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MEASUREMENT OF PAVEMENT SMOOTHNESS FOR CONSTRUCTION QUALITY CONTROL

Final Report

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16. Abstract This research study of pavement smoothness measurement was conducted in order to develop and implement an improved highway smoothness construction specification on asphalt concrete pavements. Achieving a higher level of smoothness on highways during construction results in savings to the taxpayer due to reduced wear and tear on vehicles, and longer highway life. Although the current ADOT specification used for highway smoothness addresses localized smoothness problems, it is difficult to administer due to the measurement system used, and provides little impetus to the contractor to improve his quality of work with respect to overall highway smoothness.

This study provided data to assist ADOT in developing a new smoothness specification that would provide incentive to contractors to construct smoother pavements and which is easier for ADOT to administer. In order to provide incentive to contractors, a pavement smoothness construction quality control draft specification and associated measurement procedure was produced.

Based upon these criteria, this study has recommended several changes to the ADOT highway smoothness specification for asphalt concrete highways:

- relative to measurement
  - a. new smoothness measurement technique
  - b. different smoothness measuring device used
- relative to the specification
  - a. accommodation of the new smoothness measurement procedure
  - b. inclusion of an incentive/penalty clause

The envisioned consequences of these changes is that the contractors would not only have the incentive to improve highway smoothness quality, but also the means, as provided by ADOT, to assess smoothness quality in a timely manner, improve that quality as needed, and then adjust normal construction procedures in order to construct smoother highways.

17. Key Words

pavement smoothness, pavement roughness, construction quality control of pavements

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CHAPTER 1. INTRODUCTION

The Arizona Department of Transportation (ADOT) sponsored this research study of pavement smoothness measurement in order to develop and implement an improved highway smoothness construction specification on asphalt concrete pavements. Achieving a higher level of smoothness on highways during construction results in savings to the taxpayer, due both to reduced wear and tear on vehicles, and longer highway life.

Although the current ADOT specification used for highway smoothness addresses localized smoothness problems, it is difficult to administer due to the measurement system used, and provides little impetus to the contractor to improve his quality of work with respect to overall highway smoothness.

The goal of this study is to provide data to assist ADOT in developing a new smoothness specification that can provide incentive to contractors to construct smoother pavements which is also easier for ADOT to administer. In order to provide incentive to contractors, a specification and associated measurement procedure was needed that would be applied quickly, thoroughly, and consistently across construction projects.

Based upon these criteria, this study has recommended several changes to the ADOT highway smoothness specification for asphalt concrete highways:

- relative to measurement
  - a. new smoothness measurement technique
  - b. different smoothness measuring device used

- relative to the specification
  - a. accommodation of the new smoothness measurement procedure
  - b. inclusion of an incentive/penalty clause

The envisioned consequences of these changes is that the contractors would not only have the incentive to improve highway smoothness quality, but also the means, as provided by ADOT, to assess smoothness quality in a timely manner, improve that quality as needed, and then adjust normal construction procedures in order to construct smoother highways.

At this time, ADOT staff is qualified to measure smoothness using the techniques and equipment recommended during the course of this study. A draft of a new smoothness specification, as documented in this report, has been presented to and reviewed by ADOT. A version of this specification is now being tested on selected ADOT construction projects.

Following adequate review and testing, it is anticipated that ADOT will adopt a new standard highway smoothness specification, either as tested, or as modified based upon the consequences of the ongoing specification testing.

GOALS, OBJECTIVES AND SCOPE OF THE STUDY

The goal of this project is to develop a method ADOT can use to rapidly survey newly constructed or newly overlaid asphalt concrete pavements to ascertain their smoothness for compliance with an appropriate specification. This new specification will be designed to be responsive to objective components of smoothness or roughness of the pavement, as well as to subjective components which are commonly referred to as "ride quality".

In order to meet this goal, three objectives must be met. The primary objective is the development of the smoothness specification. Then, in order to implement the specification, developing quality testing capabilities with the Maysmeter and profilometer roughness measuring devices are secondary objectives that must be achieved.

This new smoothness specification will be easier to administer by ADOT and is intended to provide incentive for contractors to construct pavements of higher quality. The smoother end of the ride quality scale based on this new specification should be eligible for some type of incentive compensation to the contractor, and the rougher end of the scale could be subjected to penalty payment. The tasks to accomplish these objectives and their current status are summarized below.

DESCRIPTION OF TASKS, PHASES, AND WORK ITEMS

This project was divided into two phases:

PHASE I. Selection of pavement roughness equipment

PHASE II. Implementation of pavement roughness quality control procedures

Each phase consisted of three tasks and each task was further divided into work items.

Phase 1. Selection of Pavement Roughness Equipment

The tasks for this phase were:

Task 1. Engineering Evaluation of Roughness Measuring Equipment

Task 2. Preliminary Equipment Testing

Task 3. Interim Documentation and Recommendations

Task 1. Engineering Evaluation of Roughness Measuring Equipment: This task covered evaluation of the state-of-the-art of roughness measurements for highway construction quality control, including a review of: a) current measurement practices in other states, b) roughness statistic that could be used to define the smoothness of pavements surfaces, c) characteristics required in a roughness measuring device for monitoring pavement smoothness in construction/ rehabilitation projects, and d) candidate equipment.

The current state-of-the-art of roughness measuring equipment was documented in Technical Memorandum 60-1 (Reference 1) which also contains recommendations of candidate roughness equipment and a preliminary experiment design for equipment testing.

Task 2. Preliminary Equipment Testing: Preliminary testing of the candidate equipment has been performed on a variety of tests sections near

Austin, Texas in order to evaluate four types of equipment and select devices which best meet the requirements of the project.

Task 3. Interim Documentation and Recommendations: The results of preliminary field tests, data analysis and findings were documented in an interim report (Reference 2). Recommendations concerning final ranking of the tested roughness equipment are also contained in this report.

Phase II - Implementation of Pavement Roughness Quality Control Procedures

The purpose of Phase II was to complete the total development and implementation of pavement roughness specifications for the control and acceptance of asphalt concrete highway construction in Arizona. The scope of this phase included the development of draft specifications, the purchase and testing of appropriate measurement equipment, full scale field testing, training and the development and implementation of final specifications.

The tasks in Phase II were:

Task 4. Preliminary Arizona Field Testing

Task 5. Comprehensive Arizona Field Evaluation Plan

Task 6. Final Analysis, Report and Implementation

Task 4. Preliminary Work Activities: The purpose of Task 4 was to perform a number of preliminary activities, which were required to initiate the work on the roughness specification. There were a number of work items as follows:

- Work Item 9. Research Equipment Availability and Costs
- Work Item 10. Assist ADOT in Personnel Hiring
- Work Item 11. Finalize Maysmeter Capability for Construction Control

- Work Item 12. Purchase Law Model 690D Profilometer (690D) for Calibration Control

- Work Item 13. Write First Draft Specification

Task 5. Comprehensive Arizona Field Evaluation Plan: The intent of Task 5 was to develop extensive field data from actual projects using the devices that were selected in Phase I. This testing on new ADOT projects the draft led to specification developed in Work Item 13. Task 5 has the following work items:

- Work Item 14 - Calibrate Maysmeters

- Work Item 15 - Select Test Sites/Develop Testing Plan

- Work Item 16 - Implement Field Testing using the Maysmeters

- Work Item 17 - Receive/Check out new 690D Profilometer

- Work Item 18 - Implement Full Scale Field Testing with both the Maysmeters and the Profilometer

Task 6. Final Analysis, Report, Implementation: Work items in this task were intended to complete the final implementation of a roughness specification. Task 5 included data analysis, the finalization of the specification which includes penalties, bonus clauses and training. The work items associated with Task 6 were as follows:

- Work Item 19 - Complete Data base Analyses

- Work Item 20 - Finalize Roughness Specification

REPORT FORMAT

The chapters in this report correspond to the project objectives, namely: selection of roughness measuring equipment, establishing a Maysmeter testing capability, establishing a profilometer testing capability, and developing a smoothness specification. Chapter Two documents the work done in Phase One. Phase Two Project work is covered in Chapters Three, Four, and Five. The accomplishment of Phase Two, Tasks and Work Items is distributed unevenly across Chapters Three, Four and Five. This is the case because the objectives as separately documented in the chapters were achieved concurrently while the tasks and work items give a chronological indication of how the work was accomplished. Table 1-1 shows the relationship between Phase Two Tasks and the objectives specific chapters of this report.

Table 1-1. Report Chapter/Project Task Relationship.

TASK/WORK ITEMS	CHAPTER Three	CHAPTER Four	CHAPTER Five
TASK 4. PRELIMINARY WORK ACTIVITIES			
Work Item 9 - Research Equipment Availability and Costs		X	X
Work Item 10 - Assist ADOT in Personnel Hiring		X	X
Work Item 11 - Finalize Maysmeter Capability for Construction Control Quality		X	
Work Item 12 - Purchase 690D Profilometer for Calibration Control			X
Work Item 13 - Write First Draft Specification	X		
TASK 5 - COMPREHENSIVE ARIZONA FIELD EVALUATION PLAN			
Work Item 14 - Calibrate Maysmeters		X	
Work Item 15 - Select Test Sites/Develop Testing Plan	X		
Work Item 16 - Implement Field Testing using the Maysmeter	X	X	
Work Item 17 - Receive/Check out Profilometer			X
Work Item 18 - Implement Full Scale Field Testing with both the Maysmeter and the Profilometer		X	X
TASK 6 - FINAL ANALYSIS, REPORT, IMPLEMENTATION			
Work Item 19 - Complete Data Base Analyses	X		
Work Item 20 - Finalize Roughness Specification	X		

Chapter 3. Construction Smoothness Specification Development
Chapter 4. Maysmeter Testing Capabilities
Chapter 5. Profilometer Testing Capabilities

CHAPTER 2. SELECTION OF SMOOTHNESS MEASURING EQUIPMENT

An office evaluation of the candidate roughness equipment (690D Profilometer, Law Model 8300 Roughness Surveyor (8300 RS), Maysmeter, and several models of Profilograph) was performed early in this study which included a review of equipment specifications, principles of operation and operating procedures. Field testing of roughness devices followed and was completed in a four month period (April - July 1986). Roughness data was collected by the 690D Profilometer, 8300 RS and a Maysmeter on 28 flexible pavement sections near Austin, Texas which vary from smooth to very rough. Due to practical constraints (such as the speed of operation), the profilographs were tested on 12 selected sections, three from each of the four roughness groups.

LITERATURE/OFFICE EVALUATION

Data analyses and interpretation included a comparison of summary statistics (means and coefficients of variation); analysis of variance to investigate repeatability, reproducibility and accuracy over an interval of time, and speed dependency. A study also was performed to determine correlations of the output of each device with the Maysmeter and with SI, MO, and the RMSVA roughness statistics derived from the analysis of longitudinal profiles measured by the 690D Profilometer. In addition, operational and performance criteria were used to evaluate and rank these devices. Major findings for each device are summarized below.

690D Profilometer

The 690D Profilometer generated high quality, accurate, and repeatable profile data. This equipment had the highest initial cost, however, it had the broadest use and good long-term benefits. It ranked highest overall in all phases of the comparison.

8300 RS

When this device was functioning, it measured roughness at speeds of 40 to 50 mph with good repeatability and reproducibility. Speed effects were insignificant. However, in these tests, the equipment often failed to function on certain pavements. Wet pavement and rain also restricted operation of the 8300 RS. The durability and reliability of the 8300 RS was rated low due to frequent breakdowns and failures encountered during field tests. If the durability and reliability were improved, this device would have ranked much higher.

Maysmeter

The Maysmeter proved to be a simple, durable, and highly productive device. It was easy to maintain and operate; however, the device was relatively speed dependent and needed regular calibration with standard test sections. It rated "good" as a control device and was recommended for field trials.

California Profilograph

The California Profilograph was operated manually and at a slow speed. It required lane closure and traffic control during normal operation. It was satisfactory if used for construction smoothness control in untrafficked areas. The significant limitation of the profilograph was the laborious, time consuming, and subjective data analysis. Its data quality was found to be good but the device does not meet ADOT criteria for operation under traffic.

Rainhart Profilograph

The Rainhart Profilograph was similar to the California Profilograph in operational characteristics and capabilities. It was similarly rated.

RECOMMENDATIONS

It was recommended that the 690D Profilometer be field tested in Arizona along with the Maysmeter. The 8300 RS was not recommended for use because of operating difficulties. These difficulties could lead to legal defensibility problems for the final specification. The Profilographs did not meet the general ADOT criteria to be operated before and after overlay on in-service roads at normal speeds.

CANDIDATE ROUGHNESS EQUIPMENT SELECTION

Candidate roughness equipment for preliminary field testing was recommended after a review of technical information, field data to date, and hands-on experience of the authors (Reference 1). The recommendations reflected that the objectives of this study were best fulfilled by evaluating and adopting equipment which was commercially available and therefore most easily obtained, tested, and adapted for use. The recommendations were discussed with the ADOT staff, and the selection was finalized by ADOT.

Candidate roughness equipment selected for preliminary field testing near Austin, Texas included:

Model 690D Surface Dynamics Profilometer (690D)

Model 8300 Roughness Surveyor (8300 RS)

Mays Ride Meter (MRM or Maysmeter)

California type Profilograph

Each roughness device generated its own individual measurement of pavement roughness. Each used a different readout scale. The following desirable features were considered in selecting the candidate roughness equipment:

- Availability
- Capability to generate acceptable roughness summary statistics which are repeatable, stable over time, and closely correlated with the MRM output.
- Ability to compare with acceptable reference roughness profiling equipment, such as SD Profilometer, regarding accuracy, robustness, repeatability, reliability, and credibility.

- Acceptability of important operating characteristics, such as measurement speed, speed dependency of roughness output, ease of operation, calibration requirements, extent of automation in data collection and processing, productivity, and operating costs.

- Accessibility to service facilities and promptness of repair.

- Capability to generate an output that can be used immediately.

Overview of Candidate Equipment

All roughness equipment included in the candidate list, with the exception of the 690D Profilometer, was provided to the project by Arizona DOT and ARE Inc.

690D Profilometer. It was considered imperative to use the SD Profilometer as one candidate device because it provided the full spectrum of profile wavelength output, which no other device provided at the time. Based on a ten year overview of this field the 690D Profilometer was considered the most versatile and complete instrument available in the USA.

Field use of a profilometer was evaluated by review of a Texas State Department of Highways and Public Transportation (TSDHPT) owned 690D Profilometer unit as it measured pavement roughness on several test sections near Austin on a regular basis. TSDHPT also provided a record of recently performed roughness measurements from those sections.

8300 RS. An ADOT owned device was provided for preliminary field testing. Because the device worked on the principles of a profilometer it had great potential. It also was less expensive than the SD Profilometer, but operated in only one wheelpath.

The Mays Ride Meter. The MRM is a response type road roughness meter mounted either on a vehicle or a dedicated trailer. An MRM measures the vertical movement of the rear axle of the vehicle or trailer relative to the frame and presents the results in summary statistics. Once mounted on a vehicle or trailer, the entire system is commonly referred to as a Maysmeter.

Profilographs. Multiple-wheeled profilographs are low speed profiling devices which have been used in California for over 30 years. Several other states, including Arizona, also have used profilographs for construction smoothness control. The Arizona DOT has operated California Profilographs. Rainhart Profilographs have been used by several other agencies, including ARE Inc and some districts of the Texas SDHPT.

Rejected Equipment

The CHLOE Profilometer was considered in the proposed list of candidate devices. This choice was primarily based on the high quality of the device's transfer function. Darlington (Reference 3) plotted the response ratio of various roughness devices which illustrated that regarding output quality that the CHLOE profilometer was next best to the 690D Profilometer. Its operating speed was slow but not slow enough to severely limit construction smoothness evaluation. However, the CHLOE Profilometer was deleted from the final list because of its history of mechanical troubles and the difficulty of finding a working unit. A CHLOE Profilometer this owned by the Arizona DOT but has never worked due to malfunctions.

Also considered were the Techwest Photologger and the Portable Universal Roughness Device, which use accelerometer responses to produce roughness statistics. The Arizona DOT also considered acquiring a Techwest device at the time of this study. These devices were not included in the candidate list for the following reasons:

- A dedicated device should be a preferred choice. However, the Techwest Photologger is a multiple purpose device. Its primary function is photologging (essentially for inventory, and monitoring geometrics, safety features, and traffic characteristics).

- The performance of an accelerometer mounted device is questionable. Experiences with these devices are limited and highly variable. These devices do not measure profile, and unlike the MRM, are relatively new in the area of roughness measurement.

Other equipment considered but not selected for the candidate list included: The French APL (Longitudinal Profile Analyzer), ARAN (Automatic Road Analyzer), Laser RST (Road Surface Tester), PASCO Roadrecon, SIometer and South Dakota Profilometer. The French APL was rejected because it is not currently available in the USA. The roughness devices on "survey vehicles" such as ARAN, Laser RST, and PASCO Roadrecon were not recommended because they are integrated into a system much larger and more complex than needed for construction smoothness control. The SIometer (developed for the Texas SDHPT) and the South Dakota Profilometer (developed by the South Dakota DOT) were created for specific agencies were not available on a commercial basis at the time of Phase 1 of this study (1985-1986). Experience and data pertaining to these devices was limited at that time. The state-of-the-art memo (Reference 1) presents brief technical reviews of all these devices.

COMPARISON OF CANDIDATE DEVICES

Candidate roughness devices vary in their principles of operation, output, format, quality of data, definition of the roughness summary statistics, as well as costs. A preliminary comparison of these devices based on an office evaluation of the equipment specifications and hands-on experience is presented in this section.

Usefulness of Data for Pavement Smoothness Evaluation

The primary purpose of evaluating pavement smoothness is the control of longitudinal roughness of a pavement surface. Haas and Hudson (Reference 22) refer to pavement roughness as the "distortion of ride quality." Hudson (Reference 23) defines road roughness and smoothness as being opposite ends of the same scale. A pavement profile does the best job of characterizing road roughness (Reference 25). In terms of pavement profile, roughness can be defined as the summation of variations in the surface profile of the pavement. Profiles in this sense are limited to wavelengths in the surface of the pavement between approximately 0.1 and 500 ft. A 10-foot straightedge has conventionally been used for pavement construction smoothness control in Arizona and several other states (Reference 1). The use of a 10-ft. straightedge does not adequately measure and control longitudinal roughness. It will miss wavelengths longer than its span and can distort wavelengths that are harmonic of its span. In the case of a sine wave of long wavelength, the straightedge will just ride on it. On the other hand, a 10-foot straightedge will probably miss shorter wavelengths if the sampling interval is 10 feet or more. The problems with rolling straightedges or profilographs are evident. They show a very erratic response ratio (varying from 0 to 2.0) depending on the wavelength of the roughness observed in the pavement.

The Arizona DOT clearly and correctly decided that their 10-foot straightedge smoothness evaluation method did not adequately detect or account for repeated wavelengths or roughness in the highway. In order to account for such roughness, it was essential to obtain a device which has a reference mechanism twice as long as any wavelength to be detected by the instrument. A multi-wheel profilograph or land plane-type device with a 30-foot reference beam would be more useful in evaluating pavement roughness than a typical ten-foot straightedge, yet, it may not be adequate for detecting repeated roughness of longer wavelengths.

Darlington's analysis (Reference 3) shows that the roughometer-type device yields reasonable results only for wavelengths in the range of 4 to 14 feet. Various response-type systems, such as the Maysmeter and PCA meter, have a response similar to the BPR Roughometer, as shown by Gillespie et al. in NCHRP Report 228 (Reference 4). The Maysmeter is preferably operated only at high speeds (up to 55 mph) because response is dependent on speed. The Maysmeter has been around for years. All road meters measure a dynamic effect on roughness in the form of a summary statistic which does not define the pavement profile.

In contrast, a profiling device measures complete information about the pavement profile which can be evaluated according to specific needs. Low-speed systems, such as the CHLOE Profilometer, are moving reference planes. High-speed profilometers such as the 690D Profilometer, are the most desirable as illustrated in Table 2-1, but are rather expensive systems. The 690D

Table 2-1. Comparisons of Pavement Roughness Devices.

PARAMETERS	SURFACE DYNAMICS PROFILOMETER	MODEL 8300 RS	MAYSMETER	CALIFORNIA PROFILOGRAPH	RAINHART PROFILOGRAPH
• VEHICLE REQUIREMENT	Dedicated Van	Dedicated car or van	Dedicated car or towing vehicle	Towing vehicle and trailer	Towing vehicle
• PRINCIPLE	Profile	Profile (reduced to the simulated output of road meters)	Reoponse - type output	Profilogram	Profilogram and roughness counts
• HISTORY OF USE	> 15 Years	3 Years	> 15 Years	> 20 Years	>15 Years
• DESIGNATION OF MEASUREMENT	SI, MO, RMSVA	Mays index, RMSA index	MRM index	Profile index	Profile index
• SPEED WHILE MEASURING	20 to 50 mph	20 to 60 mph	20 to 60 mph	2 mph	2 mph
• LANE CLOSURE AND TRAFFIC CONTROL DURING TEST	Not Required	Not required	Not required	Required	Required
• OPERATING CREW SIZE	2 (Operator, driver)	2 (Operator, driver)	2 (operator, driver)	One operator *	One operator
• IN-FIELD SET UP REQUIREMENTS	Calibration of recorder and output	Bounce test for system checkup, verification of accelerometer's and transducer's calibrations	None	Assembly of the profilograph and setup of stripchart recorder	Change from towing to test configuration and set-up of strip chart recorder
• SECTION LENGTH	No limit	Not recommended for less than 0.1 mile	Not recommended for less than 0.1 mile	No Limit	No limit
• ROUGHNESS DATA COLLECTION IN FIELD	Magnetic tapes or index	Index on printout and possibly cassette tape	Length of chart-record or electronic counter	Strip chart	Unfiltered and filtered counters, strip chart

* Assistance required for assembly and disassembly

Table 2-1. Comparisons of Pavement Roughness Devices (cont'd).

PARAMETERS	SURFACE DYNAMICS PROFILOMETER	MODEL 8300 RS	MAYSMETER	CALIFORNIA PROFILOGRAPH	RAINHART PROFILOGRAPH
• OPERATION (AUTOMATED OR MANUAL)	Automated	Automated	Automated	Manual	Manual
• DETERMINATION OF SECTION LENGTH	Distance measuring instrument	Distance encoder	Car odometer or distance measuring instrument	Measuring tape or wheel (or from strip chart)	Counter (or from strip chart)
• ENVIRONMENTAL RESTRICTION ON INSTRUMENTS	None recommended by manufacture	Test not recommended on wet pavements	None	None	None
• OTHER IN-FIELD INPUTS OR ADJUSTMENTS	None	Ambient temperature input required	Tire pressure check	None	None
• IN FIELD DATA PROCESSING	Complete processing possible	Complete processing and print out	Complete processing (no print out)	None	None
• OFFICE DATA PROCESSING	Complete processing	Tabulating and correlating with SI	Measuring chart length, tabulating counts and correlating with SI	Calculating roughness counts and profile index	Calculating profile index
• LONG-TERM PERFORMANCE	Durable, wheels are susceptable to cutting and may require replacement	Limited use and experience shows need for improvements	Durable, Satisfactory	Durable, Satisfactory	Durable, Satisfactory
• COST	$250,000 complete with all software options	$39,000 with installation	$2,615 for transmitter with recorder ($250 for installation)	$12,000 for 1 - 3 units ($400 shipping cost)	$10,235 for complete unit
OPTIONS	$4000 - $6000 can be deducted for each software (8 - 10 softwares)	——	Trailer = $6,596 Digital counter = $2,200	Recorder box = $370 Parking brake = $285	——
VEHICLE	Dedicated van included in this cost	Customer's vehicle	Customer's vehicle	Customer's transport vehicle	Customer's towing vehicle

Profilometer is a self-calibrating profiling device that has been available for over 20 years.

The 8300 RS is appealing because it claims to calculate pavement profile and the resulting summary statistics which are theoretically vehicle-independent and speed-independent. However, the reliability and robustness of the 8300 RS are suspect.

Comparison of other Parameters

Table 2-1 summarizes useful information associated with the candidate devices. Although the 690D Profilometer was the most expensive equipment, it was also the most versatile. It generated reliable and accurate data at a high production rate. On the other hand, a profilograph was the least expensive roughness device, but it was slow, less productive, labor intensive, and made data processing both time consuming and subjective.

PRELIMINARY EQUIPMENT TESTING & EVALUATION PLAN

A detailed plan was made for preliminary equipment testing and evaluation in Austin of the candidate equipment. The two primary considerations were (1) test sections on selected flexible pavements had to cover all possible variations of roughness, ranging from very smooth to very rough, and (2) field testing of the devices has to be accomplished within a short time frame, or side-by-side when feasible.

Experimental Design

The objective of the field testing program was to evaluate performance capabilities and limitations of the candidate devices. Careful establishment of the experimental design simplifies statistical analysis at later stages. Statistical plans consider how the variables, controlled or uncontrolled, fit together into a scheme which meets specific objectives, yet satisfies practical constraints of time and money. A designed experiment provides the maximum amount of information relevant to the problem by the most efficient use of the available resources.

In order to test the ability to measure roughness data collected for this purpose was grouped by roughness level of the highway and speed of the measuring device. As such, their effects on roughness could be evaluated directly and were under the control of the experimenter.

For this study variables held constant were:

1. Type of pavement (All surfaces are flexible.)

2. Standard operating procedures for each device. (It is important to use the equipment in the configuration and manner which the manufacturer considers to be most appropriate.)

3. Position of device on test section. (The 690D Profilometer measures roughness on both the outside and inside wheelpaths and an average output is calculated. The Maysmeter averages roughness of both wheelpaths. In each test section the other devices measured roughness only in the outside wheelpath, approximately three feet from the pavement edge.)

4. The 8300 RS was installed only on one dedicated van. (Vehicle dependency for this device was not investigated in this study.)

As output from the data processing and interpretation phase, one or more summary statistics, or "roughness numbers," were produced for each test device. SI values were also calculated when applicable. Each summary measurement or statistic was examined and compared to select the most appropriate for each device. As required by contract, the first comparisons were a correlation analysis of Maysmeter output with the outputs of other devices for the test sections. Correlations and regression analyses were performed to evaluate the accuracy, precision, repeatability, and other aspects of the output for each device over the range of test sections. Profilometer data available from Texas SDHPT measurements was used as a comparison standard. Typical summary statistics included RMSVA, MO, Maysmeter index, Mays index generated by 8300 RS, and profile index.

Test Sections

Several flexible pavements with known roughness histories were desirable for the preliminary field testing of candidate devices. For that reason, it was most cost-effective to conduct tests near Austin, Texas where the Texas SDHPT and Center for Transportation Research of the University of Texas at Austin maintain 25-30 test sections which have already been measured extensively on a quarterly basis for over 15 years by the 690D Profilometer.

The test sections chosen for the preliminary equipment testing represented a random sample of flexible pavement sections within the levels of roughness groups defined as primary variables. Table 2-2 lists 28 sections along with their average serviceability index (SI) values as determined from the 690D Profilometer data collected in April 1986. They range from very smooth to very rough. The SI values are defined on a scale of 0-5 as described below.

SI	Subjective Condition Rating	Roughness Range
5	- - - - - -	Smoothest
	Very Good	
4	- - - - - -	
	Good	
3	- - - - - -	
	Fair	
2	- - - - - -	
	Poor	
1	- - - - - -	
	Very Poor	
0	- - - - - -	Roughest

All sections were located in Travis County, Texas. Each section is 0.2 miles long. These sections were selected from highways and roads maintained by the Texas SDHPT and Travis County, Texas.

FIELD TESTING OF CANDIDATE ROUGHNESS EQUIPMENT

Field testing of candidate equipment was planned for May 1986. Key steps to arrange field testing work and to collect roughness data of candidate devices follow:

Table 2-2. Average Roughness Estimates for Selected Austin, Texas Test Sections (The Texas SD Profilometer Data Collected in April 1986).

Section No.	SI	Highway Direction & Location
1	2.11	Decker Lake Rd. (WB) Approx. .2 miles west of FM 973.
2	1.74	Scenic Loop Rd. (NB) .5 miles north of Knuckles Crossing Rd.
3	3.16	FM 973 (NB) .5 miles north of Burleson Rd.
4	1.37	Decker Lake Rd. (EB) Approx. .3 miles west of FM 973.
5	3.61	SH 71 (WB) Just east of FM 973.
6	2.12	McAngus R. (EB) .98 miles east of RM 973.
7	4.60	US 183 (SB) 1.5 miles north of Burleson Rd.
8	3.52	FM 973 (SB) .4 miles south of FM 969.
9	3.98	US 290 (EB) .20 miles east of FM 973.
10	4.40	IH-35 (SB) Just South of 1325 overpass.
11	2.67	Pflugerville Rd. (WB) Just west of Section #38 at Grace Co. Mail Box
14	4.03	FM-1325 (B-NB) Just North of Wells Branch
19	4.15	US 183 (NB) At FM 969 overpass.
23	4.01	SH 71 (WB) Just west of Montopolis Dr.
28	3.13	Loop 360 (NB) Just right at the Taco Bell office.
30	2.12	Dessau Rd. (SB) .8 mile south of FM 685 at fire plug.
31	3.37	FM 685 (NB) Begin at Glamour Pool sign
32	4.41	FM-620 (NB) .22 mile north of FM 2222
33	4.30	FM-620 (NB) .36 mile north of U.S. 183.
34	3.76	FM-620 (NB) 3.10 miles north of U.S. 183.
35	2.73	Dessau Road (NB) 1.75 miles south FM 685.
36	4.45	FM 685 (NB) 1.07 miles north FM 1825.
37	4.44	FM 1825 (EB) .29 miles east IH-35 EFR.
40	3.76	FM 973 (SB) .56 miles south of Schmidt Ln.
41	3.41	FM 3177 (SB) .90 miles south of U.S. 190
44	1.15	Decker Lake Rd. (EB) .70 miles east of FM 3177.
55	2.96	FM 969 (WB) Mi. marker 6 east of FM 3177.
56	1.14	Gregg Manor Rd. (NB) .4 miles north of U.S. 290.

- Finalize testing schedule

- Obtain the Texas SDHPT 690D Profilometer data for Austin test sections

- Provide an ARE Inc technician to be trained on the Model 8300 RS and California Profilograph by the ADOT staff in Phoenix Arizona

- Transport the 8300 RS and the California Profilograph from Phoenix, Arizona to Austin, Texas

- Install the 8300 RS on an ARE Inc van and conduct preliminary runs

- Arrange traffic control

- Perform field tests of the 8300 RS, California Profilograph, and ARE Inc Maysmeter following the plan of designed experiments

- Perform additional reliability tests with the 8300 RS

- Return the 8300 RS and California Profilograph to the Arizona DOT

Equipment Availability in Austin

The Texas SDHPT supported this study by providing full access to roughness data collected by its 690D Profilometer in April 1986. ARE Inc obtained printouts of the 690D Profilometer profile data analyzed by the Department's VERTAC computer program for all of the Austin sections. The approach resulted in considerable cost savings to this project.

8300 RS. The 8300 RS system was disassembled and removed from the ADOT's dedicated vehicle and brought to Austin, Texas where ARE Inc technicians installed it on a dedicated van. The transducer canister was mounted on the right side of the van's rear end after attaching the canister mounting bracket. The distance encoder was installed on the left rear wheel. Keyboard, printer and computer, and all connecting and power cables were installed using directions in the 8300 RS operator's manual. (K.J. Law Inc, the manufacturer provided a senior technician who assisted ARE Inc technicians with distance encoder calibrations and preliminary trial runs.) The same ARE Inc technician was used to drive the 8300 RS during all field tests.

Maysmeter. A trailer mounted Maysmeter owned by ARE Inc was used in this study. Preliminary tests were performed to check the Maysmeter calibration and consistency of results. No significant problems were observed. The same technician who drove the 8300 RS was used for all Maysmeter work to ensure uniformity in the lateral position of both test devices while driving on the test sections. Tire pressure and other operating conditions of the Maysmeter trailer were regularly checked.

California Profilograph. Prior to field tests, the California Profilograph was transported from Phoenix to Austin and assembled using the operator's manual (Reference 25). Trial runs were made to train the operators.

Ranking Criteria

It is important to establish appropriate criteria when comparing the devices in the preliminary tests. The selection criteria used on this task were as follows:

REPEATABILITY	Variations between repeat runs made at the same time are important considerations for this study. The repeatability errors are affected by transverse and longitudinal placement, measurement speed, and the inherent scaling of sensors.
ACCURACY AND REPRODUCIBILITY	This criterion is the variation between measurements made on the same test section using the same operating procedures but at different times over an extended period. Accuracy is related to an instrument's ability to reproduce a "true" or correct value.

CALIBRATION ERRORS	This error is related to long-term drift and shift of output, crucial when considering response-type devices. A reliable reference, such as the SD Profilometer measurements, is necessary to evaluate calibration error.
PRODUCTIVITY	Productivity concerns the number of measurements made per unit of time and is related to the speed with which the device measures roughness numbers for a large quantity of pavement. High productivity is desirable and reduces the unit cost of providing proper roughness construction quality control.
EASE OF DATA HANDLING	A device may be able to collect large amounts of roughness data in a short time, but this data may not be directly useful for smoothness evaluation without further processing. The ease and speed with which meaningful results can be produced is a rating factor.
TRAFFIC INTERFERENCE AND HANDLING REQUIREMENT	Lane closure and traffic control are necessary for slow speed devices for routine roughness measurements. This concerns safety and added cost in heavily trafficked areas.
EQUIPMENT DURABILITY AND ROBUSTNESS	Long-term performance of a device is affected by its durability and robustness. How often does a device breakdown?
RELIABILITY AND PRECISION OF INSTRUMENTS	Good quality roughness measurements are expected only if the reliability and precision of an instrument are acceptable. These criteria are necessary for dependable and satisfactory use of the equipment in routine operation.

EQUIPMENT VERSATILITY	Equipment versatility enables the user agency to develop several applications for the device and provides cost-effective operation on long- term basis.
SENSITIVITY AND CALIBRATION REQUIREMENT OF SENSORS AND MEASURING INSTRUMENTS	These criteria are concerned with instrumentation evaluation and may affect equipment reliability, precision, and accuracy of data.
AUTOMATION IN DATA COLLECTION AND PROCESSING	Fast automatic data collection and processing is a desirable feature. It increases productivity and reduces the chances of errors due to human factors.
EXTENT, QUALITY, AND USEFULNESS OF COLLECTED DATA	These are equally important criteria. A device with high capital cost can provide good cost benefits if its data are quickly produced, are more useful and find more applications than a less expensive device.
ENVIRONMENTAL RESTRICTION ON MEASUREMENTS	Environmental restrictions like rain, wet pavement or abnormal temperature limit productivity and full use of the equipment and may affect quality and accuracy of data. Different equipment may be affected to varied degrees by these restrictions.
SYSTEM SET-UP AND OPERATION COMPLEXITY	System set-up complexity refers to laborious, time consuming or complicated procedures required to set-up the device for operation. For example, the California profilograph is required to be assembled at the test site. Similarly operation complexity refers to slow, laborious or complicated operating procedure. These are also important parameters which influence productivity and may pose varied training and education requirements on the operator(s) resulting in high operating costs.

OPERATING CREW SIZE	The number of persons required to operate the equipment is necessary information for comparison of the candidate devices because the number of operating persons influences operating costs and unit data costs.

<u>Summary of Field Testing Work</u>

The field testing work started in May 1986 and finished during the third week of July 1986. This unexpectedly long period was the result of:

- Frequent failures and breakdowns of the 8300 RS device.
- Delays caused by the slow speed of the profilograph and associated traffic control coordination with local authorities.
- Delays in test schedules resulting from rains.

The 8300 RS device was disassembled and packed, and returned to the Arizona DOT along with the California Profilograph on July 28, 1986.

The field tests were monitored and the test data recorded on specially design test forms (See Figure 2-1). Table 2-3 compares several parameters associated with the field tests carried out with each roughness device. These include:

- Total number of sections tested.
- Period during which field tests were performed.
- Number of times when major equipment failures/or breakdowns were encountered.
- Average test duration.
- Number of operators.

FIELD DATA COLLECTION FORM

PROJECT NO. HPR 1-29 (217)
MEASUREMENT OF PAVEMENT SMOOTHNESS

ARE PROJECT: AZ-60

PRELIMINARY TESTING OF CANDIDATE ROUGHNESS DEVICES

Device Model 8300 ____________ Date

Y	Y	M	M	D	D

Operator ____________ Driver ____________ Recorder ____________

Time of day the device and operator arrives at section ________

Test Section No. ______ Direction ______ Wheel path (circle) inside/outside

Section Description ________________________________

Weather __________ Cloud Cover __________ Ambient Temperature (°F) ______

Speed while measuring ________MPH In-field setup time ________

(Minimum 3 repeat runs at every section)

Run No.	Time Started	READINGS			Time Finished	Comments
		First Sampling	Second Sampling	Third Sampling		
1						
2						
3						
Mean						

Data presentation form (circle) counter/digital/chart/tape/disc

Calibration requirement ____________ Tire pressure (warm) ____________

Demobilize time ____________ Time leave site ____________

Specific Notes ________________________________

WU/AZ60/Pk TEST/5-13-86

Figure 2-1. A Sample Data Collection Form Used During Roughness Measurements.

Table 2-3. A Comparison of Various Parameters Associated With the Roughness Field Tests.

Parameters	690D Profilometer	Model 8300RS	Maysmeter	California Profilograph	Rainhart Profilograph
1. Number of Sections tested	28	28	28	12	12
2. Field tests started: completed:	[April 1986]	5/14/86 7/18/86	5/20/86 5/29/86	6/16/86 7/16/86	6/16/86 7/16/86
3. Major equipment failures	None	Yes	None	None	Yes
4. Minor break-downs	None	several times	None	Once	Once
5. Major output in field	Digital profile data on magnetic tape	Hard copy print out	Counts recorded manually on forms	Strip chart record	Strip chart and counts records
6. Output after office data processing	Roughness statistics	None	None	Profile Index	Profile Index
7. Form of office data processing	Comptuer Program	Not Required	Not Required	Manual	Manual
8. Measurement speed	20 mph	40,50 mph	40,50 mph	2 mph	2 mph
9. Simulation speed (for roughness statistics)	50 mph	50 mph	N/A	N/A	N/A
10. Number of Operators (including driver/assistant)	2	2	2	2	2
11. Average test duration (minutes)*	= 20 min (estimate only)	13-27 min	10-35 **	31-41 **	29-45 **
12. Traffic control required	No	No	No	Yes	Yes
13. Vehicle requirements	Dedicated Van	Van-Mounted	PU truck for towing	Trailer (for transportation) Towed by PU	PU truck for towing

* Based on: 3 repeat runs for 690D Profilometer and profilograph tests
6 repeat runs for Model 8300RS and Maysmeter

** In addition, 15-20 minutes set-up time and 10-15 minutes of demobilization time were required for the profilograph tests.

- Traffic control requirements.

Information provided about the 690D Profilometer is based on the experience of University of Texas researchers at the Center for Transportation Research.

690D Profilometer Data

The profilometer data was measured at a speed of 20 mph. A sample sheet of the processed roughness data measured by the Texas 690D Profilometer is presented in Figure 2-2. These measurements were performed during April 1986. Generally, three repeat runs were made of every section. The output was generated by the VERTAC program (Reference 10) which analyzed the measured profile data and produced the following summary statistics at a simulated speed of 50 mph.

- RMSVA, ft/sec^2, (right wheelpath, left wheelpath, combined at base lengths of 0.5, 1.0, 2.0, 4.0, 8.0, 16.0, 32.0, 64.0 and 128.0 feet)

- SI (Serviceability Index per AASHO Road Test definition) estimate associated with each of the above base lengths.

- MO, counts/0.2 mile (MRM simulated statistic).

- SI for the whole section involving composite/ RMSVA base lengths

Detailed explanations of various roughness statistics were presented in Chapter 5 of the Interim Report (Reference 2).

8300 RS Testing

8300 RS was used during May 1986 to measure roughness on the test sections for initial and replicate data sets. Table 2-3 summarized significant test parameters associated with the field testing of this device. However, it should be noted that:

- Roughness was measured at speeds of 40 and 50 mph. The manufacturer does not recommend running this device below 40 mph.

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AUSTIN TEST SECTIONS APR,86 SECTION NO. 32          RUN3

1056 FT. SECTION  BEGINS    0 FT. FROM MARK  0 IN FILE PROF3

        GAINR: 1000.0              GAINL: 1000.0

RMS VERTICAL ACCELERATION (FT/SEC SQ) AT 50 MPH:

BASE LENGTH    RIGHT      LEFT     COMBINED     ESTIMATED SI

      0.5      70.35     33.32     51.83          3.06
      1.0      19.75     10.45     15.10          3.56
      2.0       4.99      3.33      4.16          4.44
      4.0       1.71      1.24      1.48          4.43
      8.0       0.60      0.54      0.57          3.99
     16.0       0.36      0.31      0.33          3.64
     32.0       0.25      0.21      0.23          3.14
     64.0       0.14      0.13      0.13          2.70
    128.0  .    0.04      0.03      0.04          3.01

MO (MRM SIMSTAT) (COUNTS/.2 MILE):      27.91

FLEXIBLE PAVEMENT SERVICEABILITY:       4.42

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AUSTIN TEST SECTIONS APR,86 SECTION NO. 33          RUN1

1056 FT. SECTION  BEGINS    0 FT. FROM MARK  0 IN FILE PROF4

        GAINR: 1000.0              GAINL: 1000.0

RMS VERTICAL ACCELERATION (FT/SEC SQ) AT 50 MPH:

BASE LENGTH    RIGHT      LEFT     COMBINED     ESTIMATED SI

      0.5      65.20     36.49     50.85          3.07
      1.0      18.36     11.77     15.07          3.56
      2.0       4.94      3.81      4.38          4.36
      4.0       1.89      1.42      1.65          4.26
      8.0       0.79      0.58      0.69          3.79
     16.0       0.42      0.27      0.35          3.60
     32.0       0.18      0.13      0.15          3.71
     64.0       0.07      0.06      0.06          3.64
    128.0       0.01      0.01      0.01          3.84

MO (MRM SIMSTAT) (COUNTS/.2 MILE):      32.41

FLEXIBLE PAVEMENT SERVICEABILITY:       4.30

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Figure 2-2. A Sample of Partial Output of the 690D Profilometer Data.

- Roughness measurements with this equipment did not require lane closure or traffic controls because the equipment operated at "normal" highway speeds.

- Average duration of six test runs (three at 40 mph and three at 50 mph) was approximately 25 minutes for a 0.2 mile test section.

- The bounce test was made at the beginning of every test day for system verification. The test took 10 to 15 minutes.

- When the system check is satisfactory, it takes merely 2 or 3 minutes to be ready for testing. This time is used to enter or change identification information, a task that can be accomplished by the operator while the driver moves the vehicle to the test section.

Problems and Failures. Several problems and failures occurred during the first two sets of tests and later during additional reliability testing. Numerous spare parts were provided by ADOT and the manufacturer K.J. Law during the three months of testing. In addition, it was necessary to ship the CPU box (computer unit) to K.J. Law Inc. for checkup. Acoustic errors accounted for most problems. Malfunction of the acoustic preamp circuit board (PCB) occurred several times. K.J. Law Inc. provided full cooperation and assistance to overcome equipment failures.

Operating Restrictions. Roughness measurement cannot be made on wet pavement due to the influence on ultrasonic sensors. On certain rough textured chip sealed and surface treated pavements the equipment often gave an acoustic error message and did not measure roughness.

Output. The 8300 RS has digital display capability of the roughness readings at every 0.1 mile and simultaneously can print the results on a hard copy. A major advantage of the device is that it generated roughness statistics immediately after a test. A sample output is presented in Figure 2-3. The following roughness statistics were printed:

K.J. LAW ENGINEERS INC. ROUGHNESS SURVEYOR MODEL 8300

MONDAY 05/19/86 14:03:15

RUN NUMBER:	3
ROAD DESCRIPTION:	NO.36
DIRECTION MEASURED:	NORTH
LANE:	ROWP
BEGINING MILEPOST:	50.00
SIMULATED SPEED (MPH):	50.0

MILEPOST	DISTANCE TRAVELED	MAYS INDEX	RMSA INDEX
50.1	0.10	101	18.5
50.2	0.20	76	14.4

Figure 2-3. A Sample Output of Model 8300 RS Data.

MAYS Index: inches/mile

RMSA: inches/mile

Reliability Tests. After nearly one month of trials, failures, trouble shooting, and replacements of parts, a K.J. Law technician arrived in Austin and made the 8300 RS device function satisfactorily beginning on July 14, 1986. Reliability tests were made on test sections 4, 19, 44, and 55. All data were collected during July 15-18, 1986 and represented periodic intervals between 9 am and 7 pm.

Maysmeter Testing

The calibration of the Maysmeter Distance Measuring Instrument (DMI) was checked and found to be satisfactory during April 1986. The initial and replicate tests were completed during May 1986 on all test sections. Information related to the Maysmeter testing is included in Table 2-3. Points of interest are summarized below:

- Roughness was measured at speeds of 40 and 50 mph. ADOT uses 45 and 50 mph for MRM tests. The speed of 50 mph is a widely accepted standard speed for Maysmeter testing; therefore, this speed was adapted for the 8300 RS tests.

- Traffic control was not required for Maysmeter tests because of its normal highway driving speed during roughness measurement.

- The duration of six test runs (three at 40 mph and three at 50 mph) ranged between 20 and 30 minutes for a 0.2 mile test section.

- No significant equipment problems or failures were encountered during the field tests.

Roughness counts are shown on a digital display at the end of each 0.2 mile test run and recorded manually on data forms. The unit of measurement is MRM counts/0.2 mile.

Profilograph Testing

California Profilograph tests were completed in a one month period (June 16 - July 16, 1986). In addition, the Rainhart Profilograph was also used to measure roughness. Due to the slow speed (2 mph) at which these profilographs were pushed, lane closure and traffic control were necessary during measurements. Because of practical constraints and heavy traffic, it was not possible to make profilograph tests on all test sections. Therefore, only 12 selected sections (three from each roughness group) were measured by the profilographs. Table 2-4 lists the sections.

Profilographs were tested one after the other. Time for three test runs ranged between 60 and 90 minutes. The California Profilograph was easier to push and smoother to operate.

Traffic Control. On four-lane roadways, the test lane was closed using guidelines in the Texas Manual of uniform traffic control (Reference 26). An arrow board sign truck was used during these tests. On two-lane roadways, two flagmen were also used.

California Profilograph Data. There were no equipment problems during roughness measurements made in the initial and replicate sets of tests, until the last run of the last day when one of the averaging wheels broke off from its welded joint on the assembly. Figure 2-4 illustrates a copy of partial output from the strip chart recorded of the California profilograph. Unlike the Rainhart Profilograph, there is no counter on the California Profilograph. Roughness counts are measured from profilogram (output of the strip chart recorder) using a 0.2 inch blanking band. This manual procedure is described in References 20 and 25.

Rainhart Profilograph Data. The initial set of roughness measurements was made using the option of a longitudinal scale of one inch equal to 10 feet on the strip chart recorder. This data set was not used in the data analysis and comparison. The replicate set of data was collected simultaneously with the California Profilograph test using the option of a longitudinal scale of one inch

Table 2-4. List of Test Sections Used for Profilograph Tests.

Roughness Group	SI Range	Test Sections*			Sections Selected for Profilograph Tests	Average SI
		4 Lane Heavy Traffic Highway	4 Lane Moderate Traffic Highway	2 Lane Roadway		
1	4.01 - 5.0	7, 10, 14, 19, 23, 37	32, 33, 36	-	32 33 36	4.41 4.30 4.45
2	3.01 - 4.0	5, 9, 28	31, 34, 41	3, 8, 40	31 34 41	3.37 3.76 3.41
3	2.01 - 3.0	55	-	1, 6, 11 30, 35	6 11 35	2.12 2.67 2.73
4	0.0 - 2.0	-	-	2, 4, 44, 56	4 44 56	1.37 1.15 1.14

* All test sections are on outside lane except section #36 which is located on the inside lane.

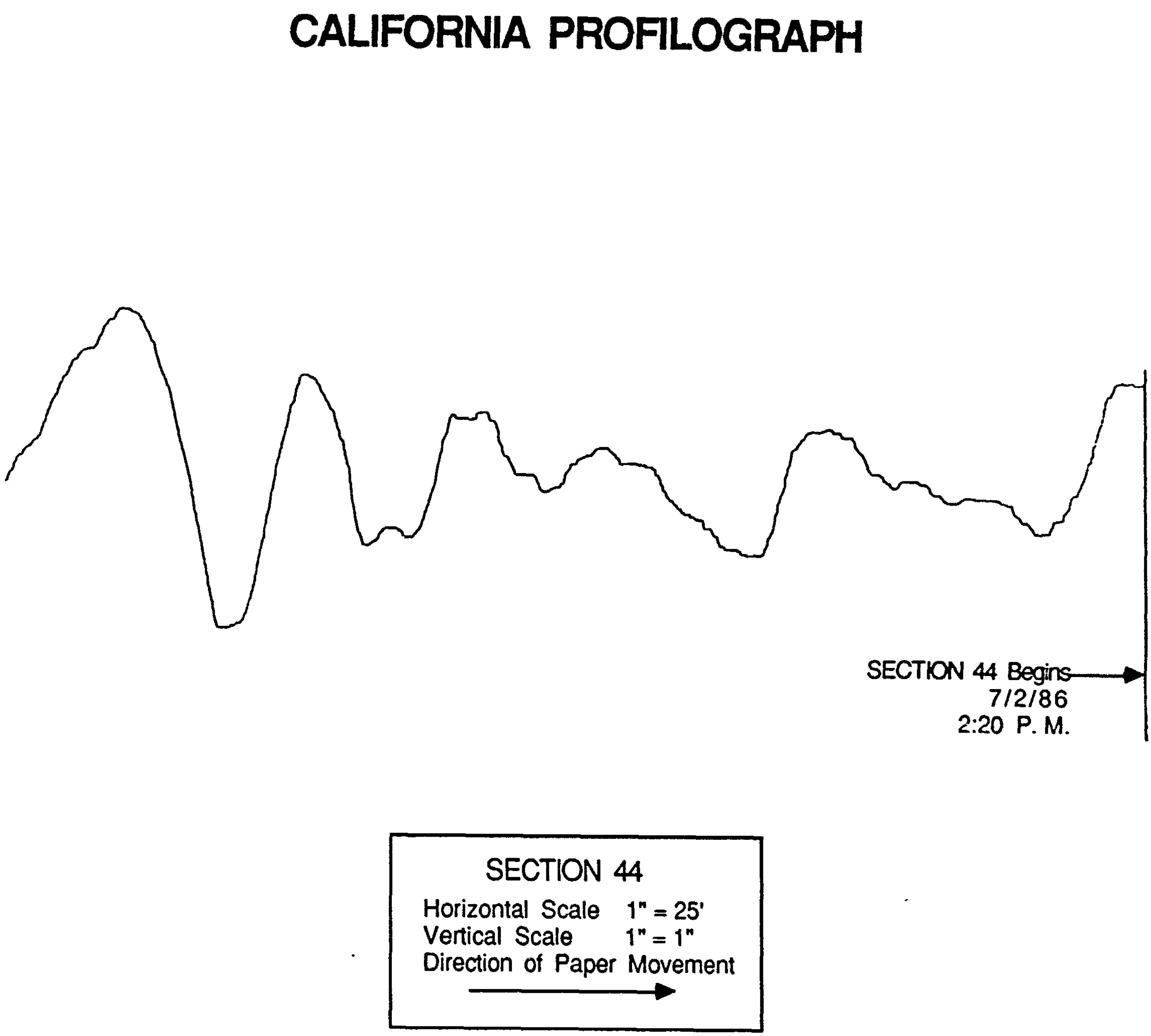

Figure 2-4. Example of a Strip Chart Record of the California Profilograph.

equal to 25 feet. The Rainhart Profilograph outputs on strip charts was manually analyzed by using 0.1 inch blanking band.

Summary of Roughness Data

Table 2-5 presents a factorial representation of the collected data used for analysis and comparison. During all Maysmeter and 8300 RS tests the same driver-operator was used. Profilograph tests were made with two to four different operators. Operations of both profilographs were easy to learn. Therefore, operator error should not be significant. Roughness measurements from strip charts were accomplished by two of the equipment operators.

A listing of the roughness data for each of the five devices was included in Appendix B of the Interim Report as were detailed analyses (Reference 2).

8300 RS Reliability Tests

Summary statistics based on the Mays Index data collected during reliability tests are presented in Table 2-6. A comparison of means and analysis of variance show:

- The 8300 RS roughness measurements made at different times of day show some variation.

- There is no significant effect of speed of measurement on the 8300 RS output.

The same dedicated vehicle was used during all field tests of the 8300 RS device. Therefore vehicle dependency could not be investigated.

PRIMARY EVALUATION OF CANDIDATE EQUIPMENT

Comparative evaluation of all four candidate roughness devices (690D Profilometer, 8300 RS, Maysmeter and California Profilograph) was made from the following two perspectives:

Table 2-5. Summary of Roughness Data.

DEVICES	INITIAL (I) REPLICATE (R)	ROUGHNESS GROUP A: Number of Sections Tested	A: Repeat Runs / Section	B: Number of Sections Tested	B: Repeat Runs / Section	C: Number of Sections Tested	C: Repeat Runs / Section	D: Number of Sections Tested	D: Repeat Runs / Section	OPERATING CREW SIZE
690D Profilometer	I	9	3	9	3	6	3	4	3	2 (Operator - Driver) *
Model 8300 RS	I	9	3	9	3	6	3	4	3	2 (Operator - Driver)*
	R	9	3	9	3	6	3	4	3	
Maysmeter	I	9	3	9	3	6	3	4	3	2 (Operator - Driver)*
	R	9	3	9	3	6	3	4	3	
California Profilograph	I	3	3	3	3	3	3	4	3	2 (one Operator, one Assistant)
	R	3	3	3	3	3	3	3	3	
Rainhart Profilograph	R	3	3	3	3	3	3	3	3	2 (one Operator, one Assistant)

* Same team of operator - driver was used for all tests of this device

Table 2-6. Summary Statistics of Model 8300 RS Reliability Data.

Time of Test	Date	Speed	Section Number			
			44	04	55	19
9:05 am	07/16/86	40 mph	362.7* (0.02)**	315.5 (0.03)	150.7 (0.08)	65.7 (0.09)
		50 mph	360.2 (0.01)	309.8 (0.03)	145.8 (0.07)	70.5 (0.08)
10:15 am	07/15/86	40 mph	352.8 (0.04)	307.2 (0.02)	147.3 (0.04)	64.3 (0.02)
		50 mph	372.7 (0.01)	307.8 (0.03)	146.3 (0.05)	62.8 (0.05)
12:17 pm	07/15/86	40 mph	362.3 (0.01)	310.3 (0.06)	142.67 (0.03)	65.0 (0.09)
		50 mph	369.8 (0.01)	305.2 (0.01)	148.3 (0.08)	64.8 (0.10)
1:50 pm	07/15/86	40 mph	352.8 (0.01)	304.0 (0.03)	150.5 (0.04)	62.3 (0.08)
		50 mph	353.3 (0.02)	308.7 (0.01)	145.0 (0.08)	57.5 (0.03)
	07/18/86	40 mph	365.5 (0.03)	318.3 (0.01)	174.7 (0.05)	58.0 (0.05)
		50 mph	359.0 (0.02)	321.2 (0.001)	152.7 (0.09)	60.2 (0.05)

* Mean (inch/mile)
** Coefficient of variation

- Evaluation and comparison based on the analyses and interpretation of the roughness data.

- Technical evaluation and comparison of the performance based on hands-on experience and field tests performed in Austin, Texas.

The Rainhart Profilograph was not ranked in these evaluations and comparisons because it was not an original part of the study and the California Profilograph fulfills the requirements for profilograph type roughness measuring devices.

Tables 2-7 and 2-8 summarize various evaluation criteria and the associated findings for each of the four candidate devices. These findings are briefly discussed below.

<u>Quality of Roughness Data Evaluation</u>

Analyses of the roughness data by sound statistical methods indicated that the candidate devices could be ranked considering repeatability, accuracy and reproducibility, speed dependency and correlation with RMSVA statistics.

<u>Repeatability</u>. Repeatability errors were related to variations within three repeat runs made on each section. The repeatability error within a section at a given time is indicative of the precision of a particular measurement. This type of error was small for all devices when compared to variations due to roughness levels and sections within these levels. However, comparing the coefficient of variation calculated for the repeat measurements for each device the devices were rated as shown in Table 2-7. The 690D Profilometer data showed the least variation and the California Profilograph showed the largest variation.

<u>Accuracy and Reproducibility</u>. This criterion was the variation between replicate measurements made on a test section using the same operating procedure. The 8300 RS and California Profilograph showed better reproducibility than the Maysmeter as noted in Table 2-7.

Table 2-7. A Summary of Evaluation and Ranking of the Candidate Roughness Devices.

Criteria	690D Profilometer	Model 8300 RS	Maysmeter	California Profilograph
1. Quality of Roughness Data				
Repeatability	1	2	2	3
Accuracy and Reproducibility	1	2	3	2
Speed dependency	1	1	2	1
Correlation with Maysmeter	1	1	1	2
2. Instrumentation Precision and Reliability				
Precision	1	2	2	3
Reliability	2	4	2	2
Distance Accuracy	1	1	1	2
Sensitivity to Calibration	1	2	2	1
3. Operating Restrictions				
Environmental Effects	2	5	1	2
Traffic Interference	1	1	1	3
Operating Speed	1	1	1	2
4. Set-up and operating complexities				
Set-up Complexity	1	1	1	4
Operating Complexity	2	1	1	3
5. Equipment Durability and Robustness	1	5	2	2
6. Automated Data Collection and Processing				
Computer Compatability	1	2	3	4
Availability and Quality of data on-board	1	2	3	4
Productivity	1	1	1	4
7. Equipment versatility	1	3	3	4
8. Cost	4 (Highest)	3	1	1

Rankings: 1 = Very Good 2 = Good 3 = Fair 4 = Poor 5 = Very Poor
Note: Table 20B summarizes overall ranking of the candidate devices.

Table 2-8. Overall Ranking of the Candidate Devices.

Criteria	690D Profilometer	Model 8300 RS	Maysmeter	California Profilograph
1. <u>Quality of Roughness Data</u>				
a) Total ranking score	(4)	(6)	(8)	(8)
b) Ranking	1	2	3	3
2. <u>Instrumentation Precision and Reliability</u>				
a) Total ranking score	(5)	(9)	(7)	(8)
b) Ranking	1	4	2	3
3. <u>Operating Restrictions</u>				
a) Total ranking score	(4)	(7)	(3)	(7)
b) Ranking	2	4	1	4
4. <u>Set-up and Operating Complexities</u>				
a) Total ranking score	(3)	(2)	(2)	(7)
b) Ranking	2	1	1	3
5. <u>Equipment Durability</u>				
a) Total ranking score	(1)	(5)	(2)	(2)
b) Ranking	1	4	2	2
6. <u>Automated Data Collection and Processing</u>				
a) Total ranking score	(2)	(4)	(6)	(8)
b) Ranking	1	2	3	5
7. <u>Equipment Output</u>				
a) Total ranking score	(2)	(5)	(5)	(8)
b) Ranking	1	2	2	4
8. <u>First Cost</u>				
a) Total ranking score	(4)	(2)	(1)	(1)
b) Ranking	4	3	1	1
Sum of Total ranking score	(25)	(40)	(33)	(49)
Sum of Rankings	13	24	15	25
*OVERALL RANKING	1	3	2	3

a) Numbers in circles show total ranking scores in each category (based on Table 20A).

b) Ranking in each category based on total ranking scores.

* Overall rating of each device (1 = Very good, 2 = Good, 3 = Fair, 4 = Poor, 5 = Very Poor).

Speed Dependency. The influence of speed on roughness measurements was investigated for the Maysmeter and 8300 RS. Both of these devices were operated at 40 and 50 mph. In general, the Maysmeter showed significant variation across the two speeds. On the other hand, the 8300 RS showed no significant effect of speed on the roughness measurement. The SD Profilometer and California Profilograph were operated at a single speed which represented the standard operating speed for these two devices.

Correlation with the Maysmeter. The study required correlation of each device with the Maysmeter. The output of each device correlated high with the Maysmeter output. Every device with an absolute value of equal to or greater than 0.9 for its correlation coefficient was assigned a ranking of one. Both the 690D Profilometer and 8300 RS were assigned a ranking of one. The California Profilograph was assigned a ranking of 2 because its correlation coefficient was 0.858.

Instrumentation Precision and Reliability Evaluation

The 690D Profilometer proved to be a reliable and precise instrument. Monitoring of field tests and hands-on experience suggested the following parameters for comparison.

Precision. Any acceptable measuring instrument and technique must provide precise output. The 690D Profilometer ranked highest in this category. The 8300 RS measurement was sensitive to temperature. However, the system could compensate for temperature if proper inputs were made by the operator. The Maysmeter provided proven precision based on experience if speed was held constant. This was more important on very rough surfaces. The least precision was shown by the profilograph because of purely mechanical linkage and manual data interpretation.

Reliability. In-use reliability is a critical element of an instrument's performance. During the field tests, the 8300 RS showed poor reliability. Frequent breakdowns occurred and insufficient trouble shooting guidelines were provided in the operator's manual. It, therefore, ranked lowest in Table 2-7 in this category. The 690D Profilometer used in the field tests was given a high ranking of one in this category.

Distance Accuracy. With the exception of the profilograph, other devices showed acceptable distance accuracy. The profilograph gave 4 to 5 feet of error in every 1000 feet. It was possible, however, to take into account this error if it was consistent. The Profilograph was thus assigned a ranking of 2 as shown in Table 2-7.

Sensitivity to Calibration. The 690D Profilometer is self-calibrated. The Maysmeter and 8300 RS were harder to calibrate. The profilograph did not need any specific calibration if properly setup.

Operating Restrictions Evaluation

Several parameters contributed to operating restrictions and subsequently affect the quality and productivity of roughness measurements.

Environmental Effects. Operational restrictions due to rains, wet pavement and very low temperature gave the 8300 RS the lowest ranking in this category. In addition, sometimes it did not measure roughness on certain types of coarse textured pavement surfaces. These restrictions primarily applied to the operation of the ultrasonic sensors. The profilograph was operated manually. It was difficult and somewhat unsafe to operate in rain. The SD Profilometer could be operated on wet pavement, but it was also somewhat impractical to operate in heavy rains because of the chance of damaging the transducers. The Maysmeter was the least restricted device regarding environmental operating factors.

Traffic Interference. In normal operation, the profilograph was operated with lane closure and traffic control. For newly constructed pavements (not open to traffic) this was not a critical restriction. On the other hand, if roughness measurements were required before overlay and rehabilitation work, then the profilograph test incurred higher operating cost due to traffic control and lane closure. This higher cost would also occur if roughness measurements were required after rehabilitation work, as was the case in urban or heavily trafficked areas. Therefore, a ranking of 3 was assigned to the profilograph as shown in Table 2-7.

Operating Speed. A slow measurement speed restricts productivity during normal operation of the profilograph. However, it did not appear critical for short lengths of newly constructed pavements which were being monitored for construction smooth control. All other devices operated at higher speeds.

Set-up and Operating Complexities Evaluation

The California Profilograph ranked lowest in the category of set-up complexity because it required two persons and about 15 minutes for initial assembly and set-up of the device. The profilograph again ranked lowest in the category of operating complexity. It was operated manually and was very sensitive to steering maneuvers. After the test, it was moved back manually to the starting point for repeat measurement. The stripchart paper adjustment and identification data were made manually. This manual procedure made its operation easy but laborious and slow. On the other hand, the 690D profilometer's operation required a good educational background and training. The 8300 RS and Maysmeter rank highest here because of the simplicity of their operating procedure and the relatively short training time required for operators.

Equipment Durability and Robustness Evaluation

These were important considerations for evaluating long-term performance of a device. Based on experience and usage record, the 690D Profilometer ranked highest in this category. The Maysmeter was ranked second because long experience shows it is durable and robust if properly maintained and operated. During these field tests, no breakdown of the Maysmeter occurred. The profilograph ranked high like the Maysmeter. It was relatively simple and easy to maintain. However, one of the support wheels broke away during the last test run of these field tests. These three devices all had several years of prior satisfactory use and shake down.

The 8300 RS was ranked lowest in this category because of the frequent breakdowns and equipment failures experienced during three months of testing. However, improved design of the 8300 RS system could change this adverse ranking.

Automated Data Collection and Processing Evaluation

Automated data collection and processing were evaluated in the following parameters.

Computer Compatibility. The 690D Profilometer was the best device in this category. The digitized data could be processed using the on-board computer or it could be transferred directly to a mainframe computer for processing. The 8300 RS data could be recorded on a cassette but it would need further work to be compatible to a mainframe or office computer facility. The Maysmeter and Profilograph as tested were not computer compatible.

Availability and Quality of On-Board Data. The 690D Profilometer ranked highest because it could save and process profile points using the on- board computer. The 8300 RS ranked second because it printed summary statistics and section identification information using the on-board printer, but it did not save the profile data. The Maysmeter ranked next, since it only displayed roughness measurements but summarized them automatically. The profilograph generated only a strip chart record and did not give a roughness statistic in the field. Office processing was necessary to calculate the Profile Index. Therefore, the profilograph ranked lowest in this category.

Equipment Output Evaluation

Versatility. The 690D Profilometer was the most versatile equipment tested. It generated digitized profile data, which provided the best source for calculating roughness statistics at the time of measurement and in the future. It provided repeatable and stable data that could be used to calibrate and/or verify other devices. The profilograph was the lowest ranked device in this category because its application was limited and its final output was subjective.

Productivity. The Profilograph was the least productive device because of its slow measurement speed and time consuming data processing. The other three devices were more productive and approximately equal in potential output. However, the observed production was greatest for the 690D Profilometer because it required the least calibration time and experienced fewer breakdowns than the 8300 RS.

Initial Cost

With respect to initial or capital costs, the 690D Profilometer was the most expensive device and, therefore, ranked lowest. The profilograph and the Maysmeter were the least expensive, followed by 8300 RS. However, first cost was only a part of the cost picture. Life cycle costs are presented in a later section of this chapter.

Overall Ranking of Candidate Equipment

The information presented above and in Table 2-7 must be summarized. Table 2-8 summarizes total ranking scores and overall ranking of these devices. From a practical point of view, the reliability and durability of the 8300 RS system was low. The California Profilograph has the obvious limitation of subjective data analysis, which also was laborious. The Maysmeter needed regular calibration. On the other hand, the 690D Profilometer was the most expensive device. Considering all the various evaluation criteria, the following overall ranking of these four roughness devices emerged.

Device	Rank	
690D Profilometer	1	(Very good)
Maysmeter	2	(Good)
California Profilograph	3	(Fair; but it was slow, laborious to use and gave subjective results.)
8300 RS	3	(Fair; but would be good if the equipment durability and reliability was improved.)

Other Evaluation Considerations. In addition to the evaluation criteria just mentioned, other considerations must be discussed. They are:

- Life-cycle costs
- Legal defensibility
- State DOT experience
- Impacts of the 1985 AASHTO proposed specification
- Technology impacts
- Miscellaneous additional factors

Life-cycle Cost Analysis

In order to more adequately compare the costs of owning and operating the potential equipment, a life-cycle cost analysis was performed.

Table 2-9 presents data used for calculating equipment cost, maintenance cost (in addition to investment, storage and insurance) and operating cost. The annual investment and insurance costs were computed as 7.5% of the declining principal balance assuming equal payments over the expected life of each device. These costs were then translated to unit costs per lane mile based on the estimated annual use of 630 lane miles per year suggested by ADOT personnel as the probable acceptance testing use per year.

Table 2-10 summarizes the results of an alternative economic evaluation over an analysis of 30 years. Estimated equipment replacement costs (Profilometer at 15 years and the other two devices at 10 and 20 years) were used in this life-cycle analysis. The analysis was performed for testing 630 lane miles of new construction and overlays per year. The analysis shows that the Maysmeter is the least costly device under the conditions assumed in these computations.

Table 2-9. Life-cycle cost analysis of pavement smoothness measurements.

(Equipment Cost Analysis)

Items	690D Profilometer	Maysmeter	Profilograph
Acquisition Cost	$250,000.00 with van	$11,661+10,000 for towing vehicle	$13,055+10,000 for trans- port vehicle
Expected Life, Years	15	10	10
Salvage value, %	20	10	10
Ownership cost			
Depreciation (D): D = Acquisition Cost [1 - salvage/100]/Life	$13,333.33/year	$1,949.49/year	$2,074.95/year
Investment, insurance (S):	$ 9,999.85/year	$ 893.52/year	$ 951.02/year
Maintenance and repair:	$2000.00/year (=0.15D)	$974.75/year (=0.5D)	$1,037.48/year (=0.5D)
Maintenance and Service of on-board computer:	$2000.00/year (=0.15D)	0.00	0.00
Total ownership Cost (CO):	$27,332.85/year	$3,817.76/year	$4,063.45/year
Unit cost of equip-ment(CE): (For 630 lane mile per year; assuming three repeat runs per measurement) CE = (CO)/(630 x 3)	$14.46/lane mile	$2.02/lane mile	$2.15/lane mile
Maintenance invest-ment, insurance & cost only:	$ 7.41/lane mile	$0.99/lane mile	$1.05/lane mile

Note: Assuming: New construction (15 projects per year; 3 mile long projects; 3 lanes each way) is about 270 lane miles/year

Overlay (30 projects per year; 6 mile long projects; 2 lane each way) is about 360 lane miles/year.

Table 2-9. Life-Cycle cost analysis of pavement smoothness measurements. (continued)

(Operating Cost Analysis)

Items	690D Profilometer	Maysmeter	Profilograph
Equipment	$14.46/lane mile	$2.02/lane mile	$2.15/lane mile
*Calibration	$0.00/lane mile	$7.94/lane mile	0.00
Transportation/ towing vehicles: Vehicle traveling ($.10/mile)			
a) on test section (3 repeat measurements)	$0.30/lane mile	$0.30/lane mile	$0.00/lane mile
b) to test section and back to central office (assume 100 mile each way) For 45 projects per year	$1.43/lane mile	$1.43/lane mile	$1.43/lane mile
Traffic Control (4 hrs. per lane mile $50 per hr.)	not applicable	not applicable	$20.00/lane mile
Operation 2 operator (rate includes overhead or boarding and lodging) for 150 days/year. Assuming 2 days per new construction project and 4 days per overlay project (before and after)	$71.42/lane mile ($150/day/operator)	$57.14/lane mile ($120/day/operator)	$57.14/lane mile ($120/day/operator)
TOTAL COST PER LANE MILE	$87.61	$68.83	$81.02
TOTAL OPERATING COST PER LANE MILE (without equipment cost)	$73.15	$66.81	$78.57

Note: These cost estimates are based on 630 lane miles/year of new and overlay construction.

*Assume that the Maysmeter is calibrated six times a year at $500 each (Calibration sections are checked by a profile device or rod and level procedure four times per year).

Table 2.10. Alternative Life-cycle Cost Analysis of Pavement Smoothness Measurement Equipment.

Analysis for 630 lane miles/year

Year	PWF *	PROFILOMETER Equipment $ 250000 per unit	PROFILOMETER Maintenance $14.02 per lane mile	PROFILOMETER Operation $73.15 per lane mile
0	1.000	250000.00	8832.60	46084.50
1	0.963		8505.15	44376.02
2	0.927		8189.84	42730.88
3	0.893		7886.22	41146.73
4	0.860		7593.86	39621.31
5	0.828		7312.33	38152.45
6	0.797		7041.25	36738.03
7	0.768		6780.21	35376.05
8	0.739		6528.85	34064.57
9	0.712		6286.81	32801.70
10	0.685		6053.74	31585.65
11	0.660		5829.31	30414.69
12	0.636		5613.20	29287.13
13	0.612		5405.10	28201.38
14	0.589		5204.72	27155.88
15	0.567	-28370.86	5011.77	26149.14
		141854.30		
16	0.546		4825.97	25179.72
17	0.526		4647.06	24246.24
18	0.507		4474.78	23347.36
19	0.488		4308.89	22481.81
20	0.470		4149.14	21648.35
21	0.452		3995.32	20845.79
22	0.436		3847.21	20072.98
23	0.419		3704.58	19328.82
24	0.404		3567.24	18612.25
25	0.389		3434.99	17922.24
26	0.374		3307.65	17257.82
27	0.361		3185.03	16618.02
28	0.347		3066.95	16001.95
29	0.334		2953.25	15408.71
30	0.322	-16098.11	2843.76	14837.47
**TPW		$ 347385.32	164386.78	857695.67
***AE Annuity		$ 19725.06	9334.13	48701.25
Total TPW Cost		$ 1369467.78		
Total AE Annuity		$ 77760.44		
Ranking			3 (Fair)	
Operational Cost Ranking				2

Year	PWF *	MAYSMETER Equipment $ 21661 per unit	MAYSMETER Maintenance $1.46 per lane mile	MAYSMETER Operation $66.81 per lane mile	PROFILOGRAPH Equipment $ 23055 per unit	PROFILOGRAPH Maintenance $1.56 per lane mile	PROFILOGRAPH Operation $78.57 per lane mile
0	1.000	21661.00	919.80	42090.30	23055.00	982.80	49499.10
1	0.963		885.70	40529.90		946.36	47664.03
2	0.927		852.87	39027.35		911.28	45897.00
3	0.893		821.25	37580.50		877.50	44195.47
4	0.860		790.80	36187.29		844.97	42557.03
5	0.828		761.48	34845.73		813.64	40979.32
6	0.797		733.25	33553.90		783.48	39460.11
7	0.768		706.07	32309.97		754.43	37997.22
8	0.739		679.89	31112.15		726.46	36588.56
9	0.712		654.69	29958.74		699.53	35232.12
10	0.685	-1484.61	630.42	28848.09	-1580.16	673.60	33925.97
		14846.14			15801.57		
11	0.660		607.05	27778.61		648.62	32668.24
12	0.636		584.54	26748.78		624.58	31457.14
13	0.612		562.87	25757.13		601.42	30290.94
14	0.589		542.00	24802.25		579.13	29167.98
15	0.567		521.91	23882.76		557.66	28086.64
16	0.546		502.56	22997.36		536.98	27045.39
17	0.526		483.93	22144.79		517.08	26042.75
18	0.507		465.99	21323.82		497.91	25077.27
19	0.488		448.71	20533.29		479.45	24147.59
20	0.470	-1017.53	432.08	19772.06	-1083.02	461.67	23252.37
		10175.33			10830.17		
21	0.452		416.06	19039.06		444.56	22390.34
22	0.436		400.64	18333.23		428.08	21560.27
23	0.419		385.78	17653.57		412.21	20760.98
24	0.404		371.48	16999.10		396.93	19991.31
25	0.389		357.71	16368.90		382.21	19250.18
26	0.374		344.45	15762.06		368.04	18536.52
27	0.361		331.68	15177.72		354.40	17849.32
28	0.347		319.38	14615.04		341.26	17187.60
29	0.334		307.54	14073.22		328.61	16550.41
30	0.322	-724.25	296.14	13551.49	-770.86	316.42	15936.84
**TPW		43456.07	17118.74	783358.14	46252.70	18291.25	921246.05
***AE Annuity		2467.50	972.03	44480.25	2626.30	1038.60	52309.73
Total TPW Cost			843932.94			985790.00	
Total AE Annuity			47919.78			55974.64	
Ranking			1 (Very Good)			2 (Good)	
Operational Cost Ranking				1			3

ECONOMIC VARIABLES USED IN ANALYSIS:
Nominal Discount Rate,r= 8% Real Discount Rate,e=[(1+i/100)/(1+r/100)](100)= 3.85%
Inflation Rate,i= 4% Analysis Period= 30 years

* PWF=Present Worth Factor= [1/(1+e/100)^n], where n=year
** TPW=Total Present Worth
*** AE Annuity=[(e/100)/(1-(1+e/100)^-n)]
NOTE: Negative equipment costs represent salvage values.
20% Salvage value for Profilometer
10% Salvage value for Maysmeter and Profilograph

Ranking Criteria	690D Profilometer	Maysmeter	Profilograph
Estimated Annual Equivalent Total Costs:	Fair $77,760	Very Good $47,920	Good $55,975
Estimated Annual operating cost only:	Good $48,701	Very Good $44,480	Fair $52,310

On the basis of this economic analysis, the Maysmeter was the most economical device to own and operate for smoothness acceptance testing, followed by the Profilometer. Comparing only operating costs, the profilograph was the most expensive device.

While these cost data are useful, they are not conclusive since the instruments may have other uses to amortize the cost. In particular, the 690D Profilometer can be used for any type of roughness measurements to be made on roads within the state, including all data required for pavement management. Some of these factors are covered in a following section as "Additional Benefits".

Legal Defensibility

Good repeatability, accuracy and reliability of the instrument are important to implement a legally defensible smoothness specification. The 690D Profilometer was the best instrument in this regard.

There has not been significant experience in legal testing of pavement smoothness specification enforcement; however, the defensibility of any specification is related to the accuracy and precision with which the measurements required to enforce the specification can be made. This is, therefore, the best basis on which to judge satisfaction of the device. The 690D Profilometer was the most accurate and reliable of the tested instruments, it therefore is likely the most legally defensible.

The other major aspect of accurate measurements was the calibration of the device. The 690D Profilometer was calibrated internally and therefore, could be certified as producing accurate and precise measurements on a day-to-day, hour-to-hour basis and thus is more legally defensible.

State DOT experience with the Maysmeter. Contacts were made with six State Departments of Transportation including Georgia, Tennessee, South Carolina, Florida, Mississippi, and Louisiana, to determine how successful the use of the Maysmeter, to evaluate smoothness of pavements for construction acceptance, has been. Three of the states, Georgia, South Carolina, and Tennessee, currently have specifications using Maysmeter values (inches per mile) as their criteria for final acceptance of newly constructed pavement surfaces. Table 2-11 summarizes our telephone contacts in 1986.

The leading proponent of using the Maysmeter for smoothness acceptance was the State of Georgia. Their program was started in 1978. They asserted that during this period, the statewide average roughness readings had been reduced by 60%. This indicated a significant improvement in the riding quality of new highways in the State of Georgia.

Both South Carolina and Tennessee have been using their Maysmeter acceptance procedure for about 2 years starting in 1984 and for the most part were pleased with the results. In each case, they started with a value which they felt could be obtained readily and since then have been modifying the value to be more restrictive.

The State of Florida has used the Maysmeter as a screening device on new paving. Their draft specification called for an acceptable Maysmeter value and a straightedge value. If the actual Maysmeter run indicates a value less than that specified, then the pavement is acceptable. If, on the other hand, the Maysmeter value is high, then the final determination is based upon the use of a straightedge measurement. The use of a straightedge then allows for confirmation of the effectiveness of the remedial action taken.

Table 2-11. Summary of Maysmeter evaluation telephone survey.

GEORGIA

Dennis Richardson 404/363-7583

Used Maysmeter extensively since 1978. They have 9 units and make runs on all layers of construction and give chart results to contractors. Final acceptance is based on Maysmeter runs.

TENNESSEE

George Bradshaw 615/673-6277

Used Maysmeter for two years for acceptance. Specification provides for withholding funds, as liquidated damages, from contractors payment for values over those specified.

SOUTH CAROLINA

D.H. Freeman 803/737-1308

Used Maysmeter as acceptance tool on Interstate and Primary highways. Require corrective action when value exceeds those specified.

FLORIDA

Gale Page 904/372-5304

Does not use Maysmeter for acceptance on routine basis. Due to pressure by paving association, they use Maysmeter to screen surfaces on some projects. Then they check corrective action with a straightedge.

MISSISSIPPI

D.R. Norton 601/354-7172

Have used Maysmeter on one project to confirm effectiveness of corrective action by contractor.

LOUISIANA

Bill Temple 504/342-7878

They have Maysmeters but do not use them for surface control.

Two areas of strong agreement in the discussions emerged from those states using the Maysmeter routinely. First, they agreed that efforts are required to improve the repeatability of a given Mays unit and that variability between two or more units. Second, they felt it was essential that adequate time be allowed when introducing the procedure to secure the support of contractors.

As pointed out in the Interim Report Appendix A, the consistency of the Maysmeter is dependent upon the uniformity of certain mechanical features of the equipment. Repeatability may be affected by tire inflation pressure, hysteresis in the suspension system, trailer wheel alignment and other features. The State of Georgia modified equipment it purchased with new parts that cost approximately $750. With these modifications they claim to obtain a statewide repeatability of within 5%. In addition to the equipment modifications, they utilized frequent maintenance and calibration checks.

It is also evident that the successful use of these acceptance procedures was highly dependent upon the attitude of the paving contractors. Where sufficient time had been used to ease into the program, there appeared to be an atmosphere of cooperation between the state and the contractors. The State of Georgia used the Maysmeter on all levels of the pavement structure and advise the contractor of the existing condition. This allowed the contractor to adjust for smoothness before reaching the final surface.

Only one court action filed against the Maysmeter acceptance procedure was uncovered in this survey. This was in the State of Georgia. After studying the calibration and maintenance procedures being used by the State, the complainant withdrew the suit. Each of the other states using the Maysmeter reported some opposition from their contractors. However, with the passing of time, these problems have subsided.

It appears that there is considerable potential for using the Maysmeter as an acceptance device, however, results are mixed. As is usually true, the introduction of a new procedure must be carried out with careful planning and with sufficient time for the procedure to be accepted.

Impact of Departing from the 1985 AASHTO Proposed Specification

The 1985 AASHTO specification addresses smoothness acceptance testing of portland cement concrete pavements. It specifies a California type profilograph for smoothness testing. The acceptance criteria and pay adjustment scale are based on an average value of the profile index. The use of a Maysmeter and 690D Profilometer requires a different roughness statistic for smoothness acceptance testing. At the time of this evaluation (1985), no satisfactory AASHTO specification existed for asphalt pavements. A number of states DOT's were contacted in 1985 and none of them had been adhering to an AASHTO specification.

Furthermore, in the fall of 1985 we contacted the ASTM, whose Committee E17 has a subcommittee which actively pursues the development of standard roughness specifications. At that time no standard existed for construction acceptance of asphalt pavements.

Impact of Technology Changes or New Procedures

At any time there is the possibility that equipment in standard use will be improved or replaced by new technology. The best example of this may be, for example, the regular improvements made in micro computers. Fortunately in the area of pavement measurements such rapid changes had not occurred. For the past 18 years the best roughness measurement devices in the world have been the GM profilometer, of which the 690D Profilometer is the latest model (circa 1986). Many improvements have and will be made to this device, but these have historically been modular and could be added to existing profilometer models.

On the other hand no major improvements have been made in the Maysmeter or the Profilographs since 1975. On the basis of overall assessment of the available technology it appears highly unlikely that any major technology changes will occur in the near future to replace or upset the instrument selected from this evaluation.

Additional Factors and Benefits of Candidate Devices

The basic analysis and comparison presented here compares common factors in written and tabular form. However, there are additional factors and benefits related to certain of the devices.

Maysmeter. The characteristics and benefits of this device were fairly evaluated in the previous information. The only additional benefit to be derived with the Maysmeter is the results obtained from prior experience of several other states in trying to use the device for construction acceptance.

Profilograph. The characteristics and benefits of this device were fairly evaluated in the previous information. One benefit does derive due to the experience gained in California and the fact that AASHTO has a construction smoothness specification related to its use.

690D Profilometer. This device was the most versatile and useful device tested. Thus, there are several extra benefits to be derived from its use. These can be summarized as follows:

- This device offers the best capability for removing data exceptions for the record such as cattle guards, and railroad crossings.

- The on-board computer provides considerable capability to compare before and after profits and also to estimate level-up quantities. Many other uses can be made of the computer.

- The 690D Profilometer can be used as a control device to calibrate other roughness devices in use in the States.

- The 690D Profilometer profile can be used to simulate current and historical measurements of roughness to provide a realistic and adequate transition from current methods.

- The operating speed and mobility of the device will provide a much greater roughness output than other devices. Thus it can be used for many things other than acceptance testing.

- Due to fast turnaround, operating specs, and output, the 690D Profilometer can easily be used for before and after tests of overlap and can provide "retests" during construction acceptance.

- A number of computer programs such as "Levelup" have been developed for the 690D Profilometer. Additional programs will undoubtedly be added and these will provide additional benefits.

EQUIPMENT SELECTION FOR CONSTRUCTION SMOOTHNESS ACCEPTANCE TESTING

Given the overall rankings of the instruments shown above, it now remained to select those instruments that could best be used by the Arizona DOT for construction smoothness acceptance testing of flexible pavements, taking into account the overall rankings of quality and acceptability, as well as the availability of the devices in Arizona and the practicality of their use.

Ranking of candidate devices was also based on several other considerations which are important for selecting one or more devices for further field trials in Arizona. These are:

- The device should have a proven record of long-term durability and in-use reliability. This is desirable if the construction smoothness acceptance testing program is to be managed by a central office. It is also essential to avoid unnecessary delays to the contractor.

- The device should be able to measure data of satisfactory quality consistently.

- The device should be capable of implementing a legally defensible construction smoothness specification.

The 690D Profilometer was the most accurate roughness measuring device. On the other hand, the 8300 RS proved to be rather unreliable in the experience of the ADOT staff and based on our experience in the comparison tests. It was our recommendation that the 8300 RS not be selected for construction quality control.

The remaining two devices, the Maysmeter and the California Profilograph, both could be used to provide acceptable results for construction quality control in ADOT. The Maysmeter could be used as-is, with the addition of a quality calibration program. The subjective data processing and summarization technique used with the output of the California Profilograph was deemed inadequate.

Work was needed to upgrade the data summarizing characteristics for the California profilograph. As illustrated in Figure 2-5, the California Profilograph data showed relatively larger variations on smooth pavements. Various possibilities were examined for improving the data summarization characteristics of the Profilograph (Reference 28) and reported it in Appendix A of this project's Interim Report.

To summarize this section, there was reason to examine the 690D Profilometer, the Maysmeter and the California Profilograph for final selection of one or two devices for preliminary testing in Arizona to further estimate the best smoothness acceptance specification for ADOT. With regard to good repeatability, the 690D Profilometer was the best device. The Maysmeter was preferred over the profilograph as shown in Figure 2-5. All these devices could be used for test and retest and prior to or after overlay. The Maysmeter generated results immediately in the field. The 690D Profilometer also produced results using on-board computers. However, the profilograph data was analyzed in the office, which was laborious and somewhat subjective.

Based on the results of this evaluation, the consultant recommended field testing in Arizona of the 690D Profilometer plus one other device, either the Maysmeter or Profilograph. ADOT agreed with the Profilometer recommendation and also selected the Maysmeter as the second roughness device to be field tested.

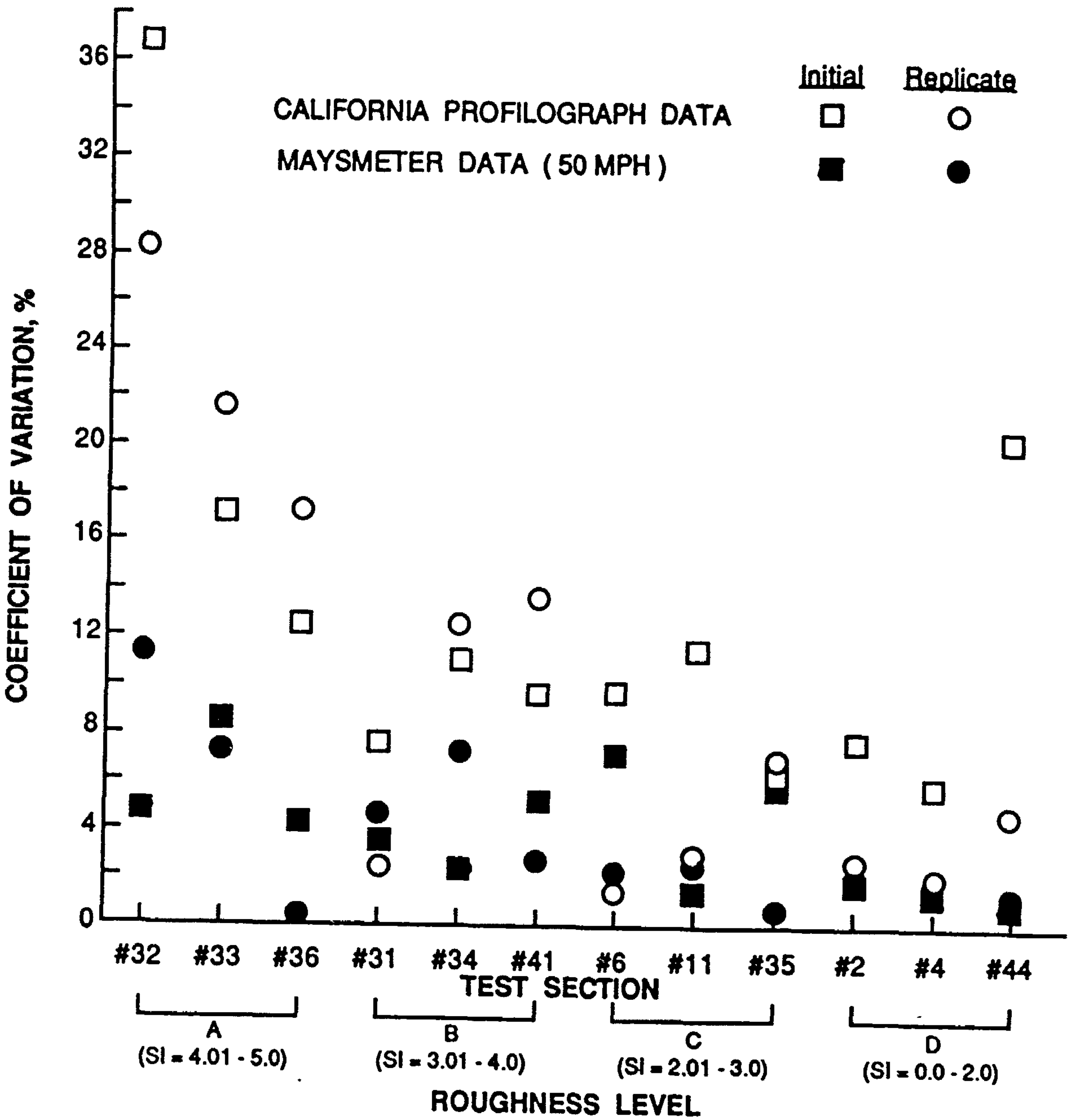

Figure 2-5. Illustration of the Extent of Variability in the Roughness Data Measured by the California Profilograph and Maysmeter.

CONSEQUENCES OF THE EVALUATION

To develop a specification testing capability and a data base of information from which to develop the final specification, field measurements in Arizona were planned. Since the 690D Profilometer would ultimately serve as the principal measurement instrument (golden Maysmeter) for calibration of the Maysmeter one was ordered from K.J. Law. However, due to the manufacturing time required and the need to start field measurements in the summer construction season of 1987, the Maysmeters were initially calibrated against rod and level roughness measurements on 16 selected calibration sections near Phoenix. This rod and level procedure, although only an interim step, was documented in project technical memorandum number 5 (Reference 34). Field testing of the Maysmeter and Profilometer is documented in Chapters 4 and 5, respectively,

CHAPTER 3. SPECIFICATION DEVELOPMENT

RESULTS

In order to implement a smoothness specification three documents have been developed. These three documents either describe the actual specification or the associated acceptance testing procedures:

1. Pavement Smoothness Specification for AC

2. Arizona Test Method 829

3. Method of Test for Determining Pavement Smoothness

Documents number one and two are the result of a combined effort of ARE Inc. and ADOT staff. These results are the consequence of several draft preparations each followed by discussions by ARE Inc. and ADOT staff.

Documents number one and two follow on the next pages. Document number three, The Method of Test for Determining Pavement Smoothness, is contained as Appendix A of this report.

SPECIFICATION DEVELOPMENT WORK ITEMS

A smoothness specification is being implemented by ADOT in order to provide a more comfortable ride on controlled state highways and to prolong the life of state pavements, thus saving taxpayer dollars. Both the specification and testing capability have been developed under this contract, ADOT # 83-42. Currently, the specification developed under this contract, and documented in documents one and two, is being tested on selected ADOT construction projects. Successful testing will be followed by final adoption of the specification and associated testing methods.

On this project there were five work items associated with specification development. They are:

SECTION 407 - ASPHALTIC CONCRETE FRICTION COURSE:

407-10.11 Pavement Smoothness: is hereby added to the Standard Specifications:

The final pavement surface shall be evaluated for smoothness by testing.

Testing will be performed by the Department in accordance with the provisions of Arizona Test Method 829. At the completion of mainline paving, the contractor shall notify the Engineer in writing that the pavement is ready for testing. The Engineer will then evaluate the roadway. If the Engineer determines that additional roadway preparation is required, the contractor shall perform such preparation as directed by the Engineer. The contractor shall ensure that the road can be driven safely at the design speed. If requested by the Engineer, the contractor shall broom the pavement immediately prior to testing. No measurement or direct payment will be made for preparing the roadway, the cost being considered as included in the price of contract items.

The testing will be performed within seven days after the Engineer has accepted the roadway for testing. The Engineer will notify the contractor of the test results no later than 7 days after the testing has been performed.

Testing will be done on mainline traffic lanes only, and will include the full length of the pavement placed under the contract. Distress lanes, shoulders, ramps, tapers, cross roads, and frontage roads will not be tested. Testing will not be performed on any portions that cannot be made safe for testing at the design speed, or on any lanes of less than 0.30 mile in length.

Testing will not be done when the ambient air temperature is less than 40 degrees Fahrenheit or during rain or other weather conditions determined to be inclement by the Engineer.

Any 0.1 lane-mile increment having an Actual Smoothness (AS) equal to or greater than the Correction Value (CV) shall be repaired. Upon completion of the repairs, the 0.1 lane-mile increment containing the repaired area will be re-tested.

The Correction Value (CV) for this contract is 100 inches per mile.

If repairs are required, the contractor shall prepare a written repair proposal detailing corrective actions and submit the proposal to the Engineer within 10 working days after the contractor's receipt of test results. Within three working days, the Engineer will review the submitted proposal and either accept it, or reject it and ask for a new proposal. The Engineer's decision shall be final.

If, after the first attempt to repair the pavement, the actual Smoothness (AS) is still equal to or greater than the Correction Value (CV), additional repairs and testing shall be performed as directed by the Engineer.

In addition to the Smoothness requirements, the pavement surface may be tested with a ten-foot straightedge. The surface shall not vary by more than 1/8 inch from the lower edge of the straightedge in the direction parallel to the center line of the roadway.

Remedial work, including furnishing materials, required to correct pavement smoothness deficiencies shall be performed by the contractor at no additional cost to the Department.

Traffic control costs during the initial smoothness testing period will be reimbursed under the provisions of Section 701 of the Specifications. Any additional traffic control costs incurred, outside the normal scope of work, due to pavement repairs and subsequent pavement smoothness measurements shall be borne solely by the contractor.

407-12 Basis of Payment: the Standard Specifications is modified to add:

An Incentive/Disincentive Value will be added or subtracted from the contract monies due the contractor based on the following:

The Incentive/Disincentive Value (IDV), plus or minus, for each 0.1 lane-mile shall be determined from the following formulas:

When $AS < TV-2$

$$IDV = ((TV-2 - AS) / TV) * IDB$$

When $AS > TV+2$

$$IDV = ((TV+2 - AS) / TV) * IDB$$

The Actual Smoothness Value (AS) shall be determined in accordance with Arizona Test Method 829.

The Incentive/Disincentive Base (IDB) for this contract is $1,000.00 for each 0.1 lane-mile increment or fraction thereof.

The Target Smoothness Value (TV) [in Mays count in/mi]
Surface Course Type

Construction type and road functional class	Friction course	Seal coat or asphaltic concrete
New construction, mill and re-place or overlays on Interstates	35.	49.
Overlays on non-Interstates	49.	56.

The total Incentive/Disincentive Value, plus or minus, for the contract shall be the summation of the individual Incentive/Disincentive Values for the respective 0.1 lane-mile segments.

Incentive/Disincentive Value will not be applied to pavement in distress lanes, shoulders, ramps, tapers, cross roads, or frontage roads.

EVALUATION OF PAVEMENT SMOOTHNESS
ARIZONA TEST METHOD 829
PAVEMENT CONSTRUCTION SMOOTHNESS EVALUATION

SCOPE

1. This test method describes a procedure for measuring the smoothness of pavements.

SUMMARY OF METHOD

2. Smoothness measurements are taken with a Mays Ride Meter at 0.1 mile increments on each traffic lane of the pavement. Measurements are reported as Mays count in inches per mile (in/mi).

APPARATUS

3. The equipment used is a Mays Ride Meter calibrated, at 50 mph, to a KJ Law Profilometer or other Class I or II roughness measuring device (see FHWA Order M 5600.1A, Chapter 3, page J-3).

METHOD OF MEASURING

4. a. The measuring vehicle is driven over the lane(s) to be tested and the smoothness for each 0.1 mile increment is recorded.

   b. The measuring speed for the Mays Ride Meter will be 50 mph (+2 or -2 mph).

   c. The measurement is repeated three (3) times

   d. Any runs not considered acceptable by the operator are discarded and additional runs made until three (3) runs, acceptable to the operator, have been obtained.

   e. Standard procedures for vehicle operation are repeated in: "Method to Test for Determining Pavement Smoothness" Appendix A of Final Report on ADOT Contract 83-42 "Measurement of Pavement Smoothness"

CALCULATIONS

5. The three (3) repeat measurements, for each 0.1 mile increment, are averaged to produce the actual smoothness value (ASV) for each 0.1 mile increment. Results shall be repeated in Mays counts to the nearest 0.1 inch/mile.

REPORT

6. A report will be prepared showing the date of test, operators, vehicle identification, the location of each increment, the values of each run, and the average of the three runs for each increment.

Work Item 13 - Write the First Draft Specification

Work Item 15 - Select Test Sites and Develop Testing Plan

Work Item 16 - Implement Field Testing Using the Maysmeter

Work Item 19 - Complete Data Analysis

Work Item 20 - Finalize Specification

A discussion of specification development follows the order of the work items listed above. First the conceptualization of the specification will be discussed which led to the first draft specification. Next, work items 15, 16, and 19 will be discussed together under the title, "Project Testing and Evaluation". Based on the information gathered and analyzed, the third and final portion of this chapter will justify the quantities used in the actual specification as previously reported.

WRITE THE FIRST DRAFT SPECIFICATION

The first step in specification development was a review of related specifications from other agencies. This review concentrated on the Georgia DOT smoothness specifications, the FHWA "Quality Level Analysis - Standard Deviation Method", and discussions with ADOT staff regarding their opinions on specification representation. Several questions were then formulated, the resolution of which resulted in the current specifications, structure, form, and intent. The questions included the following:

1. Should there be just penalties or both incentives and disincentives?

2. What type of incentives and/or disincentives should there be?

3. At what level of smoothness should these incentives and/or disincentives first be employed?

4. Should the level of smoothness for which incentives are applied be constant across all construction projects, or should it vary depending on the type construction project and/or where that project occurs?

5. Should the roughness on the highway prior to construction affect the roughness levels where incentives are applied based on construction?

6. As smoothness changes, how much incentive and/or disincentive should be applied?

7. If incentives and disincentives can be applied should there be a "free" zone of smoothness where no incentive or disincentive is applied?

Questions 1 and 2 were resolved heuristically. ADOT opted for a specification that included both incentives and disincentives. The general feeling was that the implementation of the specification should have a positive effect on the contractors. In that way both contractors and ADOT staff would work cooperatively. Once the "incentive" scheme was adopted then money was chosen as the type of incentive/disincentive. In a strictly penalty oriented specification, an agency can either inflict dollar penalties or alternatively have the contractor fix the road, thus correcting the problem that caused the penalty. When incentives are included, however, the road repair disincentive has no associated incentive. With money you can either: give some extra or take some away, on the other hand, there is no way to "un" repair a road. As such, money is the chosen means of applying incentives and/or disincentives.

All the remaining questions were a function of smoothness level. As a result it was decided that on this project information needed to be collected and analyzed relative to: 1. what is the average smoothness of recently constructed Arizona highways, and 2. what is the range of smoothness for these highways. The collection and analysis of this data is discussed in the next section, "Project Testing and Evaluation of Smoothness on Newly Constructed Pavements".

This chapter will conclude with a section resolving questions 3 through 7. Relative to the stated specification, questions 3 through 7 translate into justifying three items in the specification. They are the Target Smoothness

Value (TV), the Incentive/Disincentive Base (IDB), and the zero dollar penalty zone which in the specification is +/- 2 Mays units. Questions 3, 4, and 5 are resolved by identifying and justifying the Target Smoothness Value (TV). Question 6 is resolved by qualifying the Incentive/Disincentive Base (IDB). Questions 7 is resolved by justifying the zero dollar penalty zone. Using the data collected and analyzed on this project, information from the state of Georgia, typical Arizona unit construction cost estimates, and various analysis methods these questions were resolved and their answers justified.

PROJECT TESTING AND EVALUATION OF SMOOTHNESS ON NEWLY CONSTRUCTED PAVEMENTS

An experimental factorial was developed to provide data on the average smoothness and the range of smoothness for newly constructed pavements. Data was collected using the ADOT Maysmeters calibrated using rod and level techniques. The pavements measured were all constructed following normal specifications and construction methods.

Experimental Design

There are many factors that can affect smoothness in newly constructed pavements. Before any initial target levels for roughness of new pavement surfaces could be established, it was necessary to analyze these factors and their interactions in as much detail as possible to determine how they affect new pavement roughness. Initial discussions between the project staff and ADOT personnel focused on the following factors as having a quantifiable effect on pavement roughness.

- Age - 0-12 months, 12-24 months, 24+ months
- Road classification - Interstate, Primary, Secondary
- Surface type - densely graded, open graded
- Climate zone - basin and range, central highlands, Colorado province
- Construction type - new construction, mill and replace, and overlay

A considerable amount of effort was spent in an attempt to develop new construction data that represented each of the above factors. These initial efforts were hampered by data that was either not available in the format listed above or was not current enough to meet our requirements. It also proved difficult to classify each pavement according to age. A particular project that may have fallen in the 0-12 month category would slip to the 12-24 month category before testing would commence. Also, many of the projects were constructed over a period of a year or two. Due to the sequencing and phasing of construction, some of the pavement would be a year old before all the pavement was put down.

Later in the experimental design process, some new data became available from the ADOT pavement management data base that greatly enhanced the accuracy of the experimental design. With this newly acquired data, the design of the experiment was simplified. The project team decided to focus primarily on projects that were less than one year old. By doing this, we were able to eliminate age as a factor in the factorial. Secondly, surface types in the PMS data were more clearly defined as friction course (FC), sealcoat (SC), or overlay (OL). Lastly, the three road classifications were changed to Interstate, U.S. routes, and state routes. Climate zone and construction types were not changed. This final experiment design resulted in the factorial shown in Table 3-1.

Project Availability

Using the newly designed factorial and data furnished from ADOT, the second step was to insert the pavement projects into the factorial. We quickly found that certain combinations of factors were plentiful in number while others were nonexistent. For example, very few projects were classified as new construction. Most projects were rehabilitations and reconstructions to the existing highway network. Also, when placing projects in each cell of the factorial, it quickly became obvious that many of the factors chosen were not mutually exclusive. For example, with the exception of just one project, all interstate projects had friction courses for surface type while the majority of U.S. and state routes were strictly sealcoats. These problems and others are further documented in the section entitled, "Statistical Data Analysis."

Table 3-1. Original Factorial Design and Sections Found.

Roadway Functional Classification			Interstate Route			U.S. Route			State Route		
Construction Type			Overlay	Mill and Replace	New Construction	Overlay	Mill and Replace	New Construction	Overlay	Mill and Replace	New Construction
Climate Zone: Colorado Province	Surface Type	Frictional Course	17-2-102 40-3-59 1	IR 40-4-120 IR 40-5-76 2	3	4	5	6	7	8	9
		Seal Coat	10	11	12	S336- -937* F 037-3-917 064-1-505 13	14	15	S244- -908 F 053-2-915 069-1-902 053-2-917 16	17	18
		Asphaltic Concrete	19	20	21	22	23	24	25	26	F 053-2-511 27
Central Highlands	Surface Type	Frictional Course	28	IR 17-1-168 IR 17-2-98 29	30	31	F 022-3-56 32	33	F 053-1-944 34	35	36
		Seal Coat	37	38	39	40	F 022-4-946 41	F 051-2-34 42	S 215- -909 058 -1-2 43	44	45
		Asphaltic Concrete	46	47	48	49	50	VLT435- -501 51	S 348- -906 52	53	54
Basin & Range	Surface Type	Frictional Course	55	IR 8-2-88 IR 8-2-86 IR 8-1-85 IR10-3-242 IR10-5-62 56	57	F 039-1-919 58	59	60	61	F 063-2-911 62	63
		Seal Coat	64	65	66	F 016-1-922 67	68	69	S 316- -19 70	RS 581- -4 71	72
		Asphaltic Concrete	73	10-2-131 74	75	76	F 031-1-26* F 022-3-54 77	78	S 577- -501 79	80	S 251- -504 81

* - Eliminated due to difficult data collection conditions

Field Test Plan

To coordinate the efficient collection of Maysmeter roughness data on the selected sections, the projects were broken up into geographical areas throughout Arizona. A route through each geographical area was plotted on a map with the location of each test section clearly defined. The ADOT test crew would test sections along each route. These routes would take anywhere from two to four days to complete. The entire sequence of tests lasted longer than expected. Delays in the field such as heavy traffic and scheduling errors were the cause of most of the delay.

Overall, the field testing went smoothly. Several test sections were found to have mountain terrain gradients and curvature where the test crew could not maintain speed or stay consistently in one lane during testing. Still, other sections were found to be in highly congested and signalized urban areas. On these sections, it was impossible to maintain speed and these sections were consequently eliminated from the analysis. These projects are discussed in some detail in the next section. Due to the hard work and enthusiasm in the data collection efforts of the test crew, the testing went extremely well overall. The next section discusses the statistical analysis of this data and the ultimate reduction of the experimental factorial.

Statistical Analysis of Maysmeter Data

As stated earlier, the purpose of the Maysmeter roughness experiment was to investigate some of the possible factors that cause differences in profile of newly constructed pavements. Within the levels of the factors that cause the differences, models can be constructed that provide incentives or penalties to contractors. If a given contractor can substantially exceed the set target specifications for a certain type of pavement he may be rewarded with a bonus payment. If he fails to meet the minimum of the specification, he may be penalized.

The experiment was set up with 81 (each cell is numbered in Table 3-1) combinations of levels of factors or cells. It was hoped that about five sections of pavements would be found to fill each cell. For the reasons stated in the previous sections, it was impossible to find this many sections, but for those found, a Maysmeter was run over them to measure the roughness (Maysmeter values MMO were recorded). All lanes were tested and two repetitions were done on each lane. The experiment design included the following factors and their levels:

1. Roadway Functional Classification
   a. Interstate Route
   b. U.S. Route
   c. State Route

2. Construction Type
   a. Overlay
   b. Mill and Replace
   c. New Construction

3. Climate Zone
   a. Basin and Range
   b. Central Highlands
   c. Colorado Province

4. Surface Type
   a. Frictional Course
   b. Seal Coat
   c. Asphaltic Concrete

Upon review of the notes and data submitted by the ADOT test crew, there were three projects that were eliminated from the analysis. Project S336-937 was eliminated because the test crew could not maintain a constant speed during testing. This roadway followed Oak Creek Canyon's mountainous and winding terrain.

Project F031-1-26 was also eliminated. This project was located on a Tucson, urban 6-lane divided roadway. It was not possible to maintain constant speed during testing due to traffic and signalization. RS274-8 was also eliminated due to high traffic in an urban area and an inability to maintain speed.

From the data provided, it appeared that very little new construction was taking place in Arizona during the 1988 and 1989 construction season. Consequently, only four projects were found that fell in this category. This was not enough data to warrant keeping "New Construction" as a separate level in the factorial. Therefore, these four data points were combined with Mill and Replace due to similarities in construction techniques.

The remaining variables were examined in a systematic approach to determine their significance in predicting MMO. In the following paragraphs, each step is clearly defined and the resulting conclusions are stated in concise format.

From the data base shown in Table 3-2, it can be seen that in addition to the four main factors in the experiment, there were two variables regarded as co-variables in the study. The first covariable was Maysmeter speed and included two levels, 35 and 50 mph. The second covariable was lane number and included lanes 1, 2, and 3.

Influence of Measurement Lane. The initial step in the statistical analysis of the data was to develop a one to one correlation table that included all four main factors and both co-variables. This table gives a good indication of which variables in the data base have the most significant affect on MMO. The microcomputer-based statistical package "Statistical Package for Social Sciences" (SPSS PCT) was used for the analysis.

ONE TO ONE CORRELATIONS OF ADOT MAYSMETER ROUGHNESS DATA

Correlations:	ROADCLAS	CONSTYPE	CLIMZONE	SURFTYPE	LANE_NO	SPEED	MMO
ROADCLAS	1.0000						
CONSTYPE	.1700	1.0000					
CLIMZONE	.0628	.2240	1.0000				
SURFTYPE	.5413**	-.2253	-.1734	1.0000			
LANE_NO	.2490*	.2609*	.1568	-.0950	1.0000		
SPEED	.2018	-.2344*	-.0297	.4775**	.0207	1.0000	
MMO	-.3770**	-.2565*	.0517	-.3941**	.0089	-.1718	1.0000

Table 3-2. Database of Arizona DOT Maysmeter Roughness Measurements.

30-Apr-90

PROJECT #	HIGHWAY	TEST DATE	ROAD. CLASS.	CONSTR. TYPE	SURF. TYPE	MILE POST	DIR.	LN. #	TEST SPEED (MPH)	READ. #1 (IN)	READ. DIST. #1 (Miles)	READ. #2 (IN)	READ. DIST. #2 (Miles)	AVER. MM READ. (IPM)	MM STD. DEV. (IPM)
F031-1-26	US89	10-26-89	0	1	-1	72	NB	1	50	257.4	2.000	232.3	2.000	122	6.3
F031-1-26	US89	10-26-89	0	1	-1	72	NB	2	50	180.9	2.000	190.5	2.000	93	2.4
F031-1-26	US89	10-26-89	0	1	-1	72	NB	3	50	182.7	2.000	186.2	2.000	92	0.9
F031-1-26	US89	10-26-89	0	1	-1	74	SB	1	50	229.6	2.000	207.5	2.000	109	5.5
F031-1-26	US89	10-26-89	0	1	-1	74	SB	2	50	165.5	2.000	154.0	2.000	80	2.9
F031-1-26	US89	10-26-89	0	1	-1	74	SB	3	50	190.9	2.000	182.0	2.000	93	2.2
IR10-5-62	1-10	11-3-89	1	1	1	268	EB	1	50	149.0	3.900	132.1	3.900	36	2.2
IR10-5-62	1-10	11-3-89	1	1	1	268	EB	2	50	152.2	3.900	147.4	3.900	38	0.6
IR10-5-62	1-10	11-3-89	1	1	1	272	WB	1	50	126.0	3.900	122.5	3.900	32	0.4
IR10-5-62	1-10	11-3-89	1	1	1	272	WB	2	50	140.4	3.900	150.7	3.900	37	1.3
S577-501	SR92	10-26-89	-1	0	-1	323	EB	1	50	82.6	2.000	86.6	2.000	42	1.0
S577-501	SR92	10-26-89	-1	0	-1	323	EB	2	50	109.4	2.000	111.4	2.000	55	0.5
S577-501	SR92	10-26-89	-1	0	-1	325	WB	1	50	108.6	2.000	115.0	2.000	56	1.6
S577-501	SR92	10-26-89	-1	0	-1	325	WB	2	50	128.2	2.000	128.8	2.000	64	0.2
F016-1-922	US80	10-26-89	0	0	0	232	EB	1	50	613.5	7.000	631.4	7.000	89	1.3
F016-1-922	US80	10-26-89	0	0	0	339	WB	1	50	698.8	7.000	721.1	7.000	101	1.6
S316- -19	S177	10-27-89	-1	0	0	148	NB	1	50	244.6	4.000	235.0	4.000	60	1.2
S316- -19	S177	10-27-89	-1	0	0	152	SB	1	50	201.8	4.000	190.0	4.000	49	1.5
F022-4-946	US70	11-1-89	0	1	0	271	EB	1	50	240.8	3.850	241.8	3.850	63	0.1
F022-4-946	US70	11-1-89	0	1	0	275	WB	1	50	277.2	3.850	277.3	3.850	72	0.0
F051-2-34	US666	11-2-89	0	1	0	139	EB	1	50	226.9	5.000	223.2	5.000	45	0.4
F051-2-34	US666	11-2-89	0	1	0	144	WB	1	50	220.5	5.000	221.3	5.000	44	0.1
S348- -906	S78	11-5-89	-1	0	-1	158	EB	1	35	518.4	6.950	-	-	75	-
S348- -906	S78	11-5-89	-1	0	-1	165	WB	1	35	541.4	6.950	-	-	78	-
S215- -909	S73	11-8-89	-1	0	0	324	NB	1	50	563.6	6.900	550.2	6.900	81	1.0
S215- -909	S73	11-8-89	-1	0	0	331	SB	1	50	494.4	6.900	499.5	6.900	72	0.4
IR17-2-98	I17	10-4-88	1	1	1	287	NB	1	50	119.7	2.900	117.7	2.900	41	0.3
IR17-2-98	I17	10-4-88	1	1	1	287	NB	2	50	148.5	2.900	147.8	2.900	51	0.1
IR17-2-98	I17	10-4-88	1	1	1	290	SB	1	50	131.5	2.900	110.4	2.900	42	3.6
IR17-2-98	I17	10-4-88	1	1	1	290	SB	2	50	115.2	2.910	114.6	2.910	39	0.1
VLT435- -501	US89A	10-12-89	0	1	-1	351	NB	1	35	70.0	1.980	66.7	1.980	35	0.8
VLT435- -501	US89A	10-12-89	0	1	-1	351	NB	2	35	102.2	1.990	100.2	1.990	51	0.5
VLT435- -501	US89A	10-12-89	0	1	-1	353	SB	1	35	69.7	1.980	70.4	1.980	35	0.2
VLT435- -501	US89A	10-12-89	0	1	-1	353	SB	2	35	87.5	1.980	89.8	1.980	45	0.6
S366- -937	US 89A	10-12-89	0	0	0	390	NB	1	35	960.5	10.900	968.0	10.900	88	0.3
S366- -937	US 89A	10-12-89	0	0	0	401	SB	1	35	988.6	10.900	971.4	10.900	90	0.8
IR17-2-102	I17	10-13-89	1	0	1	323	NB	1	50	271.7	9.995	310.1	9.998	29	1.9
IR17-1-168	I17	10-18-89	1	1	1	256	NB	1	50	241.1	5.971	260.6	5.970	42	1.6
IR17-1-168	I17	10-18-89	1	1	1	256	NB	2	50	239.1	5.988	265.1	5.964	42	2.3
IR17-1-168	I17	10-18-89	1	1	1	262	SB	1	50	292.5	5.948	300.6	5.954	50	0.7
IR17-1-168	I17	10-18-89	1	1	1	262	SB	2	50	248.4	5.953	249.0	5.949	42	0.1
IR40-5-76	I40	10-19-89	1	1	1	290	EB	1	50	299.9	6.956	293.8	6.954	43	0.4
IR40-5-76	I40	10-19-89	1	1	1	290	EB	2	50	314.0	6.957	276.5	6.957	42	2.7
IR40-5-76	I40	10-19-89	1	1	1	297	WB	1	50	267.6	6.972	277.0	6.972	39	0.7
IR40-5-76	I40	10-19-89	1	1	1	297	WB	2	50	228.8	5.998	230.9	6.020	38	0.1
IR4-4-120	I-40	10-19-89	1	1	1	258	EB	1	50	490.1	11.000	481.9	11.000	44	0.4
IR4-4-120	I-40	10-19-89	1	1	1	258	EB	2	50	484.7	11.000	405.0	11.000	40	3.6
S244- -908	SR87	10-19-89	-1	0	0	346	NB	1	50	747.2	9.880	757.9	9.880	76	0.5
S244- -908	SR87	10-19-89	-1	0	0	356	SB	1	50	711.6	9.839	729.7	9.875	73	0.8
F022-3-54	US60	10-20-89	0	1	-1	179	EB	1	35	239.4	2.950	248.9	2.950	83	1.6
F022-3-54	US60	10-20-89	0	1	-1	179	EB	2	35	263.0	2.950	264.6	2.950	89	0.3
F022-3-54	US60	10-20-89	0	1	-1	182	WB	1	35	233.6	2.980	234.8	2.980	79	0.2
F022-3-54	US60	10-20-89	0	1	-1	182	WB	2	35	199.2	2.950	144.7	2.000	70	2.4
IR10-3-242	IR-10	10-25-89	1	1	1	178	EB	1	50	259.8	7.000	203.2	7.000	33	4.0
IR10-3-242	IR-10	10-25-89	1	1	1	178	EB	2	50	227.3	7.000	261.4	7.000	35	2.4
IR8-2-86	IR8	10-25-89	1	1	1	166	WB	1	50	200.3	5.000	199.5	5.000	40	0.1
IR8-2-86	IR8	10-25-89	1	1	1	166	WB	2	50	222.1	5.000	215.9	5.000	44	0.6
IR8-2-86	IR8	10-25-89	1	1	1	161	EB	1	50	232.2	5.000	230.7	5.000	46	0.1
IR8-2-86	IR8	10-25-89	1	1	1	161	EB	2	50	228.8	5.000	200.8	5.000	43	2.8
F022-3-56	US60	10-27-89	0	1	1	201	WB	1	50	350.3	6.950	365.7	6.950	52	1.1
F022-3-56	US60	10-27-89	0	1	1	201	WB	2	50	247.8	6.950	269.3	6.950	37	1.5
F037-3-917	US89A	11-15-89	0	0	0	572	NB	1	35	333.1	6.950	313.7	6.950	47	1.4
F037-3-917	US89A	11-15-89	0	0	0	572	SB	1	35	396.5	6.950	389.5	6.950	57	0.5
F064-1-505	US160	11-15-89	0	0	0	358	EB	1	50	529.2	7.000	501.8	7.000	74	2.0
F064-1-505	US160	11-15-89	0	0	0	358	WB	2	50	502.5	7.000	503.1	7.000	72	0.0
40-3-59	I-40	11-21-89	1	0	1	158	WB	1	50	294.4	6.000	295.0	6.000	49	0.0
40-3-59	I-40	11-21-89	1	0	1	158	WB	2	50	226.8	6.000	227.2	6.000	38	0.0
40-3-59	I-40	11-21-89	1	0	1	152	EB	1	50	195.8	6.000	202.6	6.000	33	0.6
40-3-59	I-40	11-21-89	1	0	1	152	EB	2	50	242.4	6.000	241.8	6.000	40	0.0
F058-1-2	SR169	11-16-89	-1	0	0	0	NB	1	50	231.1	4.973	212.9	4.971	45	1.8
F058-1-2	SR169	11-16-89	-1	0	0	5	SB	1	50	239.4	4.972	249.3	4.972	49	1.0
IR10-2-131	I-10	11-29-89	1	1	-1	90	WB	1	50	186.6	10.000	201.7	10.000	19	0.8
IR10-2-131	I-10	11-29-89	1	1	-1	90	WB	2	50	293.7	10.000	297.9	10.000	30	0.2
IR10-2-131	I-10	11-30-89	1	1	-1	90	EB	1	50	191.0	10.000	217.0	10.000	20	1.3
IR10-2-131	I-10	11-30-89	1	1	-1	90	EB	2	50	283.4	10.000	280.5	10.000	28	0.1

Table 3-2. Database of Arizona DOT Maysmeter Roughness Measurements (cont'd).

30-Apr-90

PROJECT #	HIGHWAY	TEST DATE	ROAD. CLASS.	CONSTR. TYPE	SURF. TYPE	MILE POST	DIR.	LN. #	TEST SPEED (MPH)	READ. #1 (IN)	READ. DIST. #1 (Miles)	READ. #2 (IN)	READ. DIST. #2 (Miles)	AVER. MM READ. (IPM)	MM STD. DEV. (IPM)
IR8-2-88	I-8	11-30-89	1	1	1	119	WB	1	50	127.4	2.874	125.2	2.876	44	0.4
IR8-2-88	I-8	11-30-89	1	1	1	119	WB	2	50	125.3	2.876	121.9	2.875	43	0.6
F053-1-944	S87	12-11-89	-1	0	1	201	NB	1	50	641.9	11.000	645.4	11.000	59	0.2
F053-1-944	S87	12-11-89	-1	0	1	212	SB	1	50	703.8	11.000	706.3	11.000	64	0.1
069-1-902	S277	12-12-89	-1	0	0	306	NB	1	50	309.7	6.000	310.0	6.000	52	0.0
069-1-902	S277	12-12-89	-1	0	0	312	SB	1	50	278.3	6.000	290.0	6.000	47	1.0
053-2-917	S260	12-12-89	-1	0	0	299	EB	1	50	679.2	10.000	698.8	10.000	69	1.0
053-2-917	S260	12-12-89	-1	0	0	309	WB	1	50	707.2	9.980	728.9	10.020	72	0.9
F053-2-915	S260	12-12-89	-1	0	0	292	WB	1	50	375.4	9.450	379.4	9.400	40	0.3
F053-2-915	S260	12-12-89	-1	0	0	283	EB	1	50	349.4	9.400	370.5	9.400	38	1.1
F053-2-511	S260	12-12-89	-1	1	-1	277	EB	1	50	107.0	2.000	106.8	2.000	53	0.0
F053-2-511	S260	12-12-89	-1	1	-1	277	EB	2	50	114.8	1.950	121.0	1.950	60	1.6
F053-2-511	S260	12-12-89	-1	1	-1	279	WB	1	50	97.1	1.950	98.6	1.950	50	0.4
F053-2-511	S260	12-12-89	-1	1	-1	279	WB	2	50	111.2	1.950	116.1	1.950	58	1.3
S251- -504	S287	12-13-89	-1	1	-1	113	NB	1	35	77.3	2.000	81.6	2.000	40	1.1
S251- -504	S287	12-13-89	-1	1	-1	113	NB	2	35	100.1	2.000	96.7	2.000	49	0.8
S251- -504	S287	12-13-89	-1	1	-1	115	SB	1	35	78.7	2.000	84.4	2.000	41	1.4
S251- -504	S287	12-13-89	-1	1	-1	115	SB	2	35	112.1	2.000	119.1	2.000	58	1.8
F063-2-911	S95	12-13-89	-1	1	1	142	SB	1	50	420.5	10.000	435.6	10.000	43	0.8
F063-2-911	S95	12-13-89	-1	1	1	132	NB	1	50	475.4	10.000	481.8	10.000	48	0.3
RS581- -4	S66	12-19-89	-1	1	0	62	EB	1	50	388.5	10.000	378.9	10.000	38	0.5
RS581- -4	S66	12-19-89	-1	1	0	72	WB	1	50	455.3	10.000	459.0	10.000	46	0.2
F039-1-919	US93	12-19-89	0	0	1	43	SB	1	50	740.4	10.010	725.8	10.010	73	0.7
F039-1-919	US93	12-19-89	0	0	1	53	NB	1	50	644.9	10.010	661.7	10.010	65	0.8
IR8-1-85	I8	12-19-89	1	1	1	56	EB	1	50	305.2	10.000	343.7	10.000	32	1.9
IR8-1-85	I8	12-19-89	1	1	1	56	EB	2	50	318.2	10.000	320.9	10.000	32	0.1

The first step in reducing the size of the factorial was to examine the variable with the lowest correlation to MMO. From the correlation table, it can be seen that the covariable lane number (LANE_NO) had the lowest correlation with MMO, a value of 0.0089. From this, we can conclude that with the data provided, lane number has a negligible affect on MMO and can, therefore, be disregarded in the remaining analysis.

Influence of Speed. From Table 3-2 it is seen that the Maysmeter was run at 35 mph and 50 mph. The second step in the analysis was to find out whether or not the MMO readings were influenced by speed, in this study. To do this, we compared the MMO readings for sections with both speeds in the same cell with the following results. Appendix B shows the analyses of these cells as follows:

1. Cell one (77) (U.S. Route, Mill and Replace, Basin and Range, Asphaltic Concrete) had homogeneous variances and the means were not significantly different at the .31 probability level.

2. Cell two (13) (U.S. Route, Overlay Colorado Province, Seal Coat) showed that the difference between the MMO means of 35 mph and 50 mph not significant at the .50 probability level. It is also shown that the major difference of means was between the sections both measured at 35 mph.

For this study there is no significant difference in the means of MMO due to speed of the Maysmeter. This is consistent with earlier experiments conducted on the Maysmeter car and trailer which also showed minimal differences in MMO readings when conducted at different speeds in the Maysmeter car. In addition, the correlation between speed and MMO was only -0.172.

Influence of Climate Zones. The third step in the analyses was to determine if Climate Zones had a significant affect on MMO readings. The calculations are given in Appendix C. The specific analysis and results are given below.

1. Case 1. (Cell 56 vs 29 vs 2) compared the means for the three climate zones on Interstate Route, Mill and Replace and Frictional Course. There was no significance at the .60 probability level.

2. Case 2 compared Colorado Province with Basin and Range on U.S. Route and State Route for Overlay and Seal Coat. There was no significance at the .50 probability level.

It was concluded that the Climate Zones could be pooled for deriving roughness models.

The final analysis step involved Table 3-3. Since the four cells in the lower left hand corner are empty, this reduced 18 cell factorial can be analyzed as two partial factorials. The first factorial contains 12 cells (the last four columns of Table 3-3). ANOVA and tests for homogeneity were conducted as shown in Appendix D, case 1. The results of these analyses are the following:

A. No interactions exist amongst the remaining three factors.

[1]B. U.S. Routes and State Routes may be pooled.

C. All three Surface Types may be pooled.

D. Overlay is different from the combinations of Mill and Replace and New Construction and can remain separated.

The second partial factorial taken from Table 3-3 includes only the top row of six cells. Appendix D, Case 2 shows the specifics of the analysis. This case examines the interactions and homogeneity of the three Roadway Functional Classifications and two Construction Types. Both of these factors showed possible significance in earlier analysis. The results of this

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[1] This is primarily the result of a deficient number of data points for friction courses applied to U.S. and state routes. Only four points are available in this data base. It is quite possible that these cells warrant further investigation in the future.

Table 3-3. Preliminary Maysmeter Value (in.mi)Results of ADOT Maysmeter Field Test Plan.

Roadway Functional Classification		Interstate Route		U.S. Route		State Route		
Construction Type		Overlay	Mill & Replace and New Construction	Overlay	Mill & Replace and New Construction	Overlay	Mill & Replace and New Construction	
Surface Type	Friction Course	29.1 40.1 *1.1a*	34.0 43.3 24.4 42.3 40.6 43.5 44.0 43.3 32.2 *1.2a*	69.3 *2.1a*	44.4 *2.2a*	61.3 *3.1a*	45.3 *3.2a*	$\overline{X}$ = 43.2 SD = 11.3
	Seal Coat	*1.1b*	*1.2b*	76.0 51.5 72.7 *2.1b*	67.3 44.6 *2.2b*	46.9 70.4 49.5 54.5 74.6 76.4 39.1 *3.1b*	42.0 *3.2b*	$\overline{X}$ = 58.9 SD = 13.7
	Asphaltic Concrete	*1.1c*	*1.2c*	*2.1c*	80.2 41.4 *2.2c*	54.4 76.2 *3.1c*	46.9 55.6 *3.2c*	$\overline{X}$ = 59.1 SD = 14.3
		$\overline{X}$ = 34.6 SD = 5.5	$\overline{X}$ = 38.6 SD = 6.5	$\overline{X}$ = 67.4 SD = 9.5	$\overline{X}$ = 55.6 SD = 15.4	$\overline{X}$ = 60.3 SD = 12.8	$\overline{X}$ = 47.5 SD = 5.0	

Legend: Section IRI (in/mile)

Cell numbers are in italics

analysis were also conclusive. They are:

1. U.S. and state routes showed no significant differences and can, therefore, be combined.

2. Interstate highways were significantly smoother than U.S. and state routes and should be kept separate.

The result of the analysis is the reduced factorial shown in Table 3-4. The last step in this analysis will be to compare the data contained in these four cells. The analysis of the data represented in Table 3-4 is given in Appendix E. In summary, this data shows that the variances are homogeneous, the data are normally distributed and

[2]3. Overlay and the combination of Mill and Replace plus New Construction can all be pooled in the Interstate Routes, but

4. Overlay must be separated from the combination of Mill and Replace plus New Construction for the combination of U.S. Routes and State Routes.Conclusion

These data provide evidence that there should be the following <u>three</u> models to evaluate paving contractors in Arizona:

1. For Interstate Routes <u>one</u> model may be used.

2. For U.S. Routes and State Routes combined there should be <u>one</u> model for Overlays and a <u>second</u> model for either of Mill and Replace or New Construction.

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[2] Note: This is probably the result of only two data points available for Interstate routes with overlays (see Table 3-4). Future investigations should be focused on this specific combination of functional classification and construction type.

Table 3-4. Statistically Derived Results of Maysmeter Target Smoothness Data Analysis.

Construction Type	Roadway Functional Classification: *Interstate (1)*	Roadway Functional Classification: *Non-Interstate (0)*
Overlay (0)	N = 2 * MEAN = 34.6 SEE = ±8.2	N = 14 MEAN = 62.3 SEE = 3.1
New Construction or Mill & Replace (1)	N = 9 MEAN = 40.0 SEE = ±3.8	N = 9 MEAN = 52.0 SEE = 3.8

All units are in/mile

* Questionable results due to lack of data.

Note: See special exceptions described under "Recommendations".

Special Considerations

Evidence in this and other studies (Reference 41) have indicated that the application of a friction course can reduce roughness by 10-15 percent. However, the data collected for this study indicated that the majority of friction courses are placed on Interstate highways (only four data points indicated friction courses on U.S. and state routes). This being the case, surface types showed very little significance in the analysis.

Until further data can be collected on non-interstate routes with friction courses, it would be advisable to refrain from implementing the specifications on these projects. Likewise, interstate routes that do not include the application of a friction course should also be excluded.

JUSTIFICATION OF SPECIFICATION QUANTITIES

This section provides information to justify the selection of several specification quantities including the Target Smoothness Value (TV), Incentive/Disincentive Base (IDB), and the zero dollar incentive/disincentive zone.

Justification of Target Smoothness Value (TV) [in Mays count in/mi] (Answers Questions 3, 4, and 5)

The target smoothness value is calculated as a 10% smoothness improvement over averaged Maysmeter data collected on this project for this purpose. This data was reported in ARE Inc memo 5/2/90 "Maysmeter Data Analysis" (Reference 40). Table 3-3 and Table 3-4 are excerpts from this memo documenting the data and the averaged results reported.

In addition to the ADOT data derived statistical results illustrated in Table 3-4, there is another source of data for estimating smoothness target values. The Georgia DOT has ten years of experience with Maysmeter based construction smoothness target values. The target values to be recommended for ADOT will be derived using both data sources.

The common factor influencing target smoothness between Georgia DOT experience and ADOT data results is use of construction type to vary the target smoothness.

The primary difference between the Georgia DOT and the ADOT data results is the factors that influence the target value. Georgia has different smoothness target values based upon construction type and surface type, whereas the ADOT data results are split by construction type and roadway functional class.

Although the ADOT data derived results are statistically accurate, the sparsity of data and uneven distribution of data can produce misleading results. For example, a review of Table 3-4 shows that overlays on Interstates are smoother than original construction on Interstates. Statistically, this may or may not be true because there were only two Interstate overlay projects measured, resulting in a poor sample. Practically, it would be very difficult to justify more smoothness on rehabilitation jobs, as compared to original construction.

Similarly, the apparent difference in smoothness on new construction between Interstates and non-Interstates can be argued statistically, and also from a policy making perspective. Statistically, this difference is mostly derived from two outlier points (values 67.3 and 80.2 in cells 2.2b and 2.2c in Table 3-3 respectively). Without the outliers the smoothness difference is negligible. Also, from a practical standpoint, if contractors can achieve a high level of smoothness for new construction on Interstates, then it is reasonable to target the same smoothness for major highways that are US and/or state routes.

Finally, the surface type difference noticed in Georgia did not prove significant based on the ADOT data analysis. It is quite possible that there are no significant pavement smoothness differences due surface type in Arizona, on the other hand, however, this statistical result could be overturned with the collection and analysis of more data. As such, the conservative approach of assuming a difference due surface type is recommended.

Table 3-5 shows the ADOT smoothness data as categorized statistically (case 1), and as categorized in a manner similar to the Georgia DOT specification. For the reasons just mentioned, the Georgia DOT categorization (case 2) is being recommended.

The ADOT data statistics based upon the recommended categorization (the one also used by the Georgia DOT) are shown in Table 3-6. These calculated smoothness averages were then reduced 10% to produce the ADOT target smoothness values (see Table 3-7). Note: the target value for non-Interstate friction course overlays was further adjusted to conform to Georgia DOT experience (see Table 3-7). An ADOT data derived average in this case because there was not sufficient data (only two projects were collected) to justify its use.

Roughness Prior to Repair (Answers Question 5 [see pgs. 3-5])

The analysis of a small amount of data collected on this project did not support the hypothesis that roughness prior to the rehabilitation action greatly affected the resulting roughness after rehabilitation. This conclusion is supported in ADOT document FHWA-AZ87-254, "Rational Characterization of Pavement Structures using Deflection Analysis" (Reference 41), pp. 113-114.

Justification for an Incentive/Disincentive Base (IDB) (Answers Question 6 [see page 3-5])

Highways are assets that need periodic rehabilitation and reconstruction. Any action that decreases the time between (re)constructions affects the value of the highway in several ways. Specifically, when a rehabilitation results in an initially rougher road, studies have shown that this higher roughness persists throughout its life resulting in an earlier need for the subsequent rehabilitation. This reduction in life (time between reconstructs) means that all maintenance and interim rehabilitation work must be funded over fewer years and so the annual cost of all work is proportionally higher. For example, if one agency gets 50 years from the initial construction or reconstruction and 2 overlays, then the worth of this

Table 3-5. Comparison of Maysmeter Target Smoothness Alternative Categorizations using ADOT Smoothness Data (in/mi).

CASE 1: Statistically derived categorization

Roadway Functional Classification	Interstate Route		Non-Interstate Routes			
			U.S.	State	U.S.	State
Construction Type	Overlay	Mill & Replace and New Construction	Mill & Replace and New Construction	Mill & Replace and New Construction	Overlay	Overlay
Surface Type: Friction Course	29.1 40.1 *1.1a*	34.0 43.3 24.4 42.3 40.6 43.5 44.0 43.3 32.3 *1.2a*	44.4 *2.2a*	45.3 *3.2a*	69.3 *2.1a*	61.3 *3.1a*
Surface Type: Seal Coat	*1.1b*	*1.2b*	67.3 44.6 *2.2b*	42.0 *3.2b*	76.0 51.5 72.7 *2.1b*	46.9 70.4 49.5 54.5 74.6 76.4 39.1 *3.1b*
Surface Type: Asphaltic Concrete	*1.1c*	*1.2c*	80.2 41.4 *2.2c*	46.9 55.6 *3.2c*	*2.1c*	54.4 76.2 *3.1c*

CASE 2: Georgia DOT Categorization

Roadway Functional Classification	Interstate Route		Non-Interstate Routes			
			U.S.	State	U.S.	State
Construction Type	Overlay	Mill & Replace and New Construction	Mill & Replace and New Construction	Mill & Replace and New Construction	Overlay	Overlay
Surface Type: Friction Course	29.1 40.1 *1.1a*	34.0 43.3 24.4 42.3 40.6 43.5 44.0 43.3 32.3 *1.2a*	44.4 *2.2a*	45.3 *3.2a*	69.3 *2.1a*	61.3 *3.1a*
Surface Type: Seal Coat	*1.1b*	*1.2b*	67.3 44.6 *2.2b*	42.0 *3.2b*	76.0 51.5 72.7 *2.1b*	46.9 70.4 49.5 54.5 74.6 76.4 39.1 *3.1b*
Surface Type: Asphaltic Concrete	*1.1c*	*1.2c*	80.2 41.4 *2.2c*	46.9 55.6 *3.2c*	*2.1c*	54.4 76.2 *3.1c*

Cell numbers are in Italics

Table 3-6. Target Smoothness Results using ADOT Maysmeter Data (in/mi) and Georgia DOT Smoothness Categories.

Surface Type		Construction Type: New Construction or Mill and Replace or Interstate Overlay	Construction Type: Non-Interstate Overlay
Surface Type	Friction Course	$\mu = 39.0$ $\sigma = 6.76$ n = 13	$\mu = 65.3$ n = 2
Surface Type	Seal Coat or AC	$\mu = 54.0$ $\sigma = 14.76$ n = 7	$\mu = 61.9$ $\sigma = 13.75$ n = 12

Table 3-7. Recommended Maysmeter Target Smoothness Values (in/mi).

Surface Type		Construction Type: New Construction * or Mill and Replace or Interstate Overlay	Construction Type: Non-Interstate Overlay
Surface Type	Friction Course	35 (n = 13)	49 *** (n = 2)
Surface Type	Seal Coat or AC	49 ** (n = 7)	56 (n = 12)

* We recommend ongoing review of smoothness values after construction to investigate smoothness differences in new construction/mill and replace between Interstate and non-Interstate roads.

** This smoothness level may be lenient. Review of the ADOT data indicates that there are two outliers. Without the outliers the Target Smoothness would be 41. For now the 49 value is recommended, but we suggest ongoing review of smoothness values after construction to verify the 49 value.

*** This smoothness level was derived based upon Georgia DOT experience equating non-Interstate friction course overlays to seal coat/AC new construction. Georgia DOT experience is used due to the small amount of ADOT collected values. We recommend ongoing review of smoothness values after construction to verify the 49 value.

asset is the annualized present value of the cost of the construction and 2 overlays. If another agency gets only 25 years from the same rehabilitation strategy, then its cost will always be roughly twice as much as in the 50 year situation.

Similarly, if due to poor rehabilitation design, materials, or construction practices (roughness), life is diminished by two (2) years, then costs are increased approximately 2/50 (50 years is life between reconstructs). (NOTE: This varies depending on the selected value for the cost of money.)

An example follows, that shows cost differences using two different methods: first, by considering the entire pavement life (to reconstruction), and second, by only considering life until next treatment (on overlay or recycling). In justifying penalty/bonus amounts both of these methods ought to be reviewed.

Cost Differential Due to Loss of Pavement Life. The following example was made to illustrate the cost differential due to loss of pavement life. The assumptions are:

- 50 years total life cycle to reconstruction
- 24 years initial construction life
- 15 years 1st overlay life
- 11 years 2nd overlay life
- \$40/sq yd is cost to reconstruct pavement
- \$8/sq yd is cost to overlay section
- cost to overlay $\$8(\frac{12}{9})$ 5280ft = \$56320/lane mile;
  where 12 ft = lane width
- effect of high initial roughness on overlay is 2 year loss of life

Alternative #1: Costing the Effect Due Overlay Life Alone. Since there are 2 overlays with unequal life we will use the average overlay life of 13 years (other methods may vary results slightly).

The Equivalent Uniform Annual Cost (EUAC) of paying for the overlay cost over 13 years is:

for $i \neq 0$

$$A = \underbrace{\frac{i}{1 - (1 + i)^{-13}} \quad \underbrace{\$56320}_{\text{cost per lane mi}}}_{\text{EUAC}}$$

The EUAC of paying for the overlay cost over 11 years (reduced life) is:

$$B = \frac{i}{1 - (1 + i)^{-11}} \quad \$56320$$

NOTE: The EUAC is equal constant dollar annual payments that cover any set of costs. i is the discount rate and is equal to zero.

The equation to find the annualized cost differential spread over 13 years is:

$$(B\text{-}A) = (\text{differential cost}) \quad \alpha \sum_{j=1}^{13} (1 + i)^{-j}$$

$$\text{differential cost} = \frac{B\text{-}A}{\sum_{j=1}^{13} (1 + i)^{-j}}$$

$$= \frac{(B\text{-}A)\ (1-(1 + i)^{-13})}{i}$$

$$= \left(\quad \left[\frac{1-(1 + i)^{-13}}{1-(1 + i)^{-11}}\right] -1 \right) \quad \$56320/\text{lane mile}$$

for i = 2%

differential cost = \$56320/lane mile (0.16)

= 16% of overlay cost @ i = 2%

for i = 4%

differential cost = \$56320/lane mile (0.14)

= 14% of overlay cost @ i = 4%

for i = 0%

A = \$56320/lane mile/13

B = \$56320/lane mile/11

differential cost = 13 (B-A)

= \$56320 $(\frac{13}{11} - 1)$

= \$56320 $(^2/_{11})$

= \$56320 (0.18)

= 18% of overlay cost @ i = 0%

Alternative #2: Using Entire Life-cycle Costs. Using this same method applied to all treatments, compare the life-cycle I to the average life-cycle II.

Scenario I - Normal Life-cycle

Time (yrs):	0	24	39	50
Action:	New Construction	Overlay # 1	Overlay # 2	End Of Life Cycle
Life (yrs):	24	15	11	

Scenario II - Reduced Life-cycle Due to Increased Roughness

Time (yrs):	0	23	38	48
Action:	New Construction	Overlay # 1	Overlay # 2	End Of Life
Life (yrs):	23	15	10	

for $i \neq 0$

$$PV_I = {}^4/_3(5280)\ [\$40sy + (1 + i)^{-24}\ \$8sy + (1 + i)^{-39}\ \$8sy]$$

$$A = EAUC_I = \frac{i}{1 - (1 + i)^{-50}}\ PV_I$$

$$PV_{II} = {}^4/_3\ (5280)\ [\$40sy + (1 + i)^{-23}\ \$8sy + (1 + i)^{-38}\ \$8sy]$$

$$B = EAUC_{II} = \frac{i}{1 - (1 + i)^{-48}}\ PV_{II}$$

$$\Delta\ cost = \sum_{j=1}^{50} (B-A)\ (1 + i)^{-j}$$

$$= (B-A)\ \frac{(1-(1 + i)^{-50})}{i}$$

$$= \left(\frac{PV_B}{1-(1 + i)^{-48}} - \frac{PV_A}{1-(1 + i)^{-50}}\right)\ (1-(1 + i)^{-50})$$

$$= \left(\frac{1-(1 + i)^{-50}}{1-(1 + i)^{-48}}\ PV_B\right) - PV_A$$

for i = 2%

$$\Delta\ cost = ({}^4/_3)\ 5280 \left[\frac{1 - .3715}{1 - .3865}\ 48.83 - 48.66\right]$$

$$= \$56320\ (0.17)$$

$$\Delta \text{ cost} = 17\% \text{ of overlay cost @ } i = 2\%$$

for i = 4%

$$\Delta \text{ cost} = (^4/_3)\ 5280 \left[\frac{1 - .1407}{1 - .1522}\ 45.04 - 44.85 \right]$$

$$= \$56320\ (8)\ (0.10)$$

$$\Delta \text{ cost} = 10\% \text{ of overlay cost @ } i = 4\%$$

for i = 0%

$$A = {}^4/_3\ (5280)\ {}^{56}/_{50}$$

$$B = {}^4/_3\ (5280)\ {}^{56}/_{48}$$

$$\Delta \text{ cost} = 50\ (B\text{-}A)$$

$$= \$56320\ \frac{2}{48}$$

$$= \$56320\ (0.29)$$

$$\Delta \text{ cost} = 29\% \text{ of overlay cost @ } i = 0\%$$

Incentive/Disincentive Base. Based on the results of Table 3-8, we see that a maximum penalty of 15% of overlay construction cost is a conservative "value" loss estimate. It is conservative because only 2 year loss of life is considered, and a relatively conservative choice of discount rate is used. Furthermore, maintenance cost differentials, increased cost due to more frequent construction traffic delays and user cost differentials due to higher roughness sooner are not included, and each of these would increase the estimate.

Relative to the Incentive/Disincentive Base (IDB), a 15% loss of life translates into a IDB of $2000/.1 lane mile. This IDB is calculated as follows:

Table 3-8. Penalty Due to a 2-year Pavement Life Loss (as a % of construction cost).

	only overlay considered	entire life considered
i = 0%	18%	29%
2%	16%	17%
4%	14%	10%

1. Based on the Smoothness Specification

$$IDV = (36 - AS)\frac{IDB}{38}$$

where IDV is the Incentive/Disincentive Value and AS is the Actual Smoothness Value

This means that for every unit of smoothness change, the IDV increases by IDB/38.

2. Assuming a maximum smoothness differential of 15 away from the average smoothness, the total dollar value (IDV) for this case is:

$$15 * \frac{IDB}{38} = IDV$$

$$\text{or} \quad IDB = IDV\frac{38}{15}$$

3. Based on our previous work the maximum penalty (IDV) associated with maximum smoothness differential is 15% of construction cost. Since IDV is in units of dollars per 0.1 lane mile, 15% of construction cost translates to:

IDV = (% penalty) (construction cost)
= .15 (5630)
= 844.50/0.1 lane mile

Note a. construction cost was estimated in one example at $56,320/lane mile or $5,630/0.1 lane mile

Note b. % penalty was 15%

4. And so plugging into step 3

$$IDB = IDV\frac{38}{15}$$

$$= \$844.50\frac{38}{15}$$

= $2139.40/0.1 lane mile

or, after rounding

IDB = \$2000.00/0.1 lane mile

<u>Justification For Using a 15 Inch/Mi Roughness Range</u>. Continuing with our example, let us see why spreading a penalty cost across a roughness of 15 inches/mile is a reasonable assumption.

First, let us check that a 15 inches/mile range includes enough sections of road. Maximum deviation off the roughness mean using a 95% interval is calculated as shown below.

$$| x-\mu | = S*t^{n}_{.025}$$

A Maysmeter mean is obtained from new construction on seal coats for asphalt concrete ADOT data (left upper corner cell of Figure 3 of this document). Then, using the t statistic

$$| x-\mu | = S*t^{n}_{.025} \quad \text{where } \mu = 35 \; S = 6.76 \text{ and } n = 13$$

$$= 2.179 \times 6.76$$

$$| x-\mu | \approx 15$$

$$\mu \pm 95\% = 35 \pm 15$$

Since a high percentage (95%) of constructed roads have roughness within a 15 inch/mile band, then prorating the total penalty/bonus of \$8,500/lane mile over 15 inch/mile is reasonable.

<u>Conclusion</u>. Based on the "conservative" loss of life example here and all the subsequent conservative assumptions, i.e.

1. relatively high discount rate

2. no use of cost differential due maintenance costs or user costs

3. equal deterioration rates for roads of unequal initial roughness

4. a long estimated life for overlays and reconstruction

a much larger incentive/disincentive base (IDB) dollar figure per unit roughness is justified, than that derived here (i.e., $2,000/0.1 lane mile) As such, the $1,000.00/0.1 lane mile (IDB) figure proposed by ADOT is quite easily justified.

<u>Justification of the $0 (zero) Penalty/Bonus Interval</u>
<u>(Answers Question 7 [see page 3-5])</u>

The zero penalty/bonus interval is +/- 2 Mays count (in/mi). This was determined assuming 25% of projects would have zero penalty/bonus. The calculation of this interval uses the formula below. σ was calculated based on new construction ADOT data collected on this project (cells 1.1a, 1.2a, 2.2a, 3.2a, Table 3-5 μ=39, σ=6.76).

By using this value of σ we are assuming that eventually roughness control on construction for non-Interstates and overlays will approach today's control on new construction of friction courses (Interstates).

$$\text{+/- interval} = |x-\mu| = Z_{.25} * \sigma = .32 * \sigma$$
$$= .32 * 6.76$$
$$\text{+/- interval} = 2.16$$
$$\text{interval} \approx \text{+/-}\ 2\ \text{in/mi}$$

CHAPTER 4. MAYSMETER TESTING CAPABILITY

In order to implement a pavement construction's smoothness specification a smoothness measuring device is necessary to collect the appropriate smoothness information. The Maysmeter has been chosen by ADOT as this device. The device was chosen because of its low cost and durability, adequate measurement precision, and successful use in other states for pavement smoothness acceptance.

At this time ADOT's staff have been trained and are capable in all aspects of Maysmeter operation and maintenance. Under this contract a method of test document (technical memorandum AZ60-11) has been provided to ADOT. Information in this document includes how to operate the Maysmeter as well how to use it for testing pavement sections both for construction smoothness acceptance as well as general roughness testing. ADOT owns several Maysmeter units and during the course of this project a field crew has been hired and trained by the consultant to perform pavement smoothness acceptance testing with the Maysmeter. This crew now has two years experience in Maysmeter operations.

Of the 20 project work items, six are apropos to Maysmeter testing capability. They are:

Work Item 9 - Research Equipment Availability and Costs

Work Item 10 - Assist in Personnel Recruitment

Work Item 11 - Finalize Maysmeter Capability for Construction Quality Control

Work Item 14 - Calibrate the Maysmeter

Work Item 16 - Field Testing with the Maysmeter

Work Item 18 - Implement Field Testing

All these work items have been accomplished, resulting in a fully operational Maysmeter testing capability within ADOT for pavement smoothness acceptance.

Work Items 9, 10, 11, as they pertain to the Maysmeter testing capability are presented in the next section. The results of Work Items 14 and 16 are separately discussed as successive sections. Work Item 18, which deals with both Maysmeters and the Profilometer data collection is discussed in Chapter 5 for both instruments.

ACQUIRING A MAYSMETER CAPABILITY FOR CONSTRUCTION QUALITY CONTROL

As part of this project three types of Maysmeters were evaluated for use by ADOT for pavement smoothness acceptance testing. The three types are:

- A car mounted Maysmeter unit attached to the rear axle of a vehicle and owned by ADOT
- A trailer mounted Maysmeter which is towed by a separate vehicle and rented by ARE, Inc. for evaluation purposes
- A Georgia DOT Maysmeter which is essentially a specification enhanced car mounted Maysmeter

The purpose of this Maysmeter evaluation was to either justify use of the currently owned ADOT Maysmeter or justify its replacement for use in pavement smoothness acceptance testing. To that end a trailer mounted Maysmeter was brought to Arizona and tested side by side on pavement sections with the ADOT vehicle mounted Maysmeter. This process is documented in this project's technical memorandum, AZ60-9 (Ref 38). The results of this small study were that no significant difference in measurement or operation were found between the two Maysmeters. In the future ADOT can implement either trailer or vehicle mounted units. The trailer units have the advantage of alternative use of the tow vehicle without wear and tear on the Maysmeter device.

In the course of obtaining information relative to Georgia DOT's Maysmeter based pavement smoothness specifications, information was also collected relative to the equipment design specifications for the Georgia Maysmeter's themselves. It was found that the Georgia Maysmeters have several design enhancements intended to improve Maysmeter durability. After several years of practical experience with these machines the Georgia DOT is very happy with these design changes. For use in Arizona, the Georgia designed Maysmeter could be considered for future Maysmeter purchases. Retrofitting of the current ADOT Maysmeters, however, to meet Georgia specifications although evaluated was not implemented due to cost benefit considerations.

Equipment personnel were recruited for the operation, maintenance, and training of the 690D Profilometer and Maysmeters. Since the profilometer is a more complex device in terms of electrical, mechanical, and hydraulic devices, the personnel qualifications developed by ADOT and ARE Inc. reflected these needs. All new personnel were trained by ADOT and ARE Inc. Maysmeter training was all accomplished in Arizona as part of the Maysmeter calibration exercises and measurement of new construction projects.

CALIBRATE THE MAYSMETERS

Maysmeter measurements are dependent upon the vehicles suspension, its tires, and springs within the Maysmeter unit itself. Over the course of time the response of the springs, suspension and tires change gradually. To stabilize the Maysmeter measurements, the Maysmeter must be calibrated against a non fluctuating roughness measurement device. The results of this calibration process are adjusted Maysmeter values that are constant across time and compensate for vehicle and Maysmeter response changes.

There are two principal activities related to development of a calibration procedure for Maysmeters as follows:

- Set up a calibration course and procedure
- Adjust the calibration procedure for 690D Profilometer data

Since the 690D Profilometer was not available until late in the project, the initial calibration effort was accomplished with a rod and level survey in place of profilometer data. Project technical memorandums were written to guide ADOT in the rod and level survey (AZ60-5) (Ref 34) and Maysmeter calibration (AZ60-6) (Ref 35). The consultant trained ADOT personnel in a calibration procedure using a rod and level survey and then 17 calibration sections were selected and surveyed. Simultaneously Maysmeter information was collected for these calibration sections.

All this information was then supplied to ARE Inc. to produce the initial Maysmeter calibration equation. The algorithms used to derive this equation are discussed in this section for ADOT use whenever recalibration of Maysmeters is necessary.

The calibration process, although necessary to Maysmeter measurement stability, is both lengthy and costly. As such, Maysmeter data measurement control is a two step process. The first step is calibration control. It is a small effort that justifies or defers the need to recalibrate. The second step is the recalibration process.

Of the 17 calibration sections, four were selected as control sections. A process as documented in this project's technical memorandum AZ60-7 (Ref 36) requires repeated Maysmeter runs on these four section periodically.

<u>Calibration Procedure</u>

Maysmeter calibration has 4 essential steps.

1. Measure calibration sections with the 690D Profilometer and Maysmeters according to Appendix A, Method of Test.

2. For each calibration section input 690D Profilometer HRI (Highway Roughness Index) statistic, which represents this profile, and the Maysmeter count value into the AZCALIB program.

3. The AZCALIB program output provides a mathematical relationship (calibration equation) which transforms field measured Maysmeter values into the calibrated Maysmeter counts used in the roughness specification as the Actual Smoothness Value (AS).

4. When checking the pavement smoothness specification for asphalt concrete pavements, insert the average Maysmeter value measured for each 0.1 lane mile section into the calibration equation.

Use the calibrated results in the specification. This essentially converts all Maysmeter values in a "golden Maysmeter value" and thus makes them directly compatible. this normalizes the results for individual Maysmeter vehicles and allows ADOT the ability to operate simultaneously several units. At any point in time there should be an equation for each vehicle. This assures that calibration continues on a regular basis. Once the output values from each Maysmeters unit are adjusted using its calibration equation, then that result is compared to the Maysmeter value from the most recent recalibration runs on each section (see Method of Test - Appendix AD).

The consultant has trained ADOT's staff in the entire calibration and calibration control process. This includes: calibration testing with both the profilometer and the Maysmeter, calibration control testing with the Maysmeter, and calculation of calibration control results.

<u>Derivation of the Calibration Equation</u>

The purpose of Maysmeter calibration to obtain stable Maysmeter counts that can be used in applying the pavement construction smoothness specification. Maysmeter measurements are inherently valuable due to response changes in vehicle suspension, tire characteristics and mechanical (spring) components of the Maysmeter device. The stabilization technique entails employing a Profilometer which is a stable device, in order to create a calibration formula for Maysmeters. This calibration formula takes Mays field values and adjusts them to calibrated Mays values. An initial relationship between each Maysmeter and the 690D Profilometer is required. The initial relationship translates, for all time, profilometer roughness values (available in IRI units: inches/miles) into

Mays units (inches/0.1 miles). It has been estimated using the equation developed during the initial calibration effort. This equation is piece wise linear as follows:

$$MAYS = 0.449962 + 0.7451539 * IRI$$

for MAYS > 87.7 recalculate MAYS as

$$MAYS = -44.42259 + 1.128466 * IRI$$

IRI = International Roughness Index, inches/mile

MAYS = Calibrated Mays Counts units of inches/0.1 mile

Subsequently as recalibration becomes necessary, the AZCALIB program is applied to obtain a formula that translates field Mays measurements to calibrated Mays measurements. This formula is derived in two steps:

1. Use profilometer IRI values and Mays field values for the calibration sections and calculate a regression equation [LC] of field Mays values against IRI

   $$IRI = A_0 + A_1*MFC + A_2 * MFC*MFC$$

   Where MFC is Mays Field Counts (inches/0.1 mi)

2. Apply the initial calibration result in order to translate IRI to calibrated Mays values.

   $$MAYS = 0.449962 + 0.7451539 * (A_0 + A_1*MFC + A_2*MFC*MFC)$$

   for MAYS > 87.7 recalculate MAYS as

   $$MAYS = -44.42259 + 1.128466 * (A_0 + A_1*MFC + A_2*MFC*MFC)$$

This calibration procedure prevents the long term gradual changes and/or short term mechanical failures in the Maysmeter from influencing the implementation of the smoothness specification. It provides the basis for a legally defensible process.

IMPLEMENT FIELD TESTING USING THE MAYSMETER

During the course of this project ADOT staff has obtained field testing experience with the Maysmeter while accomplishing these project work items:

- Maysmeter calibration
- Maysmeter Calibration control
- Data collection on 38 recently completed ADOT construction projects
- Data collected on several ongoing ADOT construction projects both just prior to construction as well as after the construction was completed

In order to accomplish these work items the consultant provided to ADOT staff training in operations, testing procedures, and equipment maintenance. In addition ARE Inc served as an experienced reference source to ADOT field crews when they encountered operational problems. With two years experience ADOT's staff is now fully qualified in all phases of Maysmeter use and maintenance.

CHAPTER 5. PROFILOMETER TESTING CAPABILITY

From a financial standpoint a large portion of this project was devoted to the purchase and use of a 690D Profilometer. At the time of purchase this machine was the best commercial instrument for measuring the longitudinal smoothness of pavements. The purchase of this machine serves a dual purpose, 1) it is a calibration tool for Maysmeter measurements and (2) it is a precision smoothness measuring device which may be used for many other agency activities.

On this project the primary use of the profilometer was a calibration tool for the Maysmeters. The strategy to be employed by ADOT for smoothness collection is use of several Maysmeters which are calibrated by the 690D Profilometer. This strategy was selected because it provides accurate yet economical measurements.

During the course of this project the consultant has helped to specify, purchase, and check out a 690D Profilometer for ADOT and trained ADOT personnel in its operation both as a smoothness measuring device and as a calibration tool for Maysmeters. Documentation on use of the profilometer is included in Appendix A - Method of Test - for Determining Pavement Smoothness and projects technical memorandums AZ60-6, AZ60-7, and AZ60-8 (References 35, 36, and 37, respectively) which describe the smoothness Maysmeter calibration process. An ADOT smoothness field crew has been trained in these procedures by the consultant. At the time of this report ADOT has over two years of extensive experience in 690D Profilometer and Maysmeter data collection, data reduction, and analysis.

PROJECT WORK ACCOMPLISHED

Of the 20 project work items, five contributed to ADOT's acquiring of a profilometer testing capability. These work items include:

Work Item 9 - Research equipment availability and costs

Work Item 10 - Assist in personnel recruitment

Work Item 12 - Purchase the 690D Profilometer

Work Item 17 - Receive and check out the profilometer

Work Item 18 - Implement field testing

Research Equipment Availability and Design Specifications

Under ADOT directives and in accordance with the recommendations of Phase 1 of this project, the consultant began the purchasing process for a K.J. Law SD960 profilometer. Starting in November, 1987, K.J. Law was contacted for information regarding equipment availability, measurement precision and cost for this measurement device. Discussions concerning cost, durability, and measurement precision were initiated with current owners of this device, including: The Strategic Highway Research Program (SHRP), The Ohio Department of Transportation, and The University of Texas. This information was very useful in writing a purchase specification.

While initiating the profilometer purchase, the consultant also investigated two new developments in the area of smoothness measurement. First, a new measuring device called the Dipstick was evaluated. Second, results of a FHWA demo project which featured side by side comparison of several roughness devices measurements was reviewed.

The Dipstick was evaluated as a possible substitute for the profilometer. It is a precision smoothness measuring device, operated by hand. The Dipstick is a walking cane with a foot long base. In this base is a vertical displacement measuring device. By rotating the base end to end, an operator can move along a highway measuring the vertical displacement on a foot by foot basis. This results in a longitudinal profile of the highway which can then be use to calculate smoothness statistics.

Based on a test use of this equipment and discussions with the SHRP organization which owns such a device, it was concluded that the Dipstick could be efficiently used as a calibration tool but only if traffic protection is provided. For this project it was considered as a temporary surrogate for the then unpurchased profilometer. However, being a newly developed product, it still had some problems in regard to data collection and reduction. As a result, rod and level surveys were used as the temporary profilometer surrogate instead of the Dipstick device.

Results of the Fort Collins FHWA demo project for roughness measurement devices were reviewed by the consultant. During this demo project various smoothness measuring devices were run repeatedly across the several sections of pavement. Various profilometers, profilographs, and other smoothness measuring devices were represented. The demo project results indicated that the 690D Profilometer retained its high ranking as a smoothness measuring device.

ASSIST IN PERSONNEL RECRUITMENT FOR ADOT

ARE Inc also acquired position description questionnaires (PDQ's) from ADOT and prepared PDQ's for two new positions in the construction division. The responsibility of these positions was data collection with the profilometer and Maysmeter devices. These forms with job descriptions and qualifications were then submitted to ADOT where commensurable salary was estimated and the hiring process began. Qualifications for this position were set based on the ability to operate and maintain the 690D Profilometer which is the more complicated device. Equipment maintenance required capabilities in hydraulics, electronic, and simple mechanical maintenance. Equipment operation required a driver's license and a willingness to travel for extended periods.

PURCHASE THE 690D PROFILOMETER

In January, 1988 the consultant prepared a draft purchase specification for the 690D Profilometer. Purchase specifications used by The University of Texas at Austin and a report on the profilometer by the National Academy of Sciences was used in developing these purchase specifications. A draft purchase specification was submitted to ADOT and forwarded to the FHWA for approval. During much of 1988 this project as well as the profilometer purchase was on hold. By December, 1988 comments on the draft specification from ADOT and the FHWA had been reviewed by the consultant and discussed with the manufacturer, K.J. Law. Final specifications were then drafted and approved by ADOT, and the order was then placed with K.J. Law for a profilometer model M690DNC.

The manufacturing of the profilometer took approximately one year. During machine assembly individual components were tested for satisfactory operation Once assembled the entire unit was road tested by the manufacturer.

During this time a memo outlining the acceptance testing criteria for the SHRP profilometer was sent to ADOT by ARE Inc. This criteria was used as a guideline for the acceptance testing of ADOT's profilometer.

RECEIPT AND CHECK OUT THE PROFILOMETER

There are four activities associated with the acceptance testing of the 690D Profilometer including:

1. Check out the profilometer at the K.J. Law manufacturing site in Detroit.
2. Deliver the profilometer to Phoenix and operate it on several calibration sections already measured by rod and level and the Maysmeter.
3. Attend the SHRP profilometer in Austin, Texas and operate the ADOT profilometer side by side against SHRP owned profilometers.
4. Train ADOT crews in profilometer operations and maintenance and have them operate the device for several months in order to confirm its satisfactory operation prior to final acceptance of the device by ADOT.

The results of these activities is a 690D Profilometer unit which is fully operational and under the control of ADOT. Following a check out of the profilometer in Detroit by the consultant, the device was delivered to ADOT in Phoenix in early February, 1990 by K.J. Law Engineers. The ADOT crew was trained in its operational use. Following the training the crew drove the profilometer to Austin, Texas to participate in the profilometer workshop sponsored by the Strategic Highway Research Program. The workshop provided an ideal shakedown and training forum for the ADOT profilometer. The profilometer was returned to Phoenix following the workshop where it was scheduled to begin measurements on construction projects in the Phoenix area. During this time a problem with the on board generator occurred and was resolved.

Data from the ADOT profilometer obtained during the SHRP profilometer workshop was analyzed statistically to evaluate repeatability and variations in measurements. This analysis is documented in the technical memorandum AZ60-10 (Reference 39). The analysis showed that the profilometer performs similarly to the five other profilometers participating in the workshop. The good performance of the ADOT profilometer was a strong indication of its acceptability.

FULL SCALE FIELD TESTING

Since the acceptance of the profilometer, ADOT field crews have accumulated over two years experience with the profilometer. Relative to this project the profilometer was put to use measuring calibration sections as per the specifications in technical memorandum AZ60-7 (Reference 36). Additionally, roughness data on several construction projects was collected before and after construction using both the Maysmeter and profilometer. The results of this testing confirmed the good correlation between Maysmeter rough smoothness and profilometer's smoothness values on newly constructed pavements.

SHAKEDOWN PROBLEMS

During the course acceptance of testing several additional problems were identified. They include delivery of the proper tires, delivery and installation of a locking hood release, system generator replacement, and delivery of the following software components: slab fault measuring, joint fault counting, Texas PSI calculation program, and the ability to download profilometer data to IBM diskettes in ASCII format. All these problems were resolved prior to final profilometer acceptance in 1990.

SUMMARY

ADOT has a fully operational 690D Profilometer for controlling Maysmeter calibration and collecting numerous other important information for ADOT.

CHAPTER 6. SUMMARY AND RECOMMENDATIONS

SUMMARY

The Arizona Department of Transportation (ADOT) sponsored this research study of pavement smoothness measurement in order to develop and implement an improved highway smoothness construction specification on asphalt concrete pavements. Achieving a higher level of smoothness on highways during construction results in savings to the taxpayer, due both to reduced wear and tear on vehicles, and longer highway life.

The goal of this study is to provide data to assist ADOT in developing a new smoothness specification that can provide incentive to contractors to construct smoother pavements which is also easier for ADOT to administer. In order to provide incentive to contractors, a specification and associated measurement procedure was needed that would be applied quickly, thoroughly, and consistently across construction projects.

Based upon these criteria, this study has recommended several changes to the ADOT highway smoothness specification for asphalt concrete highways:

- relative to measurement
  - a. new smoothness measurement technique
  - b. different smoothness measuring device used

- relative to the specification
  - a. accommodation of the new smoothness measurement procedure
  - b. inclusion of an incentive/penalty clause

The envisioned consequences of these changes is that the contractors would not only have the incentive to improve highway smoothness quality, but also the means, as provided by ADOT, to assess smoothness quality in a timely manner, improve the quality as needed, and the adjust normal construction procedures in order to construct smoother highways.

Following adequate review and testing, it is anticipated that ADOT will adopt a new standard highway smoothness specification, either as tested, or as modified based upon the consequences of the ongoing specification testing.

CONCLUSIONS

This study has resulted in a number of important conclusions with respect to the measurement and use of roughness information by Arizona DOT. These conclusions are as follows:

1. The Model 690D Surface Dynamics Profilometer manufactured by K.J. Law is an excellent device for obtaining exact roadway profile statistics and it has a number of important uses as follows:

    a. Can be used to calibrate response type road roughness meters (RTRRMs) since its provides exact profile information very cost effectively.

    b. Is an excellent measurement device itself which can be used for other research and road roughness measurement projects such as the development of highway user cost models.

    c. Can be used to provide international roughness index (IRI) data for all highway performance monitoring system (HPMS) sections in Arizona as recently mandated by the Federal Highway Administration.

2. A roughness calibration course has been established in Phoenix and calibration procedures have been implemented for long term pavement performance data collection and the quality assurance and quality control of that data.

3. Arizona DOT has a team of engineers and technicians fully trained and an operational unit which can provide roughness data for all ADOT applications including the control of construction

specifications, HPMS data requirements, and pavement management systems (PMS) input.

4. The incentive form of construction smoothness specification for asphalt concrete (Section 407) of the AZDOT Specifications Manual provides a mechanism to produce smoother pavements over time at a net savings to the Arizona tax payer.

5. Arizona DOT now has the latest state of the art for highway roughness measurements.

FUTURE WORK RECOMMENDATIONS

Based on the results there are several recommendations for future work and developments in this technical area. Continued research and development by the Arizona DOT can continue to verify and enhance the results of this study. These recommendations include the following:

1. Test implement the construction smoothness specification for more construction projects with different existing pavement types and quality situations to enhance its acceptance and robustness. This will also validate all of the procedures.

2. Make necessary specifications quantities adjustments based on implementation experience and findings to improve pavement quality in Arizona.

3. Monitor specifications results by individual contractor's to provide contractors feedback for adjusting their methods and procedures for the overall goal of smoother pavements in Arizona.

REFERENCES

1. Hudson, W.R., Uddin, W., and Elkins, G.E., "Current State-of-the-Art for Evaluating Pavement Smoothness," Technical Memorandum 60-1 Prepared by ARE Inc, Austin, Texas for Arizona Department of Transportation, January 1986.

2. Uddin, W., Elkins, G.E., and Hudson, W.R., "Measurement of Pavement Smoothness", Interim Report, Arizona Department of Transportation, Project No. HPR-1-29(217), Prepared by ARE Inc, Austin, Texas for Arizona Department of Transportation, October 1986.

3. Darlington, J.R., "Evaluation and Application Study of the General Motors Corporation Rapid Travel Profilometer," Michigan Department of State Highways, Report R-731, April 1973.

4. Gillespie, T.D., Sayers, M.W., and Segel, L., "Calibration of Response-Type Road Roughness Measuring Systems," NCHRP Report 228, December 1980.

5. Spangler, E.B., and Kelly, W.J., "Servo Seismic Method of Measuring Road profile," Highway Research Board, Bulletin 328, 1962, pp 33-51.

6. Spangler, E.B., and Kelly W.J., "GMR Road Profilometer - A Method for Measuring Road Profile," Highway Research Record 121, 1966, pp 27-54.

7. Spangler, E.B., "Inertial Profilometer Uses in the Pavement Management Process," Transportation Research Record 893, Transportation Research Board, Washington, D.C., 1982, pp 20-27.

8. Claros, G.J., W.R. Hudson, and C.E. Lee, "Performance of Analog and the Digital Profilometer with Wheels and with Non-Contact Transducers," Research Report No. 251-3F, Center for Transportation Research, The University of Texas at Austin, April 1985.

9. Spangler, E.B., "Digital Noncontact Inertial Profilometer and Associated Computer Programs," Report No. FHWA-TS-85-210, The Pennsylvania Transportation Institute, The Pennsylvania State University, University Park, Pennsylvania, May 1985, pp 39-46.

10. McKenzie, David W., Hudson, W. Ronald, and Lee, C.E., "The Use of Road Profile Statistics for Maysmeter Calibrations," Research Report 251-1, Center for Transportation Research, The University of Texas at Austin, August 1982.

11. K.J. Law Engineers Inc, "Model 8300 Roughness Surveyor Operator's Manual".

12. Law, K.J., "Model 8300 Roughness Surveyor," Report No. FHWA-TS-85-210, The Pennsylvania Transportation Institute, The Pennsylvania State University, University Park, Pennsylvania, May 1985, pp 47-55.

13. Rainhart Co., "Mays Ride Meter Booklet," 3rd Edition, Austin, Texas, 1972.

14. "Equipment for Collecting Pavement Roughness Information," Report No. 2-1, Texas State Department of Highways and Public Transportation, 1976.

15. NU-METRICS, "DMI Instruction Manual," Revised August 1976.

16. Linder, Steven, "Maysmeter Digital Device Operations," 1983, (Unpublished).

17. Visser, Alex and Queiroz, Cesar V., "Roughness Measurement Systems," Working Document 10 of the Research on the Interrelationships Between Cost of Highway Construction, Maintenance and Utilization for Brazilian Ministry of Transport, United Nations Development Program, International Bank of Reconstruction and Development, July 1979.

18. Hveem, F.N., "Devices for Recording and Evaluation Pavement Roughness," Bulletin No. 264, Highway Research Board, 1960.

19. McCracken Concrete Pipe Machine Company, "McCracken Profile Reader - Product Bulletin".

20. Rainhart Company, "Rainhart Profilograph Booklet," Austin, Texas, 1969.

21. "Development of a Construction Control Profilograph," Report Number 49-3F, Texas Highway Department, 1968.

22. Haas, R.C.G., and Hudson, W.R., Pavement Management Systems, New York: McGraw-Hill, Chapters 6, 7, and 8, 1978.

23. Hudson, W. Ronald "Road Roughness: Its Elements and Measurement," Transportation Research Record 836, Transportation Research Board, Washington, D.C. 1981, pp 1-7.

24. Carey, W.N. Jr., "Uses of Surface Profile Measurements," Introductory Remarks SR 133, Pavement Evaluation Using Road Meters, Highway Research Board, Washington, D.C., 1973.

25. "General Instructions for Assembly and Disassembly of Hveem Hand Propelled Profilographs," State of California, Department of Public Works, Division of Highways, July 1963.

26. "Texas Manual on Uniform Traffic Control Devices," Texas State Department of Highways and Public Transportation, 1980.

27. Sayers, Michael, "Development, Implementation, and Application of the Reference Quarter-Car Simulation," ASTM STP884, American Society for Testing and Materials, 1985, pp 25-47.

28. Hudson, W.R., Dan Halbach, J.P. Zaniewski, and Len Moser, "Root-Mean Square Vertical Acceleration as a Summary Roughness Statistic," ASTM STP884, American Society for Testing and Materials, 1985, pp 3-24.

29. James Cox and Sons Inc. "CS8200 Profilograph - Product Bulletin," Colfax, California, 1986.

30. Sayers, M.W., T.D. Gillespie, C.A.V. Queiroz, "The International Road Roughness Experiment Establishing Correlation and a Calibration Standard for Measurements" World Bank Technical Paper Number 45, Washington, D.C. 1986.

31. Caldwell, L.L., "Georgia DOT Smoothness Specifications", Technical Memorandum 60-2 Prepared by ARE Inc, Austin, Texas for Arizona Department of Transportation, February 1988.

32. Caldwell, L.L., "Trip Report, November 17, 1988", Technical Memorandum 60-3 Prepared by ARE Inc, Austin, Texas for Arizona Department of Transportation, November 1988.

33. Caldwell, L.L., "Trip Report, December 7, 1988", Technical Memorandum 60-4 Prepared by ARE Inc, Austin, Texas for Arizona Department of Transportation, December 1988.

34. Caldwell, L.L., "Procedure for Rod and Level Survey of Calibration Sections," Technical Memorandum 60-5 Prepared by ARE Inc, Austin, Texas for Arizona Department of Transportation, December 1988.

35. Caldwell, L.L., "Maysmeter Calibration Runs", Technical Memorandum 60-6 Prepared by ARE Inc, Austin, Texas for Arizona Department of Transportation, December 1988.

36. Caldwell, L.L., "Maysmeter Calibration Control", Technical Memorandum 60-7 Prepared by ARE Inc, Austin, Texas for Arizona Department of Transportation, January 1989.

37. Caldwell, L.L., "Selection of Control Sections From December 1988 Calibration Runs", Technical Memorandum 60-8 Prepared by ARE Inc, Austin, Texas for Arizona Department of Transportation, February 1989.

38. Caldwell, L.L., "Subjective Rating of Maysmeter Systems", Technical Memorandum 60-9 Prepared by ARE Inc, Austin, Texas for Arizona Department of Transportation, March 1989.

39. Caldwell, L.L., "Analysis of Arizona Profilometer Data Taken During the February 1990 Profilometer Workshop in Austin, Texas," Technical Memorandum 60-10 Prepared by ARE Inc, Austin, Texas for Arizona Department of Transportation, June 1990.

40. Moody, Eric D., "Maysmeter Data Analysis", Technical Memorandum 60-11 Prepared by ARE Inc, Austin, Texas for Arizona Department of Transportation, May 1990.

41. "Rational Characterization of Pavement Structures Using Deflection Analysis Final Report", Volume 1, Center for Advanced Research in Transportation, Arizona State University, Report No. FHWA-AZ87-254, December 1988.

APPENDIX A

METHOD OF TEST FOR DETERMINING PAVEMENT SMOOTHNESS

1. Scope

1.1 This method covers the determination of the Highway Roughness Index (HRI) for asphaltic concrete pavement. The primary test procedure involves use of the Maysmeter. A supplementary procedure is included which uses the Surface Dynamics Profilometer. The supplementary procedure should be used if 1) the primary procedure yields questionable results, 2) the Maysmeter cannot be used due to speed constraints, or 3) the Maysmeter is unavailable.

2. Referenced Material. The following references cover various important detailed aspects of the method:

Appendix AA. Equipment Operational Guidelines
Appendix AB. Profilometer Calibration
Appendix AC. Profile Survey of Calibration Sites
Appendix AD. Maysmeter Calibration
Appendix AE. Maysmeter Calibration Control

3. Significance

3.1 Pavement smoothness directly affects road serviceability (ride quality) and indirectly has strong effect on vehicle operating cost and user safety. Quantification of smoothness by the procedures outlined in this method can be used to evaluate a given roadway section or project of any length. Quantitative measurements of road smoothness can be used 1) as a means of monitoring the riding quality of the road network, 2) as pavement management information needed for use in prioritizing and allocating highway maintenance funds, 3) as a measure of the quality of new construction, and 4) when summarized historically as a measure of pavement performance that can be used to evaluate alternate pavement design, construction and rehabilitation strategies.

4. Terminology

4.1	Calibration -	(A) To systematically correlate the response unit of measurement generated by the Maysmeter against a standard roughness summary or index based on accurate profile measurements taken with a profiling device (usually a Law Profilometer).
4.2	Calibration control -	The technique of monitoring on a regular basis the calibration of the Maysmeter This process involves running a series of tests on a subset of calibration sections and statistically analyzing the test results.
4.3	Calibration sections -	Roadway sections used for calibration of the Maysmeter. Several 0.2 mile long sections are selected which have a known or pre-measured profile and range individually from very smooth to rough.
4.4	Project -	Refers to an Arizona Department of Transportation paving job where pavement profile is to be measured. A project includes the full length of all of the lanes.
4.5	Section -	Refers to a lane within a project.
4.6	Highway Roughness Index -(HRI)	A standard unit of measurement used to qualitatively quantify the irregularities in a pavement profile. The standard is based on mathematical modeling of a vehicle's response to variations in the

longitudinal profile of a pavement. Units are in inches per mile. HRI is the average of the left wheel path and right wheel path IRI output from the K. J. Law 690D Profilometer.

5. Equipment

5.1	Maysmeter -	A response type meter used to measure the irregularities in a pavement profile.
5.2	Profilometer - (registered trademark of K.J. Law Engineers, Inc.)	A pavement profile measuring device that uses non-contact sensors and accelerometers to measure the relative distance between the vehicle and the roadway surface.
5.3	Distance Measuring Instrument (DMI) -	A device used to electronically measure distance of a section.

6. Calibration

6.1 Because the Maysmeter is a response type device subject to environmental and physical variation, the output of the device must be calibrated against a fixed standard so that stability can be achieved and results can be compared over time. This calibration is achieved by monitoring the Maysmeter response on selected calibration sections with quantified smoothness. Calibration is maintained by periodically rerunning these same sections and checking them against certain control criteria. The smoothness for each section is obtained by measuring surface profiles using the profilometer. Once the smoothness has been measured with the profilometer, the results are presented in terms of a standard roughness index known as HRI, Highway Roughness Index. The Maysmeter is run over the calibration sections and these results are correlated with the HRI using regression analysis.

6.2 Calibration Sections - ADOT has established a number of calibration sections around the Phoenix area for purposes of Maysmeter calibration (These sections are discussed further in Appendix C, Profile Survey of Calibration Sites). The sections were selected to cover a wide range of smoothness. At least four of the calibration sections shall also serve as calibration control sections and shall be used to monitor the Maysmeter calibration.

7. Procedure

7.1 Section Identification. The section to be tested shall normally be the full length of a project. Bridges, bridge approaches, railroad crossing, and intersections are excluded from testing by this method. Each lane of the project shall be tested. All testing shall be conducted in the normal direction of travel.

7.1.1 Limits - When possible, the section limits shall correspond to the project limits and station numbers. Tests shall be run with the beginning point corresponding to either the lowest or highest station number on the project, depending on the direction of travel. If station numbers are not available, then a zero (0) point shall be established for each section at the project limit first encountered in the normal direction of travel. The project limits should be clearly identified (preferable by paint marks or reflective tape) on the pavement to facilitate initiation and ending of measurements and for possible future measurements.

7.2 Primary Testing

7.2.1 Primary testing for evaluating pavement smoothness shall be conducted using the Maysmeter. Insure that the Maysmeter is operationally ready for testing based on the guidelines of Appendix A (Equipment Operational Guidelines).

7.2.2 Insure the Maysmeter has been properly calibrated using the criteria in Appendix D (Maysmeter Calibration) and that the

Maysmeter calibration is valid based on the criteria in Appendix E (Maysmeter Calibration Control).

7.2.3 When practical, test speed shall be 50 mph. If conditions exist that will not permit testing at 50 mph, then a test speed of 35 mph shall be used. If it is not possible to test at 50 mph or 35 mph, then primary testing shall not be performed.

7.2.4 Data shall be collected continuously during the test run with accumulated Maysmeter count recorded for each 0.1 mile interval. If the last interval of the section is less than 0.1 mile in length, the count for the last interval will be recorded along with the interval length. Data collection shall begin as the rear axle of the vehicle crosses the beginning project limits and end as the rear axle crosses the ending project limits.

7.2.5 Prior to initiating the test run, the Maysmeter vehicle speed shall be stabilized. An acceleration zone at least 500 feet in length should be provided ahead of the beginning project limits to permit the vehicle to be brought up to speed. The test speed shall be maintained throughout the test run using the vehicle cruise control. If the speed cannot be maintained constant for any reason, the run shall be aborted.

7.2.6 The Maysmeter vehicle driver shall attempt to align the wheels of the vehicle with the wheelpaths of the lane being tested and maintain this orientation during the test run. It may be helpful to visually center the vehicle in the test lane and use a vehicle reference point (such as the fender edge or hood center) to check vehicle orientation during the test run.

7.2.7 Five test runs shall be made on each section. Quality of the data shall be verified as discussed in Item 9. Data Quality Control.

7.3 Supplementary Testing

7.3.1 Supplementary testing for evaluating pavement smoothness shall be conducted using the profilometer. This procedure shall be used for referee testing whenever the validity of smoothness as quantified by the Maysmeter is in question or whenever primary testing cannot be performed. Smoothness determined from the profilometer will supersede results from the Maysmeter for acceptance of work.

7.3.2 Insure the profilometer is operationally ready for testing based on the guidelines of Appendix A (Equipment Operational Maintenance Guidelines). Insure the profilometer has been properly calibrated using the criteria of Appendix B (Profilometer Calibration).

7.3.3 Operating Speed. It is important to maintain a constant vehicle speed during a profile measurement run. The average speed to maintain is 50 mph. If it is not possible to test at 50 mph, then a slower speed may be used. It is important to avoid changes in speed that may jerk the vehicle or cause it to pitch on its suspension. Cruise control should be used through the section to better maintain uniform speed. Changes in throttle pressure to correct vehicle speed should be done slowly and evenly.

7.3.4 Filter Wave Length. The filter wavelength used during the profile measurement run shall be 300 feet.

7.3.5 Event Initiation. The road profile program uses "event marks" to initiate data acquisition. The event marks can be generated by either the photocell event detector, or the operator activated event pendant. Photocell initiator is the preferred method. This method requires reflective pavement marking tape to be placed across the pavement at the project limits. Depending on the reflectivity of the tape, the detector threshold control located on the front of the console may require some adjustment to trigger properly. Photocell initiation should only be used if it is absolutely safe for the operator to place the tape on the pavement. If conditions make the placement of tape unsafe, the event pendant should be used. This method requires the operator to "judge" the starting point for data acquisition. The use of a reference point on the side of the pavement, like a painted lath at the beginning threshold, is helpful in doing this. Several runs may be needed to practice starting data acquisition by this method.

7.3.6 Stop Method. Data acquisition termination shall be done by selecting 'distance' as the stop method. The distance should be set based on the project limits.

7.3.7 Number of Runs. The number of runs required for each section is five (5). Quality of the data shall be verified as discussed in Item 9. Data Quality Control.

7.3.8 Run Identification. The file name of the section shall be a six digit section number. The run number will be automatically updated by the computer program. If a run is terminated for any reason, the run number for the rerun will have to be edited in the computer program to ensure the proper run number sequence. The DEC computer filename will be the same as the six digit section number. The operator/driver will be identified in the following format: XXXXXXXXX/YYYYYYYY where 'XXXXXXXX' is the operator's name and 'YYYYYYYY' is the driver's name. The maximum allocated characters is 16, which includes the '/', so allowances for each person's name may be made to accommodate the other person's name as long as the total does not exceed 15.

7.3.9 Roughness Index. Using the Options Setup menu, the operator should make the appropriate entries for calculating HRI. The following options should be set:

OPTIONS SETUP

R	RIDE QUALITY INDEX IRI
I	INDEX ENABLED
W	WHEELPATH BOTH
A	AVERAGING INTERVAL 528.0 (FEET)
B	INDEX CALCULATION SPEED 50.0(MPH)
M	ALLOW RETURN TO OTHER MENUS
S	STORE HEADER OPTIONS

The operator should enter "S" (Return) to store the header options that have been entered. The program will prompt the operator for a file name to use. The operator will enter the ADOT section number with HDR extension for the file name.

7.3.10 Recording Method. Random Access Memory (RAM) is the preferred recording medium for the profile runs. This medium should be used for sections shorter than 5 miles in length. After the run is finished, the driver will pull over at a safe point and come to a complete stop so the data can be transferred to the hard disk for permanent storage prior to another profile run. All data in RAM is to be transferred to the hard disk before leaving the vicinity of the project. Magnetic Tape should be used to record profile runs for sections longer than 5 miles. If magnetic tape is used it is not necessary to transfer data to the hard disk prior to another run.

8. Data Reduction and Report

8.1 Primary Testing - The result of a test run will be Maysmeter count values for each 0.1 mile interval. These values are automatically stored in the onboard computer. Maysmeter counts should be summarized and reduced to produce an HRI value for each 0.1 mile interval for each section. This is done by first converting the Maysmeter counts to the appropriate units as described in 8.1.1 and then using the calibration equation corresponding to the test speed to predict the HRI. Development of the calibration equation is discussed in Appendix D. Maysmeter Calibration.

8.1.1 Record Maysmeter data in counts/interval for 5 runs on Worksheet 1. Calculate the average count for each interval and record. Divide the average count for each interval by the interval length to get the average smoothness for each interval in units of counts per mile. Use the Maysmeter calibration equation to convert the final smoothness in counts per mile to HRI for each interval.

8.1.2 Report - The report shall include the following:

8.1.2.1 Date

8.1.2.2 Project Number

8.1.2.3 Direction Measured

8.1.2.4 Total Distance Measured

8.1.2.5 Operator and Driver

8.1.2.6 Measuring Speed

8.1.2.7 Test Section Description

8.1.2.8 HRI Summary Statistic for Each Test Interval

8.2 Supplementary Testing - The result of a test run with the profilometer will be profile data collected from both wheelpaths in two- inch increments, stored every 6 inches based on a 12 inch running average. Onboard software permits the operator to compute the Highway Roughness Index automatically.

8.2.1 Generate the HRI for each 0.1 mile interval

8.2.2 Report test results in accordance with 8.1.2

9. Data Quality Control

Some variables that will affect smoothness readings are:

1. Pavement Texture

2. Grade of Road

3. Dips in Pavement

4. Truck Passing

5. High Winds

6. Failure to maintain same wheelpath

7. Rapid acceleration/deceleration

8. Dark or shiny pavement (lost lock/saturation) (Profilometer)

9. Saturation due to traversing highly reflective materials (Profilometer)

10. Sun Angle (Profilometer)

11. Skirt Cover (Profilometer)

9.2. To evaluate the acceptability of the data the following guidelines are presented:

9.2.1 If the variance between the runs exceeds 5% of the mean, or if other inconsistencies are present, the operator should attempt to identify the source(s) of the variation (e.g., a pavement which is highly variable in the transverse direction, equipment maladjustments or malfunctions). If adjustments of the equipment are indicated, they should be made. Then, an additional set of 5 repeat runs should be made.

9.2.2 If the variance of the second set of runs is less than 5%, and other anomalies presented in the first set are absent, then this set of runs should be used to quantify the pavement smoothness.

9.2.3 If the results of the second set of runs are consistent with those of the first set of runs, and the operator has eliminated all equipment-related sources of variation and anomalies, the operator should make note of this, and return the data to the appropriate Department personnel.

9.2.4 If the results of the second set of runs have excessive variance, or other anomalies, which are not consistent with those of the first set of runs, the operator should explore possible reasons for this inconsistency, correct any remaining problems, and conduct additional sets of runs until satisfied that valid data has been obtained. All data should be saved, and the operator should make note of all adjustments, so that the Department personnel responsible for data evaluation can select the appropriate set of data.

APPENDIX AA
EQUIPMENT OPERATIONAL GUIDELINES

The appendix provides general guidelines for operation of the Maysmeter and profilometer. These guidelines should be used in checking out the equipment prior to field testing and for actual routine equipment operations. The information presented in this appendix should supplement the equipment manufacturer's recommendations for operation and maintenance

PART I. MAYSMETER START-UP PROCEDURES AND TROUBLE SHOOTING

Description of Maysmeter

The Maysmeter system is a scientific road roughness measuring device. There are several major components to the system that should be described before describing their use. Below are some general definitions that are useful in clarifying the equipment terminology.

1. Maysmeter - This term refers to all the hardware that would be included in equipment purchase, including the readout unit, roughness transmitter, distance transmitter and wiring harness.

2. Maysmeter (or roughness) transmitter - This refers to the device that translates relative axle-body movements into electronic pulses that are representative of the roughness of the road. The transmitter is mounted in an automobile.

3. Count accumulator - Also known as the "black box", this is a totally electronic device used to display and record roughness measurements in terms of counts per unit length of roadway.

4. Distance transmitter - This term refers to the device used to transmit rotations of the speedometer cable to the DMI for recording distance measurements.

Start Up Procedures

The first step in the normal daily operation of the Maysmeter is the verification of the equipment. The check list includes:

1. Tire pressure - Low tire pressure can significantly affect roughness measurements. It is, therefore, recommended that the "hot" tire pressure of Maysmeter wheels be maintained at 30 psi (or the metric equivalent). This requires that the tires be "warmed up" by operating the Maysmeter at highway speeds for approximately 5 minutes before checking the pressure. It is also strongly recommended that a tire gauge be purchased and tire pressure be checked exclusively with that gauge. This prevents any error due to differences in tire gauge calibration.

2. Battery - Proper operation of the Maysmeter depends on a constant high voltage from the vehicle battery. Therefore, the operating crew should check the output of the battery routinely.

3. Transmitter pulley - before each day's use, the pulley on the back of the Maysmeter should be checked. The side marked "Top" should be up, and the side marked "SPLICE" should be down.

4. Transmitter cable - For proper operation, it is necessary to avoid slippage between the transmitter cable and pulley. Therefore, the cable should be checked routinely to be sure that there is enough tension to avoid slippage. One sign of insufficient tension is a transmitter pulley that does not maintain its proper position.

Once it has been determined that the Maysmeter vehicle is functioning properly, field data collection may commence.

Trouble Shooting and Repair.

Although the Maysmeter has proven reliability, it is possible that operators may occasionally find problems with the system, either in the form of erroneous data or failure to obtain data in any form. The following discussion deals with the causes of such problems and prescribes possible solutions. The following is a list of causes to certain problems that may arise.

1. Some problems with erroneous Maysmeter data are due to malfunctions in the transmitter. As described in the start-up procedures, a loose cable can result in pulley slippage. If the pulley is not aligned properly (i.e., with splice at the bottom), the splice in the program film may pass across the photocells and give poor or inconsistent signals. One or more of the photocells may also be out. A blown photocell would result in a systematic loss of signal. Since the four photocells work in pairs, the loss of one cell would result in a 50 percent reduction in Maysmeter count.

   A blown transmitter lamp could also result in lost signals. To replace the lamp, remove the transmitter cover (4 screws), being careful not to damage the wiring harness. A schematic diagram of an open transmitter is shown in Figure AA-1. Remove the photocell shelf (2 screws from outside the back of the housing) and replace the bulb. Turn on the bulb to test. A sharp line of light <u>must</u> illuminate the 4 tiny glass bead photocells. To focus the line, rotate the bulb in its friction clips until the filament is as near parallel with the razor blade slit as possible. If necessary, loosen the two screws that hold the lamp socket and orient until the lamp filament is parallel with the razor blade slit. After focusing, reassemble in reverse order (Reference 1).

   If problems still persist with the Maysmeter after all checks described here have been made, then the maintenance and operation manual (Ref 1) should be consulted.

2. Lacking Data - If roughness is not being recorded or if very low readings are observed, another probable cause is a misaligned program film. This problem can be detected using the strip chart recorder. Repositioning the film program drum requires the removal of the transmitter casing and the loosening of the allen screw on

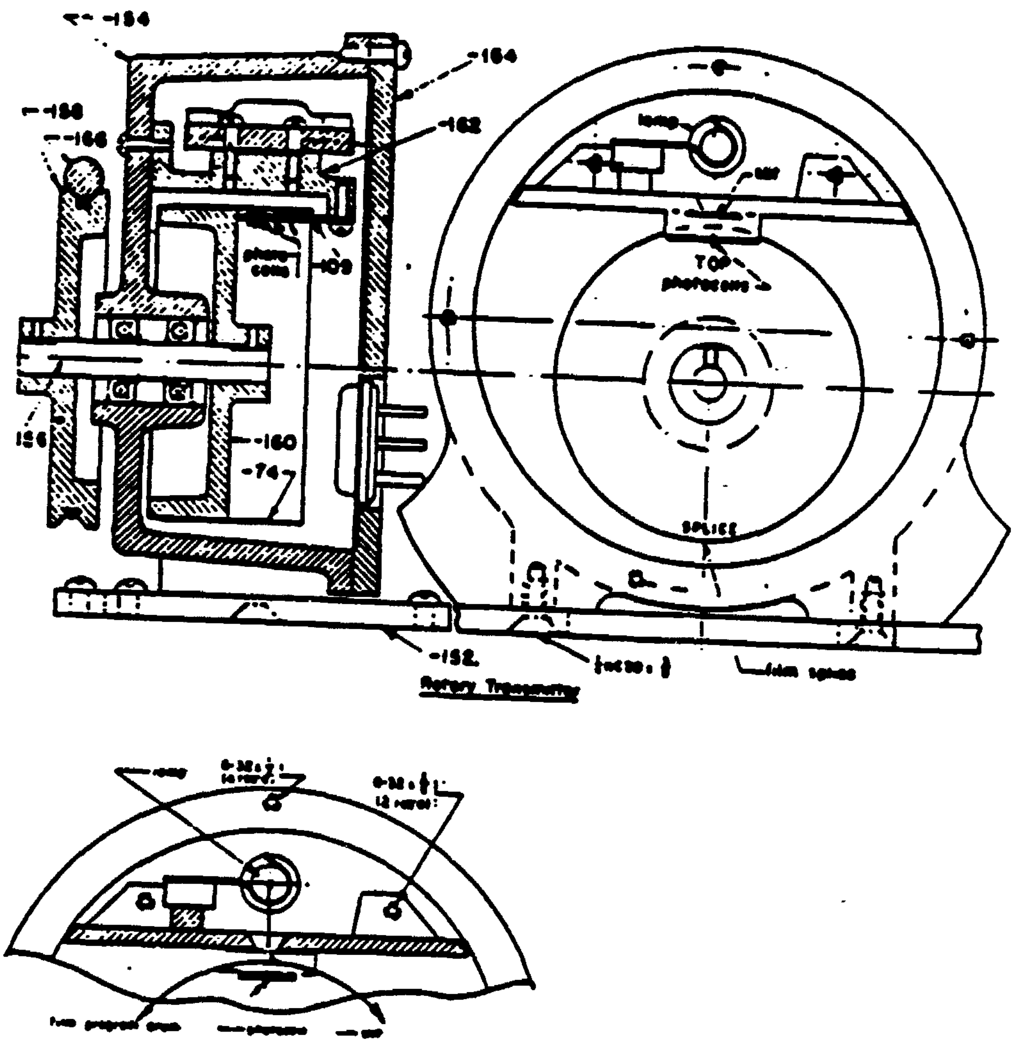

Figure AA-1. Schematic of Maysmeter Transmitter Showing Position of Lamp for Replacement (after Reference 1).

the inside of the drum. By moving the drum across the axle, the operator can find the location where rotational movement of the drum causes the most fluid movement of the roughness pen on the strip chart recorder.

Out-of-Calibration. If all of the aforementioned are determined not to be the cause of the problem, the operator should suspect an out-of- calibration condition. It is possible that a shock absorber or spring may sustain immediate significant damage during operation, especially on extremely rough roads. Control runs should be made when this condition is suspected. Maysmeter monitoring and control is covered in Appendix E.

Recommended Tools

Because many of the minor problems listed previously may occur during operation in the field, it is suggested that a tool kit be provided with the vehicle at all times. Suggested tools include:

1. Air compressor - For maintaining proper tire air pressure.

2. Tire gauge - Tire pressure should be measured exclusively with this gauge.

3. Wire strippers and clamp splicers - For repairing damage wires or cables.

4. Spare DMI sensor and targets (if DMI operation based on proximity sensor)

5. Maysmeter transmitter light bulbs.

6. Screwdrivers, wrenches, pliers,hammers and anything else necessary for disassembling and/or reassembling the transmitter.

PART II - PROFILOMETER OPERATION

Description of the Law Model 690DNC Profilometer

The model 690DNC Surface Dynamics Road Profilometer measures road profile utilizing a digital computer. The profilometer measures road profile in two wheelpaths and provides road profile display in real time. Profile data is also recorded on digital magnetic tape or hard disk for permanent record and further processing.

The system software allows for run documentation data, actual profile data, and calculated roughness statistics to be recorded together as a data file on tape or other media. This provides a convenient and simple method of record keeping.

The operator controls the system with a monitor keyboard. The monitor prompts the operator for information and makes the system easy to use. The operator may select either IRI or a MAYS index calculation, as well as the output interval for indices. The selected index value is printed on the teleprinter and is recorded with the profile data.

General Operation

The vehicle environment is especially critical since this system includes a fixed disk drive. Fixed disks operate with very close tolerances in their mechanical systems and may be damaged if operated with large temperature variations. The computer system should only operate in a temperature range of 15 to 40 degrees C (59 to 90 degrees F). Further, the rate of change of temperature should not exceed 11 degrees C/hour maximum (20 degrees F/hour maximum). If the computer is not going to be operated, the storage temperature range is 40 to 65 degrees C (-40 to 151 degrees F).

Disk drives may not operate reliably while the vehicle is in motion due to the vibrations and accelerations encountered. The computer virtual memory is configured as a disk drive and all the files required during normal system operation while in motion are copied to it. This eliminates the necessity of accessing disks during testing. Writing to mechanical disk drives during testing may cause unrecoverable errors and may even destroy existing disk files.

All computer system power is controlled through a power controller located in the bottom of the computer enclosure. For more information on the power controls refer to the Law Manual (Reference 2).

The external power cord is used for connection to a standard 30 amp. outlet or with an adapter to a standard 15 amp. outlet. The power requirements are 115 volts AC at 10 ampere. Ensure that all instrument power and computer power are off and that the generator is off before connecting to external power. When power is externally applied, a relay will automatically disconnect the generator.

Before starting the generator, ensure that external power is disconnected and that instrument and computer power are off. Depress the START/STOP Rocker switch to start the generator. Release the switch when the engine starts. If the generator does not start in a few seconds, then wait ten seconds and try again. If further difficulty is encountered, consult the ONAN Operator's Manual. Connection of power to the vehicle distribution system is delayed for a short period of time to allow the generator to come up to speed and stabilize. A clicking sound indicates that the ONAN is up to speed and stabilized and it is then safe to turn on the various equipment powered by the generator.

Data Acquisition and Handling

These data collection guidelines are described in detail below and are divided into three main groups. They are: (1) daily checks and startup procedures, (2) setting up the software for data collection and (3) using this software for field data collection.

Daily Checks and Start-Up Procedures.

1. In order to maintain the computer and various associated equipment at the proper operational temperature, care must be taken to either cool or warm the equipment to the proper temperature. During hot

periods the air conditioner should be left on to remove hot air from the interior.

2. Before starting the engine, circle the unit and perform the various daily checks:

   - overall visual check
   - tires properly inflated
   - check for loose nuts & bolts, etc.
   - check under body on the pavement for signs of leaks
   - check under hood i.e., fluid checks (oil, brake, power steering, radiator, windshield washer), battery connections belts and hoses.

3. Start the engine. When the engine is warming up check that the various operational lights and arrow board are working.

4. Clean the sunshield, mirrors and lights.

5. Turn on the generator and wait for stabilization. If the temperature is cool and damp, or cold, turn the air intake to winter conditions. If the idle is rough, adjust the fuel to air mixture (adjustment on float bowl) to obtain the ideal setting.

6. When the generator has stabilized, turn on DEC computer. Also, turn on the charger for the auxiliary battery at this time.

7. Turn on the personal computer, 'CRT', and other computer equipment.

8. Turn on the power to the tape drive. Activate load/rewind to rewind and load the tape. When the tape is finished loading and the load rewind light has stopped flashing, push the on-line button. You are now ready to write to tape. If the tape will not load and all the lights flash, the tape will have to be loosened from the real (6 - 12") so that it will load. Tc unload the tape, push the on-line button to take the tape off line. Push the unload button and it

will begin to flash. When it has stopped flashing, the tape is unloaded. Shut the power off.

9. Adjust the generator for smooth operation if necessary.

10. Warm up the system for 1/2 hour in the summer and 1 hour in colder months before making calibration checks or performing tests.

11. Clean the light sensor glass and light and the receiver glass for photo cell box.

12. Remove trash and organize the interior in preparation for the day's work. Interior seating and carpet should be sprayed as needed with a static guard to prevent static electricity from affecting the various electrical systems.

<u>Setting up the Software</u>. This portion of the field data collection guide deals with setting up the software for collecting data. For further information on the profile data collection software, the user is referred to the manufacturer's (Law) documentation manuals.

<u>Test Sequence Setups</u>

<u>A. Computer Operation.</u> Ensure that the ambient temperature and rate of change in temperature is within the system operating range. Then proceed in the following order:

1. Place the System Diskette in the Upper Drive (DU1). The upper drive (DU1) is the system "BOOT" drive and must contain the diskette with the system files. Proceed by turning the lever on the upper drive to the horizontal position and installing the System Diskette. The write protect notch should be on the left side. If it is not, turn the disk over and insert it, then rotate the lever to the vertical position.

2. Turn the power switch from Off to On.

3. Verify that the Run Light is on and the DC OK light is illuminated.

4. If the monitor does not respond then:

   a. Depress and release the "RESTART" button on the PDP 11/83 front panel.

   b. Type "^C" twice (Depress and hold "CTRL" and then hit "C").

   c. Within one minute the terminal should respond with:

      Message 04 Entering Dialogue mode

      Commands are Help, Boot, List, Setup, Map and Test.

      Type a command then press the "RETURN" key.

   d. Type "BOOT DU1" and press the "RETURN" key.

   e. The upper drive indicator should light, indicating that the disk is being accessed.

   f. If the start-up message does not appear within one minute then try your backup system disk.

   e. If the system still does not respond or the "HALT" indicator lights then DEC service is probably required.

<u>B. Keyboard Commands.</u> After the software has been loaded, the monitor will respond with a turn on message and a list of commands that may be entered from the keyboard. That list includes the following:

A FORMAT and INITIALIZE (calls the format - initialize menu)
B RUN BACKUP (calls the file backup menu)
C RUN CALIBRATE (calls the calibrate menu)
D LIST DIRECTORIES (calls the directory menu)

E TIME DATE (permits changing the time and/or date)

F RUN REPLAY (calls the replay menu)

G CONVERT PROFILE TO ASCII FORMAT (calls the raw data to ASCII convert menu)

I TRANSFER FILES TO IBM (calls the KERMIT routine to transfer files to IBM world)

P RUN PROFILE (calls the profile data collection program)

H PRINT HELP FILE (Prints the HELP file)

All commands are terminated with a return key. If you make a mistake, you may delete the individual characters with the BACKSPACE key. Do not execute a CTRL C when data is being recorded on magnetic tape as the result may be to abort the recording without closing the magtape file.

Using the Software in the Field

Header Generation. Header Generation is chosen by selecting the "P" (return) keys from the main menu list. The program will first load the system calibration factors from the disk. If the scale factor file (SCALE.CAL) is not found or if there is an error in reading the data, an error message will be displayed. The first portion of the program is devoted to obtaining the information required for record keeping. This information is called the header data. This pertinent information required prior to taking profile measurements is as follows:

The computer program will prompt the operator with the following questions:

1. "Do you want to record on Magtape Y or N. The operator will respond with a "Y" or "N" (return).

2. "Do you want to use an existing header File Y or N". The operator will respond with a "N" (return).

After the last "N" response, the computer program will lead through the header generation menus to allow entry of run parameters.

The correct menu selections for the first screen are as follows:

SURFACE PROFILE SYSTEM SET-UP

DATE DD - MMM - YY TIME HH:MM:SS

A DRIVER DISPLAY UNIT FEET

B FILTER WAVELENGTH 300.0 (FEET)

C GRAPHICS SCALE 1.00 (INCHES)

D PRINT LAST SCREEN ON EXIT DISABLED

H HELP

P FORM FEED

T TEST MODE OSCILLATOR DISABLED

To change menu selections, enter the letter corresponding to that item and hit (return). For example, to change Driver Display Units from miles to feet, enter the letter "A" (Return), to toggle the display units to 'feet'.

RUN IDENTIFICATION

A SECTION NUMBER 123456

B RUN NUMBER 1

C DEC FILE NAME NO OUTPUT

D ADOT FILE NAME 12345691.031

E OPERATOR/DRIVER XXXXXXXX/YYYYYYYY

F MAGNETIC TAPE NUMBER NNNNNNNN

The operator will enter the letter "A" (Return). The program will then allow the entry of the six digit section number for the test section to be profiled. The ADOT file name and the DEC file name should be automatically generated. The operator will then enter the letter "E" (Return) and enter the Operator/Driver names. This entry is limited to 16 characters maximum. Upon completion of this menu, the operator will enter a (Return) to proceed on to the next menu.

RUN CONTROL METHOD

A START METHOD PENDANT

B STOP METHOD PENDANT

The photocell event detector should be used when possible. If the photocell event detector cannot be used, the operator event pendant should be selected.

The stop method to be used is 'distance'. Distance will usually be the section length.

The next screen is the options setup which looks as follows when first brought up:

OPTIONS SETUP

R	RIDE QUALITY INDEX MAYS
I	INDEX DISABLED
W	WHEELPATH RIGHT
A	AVERAGING INTERVAL 528.0 (FEET)
B	INDEX CALCULATION SPEED 50.0 (MPH)
M	ALLOW RETURN TO OTHER MENUS
S	STORE HEAD OPTIONS

To change the ride quality index, the operator can enter the letter "R" (Return). The program will then toggle the entry 'IRI'. The operator can enter the letter "W" (Return) to average 'both' wheelpaths. The operator can enter the letter "A" (Return) to enter the index reporting distance. The default is '528 feet' (or 0.1 mile) index internal averaging reporting distance. After setting the options, the operator should enter "S" (return) to store the header options that have been entered. The program will prompt the operator for a file name to use. The operator will enter the ADOT section number with HDR extension for the file name. This is the header to be used in the actual data collection which will follow the bounce test.

<u>Automated Data Checks</u>

Ensuring that the data is both valid and accurate is a primary consideration for smoothness testing. The field data collection software can automatically and quickly perform operations checks on the profilometer sensors.

The following checks should be performed each day before profile measurements are collected:

1. Displacement Sensors Check

2. Bounce Test

Displacement Sensor Check

Sensors tend to drift away from calibration with time and use. This check is used to monitor the displacement sensors on a regular (daily) basis in the field and evaluate whether its sensors are still in calibration. This is done using the non-contact sensor calibration procedure presented in Appendix B, Profilometer Calibration. However, the calibration procedure is normally performed under conditions which try to minimize the influence of factors that can offset calibration results. Some of these factors include:

- use of a warped calibration plate
- use of a warped gage block
- wind rocking the vehicle
- levelness of ground
- use of generator vs. line power
- noise in the electronics

It may not be possible to control these factors in the field. For example, it may be difficult to prevent the wind from rocking the vehicle during a sensor check. Thus, operators should not automatically assume the sensors are out of calibration (even though the daily check may suggest they are), without assurance that the above factors are not influencing the sensor check.

For monitoring purposes, a daily log should be kept on each sensor indicating the current calibration factor and the main difference between measurements of the gage block and calibration plate. If the sensors are determined to be out of calibration, then the new calibration factors should be saved on disk.

Bounce Test

The operator will enter "M" (Return) to display other menus where the operator will return to the Profile Set-up Menu and select "T" (Return) to enable the Test mode oscillator. The next menu is the Run Control Method where the operator will select "A" (Return) to toggle to the pendant start. The operator will select "B" (Return) to select the pendant stop.

The operator will proceed to the options setup menu and enter a (Return) to get the profile generation portion of the program. The operator will depress the start pendant, with the profilometer at rest. The profilometer output data should remain at static conditions and show little or no variation while 'bouncing' the vehicle front to back. If the system is working correctly, the IRI output will be less than 10 (most cases: 3 to 6). If the IRI exceeds 10, refer to Chapter 9, Part C, "Acceleration Amplifier" of the Law Manual.

Data Collection Program

Before the operator chooses "P" from the main menu to select the Profile data collection program, the following should be completed:

1. Ensure that the current date and time have been entered into the computer.

2. Check that power is applied to the sensors and sensor lamps. The lost lock lights should be lit if power is not applied.

3. The shrouds must be approximately one inch off of the pavement to keep the sun from washing out the signal to the displacement receivers.

4. Select "H" (Return) from the main menu to recall the existing header created earlier under Header Generation.

The driver will then proceed to the field test section.

Once entered, the profile program will advance the profile computing mode. After starting or restarting this program, it takes 30-45 seconds for the profile to settle. Therefore the operator should approach the site with the system in operation.

It is important to maintain a constant vehicle speed during a data run. You should attain your constant speed at least 300-feet before data collection begins. It is important not to have changes in speed that may jerk the vehicle or cause it to pitch on its suspension unless safety considerations dictate a slower speed. Cruise control should be used to maintain a uniform speed. Changes in throttle pressure to correct vehicle speed should be made slowly and evenly. Also, the driver should maintain a consistent driving pattern to keep the vehicle within the wheel tracks.

After the run is finished, the driver will pull over at the safest point and come to a complete stop so that the data can be transferred to the hard disk for permanent storage. In general, this is to be done immediately after the run. However, where turnaround distances are relatively short, the operator may wait to transfer the data until all five runs have been completed. In any case, data is to be transferred to the hard disk before leaving the immediate vicinity of the test section.

REFERENCES

1. "Mays Ride Meter Booklet", Third Edition, Rainhart Co., Austin, Texas, 1973.

2. Road Profilometer Model 690DNC User's Manual, K.J. Law Engineers, Inc. 42300 W. Nine Mile Rd., Novi, Michigan 48050-3627, April 1989.

3. "SHRP-LTPP Manual for Profile Measurements", Operational Field Guidelines, Version 1.0, Operational Guide No. SHRP-LTPP-06-005, Strategic Highway Research Program, Washington, D.C. December 1989.

APPENDIX AB
PROFILOMETER CALIBRATION

This appendix provides guidance for calibration of the profilometer. Calibration consists of insuring components such as sensors and the DMI (Distance Measuring Instrument) are calibrated to provide meaningful response to signals.

The profile sensors on each profilometer have been initially calibrated by the manufacturer to an accuracy of 1% of an inch. The DMI is initially calibrated to an accuracy of 0.47%. These sensors must have certain systematic checks periodically.

For sensors, the major types of calibration to be accomplished are as follows:

1. Non-contact displacement sensor calibration
2. Accelerometer calibration
3. Front wheel distance encoder calibration

The non contact displacement sensors are calibrated by first placing a calibration plate under the light beam and leveling the plate. This surface is used as the lower reference surface. A one inch block is then placed under the beam and removed to provide the one inch displacement. The non-contact sensor 'scale factors' are computed so that the A/D converter output change, due to the one inch displacement, when multiplied by the "scale factor" results in exactly a one inch change.

The accelerometers have a special calibration coil wound on the sensing mass of the transducer. A current through this calibration coil exerts a force on the sensing mass which is interpreted by the accelerometer as an acceleration. The analog accelerometer electronics are designed so that the computer can switch precise current throughout the calibration coil to represent exactly one "G" (32.172 feet/sec/sec). The calibration coil is aligned with the sensing axis of the accelerometer so that accurate calibration can be performed even if the vehicle is not level. The accelerometer "scale factors" are computed so that the A/D converter output change, due to the Cal coil current representing one G excitation, when multiplied by the "scale factor" results in exactly a one "G" change.

Distance and the velocity of the vehicle are measured by an encoder mounted on the left front wheel. The encoder output is demodulated by the distance encoder signal conditioning board and provides pulses to the computer for the comparison of distance and velocity. The distance encoder produces two signals in quadrature (one signal is delayed by 90 degrees) at 20 pulses per foot traveled. The quadrature detector signals allow true detection of motion in the presence of vibrations in the encoder assembly.

CALIBRATION PROCEDURES

Calibration Frequency

The calibration of on-board sensors should be conducted by the profilometer operator on a weekly basis during extensive use. In addition, it should be performed whenever problems are suspected. As much as possible, calibration of non central displacement sensors and accelormeters should be performed under controlled conditions (using an enclosed building to prevent wind moving the vehicle and using more reliably constant line power, rather than generator power. While profilometer operators may conduct the calibration tests, any major adjustments indicted by the calibration analysis should not be made to the profilometer unit without the specific approval of the Department.

Calibration Programs

Non-contact Sensor Calibration

The operator will select the "C" followed by the Return Key from the main menu to execute the command which calls the calibration menu. Since this program measures the vehicle displacement directly, extreme care must

be used so that no vehicle motion is caused during the measurement. The calibration plate provided with the profilometer tools will be used as the starting reference. The following sequence must be done in order:

1. Enter "R" (return) to start the non-contact sensor calibration for the right side. ("L for the left side).

2. A prompt to insert and level the calibration plate under the beam is displayed. Level the plate by adjusting the three leveling screws so that a stable level surface can be easily obtained using the level bubble provided on the plate.

(NOTE! EXTREME CARE MUST BE USED SO THAT THE VERTICAL VEHICLE MOTION DO|w NOT OCCUR DURING STEPS 3 AND 5)

3. When ready enter "Y" (return), signaling the computer to take readings.

4. The computer program will prompt for the insertion of the one inch block. Place the one inch block very carefully on the plate under the light beam which is shining on the plate.

5. When ready enter "Y" (return), signaling the computer to take readings.

6. The computer program will calculate the mean value for the reading taken in Step 3 and 5 and calculate the difference between the means. If the difference doest not vary by +/- 1% of 1 inch, then check the left side by repeating the first 6 steps.

7. If either or both sensors have displacements which vary beyond 1% from 1 inch, then enter the new scale factors by answering the prompt for new scale factors with a "Y" (return).

(NOTE! If a new scale factor is computed it must be saved on the disk and the backup program disk or it will be lost when the Cal program is exited.)

<u>Accelerometer Calibration</u>

Locate a level area to park the profilometer. When perfectly level, the accelerometer output should be zero. A zero output is not required for a good calibration but should be attained when possible. If the accelerometer zero value exceeds +/-0.3 feet/sec^2, electrical recalibration of the amplifiers must be performed.

The operator will select "C" followed by the Return Key from the main menu to execute the command which calls the calibrate menu. Since this program measures the vehicle displacement directly, extreme care must be taken so that vehicle motion is not caused during the measurement. If any difficulty performing this check occurs due to wind rocking the vehicle, find an enclosed building, or park the profilometer on the side of a building protected from the wind.

1. Enter "A" (return) to start the accelerometer calibration. When the command is entered, the program takes measurements of each accelerometer, then computes and displays the mean as the zero value on the monitor.

2. The 1 G test current is turned on to each accelerometer and measurements are taken on each accelerometer. The new scale factors used in the calculations are displayed on the monitor.

3. If the 1 G values are more than 1% away from nominal values a message is displayed and prompts the operator if he wants to save the new scale factors. The operator will enter "Y" (Return) to the prompt.

(NOTE! If a new scale factor is computed it must be saved on the disk and the backup program disk or it will be lost when the Cal program is exited.)

Distance Measuring Instrument Calibration

To perform the DMI Calibration, an accurately measured section of 1000 feet to a mile in length must be utilized. A tape measure should be used to measure out a 1000' section on a reasonably level pavement with low traffic volume. Care must be taken to measure the section accurately.

To execute the command which calls the calibrate menu, the profilometer operator will proceed by entering a "C", followed by the Return Key from the main menu.

1. The monitor will display the message, "Drivers display to be in feet or miles?". The operator will select the feet option.

2. The program will then print the current distance encoder scale factor as read from the disk. The factor has units of feet per 100 pulses (i.e., 20 pulses per foot is 5.0 feet per 100 pulses).

3. The program will display the following options:

a. "Drive a Measured Distance" (Type "D")

b. "Simulate Distance encoder with Oscillator: (Type "S")

c. "Exit" (Type "E")

The operator enters "D" (Return) which will require the vehicle to be driven over a measured distance.

4. Start the distance measurement with the pendant and slowly traverse the section to the end. Use a straight edge at right angle to the entrance door as a guide. End the distance measurement with the pendant. The operator will enter the length of the section in feet.

5. The program will then compute a new encoder scale factor and print out the value. The operator will then save this new scale factor on disk before exiting the program and returning to the main program.

APPENDIX AC
PROFILE SURVEY OF CALIBRATION SECTIONS

This appendix provides procedures for 1) selecting roadway sections to serve as calibration sections for the Maysmeter and 2) determining the Highway Roughness Index (HRI) of the Maysmeter Calibration Sections.

The HRI is correlated to Maysmeter output using the criteria of Appendix D (Maysmeter Calibration). Because roadway roughness changes are time, the HRI should be determined regularly for these sections from profile surveys using the profilometer. His recommended that all of calibration sections be profiled whenever Maysmeter calibration is required.

SELECTION OF CALIBRATION SECTIONS

The following calibration section selection criteria are provided to identify sections which would be both stable and consistent for roughness calibration purposes. This criteria should be used whenever it is necessary to add a new section to the set of calibration section.

a) <u>Section Length</u>. Each section is 0.2 miles (1056 feet) long and should have enough distance both before and after the section so that the profilometer vehicle can speed up to and slow down safely from 50 mph.

b) <u>Number of Calibration Sections Required</u>. The calibration procedure requires that at least 15 calibration sections be selected to give statistical significance to the final calibration equation. ADOT currently uses 17 sections. If a lower number of sections is used, the resulting equation may not accurately predict the full possible range of HRI values that may be experienced in actual field applications.

c) <u>Range of Roughness</u>. It is important that a wide range of roughness be considered when choosing the calibration sections. To simplify this, sections will be classified as either being smooth, moderately rough or very rough. There should be approximately 1/3 of the sections in each of the roughness categories. It should be realized that there will be a range of roughness within each of the three categories and that in many cases, it will be difficult to distinguish between a very rough and moderately rough section or moderately rough and a smooth section. The important point is that within the set of calibrations sections, there should be sections ranging from very smooth to very rough, and the range should be as evenly distributed as possible. The reason for this is to give the final calibration equation applicability on a road with any level of roughness. It is desirable that each section not have extensive pothole patching or severe alligator cracking as these types of distress can be unstable and inconsistent from a roughness standpoint. Pavements with loose surface materials will obviously change their profile under the action of wheel loads and environment and are therefore undesirable for calibration purposes.

It is also desirable not to have roughness calibration sections which exhibit roughness in the shorter wave lengths. Examples of these types of sections are those which are relatively smooth, but exhibit significant roughness at either joints (PCC pavements) or transverse cracks. The problem with using these for calibration is that their roughness is measurable with the Maysmeter, but may not necessarily be completely measured by the profilometer.

d) Alignment and Grade of Section. A calibration section should be as straight as possible. Some horizontal or vertical curvature is tolerable but undesirable. The section should have as small a grade as possible. If the section is in a hilly region, it should be chosen in the valley or on the top of a large hill to give the section as close to a 0 percent grade as possible. The use of relatively straight sections with little grade reduces the variability in Maysmeter calibration runs.

e) Safety Considerations. If at all possible, a calibration section should be located on a very lightly trafficked and wide roadway. The survey procedure will need to be repeated every month, therefore, it is desirable to locate sections on roads with as little traffic as possible. If a section must be located on a busy road, the road should have at least two traffic lanes in each di|wction. Extra care should be taken to protect the profile survey operations.

f) Section Marking. The threshold of the section (Station 0+00) should be established using a suitable white road paint. In addition to identifying the section threshold, the paint marking will be used to initiate profilometer data acquisition through photocell triggering. The threshold identification should include a 4 inch wide transverse paint stripe across the test lane. It is also useful to paint the section number near the threshold to aid in section identification. Besides the markings placed in the actual traffic lane, a large stripe should be painted on the shoulder to aid the Maysmeter operator in subsequent calibration runs.

The following sections are currently designated as ADOT Calibration Sections:

Section No.	Roadway Direction and Location
1	27th Ave, SBL-1, Southern Ave to Baseline Rd.
2	Baseline Rd, WBL-1, 27th Ave to 35th Ave
3	43rd Ave, NBL-1, Baseline Rd to Southern Ave
4	35th Ave, SBL-1, Baseline Rd to Dobbins
5*	Dobbins, EBL-1, 35th Ave to 27th Ave
6	Dobbins, EBL-1, 35th Ave to 27th Ave
7*	27th Ave, NBL-1, Dobbins to Baseline Rd
8	Baseline Rd, EBL-1, 27th Ave to 19th Ave
9*	99th Ave, NBL-2, Van Buren to I-10
10*	SR 85, SBL-1, MP174.55 to MP174.35
11	SR 85, SBL-1, MP173.60 to 173.40
12	SR85 Spur, NBL-1, MP153.50 to 153.70
13	I-10, EBL-2, MP123.30 to 123.50
14	I-10, WBL-2, MP124.40 to 124.20
15	I-10, WBL-2, MP124.15 to 123.95
16	
17	

* Those sections are also designated calibration control sections

PROFILOMETER MEASUREMENTS

The HRI is determined for each calibration section by profiling the section with the profilometer. HRI will be determined from the entire section length, resulting in a single HRI value in units of inches per mile for each calibration section. These data will provide the standard upon which the Maysmeter calibration will be based.

Pavement smoothness can change with time as a function of variables such as traffic and environment. Most notably, pavement distress and maintenance can affect the wheelpath profile. As a result the profile of pavement sections and for calibration of smoothness measuring equipment must be measured regularly. It is recommended that profilometer measurements be made monthly.

Prior to profiling the calibration sections, insure the profilometer is in proper calibration using criteria of Appendix B (Profilometer Calibration).

The following test criteria should be used when making the profile runs.

1) Operating Speed - 50 mph

2) Filter Wavelength - 300 feet

3) Event Initiation - The road profile program uses "event marks" to initiate data acquisition. The event marks should be generated by the photocell event detector. The section should incorporate a white paint stripe at the threshold for this purpose.

4) Stop Method - Termination is done by selecting "distance" as the stop method. The distance should be set at 1,056 feet.

5) Number of Runs - 5 runs should be made for each speed.

Form 1. Calibration Section HRI

Date_______________ Operator/Driver______________________

Profiling Speed______________mph

Filter Wavelength_____________ft

Calibration Section No.	HRI For Each Run (inches/mile) 1	2	3	4	5	Average HRI, inches/mile
1						
2						
3						
4						
5						
6						
7						
8						
9						
10						
11						
12						
13						
14						
15						
16						
17						

HRI Summary

HRI values for each calibration section should be recorded on Form 1 for each run. Calculate the average HRI for each section and record. The average HRI for each section should be used in establishing the Maysmeter calibration as discussed in Appendix D (Maysmeter Calibration).

APPENDIX AD

MAYSMETER CALIBRATION

This appendix provides guidance for performing Maysmeter calibration runs. Data obtained from the calibration runs will be correlated with Highway Roughness Index, HRI, determined from profilometer measurements of the calibration sections. It is recommended that profilometer measurement of the calibration sections be performed within two weeks of Maysmeter calibration runs.

Knowledge of the operation of the Maysmeter is assumed. This appendix does not address preliminary activities that may be required before making calibration runs (such as checking tire pressure, system warm-up and verification of DMI accuracy). These activities are discussed in Appendix A (Equipment Operational Guidelines). It is assumed preliminary activities have been completed and the crew is ready to begin measurement runs.

The Maysmeter should be set to provide a count for the section length. Maysmeter calibration runs will be made at 35 and 50 mph. Five (5) runs should be made on each calibration section. To minimize bias from changes in vehicle suspension (as springs and shocks warm up and fuel weight changes) sections should be run in a loop 5 times rather than obtaining 5 successive repetitions on a section. To complete the runs will require traversing the loop 10 times (2 speeds x 5 repetitions). All calibration runs for one speed should be made followed by the runs for the other speed. Two operators are recommended for performing the calibration runs. One operator will drive; the other will operate the Maysmeter. If one operator becomes fatigued, the two can switch duties.

When making roughness calibration runs, three important conditions must be satisfied:

1. The driver must bring the vehicle up to a stable speed <u>before</u> entering the section. There should be as little acceleration or deceleration as possible after entering the section. Vehicle cruise control should be used to maintain constant speed

2. The driver should keep the Maysmeter vehicle in the center of the lane. Using the vehicle fender or hood center as a reference may help the driver to maintain the "center of the lane" orientation.

3. The operator should initiate the roughness count when the wheels of the transmitter axle cross the threshold of the section. For the ADOT unit the count should start when the rear axle crosses the start of the section. This is to insure that the Maysmeter measures the same roughness course that was measured by the profilometer. To facilitate this, it is recommended that a colored stake or lath be placed near the road shoulder or a colored paint mark be placed on the shoulder. The marker should be positioned longitudinally along the road such that the operator will see it directly out of his window when the transmitter axle wheels cross the section threshold.

Maysmeter roughness data is obtained for all calibration sections. The data should be recorded, averaged per calibration section and each average divided by two in order to get Maysmeter data in units of inches/0.1mile. After all sections have been run, the data should be returned to the office where a regression analysis will be performed on the data relating the average Maysmeter count values to recently determined HRI values. Calibration equations will result from the regression analysis measured by the Maysmeter on other pavements in terms of calibrated Mays values (in/0.1mi) which can be used to express roughness.

CALIBRATION EQUATION

AZCALIB is the computer program which is used for determining the Maysmeter calibration equation. Basically this program generates an equation calculating calibrated Mays values (in/0.1mi) based on Maysmeter field values (in/0.1mi). It is these equations that are the final product of the calibration procedure. The equation has the following form:

$$MAYS = A_o + A_1(MFC) + A_2(MFC)^2$$

Where MAYS is calibrated Mays values in in./0.1mi

MFC Maysmeter field values in in./0.1mi

A_o, A_1 and A_2 are the regression coefficients

The squared term in the equation allows the program to fit a curve to the data. Although the quadratic fit may improve the correlation slightly, unless there is an obvious curve in the data, the user should use a linear relationship.

Although the calibration equation deals only with Maysmeter values the actual calibrating instrument is the 690D Profilometer. The smoothness statistics generated by the profilometer are HRI rather than Mays values. In order to produce the calibration equation, then, a two step algebraic process is performed. In the first step, maysmeter field counts are transformed to HRI values by way of a regression equation calculated at each calibration effort and yielding "calibrated" results expressed in HRI units. In the second step, profilometer HRI values are transformed to calibrated maysmeter values by way of a regression equation that was calculated during this project and transforms HRI into maysmeter values.

Description of Program AZCALIB

The input data form for the program AZCALIB is presented in Table D.1. The first card (record) allows the user to enter a title or description of the problem. The second card (record) represents the typical form for entering the data from a single calibration section, including its number, Highway Roughness Index (HRI) and corresponding average Maysmeter count. There should be one of these cards (records) for each calibration section. The last card (record) shown is used to identify the end of the data.

AZCALIB is an interactive program and therefore, requires the user to respond to two questions:

1. INPUT NAME OF DATA FILE? - File name of input data.
2. DO YOU WANT A LINEAR REGRESSION? (Y/N) - Is linear regression equation desired? (If "Y", A_2 in regression equation will be zero. Any other response will result in a quadratic regression equation.)

Sample output from the AZCALIB computer program is provided after Table AD-1.

Table AD-1. Input data format for AZCALIB program

Card (Record) Nos.	Column Nos.	Description of Input Variable
First	1-72	Data description (including date and vehicle speed to which regression equation will apply).
Data Card	1-5	Calibration section number
	6-15	Average Highway Roughness Index (HRI) for section
	16-25	Average Maysmeter Count (MC) for section
Last	1-3	Enter the letters "END" to identify end of data

APPENDIX AE

MAYSMETER CALIBRATION CONTROL

This appendix provides guidance for controlling Maysmeter calibration. The process for calibration of the Maysmeter is discussed in Appendix D, Maysmeter Calibration. Calibration control constitutes an important monitoring process which should be undertaken in any long-term application of Maysmeter testing. It allows the user of a calibrated Maysmeter to determine when the calibration is no longer valid due to changes in the Maysmeter response characteristics and provides a basis for recalibration.

The Maysmeter system is subject to instability. Suspension components (shocks, springs, and tires) wear with time. As the vehicle's response to roughness changes as a function of this wearing, so will the Maysmeter output. This change can be significant enough to invalidate the calibration of the Maysmeter. To make the determination of calibration validity, one needs to periodically monitor the Maysmeter's response on control sections and then statistically test for a significant change in the response per section and across time. Once the Maysmeter calibration is invalid, it will be necessary to recalibrate the Maysmeter, including reprofiling the calibration course using the profilometer.

Four control sections are selected from the set of seventeen calibration sections near Phoenix. The following criteria is considered in the selection

1. Average roughness value. The control procedure requires that of the four sections, two should be rough and two should be smooth.

2. Stability of the section. Since control sections are used to control the calibration of the Maysmeter over an extended period of time, it is essential that the sections be as stable as possible in terms of traffic and type of distress observed. Any change in roughness reading in any section should be attributable, as much as possible, to changes in the Maysmeter rather than to changes in the section itself.

3. Difference between wheelpaths. It is desirable that the two wheelpaths on a given control section have as close to the same roughness as possible.

4. Closeness to calibration curve. Because the control procedures are intended to monitor the calibration of the Maysmeter, it is desirable that the type roughness of the control sections fall as closely as possible to the original calibration curve. This is easily achieved by selecting the control sections from the set of calibration sections.

5. Longitudinal distribution of roughness. It is also desirable that the roughness of a control section be evenly distributed across the entire length of the section. Areas of uncharacteristically rough or smooth pavement within the 0.2 mile long section should be avoided, especially near the beginning or end of the section.

These criteria are listed in a somewhat relative order of importance. Judgement should be considered when applying these criteria, since it is unlikely that all five criteria will be met by any given section. It is also possible that one of the five criteria will not be satisfied by any of the candidate control sections. Thus, these criteria are considered as guidelines and not absolutes.

The current calibration control sections are:

Section No.		Roadway Direction and Location
5	Rough	Dobbins, EBL-1, 35th Ave to 27th Ave
7	Rough	27th Ave, NBL-1, Dobbins to Baseline Ave
9	Smooth	99th Ave, NBL-2, Van Buren to I-10
10	Smooth	SR85, SBL-1, MP174.55 to MP174.35

INITIAL RUNS

Each control section will be run twenty times at the 35 and 50 mph vehicle speeds to provide a statistically sound basis for future comparisons. It is desirable to make the initial runs shortly after (within 1-2 weeks) the Maysmeter calibration runs are made. The mean $\overline{X}_{20}$ and standard deviation S_{20}, should be tabulated on the form shown in Figure AE-1 for each set of initial control runs.

CONTROL PROCEDURE

Every two weeks or after every 2000 miles (whichever comes first), the Maysmeter should be run on the four control monitoring sections at both the 35 and 50 mph vehicle speeds. For these monitoring runs, however, only five runs are required at each speed. The mean X_5 for each set of these monitoring control runs should be recorded on the form in Figure AE-1.

The form presented in Figure 1 is used to establish the criteria needed to determine whether Maysmeter calibration is necessary. A t-test is used to determine if the mean value of the 5 monitoring runs is significantly different from the mean value of the 20 control runs. The t-test value is calculated as

$$\text{t-test value} = \frac{|\overline{X}_5 - \overline{X}_{20}|}{2 * S_{2C}}$$

This value is compared against a critical value of 1.74. When the t-test value is greater than 1.74 then the five run average is significantly different than the twenty run average (with a small margin of error).

Notice in Figure 1 that there are eight tests comparing the computed t-test value against a critical value. If the computed t-test value is equal to or greater than the critical value, then the control section is said to be out of

Figure AE-1. Maysmeter Control Form for 5 Monitoring Runs.

Date (Month/Year): ____________ Operator: ____________

Vehicle Speed (mph)	Control Section No.	Statistics of Runs			t - test	Critical Value (C.V.)	Out-of-Control[A]	
		Mean, $\overline{X}_5$	Mean, $\overline{X}_{20}$	Std Dev, S_{20}	$\frac{\lvert \overline{x}_5 - \overline{x}_{20} \rvert}{2 \cdot S_{20}}$		Yes t-test > C.V.	No
35	CS-1					1.74		
	CS-2					1.74		
	CS-3					1.74		
	CS-4					1.74		
50	CS-1					1.74		
	CS-2					1.74		
	CS-3					1.74		
	CS-4					1.74		

[A] A section is said to be out of control if the t-test number $\frac{\lvert \overline{x}_5 - \overline{x}_{20} \rvert}{2 \cdot S_{20}}$ is greater than or equal to the critical value (C.V.).

control. Once two (or more) sections are out of control then the Maysmeter will need to be recalibrated. Prior to recalibration, the suspension components of the Maysmeter vehicle should be checked and worn parts replaced.

It may be possible to bring a section that is out of control back in control by performing additional monitoring runs on the section. Additional runs will provide better estimates of the monitoring run statistics. The expense of obtaining additional monitoring runs is minimal compared to the expense of Maysmeter recalibration. It is recommended that out of control sections be verified by additional runs as follows.

If two or more sections are out of control, 5 additional runs should be made on the out of control sections. A new t-test value should be computed from

$$\text{t-test value} = \frac{|\bar{X}_{10} - \bar{X}_{20}|}{2.58 * S_{20}}$$

where X_{10} is the mean of the combined 10 monitoring runs and S_{20} is the standard deviation of the 20 initial runs. The critical value remains at 1.74. The new computed t-test value should be compared against the critical value to determine if the sections are still out of control. The form shown in Figure AE-2 should be used when 10 monitoring runs are made.

Figure AE-2. Maysmeter Control Form for 10 Monitoring Runs.

Date (Month/Year): ____________ Operator: ____________

Vehicle Speed (mph)	Control Section No.	Statistics of Runs			t - test $\frac{\lvert \bar{X}_{10} - \bar{X}_{20} \rvert}{2.58 \cdot S_{20}}$	Critical Value (C.V.)	Out-of-Control [A]	
		Mean, $\bar{X}_{10}$	Mean, $\bar{X}_{20}$	Std Dev, S_{20}			Yes (t-test > C.V.)	No
35	CS-1					1.74		
	CS-2					1.74		
	CS-3					1.74		
	CS-4					1.74		
50	CS-1					1.74		
	CS-2					1.74		
	CS-3					1.74		
	CS-4					1.74		

[A] A section is said to be out of control if the t-test number $\frac{\lvert \bar{X}_{10} - \bar{X}_{20} \rvert}{2.58 \cdot S_{20}}$ is greater than or equal to the critical value (C.V.).

If two or more sections are still out of control after 10 monitoring runs, the process may be repeated for 5 additional runs to see if the sections can be brought back into control. The critical value for 15 monitoring runs remains at 1.74 and the test value is computed as

$$\text{t-test value} = \frac{|\bar{X}_{15} - \bar{X}_{20}|}{2.93 * S_{20}}$$

The form shown in Figure AE-3 should be used when 15 monitoring runs are made. If two or more sections are still out of control after 15 monitoring runs then the Maysmeter should be recalibrated.

Figure AE-4 provides a worksheet that may be used to record Maysmeter data and compute means and standard deviations needed for the Maysmeter Control Form. Some calculators can compute these statistics and can be used instead of the worksheet.

Figure AE-3. Maysmeter Control Form for 15 Monitoring Runs.

Date (Month/Year): ____________ Operator: ____________

Vehicle Speed (mph)	Control Section No.	Statistics of Runs			t - test	Critical Value (C.V.)	Out-of-Control [A]	
		Mean, $\overline{X}_{15}$	Mean, $\overline{X}_{20}$	Std Dev, S_{20}	$\frac{\lvert \overline{x}_{10} - \overline{x}_{20} \rvert}{2.93 \cdot S_{20}}$		Yes (t-test > C.V.)	No
35	CS-1					1.74		
	CS-2					1.74		
	CS-3					1.74		
	CS-4					1.74		
50	CS-1					1.74		
	CS-2					1.74		
	CS-3					1.74		
	CS-4					1.74		

[A] A section is said to be out of control if the t-test number $\frac{\lvert \overline{x}_{15} - \overline{x}_{20} \rvert}{2.93 \cdot S_{20}}$ is greater than or equal to the critical value (C.V.).

Figure AE-4. Worksheet for Calculation of $\bar{X}$ and S.

(A) Meas No.	(B) X	(C) Sum of X	(D) X^2	(E) Sum of X^2	(F) $\bar{X}$ col. (C)/col. (A)	(G) S*
1						
2						
3						
4						
5						

Continue Summing columns (C) & (E)

6						
7						
8						
9						
10						

Continue Summing columns (C) & (E)

11						
12						
13						
14						
15						

Continue Summing columns (C) & (E)

16						
17						
18						
19						
20						

$$^{*}S = SQRT\left(\frac{\text{col. (E)} - \frac{\text{col. (C)} * \text{col. (C)}}{\text{col. (A)}}}{\text{col. (A)} - 1}\right)$$

APPENDIX B
MAYSMETER ROUGHNESS DIFFERENTIAL DUE VEHICLE SPEED ANALYSIS

CELL ONE (77)

ONE WAY AOV FOR Y - A

MPH	MEAN	SAMPLE SIZE (RUNS)	GROUP VARIANCE
50	983.2	6	2.265E+04
35	801.7	4	6.668E+03
TOTAL	910.6	10	

SOURCE	DF	SS	MS	F	P
BETWEEN	1	7.899E+04	7.899E+04	4.74	0.3108
WITHIN	8	1.333E+05	1.666E+04		
TOTAL	9	2.123E+05			

	CHI SQ	DF	P
BARLETT'S TEST OF EQUAL VARIANCES	1.03	1	0.3108

CELL TWO (13)

MPH	MEAN	SAMPLE SIZE (RUNS)	GROUP VARIANCE
35	877.0	2	8.000
35	515.0	2	5.000E+03
50	727.0	2	162.0
TOTAL	709.7		

ANOVA

Source	df	Mean Square	F	P
35 vs 50	1	1352	.77	< .50
Between 35	1	142, 129		
within	3	1753		
TOTAL	5			

APPENDIX C
MAYSMETER ROUGHNESS DIFFERENTIAL DUE CHANGING CLIMATIC ZONE ANALYSIS

CASE 1

CELL NO.	MEAN	SAMPLE SIZE	GROUP VARIANCE
56	392.6	5	3.203E+03
29	342.0	2	1.921E+04
2	414.5	2	144.5
TOTAL	386.2	9	

SOURCE	DF	SS	MS	F	P
BETWEEN	2	5.714E+03	2.857E+03	0.53	0.6123
WITHIN	6	3.217E+04	5.361E+-3		
TOTAL	8	3.788E+04			

	CHI SQ	DF	P
BARLETT'S TEST OF EQUAL VARIANCES	3.20	2	0.2021

CASES INCLUDED 9 MISSING CASES 0

VIEW DATA

<u>Interstate, Milland Replace, Frictional Course</u>

CASE	A	Y	
1	1.0000	340.00	Basin and Range
2	1.0000	433.00	
3	1.0000	435.00	
4	1.0000	433.00	
5	1.0000	322.00	
6	2.0000	244.00	Central Highlands
7	2.0000	440.00	
8	3.0000	406.00	Colorado Province
9	3.0000	423.00	

<u>Conclusion</u>: Case 1 - All three climate zones are equal.

CASE 2: Seal Coat & Overlay

Cell Numbers: 67, 70, 13, 16

ANALYSIS OF VARIANCE TABLE FOR Y

SOURCE	DF	SS	MS	F	P
A (A)	1	420.25	420.25	< 1	> .50
B (B)	1	4.8620E+04	4.8620E+04		
A*B	1	4.3890E+04	4.3890E+04		
C (C)					
A*B*C*	(5) 12	6.3013E+04	12603		
TOTAL	15	1.5594E+05			
GRAND AVERAGE	1	6.7055E+06			

12603 Correct error MS
5 63013. because cells filled
to 4 each

APPENDIX D
TWO PARTIAL FACTORIAL ANALYSES OF MAYSMETER ROUGHNESS

CASE 1: State and U.S. Route Data (see Table 3-3)

A N A L Y S I S   O F   V A R I A N C E

MMO
BY ROADCLAS
CONSTYPE
SURFTYPE

Source of Variation	Sum of Squares	DF	Mean Square	F	Signif of F
Main Effects	108636.637	4	27159.159	1.098	.401
ROADCLAS	37093.827	1	37093.827	1.500	.244
CONSTYPE	92453.015	1	92453.015	3.738	.077
SURFTYPE	20933.136	2	10466.568	.423	.664
2-way Interactions	7030.598	5	1406.120	.057	.997
ROADCLAS CONSTYPE	85.741	1	85.741	.003	.954
ROADCLAS SURFTYPE	2799.488	2	1399.744	.057	.945
CONSTYPE SURFTYPE	3688.321	2	1844.161	.075	.929
3-way Intersections	3708.974	1	3708.974	.150	.705
ROADCLAS CONSTYPE SURFTYPE	3708.974	1	3708.974	.150	.705
Explained	119376.209	10	11937.621	.483	.871
Residual	296799.095	12	24733.258		
Total	416175.304	22	18917.059		

34 Cases were processed.
11 Cases (32.4 PCT) were missing.

Main Effects

CASE 2: Functional Course Data (see Table 3-3)

A N A L Y S I S   O F   V A R I A N C E

BY: MMO
ROADCLAS
CONSTYPE

Source of Variation	Sum of Squares	DF	Mean Square	F	Signif of F
Main Effects	331717.755	3	110572.585	8.815	.000
ROADCLAS	189968.415	2	94984.207	7.572	.002
CONSTYPE	43936.920	1	43936.920	3.503	.072
2-way Interactions	38993.324	2	19496.662	1.554	.229
ROADCLAS CONSTYPE	38993.324	2	19496.662	1.554	.229
Explained	370711.079	5	74142.216	5.911	.001
Residual	351219.539	28	12543.555		
Total	721930.618	33	21876.685		

34 Cases were processed.
0 Cases (0.0 PCT) were missing.

APPENDIX E
FOUR CELL MAYSMETER DATA ANALYSIS

CASE 1

ANOVA

Source	df	MS	F	P
Construction Type Mill & Overlay vs New	1	14,129	1.1	N.S.
Roadway Func. Class (Interstate vs U.S. & State)	1	590,920	44.2	< .01
Interaction	1	72,540	5.4	< .05
Error	30	13,370		

CASE 2

One Way Adv. for Y - A

A	MEAN	SAMPLE SIZE	GROUP VARIANCE
1	346.0	2	6.050E+03
2	623.4	14	1.641E+04
3	386.2	9	4.735E+03
4	519.7	9	1.798E+04
TOTAL	516.9	34	

SOURCE	DF	SS	MS	F	P
BETWEEN	3	3.710E+05	1.237E+05	9.25	0.0002
WITHIN	30	4.011E+05	1.337E+04		
TOTAL	33	7.722E+05			

	CHI SQ	DF	P
BARLETT'S TEST OF EQUAL VARIANCES	3.54	3	0.3154

CASE 3

ANALYSIS OF VARIANCE TABLE FOR Y

SOURCE	DF	SS	MS	F	P
A (A)	1	0.0000	0.0000	M	M
B (B)	3	1.3551E+06	4.5169E+05	58.56	0.0000
A*B	3	0.0000	0.0000	M	M
C (C)					
A*B*C	104	8.0225E+05	7713.9		
TOTAL	111	2.1573E+06			
GRAND AVERAGE	1	2.4617E+07			

LEAST SIGNIFICANT DIFFERENCE PAIRWISE COMPARISONS OF Y BY B

B	MEAN	HOMOGENEOUS GROUPS
3	623.4	I
4	519.6	.. I
2	386.2	 I
1	346.0	 I

There are three groups in which the means are not signif. diff. from one another.