of pavement transverse profile and rutting.

Test Method

The purpose of this test was to determine if operational speed significantly affects the subsystem outputs. For a given test section, different operational speeds were selected and the difference caused by them was statistically examined. The ANOVA methodology was used in this evaluation.

Field Test and Data Collection

Field tests were conducted in June of 1989 on Austin Test section ATS01. Operational speeds were 30 mph, 40 mph, and 50 mph, with four repeat runs for each speed. According to the results of the repeatability evaluation, the smaller the report interval, the better the repeatability. In order to evaluate the impact of operational speed correctly, report intervals of 0.005 and 0.01 mile were applied.

Test Results

Tables 5.14 and 5.15 (see page 50) show the transverse profile data collected from ATS01 at report intervals 0.005 and 0.01 mile, respectively, and Table 5.16 shows the data of the rut depth index R_1 at a report interval of 0.005 mile only. Since there were four runs and three different speeds, the degrees of freedom for ANOVA were:

$$n_1 = n-1 = 2 \qquad n_2 = n \times (N-1) = 12$$

For significance level a = 0.05, the statistical F value from a F distribution table was

$$Fa^{(n_1,\, n_2)} = 4.26$$

In this evaluation, the proposed statistical hypothesis Ho is

Ho: The factor of the operational speed has no statistically significant impact on the rut depth subsystem at a significance level a = 0.05.

The evaluation results, based on transverse profile data and rut depth index, are presented in Tables 5.17 and 5.18 (see Page 51), respectively. It can be demonstrated from these tables that all calculated F values are smaller than the statistical F value, $Fa^{(n1,\, n2)}$, meaning the hypothesis Ho should be accepted. In fact, because the rut bar is in front of the ARAN unit, the effect of the operational speed on the suspension system is not effectively transferred to the ultrasonic sensors. Therefore, operational speed has little effect on the distance between the sensor and pavement surface.

Table 5.14 Transverse profile data (0.1 inch) from ATS01 at 30, 40, and 50 mph (report interval = 0.005 mile)

		Speed (mph)					Speed (mph)					Speed (mph)		
	Run	30	40	50		Run	30	40	50		Run	30	40	50
Sensor #4	1	155	156	156	Sensor #5	1	153	154	154	Sensor #6	1	152	153	153
	2	156	156	157		2	154	153	154		2	152	152	153
	3	156	155	156		3	154	153	154		3	152	151	152
	4	155	155	156		4	153	153	154		4	152	151	152
		Speed (mph)					Speed (mph)					Speed (mph)		
	Run	30	40	50		Run	30	40	50		Run	30	40	50
Sensor #7	1	154	155	154	Sensor #8	1	156	157	156	Sensor #9	1	158	159	158
	2	154	154	155		2	156	156	156		2	158	158	158
	3	154	153	154		3	156	155	156		3	158	157	158
	4	155	154	154		4	156	155	155		4	158	157	158

Table 5.15 Transverse profile data (0.1 inch) from ATS01 at 30, 40, and 50 mph (report interval = 0.01 mile). The data in this table were measured after the suspension system of the ARAN unit was changed

		Speed (mph)					Speed (mph)					Speed (mph)		
	Run	30	40	50		Run	30	40	50		Run	30	40	50
Sensor #4	1	140	139	141	Sensor #5	1	139	137	139	Sensor #6	1	139	138	140
	2	139	141	140		2	138	139	138		2	138	139	138
	3	140	139	140		3	139	137	138		3	138	137	138
	4	140	139	141		4	138	137	139		4	138	137	139
		Speed (mph)					Speed (mph)					Speed (mph)		
	Run	30	40	50		Run	30	40	50		Run	30	40	50
Sensor #7	1	142	140	142	Sensor #8	1	143	142	144	Sensor #9	1	144	143	145
	2	141	142	141		2	142	143	143		2	144	145	144
	3	141	140	140		3	142	142	142		3	144	143	144
	4	141	139	141		4	142	141	143		4	144	143	145

Table 5.16 Data of the Rut depth index R1 for the test of impact of operational speed (report interval = 0.005 mile)

		R1		
Operational Speed		30 mph	40 mph	50 mph
Run	1	1.000	0.954	1.009
	2	1.001	1.062	1.156
	3	1.420	0.998	1.184
	4	1.288	1.030	1.122

Table 5.17 Results of one-way ANOVA for operational Speed Effect; Opera-tional Speed = 30, 40, and 50 mph; $F_{\alpha}(n_1, n_2) = 4.26$

Report Interval (mile)	Sensor #	4	5	6	7	8	9
0.005	F Value	2.455	2.973	1.388	0.201	0.201	0.256
	Ho	$F>F_{\alpha}(n_1, n_2)$ ACCEPT Ho	$F>F_{\alpha}(n_1, n_2)$ ACCEPT Ho	$F>F_{\alpha}(n_1, n_2)$ ACCEPT Ho	$F>F_{\alpha}(n_1, n_2)$ ACCEPT Ho	$F>F_{\alpha}(n_1, n_2)$ ACCEPT Ho	$F>F_{\alpha}(n_1, n_2)$ ACCEPT Ho
0.01	F Value	2.058	2.405	1.440	1.303	2.058	2.250
	Ho	$F>F_{\alpha}(n_1, n_2)$ ACCEPT Ho	$F>F_{\alpha}(n_1, n_2)$ ACCEPT Ho	$F>F_{\alpha}(n_1, n_2)$ ACCEPT Ho	$F>F_{\alpha}(n_1, n_2)$ ACCEPT Ho	$F>F_{\alpha}(n_1, n_2)$ ACCEPT Ho	$F>F_{\alpha}(n_1, n_2)$ ACCEPT Ho

Table 5.18 Results of one-way ANOVA for the impact of operational Speed; Oper-ational Speed = 30, 40, and 50 mph; $F_{\alpha}(n_1, n_2) = 4.26$

F Value	1.617
Ho	$F>F_{\alpha}(n_1, n_2)$ ACCEPT Ho

CHAPTER 6. DEVELOPMENT OF A PROCEDURE QUANTIFYING TRANSVERSE PROFILE AND RUTTING OF PAVEMENTS

BACKGROUND

The amount of rutting present on flexible pavements is an important distress parameter to consider when making judgements concerning rehabilitation and maintenance. Severe rutting results in poor serviceability and, more importantly, is dangerous to the riding public. Millions of dollars are spent nationwide each year on rehabilitation and maintenance of flexible pavements damaged by rutting. The network-level decisions regarding which pavements to rehabilitate should be based on some quantitative rut index—one that is both cost-effective and safe.

The Texas SDHPT has been collecting rut depth data for several years. These data have been collected by condition survey teams using a process that involves placing a straightedge across a travel lane and physically measuring the depth of the individual ruts. Because this method of collecting information on rutting is both slow and dangerous, the Texas SDHPT is investigating an alternative method for collecting network-level rut depth information under normal traffic conditions using the ARAN unit. The rut depth subsystem of the ARAN unit is primarily used to collect transverse profile data and thereby the rut depth data.

The pavement transverse profile has been evaluated according to its geometric characteristics (Refs 9, 16, 19), including the rut depth indices R_1 and R_2 defined in the last chapter. This type of evaluation has been limited to the space domain. In addition to depth of rutting, the geometric shape of the transverse profiles is of importance in evaluating the safety and comfort of the traveling public. An extreme case would be one in which transverse profiles were perfectly flat with constant transverse slope; in such a case depth of rutting would be zero. But the transverse slope would still affect safety and passenger comfort.

This chapter presents a procedure quantifying the transverse profiles and rutting in the polynomial domain. The terms *transverse profile smoothness* and *rutting* are used synonymously throughout the remainder of this chapter. The formulas and calculations presented are based on transverse profile data collected by the ARAN unit, but the methodology can be applied to any rut depth monitoring system as long the reported information is similar in terms of number of sensors and measurement principle.

MEASUREMENT OF RELATIVE TRANSVERSE PROFILES

Pavement transverse profiles can be measured using a rut bar similar to the one shown in Figure 6.1. The rut bar has eleven ultrasonic sensors which measure the distance between the pavement surface and the individual sensor. The horizontal distance between any two adjacent sensors is 1 foot. If a right-angle coordinate system is defined as shown in Figure 6.1, then

$$\{X_i,\ i = 1, 2, ..., 11\} = \{-5, -4, -3, -2, -1, 0, 1, 2, 3, 4, 5\}\ \text{(ft.)}$$

and

$$Y_i + W_i = C\ \text{(all i)} \tag{6.1}$$

where

C = a constant,

$\{X_i, i=1, 2, ..., 11\}$ = the transverse distance sequence in horizontal axis,

$\{Y_i, i=1, 2, ..., 11\}$ = the measured data sequence by the individual ultrasonic sensors, and

$\{W_i, i=1, 2, ..., 11\}$ = the discrete transverse profile sequence.

Therefore,

$$W_i = C - Y_i\ \text{(all i)} \tag{6.2}$$

In order to obtain W_i, a reference level of the transverse profile should be given. If the mean value of the transverse profile sequence, $\{W_i, i=1, 2, ..., 11\}$ is taken as the reference level, the relative discrete transverse profile sequence, $\{T_i\}$, can be defined as follows

$$T_i = W_i - \overline{W}(all\ i) \quad (6.3)$$

where

$$\overline{W} = \frac{1}{11}\sum_{i=1}^{11} W_i = \frac{1}{11}\sum_{i=1}^{11}(C - Y_i) = C - \overline{Y} \quad (6.4)$$

and

$$\overline{Y} = \frac{1}{11}\sum_{i=1}^{11} Y_i$$

By combining equations (6.2), (6.3), and (6.4), the relative transverse profile sequence can be described by equation (6.5).

$$T_i = C - Y_i - C + Y = -(Y_i - Y) \quad (6.5)$$

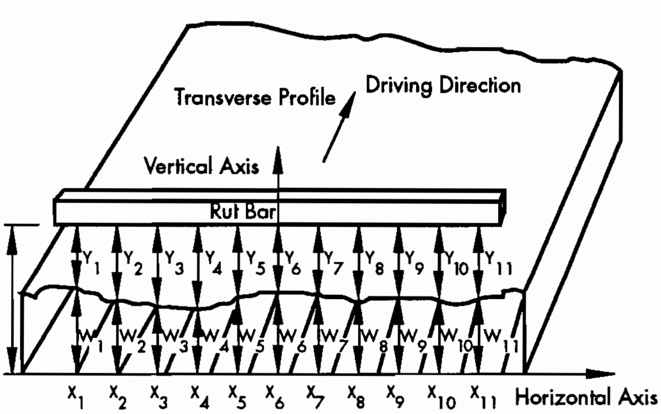


Figure 6.1. Transverse profile measurement by rut bar

TRANSFORM OF RELATIVE TRANSVERSE PROFILES

Relative transverse profiles cannot quantitatively characterize transverse profile smoothness and rutting; they can only demonstrate them graphically. The relative transverse profiles do, however, include some important information. In a practical engineering sense, the purpose of measuring transverse profiles is to obtain some objective statistics to evaluate transverse profile smoothness and associated rutting.

A relative transverse profile $\{T_i\}$ can be approximately fitted by a mathematical function:

$$T_i = F(X_i)\ (all\ i) \quad (6.6)$$

where $F(X_i)$ is a continuous function of transverse distance X_i. One suitable model of $F(X_i)$ is the polynomial function:

$$F(X) = A_0 + A_1 X + A_2X^2 + \dots + A_mX^m \quad (6.7)$$

where A_j (j=0, 1, ..., m) are the constant coefficients, and m is the order of polynomial function. In this study, m=5 was chosen. Then, by the notation shown in Figure 6.1, the above equation can be represented as follows:

$$T_i = A_0 + A_1 (X_i) + A_2(X_i)^2 + A_3(X_i)^3 + A_4(X_i)^4 + A_5(X_i)^5\ (all\ i) \quad (6.8)$$

An explanation of equation (6.8) is that the transverse profile shown in Figure 6.1 is the weighted summation of polynomials with weights (A_0, A_1, A_2, A_3, A_4 and A_5). Therefore, the coefficients, A_0, A_1, A_2, A_3, A_4 and A_5, approximately reflect the geometric or graphic characteristics of the transverse profile and rut depth. In fact, this approach could be considered a "transformation" of the variables $\{T_i\}$ in the "space domain" to the variables $\{A_j\}$ in the "polynomial domain." Symbolically, this transformation is expressed as

$$\{T_i\} \Rightarrow \{A_j\} \quad (6.9)$$

Only the magnitudes of the regression coefficients shown in equation (6.7) are of concern, because the magnitude A_j indicates the weight of the component of j^{th}-order polynomial function in the associated transverse profile. The transformation shown in Equation (6.9) can be symbolically represented by Equation (6.10)

$$\{T_i\} \Rightarrow \{a_j\} \quad (6.10)$$

where

$$a_j = |A_j|, (j=0, 1, \dots, 5) \quad (6.11)$$

The transformation described above is defined as the "polynomial transform" in the remainder of this chapter, and the symbol "⇒" represents irreversible polynomial transform.

It might be expected that one or more of the polynomial transform coefficients, a_j, could be sensitive to transverse profile smoothness. An extreme case would be one in which all the polynomial transform coefficients are zero, which would indicate that the corresponding transverse profile is ideally constant or perfectly smooth with no rutting. Some or all of the coefficients, a_j, would be relatively large if the conditions of the transverse profile rutting are relatively poor. But the magnitudes of the coefficients, a_j, depend on the graphic characteristic or shape of the associated relative transverse profile. That is the larger a_j, the more j^{th}-order polynomial component there is in the transverse profile.

Applying the polynomial transform to evaluate pavement transverse profile roughness and rutting conditions would be helpful in understanding the idea presented above. Figure 6.2 shows two transverse profiles from Austin Test Sections ATS04 and ATS28. Test section ATS28 is known to have less rutting and a smoother transverse profile than ATS04; but this evaluation is based on subjective judgment; quantitative analysis must be conducted to substantiate such a subjective evaluation. If the polynomial transform is applied to these two sections, the polynomial transform coefficients of ATS04 and ATS28 can be listed as follows:

ATS04	ATS28
a_0 = 1.305	a_0 = 6.434x10-3
a_1 = 1.128	a_1 = 0.2623
a_2 = 0.610	a_2 = 4.429x10-3
a_3 = 0.110	a_3 = 1.286x10-2
a_4 = 2.695x10-2	a_4 = 2.331x10-4
a_5 = 5.128x10-4	a_5 = 2.885x10-4

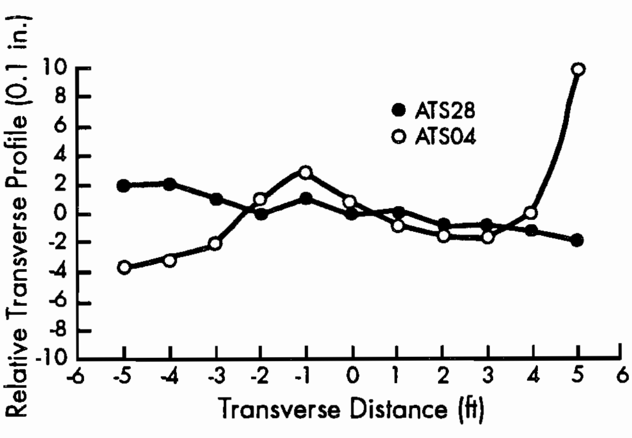


Figure 6.2 Graphs of relative transverse profiles of ATS04 and ATS28

From these coefficients, it can be seen that all the polynomial transform coefficients of ATS04 are larger than those of ATS28. This example supports the statement that the magnitudes of the coefficients, a_j, to a certain degree, indicate the conditions of transverse profile smoothness and the associated rutting.

In order to utilize the polynomial transform coefficients, a linear multiple regression model shown in equation (6.12) is adequate to quantify transverse smoothness and rutting (TSR).

$$TSR = K_1 + K_2 a_0 + K_3 a_1 + K_4 a_2 + K_5 a_3 + K_6 a_4 + K_7 a_5 \quad (6.12)$$

where

TSR = transverse smoothness and rutting index, and

K_n = n^{th} coefficient of the regression model ($n = 1, 2, ..., 7$).

DEVELOPMENT OF TRANSVERSE PROFILE INDEX

A standard reference is needed to develop a new index characterizing transverse profiles and rutting. In evaluating pavement transverse profile smoothness and rutting, two statistics are often used: mean value and standard deviation of the measured transverse profile data. But these statistics do not take into account the sequence of the data. In other words, the graphic characteristics of the transverse profiles do not affect the two statistics if the data sequence values of the associated transverse profile are kept the same.

Pavement transverse profile characteristics can be obtained from the polynomial transform. The regression model shown in equation (6.12) may be a good candidate for evaluating transverse profile smoothness and rutting, even though it is a dimensionless unit. The procedure of the modeling and data analysis for developing indices characterizing transverse profiles will be presented later in this chapter. The Texas Automatic Road Analyzer (ARAN) was used as the measuring device to collect pavement serviceability index and transverse profile data.

Reference Selection

Transverse profile standard deviation (SD) and rut depth index (R_1) defined in the last chapter were chosen as the references in developing a new index characterizing transverse profiles. The serviceability index (SI) was also considered as a reference. Since the roughness measuring subsystem of the ARAN unit is a response-type road roughness measuring system, the measured SI values are the responses of the measuring vehicle to longitudinal and transverse pavement roughness. It can be expected that SI should have some correlation with transverse profile roughness and rutting.

Data Collection and Processing

Field data collection was conducted in the summer of 1989 using the ARAN unit. Table 6.1 shows the measured transverse profile data collected from several flexible pavements. Raw data from Table 6.1 was converted to mean values in order to obtain relative transverse profiles.

Table 6.2 shows the fifth-order polynomial curve-fitting coefficients of the relative transverse profile data, correlation coefficients of the curve-fitting, and reference statistics. Linear correlation between the statistics, and between the coefficients and the statistics, can be conducted to evaluate the sensitivity of the coefficients and statistics in terms of R^2 values. Table 6.3 presents the correlation analysis results. The values in the table are R^2 values.

From Table 6.3, it can be seen that the coefficients a_2 and a_4 have fair correlation with SI. This further indicates that the measured roughness from a response-type roughness measuring system has some correlation with transverse profile characteristics. That is, the response of a vehicle is not only due to the longitudinal roughness, but also to transverse profile smoothness. However, this cannot be seen from just the standard deviation (SD) of the transverse profile. This is confirmed by a low correlation between SI and SD.

Index Specifications and Development

The multiple regression model shown in equation (6.12) will be considered as the basis for the index modeling. Specifications of the model are necessary because it is improper to use all of the polynomial transform coefficients. The specifications can be judged by factors such as the R^2 value, the sign of coefficient, the absolute magnitude of coefficient, and simplicity, etc.

Table 6.4 lists the regression model specifications that consider several of the most-often used combinations of the polynomial coefficients. The indices SI, SD, and R_1 are dependent variables, and the polynomial transform coefficients a_j (j=0, ..., 5) are independent variables. Table 6.5 shows the results of the multiple regression models specified in Table 6.4.

Several important factors, including R^2, coefficient sign, absolute magnitude of coefficient, and simplicity, need to be considered when choosing

Table 6.1 Transverse profile data of Austin test sections

	Ultrasonic Sensors (0.1 in.)										
ATS	1	2	3	4	5	6	7	8	9	10	11
01	145.5	138.3	143.4	139.2	141	137.4	142	141.5	138	143.5	137.5
03	142.8	138.8	142.4	139.2	140.8	142	145.2	145	143.4	145.2	145.2
04	143.8	137.3	143.3	139.3	142.3	139.5	140.3	141.8	141	142	130.5
07	144	141.7	143.7	143	143	142	145	143.3	142	144	145.7
08	141.7	140.7	141.7	141.7	141.7	141.3	145	143	142	144	146
09	140.7	141	141	141	142	141.7	144.7	143.3	142.3	144	146
12	142.3	141.3	142.3	142.7	143	142	147	143.7	142	145	148.7
15	142.5	141	142	141	141	141.5	145	142.5	142	144	146.5
19	138.7	142	140.7	142	142	142	145.3	143.7	142.7	144.7	146.3
20	137.7	141	139.7	141	141	140.7	145.7	142.7	141	144	147
22	142.3	140.3	142.3	142	142.3	140.7	145	142	141	143.3	146
25	146	139	144	140	142	138.3	142.7	142	139.3	144	138
27	141.3	141.3	141	142.3	142	142	144	143	142.3	143.3	144
28	141	142	141	143	142	143	144.3	144	143	144	145
30	152.3	139	149.7	142	146.7	138.7	146	139.3	137	142.7	147.7
31	142.7	138.7	142.7	140	141.7	139.7	142.7	142.3	139.7	143.7	143.3
41	145	141.7	144	142.7	144	141	140.7	140	140	140	139.7
42	140.7	140.3	141	142	142	141	143	142	141	143	143
43	140	140	140	141	141	141	142.3	142	141	143	142
55	142.3	138	142	140	142	138.7	141	141	139	141.7	140

Table 6.2 Transverse profile polynomal transform coefficients and longitudinal and transverse profile statistics

	Coefficients of Polynominal Transform and R^2 Values							Statistical Indices		
ATS	A0	A1	A2	A3	A4	A5	R^2	SI	SD	R1
01	3.009	−0.5435	−0.6773	1.338E-2	2.113E-2	1.619E-3	0.97	2.61	2.775	−3.248
03	1.462	−2.149	−0.2341	0.1866	4.953E-3	−4.423E-3	0.98	3.67	2.370	−1.845
04	1.305	−1.128	−0.6103	0.1102	2.695E-2	−5.128E-4	0.97	1.96	3.703	−1.250
07	1.486	−8.536E-2	−0.2290	−8.559E-3	4.516E-3	2.083E-4	0.97	4.40	1.257	−1.725
08	1.287	−0.4140	−0.2027	4.050E-3	4.167E-3	−1.923E-4	0.98	4.03	1.683	−1.464
09	0.8155	−0.5950	−0.1449	2.674E-2	3.176E-3	−9.776E-4	0.98	3.76	1.758	−0.989
12	1.856	−0.1118	−0.2837	−3.821E-2	5.536E-3	6.731E-4	0.98	4.37	2.334	−2.127
15	1.285	−0.4829	−0.1307	7.503E-3	1.457E-4	−1.603E-4	0.99	4.28	1.804	−1.727
19	0.5372	−0.3694	−0.1628	−7.233E-3	6.148E-3	−3.365E-4	1.00	4.17	2.160	−0.452
20	1.126	−0.1454	−0.2463	−4.861E-2	7.488E-3	6.891E-4	1.00	3.57	2.695	−1.216
22	1.862	1.867E-2	−0.3016	−2.899E-2	6.468E-3	5.289E-4	0.98	4.40	1.734	−2.180
25	2.827	−0.5363	−0.6521	1.773E-2	2.075E-2	1.442E-3	0.99	3.12	2.653	−3.068
27	0.4207	−0.1398	−8.814E-2	−2.316E-2	2.593E-3	7.051E-4	0.91	4.29	1.049	−0.332
28	6.434E-3	−0.2623	−4.429E-3	−1.286E-2	2.331E-4	2.885E-4	0.92	4.43	1.328	0.223
30	6.137	−0.9310	−0.9022	4.458E-2	1.623E-2	−1.026E-3	0.99	2.18	5.054	−7.727
31	2.226	−0.8512	−0.4268	8.402E-2	1.145E-2	−2.083E-3	0.93	3.58	1.721	−2.443
41	0.9126	−0.9509	−0.1633	5.597E-2	4.050E-3	−1.555E-3	0.99	3.93	1.914	−1.107
42	0.8545	−2.294E-2	−0.2128	−2.164E-2	7.168E-3	5.289E-4	0.84	4.24	0.988	−0.720
43	0.4280	−0.3217	−0.1402	−2.375E-3	5.478E-3	2.885E-4	0.86	4.42	1.010	−0.232
55	1.957	−0.4272	−0.4403	5.570E-2	1.375E-2	−1.186E-3	0.90	2.95	1.480	−1.964

Table 6.3 R^2 Values Between Polynomial Transform Coefficients and the Statistics SI, SD, and R_1

Statistics	a_0	a_1	a_2	a_3	a_4	a_5
SI	.430	.222	.762	.149	.784	.076
SD	.585	.193	.636	.104	.415	.037
TD	.985	.067	.697	.013	.232	.049

Table 6.4 Specifications for the multiple regression model

Independent Variables a_0 a_1 a_2 a_3 a_4 a_5	Models	Dependent Variables: SI, SD, R_1
	1	a_0 a_1 a_2 a_3 a_4 a_5
	2	a_1 a_2 a_3 a_4 a_5
	3	a_1 a_2 a_3 a_4
	4	a_2 a_3 a_4 a_5
	5	a_0 a_2 a_4
	6	a_2 a_3 a_4
	7	a_2 a_4

Table 6.5 Coefficients and R^2 Values of All Regression Models. SI, SD, and R_1 are dependent variables, while a_i (i=0, 1, ..., 5) are independent variables

Dependent Variables	Independent Variables	Model 1		Model 2		Model 3		Model 4		Model 5		Model 6		Model 7	
		Coefficients and R^2 Values of All Regression Models													
SI	Constant	4.739	R^2 = 0.912	4.704	R^2 = 0.895	4.732	R^2 = 0.875	4.685	R^2 = 0.860	4.646	R^2 = 0.839	4.703	R^2 = 0.855	4.611	R^2 = 0.822
	a_0	6.718								6.626					
	a_1	-0.552		-0.600		-0.423									
	a_2	-68.70		-1.395		-1.139		-1.593		-67.68		-1.411		-1.365	
	a_3	-2.383		-1.153		0.742		-5.192				-3.245			
	a_4	1152.7		-45.09		-54.03		-42.42		1125.4		-48.09		-54.12	
	a_5	234.96		216.42				107.39							
SD	Constant	0.919	R^2 = 0.812	0.933	R^2 = 0.810	0.860	R^2 = 0.706	0.971	R^2 = 0.751	1.006	R^2 = 0.654	0.894	R^2 = 0.688	1.016	R^2 = 0.653
	a_0	-2.966								-1.842					
	a_1	0.981		1.002		0.486									
	a_2	34.60		4.883		4.137		5.215		22.82		4.449		4.388	
	a_3	6.690		6.306		-0.279		12.45				4.300			
	a_4	-592.5		-63.69		-37.59		-68.16		-364.3		-44.42		-36.42	
	a_5	-640.2		-632.1				-450.0							
R1	Constant	0.172	R^2 = 0.999	0.170	R^2 = 0.999	0.187	R^2 = 0.997	0.160	R^2 = 0.997	0.143	R^2 = 0.995	0.106	R^2 = 0.994	0.078	R^2 = 0.993
	a_0	0.285								0.143					
	a_1	-0.274		-0.276		-0.158									
	a_2	-16.20		-13.34		-13.17		-13.44		-14.69		-13.13		-13.11	
	a_3	-1.235		-1.198		0.301		-2.888				-1.011			
	a_4	314.9		264.1		258.2		265.3		283.6		259.5		257.7	
	a_5	144.7		143.9				93.81							

the models. These factors can be determined from Table 6.5. The model choice for SI, SD, and R_1 are discussed below.

SI. Besides longitudinal profile roughness, pavement serviceability index (SI) measured by a response-type roughness measuring system such as the ARAN unit is affected by the transverse profile smoothness. The smoother the transverse profile, the better the serviceability, or the smaller the SI. Mathematically, this logical relationship requires the coefficients of the regression model shown in equation (6.12) to have negative signs according to the meaning of the polynomial transform coefficients. The multiple regression results shown in Table 6.5 indicate that only Modes 6 and 7 are adequate if the signs are considered. However, the R^2 value of Model 6 is larger than that of Model 7. Therefore, Model 6 was chosen.

SD. Since transverse profile data standard deviation (SD) does not address the sequence of transverse profile data, the graphic characteristic of the transverse profile does not significantly affect the SD value. Therefore, there is not a strict requirement for the signs of the coefficients of the multiple regression model shown in equation (6.12). Model 1 was chosen as the multiple regression model of equation (6.12) because it has the best correlation with SD (higher R^2 value).

***R_1*.** According to the definition of R_1, the entire transverse profile is not considered. Therefore, there is no strict requirement on the signs of the model of equation (6.12). Model 3 was chosen because of simplicity and high R^2 value.

Based on the three references—SI, SD, and R_1—and the results of model choice, the three resulting models are as follows:

a. Based on SI

$$TSR_S = 4.703 - 1.411\, a_2 - 3.245\, a_3 - 48.09\, a_4 \qquad (6.13)$$

b. Based on SD

$$TSR_{SD} = 0.919 - 2.966\, a_0 + 0.981\, a_1 + 34.60\, a_2 + 6.690\, a_3 - 592.5\, a_4 - 640.2\, a_5 \qquad (6.14)$$

c. Based on R_1

$$TSR_R = 0.187 - 0.158\, a_1 - 13.17\, a_2 + 0.301\, a_3 + 258.2\, a_4 \qquad (6.15)$$

The TSRs shown in equations (6.13), (6.14), and (6.15) can be considered as the indices characterizing transverse profile smoothness or rutting.

The following example would be useful in explaining the application of the polynomial transform described before. In this example, equation (6.14) will be used. The polynomial transform can be expressed by a curve, such that the horizontal axis is the polynomial order, j, and the vertical axis is the weighted polynomial transform coefficient, $\{|K_{j+2}| \times a_j\}$ (j=0, ..., 5), as expressed in equation (6.12). But the weights are the absolute values of the associated coefficients of the multiple regression models. From equation (6.14), the weights can be listed as follows:

Polynomial Order, j	Poly. Transform Coef.	Weight
0	a_0	2.966
1	a_1	0.981
2	a_2	34.60
3	a_3	6.690
4	a_4	592.5
5	a_5	640.2

Figure 6.3 shows the weighted polynomial transforms for test sections ATS04 and ATS28. The conditions of transverse profile smoothness on ATS04 and ATS28 can be easily distinguished according the meaning of polynomial transform. It should be mentioned that the rutting judgment from Figure 6.2 is qualitative, while that from Figure 6.3 is quantitative. The two judgments differ. In fact, the index TSR_{SD} is the area under the weighted polynomial transform curve plus a constant.

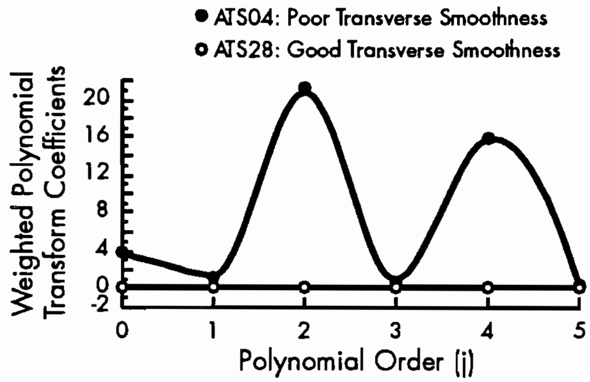


Figure 6.3 Weighted polynomial transforms for the transverse profiles of ATS04 and ATS28

Figures 6.4, 6.5, and 6.6 show the correlation of the multiple regression models with the references SI, SD, and R_1, respectively. The regression model shown in equation (6.15) has a very good correlation with R_1.

SUMMARY

(1) In the development of the indices characterizing transverse profiles, three references—SI, SD, and R_1—were selected. The purpose of choosing these references was to prove that the developed theoretical model concept and structure correlate with the chosen references. The correlations also prove the implied use and applicability of the polynomial transform in evaluating pavement transverse profile smoothness. Of course, better models can be found if the polynomial transform coefficients are directly correlated with subjective judgments on safety of traveling public and passenger comfort. Judgments on rutting by a survey panel could also be used to calibrate the model coefficients.

(2) The multiple regression model Equation (6.12) can quantitatively reflect the graphical characteristic of the transverse profiles. The index (TSR) was developed to evaluate the transverse profile of an asphaltic pavement section. However, the resulting correlation analysis showed poor correlation between the references SI, SD, and R_1 as follows:

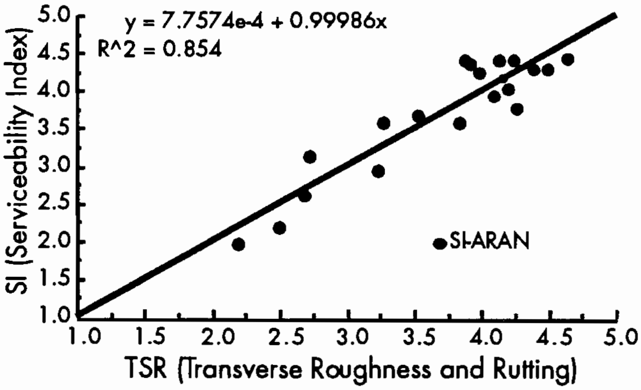


Figure 6.4 Correlation between SI and TSR (TSR based on equation 6.13)

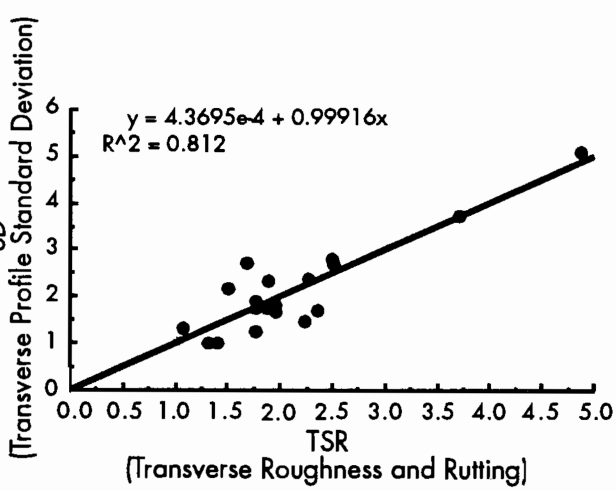


Figure 6.5 Correlation between SD and TSR (TSR based on equation 6.14)

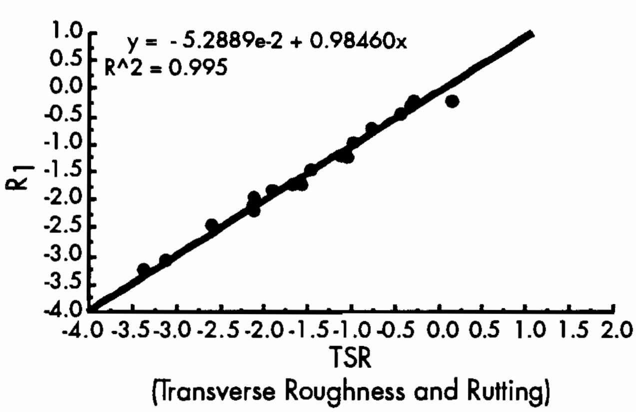


Figure 6.6 Correlation between R_1 and TSR (TSR based on equation 6.15)

Reference Pairs	R^2 Values
SI - SD	0.635
SI - R_1	0.376
SD - R_1	0.595

The indices (TSRs) from equations (6.13), (6.14), and (6.15) should correlate with SI, SD, and R_1, respectively. They can be used to evaluate pavement smoothness and rutting conditions.

(3) In new pavement construction, longitudinal roughness is usually employed to evaluate whether the constructed pavement satisfies the design requirements. While research has focused on the longitudinal roughness specifications (Ref 14), the transverse smoothness of the newly constructed pavement is also an important factor in determining if the constructed pavement satisfies the design requirement. In this case, the index TSR might be a good candidate for a quality control statistic in evaluating newly constructed pavement. Further research should be conducted to apply the developed methodology more effectively.

(4) There are certain differences among the multiple regression models of equations (6.13), (6.14), and (6.15). These models evaluate pavement transverse profile smoothness from different approaches according to their associated references. For TSR_{SI} from equation (6.13), the larger the TSR_{SI}, the better the transverse profile smoothness, because the model was derived from correlation with SI. But for TSR_{SD} and TSR_R from equations (6.14), and (6.15), the smaller the TSR_{SD} and TSR_R, the better the transverse profile smoothness, because the models were derived from correlations with SD and R_1, respectively.

(5) Although the conducted study was based on the rut depth subsystem of the ARAN unit, the methodology developing transverse profile smoothness and rutting indices can be applied to any system which has a rut bar with sensor configuration as shown in Figure 6.1. The modeling coefficients need to be recalculated if a different system is used.

CHAPTER 7. SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

SUMMARY AND CONCLUSIONS

As part of a pavement evaluation system, the ARAN unit is used primarily in urban areas for the collecting of data and for the routine surveying of pavement conditions.

The objective of this research was to evaluate and implement the roughness measuring subsystem, orientation subsystem, and rut depth subsystem of the ARAN unit. Both the evaluation and implementation of the roughness measuring subsystem, covered in the first phase of this research, are reported in Ref 28. This report covers the second phase of the study; that is, the evaluation and implementation of the orientation and rut depth subsystems.

Tests were conducted to evaluate static, dynamic, and operational performance. The evaluation of these tests for accuracy, repeatability, impacts of report interval and operational speed, and static and dynamic response are critical in determining the reliability of the related subsystems. Another aspect of this study was the development of a procedure quantifying transverse profiles and pavement rutting using transverse profile data.

Most of the results from this study are based on field tests and data collected from Austin Test Sections (ATS). Several methods were used to compare the responses of the ARAN unit to the selected references, such as the Face Dipstick and test section geometric plan.

The major findings of this study are as follows:

(1) As shown in Figure 2.5, the basic outputs of the orientation subsystem are HEADING, PITCH, and ROLL, related to roadway curve, slope, and crossfall or superelevation. These three variables could be used to indicate the operating safety of a roadway and passenger comfort.

(2) According to the static and dynamic drift error tests and the results shown in Figs 4.2 and 4.3, both the static and dynamic drift errors in HEADING are significant. Although a model is used to cancel the static drift error in PITCH, and no static drift was found, dynamic drift error was found in PITCH. This may be due to either vibrations of the ARAN unit during the repeat runs, or to the roughness of the sections chosen for the test.

(3) The dynamic performance of the orientation subsystem satisfied general requirements for operation. The subsystem has adequate dynamic measurement accuracy, with respect to the references employed.

(4) As discussed in Chapter 5 regarding the operational tests, data report length for HEADING, PITCH, and ROLL depends on the selection of the report interval. When the interval is 0.05 or 0.1-mile, the report length of HEADING and PITCH is less than the pavement section length; consequently, the outputs measured at these intervals might not be reliable.

(5) Except for the output HEADING, the other outputs of the orientation subsystem show relatively poor repeatability in terms of the summarized data. If PITCH and ROLL are to be used to evaluate pavement conditions, operating safety, passenger comfort, and roadway geometric characteristics, the summarized PITCH and ROLL should not be used until the gyro is tested and perhaps recalibrated by the manufacturer.

(6) Test results have shown that the choice of report interval affects the outputs, HEADING and PITCH, of the orientation subsystem. This is because the data report length is dependent on the selection of the report interval, and longer report intervals result in loss of the detailed ROLL information.

(7) Operational speed is not an important factor in the function of the orientation subsystem. Field tests and the working principle of the gyroscopes have shown that the speed does not affect the outputs HEADING, PITCH, and ROLL.

(8) Test of the rut depth subsystem showed reliable static performance. Typical static performance is listed below.

   (a) Vibration caused by the engine and generator in the ARAN unit do not significantly affect the readings of the ultrasonic sensors.

(b) The combined linearity of the ultrasonic sensors and their associated electronics was confirmed through the static performance test. This linearity makes the measurement of the transverse profiles and rut depth feasible.

(c) The depth of field or measuring range of the ultrasonic sensors is from 10.0 inches to 20.0 inches from the rut bar.

(d) The projection area of the ultrasonic sensors is a circle with a diameter equal to 3.5 inches at normal mounting and operating heights.

(e) The resolution of the rut depth subsystem is 0.1 inches.

(f) The average accuracy index (AI) of each individual sensor is less than 0.1 inches; thus, the static accuracy of this subsystem is adequate.

(9) As a result of the comparison between the two relative transverse profiles measured by the Face Dipstick and the rut depth subsystem, the rut depth subsystem of the ARAN unit was found to have a statistically reliable dynamic measurement accuracy which can be seen from Figure 5.9.

(10) The three-dimensional pavement profiles measured by the Face Dipstick and the rut depth subsystem of the ARAN unit are qualitatively similar, suggesting some confidence in the performance of the rut depth subsystem.

(11) Repeatability of the rut depth subsystem is affected by the report interval. If intervals of 0.005 or 0.01-mile are used, the repeatability is relatively good.

(12) Except for repeatability, statistical tests indicated that the report intervals 0.005, 0.01, and 0.05-mile, do not result in significantly different outputs of the rut depth subsystem. However, at a 0.1-mile interval, the difference was significant.

(13) The impact of operational speed on the rut depth subsystem at report intervals 0.005 and 0.01-mile was negligible.

(14) A procedure was developed to quantify transverse profiles and rutting, based on a polynomial transform. The resulting indices show good correlations with existing rut depth indices and serviceability index. However, better rut depth index models could be found if the polynomial transform coefficients were directly correlated with subjective judgment of transverse profile roughness and rutting.

(15) The procedure quantifying transverse profiles and rutting was based on the data measured by the rut depth subsystem of the ARAN unit, but can be applied to any system with a rut bar with a sufficient number of sensors.

RECOMMENDATIONS

The following recommendations are based on the findings of this study:

(1) If the orientation subsystem is to be used, the report interval should be no greater than 0.01-mile.

(2) In principle, operational speed does not affect the orientation subsystem. But a high speed of about 50 mph is recommended to reduce the effects of drift error in the gyroscopes.

(3) Because of limited funds, time, and field data, the reliability of the rut depth subsystem was not fully evaluated. A more complete correlation analysis is recommended for future evaluation. Pavement test sections should be selected, and a standard reference instrument should be compared to the ARAN rut depth data output.

(4) In order to collect transverse profile and rut depth data correctly and with good repeatability, it is recommended that report intervals of 0.01-mile or less be used.

(5) The results of this project suggest that the ARAN unit can generally be used for network-level surveys if care is taken with calibration, report intervals and operating speed. Work dedicated to upgrading and improving the system should continue.

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