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**7. Author(s)**
Carl B. Bertrand, Robert Harrison, and B. Frank McCullough

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**16. Abstract**

The Federal Highway Administration has produced a Highway Performance Monitoring System Field Manual as a guide to the individual states. The Field Manual contains an Appendix J which describes and specifies the proper calibration and reporting procedures for pavement roughness measurements. The Texas State Department of Highways and Public Transportation's Maintenance and Operations Division, Pavement Management Section, were responsible for compliance with the Appendix J mandate by the State of Texas. The Center for Transportation Research (CTR) was contracted with to make certain Texas was in compliance with the FHWA's Appendix J procedures. This report details the procedures used for the selection of the nine specified calibration sites and how these sites were marked and laid out and includes details of how the Class I instrument's surface profile and the resulting IRI statistics were determined. The roughness monitoring instruments used in Texas and their outputs are described. Regression plots by wheel path for both first and second degree fits are presented for each pavement roughness monitoring instrument. A set of conclusions based on CTR's experiences and the resulting concerns over some of the procedures outlined in Appendix J are presented. Finally, recommendations and topics for possible future research are presented. These recommendations and topics are based on the findings of this evaluation effort and attempt to address areas in Appendix J where more specific instructions are needed to truly standardize the national pavement roughness calibration procedures and the resulting roughness statistics.

**17. Key Words**
International Roughness Index, Serviceability Index, Root Mean Square of Vertical Acceleration, Dipstick, modified K. J. Law Profilometer, Maysmeter, Walker SIometer

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# EVALUATION OF FHWA REQUIREMENTS FOR THE CALIBRATION OF PAVEMENT ROUGHNESS INSTRUMENTATION

by

Carl B. Bertrand
Robert Harrison
B. Frank McCullough

**Research Report Number 969-2F**

Research Project 3-18-88/9-969

Evaluation of FHWA Requirements for the Collection of Pavement Roughness Data

conducted for

**Texas State Department of Highways and Public Transportation**

by the

**CENTER FOR TRANSPORTATION RESEARCH**

Bureau of Engineering Research
THE UNIVERSITY OF TEXAS AT AUSTIN

February 1990

The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily represent the official views or policies of the Texas State Department of Highways and Public Transportation. This report does not constitute a standard, specification, or regulation.

There was no invention or discovery conceived or first actuallly reduced to practice in the course of or under this contract, including any art, method, process, machine, manufacture, design or composition of matter, or any new and useful improvement thereof, or any variety of plant which is or may be patentable under the patent laws of the United States of America or any foreign country.

# PREFACE

This is the second report presenting the results of Research Project 3-18-88/89-969, "Evaluation of FHWA Requirements for the Calibration of Pavement Roughness Data." This project was initiated to make certain that the State of Texas was in compliance with the FHWA's Highway Performance Monitoring System (HPMS) Field Manual Appendix J mandate. The Texas State Department of Highways and Public Transportation (SDHPT) Maintenance and Operations Division, Pavement Management Section, was responsible for Texas compliance, and the Center for Transportation Research (CTR) was contracted with to make certain that the pavement roughness calibration and reporting procedures used in Texas were in compliance with Appendix J.

Conclusions and recommendations based on CTR experience and the field results from implementing Appendix J are included in this research report. The assistance of Texas SDHPT D-18 Pavement Management Section staff and CTR staff personnel, Mr. Bill Moffeit, and Mr. Joel Tompkins are greatly appreciated.

Carl B. Bertrand
Robert Harrison
B. Frank McCullough

# LIST OF REPORTS

Research Report 969-1, "Field Evaluation 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 of 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.

Research Report 969-2F, "Evaluation of FHWA Requirements for the Collection of Pavement Roughness Data, " by Carl B. Bertrand, Robert Harrison, and B. Frank McCullough, presents the procedures followed by CTR to assure compliance of the State of Texas with the Appendix J mandate. Conclusions and recommendations based on CTR experience are presented to help standardize the roughness calibration and reporting procedures for the different types and classifications of roughness instrumentation. February 1990.

# ABSTRACT

The Federal Highway Administration has produced a Highway Performance Monitoring System Field Manual as a guide to the individual states. The Field Manual contains an Appendix J which describes and specifies the proper calibration and reporting procedures for pavement roughness measurements. The Texas State Department of Highways and Public Transportation's Maintenance and Operations Division, Pavement Management Section, was responsible for compliance with the Appendix J mandate by the State of Texas. The Center for Transportation Research (CTR) was contracted with to make certain Texas was in compliance with the FHWA's Appendix J procedures. This report details the procedures used for the selection of the nine specified calibration sites and how these sites were marked and laid out and includes details of how the Class I instrument's surface profile and the resulting IRI statistics were determined. The roughness monitoring instruments used in Texas and their outputs are described. Regression plots by wheel path for both first and second degree fits are presented for each pavement roughness monitoring instrument. A set of conclusions based on CTR's experiences and the resulting concerns over some of the procedures outlined in Appendix J are presented. Finally, recommendations and topics for possible future research are presented. These recommendations and topics are based on the findings of this evaluation effort and attempt to address areas in Appendix J where more specific instructions are needed to standardize the national pavement roughness calibration procedures and the resulting roughness statistics.

KEY WORDS: International Roughness Index, Serviceability Index, Root Mean Square of Vertical Acceleration, Walker Slope Variance, Mean Absolute Slope, texture, Dipstick, modified K.J. Law Profilometer, Walker Slometer, Maysmeter, Automatic Road Analyzer, Response-Type Road Roughness Measuring Systems.

# SUMMARY

This evaluation report describes the procedures used by the Center for Transportation Research for assuring State of Texas compliance with the FHWA Highway Performance Monitoring System (HPMS) Appendix J mandate. Calibration site selection and the process used for laying out these sites are described. The method for obtaining the required Class I profiles of these calibration sites are discussed. The Texas pavement roughness instrumentation fleet and the associated roughness statistics are described.

The resulting regression equations for each individual roughness monitoring instrument are presented. Plots representing the data points from the nine calibration sites which were used to obtain the regression equations are included. Conclusions and recommendations based on CTR's experience during the implementation of the Appendix J procedures are discussed. Future research topics which could be of further assistance in standardizing roughness calibration procedures and the way roughness is reported are described.

# IMPLEMENTATION STATEMENT

The FHWA's Highway Performance Monitoring System (HPMS) Field Manual Appendix J specifies the procedures for calibration of pavement roughness instrumentation and the reporting of IRI as the roughness statistic. The Texas State Department of Highways and Public Transportation (SDHPT) Maintenance and Operations Division, Pavement Management Section, was responsible for Texas compliance with the Appendix J mandate. Center for Transportation Research staff were contracted to locate, lay out, and determine the surface roughness in terms of IRI for the nine specified calibration sites. The manual version of the Face Dipstick was chosen as the Class I instrument for the roughness determination. Each of the Texas SDHPT's high speed roughness instruments was used to evaluate the roughness of the calibration sites. Regression equations for each instrument based on its response at different speeds of operation were generated and reported. Conclusions and recommendations for future modifications to make the Appendix J procedures more uniform and standardized are presented.

# TABLE OF CONTENTS

# SCOPE

The Center for Transportation Research (CTR) at The University of Texas at Austin has contracted with the Maintenance and Operations Division, Pavement Management Section, of the Texas State Department of Highways and Public Transportation (SDHPT) to make certain that the State of Texas is in compliance with Appendix J of the Highway Performance Monitoring System (HPMS) Field Manual (Ref 1). Appendix J specifies the procedures for calibrating each state's pavement roughness monitoring equipment. Appendix J also specifies that all pavement roughness for Highway Performance Monitoring System (HPMS) purposes will be reported in terms of the International Roughness Index (IRI) in inches per mile. The Texas SDHPT, as well as all other state highway authorities, is required to comply with the Appendix J mandate by September 1, 1989. Both the calibration procedures and the IRI statistic are new concepts to the Texas SDHPT. As such, a detailed study was needed to evaluate the calibration procedures and the implications for the State of Texas regarding compliance with the Appendix J mandate.

This research report describes in detail the procedures CTR used for calibration of the state's pavement roughness monitoring equipment to assure compliance with Appendix J. These procedures include the selection of the calibration sites, how the sites were laid out, the Class I surface profiling instrument used, and how the IRI statistic was calculated. In addition, the regression procedures and the resulting calibration equations for each type of Texas SDHPT pavement roughness equipment are discussed. This report also contains a section on how the Appendix J mandate might be improved to provide more uniform calibrations and roughness reporting procedures. Finally, a set of conclusions and recommendations are presented based on CTR's experience and the specific needs of the Texas SDHPT.

# BACKGROUND

The Federal Highway Administration (FHWA) has been interested in setting national procedures and standards for monitoring and reporting pavement conditions, including 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 and reported its findings in December 1987 (Ref 1). Appendix J of the Highway Performance Monitoring System (HPMS) Field Manual was an attempt to establish a practical, uniform, and calibrated measure of the pavement roughness which would have national consistency. The group determined that the reporting statistic would be IRI and outlined calibration procedures for correlating (using regression equations) all pavement roughness equipment in operation throughout the United States.

The Highway Performance Monitoring System (HPMS) Appendix J classifies existing roughness instruments in terms of their ability to produce profile data, the maximum error associated with their operation, and the measurement interval between elevations. Texas has the entire spectrum, Classes I, II, and III, of roughness monitoring equipment available for its use in the collection of pavement roughness data. The Texas SDHPT was interested in evaluating a Class I instrument, the auto-read version of the Face Dipstick, for use in Appendix J calibration procedure compliance.

The original prototype version of the auto-read Dipstick looked very promising as a cost-effective substitute for the rod and level survey (Ref 2). CTR conducted an extensive evaluation of the latest model of the auto-read version of the Face Dipstick. The final conclusions presented in the evaluation are that the auto-read version is unreliable and is not recommended for use in Appendix J compliance or on any pavement roughness monitoring project (Ref 3). However, the manual-read version of the Dipstick was also evaluated by the CTR staff. This version has proved to be the most reliable, repeatable, and cost-effective method for obtaining the "known profile" for the IRI calculations and the calibration of the lower classifications of roughness instrumentation. Therefore, the manual-read version of the Face Dipstick was used in this research and for Texas SDHPT compliance with the Appendix J mandate.

This research was necessary because the Appendix J procedures and the IRI reporting statistic were new to the State of Texas. Several inconsistent and ambiguous statements were found during the compliance process. It was not the intent of the Texas SDHPT or the CTR staff to attack the procedures as stated. On the other hand, it was felt that the national standardization of pavement roughness calibration and reporting procedures should be an evolutionary process. The goal of the Texas SDHPT is to comply with the stated procedures and to have input regarding possible changes needed in the evolution of the Appendix J procedures.

# PAVEMENT ROUGHNESS INSTRUMENT CALIBRATION

The following sections relate the specific procedures used by CTR staff to conduct the Appendix J calibration and regression correlations. The procedures presented in Appendix J were followed when specific information regarding calibration details was available. When decisions had to be made concerning the intent of ambiguous sections contained in Appendix J, Texas SDHPT personnel were consulted for past experience and guidance. Decisions regarding specific parameters or procedures were made based on the judgement of CTR staff and Texas SDHPT personnel. These decisions were documented for this research report.

## SITE SELECTION

The Texas SDHPT has been using 32 selected calibration sites, each 0.2 mile in length, around the Austin area for several years. These sections have been located on rural low-volume roads so that the surface profile would change as little as possible over time. This was one of the major concerns of Appendix J in the selection of calibration sites. These sections also have a recent pavement roughness history, which could be useful in the future for determining whether the profiled surface has changed or whether instruments are out of calibration. The calibration sections have historically been identified by the title Austin Test Section (ATS) followed by a number designation. For example, Austin Test Section Number 16 will be identified as ATS16 throughout this report. Details of the location of each ATS are available from CTR and the Texas SDHPT.

The actual selection of the nine Appendix J required sites was accomplished using the following procedure. The output of the Class II Texas modified K.J. Law profilometer was used to obtain a relative roughness value in terms of Serviceability Index (SI) for each of the existing calibration sections. The average of three runs was used for determination of the final roughness statistic (SI). The profilometer also was capable of producing the IRI statistic for each wheel path. The average IRI from both wheel paths was used to rank the calibration sections in accordance with the Appendix J mandate. The sections were categorized into three ranges of roughness: smooth sections, with IRI<190; medium sections, with IRI's from 191 to 320; and rough sections, with IRI>320.

The final selection of nine calibration sites, three from each roughness range, was made based on the following considerations. The traffic volume on each potential site and the associated traffic control necessary to produce a Class I profile was considered. Each section had to be as straight as possible and contain enough acceleration and deceleration length to stabilize the high-speed equipment and to obtain and maintain the proper calibration velocity. The selected calibration sections were also picked from sections exhibiting a minimum grade change through their length. All of the selected calibration sections were paved with asphalt even though concrete pavement exists in Texas. No concrete sections were selected because none was conveniently located near enough to the Austin area to make calibration on concrete practical.

The most difficult sections to select were the rough and medium sections. Several sections, based on the profilometer output, showed one wheel path to be in the rough range, IRI>320, while the other wheel path was in the medium range. The same circumstances occurred in the selection of the medium rough sections. This situation was further confused by the fact that the only indication of the surface roughness was from the Class II profilometer, which had never been calibrated in terms of IRI.

The resulting selection of calibration sites does not strictly adhere to the range categories specified in Appendix J, for the reasons stated above. In this report the three selected rough sections are referred to as ATS04, ATS16, and ATS21; the three medium sections are ATS01, ATS25, and ATS31; and the three smooth sections are ATS41, ATS42, and ATS43. This identification system was adopted to maintain consistency with the Texas SDHPT's nomenclature system.

## SITE LAYOUT

The nine selected calibration sites were all laid out using the same procedure. Both wheel paths in the travel lane were marked for profiling. When there were two travel lanes in the same direction of travel, the outside lane was always used. The width between the two wheel paths was chosen to be 52 inches. This distance was determined because the lasers on the Class II profilometer are 52 inches apart and the SDHPT personnel were interested in obtaining the best correlations between the Dipstick and the Texas profilometer. Every high-speed-pavement instrument in the SDHPT fleet has a different wheel base width and, consequently, follows a different wheel path. For instance, the wheel base for the profilometer is 65 inches; the ARAN is 74 inches from the center line of the dual rear wheels; the wheel base of the Cheverolet Celebrity SIometer is 57 inches; the Dodge Diplomat wheel base is 60 inches; and the Maysmeter wheel base is 68 inches. The decision on wheel path spacing and whether or not to use both wheel paths is left to the individual states.

The wheel paths in each calibration section were all marked using the following procedure. On sections with one travel lane in each direction, the inside wheel path was located 3 feet from the center line of the roadway. On sections with two travel lanes in each direction the outside lane was used for calibration purposes, as stated above. The inside wheel path on these sections was located 3 feet from the traffic stripe dividing the travel lanes. The outside wheel path of each section was located 52 inches from the inside wheel path (Fig 1).

A string line was pulled longitudinally down each wheel path with the spacing indicated above. Spray paint was used to paint a series of dots down the string line. This procedure accomplished three tasks. First, the dots were used by the Dipstick operators as a reference to maintain the proper wheel path throughout the length of each section. Second, the inside wheel path was used by the SDHPT roughness equipment operators as a guide line for maintaining relatively the same vehicle position in each travel lane during repeat runs. Third, the painted dots allowed a relatively time-stable marking on each calibration site for future use.

The start and stop locations of each calibration site were clearly marked for the vehicle operators. This was accomplished by laying a strip of white traffic tape across each travel lane at the proper locations. A strip of yellow traffic tape was also laid across each section and was used as an operator-ready indicator. This operator-ready indicator was located 200 feet before each start line. The operator-ready stripe warned the operators that the beginning of the calibration section was 200 feet away and that the vehicle to be calibrated should be traveling at the proper velocity. This approach distance of 200 feet was also meant to allow the vehicles enough time to stabilize before the actual profile readings were taken. After several 50-mph calibration runs using the Walker SIometers, it appeared that the 200-foot approach should be extended to 500 feet for stabilization purposes. The inside wheel path in each calibration section was extended and marked from the start location to the operator-ready location. This series of dots allowed the operators to align the vehicles in relatively the same wheel path for every repeat run. An additional set of marks was painted on the pavement shoulder of each site at a spacing of 100 feet. These marks served as distance references for the Dipstick operators.

## CLASS I PROFILING

The manual-read version of the Face Dipstick was chosen as the Class I profiling instrument for the calibration of the high-speed pavement roughness instrumentation. The auto-read version of the Dipstick was found to be unreliable (Ref 3) and was not considered for this calibration exercise. The Dipstick was chosen over rod and level surveys because the Dipstick had been shown to be more cost-effective than the rod and level, mainly in terms of the man-hours needed to generate the necessary

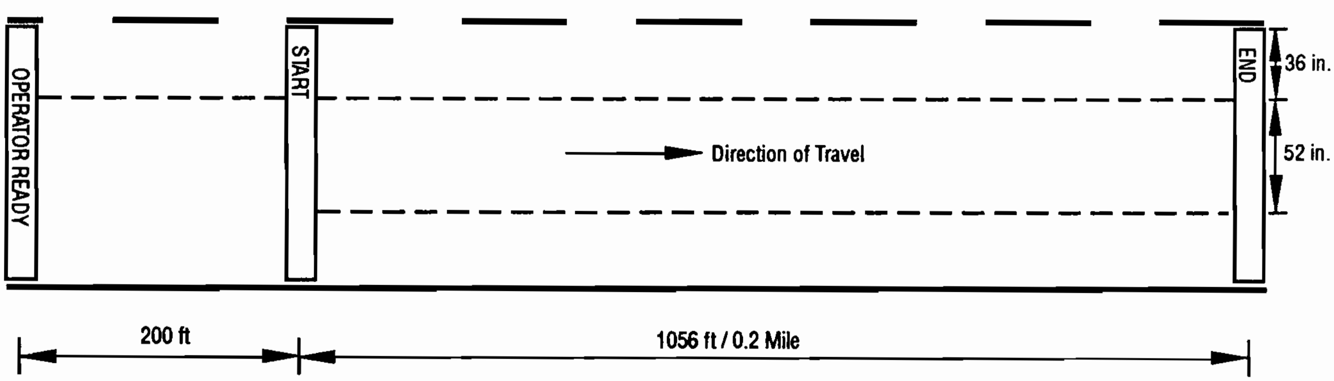


**Fig 1. Calibration site layout.**

elevation data and to obtain the required IRI statistic. Programs for conversion of Dipstick elevations into IRI were already available.

The operation of the Dipstick was checked daily before the actual profile data were taken. This included replacing the batteries daily and making certain that the ball and socket feet joints were well lubricated and were able to move freely. The rubber foot pads were checked daily to make certain that they adhered properly to the Dipstick's feet. The manufacturer's recommended body leveling procedure was followed before each profile run was conducted and adjustments were made if necessary. The Dipstick was checked for level after each profile run to help make certain that the elevation data for each run were accurate. The calibration of the Dipstick's inclinometer was checked daily using the calibration check gauge block provided by the Face Company.

Two crew members were needed to take the Dipstick elevation data. One crew member walked the Dipstick down the wheel path and called out the displayed number. The Dipstick elevation data were recorded manually onto data recording forms by the second crew member. A sample of the data recording forms is shown in Appendix A. Information recorded on these forms included the calibration site number, wheel path location, direction of travel, date, start and stop times, weather conditions, and names of the instrument operator and the data recorder.

On two calibration sites the elevation data were recorded on audio tape using a battery-operated cassette recorder and a microphone clipped to the lapel of the Dipstick operator. This was done because the traffic volume was heavy enough to require flagmen to control vehicle passage around the Dipstick operators. However, the traffic volume was not heavy enough to warrant total lane closure. One of these two sites had to be rerun because the wind and vehicle noise made several of the elevations unrecognizable. More experimenting with microphones and the audio cassette tape recorders could effectively eliminate the need to hand-record the Dipstick data and thereby reduce the crew size to one Dipstick operator.

The nine selected calibration sites were profiled using two independent Dipsticks and the associated two-man crews. The University of Texas at Austin (UT) and the Texas Research and Development Foundation (TRDF) Dipsticks (Ref 3) were used in this calibration effort. The procedure entailed walking each Dipstick down parallel wheel paths in the same travel lane from the start stripe through the entire 0.2-mile section length in the direction of the vehicle travel. This run was called the forward run. After finishing the forward run, the Dipstick operators turned and reran the same wheel path in the opposite direction toward the start stripe. The Dipsticks were not lifted off the pavement surface and, therefore, the reference elevations were not lost.

The process of walking the Dipstick from one end of the section to the other and returning to the original starting position served several purposes. First, the two runs on the same wheel path gave two data sets for comparison purposes. Second, starting and stopping at the same location gave an indication of any length errors associated with the operation of the Dipsticks. Third, the first reading of the forward data set and the last reading of the reverse data set could be compared to give an indication of the operator bias and any closure error associated with the Dipstick's operation.

## DATA MANIPULATION

Since the raw elevation data from the Dipstick runs were handwritten onto reporting forms, it was necessary to make certain that all the data were legible and reasonable. This was accomplished as the data was transcribed into a computer. Additionally, the transcribed data had to be checked to make certain that no transcription errors had occurred. This is a painstaking and monotonous task and, therefore, is a potential source for data errors. For the two calibration sites where the data were recorded onto audio cassette tapes, the transcriber listened to the tape and hand-recorded the elevation data onto the reporting forms. This technique allowed a hard copy of all elevation data from every calibration site. After the hard copy was produced, the data from these two sections were also transcribed into the computer for analysis and generation of the IRI statistic.

The first analysis of the Dipstick data was accomplished by visually looking at the first reading of the forward run and the last reading of the reverse run from the same wheel path on the same calibration section. The differences between these readings were calculated. All the data sets except one were accepted based on this inspection. The one rejected data set was located in the inside wheel path of ATS25. The reasoning used to determine whether or not the Dipstick data were accurate, on the basis of first and last readings, was based on the manufacturer's method of closing the loop for calculating operator bias. If the difference was greater than 0.100 inch, the wheel path was rerun. Walking the Dipstick down 1,056 readings and returning to the start location with only a difference of 0.100 inch or less gave a good indication of data reliability. Table 1 presents these calculated differences by section number and wheel path.

The running-sum profiles for each wheel path in every calibration site were used as the final acceptance test for determining whether the Dipstick data were good or needed to be rerun. Appendix B includes the forward and reversed running-sum graphs for all nine calibration sites. Figures 2 and 3 show typical running-sum profiles of a wheel path using the forward run data plotted against the return data. The return run data were reversed in a computer program and the first elevations of both runs were forced to be equal. The resulting plots show how the profile changes on the same wheel path due to operator bias, foot slippage, failure to follow exactly the same wheel path line, and closure error. Figure 2 is the plot from two Dipstick runs made on the inside wheel path of ATS16. This figure represents the closest fitting forward and return runs. The difference between the last readings of these two runs is 1.034 inches. Figure 3 is the worst case and shows a difference of 23.568 inches. Table 1 shows the calculated running-sum differences for the entire set of Dipstick data on all the nine calibration sections.

After acquiring the raw elevation data from the Dipstick surveys and determining whether the data were accurate, it was necessary to calculate the IRI values. The initial IRI determinations were made using the program provided by the Face Company with the purchase of the

**TABLE 1. CALCULATED DIFFERENCES BETWEEN THE FIRST AND LAST DIPSTICK ELEVATION READINGS BY SECTION NUMBER AND WHEEL PATH**

| ATS Number | Wheel Path[1] | Start/Stop Difference (in.) | Running Sum Difference (in.) | IRI Calculation (in./mile) |
|---|---|---|---|---|
| 1 | IS(f) | 0.030 | 7.012 | 182.06 |
| | IS(r) | | | 186.14 |
| | OS(f) | 0.023 | 9.112 | 252.78 |
| | OS(r) | | | 233.97 |
| 4 | IS(f) | 0.018 | 9.792 | 245.78 |
| | IS(r) | | | 235.07 |
| | OS(f) | 0.037 | 1.531 | 326.49 |
| | OS(r) | | | 332.47 |
| 16 | IS(f) | 0.007 | 1.034 | 269.45 |
| | IS(r) | | | 272.39 |
| | OS(f) | 0.100 | 3.966 | 428.61 |
| | OS(r) | | | 433.80 |
| 21 | IS(f) | 0.047 | 2.020 | 237.39 |
| | IS(r) | | | 244.53 |
| | OS(f) | 0.006 | 3.355 | 268.13 |
| | OS(r) | | | 278.12 |
| 25 | IS(f) | 0.077 | 6.602 | 104.77 |
| | IS(r) | | | 106.86 |
| | OS(f) | 0.055 | 8.899 | 232.18 |
| | OS(r) | | | 246.56 |
| 31 | IS(f) | 0.006 | 8.899 | 131.40 |
| | IS(r) | | | 122.43 |
| | OS(f) | 0.026 | 4.890 | 188.55 |
| | OS(r) | | | 183.44 |
| 41 | IS(f) | 0.046 | 23.568 | 116.84 |
| | IS(r) | | | 94.64 |
| | OS(f) | 0.047 | 8.899 | 83.48 |
| | OS(r) | | | 111.11 |
| 42 | IS(f) | 0.097 | 14.615 | 109.44 |
| | IS(r) | | | 97.90 |
| | OS(f) | 0.097 | 2.245 | 94.00 |
| | OS(r) | | | 93.21 |
| 43 | IS(f) | 0.087 | 17.083 | 94.01 |
| | IS(r) | | | 101.11 |
| | OS(f) | 0.050 | 1.328 | 89.83 |
| | OS(r) | | | 84.69 |

[1]IS(f) and IS(r) designate inside wheel path forward and reverse runs.
OS(f) and OS(r) designate outside wheel path forward and reverse runs.

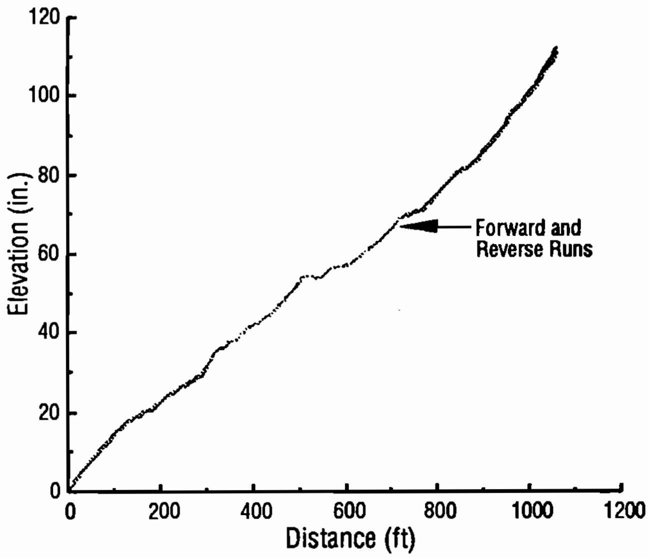


**Fig 2. Running-sum profile plot of the inside wheel path of ATS16.**

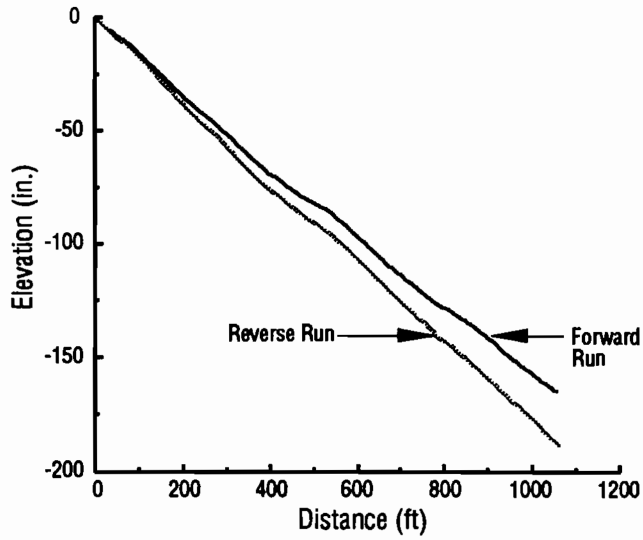


**Fig 3. Running-sum profile plot of the inside wheel path of ATS41.**

auto-read version of the Dipstick. This software was hard to use because there are few error traps and the data had to be presented to the calculation program in a very precise manner before the IRI values could be generated. TRDF had to create a program which uses Dipstick elevation data to calculate IRI in an attempt to produce software which was more user-friendly and contained error-trapping capabilities.

It was noticed that the IRI results from the Face program and the TRDF program were not the same, although both programs were derived from the same source, World Bank Technical Paper Number 46 (Ref 4), and developed independently. This situation presented the problem of determining which, if either, of the programs was giving the correct representation of IRI. CTR developed its own independent program to calculate IRI values from Dipstick data, which was also based on the World Bank Report. Figure 4 shows the resulting IRI calculations from all of the calibration sites using all three programs (Ref 5). The calculated IRI values shown in Fig 4 are the average IRI's from both wheel paths of the indicated Austin test section. It can be seen from Fig 4 that the Face and the CTR programs gave nearly the same IRI values, while the TRDF program resulted in considerable differences. Table 1 also shows the calculated IRI values for the forward and reverse runs in each wheel path on each calibration site. These values were calculated using the CTR version of the IRI program.

Problems were encountered during this programming effort which cast doubt on the ability of independent programmers using the World Bank example to produce IRI values from elevation data. The references to the units of measurement in the World Bank report are inconsistent and caused confusion during the programming effort. A set of data points needs to be included with the example, along with the correct IRI value calculated from the sample data. This would allow independent programmers a chance to verify the individual program's calculations prior to implementation. Reference 5 gives a sample data set and the resulting IRI as calculated by the Face and the CTR programs.

A program was written by CTR to calculate the Root Mean Square Vertical Acceleration (RMSVA) (Ref 6) values at different baselengths for the Dipstick data collected on the nine calibration sections. This program was written as an added check on the ability of the Class I Dipstick and the Class II profilometer outputs to be correlated by independent means. It was considered prudent to accomplish this task because of the difficulties which were encountered writing independent programs to calculate the IRI statistic from raw elevation data. Another pavement roughness statistic using elevation data as input for comparing the Dipstick's interpretation of roughness with that of the profilometer was considered important as another means of correlating the two instruments.

## REGRESSION PROCEDURE

The calibration by regression procedure outlined in the Appendix J mandate was followed by CTR to calibrate each of the Texas SDHPT high-speed pavement roughness instruments. The x-axis, which is referred to as the average reference roughness index (RRI) in Appendix J, was always the high-speed instrument's response. The x-coordinate for each data point was determined by running the roughness vehicle to be calibrated a minimum of

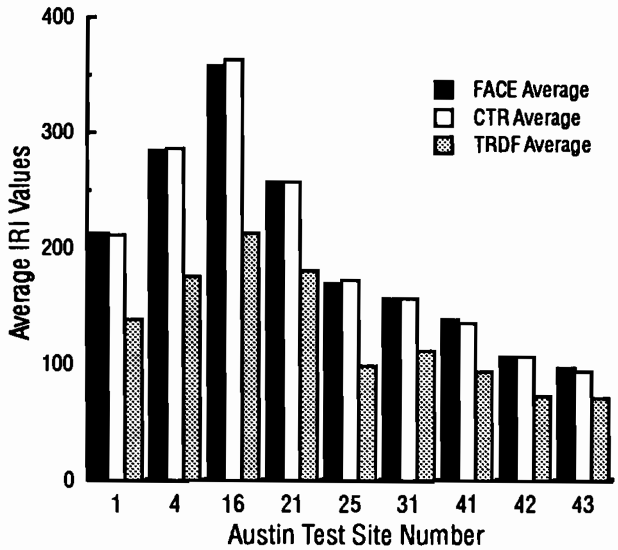


**Fig 4. Calculated IRI values for all Austin test sites using the three programs.**

times over a calibration section at each reporting speed. The operator or the computer program would note the reporting statistic for each run with each vehicle at each calibration speed. The five runs were averaged and the individual runs were compared to the average. If all individual runs were within ±10 percent of the average, the data and the average were considered acceptable. If any of the individual runs was outside of this limit, the suspect data were thrown out and another run was made. This process was continued, with the average being recomputed, until at least five acceptable runs were made. In practice, all RTRRM instrument operators were asked to make at least six runs at each speed on each calibration section before stopping to compute the average. The final average value was considered the RRI and was reported in the roughness units generated by the individual instrument type.

The y-axis was the same for every calibration curve. The Class I Dipstick data for each of the calibration sections were used for each y-coordinate. The Dipstick data were reported in terms of IRI in inches/mile. Appendix J does not indicate which wheel path, or the average of both wheel paths, to use for the y-axis values. CTR decided to average the two runs made in each wheel path and use this value as the final IRI. A separate regression equation was generated for each instrument using the following three y-axis values. One set of calibration curves used the average of the inside wheel path, another set used the average of the outside wheel path, and the last set used the average of both wheel paths in each calibration section.

Appendix J does not specifically say whether or not the regression equations generated through the calibration process have to be linear or a curve fit. If a curve fit is to be used, Appendix J does not indicate the degree of the fitted equation. Appendix J does state that for reporting purposes only the linear equation needs to be generated and reported by the states. For this project both the linear and the second-degree curve equations were derived and reported to the Texas SDHPT.

## PROFILOMETER REGRESSIONS

The Class II modified K. J. Law profilometer was the first surface roughness instrument used in the Appendix J regression procedure. The Texas SDHPT profilometer has been used for calibration purposes for years. The SDHPT personnel were interested in finding out how well the profilometer compared to the Class I Dipstick's interpretation of surface profile and the roughness statistics. The raw elevation data of the two instruments were not directly comparable because of the filtering and integration of the profilometer data. The running-sum profiles of the two instruments have been favorably compared in past research work (Ref 2). The computations of the same roughness statistics using the raw elevation data from the two instruments had not been compared.

The profilometer made six runs at 20 mph on all nine calibration sites. The CTR staff was instructed not to regress the profilometer output at 50 mph by SDHPT personnel. The profilometer data for runs made at 50 mph show nonexistent roughness spikes, which have adversely affected the summary statistics. As stated previously, the distance between the Dipsticked wheel paths was set at 52 inches. This is the distance between the lasers of the profilometer. However, the wheel base width of the profilometer is 65 inches. This fact, plus the fact that the Dipstick is a static instrument while the profilometer is dynamic, was the most likely cause of differences in the computed statistics.

The profilometer output generates several roughness statistics. The IRI's for the individual wheel paths were the main concern of this project but, as mentioned earlier, the RMSVA statistics were also compared. The profilometer also produces a pavement Serviceability Index (SI) and a simulated Maysmeter output (MO). These two statistics were regressed against the Dipstick IRI using the same averaging procedure to produce an RRI value for the x-axis. This was done to gain a better insight into how good a curve fit could be derived by regressing IRI against both the SI and the MO outputs. A sample output of a profilometer run can be seen in Appendix C. The profilometer report in Appendix C is from the first run on ATS01. It should be noticed from the header information of the report that the operator actually started monitoring the surface profile at the 200-foot operator-ready mark on ATS01. The profilometer software allows the user to select the beginning distance marker and the total length of each run. This was helpful in attempting to line up the Dipstick and the profilometer runs on the calibration sections.

The Dipstick and profilometer showed very high correlations when the IRI statistics were compared using the regression procedures outlined in Appendix J. Table 2 shows the results of the Dipstick versus the profilometer runs on all of the calibration sections. The profilometer data are the average of the six runs taken at 20 mph on each individual test site. The SI and MO values are the averages of the same six runs in each calibration site. The SI and MO values are included here as further indication of the relationship between the Dipstick and the profilometer. The Dipstick data are the average of the two runs made on each wheel path of each calibration site, as described earlier.

Several regression lines and curves were plotted from the data included in Table 2. Both first-degree and second-degree equations were generated to illustrate any differences in $R^2$ values the regressions would provide. Also, the inside versus the inside wheel path, the outside versus the outside wheel path, and the average versus the average of both wheel paths were plotted to show differences in the fitted calibration equations. Appendix D provides all of the Dipstick versus the profilometer regressions for the situations listed above. In addition, regressions were made on the average SI and MO values from the profilometer runs on the calibration sites.

In general, it can be readily seen from viewing the Appendix D plots that the best fits were obtained using the second-degree equations. This was true for the IRI, the SI, and the MO statistics. The profilometer IRI values calculated by wheel path and regressed against the corresponding Dipstick wheel path IRI showed very good correlations. But because of the static nature of the Dipstick versus the dynamic nature of the profilometer and the difficulty of maintaining the exact same wheel path lines, the average of both wheel paths showed the best fits. This trend is even more evident in the case of the SI and MO statistics, which are half-car response models.

A program was written to calculate the RMSVA values at different baselengths from the Dipstick data (Ref 7). This was done in an attempt to gain further insight into the relationship between the statistical outputs of the Dipstick and the profilometer. Since this comparison was beyond the scope of this research effort, a decision was made to compare only one calibration site within each of the three roughness ranges. The three chosen sites were ATS43 for the smooth, ATS04 for the medium, and ATS16 for the rough range. The profilometer data were not averaged for the six runs made on each test section. An effort was made to identify a typical profilometer run by looking at the six runs and selecting one that represented an average run.

After the calculated RMSVA values from the Dipstick data were obtained for the different baselengths in each wheel path for the three indicated test sites, plots were generated to compare the two instruments. The first plots were prepared to check the linearity and the ideal fit of the outputs. If the two calculated values from both instruments exhibited a perfect linear relationship, one would expect the resulting line to have an $R^2$ value of 1.000, a y-intercept at the origin, and a slope equal to one, which represents a 45° angle. Plots were generated for each wheel path and for the average of both wheel paths. Figure 5 shows a typical plot of the profilometer versus Dipstick RMSVA values. None of the plotted data exhibited a perfectly linear relationship, as would be expected. The range of $R^2$ values was from 0.997 to 1.000, the slopes ranged from 0.618 to 0.973, and the y-intercepts ranged from 0.016 to 0.487.

Bar charts showing the differences between the RMSVA values of the Dipstick and the profilometer were generated. Figure 6 is a typical example of these bar charts. The differences in RMSVA values for the outside wheel path, the inside wheel path, and the average of both wheel paths were plotted for the individual baselengths. These bar graphs are somewhat misleading, since the largest calculated values and, therefore, the largest differences were found at the shortest baselengths. Figure 7 is a more precise indication of the relationship

**TABLE 2. IRI VALUES GENERATED FROM THE DIPSTICK AND PROFILOMETER ON THE NINE CALIBRATION SITES**

| Test Site Number | Dipstick Data | | | Profilometer Data[1] | | | | |
|---|---|---|---|---|---|---|---|---|
| | Left | Right | Average | Left | Right | Average | SI[2] | MO[2] |
| ATS 01 | 184.1 | 243.29 | 213.7 | 177.01 | 233.34 | 205.18 | 2.20 | 127.96 |
| ATS 04 | 240.43 | 324.98 | 282.7 | 242.72 | 311.15 | 276.94 | 1.63 | 169.53 |
| ATS 16 | 270.92 | 431.21 | 351.07 | 266.05 | 404.87 | 335.46 | 1.16 | 216.94 |
| ATS 21 | 240.96 | 273.43 | 257.20 | 242.41 | 266.34 | 254.38 | 1.91 | 147.30 |
| ATS 25 | 107.41 | 239.37 | 173.39 | 110.44 | 275.96 | 193.20 | 2.53 | 108.46 |
| ATS 31 | 126.92 | 186.00 | 156.46 | 121.77 | 208.50 | 165.14 | 2.76 | 96.30 |
| ATS 41 | 105.74 | 97.30 | 101.52 | 80.30 | 76.29 | 78.30 | 4.23 | 34.17 |
| ATS 42 | 103.67 | 93.61 | 98.64 | 81.12 | 83.19 | 82.16 | 4.22 | 35.32 |
| ATS 43 | 97.56 | 87.26 | 92.41 | 69.38 | 78.54 | 73.96 | 4.43 | 27.54 |

1 Averages of six individual runs
2 Profilometer extrapolated data set (average of six runs)

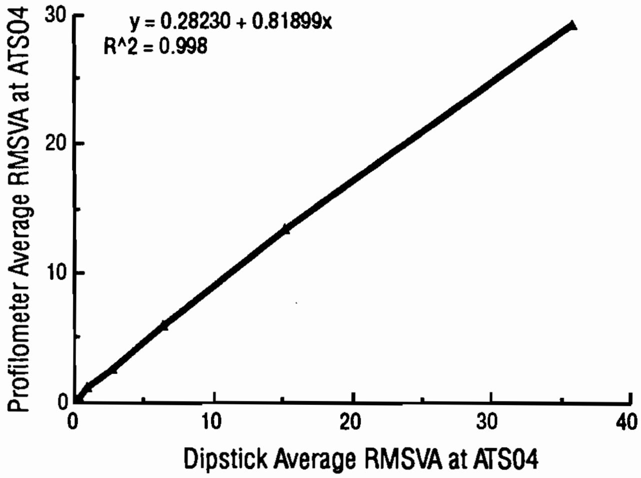


**Fig 5. Profilometer versus Dipstick RMSVA plot for average of both wheel paths on ATS04.**

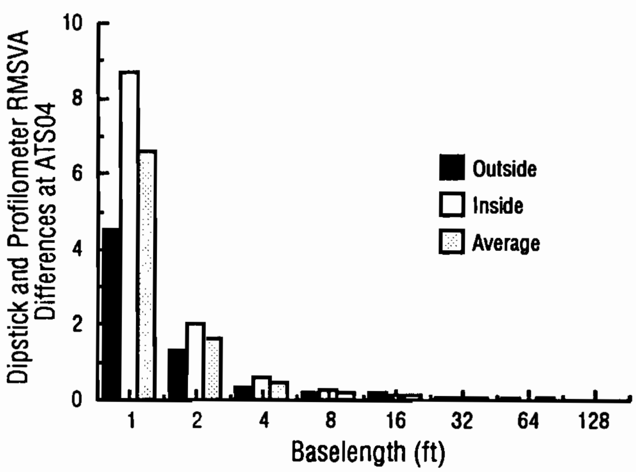


**Fig 6. Bar chart of RMSVA differences at individual baselengths.**

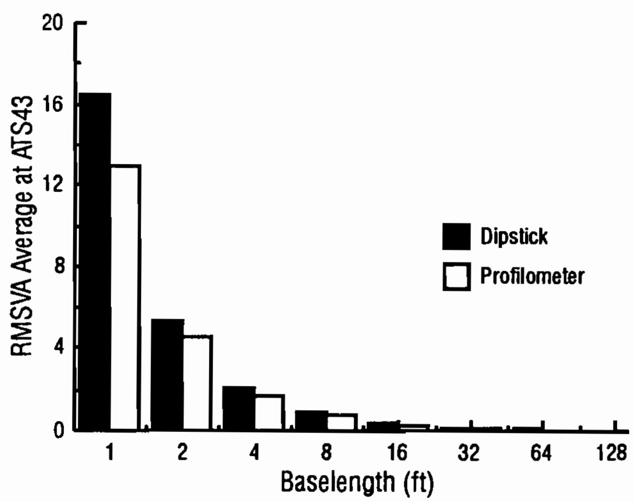


**Fig 7. Average RMSVA's from Dipstick and profilometer versus baselength.**

of the RMSVA by baselength calculated from the Dipstick and the profilometer data. This figure shows the decreasing magnitudes of RMSVA as the baselength increases. The Dipstick and the profilometer values showed the same trends. The Dipstick's RMSVA was always greater at the one-foot baselength than that of the profilometer. No trend could be discerned from wheel path to wheel path or from the averages of both wheel paths. The RMSVA's from both instruments have very high correlation and greater $R^2$ values in general than the IRI calculations.

## SIOMETER REGRESSIONS

The Walker Roughness Device (SIometer) is a Class III RTRRM device which was developed through the Texas SDHPT Cooperative Research Program. The Appendix J procedures and the modifications described in this text were used to regress the SIometer's output against the Dipstick's IRI. The output of the SIometer is a hexadecimal number called the Walker Slope Variance (WSV) number. These WSV numbers are converted into SI values through a calibration process similar to the Appendix J procedures. The profilometer SI outputs at 20 mph from all of the Austin test sections are used for this calibration process. Each individual SIometer is run on the calibration sections and an equation is generated to produce an SI value based on the profilometer outputs.

The total number of SIometers in service in the State of Texas is 12. Due to the large number of regression plots which were generated for the Appendix J compliance, only selected plots are used to demonstrate the results. Tables 3 and 4 were prepared for reviewing the regressions generated from the SIometer calibrations. These tables indicate the vehicle ID number, the individual wheel path or average wheel path used, the regression equation, and the resulting $R^2$ values for the SIometers. Only the second-degree curve fits are represented in these tables because the linear fits showed such low $R^2$ values. Table 3 is information for the operating speed of 50 mph while Table 4 is for the 35-mph speed. The operators of the vehicles were provided with a standard reporting form. This form can be seen in Appendix E of this report. The operators were asked to make six runs at each calibration speed and manually record the resulting WSV numbers for each run on each of the nine calibration sections.

The WSV hexadecimal numbers had to be converted to decimal equivalencies, so that the ±10 percent cutoff limit could be evaluated. The wide range of WSV numbers generated from each vehicle on the calibration sites made it impossible for every vehicle to meet the ±10 percent cutoff value for every run on every calibration section. The first test runs were made at the 50-mph speed.

**TABLE 3. IRI VS WSV BY VEHICLE AT 50 MPH**

| Vehicle | Wheel Path | Correlation Equation | $R^2$ |
|---|---|---|---|
| 437B | Average | $Y = 69.40 + (0.11)X - (1.02e-5)X^2$ | 0.984 |
| | Inside | $Y = 74.30 + (8.16e-2)X - (8.07e-6)X^2$ | 0.868 |
| | Outside | $Y = 66.18 + (0.13)X - (1.18e-5)X^2$ | 0.976 |
| 440B | Average | $Y = 62.47 + (0.13)X - (1.42e-5)X^2$ | 0.947 |
| | Inside | $Y = 73.52 + (8.99e-2)X - (1.00e-5)X^2$ | 0.784 |
| | Outside | $Y = 53.64 + (0.16)X - (1.77e-5)X^2$ | 0.971 |
| 441B | Average | $Y = 74.65 + (0.11)X - (1.06e-5)X^2$ | 0.977 |
| | Inside | $Y = 71.02 + (9.33e-2)X - (1.08e-5)X^2$ | 0.938 |
| | Outside | $Y = 79.77 + (0.12)X - (9.95e-6)X^2$ | 0.923 |
| 443A | Average | $Y = 70.63 + (0.13)X - (1.49e-5)X^2$ | 0.983 |
| | Inside | $Y = 75.93 + (9.83e-2)X - (1.16e-5)X^2$ | 0.858 |
| | Outside | $Y = 69.52 + (0.14)X - (1.43e-5)X^2$ | 0.971 |
| 443B | Average | $Y = 69.65 + (0.12)X - (1.29e-5)X^2$ | 0.995 |
| | Inside | $Y = 71.65 + (9.36e-2)X - (1.08e-5)X^2$ | 0.907 |
| | Outside | $Y = 69.52 + (0.14)X - (1.43e-5)X^2$ | 0.971 |
| 446A | Average | $Y = 65.34 + (0.16)X - (2.07e-5)X^2$ | 0.987 |
| | Inside | $Y = 67.09 + (0.12)X - (1.73e-5)X^2$ | 0.916 |
| | Outside | $Y = 65.31 + (0.18)X - (2.31e-5)X^2$ | 0.958 |
| 448A | Average | $Y = 69.29 + (0.15)X - (1.88e-5)X^2$ | 0.990 |
| | Inside | $Y = 72.40 + (0.11)X - (1.54e-5)X^2$ | 0.893 |
| | Outside | $Y = 67.61 + (0.18)X - (2.11e-5)X^2$ | 0.976 |
| 449A | Average | $Y = 51.35 + (0.18)X - (2.83e-5)X^2$ | 0.992 |
| | Inside | $Y = 57.84 + (0.14)X - (2.37e-5)X^2$ | 0.899 |
| | Outside | $Y = 47.28 + (0.22)X - (3.13e-5)X^2$ | 0.972 |
| 493A | Average | $Y = 69.06 + (0.13)X - (1.50e-5)X^2$ | 0.993 |
| | Inside | $Y = 70.95 + (0.10)X - (1.26e-5)X^2$ | 0.910 |
| | Outside | $Y = 68.84 + (0.15)X - (1.66e-5)X^2$ | 0.969 |
| 442B | Average | $Y = 66.22 + (0.11)X - (1.10e-5)X^2$ | 0.952 |
| | Inside | $Y = 76.54 + (7.90e-2)X - (7.65e-6)X^2$ | 0.785 |
| | Outside | $Y = 57.84 + (0.15)X - (1.38e-5)X^2$ | 0.980 |

After looking at the scatter of the preliminary data, project staff decided to move the operator-ready line of each site back to 500 feet, from the original 200 feet. This increased distance had a positive effect on the WSV output of the SIometers. The drivers had a greater amount of time to line up the vehicle and start the data acquisition processing. The increased distance also allowed the vehicle instrumentation more time to stabilize before the actual data were collected.

All of the SIometers were initially run at 50 mph as reported earlier. They were then run at 30 mph and the data were transformed to decimal values and regressed against the Dipstick IRI's. The outputs of the SIometers at 30 mph were very scattered. The large scatter in the 30-mph data was discussed with SDHPT Maintenance and Operations personnel, and it was decided that the calibration sections should be rerun at a speed of 35 mph. The outputs from these 35-mph runs were more consistent than the 30-mph data, but the data were not as good as the 50-mph data sets.

Tables 5 and 6 are representative data sets which were prepared to give an indication of the wide range in WSV values and the difficulty encountered in meeting the ±10 percent cutoff limit. These tables are for two separate vehicles, and values for a rough, a medium, and a smooth site are reported. One vehicle was run at 35 mph while the other was run at 50 mph. These vehicles were chosen because the range of their outputs on the selected calibration sections produced a representative spread in the data shown by all of the SIometers. Some vehicles exhibited more consistent outputs and some vehicles exhibited less consistent outputs. From the two tables it is clear that each vehicle showed decreasing WSV values with the decreasing surface roughness. The average WSV value, or the RRI, in Appendix J terms, changed with speed on the rough and medium calibration sections.

Each of the sections was run six times at each test speed, as indicated earlier. The resulting decimal equivalences were averaged to produce the required RRI value.

**TABLE 4. IRI VS. WSV BY VEHICLE AT 35 MPH**

| Vehicle | Wheel Path | Correlation Equation | $R^2$ |
|---|---|---|---|
| 156A | Average | $Y = 91.85 + (8.87e-2)X - (9.49e-6)X^2$ | 0.823 |
| | Inside | $Y = 86.05 + (7.36e-2)X - (8.68e-6)X^2$ | 0.789 |
| | Outside | $Y = 99.13 + (0.10)X - (9.66e-6)X^2$ | 0.780 |
| 167B | Average | $Y = 81.92 + (6.93e-2)X - (4.36e-6)X^2$ | 0.892 |
| | Inside | $Y = 84.42 + (5.12e-2)X - (3.47e-6)X^2$ | 0.764 |
| | Outside | $Y = 80.83 + (8.50e-2)X - (4.93e-6)X^2$ | 0.904 |
| 438B | Average | $Y = 83.50 + (9.39e-2)X - (7.87e-6)X^2$ | 0.910 |
| | Inside | $Y = 81.80 + (7.47e-2)X - (7.333-6)X^2$ | 0.827 |
| | Outside | $Y = 86.65 + (0.11)X - (7.80e-6)X^2$ | 0.890 |
| 440B | Average | $Y = 78.02 + (0.11)X - (1.19e-5)X^2$ | 0.893 |
| | Inside | $Y = 75.22 + (9.45e-2)X - (1.17e-5)X^2$ | 0.821 |
| | Outside | $Y = 82.80 + (0.13)X - (1.12e-5)X^2$ | 0.865 |
| 441B | Average | $Y = 82.67 + (9.48e-2)X - (8.23e-6)X^2$ | 0.859 |
| | Inside | $Y = 85.40 + (6.89e-2)X - (6.26e-6)X^2$ | 0.743 |
| | Outside | $Y = 81.54 + (0.12)X - (9.51e-6)X^2$ | 0.864 |
| 443A | Average | $Y = 5.60 + (9.64e-2)X - (7.62e-6)X^2$ | 0.956 |
| | Inside | $Y = 78.22 + (7.28e-2)X - (6.36e-6)X^2$ | 0.848 |
| | Outside | $Y = 74.43 + (0.12)X - (8.43e-6)X^2$ | 0.946 |
| 443B | Average | $Y = 84.60 + (7.63e-2)X - (5.33e-6)X^2$ | 0.904 |
| | Inside | $Y = 81.13 + (6.24e-2)X - (5.18e-6)X^2$ | 0.841 |
| | Outside | $Y = 89.39 + (8.75e-2)X - (5.05e-6)X^2$ | 0.877 |
| 446A | Average | $Y = 77.94 + (0.15)X - (2.01e-5)X^2$ | 0.882 |
| | Inside | $Y = 74.48 + (0.12)X - (2.06e-5)X^2$ | 0.827 |
| | Outside | $Y = 83.23 + (0.17)X - (1.78e-5)X^2$ | 0.850 |
| 448A | Average | $Y = 88.77 + (9.32e-2)X - (7.11e-6)X^2$ | 0.900 |
| | Inside | $Y = 86.42 + (7.32e-2)X - (6.72e-6)X^2$ | 0.820 |
| | Outside | $Y = 92.19 + (0.11)X - (7.07e-6)X^2$ | 0.876 |
| 449A | Average | $Y = 76.37 + (9.88e-2)X - (8.56e-6)X^2$ | 0.894 |
| | Inside | $Y = 78.66 + (7.51e-2)X - (7.21e-6)X^2$ | 0.790 |
| | Outside | $Y = 75.71 + (0.12)X - (9.21e-6)X^2$ | 0.890 |
| 493A | Average | $Y = 80.39 + (9.30e-2)X - (6.83e-6)X^2$ | 0.935 |
| | Inside | $Y = 77.09 + (7.75e-2)X - (7.37e-6)X^2$ | 0.877 |
| | Outside | $Y = 84.91 + (0.11)X - (5.97e-6))X^2$ | 0.895 |
| 442B | Average | $Y = 87.17 + (6.38e-2)X - (3.49e-6)X^2$ | 0.892 |
| | Inside | $Y = 80.99 + (5.50e-2)X - (4.04e-6)X^2$ | 0.859 |
| | Outside | $Y=94.72 + (7.00e-2)X - (2.57e-6)X^2$ | 0.846 |

**TABLE 5. TYPICAL SIOMETER WSV VALUES FOR VEHICLE ID446A RUN ON ATS01, 31, AND 43 AT 35 MPH**

| ATS Number | Average WSV[1] | Max. | Min | Run | Error Number[2] |
|---|---|---|---|---|---|
| 01 | 1845 | 2050 | 1563 | 5 | 2 |
| 31 | 498 | 522 | 461 | 5 | 0 |
| 43 | 215 | 292 | 153 | 5 | 4 |

[1]WSV values are the decimal equivalents of the hexadecimal output. Each vehicle made six runs on each section; only the best five runs were used.

[2]Total number of runs which were outside the ±10 percent cutoff.

**TABLE 6. TYPICAL SIOMETER WSV VALUES FOR VEHICLE ID440B RUN ON ATS01, 31, AND 43 AT 50 MPH**

| ATS Number | Average WSV[1] | Max. | Min | Run | Error Number[2] |
|---|---|---|---|---|---|
| 01 | 1691 | 1921 | 1546 | 5 | 1 |
| 31 | 855 | 976 | 752 | 5 | 4 |
| 43 | 204 | 217 | 188 | 5 | 0 |

[1]WSV values are the decimal equivalents of the hexadecimal output. Each vehicle made six runs on each section; only the best five runs were used.

[2]Total number of runs which were outside the ±10 percent cutoff.

If five values were within the ±10 percent cutoff limit of the calculated RRI, then the error number column on Tables 5 and 6 had a zero entry. If two values were outside of the ±10 percent limit, then the error number column read two, and so on. A record was kept of the total number of out-of-limit values for each vehicle at each test speed on each test section. The smoother calibration sections always exhibited the most out-of-range values, no matter what the speed of operation. The 35-mph data were worse; that is, there were more out-of-range values in the smooth and medium sections than for the 50-mph data.

One SIometer was used to evaluate the effect of variable speed of operation on the output of the instrument. Vehicle ID number 442B was operated at 20, 30, 35, 40, and 50 mph on all of the calibration sections. This instrument was selected at random. Table 7 lists the average output value for the best five out of six runs made at each speed on each of the nine test sections for this particular SIometer. It can be seen from Table 7 that the output from the same vehicle varied greatly with speed, as would be expected from RTRRM-type instruments. The general trend of decreasing output value with a decrease in surface roughness can also be observed.

The output of each SIometer was regressed against the Dipstick output for each calibration section as described in the profilometer calibration section of this text. The Dipstick IRI values from each wheel path were used as the y-axis, with the SIometer output as the x-axis value. The average IRI from both wheel paths was also used as the y-axis value to generate another set of calibration equations. Both linear and second-degree curve fits were derived for each SIometer at each of the calibration speeds and for each of the y-axis situations described above.

The volume of graphical representations generated by the many SIometers, the different speeds of operation, the multiple wheel paths, and the linear versus curve fits make the presentation of all SIometer data impractical. The output of one SIometer was again chosen randomly to demonstrate the regression process and the typical outcomes. Appendix F shows the regression results of SIometer 438B run at the two reporting speeds of 50 and 35 mph. By comparing the graphs and the resulting regression equations in Appendix F, the effect of operational speed can be observed. It is also obvious that the curve fit is better than the linear fit in all cases. This is true for the $R^2$ values as well as the scatter of the data above and below the generated equations. At 50 mph, the Dipstick's IRI versus the SIometer's output for the outside wheel path and the average of both wheel paths yields very high $R^2$ values while the inside wheel path regressions show weaker correlations. At the 35-mph operating speed, only the average Dipstick IRI from both wheel paths fitted with a second degree equation yields $R^2$ values greater than 0.9 when compared to the SIometer output.

**TABLE 7. AVERAGE WSV[1] OUTPUT OF VEHICLE 442B FOR NINE CALIBRATION SECTIONS, VARYING THE SPEED OF OPERATION**

| ATS | Average Number | | | | |
|---|---|---|---|---|---|
| Number | 20 mph | 30 mph | 35 mph | 40 mph | 50 mph |
| 01 | 1291 | 2494 | 3886 | 2266 | 1331 |
| 04 | 2172 | 3866 | 3551 | 3238 | 2731 |
| 16 | 3836 | 4946 | 5466 | 4721 | 4164 |
| 21 | 1663 | 1951 | 2626 | 2120 | 1682 |
| 25 | 1003 | 1445 | 1064 | 1024 | 1550 |
| 31 | 670 | 1214 | 906 | 735 | 750 |
| 41 | 316 | 432 | 272 | 285 | 363 |
| 42 | 365 | 421 | 336 | 331 | 306 |
| 43 | 211 | 418 | 403 | 308 | 262 |

[1]WSV values are the decimal equivalents of the hexadecimal output. Each vehicle made six runs on each section; only the best five runs were used.

## MAYSMETER REGRESSIONS

The Texas SDHPT has been using the Class III Maysmeters for years as a pavement surface roughness monitoring device. This RTRRM instrument was regressed for calibration using the Appendix J procedures described previously. The Texas SDHPT has two Maysmeters in use statewide, but CTR was requested to calibrate only one vehicle using the Appendix J procedures. Both the 30 and 50-mph speeds were used to produce the regression equations. The operator was asked to make six runs at each calibration speed on each test section. The number of counts per 0.2 mile was recorded on the reporting form, shown in Appendix E. The average value, RRI, for each calibration section was determined so that the ±10 percent cutoff could be evaluated. If one of the runs fell outside the cutoff, another run was made and the RRI value was recalculated. The Maysmeter calibrated was able to make the ±10 percent cutoff within the first five runs on the majority of calibration sections and within six runs on all of the calibration sections.

A graphical representation of the Maysmeter calibration is given in Appendix G. The graphs were produced by plotting the Dipstick's IRI interpretation of the pavement surface versus the Maysmeter average count per 0.2 mile on the nine calibration sections. Both linear and second-degree regression equations were produced for each speed of operation. The Maysmeter showed a speed-dependent response with the 50-mph data being the best-fit situation. The Maysmeter's 30-mph response consistently produced $R^2$ values of 0.90 and better. The 30-mph data did show much more scatter above and below the the regression line than did the 50-mph data. The second-degree fits again gave the highest and most consistent $R^2$ values, with the data being evenly distributed about the curve. The average Dipstick IRI values from both wheel paths again showed the best fits.

## ARAN REGRESSIONS

The Automatic Road Analyzer (ARAN) is a Class III RTRRM device which produces three pavement roughness statistics. These three statistics are RMSVA, Mean Absolute Slope (MAS), and texture. It was also supposed to produce IRI values from an estimated profile. As of this time, the Texas SDHPT has been unable to obtain IRI values from the ARAN data which were collected. All three of the reporting statistics were regressed against the Dipstick data. The ARAN was run at 30 and 50 mph on all of the calibration sections for Highway Performance Monitoring System (HPMS) Appendix J reporting purposes. The raw data were stored on floppy disks and the reporting statistics were generated on a separate computer using the View software provided with the ARAN.

All of the roughness statistics from the ARAN are generated by the signals from the axle and body accelerometers as the unit travels down the roadway. The signals from the accelerometers are processed through both hardware and software filters. The RMSVA and the MAS statistics from the ARAN unit are derived through a software band-pass filter which passes wavelengths of 1 to 300 feet. The RMSVA values are not broken down into values for baselength ranges as they are for the profilometer and as was done for the Dipstick data. Texture is the high-frequency component of roughness and is derived from a software high-pass filter which passes wavelengths of up to 2 feet.

The ARAN was run six times over each calibration section. The average of the first five runs was calculated and the ±10 percent cutoff limitation was checked for each set of data at each site for all of the reporting statistics. Each roughness statistic from the ARAN at each operating speed was regressed against the Dipstick IRI values. Both a linear and a second-degree calibration equation were generated for each data set. The $R^2$ values were computed for each regression fit.

The resulting graphs, equations, and $R^2$ values are shown in Appendix H. It can be seen from Appendix H that the best statistical output from the regression against the Dipstick IRI is the MAS statistic. The MAS statistic does not appear to be as speed-dependent as the other two statistics. The curve fits are only slightly better than the line fits for the MAS statistic. The average Dipstick IRI of both wheel paths shows the highest $R^2$ values as has been seen throughout the Appendix J compliance effort.

The texture statistic shows the worst $R^2$ values for the spectrum of the regression analysis. The 50-mph data are worse than the 30-mph data. The second-degree curve fits exhibit curvature in opposite directions, depending on which IRI value is used for the regression. The scatter in the data is significant, with the 50-mph regressions showing spikes above and below the regression line near texture = 200. The texture statistic does not appear to differentiate between the rough and medium rough sections with unique data.

The RMSVA data from the ARAN are not presented by baselength as they are with the profilometer and the Dipstick program, which was written for this analysis. The RMSVA regressions were slightly better, as far as $R^2$ values are concerned, for the 50-mph data. There were also smaller differences in $R^2$ value between the line fit and the curve fit at 50 mph. The best fit for the 30-mph data was the Dipstick IRI for the outside wheel path, while the best fit for the 50-mph data was the average IRI from both wheel paths.

# CONCLUSIONS

The initial intent of the Appendix J procedures was to provide guidelines to the individual states for determining and reporting pavement roughness statistics. The calibration and reporting procedures outlined in Appendix J are believed to be an excellent attempt at national standardization in the pavement roughness area. The purpose of standardization is to make certain that all state highway authorities use the same procedures for determining surface roughness, using a wide variety of instrumentation. If this were the case, all of the roughness data throughout the United States would be comparable. Comparable roughness data would be a valuable tool for the decision-making process.

After the Appendix J procedures were followed, a number of concerns have become evident. These concerns have to do with making the Appendix J procedures clearer, generally more objective, and less subjective in some areas. This report is not attempting to undermine the standardization process. On the contrary, it is attempting to expand the Appendix J procedures to make them more equitable, enforceable, and repeatable. The Texas SDHPT has invested both time and money in complying with the mandate, and this experience has given Texas SDHPT and CTR some insights which should be considered when revising the Appendix J procedures.

One set of Dipstick data was out of the specified acceptance range for a Class I device. The Dipstick results from the inside wheel path of ATS41 showed an error of 23.568 inches over the 1056 feet. This situation can be viewed in Table 1 and Fig 3. This wheel path should have been rerun according to the Appendix J Class I specifications. Unfortunately, this error was not detected until a week's worth of Dipstick data was brought in from the field, the data transcribed from the forms to the computer, the running-sum profiles generated, and the closure error calculated. To prevent this situation in the future, it is recommended that Class I instrument data be reduced daily and checked for errors. This particular section required lane closure, and re-running would have added to the cost of compliance. All Dipstick data in the forward and reverse directions were averaged, as previously stated. By averaging the IRI's from each of the two runs in each wheel path to produce a single IRI value, the data were smoothed. This averaging process meant that all of the IRI values used for the regressions were within the 19-inches-per-mile limit specified by Appendix J.

The next concern is based on trying to use a wheel-path-dependent instrument and summary statistic to calibrate response-type instruments. The Dipstick and the rod and level survey are manually propelled down a particular wheel path. The IRI values calculated from these surveys are also wheel-path-dependent. The Appendix J mandate does not specify which wheel path is to be used for the regression model. It is apparent from the Austin test section data that the IRI value for a particular pavement section will vary, depending on which wheel path is evaluated. This feature of the pavement roughness is more apparent on the medium and rough sections than on the smooth sections. This wheel-path dependency and the calibration of the response-type instrumentation are of legitimate concern since the majority of roughness instrumentation throughout the United States is response-type devices.

The exact location of the wheel path within a travel lane is another issue which is not addressed by the current Appendix J procedures. Although this particular issue does not appear to be as significant as the half-car versus the quarter-car model, the wheel-path location is something that needs to be considered. The Texas experience has shown that within one state there exists a large variety of wheel-base widths on the vehicle-mounted roughness instruments. Examples of the these differences have already been discussed in this report. The main issue with regard to the wheel-path location is standardization. For roughness data to be comparable between the states, this issue must be addressed and a standard applied.

The calculation of the IRI statistic from elevation data is another source of concern. The BASIC program listing for the IRI calculation is referenced in the Appendix J mandate, but it has become apparent that mistakes can and will occur during the implementation of this program listing. This situation has been discussed and could lead to doubt as to whether or not the IRI statistic is being calculated correctly. Obviously, this situation is not acceptable if data calculated using the IRI program are to be compared from programmer to programmer and from state to state. This problem could be solved very easily by providing a set of elevation data and the resulting calculated IRI value to the users for validation of their individual IRI programs.

The correlation by regression equation of the different types of pavement roughness evaluation equipment is a source of error in the standardization mandate. The Appendix J mandate leaves the decision as to the degree to which the correlation equations will be reported by the individual states to the discretion of those states. The relationships between Class I and Class III instruments are not linear. The relationships between Class I and Class II instruments *are* linear, but the slopes of the resulting lines are not equal to 1 and the y-intercept is not zero. A second-degree curve fit of Class III instrumentation yields much better $R^2$ values and, therefore, provides better-fitting regression models for the standardization of the IRI statistic. It would not seem reasonable to take the equations to the third or fourth degree since these equations yield less than desirable results. Examples of these curve fits can be seen in Figs 8 and 9. These figures exhibit higher $R^2$ values than their linear and second-degree counterparts in Appendix F, but the IRI-to-WSV relationships could not be used as calibration equations.

The specified approach distance recommended in the Appendix J mandate is 150 feet. CTR decided to move this distance back to 200 feet. This initial decision was based on past experience within the Texas SDHPT instrumentation staff. After looking at the Walker SIometer data from the Austin test sections, project staff decided that this distance needed to be moved back to 500 feet. This added distance yielded more repeatable outputs from the RTRRM instrumentation calibrated for Texas. It seems that the extra distance allowed the instruments more time to stabilize before the roughness measurements were begun. The 500 feet also allowed the operators more time to get the vehicle lined up on the wheel path at the 50-mph calibration speed.

The practice of throwing away data which are outside of the specified ±10 percent cutoff for calculating the average roughness index for each vehicle on a particular calibration site does not seem consistent with acceptable statistical procedures. These outlying data points could have a significant impact on the final regression equations generated for the individual instruments. The repeatability and the speed-dependency of RTRRM instruments have historically yielded problems, which Appendix J is attempting to resolve. If calibration of individual instruments is the goal of the Appendix J mandate, then all of the roughness data collected during the calibration process should be included.

Verification of calibration is specifically demanded immediately before roughness surveys are conducted with a particular instrument. Appendix J also states that verification of calibration will be conducted every month or every 2,000 miles of vehicle travel. This mandate is of particular concern to Texas and other states which have large land areas and highway networks to inventory. In the specific case of Texas, the RTRRM fleet of instruments is spread over several regions throughout the state. The Austin test sections used for the Appendix J procedures are as centrally located as possible, but the edges of the state are in excess of 500 miles from these sections. Traveling to and from the calibration sites uses 1,000 of the specified 2,000 miles. This leaves 1,000 miles of roadway which can be inventoried before verification of calibration becomes necessary. Also, no mechanism is in place to verify that a vehicle-mounted instrument is still in calibration after traveling the 500 miles and arriving at the job sites. The majority of the time and money spent in collecting roughness data would be spent verifying calibration of the instrumentation.

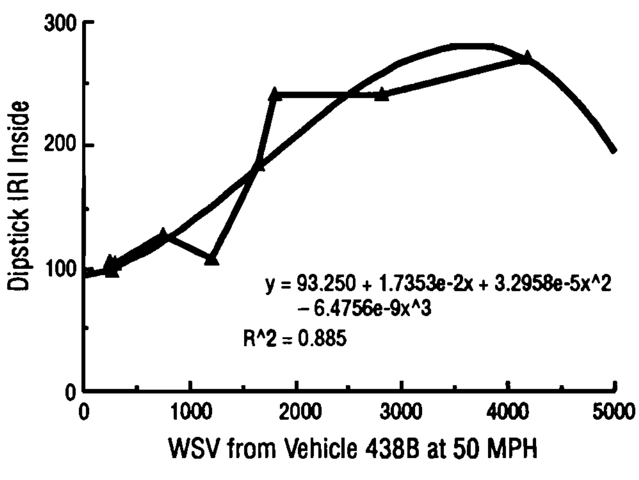


**Fig 8. Third degree curve fit of SIometer 438B data at 50 mph.**

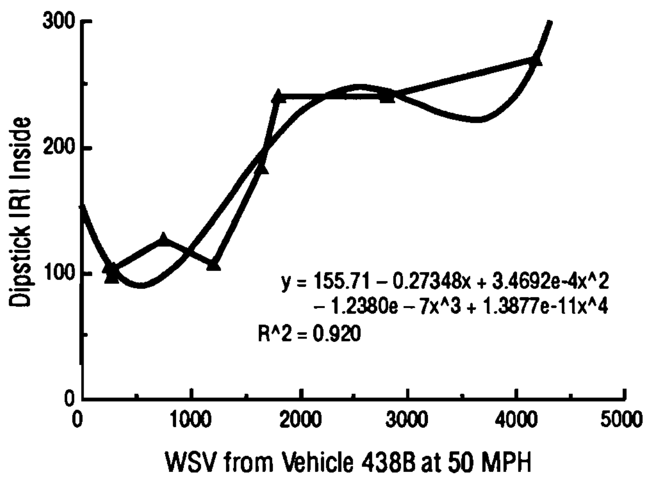


**Fig 9. Fourth degree curve fit for SIometer 438B data at 50 mph.**

# RECOMMENDATIONS

CTR and the Texas SDHPT have been as diligent as possible in following the recommended Appendix J calibration procedures. The Texas SDHPT is very interested in acquiring the most accurate and repeatable roughness data possible. This report is evidence of the determination of the Texas SDHPT to comply with the federal regulations outlined in the Highway Performance Monitoring System (HPMS) Appendix J. The conclusions reached and discussed above are meant to help provide some insight into the problems CTR and the Texas SDHPT had in following the pavement roughness calibration guidelines. The recommendations included in this section of the research report are intended to provide the means for making the Appendix J procedures less subjective and, therefore, more repeatable.

The Appendix J procedures could be called standardization procedures instead of calibration procedures. The objective of the Highway Performance Monitoring System (HPMS) Appendix J is to standardize the output of the various pavement roughness instruments. The standardized reporting statistic is identified as IRI. The standard IRI for the regression model is to be determined using a Class I profiling instrument and the appropriate surveying technique. If a Class II instrument is to be used for the standardization, its accuracy must be "validated through field comparisons of known profiles." The National Bureau of Standards is developing proposed standards for accomplishing this task (Ref 1). The proposed standards would in actuality be a set of dynamic calibration procedures. The Class II equipment manufacturers already have the static calibration procedures for each piece of equipment. These dynamic and static procedures would be closer to the accepted meaning of the term calibration, with the dynamic procedures being a verification of calibration.

The calibration by regression equation of RTRRM instruments must be accomplished by using both wheel paths on a travel lane if the reported equations are to be considered repeatable and standardized. The average roughness of both wheel paths reported by the Class I device will give the best correlations with the travel lane roughness reported by RTRRM devices. Closely associated with the wheel-path issue is the width between the wheel paths. The roughness of the two wheel paths in a travel lane can and will vary. This is especially true on the rough and medium-rough sections of pavement used for the regression modelling. The great variability between types of vehicles used to house pavement roughness evaluation instrumentation causes differences in wheel-path spacings. These issues must be addressed and standardized to produce the most effective regression models for comparisons between instruments and between states.

The operator-ready or approach time for stabilizing the dynamic instrumentation should be moved back from the specified 150 feet to at least 200 feet and probably to 500 feet. The 150-foot to 200-foot mandate should be concerned with the homogeneity of the pavement immediately before the start of the test section. It would also seem appropriate to require another 150 feet of homogeneous pavement at the end of each test section. The lack of stability made itself known while the researchers were attempting to meet the ±10 percent cutoff for repeat runs using the Texas SDHPT Walker Slometer, as has been discussed earlier in this text. If this 500-foot approach distance were made the standard and the homogeneous sections were required, RTRRM instrumentation would have a greater opportunity to make the ±10 percent cutoff limit. The Texas SDHPT Class II profilometer already has a 200-foot approach buffer in its software to make its output more repeatable. It would seem reasonable that, to obtain repeatable results from Class III RTRRM devices, longer approaches are necessary.

The ranking of the roughness ranges may have to be altered. The rough sections (IRI > 320) were difficult to locate around the Austin area. Indeed, some of the "rough sections" showed one wheel path in the rough range and one wheel path in the medium range. This situation is more evident when one takes into consideration the fact that two of the roughest Austin calibration sections will be completely reconstructed this year by Travis County: the point being that pavement sections with IRI values greater than 320 are very rough and dangerous at travel speeds approaching 50 mph. As a matter of fact, these sections are hard to find in Texas with legal speed limits of 50 mph. If they exist, they are prime candidates for reconstruction or, at a minimum, overlay. If this situation is consistent with conditions in the remainder of the states, then it would be advisable to alter the medium and rough ranges toward the smooth end of the IRI scale.

The curve-fitting procedures need to be standardized. For the best regression models on the RTRRM instruments, it was found from the CTR research effort that second-degree curve fits produced the highest $R^2$ values. The linear regression equations generated for the Texas compliance to Appendix J were good when used with the Class II profilometer, but the y-axis did not go through the origin and the slope of the line was not equal to 1 as would be expected in a perfect calibration. The $R^2$ values for the linear equations for the Class III RTRRM instruments were better if the IRI average of both wheel paths from the Class I Dipstick was used in the regression model. Since the idea of the Appendix J procedures seems to be standardization rather than calibration of the

RTRRM instruments, it would be logical to mandate the use of second-degree regression equations.

The time and distance restrictions placed on the verification of calibration need to be modified to reflect the concerns of larger states. The size of the state and the roadway mileage of the State of Texas, for example, make the 2,000-mile or once-a-month mandate for verification of calibration an expensive and time-consuming burden. There are no simple solutions to this problem. One possible solution would be the establishment of regional verification of calibration sites for regressing Class II profilometer output with that of the locally-operated RTRRM instrumentation. The Class II profilometer could be calibrated against a Class I instrument at a centrally-located site. The profilometer would then be used to classify and establish the roughness range of the regional sites. The regional sites would contain more than the nine specified sites to obtain more data points and, it is hoped, better correlation equations. The profilometer roughness calibration would have to be verified before and after the trip to the regional sites to assure that the travel distances had not changed the roughness response of the vehicle and the associated instrumentation.

The discarding of outlying data points from the instrument's response to the surface roughness is of concern from the standpoint of statistical analysis. If calibration of the instrumentation is the desired outcome of Appendix J, then it would seem invalid to throw out calibration data. It would be more reasonable to require more runs on each calibration section. The statistical mean value for each instrument's response to each calibration section could then be computed. This mean value would correspond to the average RRI value specified in Appendix J. A reasonable standard deviation for each data set could be established. This number of standard deviations could be determined based on the individual instrument's repeatability and what could be reasonably expected from past experience with the individual instrument type.

The Appendix J procedures are believed to be an excellent attempt at setting national standards and policies governing the collection and reporting of pavement roughness information. The standardization of pavement surface roughness reporting can be enhanced if some or all of the recommendations above are considered during any revisions of the Highway Performance Monitoring System (HPMS) Field Manual Appendix J procedures. It would seem impossible to address every issue from every state because of the number of different instruments used to obtain pavement surface roughness statistics. By eliminating as much subjectivity as possible from the mandated procedures, the standardization process could be greatly enhanced.

# FUTURE RESEARCH TOPICS

If Class II profilometers are available to a state, then there must be a standard verification of calibration procedure to make certain that the dynamic response to pavement roughness is in calibration. It is too expensive and time-consuming to expect Class I surveying techniques to be utilized on nine or more calibration sections to verify a Class II instrument's output. Some research in this area could lead to an acceptable verification procedure which could be uniformly applied to all of the states.

If the states are allowed to set up outlying calibration sites, a procedure must be developed and implemented. Research to determine the number of sites in each region, how the IRI values for each section would be established, and the procedures for verification of calibration would be needed. For instance, if the Class II profilometer were sent out to establish the regional RTRRM calibration sites, how would its calibration be verified, how many runs would be needed to establish the final IRI from the profilometer, etc.?

For states such as Texas which utilize roughness statistics other than IRI, some procedures need to be established for correlating the statistics to Class I instrumentation. The differences between the quarter-car statistics need to be addressed in greater depth to assure that the procedures are producing valid correlations. For example, Texas uses the 4- and 16-foot-baselength values of the RMSVA statistic to calculate the SI and MO statistics generated by the profilometer. These baselengths may or may not be correct for correlating SI and MO to the quarter-car IRI model.

Research could be undertaken to determine whether or not the Class I surveys need to include elevation data measured to the nearest 0.001 inch. If the data were collected with less accuracy and yielded the same summary roughness statistics, it could be possible to reduce the time and cost of producing Class I surveys. The auto-read version of the Face Dipstick might be made useable if the sensitivity of the instrument could be reduced without jeopardizing the integrity of the roughness statistics.

# REFERENCES


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5. Tompkins, Joel D., "Evaluation of Programs for Determining IRI from Disptick Format Data," Technical Memo 969-2, Center for Transportation Research, The University of Texas at Austin, July 13, 1989.

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

7. Tompkins, Joel D., "Comparison of RMSVA's as Calculated from the Disptick and Profilometer Data," Technical Memo 969-4, Center for Transportation Research, The University of Texas at Austin, September 14, 1989.

# APPENDIX A. DIPSTICK REPORTING FORM

## MANUAL DIPSTICK READINGS

TEST SITE:________________ DATE:________________

WHEEL PATH:________________ START TIME:________________

STOP TIME:________________

| | Distance (ft) | DIP Rdgs (in) | Distance (ft) | DIP Rdgs (in) | Distance (ft) | DIP Rdgs (in) |
|---|---|---|---|---|---|---|
| | | | | | | |
| 1 | 1 | | 31 | | 61 | |
| 2 | 2 | | 32 | | 62 | |
| 3 | 3 | | 33 | | 63 | |
| 4 | 4 | | 34 | | 64 | |
| 5 | 5 | | 35 | | 65 | |
| 6 | 6 | | 36 | | 66 | |
| 7 | 7 | | 37 | | 67 | |
| 8 | 8 | | 38 | | 68 | |
| 9 | 9 | | 39 | | 69 | |
| 10 | 10 | | 40 | | 70 | |
| 11 | 11 | | 41 | | 71 | |
| 12 | 12 | | 42 | | 72 | |
| 13 | 13 | | 43 | | 73 | |
| 14 | 14 | | 44 | | 74 | |
| 15 | 15 | | 45 | | 75 | |
| 16 | 16 | | 46 | | 76 | |
| 17 | 17 | | 47 | | 77 | |
| 18 | 18 | | 48 | | 78 | |
| 19 | 19 | | 49 | | 79 | |
| 20 | 20 | | 50 | | 80 | |
| 21 | 21 | | 51 | | 81 | |
| 22 | 22 | | 52 | | 82 | |
| 23 | 23 | | 53 | | 83 | |
| 24 | 24 | | 54 | | 84 | |
| 25 | 25 | | 55 | | 85 | |
| 26 | 26 | | 56 | | 86 | |
| 27 | 27 | | 57 | | 87 | |
| 28 | 28 | | 58 | | 88 | |
| 29 | 29 | | 59 | | 89 | |
| 30 | 30 | | 60 | | 90 | |

TAKEN BY:________________ RECORDED BY:________________

COMMENTS:________________________________

# APPENDIX B. RUNNING-SUM DIPSTICK PLOTS OF CALIBRATION SECTIONS

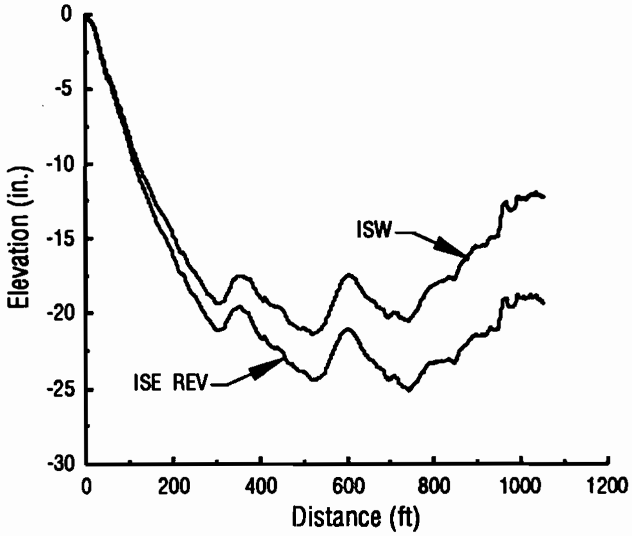



**Fig B.1. Forward and reverse running-sum plots of ATS01 inside wheel path.**

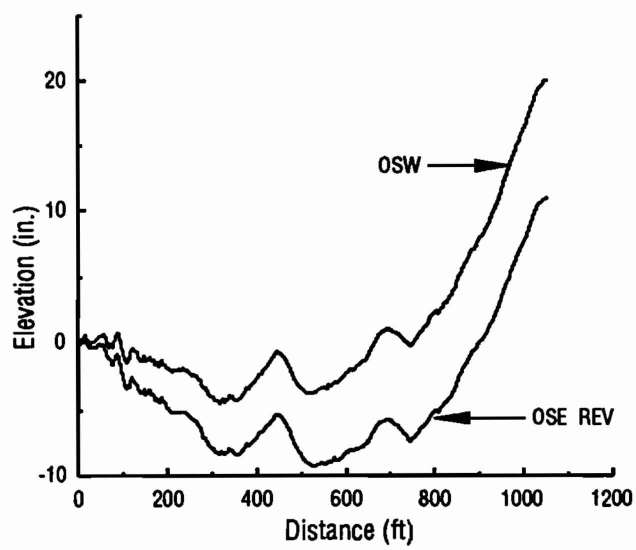



**Fig B.2. Forward and reverse running-sum plots of ATS01 outside wheel path.**

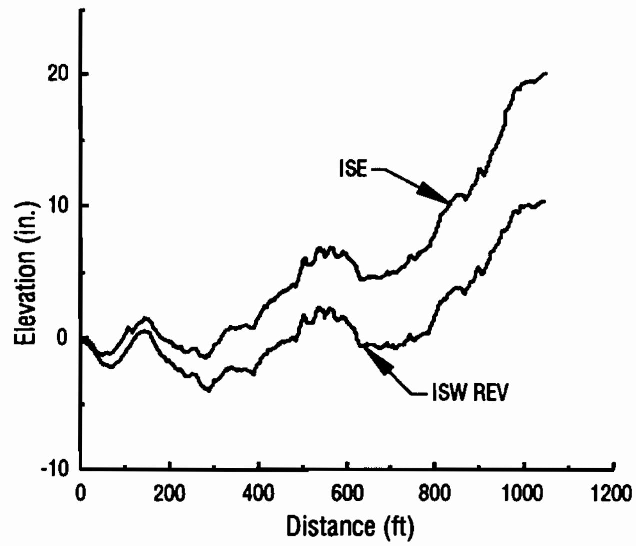



**Fig B.3. Forward and reverse running-sum plots of ATS04 inside wheel path.**

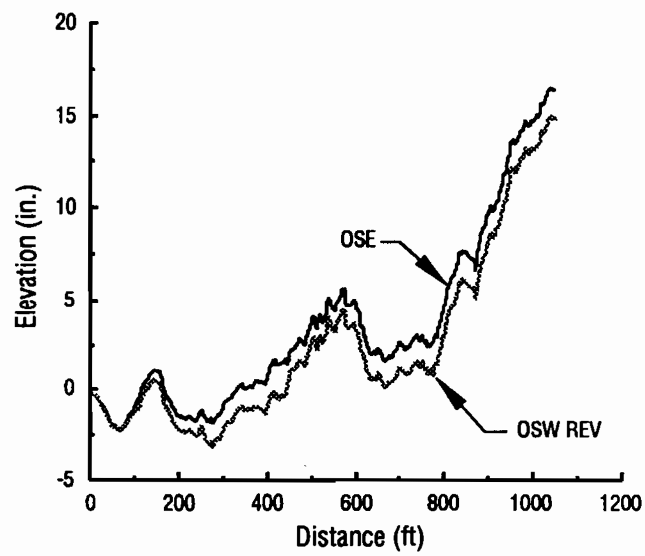
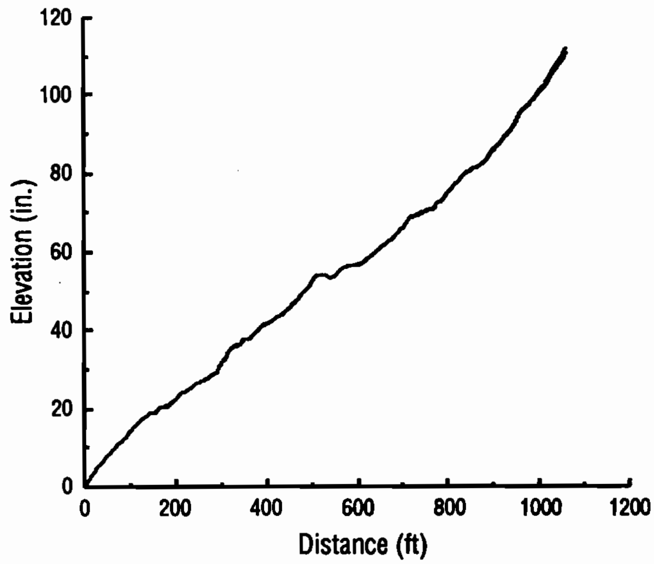



**Fig B.4. Forward and reverse running-sum plots of ATS04 outside wheel path.**




NOTE: ISE and ISW Rev are superimposed over one another.

**Fig B.5. Forward and reverse running-sum plots of ATS16 inside wheel path.**

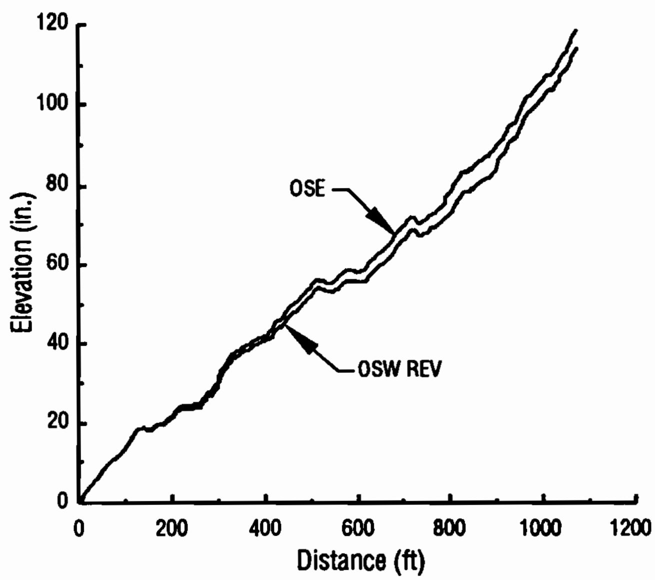



**Fig B.6. Forward and reverse running-sum plots of ATS16 outside wheel path.**

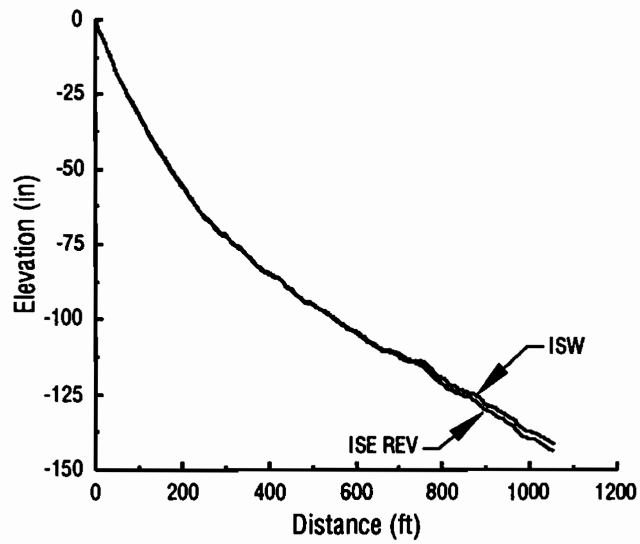



**Fig B.7. Forward and reverse running-sum plots of ATS21 inside wheel path.**

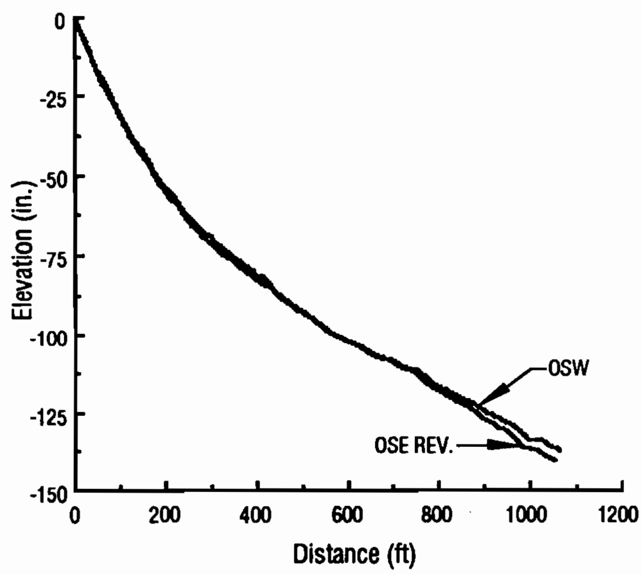



**Fig B.8. Forward and reverse running-sum plots of ATS21 outside wheel path.**

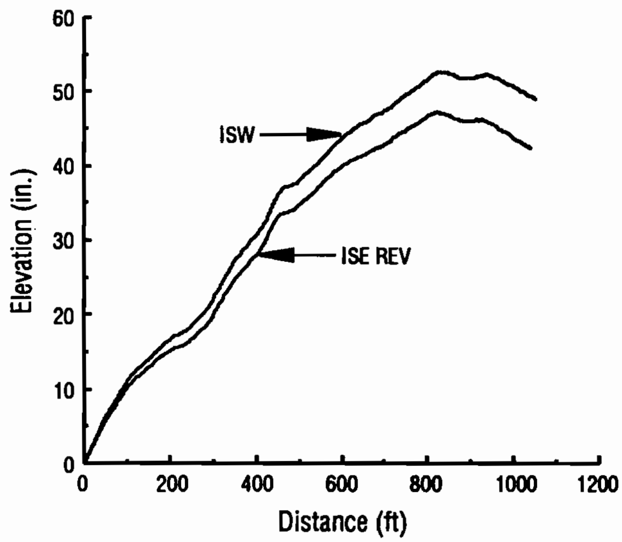



**Fig B.9. Forward and reverse running-sum plots of ATS25 inside wheel path.**

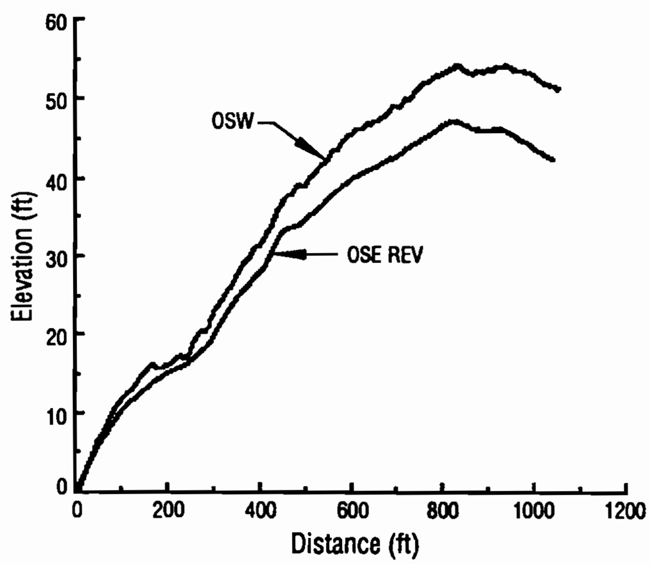



**Fig B.10. Forward and reverse running-sum plots of ATS25 outside wheel path.**

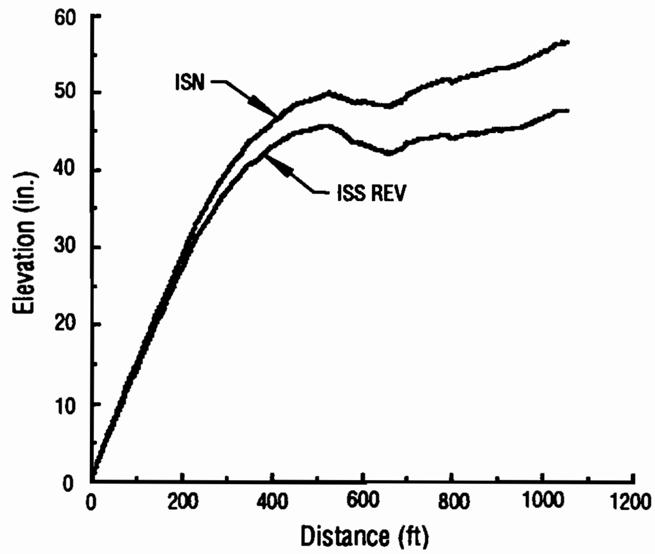



**Fig B.11. Forward and reverse running-sum plots of ATS31 inside wheel path.**

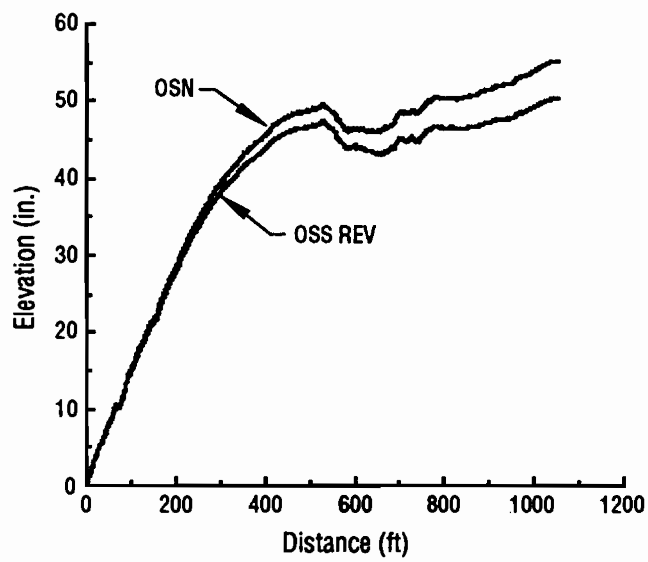



**Fig B.12. Forward and reverse running-sum plots of ATS31 outside wheel path.**

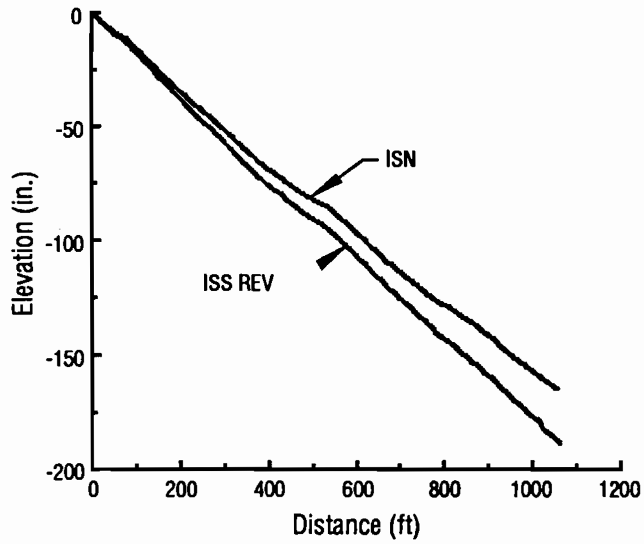



**Fig B.13. Forward and reverse running-sum plots of ATS41 inside wheel path.**

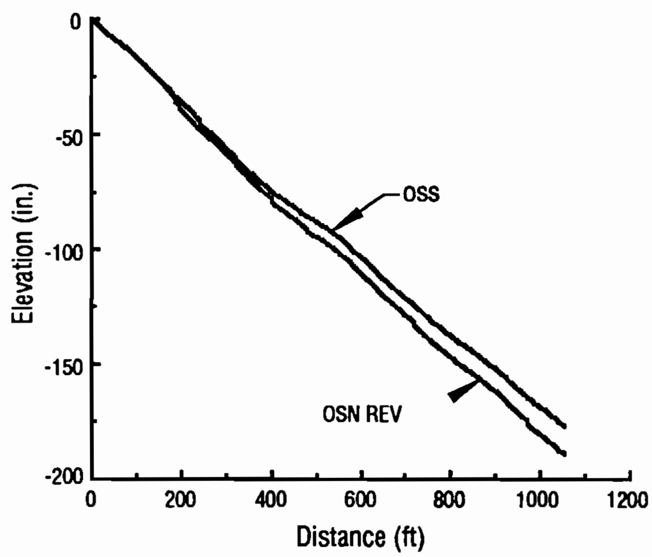



**Fig B.14. Forward and reverse running-sum plots of ATS41 outside wheel path.**

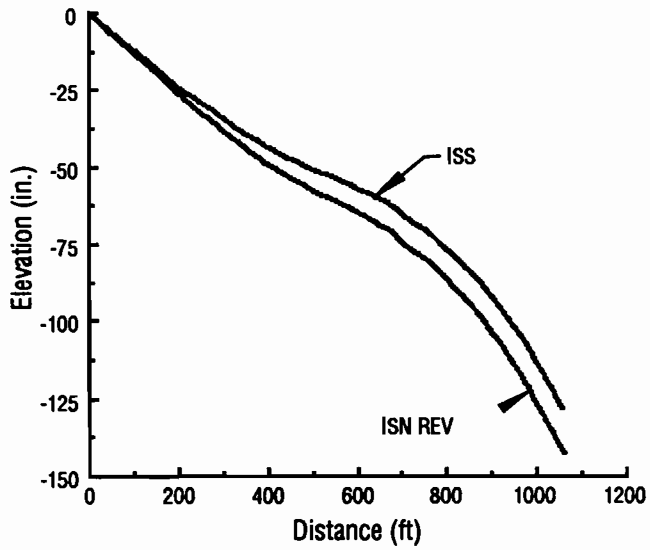
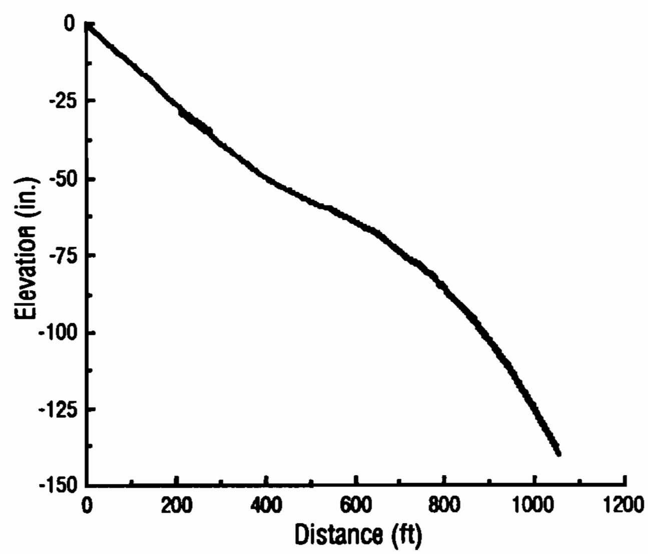



**Fig B.15. Forward and reverse running-sum plots of ATS42 inside wheel path.**




NOTE: OSS and OSN Rev graphs are superimposed over one another.

**Fig B.16. Forward and reverse running-sum plots of ATS42 outside wheel path.**

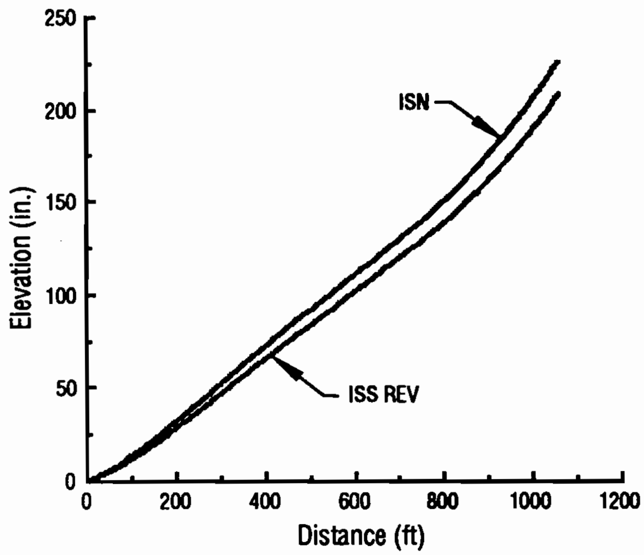
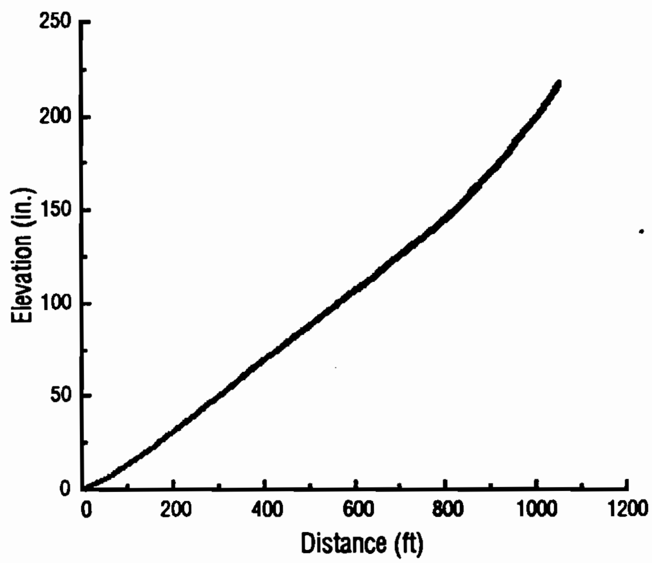



**Fig B.17. Forward and reverse running-sum plots of ATS43 inside wheel path.**




NOTE: OSN and OSS Rev graphs are superimposed over one another.

**Fig B.18. Forward and reverse running-sum plots of ATS43 outside wheel path.**

# APPENDIX C. PROFILOMETER OUTPUT SAMPLE

1056 FT. SECTION BEGINS 0 FT. FROM MARK 200 IN FILE a:01.1

STEP: 0.18 IN. AT 312.0 FT.

| BASE LENGTH | RIGHT | LEFT | COMBINED | ESTIMATED SI |
|---|---|---|---|---|
| 0.5 | 61.89 | 60.59 | 61.24 | 2.94 |
| 1.0 | 26.63 | 23.41 | 25.02 | 2.90 |
| 2.0 | 11.38 | 9.48 | 10.43 | 2.48 |
| 4.0 | 5.16 | 4.04 | 4.60 | 2.09 |
| 8.0 | 1.97 | 1.77 | 1.87 | 2.17 |
| 16.0 | 1.00 | 0.87 | 0.93 | 2.01 |
| 32.0 | 0.35 | 0.33 | 0.34 | 2.50 |
| 64.0 | 0.13 | 0.13 | 0.13 | 2.74 |
| 128.0 | 0.03 | 0.03 | 0.03 | 3.10 |

MO (MRM SIMSTAT) (COUNTS/.2 MILE): 127.88

FLEXIBLE PAVEMENT SERVICEABILITY: 2.20

INTERNATIONAL ROUGHNESS INDEX (Right wheel) (in/mile): 229.05

INTERNATIONAL ROUGHNESS INDEX (Left wheel) (in/mile): 180.20

****************************************************************

# APPENDIX D. PROFILOMETER VS. DIPSTICK CALIBRATION PLOTS

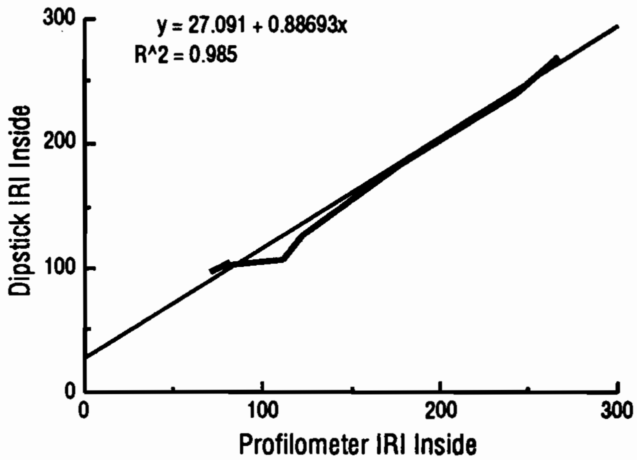



**Fig D.1. Linear fit of Dipstick IRI inside wheel paths vs. profilometer IRI inside wheel paths at 20 mph.**

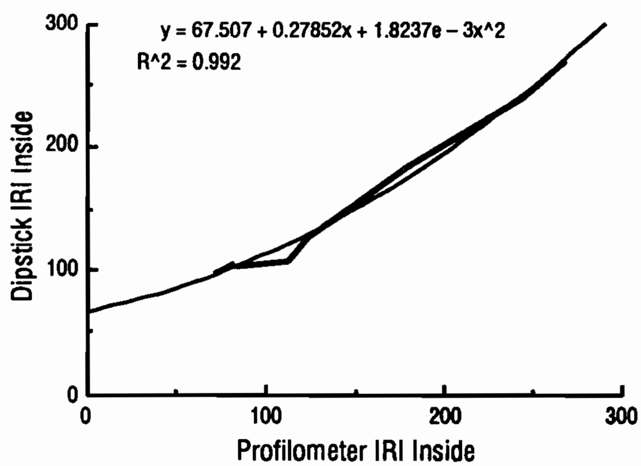



**Fig D.2. Second degree fit of Dipstick IRI inside wheel paths vs. profilometer IRI inside wheel paths at 20 mph.**

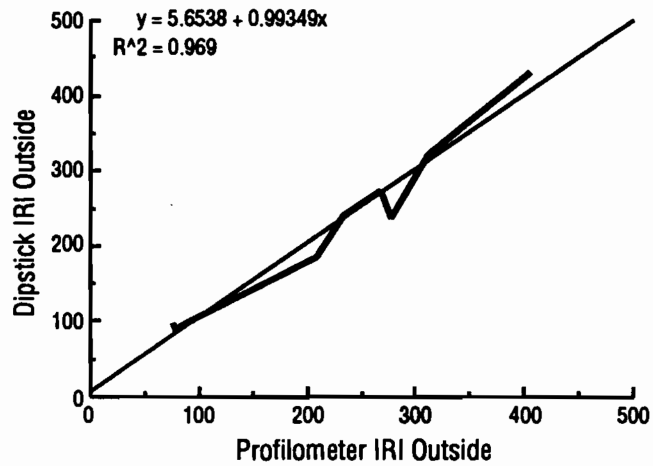



Fig D.3. Linear fit of Dipstick IRI outside wheel paths vs. profilometer IRI outside wheel paths at 20 mph.

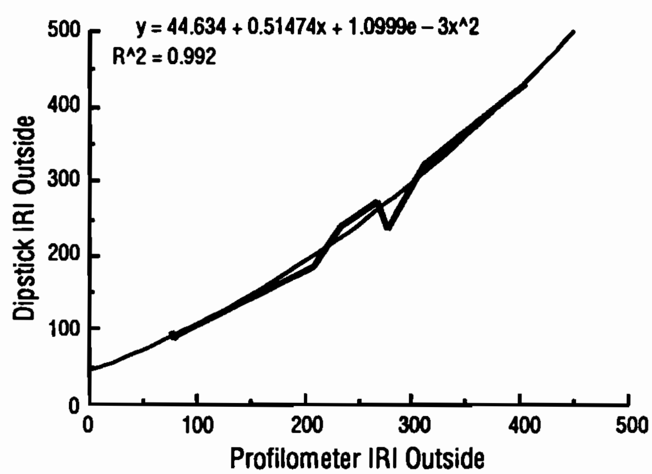



Fig D.4. Second degree fit of Dipstick IRI outside wheel paths vs. profilometer IRI outside wheel paths at 20 mph.

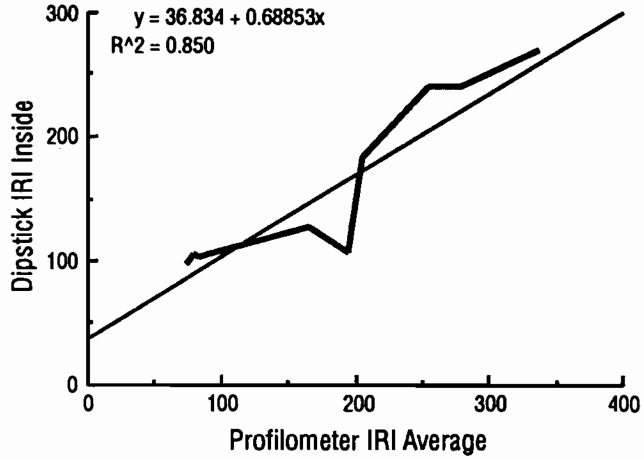



**Fig D.5. Linear fit of Dipstick IRI inside wheel paths vs. profilometer IRI for average of both wheel paths at 20 mph.**

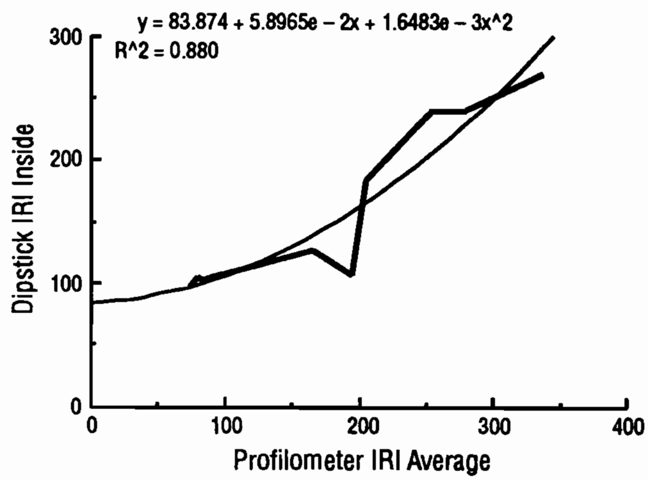



**Fig D.6. Second degree fit of Dipstick IRI inside wheel paths vs. profilometer IRI for average of both wheel paths at 20 mph.**

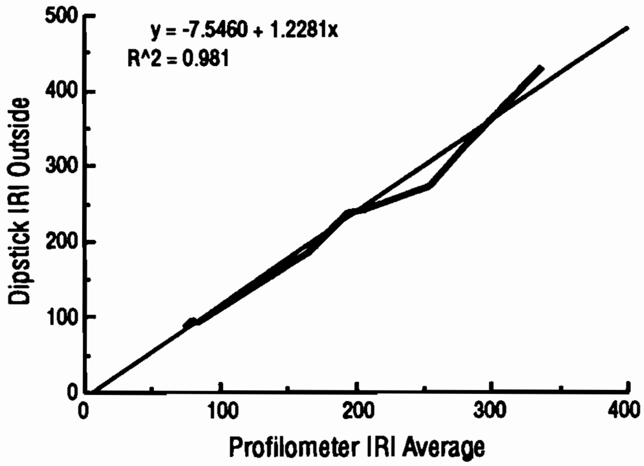



**Fig D.7. Linear fit of Dipstick IRI outside wheel paths vs. profilometer IRI for average of both wheel paths at 20 mph.**

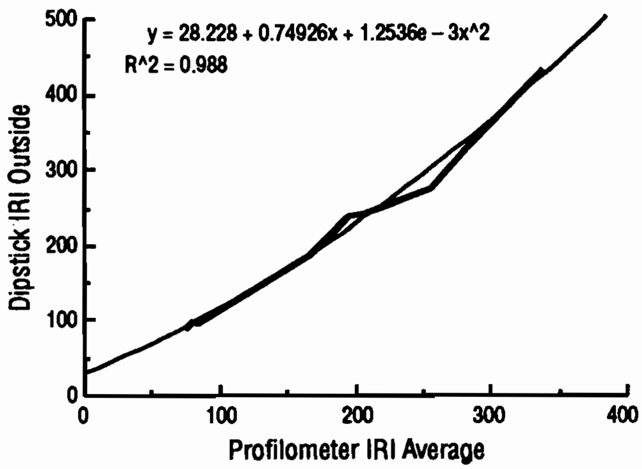



**Fig D.8. Second degree fit of Dipstick IRI outside wheel paths vs. profilometer IRI for average of both wheel paths at 20 mph.**

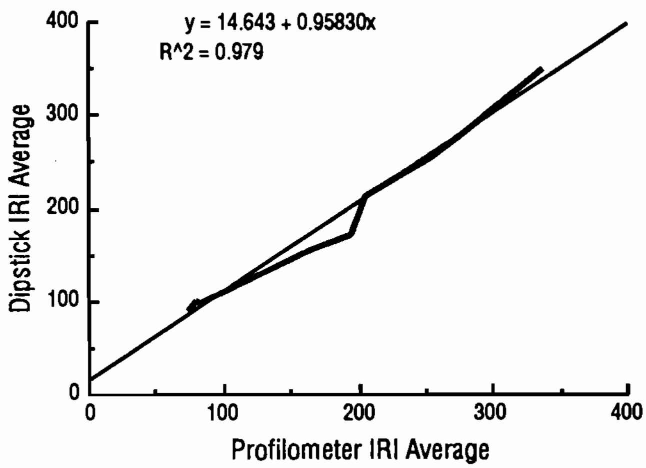



**Fig D.9. Linear fit of Dipstick IRI for average of both wheel paths vs. profilometer IRI for average of both wheel paths at 20 mph.**

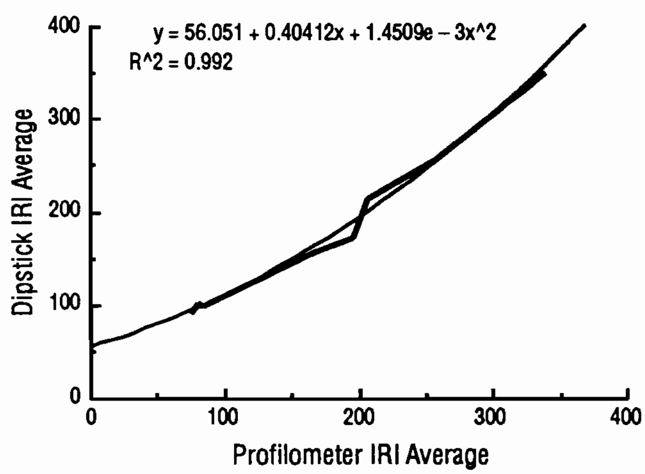



**Fig D.10. Second degree fit of Dipstick IRI for average of both wheel paths vs. profilometer IRI for average of both wheel paths at 20 mph.**

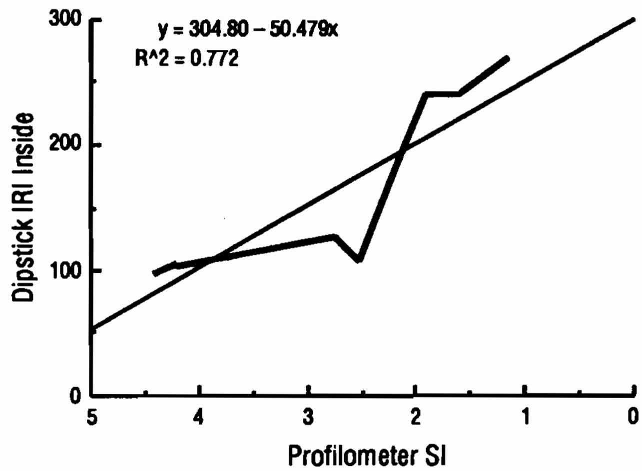



**Fig D.11. Linear fit of Dipstick IRI inside wheel paths vs. profilometer SI values at 20 mph.**

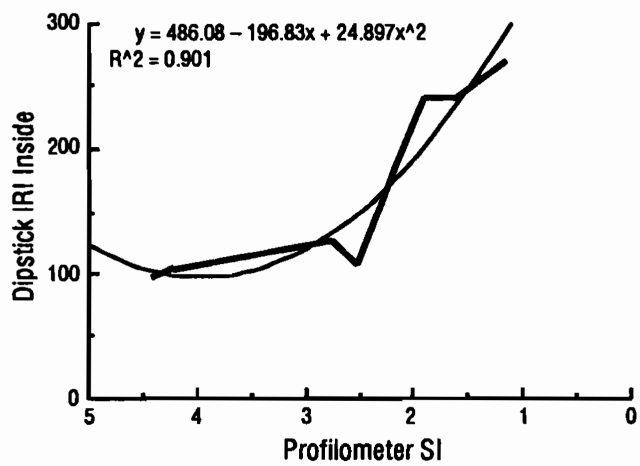



**Fig D.12. Second degree fit of Dipstick IRI inside wheel paths vs. profilometer SI values at 20 mph.**

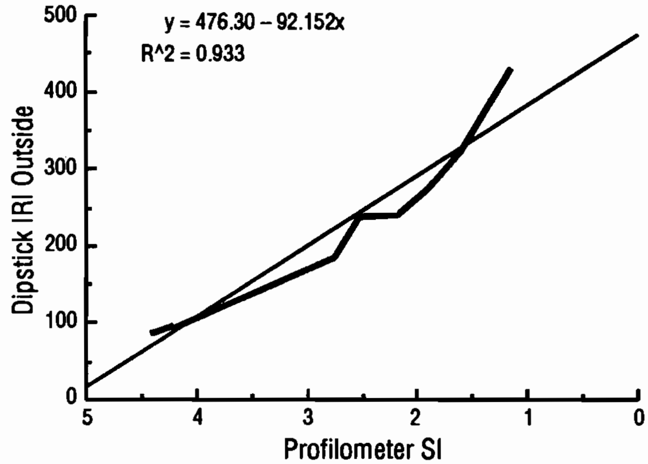



**Fig D.13. Linear fit of Dipstick IRI outside wheel paths vs. profilometer SI values at 20 mph.**

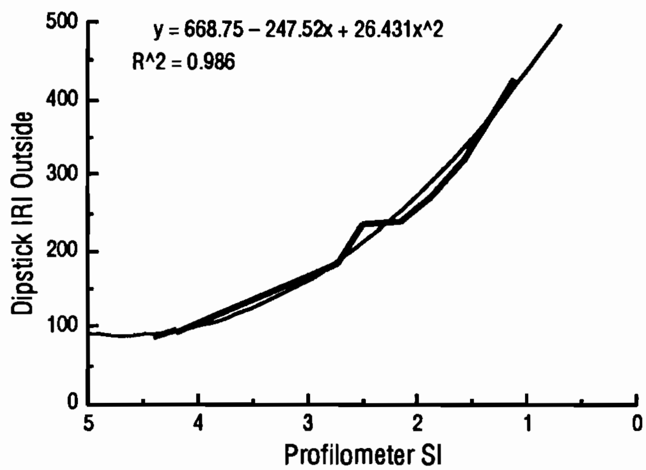



**Fig D.14. Second degree fit of Dipstick IRI outside wheel paths vs. profilometer SI values at 20 mph.**

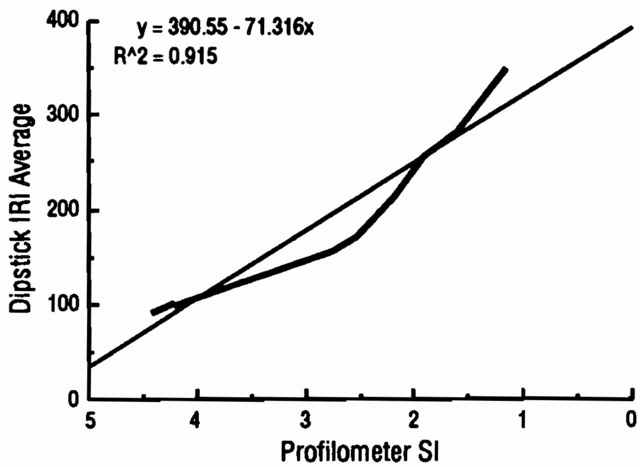



**Fig D.15. Linear fit of Dipstick IRI average of both wheel paths vs. profilometer SI values at 20 mph.**

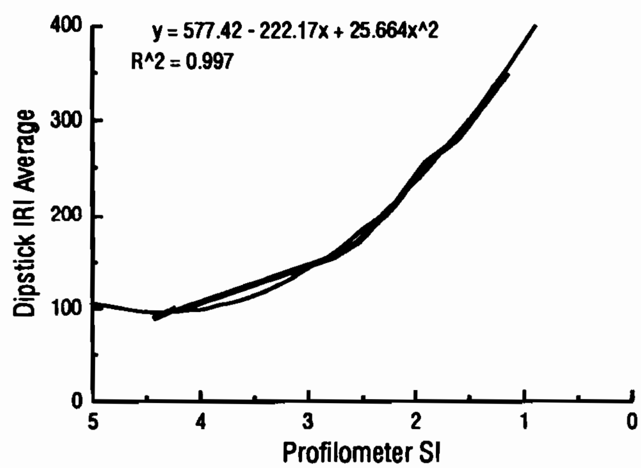



**Fig D.16. Second degree fit of dipstick IRI average of both wheel paths vs. profilometer SI values at 20 mph.**

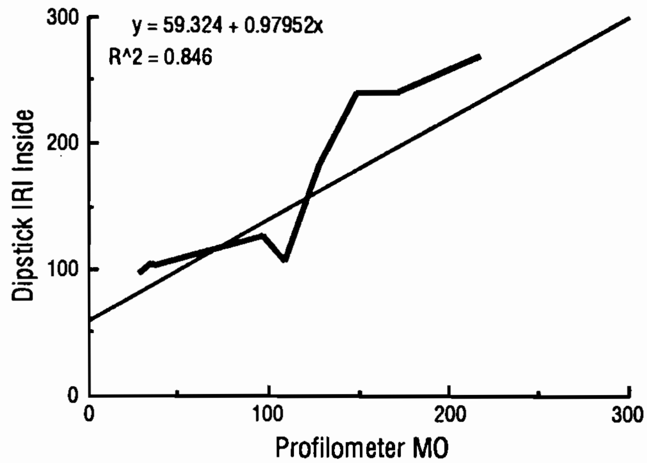



**Fig D.17. Linear fit of Dipstick IRI inside wheel paths vs. profilometer MO values at 20 mph.**

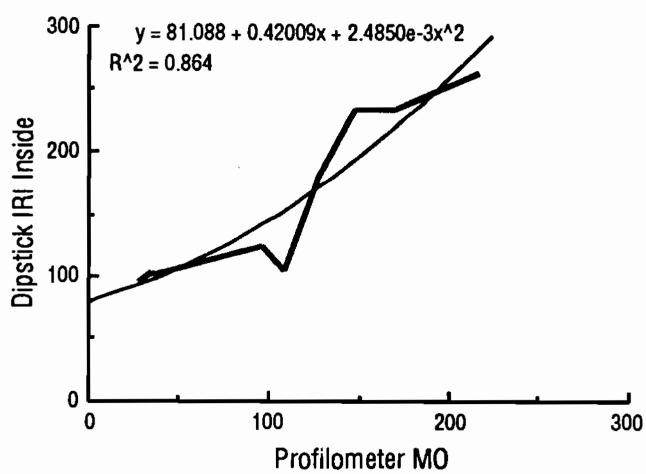



**Fig D.18. Second degree fit of Dipstick IRI inside wheel paths vs. profilometer MO values at 20 mph.**

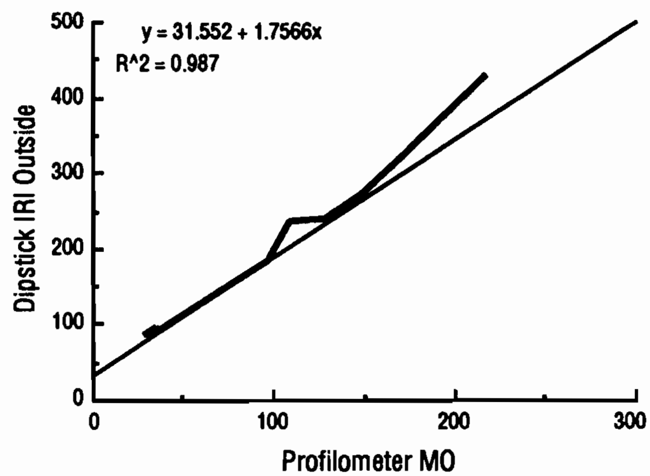



Fig D.19. Linear fit of Dipstick IRI outside wheel paths vs. profilometer MO values at 20 mph.

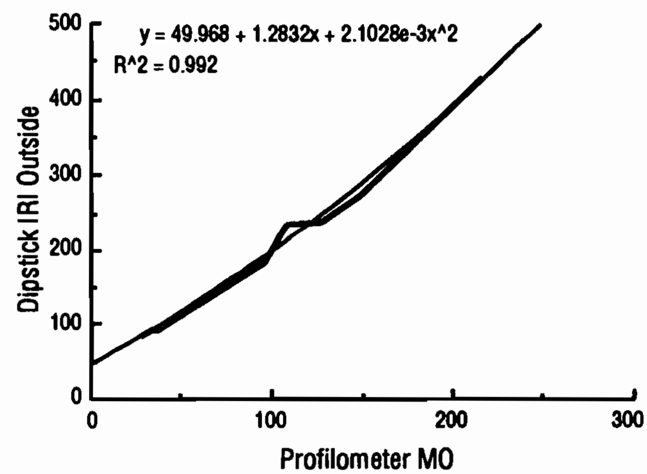



Fig D.20. Second degree fit of Dipstick IRI outside wheel paths vs. profilometer MO values at 20 mph.

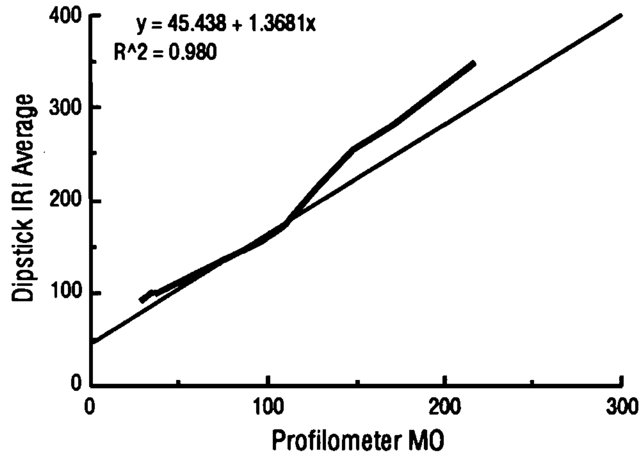



Fig D.21. Linear fit of Dipstick IRI average of both wheel paths vs. profilometer MO values at 20 mph.

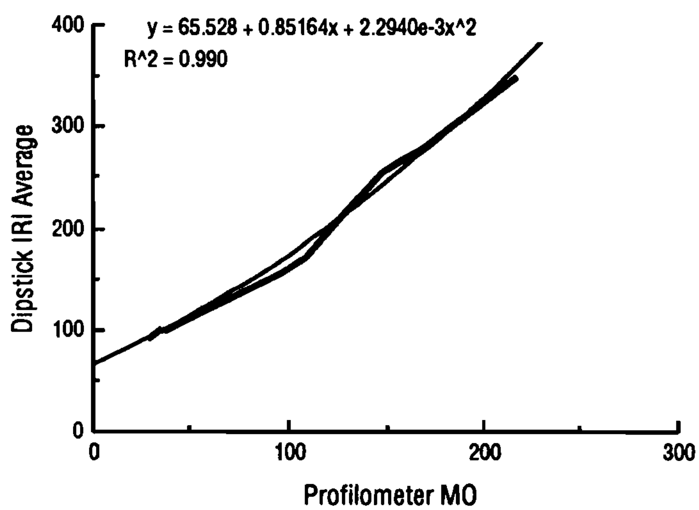



Fig D.22. Second degree fit of Dipstick IRI average of both wheel paths vs. profilometer MO values at 20 mph.

# APPENDIX E. RTRRM INSTRUMENT REPORTING FORMS

## Mays Meter Calibration Reporting Form

Date:________________ Operator:________________

Alpha #:________________ Beta #:________________

Trailer MES#:____________ Readout ID#:____________

Vehicle ID#:____________ Weather:________________

Odometer :____________ ATS #:________________

| Run # | Speed | Cnts | Est. SI | Run # | Speed | Cnts | Est. SI |
|---|---|---|---|---|---|---|---|
| 1 | 30 | | | 1 | 50 | | |
| 2 | 30 | | | 2 | 50 | | |
| 3 | 30 | | | 3 | 50 | | |
| 4 | 30 | | | 4 | 50 | | |
| 5 | 30 | | | 5 | 50 | | |
| 6 | 30 | | | 6 | 50 | | |
| AVERAGE 1 | | | | AVERAGE 1 | | | |
| 7 | 30 | | | 7 | 50 | | |
| AVERAGE 2 | | | | AVERAGE 2 | | | |
| 8 | 30 | | | 8 | 50 | | |
| AVERAGE 3 | | | | AVERAGE 3 | | | |
| 9 | 30 | | | 9 | 50 | | |
| AVERAGE 4 | | | | AVERAGE 4 | | | |
| 10 | 30 | | | 10 | 50 | | |
| AVERAGE 5 | | | | AVERAGE 5 | | | |

Reporting Instructions:

1. Make 6 runs at each reporting speed, average the counts (cnts), and enter in Average 1 row.
2. Calculate (0.10 * Average 1) = X, X represents 10% of Average 1.
3. Calculate range values: (Average 1 + X =) and (Average 1 - X=).
4. Compare Runs 1 thru 6 with range values; If at least 5 are within the range, STOP.
5. If less than 5 remain, make runs 7 thru 10 as necessary and recalculate the averages and ranges until 5 "good" runs and the resulting average are obtained.

## Slometer Roughness Calibration Reporting Form

Date:________________ Operator:____________________

Vehicle ID #:__________ Slometer MES #:______________

Acceler. ID #:__________ Weather:______________________

ATS #:______________ Calibration Coefficient:________

Odometer:___________

| Run # | Speed | SI # | WSV # | Run # | Speed | SI # | WSV # |
|---|---|---|---|---|---|---|---|
| 1 | 30 | | | 1 | 50 | | |
| 2 | 30 | | | 2 | 50 | | |
| 3 | 30 | | | 3 | 50 | | |
| 4 | 30 | | | 4 | 50 | | |
| 5 | 30 | | | 5 | 50 | | |
| 6 | 30 | | | 6 | 50 | | |
| AVERAGE 1 | | | | AVERAGE 1 | | | |
| 7 | 30 | | | 7 | 50 | | |
| AVERAGE 2 | | | | AVERAGE 2 | | | |
| 8 | 30 | | | 8 | 50 | | |
| AVERAGE 3 | | | | AVERAGE 3 | | | |
| 9 | 30 | | | 9 | 50 | | |
| AVERAGE 4 | | | | AVERAGE 4 | | | |
| 10 | 30 | | | 10 | 50 | | |
| AVERAGE 5 | | | | AVERAGE 5 | | | |

### Reporting Instructions:

1. Make 6 runs at each reporting speed, average the data, and enter in Average 1 row.
2. Calculate (0.10 * Average 1) = X, X represents 10% of Average 1.
3. Calculate range values: (Average 1 + X =) and (Average 1 - X=).
4. Compare Runs 1 thru 6 with range values; If at least 5 are within the range, STOP.
5. If less than 5 remain, make runs 7 thru 10 as necessary and recalculate the averages and ranges until 5 "good" runs and the resulting average are obtained.

# APPENDIX F. SIOMETER 438B VS. DIPSTICK CALIBRATION PLOTS

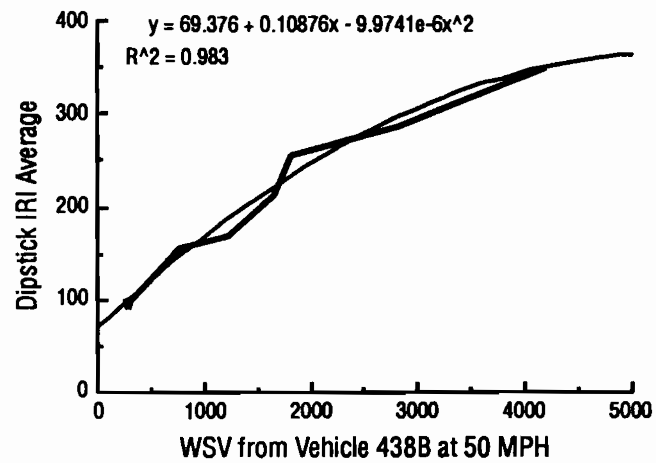



**Fig F.1. Second degree fit of Dipstick IRI for average of both wheel paths vs. SIometer WSV at 50 mph.**

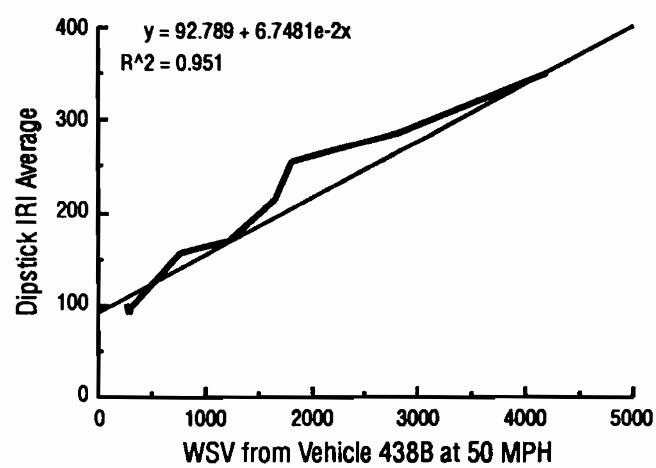



**Fig F.2. Linear fit fit of Dipstick IRI for average of both wheel paths vs. SIometer WSV at 50 mph.**

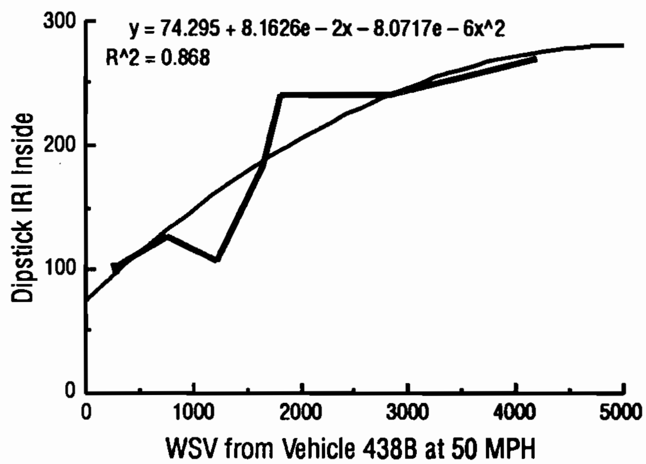



**Fig F.3. Second degree fit of Dipstick IRI inside wheel paths vs. SIometer WSV at 50 mph.**

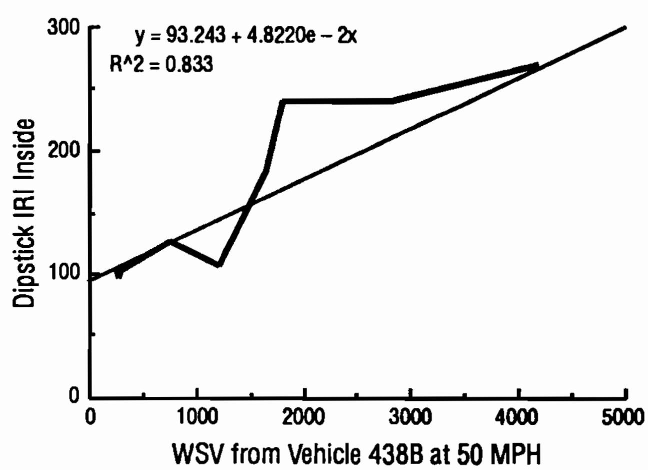



**Fig F.4. Linear fit of Dipstick IRI inside wheel paths vs. SIometer WSV at 50 mph.**

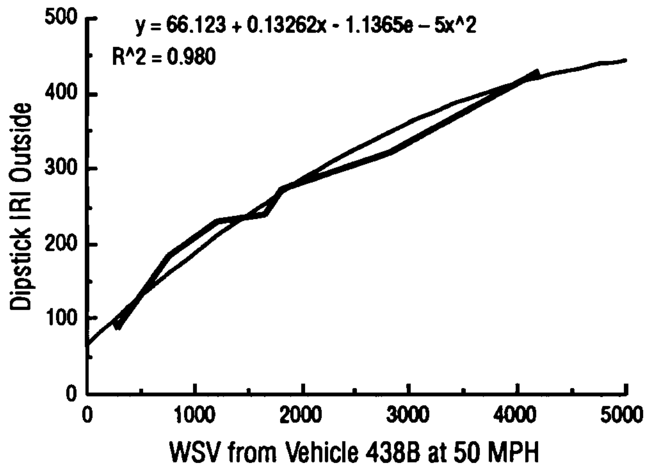



Fig F.5. Second degree fit of Dipstick IRI outside wheel paths vs. SIometer WSV at 50 mph.

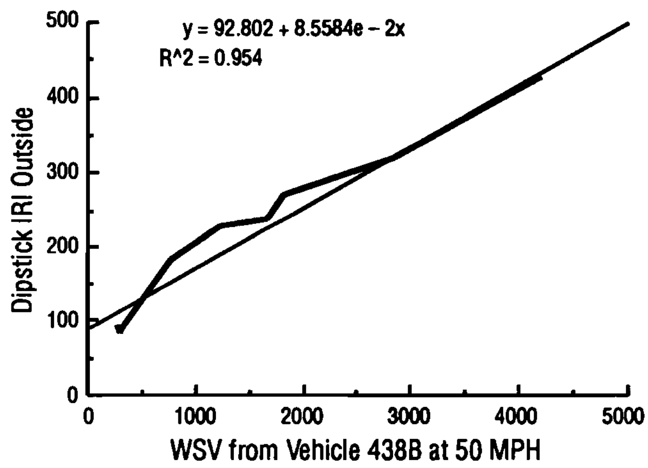



Fig F.6. Linear fit of Dipstick IRI outside wheel paths vs. SIometer WSV at 50 mph.

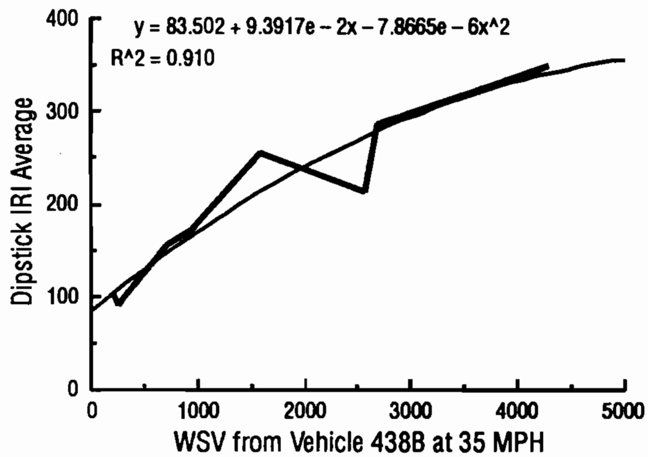



**Fig F.7. Second degree fit of Dipstick IRI for average of both wheel paths vs. SIometer WSV at 35 mph.**

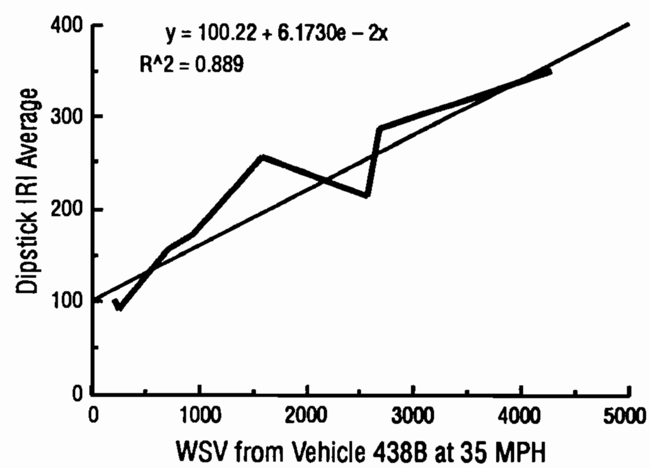



**Fig F.8. Linear fit of Dipstick IRI for average of both wheel paths vs. SIometer WSV at 35 mph.**

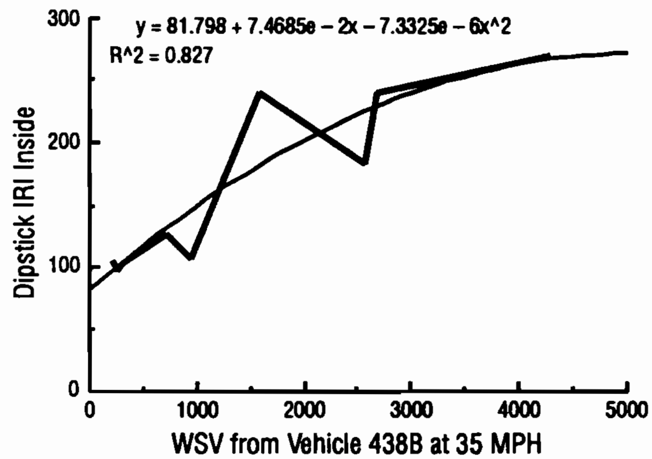



**Fig F.9. Second degree fit of Dipstick IRI inside wheel paths vs. SIometer WSV at 35 mph.**

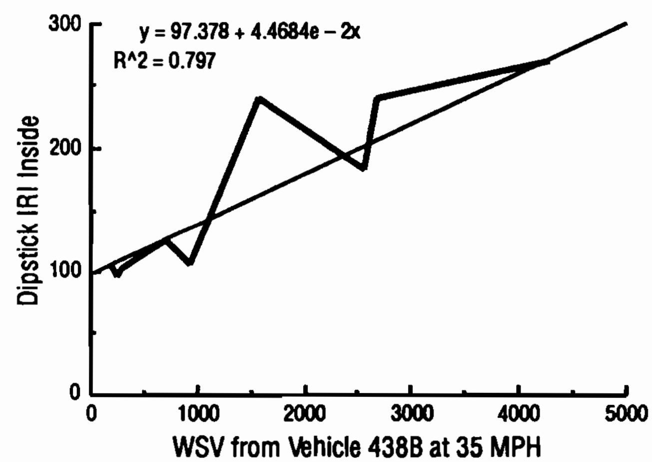



**Fig F.10. Linear fit of Dipstick IRI inside wheel paths vs. SIometer WSV at 35 mph.**

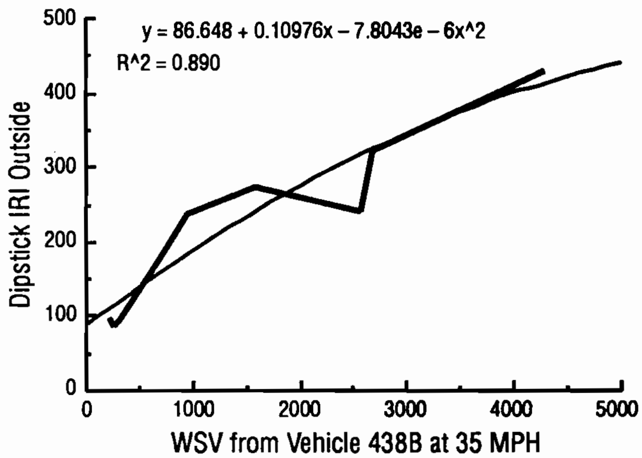



**Fig F.11. Second degree fit of Dipstick IRI outside wheel paths vs. SIometer WSV at 35 mph.**

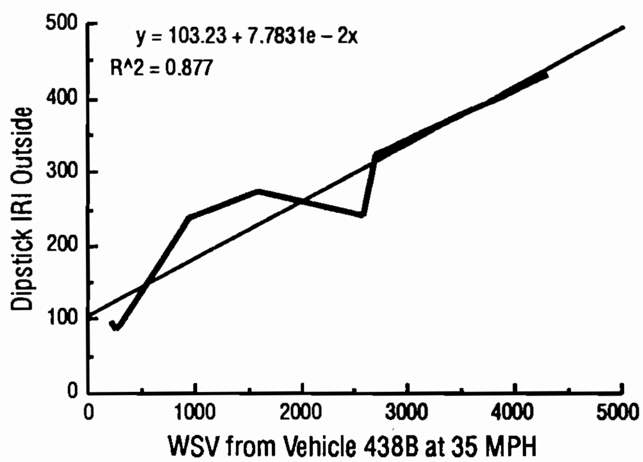



**Fig F.12. Linear fit of Dipstick IRI outside wheel paths vs. SIometer WSV at 35 mph.**

# APPENDIX G. MAYSMETER VS. DIPSTICK CALIBRATION PLOTS

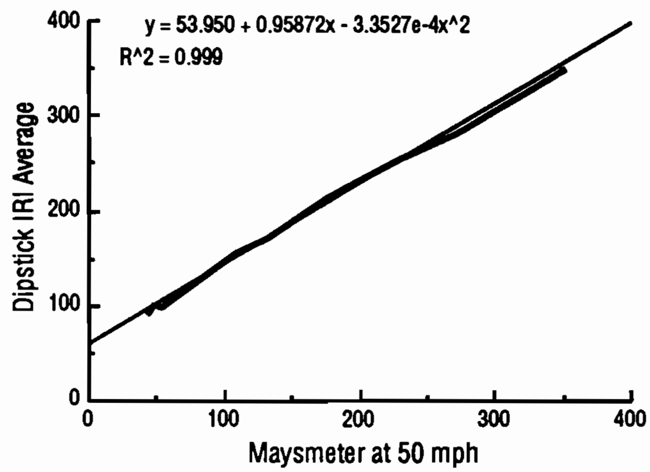



**Fig G.1. Second degree fit of Dipstick IRI for average of both wheel paths vs. Maysmeter counts at 50 mph.**

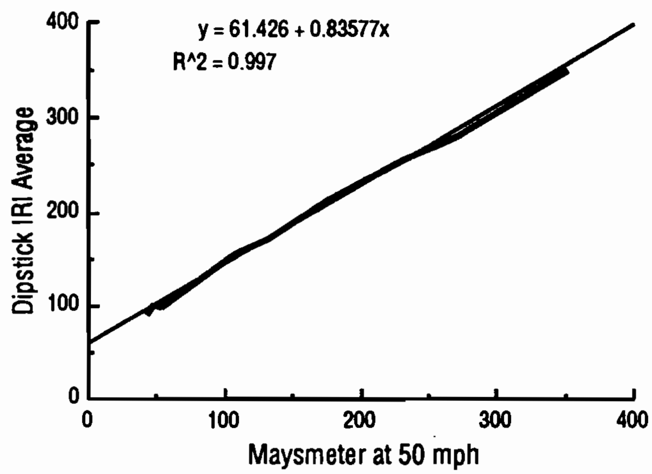



**Fig G.2. Linear fit of Dipstick IRI for average of both wheel paths vs. Maysmeter counts at 50 mph.**

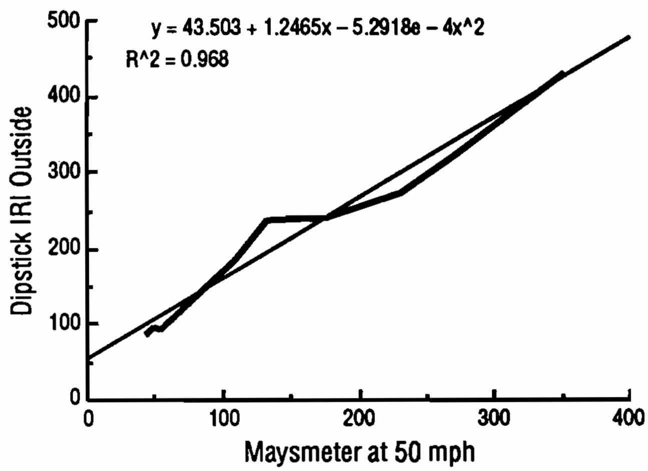



**Fig G.3. Second degree fit of Dipstick IRI outside wheel paths vs. Maysmeter counts at 50 mph.**

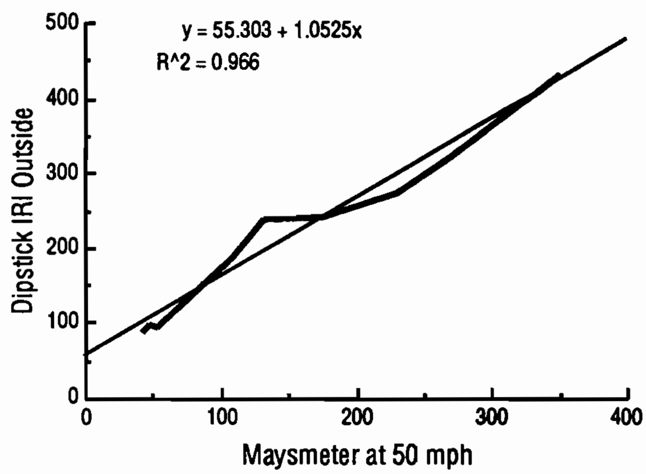



**Fig G.4. Linear fit of Dipstick IRI outside wheel paths vs. Maysmeter counts at 50 mph.**

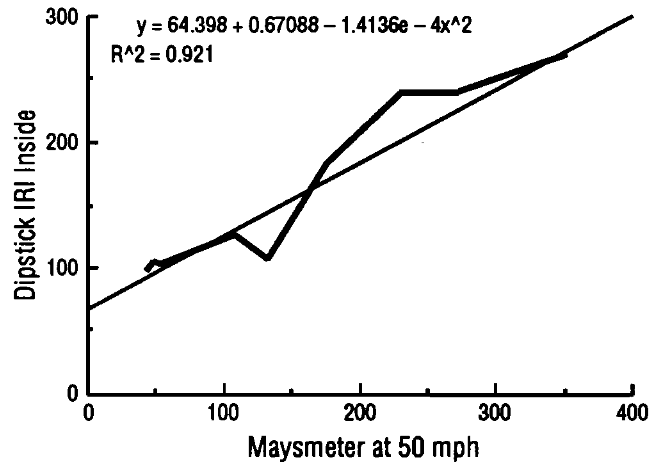



**Fig G.5. Second degree fit of Dipstick IRI inside wheel paths vs. Maysmeter counts at 50 mph.**

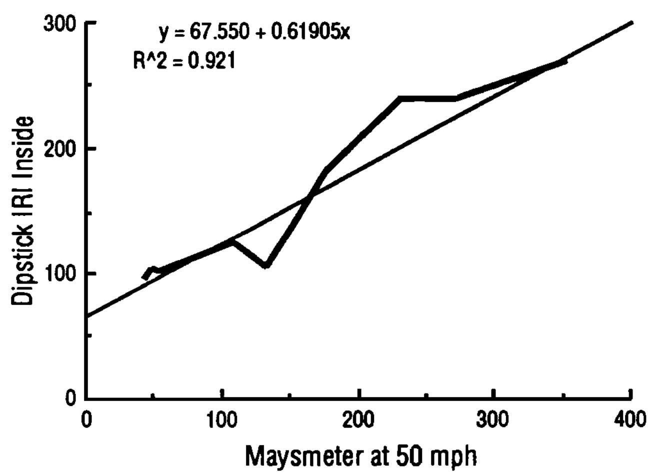



**Fig G.6. Linear fit of Dipstick IRI inside wheel paths vs. Maysmeter counts at 50 mph.**

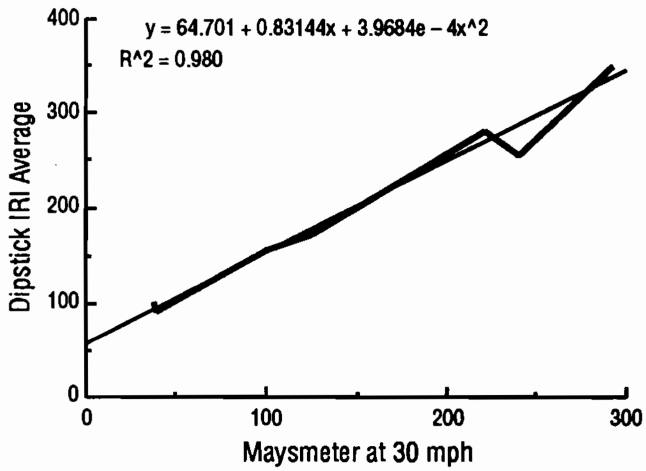



**Fig G.7. Second degree fit of Dipstick IRI for average of both wheel paths vs. Maysmeter counts at 30 mph.**

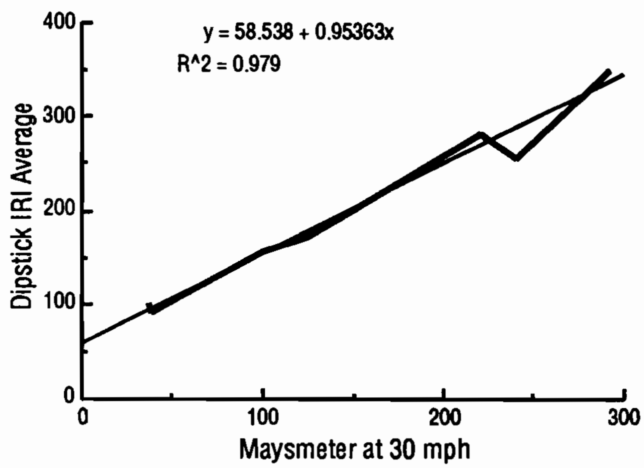



**Fig G.8. Linear fit of Dipstick IRI for average of both wheel paths vs. Maysmeter counts at 30 mph.**

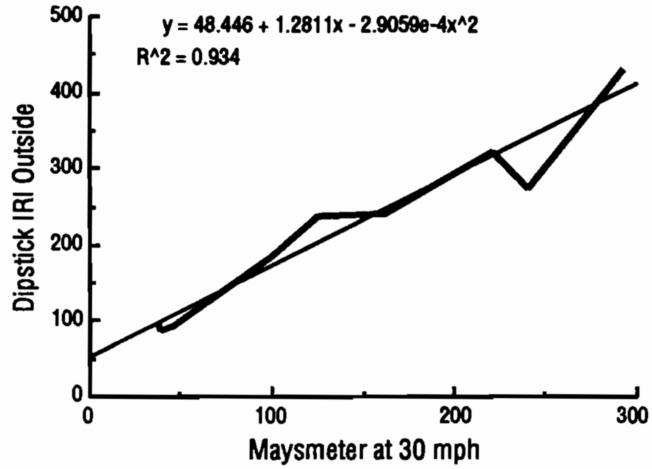



**Fig G.9. Second degree fit of Dipstick IRI outside wheel paths vs. Maysmeter counts at 30 mph.**

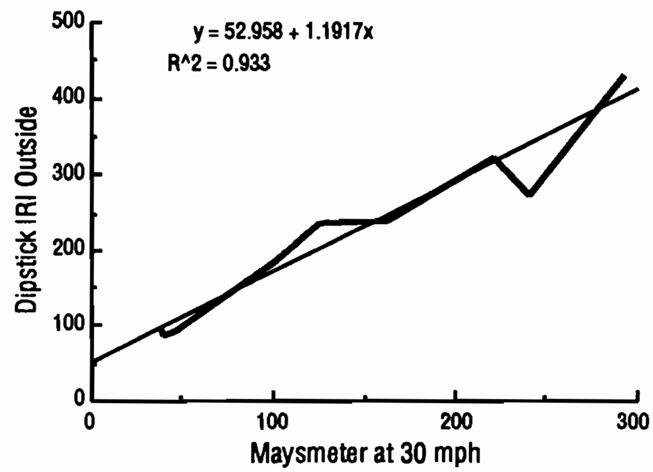



**Fig G.10. Linear fit of Dipstick IRI outside wheel paths vs. Maysmeter counts at 30 mph.**

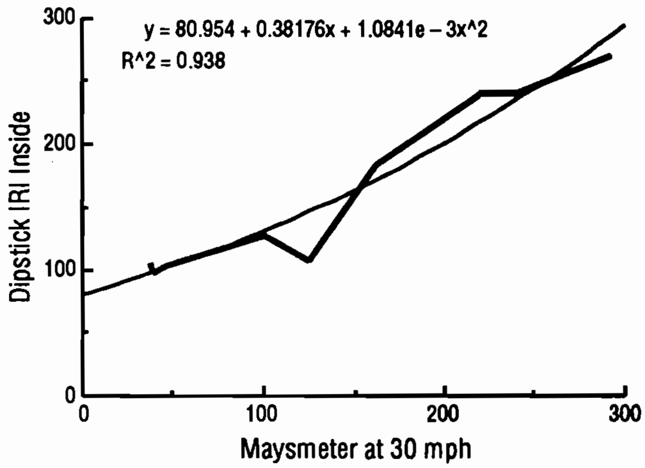



**Fig G.11. Second degree fit of Dipstick IRI inside wheel paths vs. Maysmeter counts at 30 mph.**

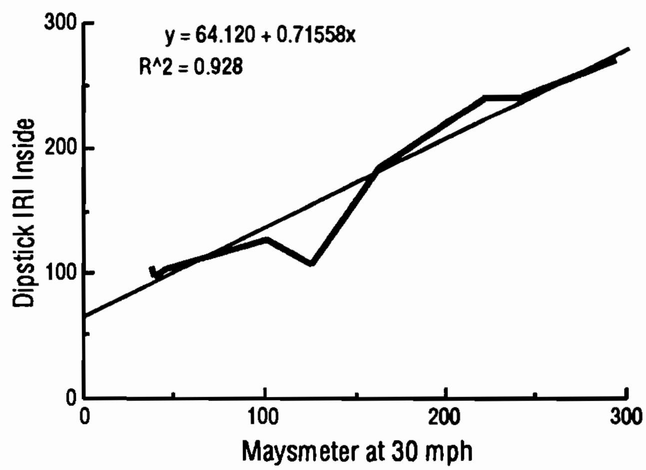



**Fig G.12. Linear fit of Dipstick IRI inside wheel paths vs. Maysmeter counts at 30 mph.**

# APPENDIX H. ARAN VS. DIPSTICK CALIBRATION PLOTS

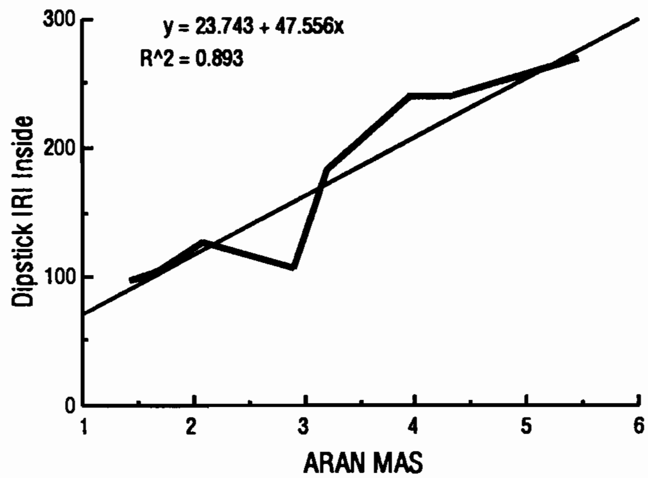



**Fig H.1. Linear fit of Dipstick IRI inside wheel paths vs. ARAN MAS at 30 mph.**

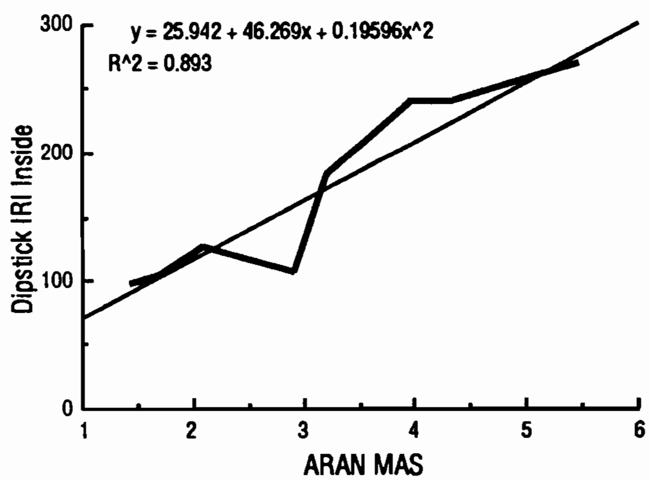



**Fig H.2. Second degree fit of Dipstick IRI inside wheel paths vs. ARAN MAS at 30 mph.**

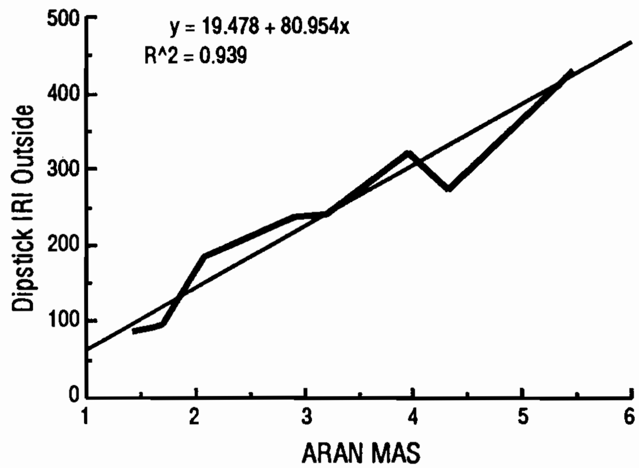



**Fig H.3. Linear fit of Dipstick IRI outside wheel paths vs. ARAN MAS at 30 mph.**

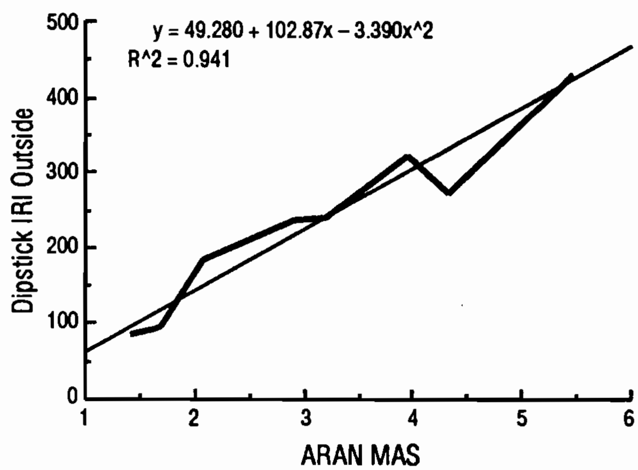



**Fig H.4. Second degree fit of Dipstick IRI outside wheel paths vs. ARAN MAS at 30 mph.**

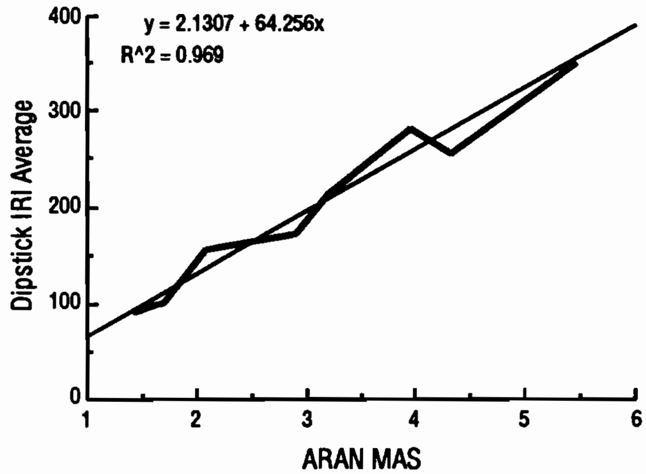



Fig H.5. Linear fit of Dipstick IRI for average of both wheel paths vs. ARAN MAS at 30 mph.

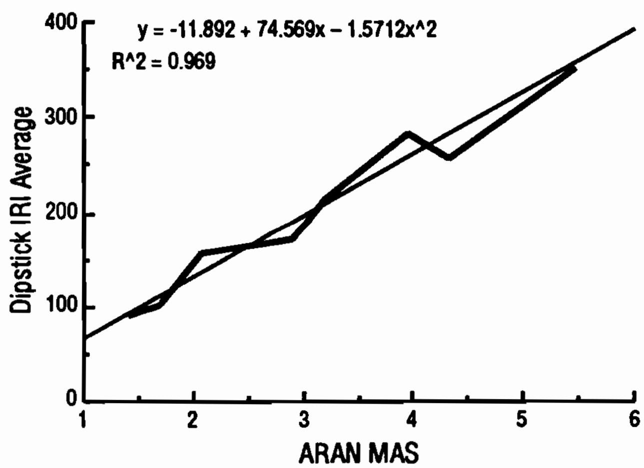



Fig H.6. Second degree fit of Dipstick IRI for average of both wheel paths vs. ARAN MAS at 30 mph.

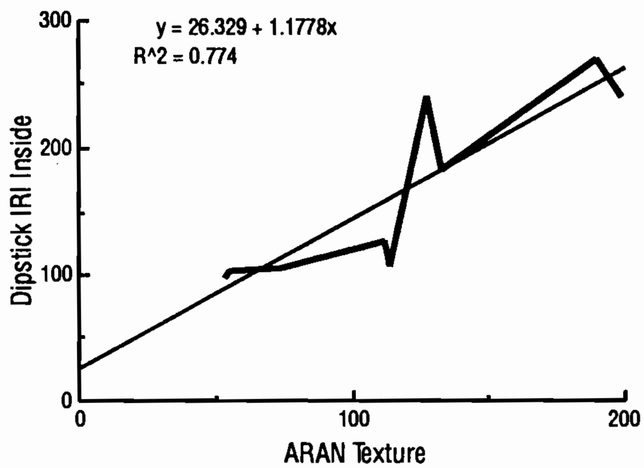



Fig H.7. Linear fit of Dipstick IRI inside wheel paths vs. ARAN Texture at 30 mph.

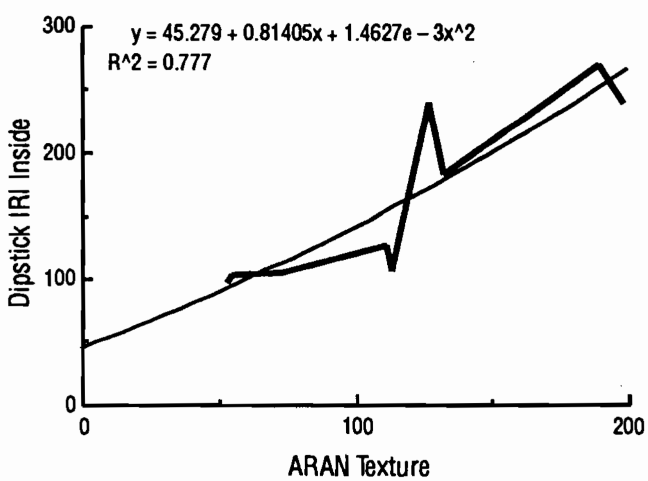



Fig H.8. Second degree fit of Dipstick IRI inside wheel paths vs. ARAN Texture at 30 mph.

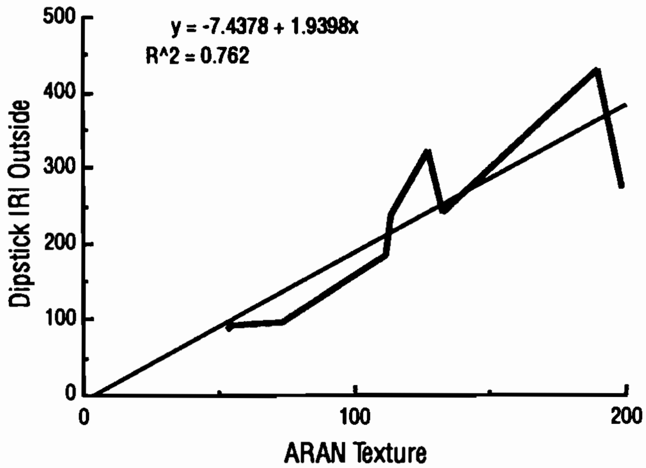



**Fig H.9. Linear fit of Dipstick IRI outside wheel paths vs. ARAN Texture at 30 mph.**

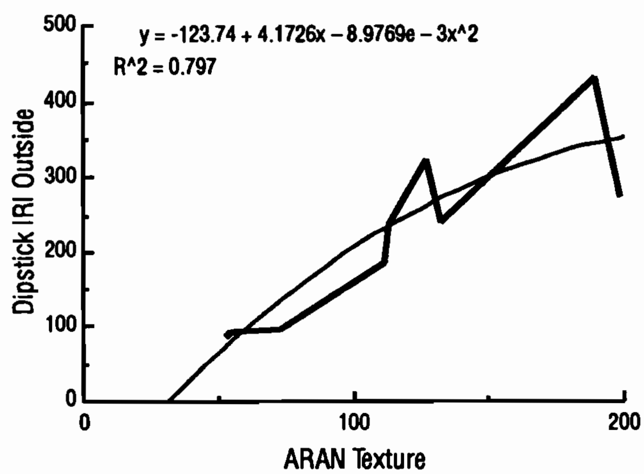



**Fig H.10. Second degree fit of Dipstick IRI outside wheel paths vs. ARAN Texture at 30 mph.**

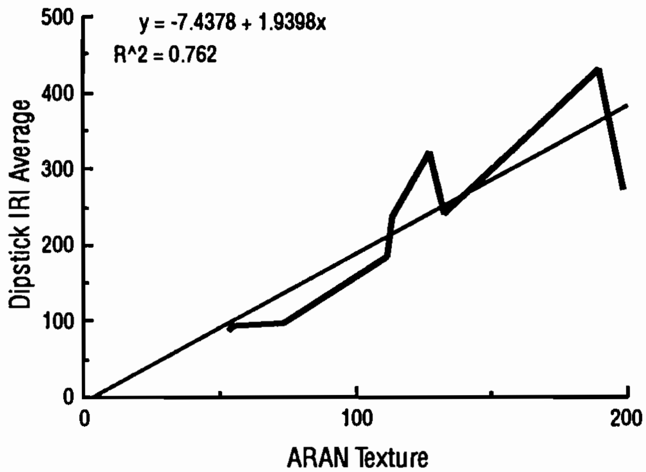



**Fig H.11. Linear fit of Dipstick IRI for average of both wheel paths vs. ARAN Texture at 30 mph.**

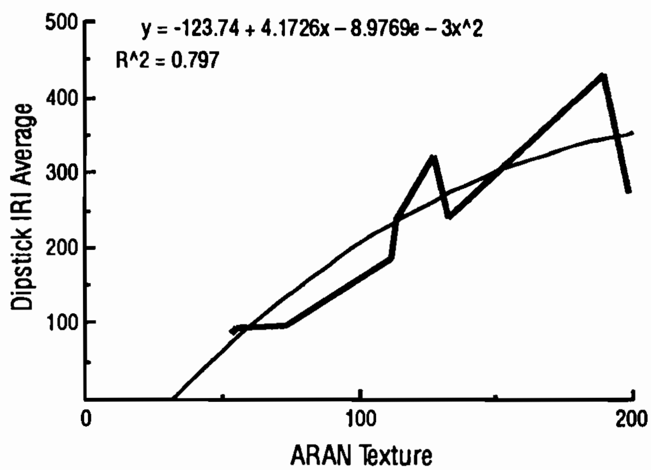



**Fig H.12. Second degree fit of Dipstick IRI for average of both wheel paths vs. ARAN Texture at 30 mph.**

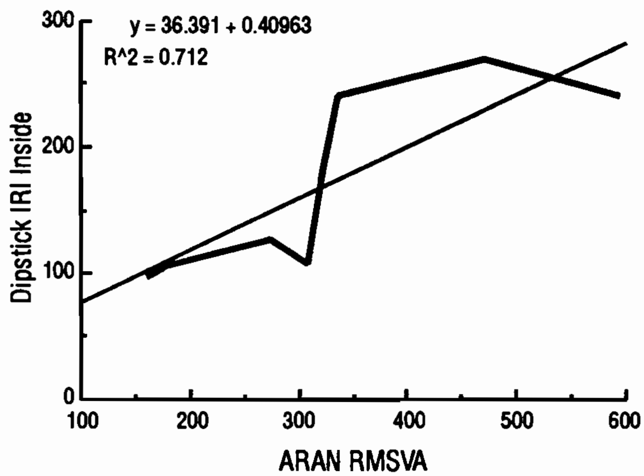



Fig H.13. Linear fit of Dipstick IRI inside wheel paths vs. ARAN RMSVA at 30 mph.

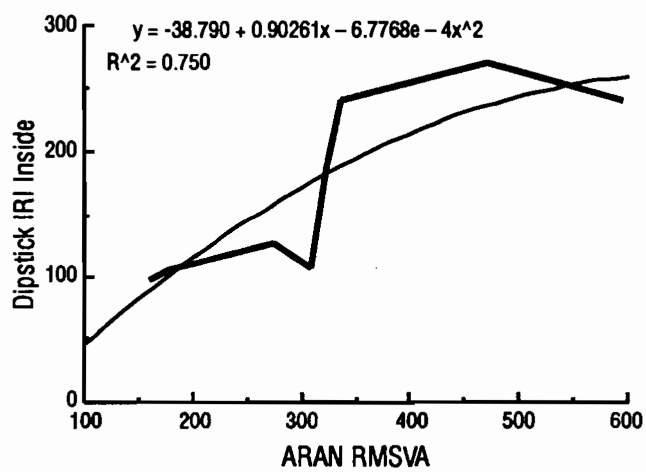



Fig H.14. Second degree fit of Dipstick IRI inside wheel paths vs. ARAN RMSVA at 30 mph.

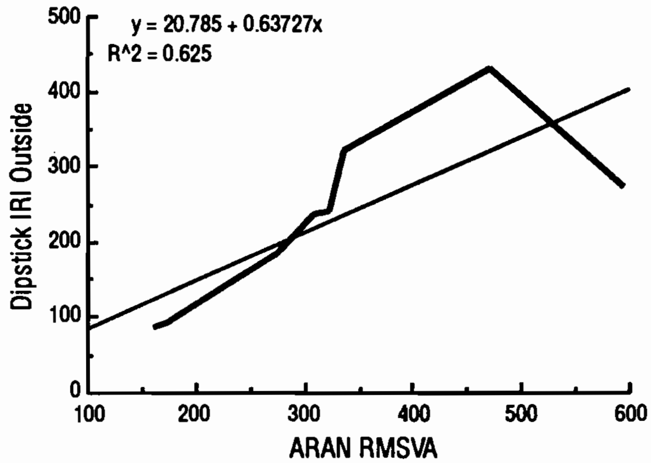



**Fig H.15. Linear fit of Dipstick IRI outside wheel paths vs. ARAN RMSVA at 30 mph.**

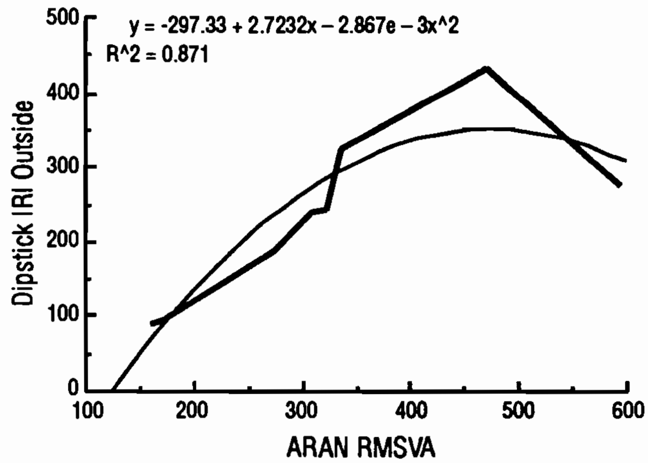



**Fig H.16. Second degree fit of Dipstick IRI outside wheel paths vs. ARAN RMSVA at 30 mph.**

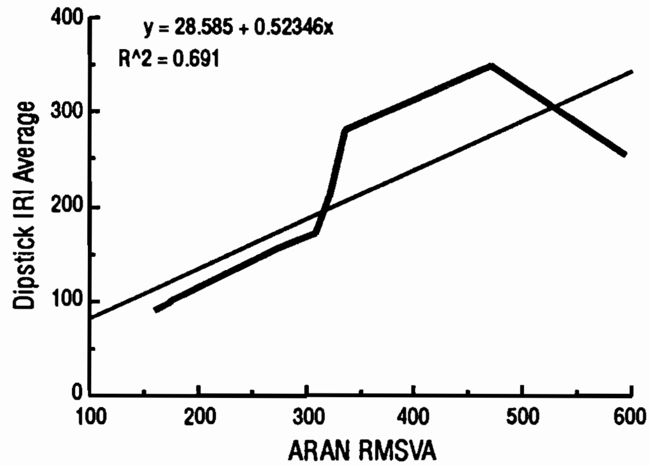



Fig H.17. Linear fit of Dipstick IRI for average of both wheel paths vs. ARAN RMSVA at 30 mph.

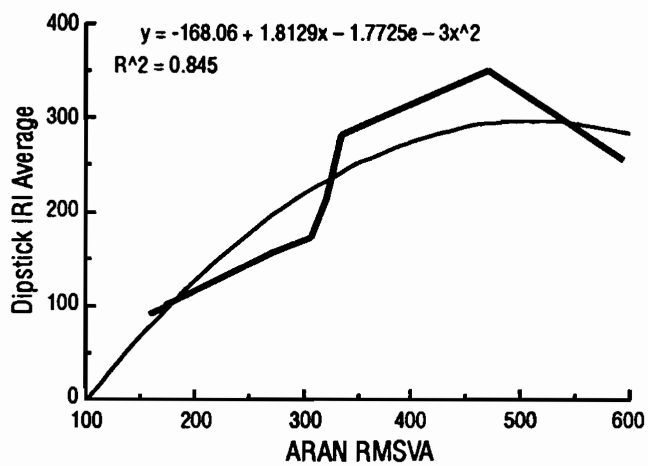



Fig H.18. Second degree fit of Dipstick IRI for average of both wheel paths vs. ARAN RMSVA at 30 mph.

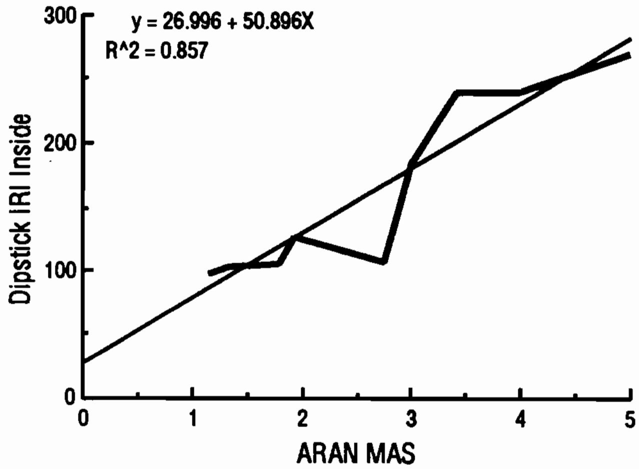



**Fig H.19. Linear fit of Dipstick IRI inside wheel paths vs. ARAN MAS at 50 mph.**

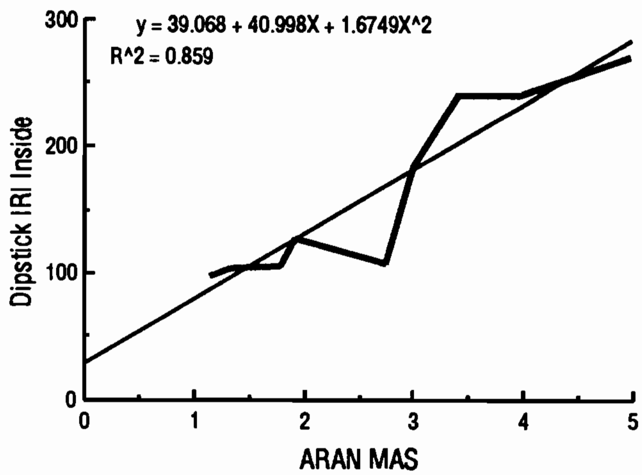



**Fig H.20. Second degree fit of Dipstick IRI inside wheel paths vs. ARAN MAS at 50 mph.**

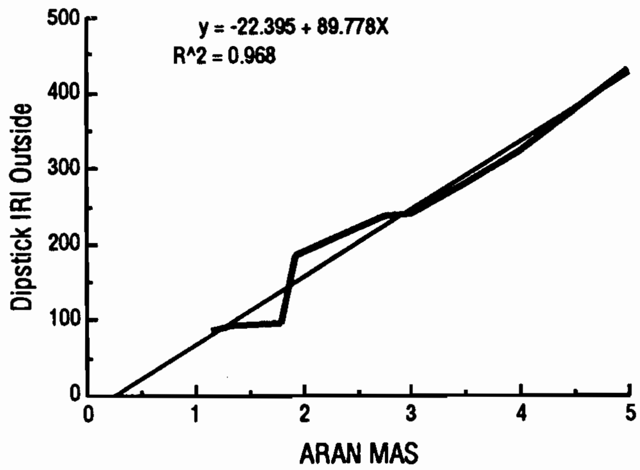



**Fig H.21. Linear fit of Dipstick IRI outside wheel paths vs. ARAN MAS at 50 mph.**

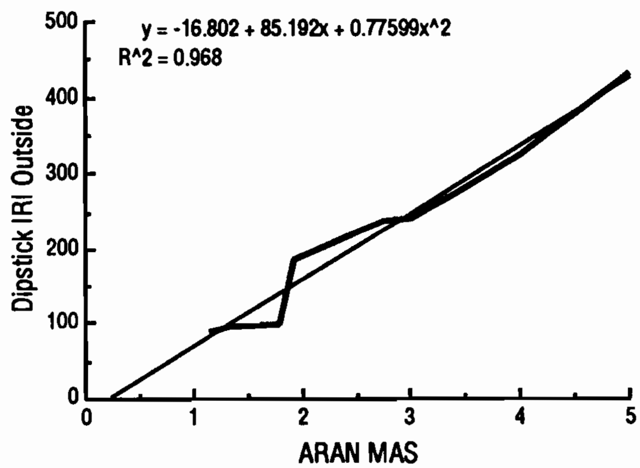



**Fig H.22. Second degree fit of Dipstick IRI outside wheel paths vs. ARAN MAS at 50 mph.**

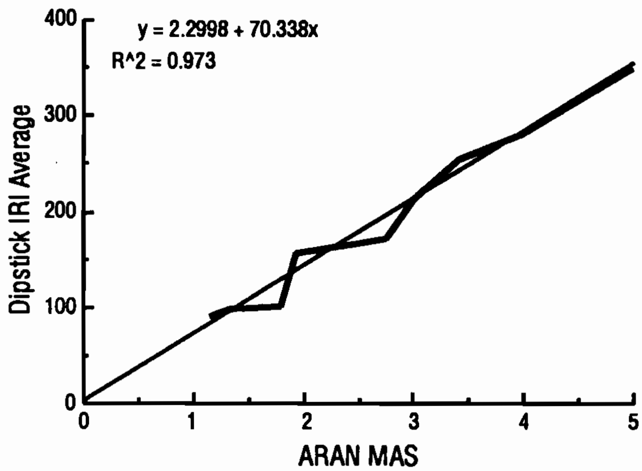



**Fig H.23. Linear fit of Dipstick IRI for average of both wheel paths vs. ARAN MAS at 50 mph.**

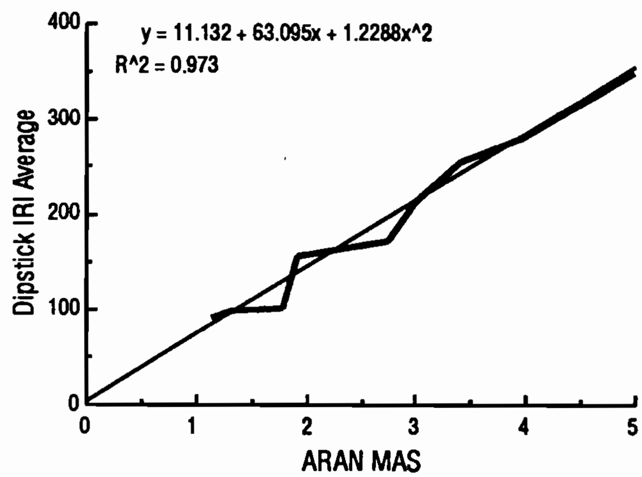



**Fig H.24. Second degree fit of Dipstick IRI for average of both wheel paths vs. ARAN MAS at 50 mph.**

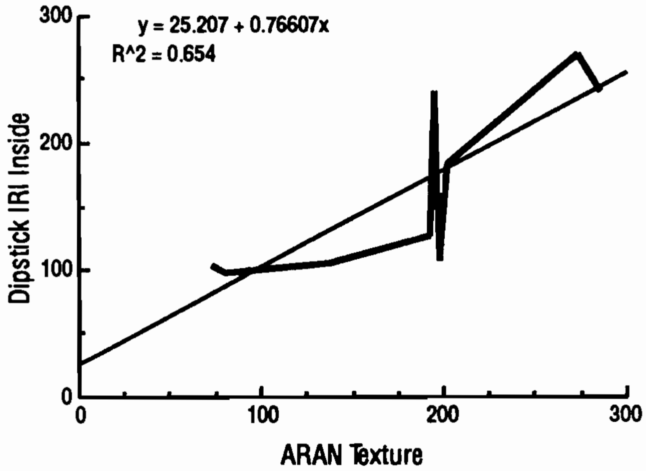



**Fig H.25. Linear fit of Dipstick IRI inside wheel paths vs. ARAN Texture at 50 mph.**

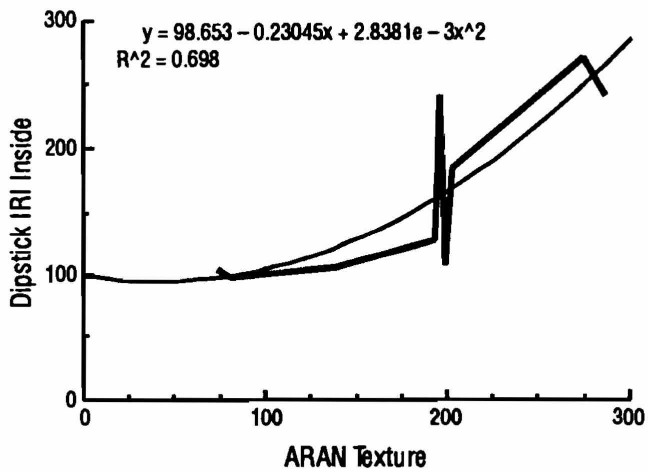



**Fig H.26. Second degree fit of Dipstick IRI inside wheel paths vs. ARAN Texture at 50 mph.**

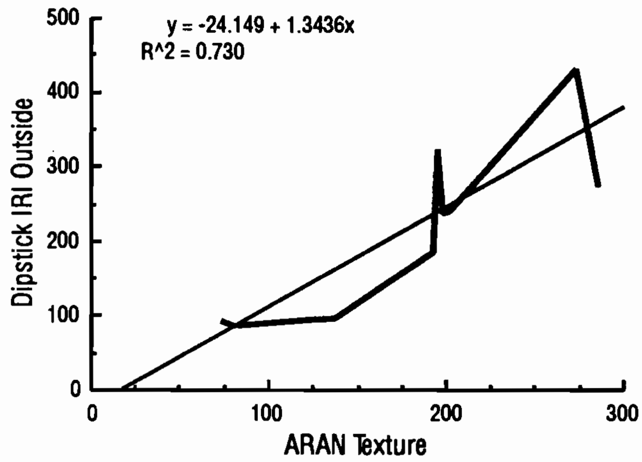



**Fig H.27. Linear fit of Dipstick IRI outside wheel paths vs. ARAN Texture at 50 mph.**

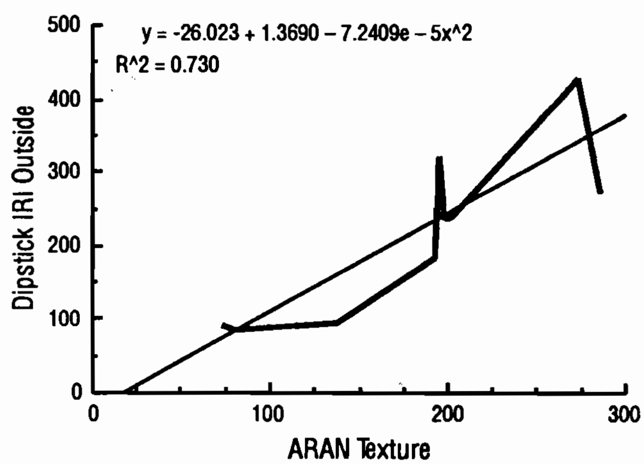



**Fig H.28. Second degree fit of Dipstick IRI outside wheel paths vs. ARAN Texture at 50 mph**

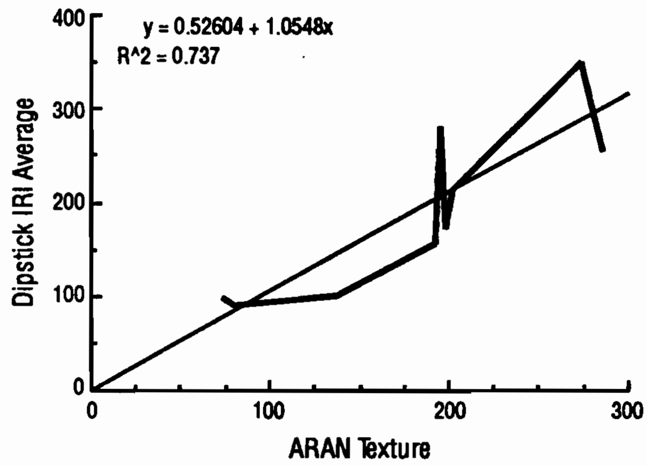



**Fig H.29. Linear fit of Dipstick IRI for average of both wheel paths vs. ARAN Texture at 50 mph.**

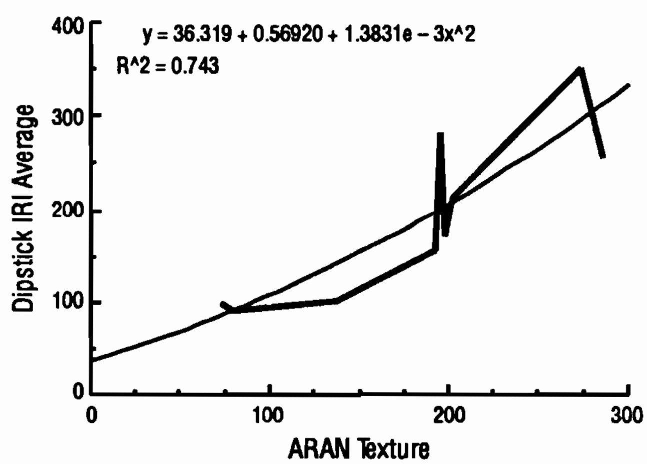



**Fig H.30. Second degree fit of Dipstick IRI for average of both wheel paths vs. ARAN Texture at 50 mph.**

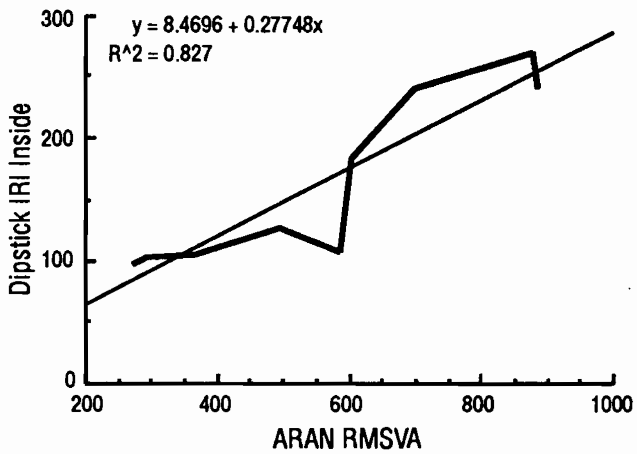



**Fig H.31. Linear fit of Dipstick IRI inside wheel paths vs. ARAN RMSVA at 50 mph.**

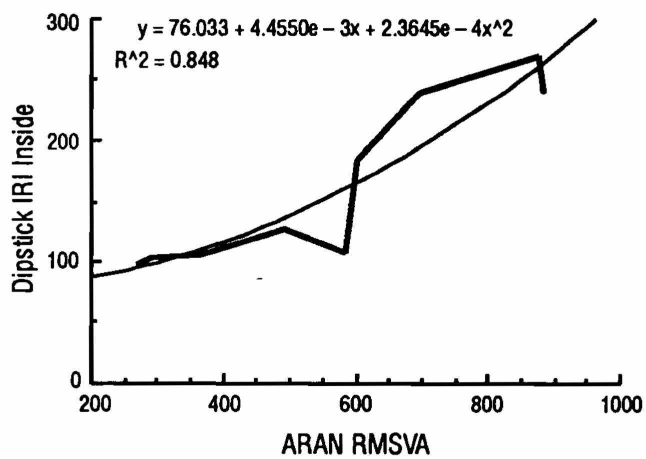



**Fig H.32. Second degree fit of Dipstick IRI inside wheel paths vs. ARAN RMSVA at 50 mph.**

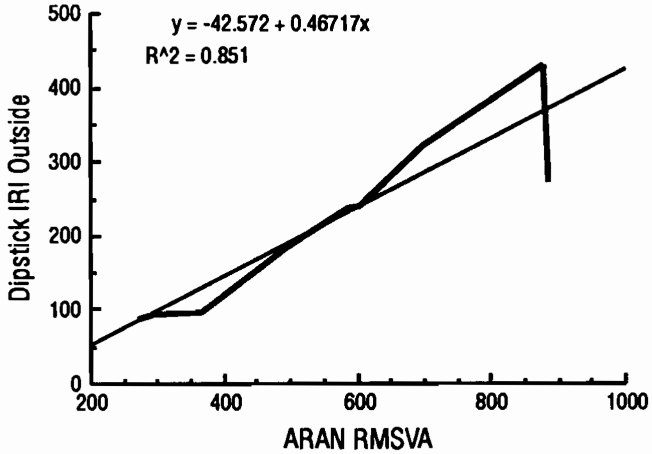



**Fig H.33. Linear fit of Dipstick IRI outside wheel paths vs. ARAN RMSVA at 50 mph.**

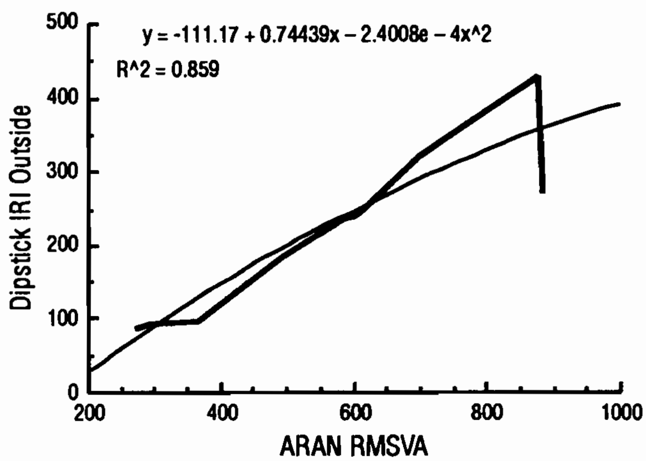



**Fig H.34. Second degree fit of Dipstick IRI outside wheel paths vs. ARAN RMSVA at 50 mph.**

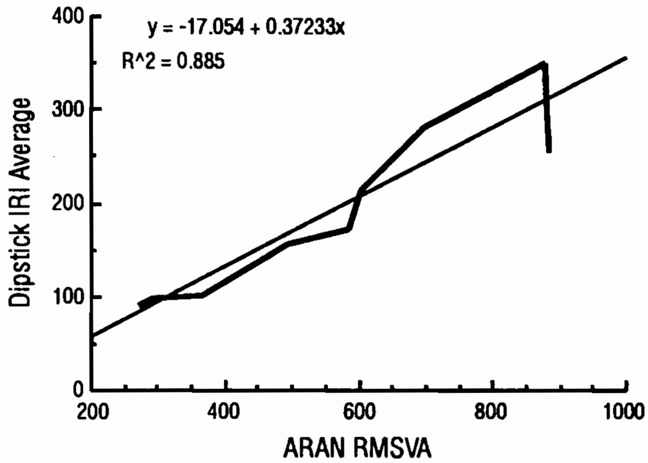



**Fig H.35. Linear fit of Dipstick IRI for average of both wheel paths vs. ARAN RMSVA at 50 mph.**

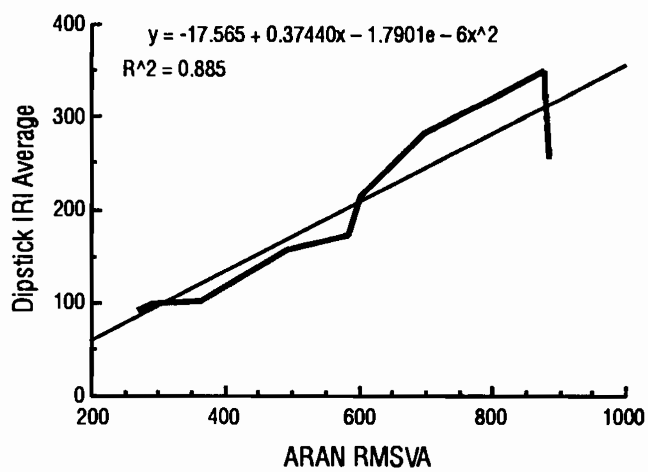



**Fig H.36. Second degree fit of Dipstick IRI for average of both wheel paths vs. ARAN RMSVA at 50 mph.**