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16. Abstract

The Federal Highway Administration has produced a Highway Performance Monitoring System Field Manual as a guideline for the individual states. The Field Manual includes an Appendix J which describes the proper calibration and reporting procedures for pavement roughness monitoring. The individual states are required to calibrate all roughness instrumentation and to report that roughness in terms of the International Roughness Index (IRI).

This report details an evaluation effort sponsored by the Texas State Department of Highways and Public Transportation Maintenance and Operations Division, Pavement Management Section. This evaluation concentrates on the field performance of the auto-read version of the Face Dipstick. This instrument is one of the Class I profiling devices identified in the Appendix J mandate. All of the lower classification of roughness monitoring instruments used by the states must be calibrated against a Class I device. The Dipstick was chosen by the Texas SDHPT because it was believed that the device would be a cost-effective and reliable substitute for the Rod and Level survey. Rod and Level and the TRRL Beam are the other two Class I profiling devices specified by Appendix J.

The evaluation effort describes concerns regarding the operation of the auto-read version of the Dipstick and the manufacturer's responses to those concerns. The field test sites utilized in the comparisons are described. The conclusions reached upon completion of the Dipstick evaluation are included. The manual-read version of the Dipstick was also included. The manual-read version of the Dipstick was also evaluated as to whether or not it would be a cost-effective Class I profiling instrument. Finally, recommendations for the Dipstick's future use based on its field performance are described.

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PREFACE

This is the first report presenting results from Research Project 3-10-87/9-969, "Evaluation of FHWA Requirement for the Collection of Pavement Roughness Data." This project was initiated to evaluate whether or not the auto-read Dipstick could be used as a reliable Class I surface profiling instrument.

The Dipstick was included in the FHWA's HPMS Field Manual Appendix J as a Class I profiling device along with the rod and level survey. The Texas SDHPT Maintenance and Operations Division, Pavement Management Section, is responsible for the State's compliance with Appendix J. Therefore, they were interested in determining whether the auto-read version of the Dipstick could be used as a cost-effective and reliable substitute for rod and level surveys. The assistance of CTR staff person, Mr. Bill Moffeit, and the Texas SDHPT D-18 Pavement Management Section staff is especially appreciated. Special thanks are given to the staff of TRDF for their assistance and cooperation in conducting this research effort.

Carl B. Bertrand
Robert Harrison
B. Frank McCullough

LIST OF REPORTS

Research Report 969-1, "Evaluation of the Performance of the Auto-Read Version of the Face Dipstick," by Carl B. Bertrand, Robert Harrison, and B. Frank McCullough, presents the results of an evaluation effort on the auto-read version of the Face Dipstick as an operational Class I profiling instrument. Problems with the Dipstick's operation, comparisons of two separate auto-read Dipsticks, and comparisons with rod and level surveys are presented in this report. August 1989.

ABSTRACT

The Federal Highway Administration has produced a Highway Performance Monitoring System Field Manual as a guideline for the individual states. The Field Manual includes an Appendix J which describes the proper calibration and reporting procedures for pavement roughness monitoring. The individual states are required to calibrate all roughness instrumentation and to report that roughness in terms of the International Roughness Index (IRI).

This report details an evaluation effort sponsored by the Texas State Department of Highways and Public Transportation's Maintenance and Operations Division, Pavement Management Section. This evaluation concentrates on the field performance of the auto-read version of the Face Dipstick. This instrument is one of the Class I profiling devices identified in the Appendix J mandate. All of the lower classification of roughness monitoring instruments used by the states must be calibrated against a Class I device. The Dipstick was chosen by the Texas SDHPT because it was believed that the device would be a cost-effective and reliable substitute for the Rod and Level survey. Rod and Level and the TRRL Beam are the other two Class I profiling devices specified by Appendix J.

The evaluation effort describes concerns regarding the operation of the auto-read version of the Dipstick and the manufacturer's responses to those concerns. The field test sites utilized in the comparisons are described. The performances of two Dipsticks against each other as well as against Rod and Level surveys are described. The conclusions reached upon completion of the Dipstick evaluation are included. The manual-read version of the Dipstick was also evaluated as to whether or not it would be a cost-effective Class I profiling instrument. Finally, recommendations for the Dipstick's future use based on its field performance are described.

KEY WORDS: Dipstick Auto-Read Road Profiler, International Roughness Index (IRI), PC-2 computer, rod and level survey, ride, roughness

SUMMARY

This report describes the calibration and reporting mandates to the states as specified in Appendix J of the Highway Performance Monitoring System Field Manual. The evaluation of the auto-read version of the Face Dipstick Road Profiler is described. This instrument is one of the Class I profiling devices identified in Appendix J as a calibration standard for other roughness monitoring devices. Two individual Dipsticks were compared to each other as well as to Rod and Level surveys. The test sites utilized for the evaluation are described and concerns regarding the Dipstick's field operation are identified.

The report concludes that the auto-read version of the Face Dipstick is not reliable or repeatable enough to be used as a calibration tool in its present configuration. It is further recommended that only the manual-read version of the Dipstick should be considered for use as a Class I profiling device.

IMPLEMENTATION STATEMENT

This report describes the calibration and reporting mandates to the states as specified in Appendix J of the Highway Performance Monitoring System Field Manual. The evaluation of the auto-read version of the Face Dipstick Road Profiler is described. This instrument is one of the Class I profiling devices identified in Appendix J as a calibration standard for other roughness monitoring devices. Two individual Dipsticks were compared to each other as well as to Rod and Level surveys. The test sites utilized for the evaluation are described and concerns regarding the Dipstick's field operation are identified.

The Face Dipstick has been recommended by the FHWA in the HPMS Field Manual Appendix J as a Class I profiling instrument. The Texas SDHPT D-18 Maintenance and Operations Division, Pavement Management Section, was interested in evaluating whether or not the auto-read version of the Face dipstick could be used as a cost-effective and reliable substitute for rod and level surveys. Two separate Dipsticks were used in this evaluation for comparison against each other and against rod and level surveys. Several operational problems occurred during this evaluation effort which make the use of the auto-read Dipstick unacceptable for collecting profile and roughness data.

TABLE OF CONTENTS

PREFACE iii

LIST OF REPORTS iii

ABSTRACT iii

SUMMARY iv

IMPLEMENTATION STATEMENT iv

SCOPE 1

BACKGROUND 1

INITIAL AUTO-READ DIPSTICK EVALUATION 2

UPDATED AUTO-READ DIPSTICK EVALUATION 3
- Original Instrument Shipment 3
- Data Transfer 3
- Operator's Manual 3
- Leveling and Calibration Check 3
- Dipstick's Feet 4
- Battery Problems 4
- Software Problems 4
- No-Reading Problem 5
- False-Reading Problem 5
- Software Enhancements 7
- Most Reliable Auto-Read Data 7

TEST SITE DESCRIPTIONS 7
- Oakmont Test Site 8
- La Grange Test Site 8
- Austin Test Sections 1 and 4 8

DESCRIPTION OF COMPARISONS OF TWO DIPSTICKS 8
- La Grange Testing 8
- Oakmont Testing 9
- Austin Test Sections 11
- Static Testing 14

CONCLUSIONS 14

RECOMMENDATIONS 15

REFERENCES 16

APPENDIX A. LIST OF EQUIPMENT DELIVERED TO THE TEXAS SDHPT 17
APPENDIX B. DIPSTICK OPERATOR'S MANUAL AND SPECIAL NOTES FOR FIELD USE OF THE ZENITH LAPTOP COMPUTER 18
APPENDIX C. DIPSTICK RDDATA PROGRAM LISTING 20
APPENDIX D. LA GRANGE TEST SITE FIGURES 24
APPENDIX E. AUSTIN TEST SITES 1 AND 4 FIGURES 28
BIBLIOGRAPHY 33

EVALUATION OF THE PERFORMANCE OF THE AUTO-READ VERSION OF THE FACE DIPSTICK

SCOPE

The initial concept of this study was to evaluate the Federal mandate for calibrating roughness instrumentation and reporting the roughness statistic, as detailed in Appendix J of the FHWA Order 5600.1A. Additionally, Appendix J specifies that all of the roughness information will be reported in terms of the International Roughness Index (IRI), and the Texas State Department of Highways and Public Transportation (SDHPT) wanted to determine the history behind this new index and how well the IRI could be regressed using Appendix J calibration procedures. One of the high resolution devices specified in Appendix J which must be used to calibrate other roughness instruments is the Face Dipstick, and the Texas SDHPT decided to purchase and evaluate the Dipstick's performance as a roughness calibration device.

This report specifically addresses the evaluation of the auto-read version of the Face Dipstick and makes recommendations for its use as a field instrument based on the evaluation conclusions. The report contains a background section on Appendix J and the calibration procedures specified in Appendix J. A history of the questions associated with the Dipstick's operation and the manufacturer's responses to these questions during the course of the evaluation effort are presented. The field test sites used for the comparison of two Dipsticks against each other and against rod and level surveys are described. Both rigid and flexible as well as new and old pavements were used in this evaluation effort. The results of the various tests performed and the comparisons made using the two Dipsticks at the field locations are described. Finally, a set of conclusions with associated recommendations based on the instrument's performance during the field testing is presented.

BACKGROUND

The Federal Highway Administration has been interested in setting national standards for monitoring and reporting pavement conditions. Part of the pavement condition monitoring is the measurement and reporting of pavement roughness. Various State Highway Agencies, FHWA personnel, and other interested parties, such as the World Bank, formed a Highway Performance Monitoring System (HPMS) Work Group. The objective of the group's work is the establishment of a practical and uniform calibrated roughness measurement procedure and the determination of the details and requirements for reporting pavement roughness.

The roughness summary numeric adopted as the HPMS data reporting unit is the International Roughness Index (IRI) in inches per mile. The guidelines for the individual state's compliance with the calibration, measurement, and reporting of this standard are outlined in Appendix J of FHWA Publication 5600.1A (Ref 1). This document defines IRI, classifies the roughness monitoring equipment, outlines the acceptable calibration procedure, sets guidelines for the collection of roughness data, and lists the reporting requirements.

The classification of the instruments used to monitor and report the pavement roughness is based on the reporting interval and the maximum error as reported in inches per mile. The roughness measuring instruments are given categories from I through IV, with Class I being the classification with the shortest measurement interval and the lowest maximum error. Examples of Class I instruments are those used with manual profiling techniques, which include rod and level surveys, the Face Dipstick, and the TRRL Beam. Class II instruments include the various types of direct profiling Profilometers and the APL Trailer. Class III instruments are the most widely used by the states and internationally and include all of the Response Type Road Roughness Meters (RTRRM) and the various rolling straight edge devices. Class IV involves subjective estimations of roughness by trained raters, and this method of roughness evaluation and classification is not suitable for HPMS purposes.

Each individual state is responsible for determining which class of instrument it will use to collect and report the roughness data to the FHWA. Class I and II instruments must be used by the states for calibration of lower classification instruments. For example, a Class II Profilometer may be used by a state to calibrate, by use of regression equations, a Class III instrument, such as a Mays Ride Meter. If a Class II instrument is used for calibration, its own calibration must be verified with the use of a Class I manual profiling instrument. Each state is mandated to document and retain records of its calibration procedures. These records must contain, as a minimum, (1) information on selection of calibration sites, (2) descriptions of those sites, (3) how and when the site profiles were obtained, (4) the frequency of the calibration runs, (5) speed(s) used, (6) minimum passes required, (7) dates, and (8) results of the calibration procedures. As previously stated, all roughness measurements and calibration data must be reported in terms of IRI.

If the individual state is using a Class III (RTRRM) device for monitoring roughness, it must use the specified calibration-through-correlation procedure for conversion of the device's output to IRI. As a minimum, nine test sites of at least 0.2 mile must be selected. Three each of the selected sites must fall into the three specified roughness categories. The three categories are classified in terms of ranges of IRI values. A smooth site has a range of IRI from 0 to 190 inches per mile, a medium site has a range of 191 to 320 inches per mile, and a rough site has a surface profile with an IRI greater than 320 inches per mile. The start and stop locations, as well as the wheel paths of each test site, should be clearly marked. There must be enough approach and deceleration distance in each test site for the equipment to reach the proper speed and stabilize its operation. The selected test sites should have low traffic volume and be on tangent sections with little or no grade.

The known or longitudinal profile of each site is determined by taking the elevations to the nearest 0.04 inch at distances of 12 inches or less through the length of each test site. A Class I and/or a Class II instrument must be used for this determination. The IRI is computed from the elevation data according to the World Bank Technical Paper Number 46 (Ref 2) procedure. These IRI computations become the Y coordinate values for the correlation graphs. The X coordinate values are determined by computing the average reference roughness index (RRI) for each test site at each operating speed specified by the state. This RRI value is calculated by averaging a minimum of five passes on each site for each RTRRM device. If an individual reading falls outside an acceptable limit (greater than 10 percent), that reading should be rejected. Another pass with the resulting output should be made to replace the questionable data. The best fit line or curve-fitting equation through the points obtained becomes the HPMS correlation equation for that particular device at the speed indicated.

Verification of the known or absolute profile of each test section must be accomplished using a Class I or II device at regularly timed intervals. This is to insure that the profile used for instrument calibration has not changed due to severe weather, traffic conditions, or pavement maintenance. The minimum time period for this verification process is specified as one year, and the process should be accomplished immediately prior to the data collection season. If data are collected by a state all year, Appendix J says that more frequent measurements of the test sites are necessary. If the profile and the resulting IRI have changed, complete recalibration of all the state's instrument pool must be accomplished. Appendix J gives the states no indication as to the magnitude of the profile and IRI changes necessary to cause a recalibration. One must assume that changes greater than the specified maximum instrument error for the Class I and II devices would have to have occurred at a test site, but no upper limit is specified.

The verification that the RTRRM devices are still in calibration must be accomplished before roughness surveys are conducted and at regular time intervals. The specified interval is at least once per month or every 2,000 miles traveled, whichever comes first. If the average RRI of an RTRRM instrument varies more than ± 5 percent from the previous average RRI for a given speed on each test site, that instrument is to be considered out of calibration and must be repaired or recalibrated or both.

The Texas SDHPT Maintenance and Operations Division, Pavement Management Section, is responsible for the maintenance of, calibration of, and data collection with the state's roughness evaluation fleet. As such, it is responsible for making sure the State of Texas is in full compliance with the FHWA Appendix J mandates. The Texas SDHPT has a wide range of roughness instrumentation which fits into the Class I, II, and III guidelines established under Appendix J. Class I instrumentation in the form of a rod and level survey is at the disposal of the SDHPT for calibration purposes. This was considered too time-consuming and too expensive to adequately fulfill the verification of the known profile mandate of Appendix J, and another method was sought. As a result, the Center for Transportation Research (CTR) and representatives of the Face Technologies Company, manufacturers of the Dipstick, held a demonstration for Texas SDHPT personnel. The Dipstick is identified as a Class I profiling instrument in Appendix J, and appears to be a time-saving and cost-effective substitute for the rod and level survey.

INITIAL AUTO-READ DIPSTICK EVALUATION

An initial evaluation was conducted by CTR (Ref 3) to determine whether or not the Dipstick instrument in its auto-read configuration could meet or exceed the manufacturer's accuracy claims and the Appendix J mandate for Class I instrumentation. It was the understanding of CTR and SDHPT personnel that the manual version of the Dipstick was the instrument identified in Appendix J as a Class I profiling instrument. The manual-read version of the Dipstick utilizes an inclinometer to determine the difference in elevation between the instrument's two feet. The distance between the feet is 12 inches which is the upper limit of the spacing for a Class I instrument. The operator views the elevation change and the sign of that change on the forward-pointing LCD display. The readings are recorded on audio cassette tape and/or handwritten for transcription at a later date.

The Face Company claims that one person using the auto-read version of the Dipstick can measure, record, and analyze up to 600 feet of elevation points with an accuracy of ± 0.0015 inch per reading in less than one hour. The auto-read version captures the elevation data by means of an onboard PC-2 computer. Data are processed and analyzed after the elevation information has been transferred to an IBM-compatible computer via an RS232 communications port. The processing program calculates IRI as well as flatness number and local surface curvature. The initial evaluation was accomplished on a prototype auto-read version of the Dipstick. Several problems were encountered during the evaluation, as would be expected on the prototype on any instrument.

The Texas SDHPT, based on the initial CTR report (Ref 3), felt that the performance of the prototype auto-read version of the Dipstick was impressive enough to warrant further investigation. This initial performance, the fact that the auto-read Dipstick seemed to be a cost-effective Class I substitute for rod and level surveys, and the fact that the instrument fit into the FHWA's Appendix J mandates made the Dipstick very attractive. These considerations resulted in the purchase of an updated version of the prototype auto-read Dipstick from the Face Company for a more thorough evaluation.

UPDATED AUTO-READ DIPSTICK EVALUATION

The updated auto-read version of the Dipstick was purchased through CTR for the Texas SDHPT for the purpose of this evaluation effort. SDHPT personnel had identified this instrument as a possible cost-effective substitute for rod and level surveys of the Texas roughness calibration sites. A Class I instrument was also required, to guarantee the accuracy of the SDHPT Class II K. J. Law modified profilometer that was to be used. The initial effort in the evaluation was concerned with determining whether or not the manufacturer had addressed the operational problems identified in CTR Tech Memo 1167-2 (Ref 3). The following sections relate the history of the evaluation after the updated Dipstick was obtained from the Face Company, and identify areas of concern about the operation of the auto-read version as a reliable and repeatable field instrument.

Original Instrument Shipment

When the Dipstick arrived from the manufacturer it was in an inoperable condition. The results of the first checkout performed on it showed that it would not take and store readings on the PC-2 computer. To isolate the problem, the PC-2 computer from the CTR Dipstick was switched with that of the Texas Research and Development Foundation's (TRDF) computer. A set of test readings were taken using the two Dipsticks and the switched PC-2's. The no-reading condition remained with the Dipstick and did not follow the computer and software, so arrangements were made to exchange the CTR Dipstick for a new one. The new Dipstick was checked out and determined to be in proper working order.

Data Transfer

When the new Dipstick instrument arrived, the memory was reset in the PC-2 to purge the acquisition software and all of the stored data, to determine if the manufacturer had addressed the problem of downloading software from the cassette tape backup or from an IBM-compatible computer system. Several problems were encountered with this operation during the initial evaluation effort. The basic problem was in the PC-2's RS232 interface. A fairly exacting procedure must be followed in order to complete the software transfer correctly: all of the individual modules must be connected and powered up before a transfer can be correctly completed. However, in the original operator's manual and in the communication software provided, this situation was not addressed, and consequently some data were lost. The manufacturer was contacted to determine whether the software, the interface cabling, or the interface itself was at fault. After trouble shooting the problem it was determined that the transfer software required that the RS232 interface be connected and powered up and the null modem installed before the software can be downloaded properly. The new version of IBM software provided by the manufacturer is menu-driven to prompt the operator through the correct procedure, but the problem is still inherent in the cassette tape backup. Unless the operator is familiar with the Dipstick's operation and requirements, it is easy to make mistakes. These mistakes will result in the software being transferred with errors such as missing program statements or with additional characters inserted on a programming statement.

Operator's Manual

The Operator's Manuals supplied by the manufacturer have not been current. The Face Company has sent several updates to the manual, but the latest one does not address the latest version of software. Some new menu screens and the additional ACII file options are not mentioned in the manual, and the manufacturer does not address the user's IBM-compatible computer and its requirements for data transfer, since the user must provide this item. The RS232 interface cabling is also dependent on the user's computer. Appendix B to this report has been prepared to address the items not included in the manufacturer's Operator's Manual, and a copy of the appendix is included in the latest CTR version of the Operator's Manual.

Leveling and Calibration Check

During the evaluation, it was learned that the leveling and calibration check procedures are tedious unless a relatively smooth and flat surface is present at the test site. The leveling of the Dipstick's body relative to the feet should be done at least once a day before readings are taken and twice a day if the Dipstick is to be used for an entire work day. The calibration check should be performed once a day. If only uneven and rough surfaces are present on the job site, it can be very difficult to get the Dipstick's feet down in exactly the same orientation after rotating the instrument. This requires the operator to check and readjust the height of the feet a number of times before the ± 0.001 inch specification can be met. However, a practical solution to this problem has been developed from our experience: the hood or trunk surface of the user's vehicle can be used as a leveling surface if it is parked on a level surface. If the Dipstick fails the calibration check, it must be returned to the Face Company for repairs since the Face Company does not give the user access to the dampening and calibration adjustments for the internal inclinometer, although during the period of time that the Dipstick was being evaluated this problem was not encountered.

Dipstick's Feet

The Dipstick's footpads have continued to be a source of concern. The Face Company originally provided a set of feet with neoprene rubber glued to the contact surface. The neoprene pads started to come unglued during the first few test runs, and the neoprene itself started to come apart after several runs on a concrete pavement, probably because of the rough microtexture. The Face Company then sent another set of feet, which used a new type of contact cement, and this set has lasted several months. The manufacturer assures CTR that they are aware of these problems and are continuing to make revisions to the footpads and the substances used on them.

The lack of smooth rotation of the ball and sockets on the Dipstick's feet is another problem which has adversely affected the Dipstick's operation. The ball and socket joint often makes a squeaking sound, and some lubrication has to be added to the joint. After some experimentation by CTR staff it was found that the most efficient lubrication was standard SAE 30-weight motor oil, which seems to last for a relatively long period of time and helps keep foreign particles from entering the joint area. The free rotation of the foot joints and the security and condition of the rubber foot pads always need to be checked before the Dipstick is used to take measurements.

Battery Problems

Determining the remaining life of the batteries inside the body of the Dipstick is a problem. There is no way to know when they are about to fail in the present version of the Dipstick. When they began to fail during the collection of a set of data, the data collected proved to be incorrect. When the batteries weakened during one of the runs, the run had to be aborted. On a second occasion, the operation of the Dipstick became slower and slower. False and no-readings were noted and the data proved to be unusable. The estimated life of a set of batteries is ten hours, which means that at the very minimum one extra set of batteries should be kept with the Dipstick at all times. If the Dipstick is used continuously for a complete six to eight-hour work day, the batteries should be changed daily. The manufacturer has been made aware of this problem and has promised to provide some type of low battery indicator in the future.

The PC-2 is also susceptible to battery problems, although it has a "good" battery indicator on the screen and its battery has required only one change during this evaluation. However, a backup set of batteries should be kept in the Dipstick's case at all times. If the PC-2 battery fails and has to be replaced, the data and acquisition software stored on the PC-2 may or may not remain intact and, in any case, are suspect. The PC-2 batteries have been removed on two separate occasions without associated software problems. On two other occasions problems occurred. The first time a test was performed to see if memory would be lost if the batteries were replaced: neither the program nor the data stored in memory was lost or changed. The next three occasions occurred when the PC-2 got "locked up" and would not accept any key stroke or command to reboot the program. As a result the operator had to pull the PC-2 batteries out and replace them to "wake up" the PC-2. One time this did not result in the loss of data or programming software; the next time, the acquisition software would not reboot and had to be reloaded into the PC-2's memory; and on the final occasion the program seemed intact and a set of data was taken. While attempting to close the data file an error statement in a program line was encountered. Listing the indicated program line showed that a space had been inserted were a character should have been. This resulted in the loss of the entire data set. The final result of this exercise is that any time the PC-2 batteries are removed, all software and data should be considered unreliable. A new data set should not be taken until the acquisition program is reinstalled. On-board data should have been saved but may have been corrupted. The 16k-byte memory module located on the back of the PC-2 has its own battery and an all reset button. If this battery fails or is removed or the reset button is pushed, all data and software stored on the PC-2 will be lost without fail.

The compartment housing the Dipstick instrument's batteries has presented another problem which involves distance errors. The battery cover must be pressed tightly into position against the Dipstick's body and secured with the cap screws. If there is even a small gap left between the body and this cover, distance errors will accumulate with every Dipstick reading. The distance between each foot is set at 12 inches. If a gap as small as 1/32 of an inch is present between the body and the cover, and the test section length is 1056 feet, a resulting distance error of 33 feet would be accumulated. This situation occurred after the first Dipstick battery change in the form of accumulated distance errors on several test runs.

Software Problems

The Dipstick reads the same foot on every other measurement. The battery or switch end of the Dipstick must be forward during the first reading, depending on which version of software is being used to acquire the data. If this orientation is reversed, the sign on all of the data collected will be reversed. This situation has caused several sets of data to exhibit a slope in a direction opposite from that of the pavement design. This can be observed in Figs 1 and 2. Figure 1 represents a set of data collected using a version of software which reads the battery end of the Dipstick first. The operator, inadvertently, had the Dipstick end marked start pointed forward. Figure 2 is the same section read with the correct orientation. The most recent software (Version 1.31) reads the Dipstick end marked "start" first, and the instrument should be oriented with this end forward at the beginning of every run.

The nomenclature used to distinguish the individual files and run numbers can cause problems to operators who are not familiar with the Dipstick software. This problem will not cause the acquisition of bad data but can be confusing to the novice Dipstick operator familiar with the normal nomenclature used in computer directory and file allocations. The PC-2 allocates data space and allows a certain number of files to be opened, depending on the operator's input to the allocation setup menu. The operator specifies the maximum number of readings in a data set. From this information the PC-2 divides the available memory space into files of equal length. Once this assignment has been made the operator cannot change the maximum number of readings without reallocating the memory space, thereby erasing all information stored in memory. The PC-2 program asks the user to provide a directory name instead of a file name. This directory is used to store all of the data collected during the current memory allocation. This directory is usually used to describe the general area where the data is collected. The PC-2 software uses the operator's input to file number to find the start of the memory location to begin a particular data set. The user can only input a number in response to the question File # to open: after the user prompts the PC-2 with an answer, the PC-2 asks the user for Run # ?. This question can and should be answered with an alphanumeric string describing this particular data set. This nomenclature has caused problems in the past, because users are expecting to answer the file number question with a descriptive string, and the run number question with a numeral representing a data set under the directory and file name specified. These conventions are inconsistent with normal DOS operating system nomenclature practices.

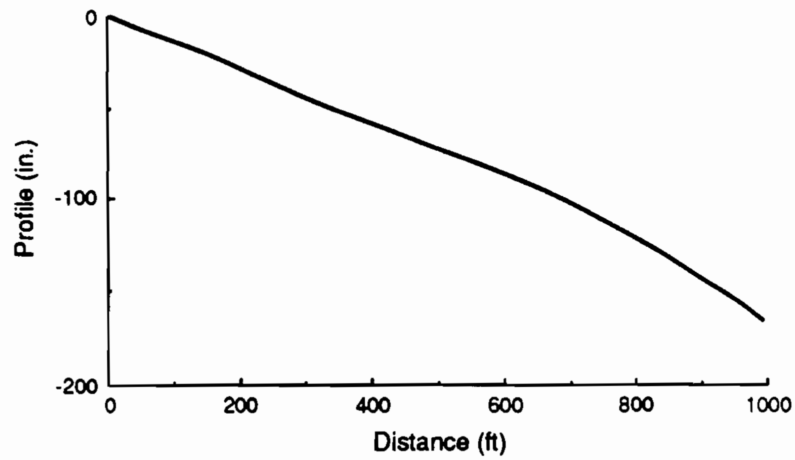

Fig 1. Dipstick data with slope reversed.

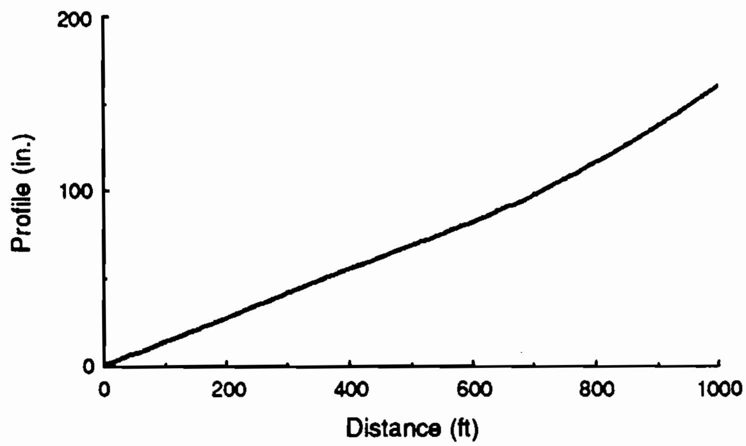

Fig 2. Dipstick data with proper slope.

No-Reading Problem

The Dipstick has failed to take readings on occasion. After the operator rotated the Dipstick to take a new reading, the screen did not go blank and the beep did not sound. This problem was discovered only after the researchers became aware of problems in the Dipstick's data collection. The beeping is not loud enough to be heard unless there is very little noise pollution in the area. The operator must look at the screen constantly to make sure it blanks and a new reading has been taken. If the operator detects that the Dipstick has not taken a reading, a new reading can be triggered before moving to the next location, thereby saving the data set. The Dipstick's body can be moved by lifting the front foot until the instrument "feels" the movement and the display blanks. The operator must make certain that the rear foot remains in position during this procedure or the reference elevation will be lost. If the operator fails to detect a no-read situation the instrument will read the wrong foot, the last reference will be lost, and the remaining elevations will be opposite in sign.

False-Reading Problem

There is a problem with the Dipstick taking false readings. This problem is the most serious drawback to the Dipstick's reliability and repeatability. The false readings can cause the reported direction of the pavement slope to change several times during a single run. This situation can be viewed in Figs 3, 4, and 5. Figure 3 shows the Dipstick

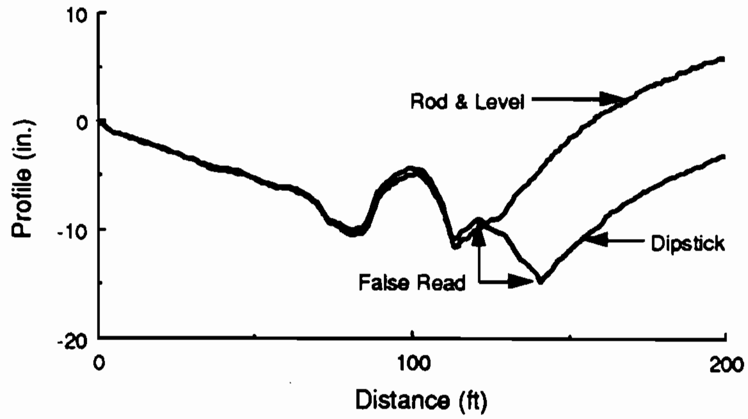

Fig 3. Dipstick data with false readings versus rod and level survey.

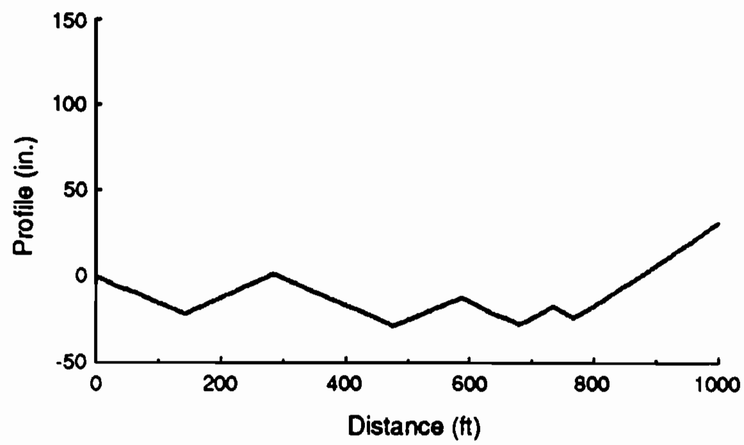

Fig 4. Dipstick data with false readings.

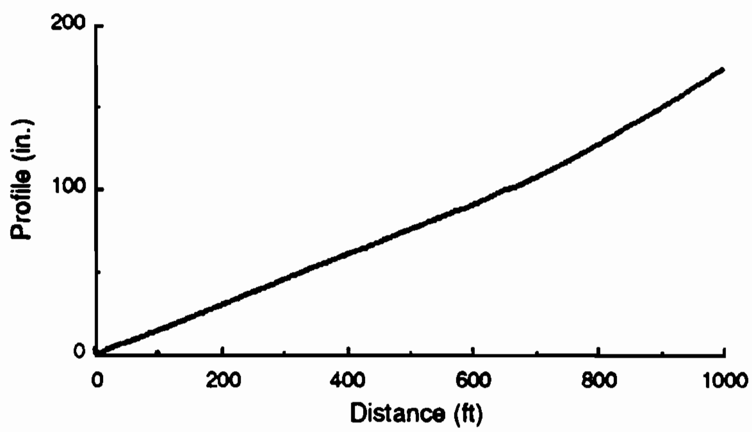

Fig 5. Profile of surface in Fig 4 with proper slope.

data with false readings overlaid on a graph of a rod and level survey of the same test site. Figures 4 and 5 are graphs of two different Dipstick runs on the same test sections. Figure 4 shows the false readings and Fig 5 shows a profile of the test section with the proper slope. The UT instrument has given up to eight false readings in sequence without being moved. This situation has occurred on three separate occasions. The Face Company has tried to correct this problem with software. The new version of Dipstick software incorporates three new features which help reduce the possibility of false reading occurrences, and gives the user the ability to edit false readings out of the data collected. Although the ability to edit data exists, the operator must know that some readings are false and which readings are false in order to use the edit capability effectively.

Software Enhancements

One of the three software modifications intended to help eliminate false readings is the addition of a range of three Dipstick operating speeds which are user-selectable during the setup routine. The logic behind this approach is as follows: by reducing the operator and acquisition speed, the untrained operator would be less likely to tilt the Dipstick and thereby make it "think" it has moved. The manufacturer believes the problem is with the operator and not with the Dipstick's operation. CTR's experience with the operation of the Dipstick and the fact that false readings occur at any of the selectable speeds refutes this belief.

The second software change utilizes the fact that each foot on the Dipstick is always forward during either an even or odd-numbered reading. After the acquisition programming is initiated, the last reading number is constantly displayed on the PC-2's screen. If the operator sees or believes that a false reading has occurred, looking at the screen will tell the user if the reading number and the Dipstick orientation are in sync. The Dipstick end which started forward is always forward on odd-numbered readings and the opposite end is always forward on even-numbered readings. This situation does not help in the determination of exactly where the false reading occurred. In cases where the operator knows a false reading occurred, this feature could, and has, saved an entire data set. If an even number of false readings has occurred during the collection of a data set and the operator does not notice one of the false readings, this software enhancement will not effectively eliminate the false reading.

The third new software feature is an edit function which is useful both during the reading of a set of data and after the data has been collected and stored. If the operator perceives a situation during the collection of a data set which needs to be corrected, the edit feature could and has saved the abortion of the run. The new edit feature allows the operator to maintain the Dipstick's elevation reference while restarting the acquisition program. This operation is accomplished by leaving the Dipstick's feet on the pavement surface, remembering the reading number, and exiting the program. The program prompts the user by asking whether or not he wishes to edit the contents of an existing file. By answering yes to this question and leaving the feet in place, it is possible to reopen the data file and start the readings at any location along the wheel path. The user is prompted through the setup routine and asked from which reading to start taking the new data. The program then tells the user which end of the Dipstick should be forward and from which reading the edit will start. The operator walks the Dipstick back a specific number of readings, makes certain the orientation is correct, and restarts the acquisition program.

The user has the option to edit the contents of saved data files during the processing of the data on the IBM computer. This feature could save a data set from being abandoned. The operator has to be aware that a problem has occurred during the data collection by taking a good set of field notes, or by using the voice-activated cassette recorder to tape field notes. If the design slope of the pavement being evaluated is known, the user could edit individual readings to correct erroneous data. If the operator is unaware of data problems or the design slope and leaves the job site, the edit feature is useless in saving a data set.

Most Reliable Auto-Read Data

The most consistent and reliable auto-read Dipstick data have been taken when the following situation is present: if there is more than one Dipstick available to take readings along parallel wheel paths, the operators are able to constantly check each other's readings and orientation. They can adequately take advantage of the edit software on the acquisition program to collect a reliable set of data. This situation is also psychologically helpful to the Dipstick operators. It takes an experienced operator 80 to 90 minutes to Dipstick 1000 feet. At this pace an operator's mind can start to wander. This results in less attention being paid to the job of Dipsticking. Consequently, it is much more likely for a false-reading or a no-reading to happen and go unnoticed. This method of Dipsticking was performed on the La Grange test sections after the initial collected data was determined to be unusable. This was the only method which allowed the researchers to collect an accurate set of data for all of the wheel paths on all four travel lanes at La Grange. Traffic control requirements are cut at least in half when this method of profiling is employed because the time required to Dipstick both wheel paths in a travel lane is cut in half. Elevation data from both wheel paths in a travel lane are required for calibration of the Texas SDHPT Profilometer.

TEST SITE DESCRIPTIONS

The test sites selected for this evaluation were at three separate locations. Each location offered distinct opportunities for the researchers to evaluate the capabilities of the Dipstick's performance in the field. This section contains a description of each of the chosen tests sites.

Oakmont Test Site

The first section was a 200-foot section of asphaltic pavement which passes through the intersection of Oakmont and West 37th Streets in Austin, Texas. This is one of the sections used in the earlier evaluation of the Dipstick (Ref 3). It is referred to as the Oakmont test site in the remainder of this text. Both the left and right-hand wheel paths of West 37th Street were marked with traffic paint. The section had been surveyed using a rod and level at 6-inch intervals by the Texas SDHPT. A temporary bench mark was established for this survey and an elevation of 100 feet was assumed. No turn was taken and the instrument was not moved during the survey. The difference in the first reading of the start location and the last reading at the start location was 0.004 foot. This difference was reported as the closure error. All of the readings in this section have an orientation of west to east. This section was chosen because it had been surveyed utilizing a Class I procedure, rod and level, and had been previously evaluated using the manufacturer's original version of the Dipstick. The section was also very convenient and readily accessible to the researchers. Traffic control, in the form of a single flagman, was all that was necessary, which made the site inexpensive to evaluate.

La Grange Test Site

The second test site was located on the US Highway 71 bypass around La Grange, Texas, and is referred to as the La Grange test site. This pavement offered some unique opportunities which helped the researchers collect valuable data for other projects as well as this one. The pavement was newly-constructed continuously reinforced concrete and had not been opened to the public at the time of the investigation. The highway was composed of a shoulder and two travel lanes in each direction. The construction and design details can be seen in Ref 4. Two 1000- foot sections were selected from the bypass and each travel lane was evaluated. The first section was located in the eastbound direction. This section was relatively flat and straight, with a gradual +1.26 percent slope. The second section at the La Grange site was in the westbound direction and contained several interesting design features. This section had a design slope of +1.00 percent, contained a super elevated curve, two transverse construction joints, and a cast-in-place bridge deck, and ended on a bridge crossing the Colorado River. No traffic control was needed during this evaluation because the section was carrying only contractor vehicles.

Austin Test Sections 1 and 4

The third test site was located on Decker Lake Road on the outskirts of Austin, Texas, in Travis County. This site was divided into two sections, which were identified as Austin test sections 1 and 4 during the Arizona Department of Transportation study (Ref 5). Austin test section 1 (ATS1) was the westbound direction and Austin test section 4 (ATS4) was the eastbound direction of the same roadway, and each was 0.2 mile in length. The sites have been used by the Texas SDHPT for a number of years for the evaluation of its high speed roughness evaluation equipment. The wheel paths of both travel lanes were evaluated. These sections were chosen because they represent very rough asphaltic pavement. The sites are located in a very rural area with low traffic volume, which made traffic control easy. Two flagmen, one at each end of the sections, were used to slow and divert traffic around the Dipstick operators.

DESCRIPTION OF COMPARISONS OF TWO DIPSTICKS

Two different Dipsticks were compared in an attempt to evaluate how different instruments performed under the same conditions. The Dipstick itself had previously been evaluated (Ref 3) for accuracy against the Class I rod and level surveys on different surface types and conditions. The researchers felt that if more Dipsticks were to be purchased or if data from another Dipstick were to be used in the future, it would be necessary to evaluate the individual instruments for repeatability and reliability. The two Dipsticks used in this study were: one purchased for this project, designated the UT Dipstick, and one purchased under the Strategic Highway Research Program (SHRP) for the Texas Research and Development Foundation (TRDF), which is referred to as the TRDF Dipstick.

Both instruments were used on the same wheel paths of all three of the test sections. Not every wheel path in each test section was run by each instrument, but a duplicate set of data was collected on at least one wheel path of each test section. The Oakmont test site allowed the direct comparison of both instruments to each other and to a rod and level survey. The use of two Dipsticks walking side by side down parallel and adjacent wheel paths allowed comparisons of speed, distance, and false readings.

Each of the wheel paths in every test section except Oakmont was marked using the same procedure. A start location was painted on the pavement across each travel lane. The wheel paths were determined by measuring the width of the travel lane and assuming a 65-inch axle width. The wheel paths were laid out by centering the axle width in the travel lane. A string line was stretched down the wheel path and a series of small dots were painted on the pavement along the string line. The distance of each run was measured using a roll-a-tape. A stop line was painted at the end of each run in each travel lane. The Oakmont section was marked using the same procedure except that the two wheel paths were centered about the center of the pavement width. These lines allowed the operators to follow relatively the same path on every test run.

La Grange Testing

The La Grange test site was measured several times with the two Dipsticks. The first two sets of data showed distance errors, false readings, and software problems. The distance errors were corrected as the result of adjustments made in the battery cover. After replacing the battery in the Dipstick body, the cover must be pushed in and held tightly against the body while the cap screws are being secured. The false reading problem has not been resolved satisfactorily at this time. The Face Company has added an edit function to the acquisition software which allowed the researchers to get a good set of data. The original software sent with the Dipstick was reading the wrong foot first and caused the sign of all the readings to be reversed.

The Face Company sent two representatives to Texas as a result of the problems described above. These representatives, along with CTR research staff, went from Austin to La Grange to rerun the test sections. Both of the Dipsticks were used at the same time on parallel and adjacent wheel paths. Runs were made in the direction of traffic flow as well as opposite to the traffic flow. The operators exchanged Dipsticks during the morning and the afternoon readings. The false readings were effectively omitted from the test data by using the edit routine and the second Dipstick as a reference point for editing measurements with the false readings.

An example of the false readings that occurred on the eastbound inside lane and the outside wheel path during one of the first test runs can be viewed in Fig 4, and the profile with the proper slope can be seen in Fig 5. The sharp changes in direction shown in Fig 4 indicate a false reading, of which there were seven. Figure 4 also shows an example of the software reading the wrong foot at the start of the run, producing a negative slope.

A comparison of data, believed to be accurate and collected on the same wheel path by the two different Dipsticks, can be seen in Figs 6 and 7. Figure 6 is a representation of the eastbound inside lane and the outside wheel path. Figure 7 is a representation of the eastbound inside lane and the inside wheel path. The plots of both of the instruments are overlaid in both figures and are barely distinguishable. These figures were generated by performing a running sum on the raw elevation data from each Dipstick and graphing the result against distance. The difference between the last readings of each instrument in Fig 6 is 2.024 inches and in Fig 7 is 0.886 inch. The distance errors were consistently within two feet of the stop locations after the battery case had been reseated. The TRDF Dipstick was operated with the wide ball and socket feet, but without the rubber pads attached. The excellent correlation between the two Dipsticks with and without the foot pads suggests that little or no slippage occurred. It is believed that the rough microtexture of the concrete pavement and the very gradual design slope allowed the TRDF Dipstick to perform well with no rubber foot pads. The fact that the ball and sockets of both Dipsticks were well lubricated with motor oil insured that the feet swiveled freely and did not "trip," which would cause slippage. It is believed that a good correlation between data sets would have been hard to obtain without the two instruments checking each other.

The other wheel paths in the La Grange Test Section were Dipsticked individually using the two instruments on parallel wheel paths. The operators were changed as mentioned earlier. The graphs from the runs made by two instruments on parallel wheel paths can be viewed in Appendix D. These figures include information with regard to which Dipstick was used to acquire the data for the graphs. Raw elevation and a running sum profile for each wheel path are included in Appendix D. It is believed that the graphical representation of the data presented in Appendix D is reliable because the two Dipsticks were used to check each other during the evaluation of the pavement surface roughness.

Oakmont Testing

The Oakmont Street test site was used to compare the output of the two instruments to the rod and level data which was previously obtained. This site also provided the researchers with a safe and convenient location to run the Dipsticks several times. The Dipsticks were evaluated for the difference in operating speed and consistency of their operation.

The new speed-selectable software function was evaluated by selecting a speed setting and traveling a known distance on the roadway. The right-hand wheel path in the eastbound direction of the Oakmont site was marked off in 10-foot intervals. The first 50 feet of the wheel path was Dipsticked at each of the three speed settings. The time it took to complete a run was monitored and an average number of readings per minute was calculated. This number was multiplied by 60 to determine the number of readings per hour. The 700 and 800 readings per hour selections were close to actual values calculated from the procedure described above. The 900 readings per hour was not attainable using the UT Dipstick. The number of readings per hour was calculated to be 835. The slowest two settings are too slow to be useful in the field unless a very short distance is to be

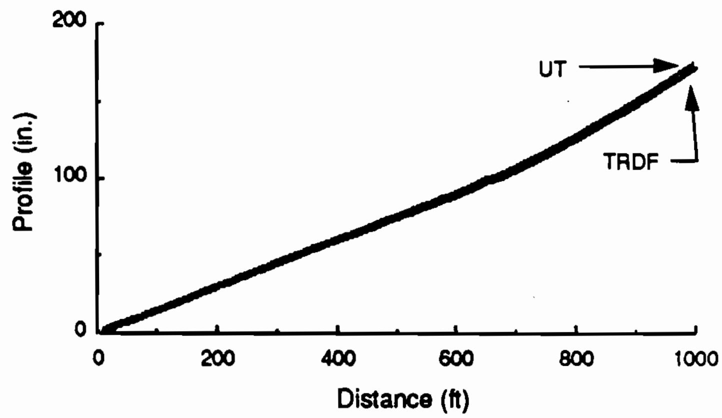

Fig 6. Dipstick comparison of eastbound, inside lane, outside wheel path at La Grange test site.

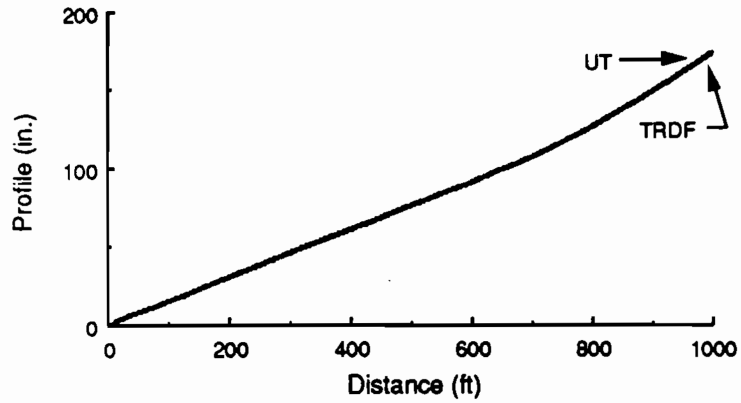

Fig 7. Dipstick comparison of eastbound, inside lane, inside wheel path of La Grange test site.

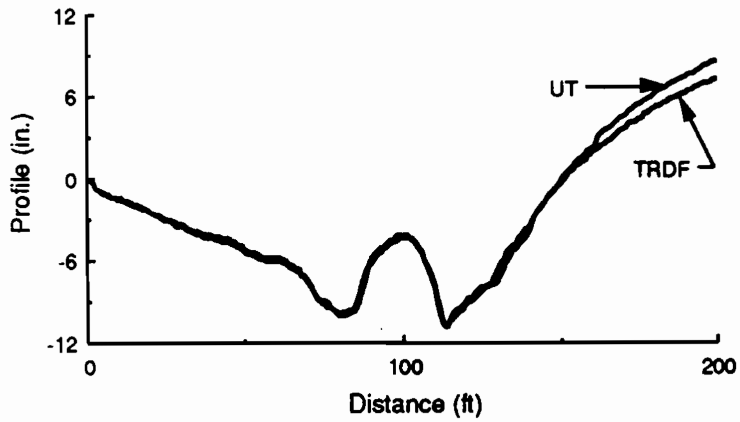

Fig 8. Dipstick comparison of eastbound, right wheel path at Oakmont test site.

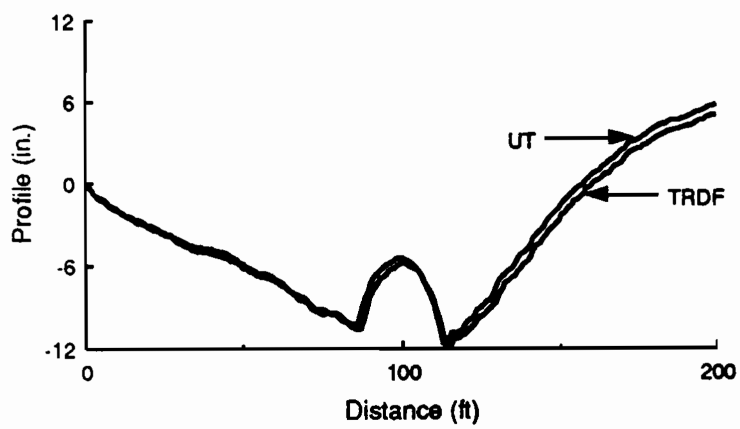

Fig 9. Dipstick comparison of eastbound, left wheel path at Oakmont test site.

Dipsticked. The slowest speed would not be useful at all after an operator becomes accustomed to operating the Dipstick at the faster speeds. If false readings or missed readings occur during a particular run, the 835 readings per hour is not possible with the UT Dipstick. The results of this test led the researchers to further investigate the possible speed difference in the two Dipsticks. This was done on the Austin test sections and is discussed later.

Four figures are presented to illustrate the direct comparison of the two Dipsticks and to compare the Dipstick's output to the rod and level profile. Figures 8 and 9 show the comparison of the running sum of the two Dipstick elevations for the right and left-hand wheel paths, respectively. The difference in elevation in the right-hand wheel path at the 200-foot location for the two instruments is 0.895 inch. The difference in the readings for the left-hand wheel path is 0.753 inch. Figures 10 and 11 show the rod and level plotted against the two Dipsticks for the left and right-hand wheel paths, respectively. The difference in the rod and level elevation and the TRDF Dipstick elevation for the left-hand wheel path at the 200-foot location is 0.654 inch. The difference between the rod and level and the UT instrument for the left-hand wheel path is 0.099 inch. The differences between the rod and level in the right-hand wheel path and TRDF and the UT Dipsticks is 1.211 inches and 0.182 inch, respectively. The TRDF Dipstick was always further from the rod and level representation of the roadway profile than the UT Dipstick. This could be explained by the foot slippage on the steep slopes encountered on the Oakmont test site. The TRDF instrument was run without using the rubber pads glued to its feet.

The TRDF Dipstick was noticeably faster and less likely to have false readings than the UT Dipstick. The faster reading time was first thought to be a function of the battery life in the Dipstick body. Further investigation refutes this theory, and it is now believed that the maximum instrument speed is dependent on the individual instrument's ability to stabilize after it has "sensed" a movement. The UT Dipstick was run five times on the right-hand wheel path and every time at least one false reading was encountered. The first three readings were taken on the same day and the operator was not aware that the false readings had occurred. The last two readings were made on the following day and the operator was watching the display blank and reappear after every rotation of the Dipstick's body. By observing the screen and checking the reading number against the Dipstick's orientation, the operator was able to capture two good sets of data. This situation can be viewed in Fig 12.

Austin Test Sections

Two test sections used by the Texas SDHPT instrumentation pool for evaluating and calibrating its roughness instruments were measured with the two Dipsticks available to the researchers. These two sections are the east and westbound directions of the same roadway. The eastbound travel lane was identified as Austin test section 1 (ATS1) and the westbound travel lane was identified as Austin test section 4 (ATS4). The beginning and end of both these test sections were marked by SDHPT personnel. Each wheel path within a travel lane was located and marked from the center line of the pavement. A string line was stretched down each wheel path and a series of dots was painted on the roadway surface to give operators a guide line and to make certain that the same wheel path was being evaluated by each instrument. A mark was also painted on the pavement of both test sections at 100-foot intervals as a guide to the operators. These guides were useful for determining distance traveled and whether the indicated reading number was reasonable. These numbers also helped during the edit routine in trying to save a set of data.

These test sections were run with the operators intent on trying to get good data sets on every run. The displays were watched constantly, and periodically the read number indicator was checked against the Dipstick's orientation. Another researcher, in the form of a traffic control flagman, walked next to the operator and acted as another pair of eyes and ears to monitor the Dipstick's performance. Time was kept on each instrument to determine relative maximum speeds.

The same problems occurred during this set of measurements as have previously been discussed. In addition, a new situation in the operation of the UT Dipstick and later, the TRDF instrument, proved to be a problem. The UT Dipstick had a few missed readings. After the instrument had been rotated, the display did not blank and the reading number did not advance. The instrument did not sense the rotation and failed to take a reading. In most cases, this did not cause a problem other than slowing the operation of the instrument. The operator would simply lift the front foot until the Dipstick felt

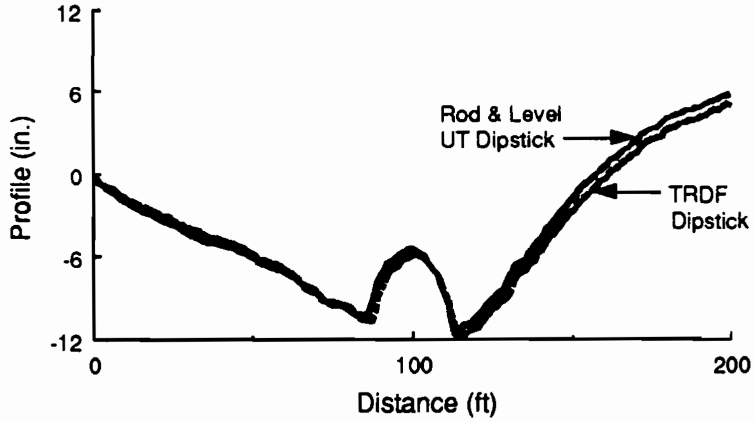

Fig 10. Rod and level versus two Dipsticks for eastbound, left wheel path at Oakmont test site.

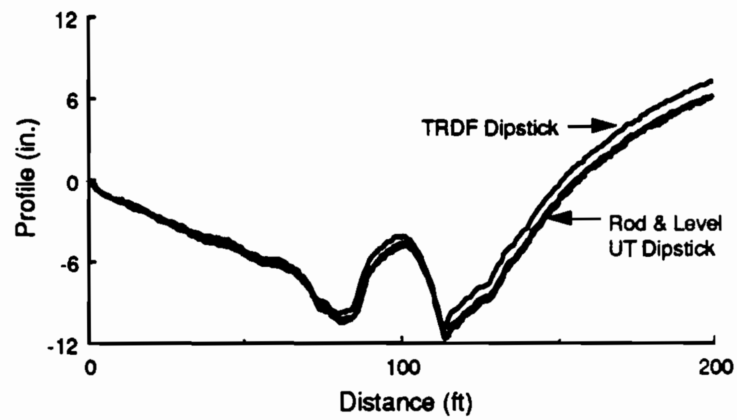

Fig 11. Rod and level versus two Dipsticks for eastbound, right wheel path at Oakmont test site.

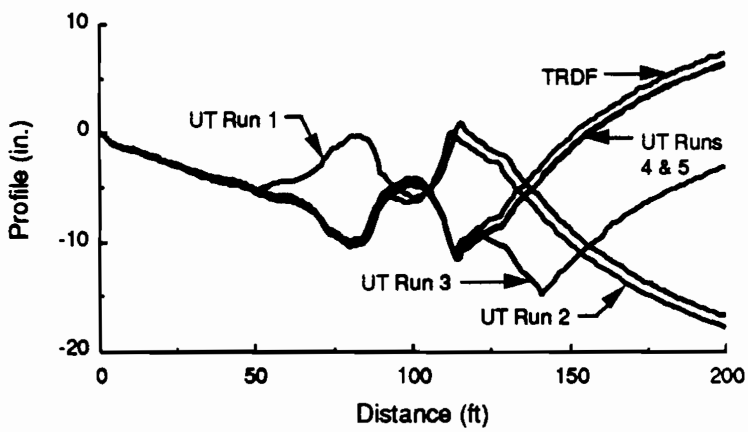

Fig 12. Comparison of multiple runs on the eastbound, right wheel path at Oakmont test site.

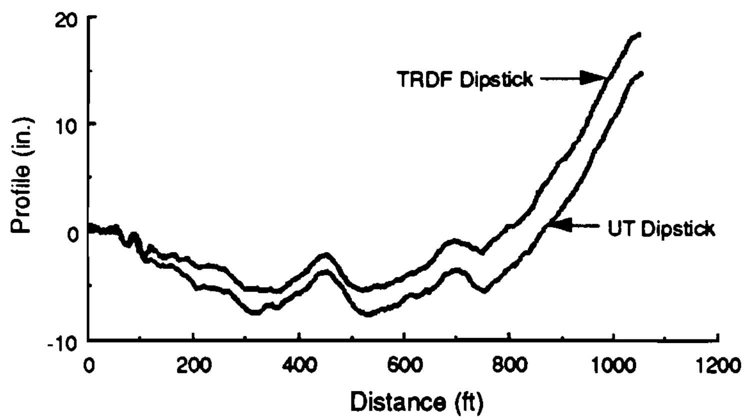

Fig 13. Dipstick comparison of inside wheel path at ATS 1.

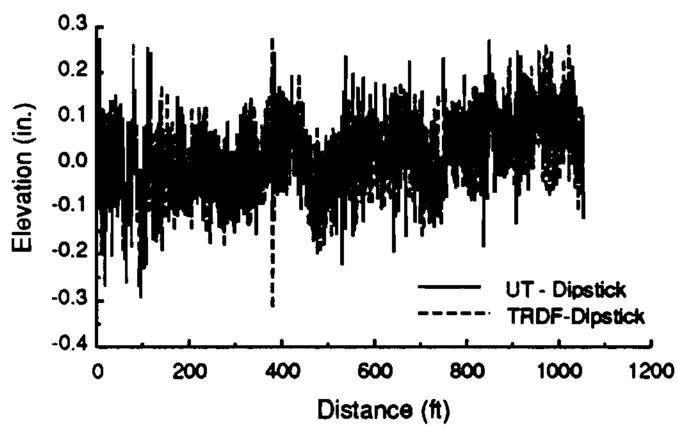

Fig 14. Dipstick elevation comparison at ATS1.

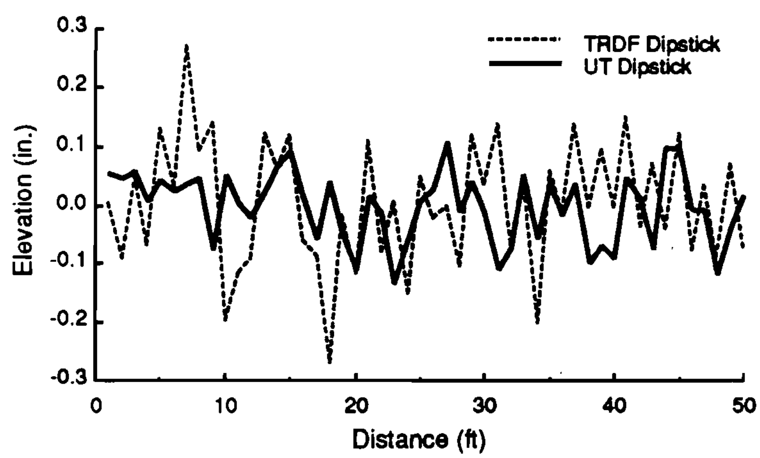

Fig 15. First 50 feet of ATS1 from Fig 14.

the movement and the display blanked. The problem occurs if the operator fails to see that the instrument did not take a reading and continues on to the next reading. This situation would be the same as taking a false reading in that the sign of all subsequent readings would be reversed, yielding a slope in the opposite direction. The distance at the end of the run would be longer by the number of no-reads during that run. Figure 13 shows an occurrence of a missed reading in which the operator noticed the situation, but while lifting the front foot from the pavement surface, lost the Dipstick's reference elevation. At an approximate distance of 100 feet into the inside wheel path of ATS1, the profiles from the two instruments diverge. This divergence is maintained throughout the remainder of the data set.

The UT instrument continued to display a greater propensity to take false readings, although the TRDF Dipstick took several false readings during four entire sets of data. The TRDF Dipstick also maintained its speed advantage over the UT instrument. The TRDF instrument was able to consistently take from 840 to 860 readings per hour. The UT Dipstick was able to approach 830 readings per hour on short runs but on the 1056 feet of the Austin test sections fell to 730 to 785 readings per hour.

The sensitivity of the instruments is of concern since the one instrument has been proven to be consistently faster, more stable, and less susceptible to false readings. To see the difference in the individual instruments, Figs 14 and 15 can be viewed. Figure 14 is the raw elevation data from the two instruments plotted on the same graph for the entire distance of the inside wheel path of ATS1. Figure 15 is the same wheel path of ATS1, but only the first 50 feet are plotted to highlight the difference in sensitivities. The TRDF Dipstick's elevations are consistently larger in both the positive and negative directions. This could be explained by the fact that it would be difficult for the two instruments to follow the exact same wheel path. However, one instrument, the TRDF Dipstick, is always taking readings of greater magnitude. This difference in sensitivity is another fact that supports the conclusion that individual instrument differences are related to their inclinometers and the associated hardware.

The PC-2's on both of the systems experienced a situation in which the computer would not respond to any key strokes. This situation, referred to as "lock up," always occurred after the PC-2's were connected to the Dipstick body and turned on. Nothing that the operator would input to the PC-2 would make it respond and the program boot. The batteries inside the PC-2 had to be removed before the computer would respond. The TRDF instrument had to be brought from the field and the acquisition program reinstalled to make it function properly. The UT Dipstick appeared to be functioning normally and a set of data was taken. The data were lost because a character in a program line had been replaced by a space during the removal and installation of the batteries. The remainder of the program seemed to be intact and no errors were reported until the operator checked the status of the data at the end of the run. The PC-2 reported an error in a line of the code and the data were nowhere to be found in the PC-2's memory.

A comparison of data plotted from the outside wheel path of ATS1 is seen in Fig 16. These plots are the UT Dipstick's representation of the wheel path taken on two different days, using the same operator. The data in run number two is suspect because the third and fifth readings were +0.88 inch. Figure 17 shows the first 100 feet of the data represented in Fig 16. There was nothing in the roadway to cause these readings. This caused the initial difference in the two profiles, and this difference is maintained throughout the run. The problem occurs when determining which data set is the correct representation of the roadway's surface.

The longer the researchers stayed at the Austin test sections to make duplicate runs for this evaluation effort, the worse the TRDF Dipstick performed. The performance deterioration started with a number of false readings and continued with no-readings being taken. One entire day's readings were useless because false readings were in every data set. The next day new batteries were put into the TRDF Dipstick, the feet were oiled, the acquisition program reinstalled, and the operator monitored the operation constantly. The result was another set of data which included false readings. Figure 18 shows a comparison of the first TRDF Dipstick readings on the outside wheel path of ATS1 with the last data set from the UT instrument. The difference at the end of the run was calculated to be 0.789 inch. The last data sets from the TRDF Dipstick were unusable and were not included in this report. The complete set of good data from both of the ATS sections is included in Appendix E.

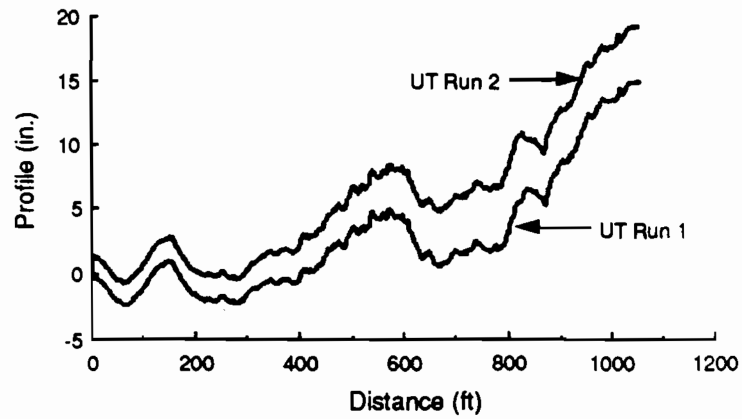

Fig 16. Comparison of two UT runs, outside wheel path at ATS4.

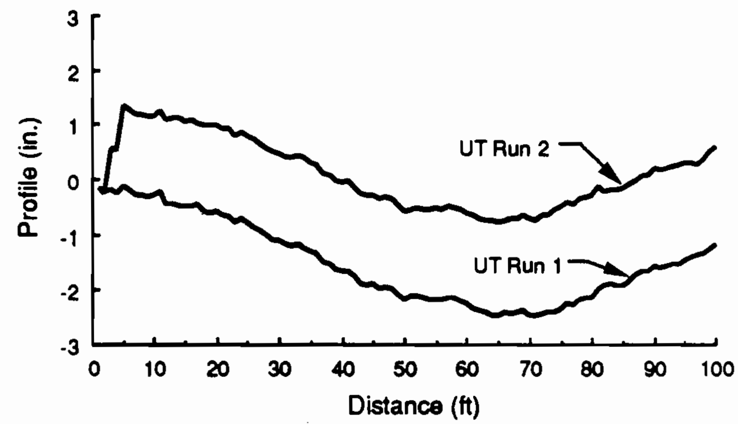

Fig 17. Comparison of first 100 feet of ATS4 outside wheel path.

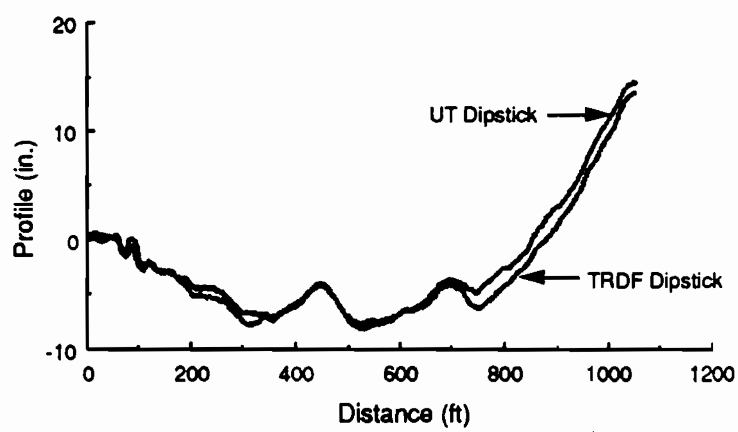

Fig 18. Comparison of two Dipsticks on outside wheel path at ATS1.

Static Testing

The UT and the TRDF Dipsticks appeared to have different operating characteristics. A static test was run on both instruments consisting of the following sequence: both instruments were turned on and their programs started. They were left in an upright attitude for approximately an hour. At the end of the hour both instruments were "walked" a known number of readings and "walked" back to their resting locations. This process was repeated hourly for six hours. The researchers were attempting to determine whether or not a false reading would occur while the Dipsticks remained motionless. No false readings were recorded during this procedure, although it was noted that the UT Dipstick had a much longer settling time than did the TRDF Dipstick. After the UT instrument was "parked" and steadied, its display would change rapidly for a few seconds as if it was searching for the correct reading. The TRDF Dipstick's display would settle rather quickly on a reading and the display would remain constant until the next movement was felt. It is believed that individual Dipstick instruments' susceptibility to false readings and the maximum speed of operation are a function of either the Dipstick's hardware or its inclinometer, or a combination of the two.

CONCLUSIONS

The Dipstick is an effective substitute for the rod and level survey but only in the manual configuration. The auto-read version of the Dipstick is capable of being operated in a manual mode by not connecting the PC-2 and recording the displayed elevation data manually. The problem of translation errors is a concern in the manual mode, but the data are correct and the translation can be checked. The primary reasons for finding a substitute for the rod and level are cost and ease of acquiring a true surface profile. The auto-read version of the Dipstick has not proven to be a reliable instrument; therefore, the operator is never 100 percent certain that the data captured is accurate.

The researchers have described the problems associated with the Dipstick to four of the Face Company representatives and have suggested changes to the auto-read version of the Dipstick. The following is a list of the suggested changes.

(1) A low battery indicator is needed, located on the Dipstick's case within easy view of the operator.

(2) The PC-2 should be raised as high on the handle as possible, to allow the operator easier access to the edit function and reading number designation.

(3) The speed choice should be eliminated because it is useless as long as individual instruments continue to exhibit different settling times and sensitivity characteristics.

(4) The Dipstick operator should have control over when a reading is taken, and this could be accomplished by using a manual trigger mounted on the Dipstick's handle.

(5) Tighter quality control of the inclinometers and interfacing hardware needs to be implemented so that individual instruments demonstrate the same sensing characteristics.

The Face Company has not yet responded with an undated auto-read version of the Dipstick for further evaluation, but has implied that at least some the recommended changes are being considered.

During the evaluation process, Radio Shack, the manufacturer of the PC-2, its RS232 interface, and the connectors used on the Dipstick, was contacted. The evaluators were attempting to raise the PC-2 computer up on the handle of the Dipstick by purchasing a set of connectors and the cabling necessary to accomplish the task. Radio Shack does not make or repair the PC-2, and the connectors are not available. Radio Shack has also ceased production of the RS232 interface, which makes it unavailable if future needs arise. This means that any and all repair work on the Dipstick and the associated hardware must be handled by the Face Company. The parts for necessary repairs to the Radio Shack products are no longer available as far as the researchers could ascertain.

The Face Company has tried to respond to the concerns as presented in this report, and they have addressed some of the issues raised in the first series of evaluations (Ref 3). The reliability problem does not appear to be software related, and the manufacturer has attempted to trap and correct erroneous data by using software. This approach, although cost-effective, does not address the issue of the individual instruments' changing response to the sensing of movement. The fact that an operator can now bend down and look at the last reading number and edit a problem does not give the instrument reliability. The test section line of measurement must be marked with precision and timely distance intervals made clearly visible before the operator can have a chance to acquire a good set of data. The other situation which lends itself to acquiring good data sets using the auto-read mode is the process of having two Dipsticks reading adjacent and parallel wheel paths at the same time and in the same direction of travel. This allows the operator of one instrument to check the orientation and reading number against the other instrument. It does not guarantee that the proper elevation will be captured and makes the Dipstick twice as costly to purchase and operate.

This research effort has been conducted in an extremely careful way to make certain that the two Dipsticks evaluated had every opportunity to perform in exactly the same way under the same conditions. Wheel paths were laid out and marked, distance intervals were marked, and the instruments were operated on the same days. One Dipstick was faster than the other, and until the last two days of data collection one instrument was more prone to false and no-readings than the other instrument. The Dipstick's hardware and the associated RS232 interface cause reading errors in the auto-read mode of operation. These are the primary reasons why the auto-read version of the Dipstick, in its present configuration, should not be considered a Class I profiling instrument. It has been learned through experience with the two Dipsticks that the operators can never be 100 percent positive that the data captured using the auto-read version of the Dipstick is correct unless there is a rod and level survey as a comparison. This fact makes the cost of the auto-read version of the Dipstick prohibitive, especially since the original consideration was to find a cost-effective substitute for a rod and level survey.

RECOMMENDATIONS

It is recommended that the issues raised in this evaluation be considered and responded to by the Face Construction Technologies Company before any additional Dipsticks are purchased. If the indicated hardware and interface changes are made, the manufacturer should demonstrate the reliability and repeatability of the modifications over a surface that has had a rod and level survey and has a known profile. Multiple passes over several days with the modified Dipstick would be expected to yield results within the acceptable precision boundaries for a Class I profiling device.

The Dipstick purchased for this evaluation can be a useful tool as long as it is used in the manual-read mode. This is because the manual-read version of the Dipstick is totally independent of software and interface hardware. Its operation depends on the operator's ability to accurately read and transcribe the elevation number displayed on the Dipstick's display windows. The operator has the opportunity to wait until the Dipstick is at rest and the display settles before taking a reading. A standard procedure can be established for the acquiring and transcribing of the data to speed the operation and help eliminate manual-read transcription errors. CTR and TRDF staff are in the process of evaluating and formulating recommended procedures for the manual-read operation of the Dipstick. The results and recommendations of the manual-read Dipstick evaluation will be reported at a later date.

A positive performance evaluation of the manual-read version of the Dipstick could make this version a useful profiling instrument. Some of the possible applications would include using the Dipstick as a Class I profiling device for the calibration of high-speed pavement roughness instrumentation. The evaluation of rutted pavement sections could be accomplished by taking transverse pavement profiles. The manual-read Dipstick could also be useful for evaluating certain pavement construction locations such as bridge decks for final contractor pavement, or for monitoring end-roughness specifications for new pavement construction.

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APPENDIX A. LIST OF EQUIPMENT DELIVERED TO THE TEXAS SDHPT

DIPSTICK EQUIPMENT

1. Auto-read Dipstick sensor unit w/batteries.
2. Two (2) dipstick adjusting pins (installed).
3. Two (2) swivel footpads w/ rubber.
4. Two (2) swivel footpads w/o rubber
5. Two (2) spilked feet.
6. 7/16 inch wrench.
7. Allen wrench (1/8 inch).
8. Dipstick handle, 3 sections.
9. Computer clamp.
10. Calibration shim (0.125 inch/3.2mm).
11. Cassette recorder w/batteries.
12. AC/DC converter 120/6v, 60 hz.
13. One (1) cassette tape.
14. Pocket computer, PC-2 with batteries.
15. AC/DC converter 120/60hz.
16. Interface cable.
17. Two (2) rolls paper for printer.
18. Black pens.
19. Color pens.
20. Printer interface for PC-2.
21. Four (4) AA batteries.
22. Six (6) 9 volt transistor batteries.
23. RS 232 serial port.
24. RS 232 connector cable.
25. Null modem.
26. Gender changer.
27. Modem, Migent.
28. Charger for modem.
29. Measuring tape (ft/m).
30. Marking crayon.
31. Aluminum carrying case.
32. Tandy DMP 106 printer w/6 foot cable.
33. Dipstick operators manual.
34. Pocket computer manual.
35. Pocket computer quick reference guide.
36. Printer/cassette interface manual.
37. Instruction manual for serial port.
38. Owner's manual for cassette.
39. Dipstick software on floppy disk (3.25 and 5.5).
40. Dipstick quickguide.
41. Operators manual for DPM106 printer.

ZENITH LAPTOP EQUIPMENT

1. Zenith laptop computer w/coprocessor and interml modem.
2. Two (2) Battery pack for laptop.
3. AC/DC converter 120/60 hz
4. Cigarette lighter adapter.
5. User guide for modem.
6. Software guide for modem.
7. User guide and command reference manual for laptop.
8. User reference guide for laptop.
9. Manual for CPS: computerized phone system.
10. Laptop software: MS-DOS v3.3, disk 1 and 2.
11. CPS software.
12. Carrying case.
13. User's manual 1200 baud modem.

APPENDIX B. DIPSTICK OPERATOR'S MANUAL AND SPECIAL NOTES FOR FIELD USE OF THE ZENITH LAPTOP COMPUTER

The following three sections in Appendix B represent edits to the Dipstick Operator's Manual and special notes for field use of the Zenith Laptop Computer.

APPENDIX B.1. DATA TRANSFER FROM PC-2 TO THE IBM COMPATIBLE COMPUTER

1. Insert the Dipstick program disk into drive A of the Zenith.
2. Type [AUTOEXEC], then press the Return key.
3. The Dipstick program will load and ask the user for the date, enter the (mm/dd/yy), then press the return key.
4. The screen will display the following information:
   Select program activity:
   (F)ile work
   (A)uxiliary routines
   (C)ommunications
5. Select (C) and the screen will display the following:
   Select communications activity:
   (L)oad data files from PC-2
   (R)eprogram PC-2 from disk
6. Select (L) and the screen will display the following:
   Data disk in drive (A, B, or C)
7. Select the correct disk drive and the screen will display the following:
   Set-up instructions for PC-2 to IBM File Transfer:
   Turn PC-2 off
   Plug RS-232 interface into back of printer
   Connect RS-232 interface to IBM-PC comm 1 serial port using male to female DB-25 cable and NULL MODEM
   Connect charger to RS-232 interface
   Turn RS-232 on
8. Turn the PC-2 on, press (I) for I/O, and the screen will display:
   Tape Modem RS232
9. Press (R) for RS-232 and the screen will display:
   Input files to send,
   1: file#=?
   x=Exit
10. Enter files numbers to transfer and the screen will display:
    Batch has all used files
    Press (ENTER) when ready
11. The IBM compatible computer screen will display:
    Waiting to receive file data from PC-2
12. Press **(ENTER)** on the PC-2 and the screen will display:
    Sending file #?
13. The IBM compatible computer screen will display:
    Receiving file XXXX
14. When transfer is complete the IBM will return to the main menu and the user should press the (ON) key twice on the PC-2.
15. If no other files need to be transfered turn off both systems, disconnect the units, and return to their proper storage.

APPENDIX B.2. FILE EDIT ROUTINE FOR THE DIPSTICK'S PC-2 COMPUTER

1. If an error is suspected while the Dipstick is in operation
   (a) write down the reading number displayed on the PC-2 screen,
   (b) do not move the dipstick from its position.
2. Press the (ON) and (**F6**) buttons on the PC-2 to stop the current readings.
3. The main menu should appear on the PC-2 screen, enter (E) for edit.
4. The screen will display "**File # to be open?**". Enter the file number which has the false data, and then press the Enter key.
5. The screen will display "**Run #?**". Enter the name of the run previously specified, and then press the Enter key.
6. The screen will display "**Date**". Enter the date and then press the enter key.
7. The screen will display"**Spec. FF# ?**". Enter the FF# previously specified and press the enter key.
8. The screen will display "**Spec. IRI ?**". Enter the IRI number previously specified and press the enter key.
9. The screen will display "**Elev tol ?**". Press the enter key for (N/A) unless a elevation total was previously specified.
10. The screen will display "**Des slope ?**" Press the enter key for (N/A) unless a design slope was previously specified.
11. The screen will display "**Oper bias ?**" Press the enter key for (N/A) unless an operator bias was previously specified.
12. The screen will display "**Pt 0 elev ?**" Press the enter key for (N/A) unless a zero point elevation was previously specified.
13. The screen will display "**Auto append file ?**" Enter (Y) yes and enter if you want to continue and edit the file.
14. The screen will display "**Resume read at reading #?**" Enter reading recorded from step one and press the enter key.
15. The screen will display "**Select survey speed ?**" and then "**700, 800, 900**" Enter (9) for 900 readings/hr and then press the enter key.
16. The screen will display "**Start at reading#XXX with battery end forward**". or "**Start at reading #XXX with switch end forward**" depending on if the reading number is even or odd.
17. Move the Dipstick into the correct position by walking it backward and orienting the body with correct end forward. Press the enter key to resume the readings.

APPENDIX B.3. BATTERY OPERATION OF THE ZENITH LAPTOP COMPUTER

The following information should be used to provide the most efficient use of the Zenith Laptop Computer in the field. If the computer is used in the battery mode for an extended period of time the peripherals and the coprocessor will consume the battery very quickly.

1. The following steps should be taken to save the charge on the battery when extended field use is required :
   (a) Disconnect all unnecessary peripherals and accessories.
   (b) Make sure the modem is turned off (modem is normally off).
   (c) Keep disk drive use to a minimum.
   (d) Keep display backlight set to lowest level possible.
   (e) Do not use the math coprocessor by either removing it from the mother board or limiting the amount of calculations performed until a 110 AC line is available.
2. To operate the processor at the slower (4.77MHz) speed set the configuration switch number 3 to the on position (the configuration switches are located under the pop-out plate on bottom of computer body).
3. To set length of time the backlight remains on after a key is pressed use the DOS MODE command. To set the new mode enter (**MODE ELn**) were **n** is the desired number of seconds for the backlight to remain on after the last key stroke.

APPENDIX C. DIPSTICK RDDATA PROGRAM LISTING

```
10 ARUN :LOCK :RADIAN :WAIT 150:BEEP 9:PRINT " RDDATA-I  (Version 1.43)"
12 PRINT "(C) 1988 Face Technologies"
13 REM      by  Allen Face  (12/1/88) - PC2 must be fitted w/ 16K RAM chip !!
20 GOSUB 900:PRINT " New   Edit   I/O   Files":GOSUB 970:IF X$="F"THEN 70
21 IF X$="N"GOSUB 400:GOSUB 195:GOTO 100
22 IF X$="E"GOSUB 475:X=1:GOSUB 400:GOTO 60
23 IF X$="I"THEN 40
26 GOTO 20
40 CLS :PRINT " Tape   Modem   RS232   X":GOSUB 970:IF X$="X"THEN 20
41 IF X$="M"THEN 560
42 GOSUB 440:CLS :W$="send":IF X$="T"THEN 46
43 GOSUB 475:GOSUB 680
44 IF X$="R"THEN 580
45 GOTO 40
46 PRINT "   From  or  To  tape ?":GOSUB 975:IF Z$="F"GOSUB 599:GOTO 48
47 IF Z$<>"T"THEN 46
48 GOSUB 590:IF Z$="F"THEN 500
49 GOSUB 475:GOTO 550
60 CLS :PRINT "Auto-append file ?  (Y/N)":GOSUB 975:IF Z$="N"THEN 20
61 IF Z$<>"Y"THEN 60
62 CLS :INPUT "Resume run @ rdg # ? ";N:IF N>LLET R=27:GOSUB 999:GOTO 62
63 GOSUB 195:N=N-1:X=N:W$="BATTERY":IF INT (N/2)=N/2 LET W$="SWITCH"
64 CLS :BEEP 9:WAIT 250:PRINT USING "";" Start @ Reading # ";N+1
65 PRINT " w/ ";W$;" end forward !!":CLS :WAIT 0:GOTO 100
70 CLS :PRINT "  Status   Allocate   X":GOSUB 970:IF X$="X"THEN 20
72 IF X$="S"GOSUB 430
76 IF X$="A"WAIT 99:GOSUB 420:GOTO 20
78 GOTO 70
90 WAIT 0:PRINT "Want to continue ?  (Y/N)":GOSUB 890:IF W$="N"THEN 20
91 IF W$="Y"RETURN
92 GOTO 90
100 GOSUB 190:A=F+64+2*X:B=0:C=1:D=8192:POKE# 3,182:POKE# 8195,182:RESTORE 199
110 FOR I=0 TO 9:READ J:POKE J,I:NEXT I
120 POKE# 3,15:FOR I=1 TO R:NEXT I:Y=9999
121 GOSUB 130:IF ABS (Z-Y)<2 THEN 140
122 Y=Z:GOTO 121
130 W=PEEK# 8193:IF W<128 FOR I=1 TO 8:NEXT I:GOTO 130
131 V=-1:IF W<192 LET V=1
132 Z=1000*(WAND 1):FOR I=2 TO 4
133 W=PEEK# @(I)-175:IF W<1 THEN 133
134 Z=Z+10^(I-2)*PEEK W
135 NEXT I:Z=V*Z:RETURN
140 A=A+2:N=N+1:IF INT (N/2)=N/2 LET Z=-Z
141 GOSUB 480:BEEP 1:POKE# 3,14:PRINT USING "";"#";N;:CURSOR 6:PRINT ": <ON> , <
F6> = exit"
142 IF N=PBEEP 99:GOSUB 299:GOTO 280
143 GOSUB 130:IF ABS (Z-Y)<99 THEN 143
144 GOTO 120
```

```
190 FOR I=0 TO 2:RESTORE 910:FOR J=66 TO 92:READ Z:IF J=66 LET Z=Z+8*I
191 POKE J+7*I,Z:NEXT J:NEXT I
192 PRINT "Press <ENTER> to start ...":GOSUB 975:IF ASC Z$<>13 THEN 192
193 CLS :RETURN
195 CLS :PAUSE "  Select survey speed :"
196 R=180:PRINT " 5oo/hr   7oo/hr   9co/hr":GOSUB 975:IF Z$="9"LET R=60
197 IF Z$="5"LET R=300
198 CLS :RETURN
199 DATA 79,1,62,74,4,44,48,65,80,76
280 IF N<3 CLS :BEEP 9:PAUSE " Minimum file  =  3 rdgs !":GOTO 20
281 Z=N:A=F+64:GOSUB 480:IF X$="N"POKE 185,PEEK 185+1
282 GOTO 20
299 CLS :PAUSE USING "";"Max filelength = ";P;" rdgs":RETURN
400 CLS :GOSUB 440:INPUT "   File # to open : ";I
401 IF I<1 OR I>OLET R=1:GOSUB 999:GOTO 20
402 GOSUB 450:IF X=0 AND L>0 BEEP 5:PAUSE " File";M;" is not empty !":GOSUB 90:P
OKE 185,PEEK 185-1
403 IF X=1 AND L=0 LET R=2:GOSUB 999:GOTO 20
404 IF X=0 FOR I=1 TO 8:@$(I)="":NEXT I:POKE F+64,0,0
410 A=F:RESTORE 920:FOR I=1 TO 8:READ Y$:Z$="":R=I+15:Y=0
411 IF X=1 OR Y=1 LET J$=@$(I):Y$=Y$+":"
412 CLS :PRINT Y$;@$(I);" ? ";:INPUT "";Z$:IF LEN Z$>8 LET R=3:GOSUB 999:GOTO 41
2
413 GOSUB 460:@$(I)=U$:B=0:C=0:D=0:IF X=1 AND LEN Z$=0 LET @$(I)=J$:GOTO 419
414 Z=VAL Z$:IF LEN Z$=0 LET @$(I)="     N/A":IF I>4 THEN 419
415 IF X=0 AND LEN Z$=0 AND (I=1 OR I=3 OR I=4)LET R=8:GOSUB 999:@$(I)="":GOTO 4
12
416 IF I=1 GOSUB 490:IF A$=""THEN 412
417 IF (I=3 AND Z<13)OR (I=4 AND Z<50)OR (I=8 AND ABS Z>99)GOSUB 999:@$(I)="":GO
TO 412
418 IF Y=0 AND ((I=5 AND Z<.25)OR (I=6 AND ABS Z>.5)OR (I=7 AND Z>.01))GOSUB 980
:Y=1:GOTO 411
419 Y=0:GOSUB 485:NEXT I:RETURN
420 CLS :BEEP 5:PRINT " Reallocating memory will":PRINT "    erase all files !!"
:GOSUB 90
421 CLS :B=0:C=0:D=0:INPUT "Name of <DIR> = ";Z$:IF LEN Z$>8 LET R=3:GOSUB 999:G
OTO 421
422 IF LEN Z$=0 LET R=8:GOSUB 999:GOTO 421
423 A$=Z$:GOSUB 490:IF A$=""THEN 421
424 GOSUB 460:A$=U$:A=186:I=1:GOSUB 485:CLS
425 R=18432-STATUS 2:CLS :CURSOR 22:PRINT "rdgs";:CURSOR 0:PRINT "File capacity
= ";:INPUT "";Z
426 IF Z<20 OR Z>(R-66)/2 OR Z>1320 LET R=4:GOSUB 999:GOTO 423
427 A=195:GOSUB 481:P=Z:J=66+2*Z:Z=INT (R/J):O=Z:POKE 194,Z
428 POKE 180,1:POKE 185,0:Z=0:FOR I=1 TO O:A=18496-J*I:GOSUB 481:NEXT I
430 CLS :GOSUB 440:WAIT 150:PRINT "  Current memory status:":PRINT "<DIR> name i
s : ";V$
431 PRINT USING "";O;" files , ";P;" rdgs/file":A=18496-O*(66+2*P):I=1
```

```
435 PRINT " 1st empty file # = ";I:WAIT 0:RETURN
440 V$="":FOR J=0 TO 7:V$=V$+CHR$ PEEK (186+J):NEXT J:O=PEEK 194:A=195:GOSUB 470
:P=Z:RETURN
450 F=18432-(O+1-I)*(66+2*P):A=F+64:GOSUB 470:L=Z:M=I:FOR J=1 TO 8
451 @$(J)="":FOR K=0 TO 7:@$(J)=@$(J)+CHR$ PEEK (F+8*J+K-8):NEXT K:NEXT J:RETURN

460 U$="        ":U$=LEFT$ (U$,8-LEN Z$)+Z$:RETURN
470 Z=256*PEEK A+PEEK (A+1):IF Z>32767 LET Z=32767-Z
471 RETURN
475 IF PEEK 185=0 LET R=16:GOSUB 999:GOTO 20
476 RETURN
480 IF Z<0 LET Z=32767-Z
481 POKE A,INT (Z/256),Z-256*INT (Z/256):RETURN
485 FOR J=1 TO 8:POKE (A+J+8*I-9),ASC MID$ (@$(I),J,1):NEXT J:RETURN
490 C=C+1:IF C>LEN A$THEN 495
491 A=ASC MID$ (A$,C,1):IF A<>32 LET D=1
492 IF (A>63 AND A<91)OR (A>47 AND A<58)OR (A>32 AND A<42 AND A<>34)OR (A=32 AND
 D=0)OR A=45 THEN 490
493 R=21:GOSUB 999:A$="":GOTO 499
495 B=B+1:I$="":IF B>OTHEN 499
496 A=18496-B*(66+2*P):GOSUB 470:IF Z=0 OR A=F+64 THEN 495
497 FOR C=0 TO 7:I$=I$+CHR$ PEEK (A-64+C):NEXT C:IF I$=A$LET R=20:GOSUB 999:A$="
":GOTO 499
498 GOTO 495
499 A=F:RETURN
500 CLS :FOR I=162 TO 178:POKE I,PEEK (I+18):NEXT I
502 PRINT "  Searching tape ....":CLOAD M
504 IF PEEK 184=143 THEN 508
506 R=15:BEEP 5:GOSUB 999:FOR I=180 TO 196:POKE I,PEEK (I-18):NEXT I:GOTO 20
508 CLOAD M:GOTO 20
550 CLS :INPUT "  Counter = ";Y$:CSIZE 2:COLOR 3:LF 2:LPRINT "CSave :":LPRINT V$
;" @ ";Y$:LF 3
552 CLS :PRINT "  Saving <DIR>: ";V$:CSAVE MV$;180,196:CSAVE MV$;STATUS 3,18431:
BEEP 9:GOTO 20
560 CLS :BEEP 5:WAIT 99:PRINT "  Modem not supported by":PRINT " this version of
 RDDATA-I":GOTO 20
580 SETCOM 300:SETDEV PO:OUTSTAT 0:CLS :BEEP 5:PAUSE " RS-232 output mode ....":
GOSUB 590
581 Q=PEEK 181:PRINT #-8,V$:PRINT #-8,Q
585 FOR X=111 TO 110+Q:I=PEEK X
586 GOSUB 450:GOSUB 595
587 FOR Y=1 TO 8:PRINT #-8,@$(Y):NEXT Y:PRINT #-8,L
588 FOR Y=1 TO L:A=F+64+2*Y:GOSUB 470:PRINT #-8,Z:NEXT Y
589 CLS :CURSOR 8:PRINT "Holding ...":NEXT X:SETDEV :GOTO 20
```

```
590 CLS :PRINT "Press <ENTER> when ready..":GOSUB 890:RETURN
595 CLS :PRINT "Sending file #":I:" ...":RETURN
599 CLS :BEEP 5:WAIT 99:PRINT " Downloading will erase":PRINT "  all files in me
mory !!":GOSUB 90:RETURN
680 CLS :PAUSE "  Input file #s to ";W$;":":J=110
681 IF J=160 BEEP 5:PAUSE "  Batch limit = 50 files":RETURN
682 CLS :CURSOR 20:PRINT "X=Exit";:CURSOR 0:PRINT USING "";J-109;": ";:INPUT "Fi
le # = ? ";Z$:IF Z$="X"RETURN
683 I=VAL Z$:IF I=0 AND PEEK 181=0 LET I=1:X=1:GOTO 686
684 IF I=0 LET R=10:GOSUB 999:GOTO 682
685 IF I<0 OR I>PEEK 194 LET R=11:GOSUB 999:GOTO 682
686 A=18496-(O+1-I)*(66+2*P):GOSUB 470:IF Z=0 AND X=1 LET I=I+1:GOTO 686
687 IF Z=0 LET R=2:GOSUB 999:GOTO 682
688 J=J+1:POKE J,I:POKE 181,PEEK 181+1:IF PEEK 181=PEEK 185 CLS :PAUSE " Batch h
as all used files":RETURN
689 IF X=0 THEN 681
690 I=I+1:GOTO 686
890 W$=INKEY$ :IF W$=""THEN 890
891 RETURN
900 WAIT 0:CLS :CLEAR :Z=STATUS 2:A=30873:GOSUB 480:POKE 181,0,0
902 IF PEEK 184=143 THEN 906
904 CLS :PRINT " WAIT for memory purge ..."
905 FOR I=STATUS 2 TO 18431:POKE I,0:NEXT I:POKE 180,0:POKE 184,143
906 IF PEEK 180=1 THEN 909
908 FOR I=1 TO 5:BEEP 2:PAUSE " Files must be allocated !":CLS :NEXT I:GOSUB 421
909 RETURN
910 DATA 6,241,146,50,56,48,64
920 DATA "Run #","Date ","Spec FF#","Spec IRI"
922 DATA "Elev tol","Dsgn slp","Op. bias","Pt 0 elv"
970 X$=INKEY$ :IF X$=""THEN 970
971 RETURN
975 Z$=INKEY$ :IF Z$=""THEN 975
976 RETURN
980 BEEP 5:CLS :PAUSE "   Confirm this value:":RETURN
999 CLS :CURSOR 9:BEEP 5:PAUSE USING "###";"CODE";R:RETURN
```

APPENDIX D. LA GRANGE TEST SITE FIGURES

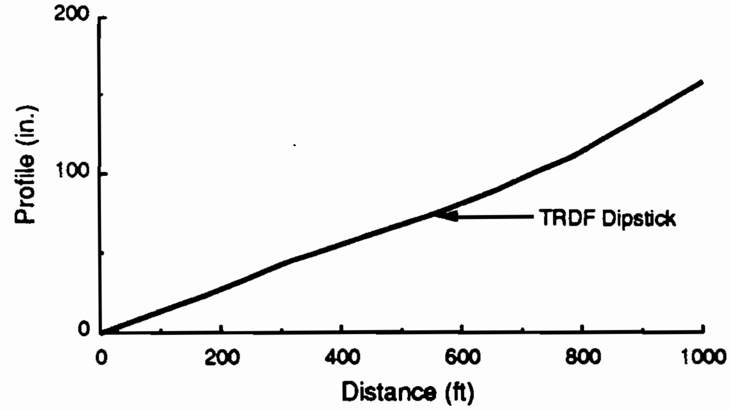

Fig D.1. Profile of eastbound, outside lane, outside wheel path.

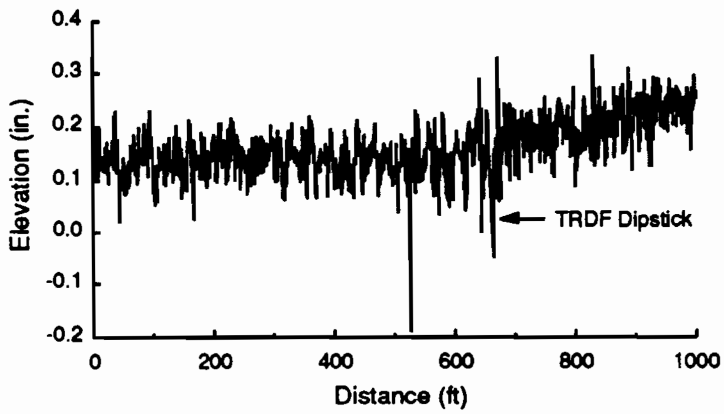

Fig D.2. Elevation of eastbound, outside lane, outside wheel path.

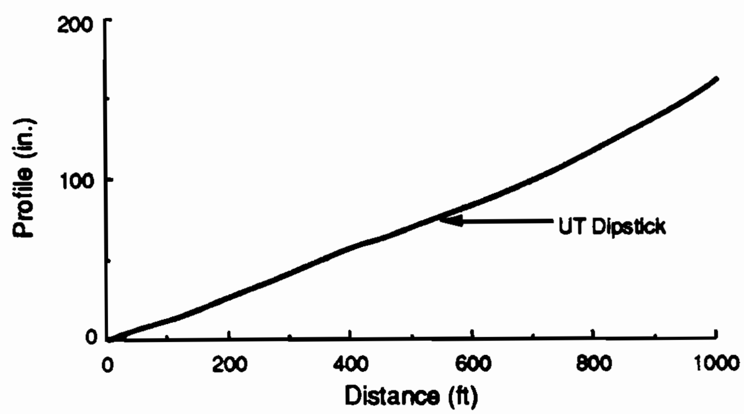

Fig D.3. Profile of eastbound, outside lane, inside wheel path.

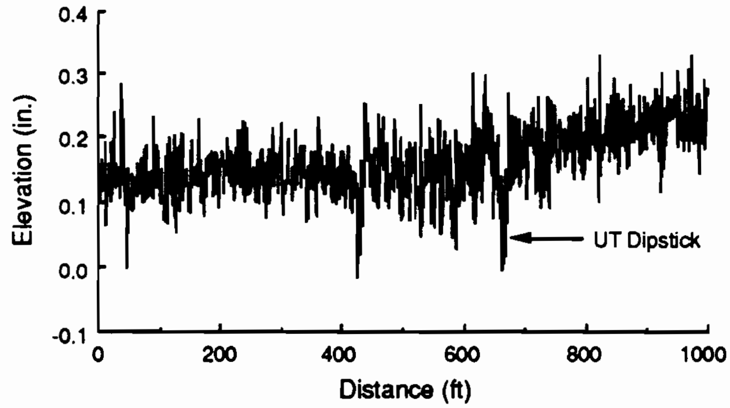

Fig D.4. Elevation of eastbound, outside lane, inside wheel path.

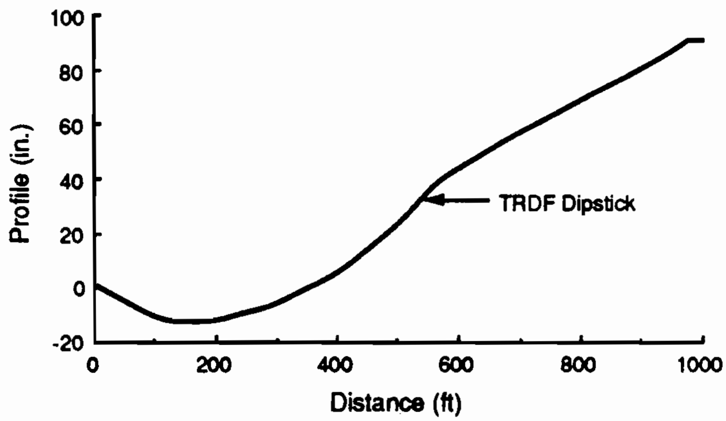

Fig D.5. Profile of westbound, outside lane, inside wheel path.

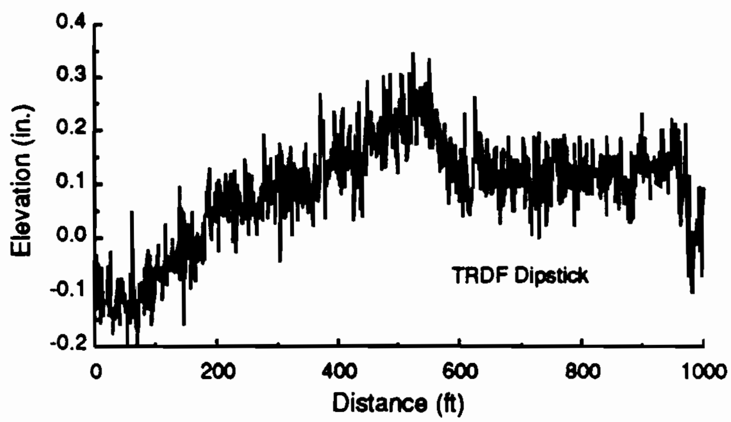

Fig D.6. Elevation of westbound, outside lane, outside wheel path.

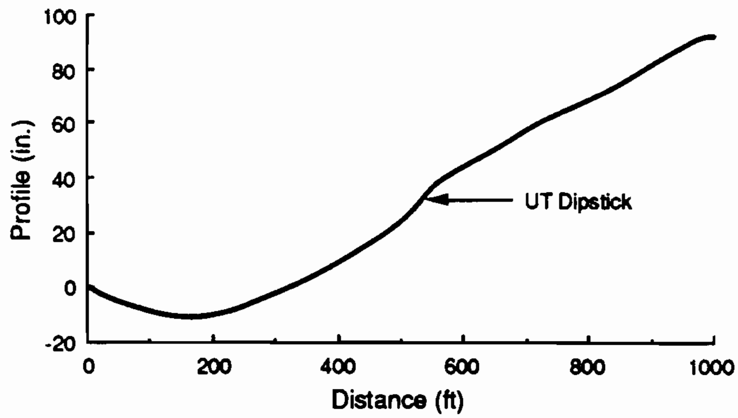

Fig D.7. Profile of westbound, outside lane, inside wheel path.

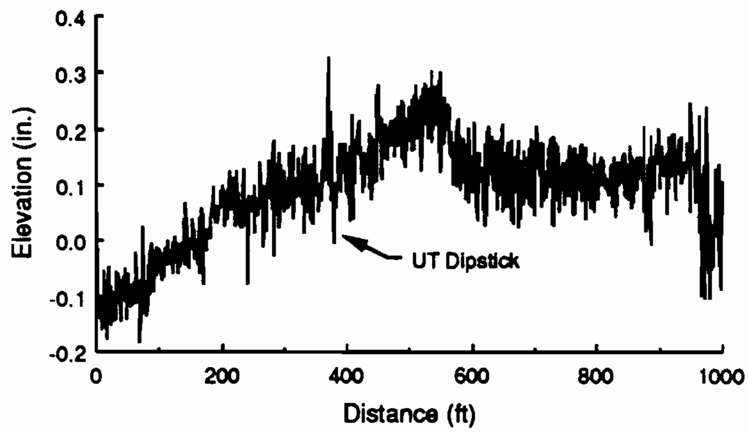

Fig D.8. Elevation of westbound, outside lane, inside wheel path.

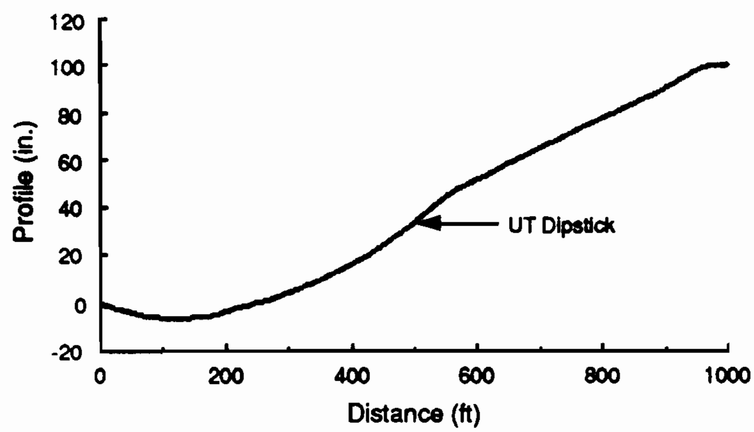

Fig D.9. Profile of westbound, inside lane, outside wheel path.

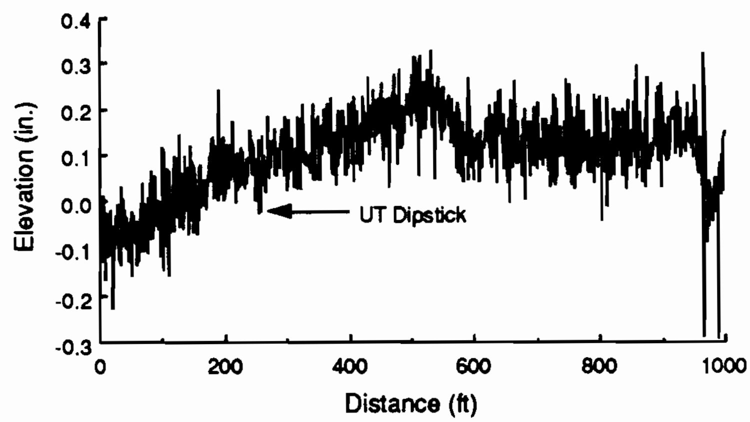

Fig D.10. Elevation of westbound, inside lane, outside wheel path.

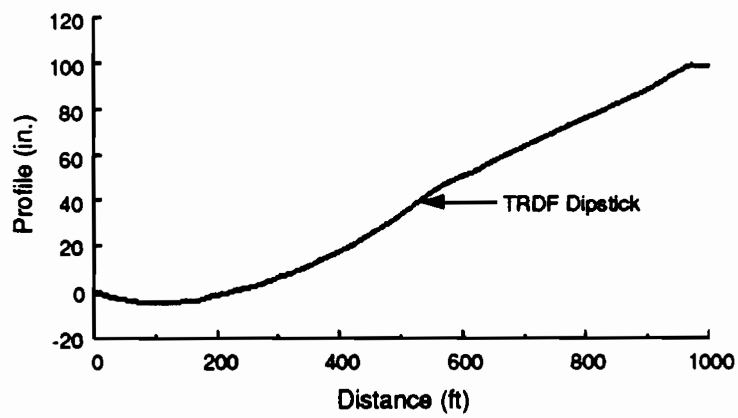

Fig D.11. Profile of westbound, inside lane, inside wheel path.

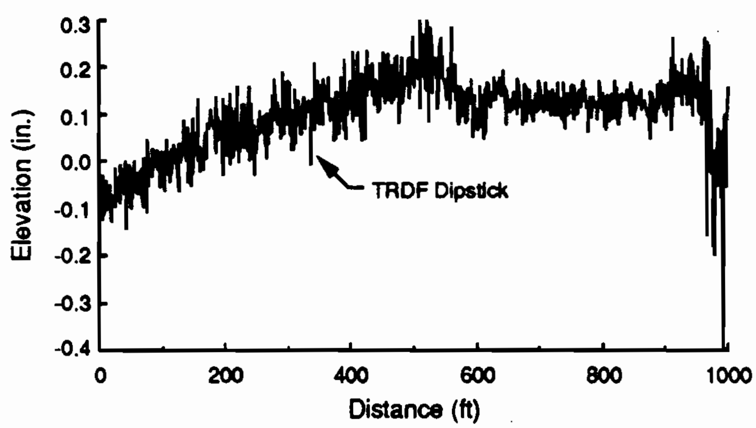

Fig D.12. Elevation of westbound, inside lane, inside wheel path.

APPENDIX E. AUSTIN TEST SITES 1 AND 4 FIGURES

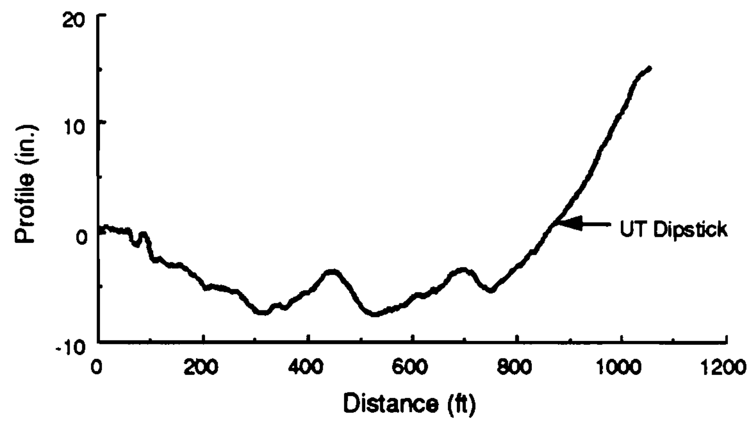

Fig E.1. Profile of ATS1, inside wheel path, run 2.

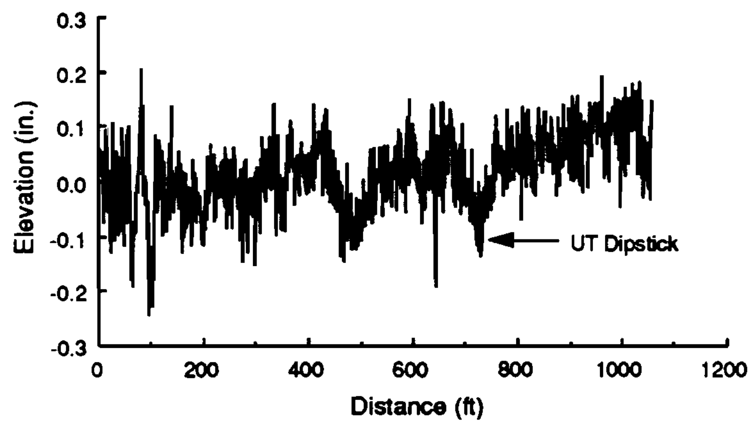

Fig E.2. Elevation of ATS1, inside wheel path, run 2.

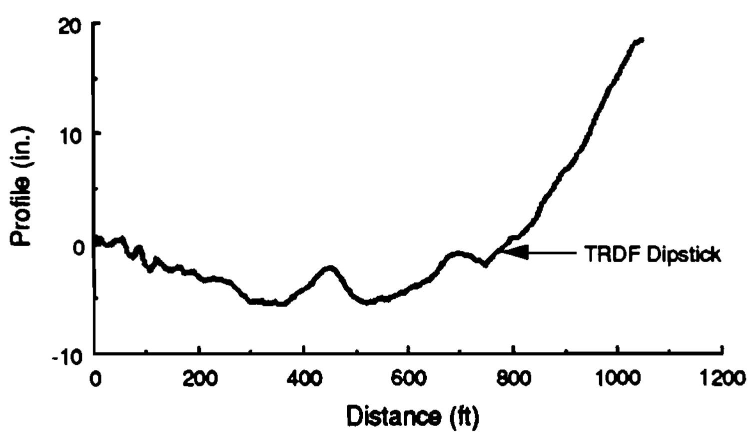

Fig E.3. Profile of ATS1, inside wheel path, run 1.

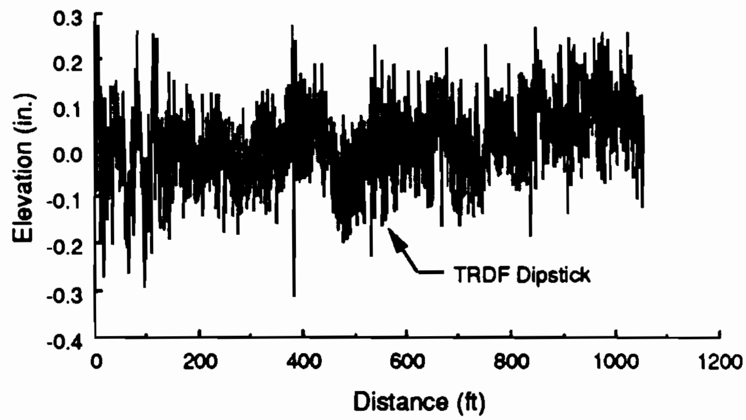

Fig E.4. Elevation of ATS1, inside wheel path, run 1.

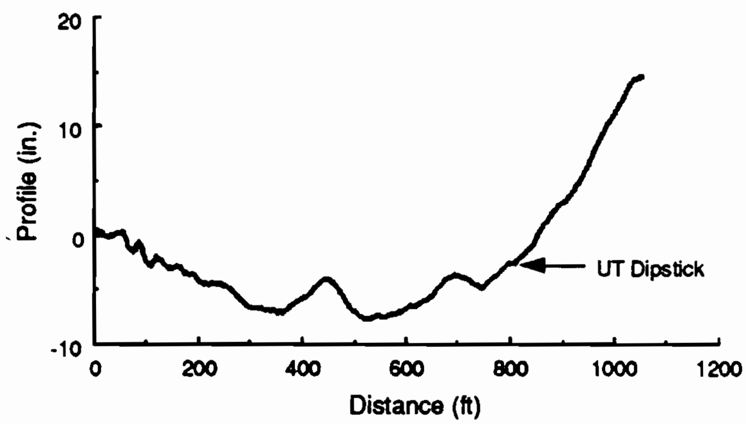

Fig E.5. Profile of ATS1, outside wheel path, run 3.

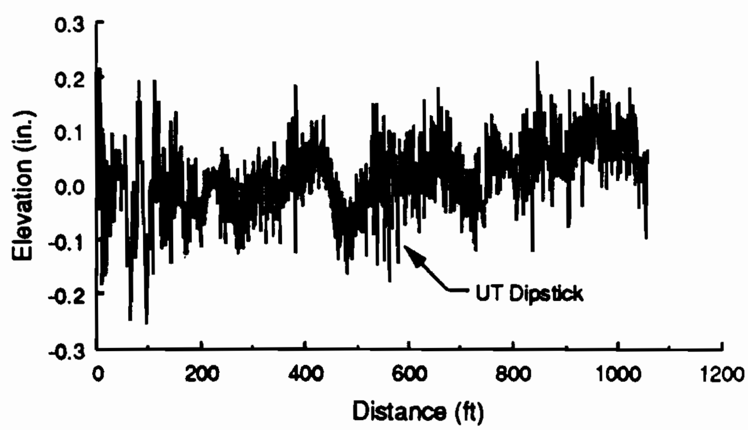

Fig E.6. Elevation of ATS1, outside wheel path, run 3.

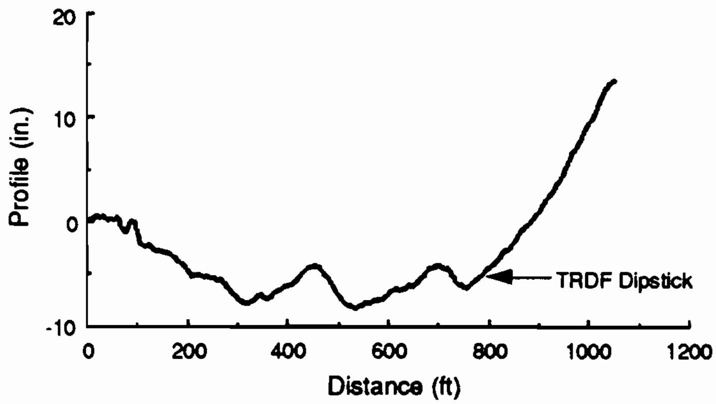

Fig E.7. Profile of ATS1, outside wheel path, run 1.

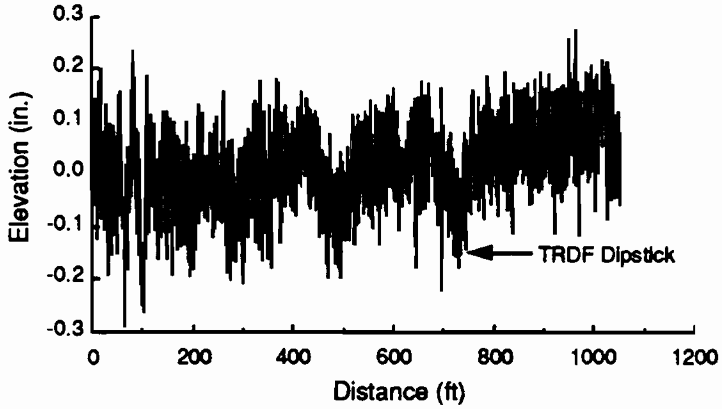

Fig E.8. Elevation of ATS1, outside wheel path, run 1.

Fig E.9. Profile of ATS4, inside wheel path, run 2.

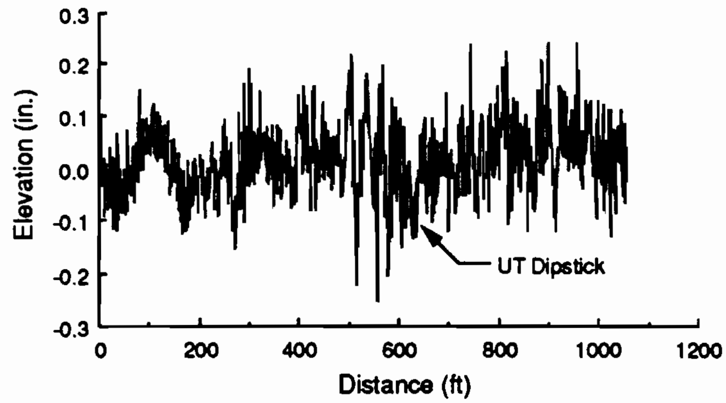

Fig E.10. Elevation of ATS4, inside wheel path, run 2.

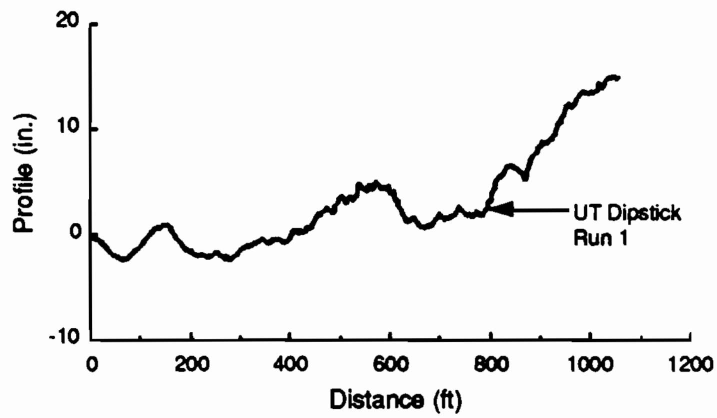

Fig E.11. Profile of ATS4, outside wheel path, run 1.

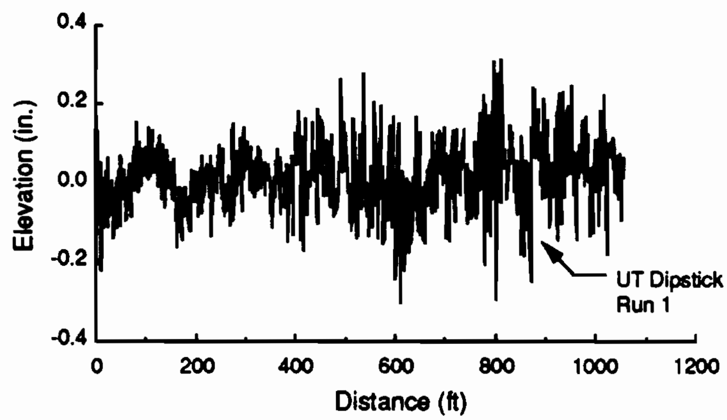

Fig E.12. Elevation of ATS4, outside wheel path, run 1.

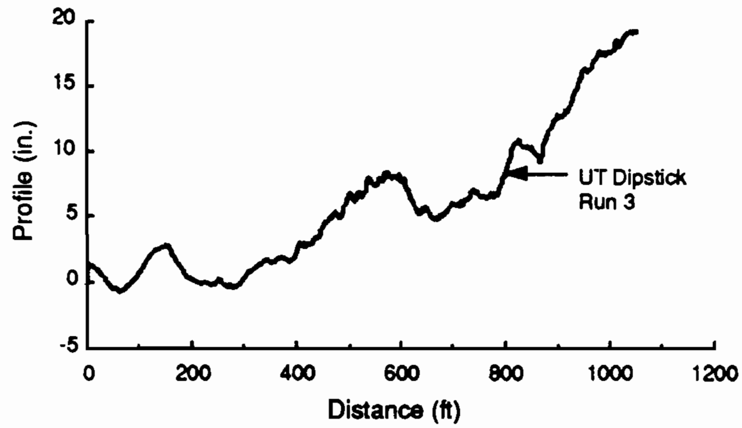

Fig E.13. Profile of ATS4, outside wheel path, run 3.

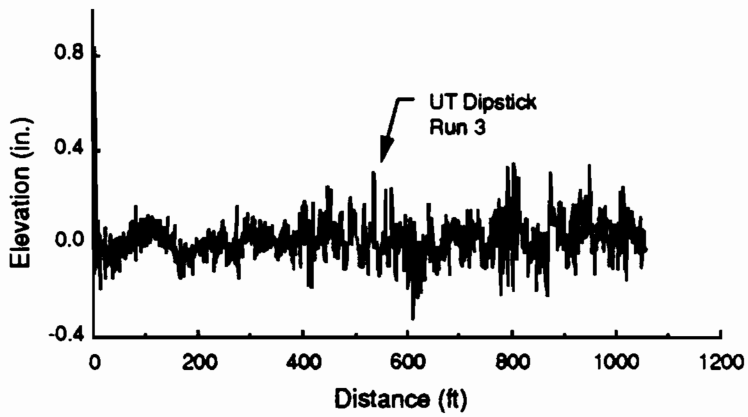

Fig E.14. Elevation of ATS4, outside wheel path, run 3.

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