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CALIBRATION PROCEDURES FOR ROADMETERS

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Federal Highway Administration

Research, Development, and Technology
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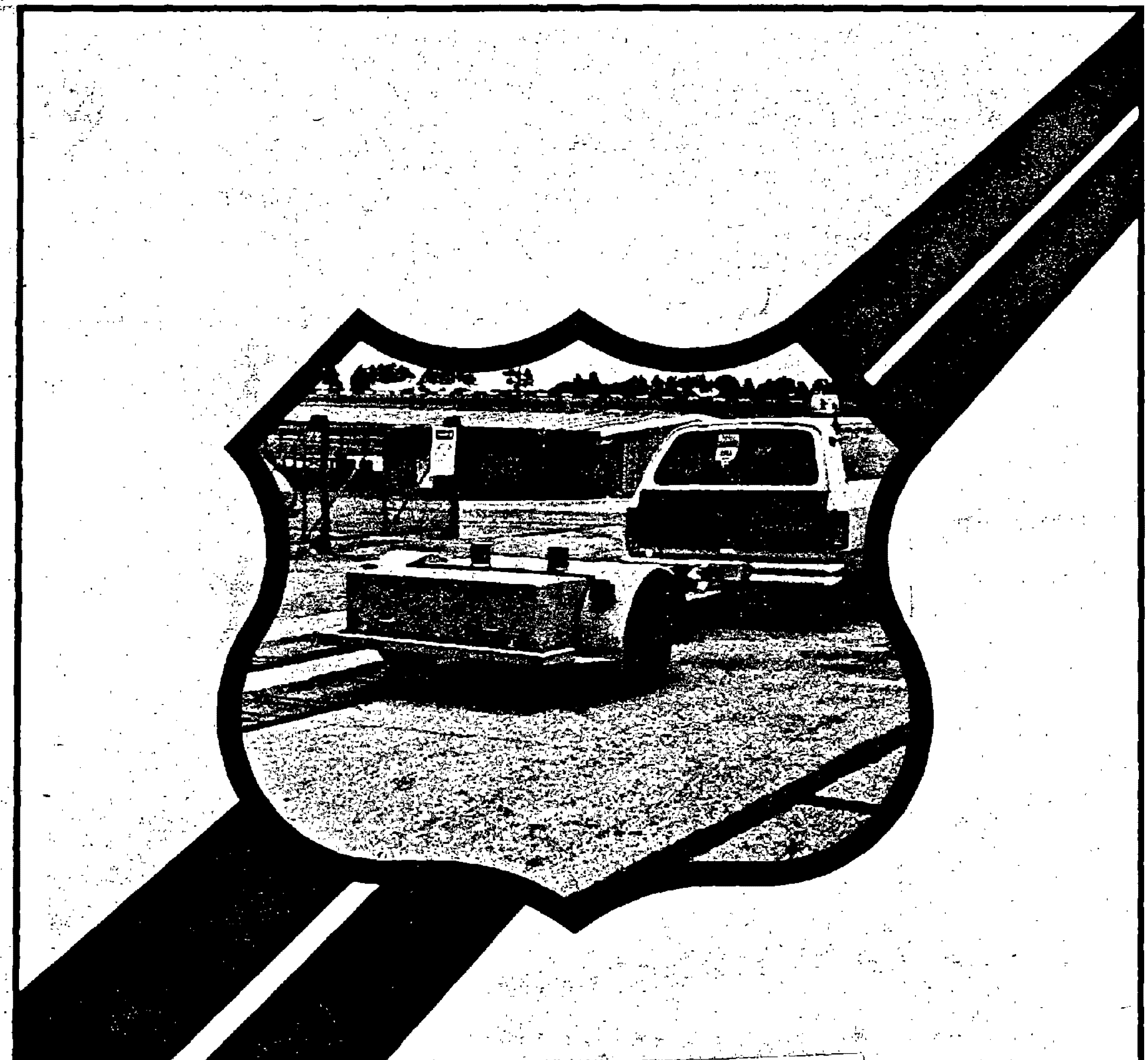

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FOREWORD

This report documents the results of a field testing program conducted by the Georgia Department of Transportation for road roughness measuring equipment. Profilometers and response-type devices were provided by several cooperative State highway agencies. The devices were tested on 52 individual pavement sections encompassing a wide variety of roughness levels and surface types. A correlation program was conducted using the test results, and a calibration procedure was developed for the response-type devices. In addition, an inexpensive non-contact roughness measuring device (the K. J. Law Model 8300 Roughness Surveyor) was evaluated during the study. The accuracy and repeatability of the device were determined, along with its ability to provide a calibration reference for response-type devices.

This report should be of interest to those individuals involved with pavement evaluation procedures and equipment. Additional copies may be obtained from this office or from the National Technical Information Service (NTIS), 5285 Port Royal Road, Springfield, Virginia 22161.

R. J. Betsold

R. J. Betsold, Director
Office of Implementation

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16. Abstract The research project was conducted to evaluate the performance of an inexpensive non-contact roughness measuring device, Roughness Surveyor, as well as the potential use of this device as a calibration reference for Response-Type Road Roughness Measuring (RTRRM) systems. A correlation was also conducted between RTRRM systems from three different States (Georgia, Florida, and Minnesota) against the Roughness Surveyor, the inertial profilometer owned by the Ohio DOT, and the profilometer designed and operated by the South Dakota DOT.

A total of sixteen test sites were selected for the correlation and calibration study with a total of 52 individual test sections encompassing a variety of roughness levels and pavement surface types. The results of the roughness testing showed an excellent correlation between all the devices. The standard error of estimate, however, was rather large for some of the linear regression equations. The units from Florida, Ohio, and South Dakota provided serviceability index ratings. An analysis of these ratings indicated that different values were obtained between the units on the same test sections.

The evaluation of the Roughness Surveyor indicated that the roughness results obtained were insensitive to speed variations. Problems were encountered with obtaining valid roughness readings on extremely rough textured surfaces, such as surface treatment. The testing repeatability of the Roughness Surveyor was not as good as that obtained with the Ohio Profilometer and slightly better than two of the three RTRRM systems. The day-to-day variability was much higher for the Roughness Surveyor than for the Ohio Profilometer and the RTRRM systems.

17. Key Words

Calibration, Profilometer, Roadmeters, Roughness Testing

18. Distribution Statement

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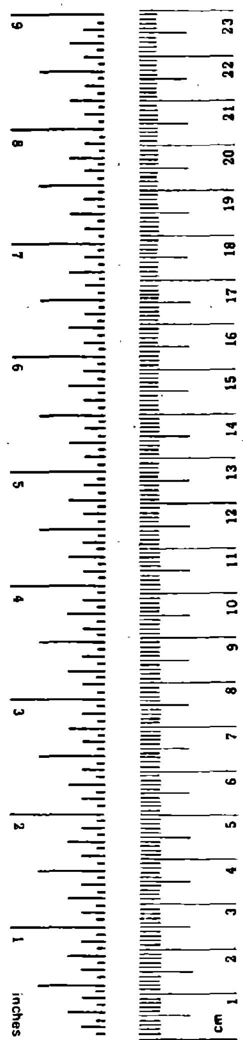
METRIC (SI*) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
	LENGTH			
in	inches	2.54	millimetres	mm
ft	feet	0.3048	metres	m
yd	yards	0.914	metres	m
mi	miles	1.61	kilometres	km
	AREA			
in²	square inches	645.2	millimetres squared	mm²
ft²	square feet	0.0929	metres squared	m²
yd²	square yards	0.836	metres squared	m²
mi²	square miles	2.59	kilometres squared	km²
ac	acres	0.395	hectares	ha
	MASS (weight)			
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams	Mg
	VOLUME			
fl oz	fluid ounces	29.57	millilitres	mL
gal	gallons	3.785	litres	L
ft³	cubic feet	0.0328	metres cubed	m³
yd³	cubic yards	0.0765	metres cubed	m³

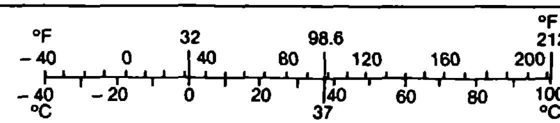
NOTE: Volumes greater than 1000 L shall be shown in m³.

Symbol	When You Know	Multiply By	To Find	Symbol
	TEMPERATURE (exact)			
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C



APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
	LENGTH			
mm	millimetres	0.039	inches	in
m	metres	3.28	feet	ft
m	metres	1.09	yards	yd
km	kilometres	0.621	miles	mi
	AREA			
mm²	millimetres squared	0.0016	square inches	in²
m²	metres squared	10.764	square feet	ft²
km²	kilometres squared	0.39	square miles	mi²
ha	hectores (10 000 m²)	2.53	acres	ac
	MASS (weight)			
g	grams	0.0353	ounces	oz
kg	kilograms	2.205	pounds	lb
Mg	megagrams (1 000 kg)	1.103	short tons	T
	VOLUME			
mL	millilitres	0.034	fluid ounces	fl oz
L	litres	0.264	gallons	gal
m³	metres cubed	35.315	cubic feet	ft³
m³	metres cubed	1.308	cubic yards	yd³
	TEMPERATURE (exact)			
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



These factors conform to the requirement of FHWA Order 5190.1A.

* SI is the symbol for the International System of Measurements

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I. INTRODUCTION

There has been an increasing interest by federal and state transportation agencies in measuring the rideability of highways and requiring a certain degree of smoothness of newly constructed and resurfaced roadways. A variety of devices for measuring the pavement surface and the response of a vehicle to the pavement profile have been available for a number of years.

A rolling straightedge has been used extensively in many agencies' specifications for years as a method for finding "bumps" and rough sections of a new pavement. Studies have shown though that the straightedge results do not necessarily indicate the rideability of the pavement since it can only measure short wavelengths (1)(2)(3).

Road roughness is generally measured by obtaining the longitudinal profile with such devices as the CHLOE, GMR Profilometer and others or by devices which measure the response of a vehicle or trailer to the road profile. The most well known and most used of these devices currently are the PCA-type roadmeter and Mays meter. All of these devices have been described and discussed in many previous publications by various research agencies (4)(5).

Some of the advantages of using a PCA-type roadmeter or Mays meter are low initial and operating cost, ease of operation, and high measuring speeds. The disadvantages are that the response output is sensitive to type of vehicle, suspension characteristics, tire pressure, speed, weight distribution, etc. Many of these disadvantages can be minimized by a user through standardization of equipment and test procedures,and by placing the transducer on specially designed trailers. Frequent calibration checks are required to insure that the various vehicle components such as shocks, wheel bearings, and tires have not deteriorated. There is also a problem with long-term changes in vehicle characteristics and suspension components.

The calibration methods and requirements for response-type roughness meters have been of concern for some time (6)(7)(8), but are becoming of increasing importance with the use of rideability requirements in construction specifications. There is also an increasing need to be able to relate the roughness results obtained by the various agencies to a common reference. Contractors working in various States have no means of relating the rideability requirements of the various specifications. The proposed Strategic Highway Research Program (SHRP) contains long-term pavement monitoring of numerous test sites around the country for which rideability will be one of the performance criteria. It must be insured that any roughness results obtained on these test sites are valid data obtained with calibrated devices if response-type meters are used.

Non-contact profilometers which obtain the longitudinal profile are excellent devices for measuring roughness since obviously the test results are not influenced by any vehicle characteristics. The profilometers are expensive, however, and have been acquired by only a few highway agencies. Most other agencies own response type meters and must rely on in-service test sections for calibration.

II. STUDY OBJECTIVES

The objectives of the research project were as follows:

1. To evaluate and demonstrate a procedure for the calibration and correlation of response-type road roughness measuring (RTRRM) systems relative to a system simulation of test section profiles.
2. To evaluate and demonstrate the operation, accuracy, and repeatability of a low cost, non-contact road roughness measuring system, the Model 8300 Roughness Surveyor.

3. To determine the feasibility of using the Roughness Surveyor as a calibration reference.

III. RESEARCH APPROACH

The testing program was developed around the use of in-service test sections and the comparisons of the response from RTRRM systems and the simulated response generated from the profiles obtained by non-contact profilometers. These test sites were used in the correlation program between several RTRRM systems as well as to develop calibration procedures and for verification and evaluation of the procedures.

In order to perform the correlations and obtain roughness data for the calibration, it was necessary to obtain the cooperation of several other highway agencies. The States of Florida, Minnesota, Ohio, and South Dakota in addition to Georgia agreed to participate in the study.

The initial phase of the study was devoted to the evaluation of the Roughness Surveyor and the selection of in-service roads to be used in the correlation program. Data was obtained to evaluate the sensitivity of the Roughness Surveyor to texture, test speed, day-to-day repeatability, test-to-test repeatability, and to evaluate operational reliability. Numerous problems were found in the original model of the Roughness Surveyor delaying the correlation program about one year until all problems were corrected.

The in-service test sections were selected to provide a variety of surface types and various levels of roughness. All the RTRRM systems and Profilometers obtained roughness data on the test sites during the same timeframes and a minimum of three repeat tests were made on each section.

IV. DESCRIPTION OF TEST SITES

A total of sixteen (16) test sites were chosen for use in the calibration and correlation program. Seven of these sites have been in use by the Georgia DOT as standard control sections for the calibration of the Department's nine Mays meters. The sections were located on Interstate routes, primary and secondary state roads, and county roads to provide for a variety of surface types, road conditions, and levels of roughness. A description of the test sites is contained in Table 2. Data were obtained on a total of 52 test sections on the 16 test sites. The distribution of the test sections by pavement type is shown in Table 1.

TABLE 1. DISTRIBUTION OF TEST SITES.

Type Surface	Number of Sections	Georgia Mays Roughness Range
Open Graded Friction Course	4	18 - 24
Dense Graded Asphaltic Concrete	28	18 - 169
Surface Treatment	2	119 - 134
Portland Cement Concrete	10	44 - 111
Ground Portland Cement Concrete	6	11 - 74
Milled Asphaltic Concrete	2	42 - 44

Each test section was one mile in length with at least two test sections for each test site.

TABLE 2. TEST SECTION IDENTIFICATION AND LOCATION.

Test Site	Road Number	County	Area Tested	Type Pavement
1	SR-7	Henry	North MP 1-2	OG
			South MP 2-1	OG
2	Camp Calvin	Clayton	East MP 0-1	AC
			West MP 1-0	AC
3	High Falls Rd.	Spalding	North MP 0-1	AC
			South MP 1-0	AC
4	SR-16	Butts	East MP 0-1	OG
			West MP 1-0	OG
5	Bailey-Jester	Spalding	North MP 0-1	ST
			South MP 1-0	
6	I-75	Butts-Lamar	North MP 200-201; 202-203	PCC Gnd.
			South MP 204-203; 202-201	PCC Gnd.
7	SR-16	Butts	East MP 2-3; 4-5	AC
			West MP 5-4; 3-2	AC
8	CR-162	Jasper	North MP 0-1	AC
			South MP 1-0	AC
9	CR-171	Jasper	North MP 0-1; 2-3	AC
			South MP 3-2; 1-0	AC
10	SR-16	Jasper	East MP 5-6; 7-8	AC
			West MP 8-7; 6-5	AC
11	SR-212	Jasper	East MP 15-14; 13-12	AC
			West MP 12-13; 14-15	AC
12	Julliette Road	Monroe	East MP 0-1; 2-3	AC
			West MP 3-2; 1-0	AC
13	I-475	Bibb-Monroe	North Inside Lane MP 11-12; 13-14	PCC
			South Outside Lane MP 14-13; 12-11	PCC Gnd.
14	I-75	Houston	North Outside Lane MP 137-138; 139-140	AC
			South Inside Lane MP 137-138; 139-140	Milled AC
15	Camp Creek Pkwy.	Fulton	East MP 1-2; 3-4	PCC New
			West MP 4-3; 2-1	PCC New
16	SR-166	Fulton	East MP 10-11; 12-13	PCC Old
			West MP 13-12; 11-10	PCC Old

V. ROUGHNESS MEASURING EQUIPMENT

The purpose of the research study was to evaluate calibration procedures for RTRRM systems using longitudinal road profiles. The most widely used RTRRM systems are the Mays meter and to a lesser extent the PCA-type meter (17). Simulated RTRRM responses to the road profiles were obtained with non-contact profilometers. The devices used in this study have been described in detail in many other publications and reports; only a brief description of the equipment will be contained in this report. The equipment used in this project by each participating State is as follows:

Florida

Florida utilizes a trailer-mounted Mays meter towed by a 1983 Dodge Ram Charger (Figure 1). The trailer is a Rainhart 890T. Standard equipment used on the Florida 890T is coil spring enclosed shock absorbers (Monroe 57-11), Michelin X radial tires, single drag-link assembly and sway-bar. The trailer weight is 780±20 pounds per wheel load.

The instrumentation is a vertical-mounted Mays transducer (Figure 2) feeding an International Cybernetics, Inc. pavement condition recorder PCR 1000.

Figure 1. Roughness Measuring Trailer - Florida.

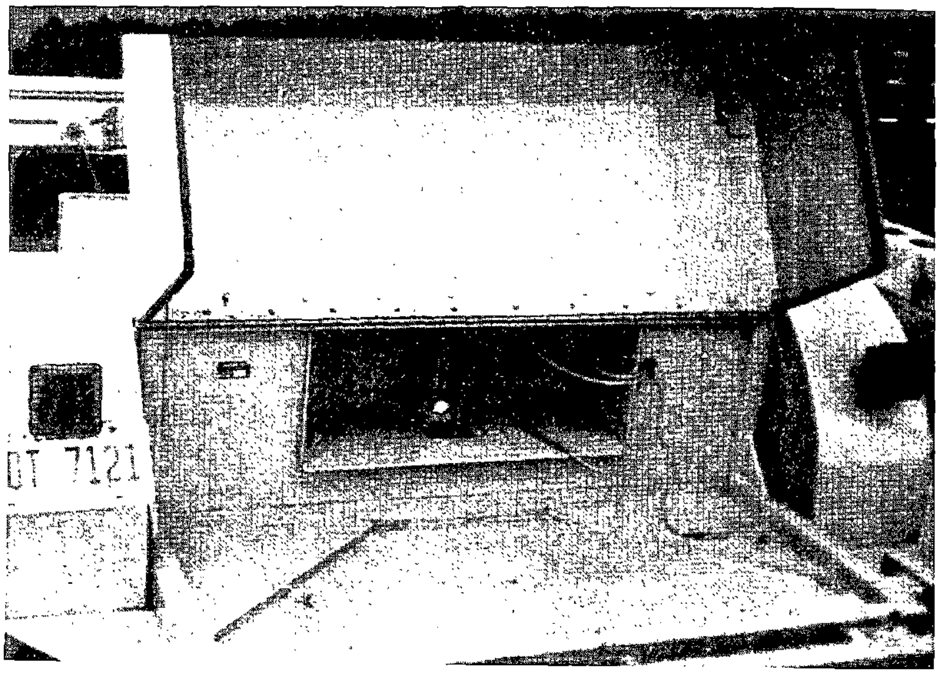


Figure 2. Vertical Mounted Mays Transducer - Florida.

Georgia - Mays

Georgia uses a modified Rainhart 890T trailer towed by a 1985 Chevrolet C10 pickup. The trailer modified from the original version has dual-parallel draglink assemblies, shock absorbers (Delco 501-58) mounted outside the springs perpendicular to the axle. Michelin X P215-75R-15 radial tires are used and inflated at 30 psi hot tire pressure with an 800 pound load over each wheel.

A swingarm assembly is used to connect the axle to the Mays rotary transducer mounted to the chasis of the trailer (Figure 3). This allows for increasing or decreasing roughness measurements utilizing the theory of angles for changing the amplitude. The roughness information is transmitted from the Mays transducer to an onboard computer (MRM) designed and developed in-house by the Georgia Department of Transportation research personnel. The speed and distance measuring equipment working in tandem with the MRM unit is a transwave model NK1200 (Figure 4).

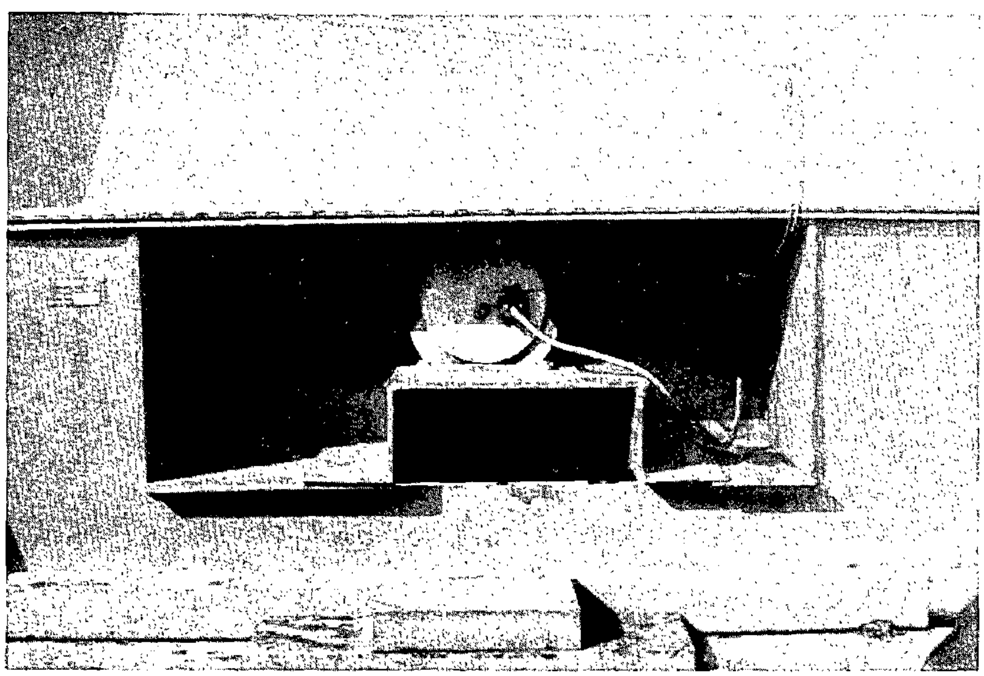


Figure 3. Mays Rotary Transducer - Georgia.

Figure 4. Mays Instrumentation - Georgia Unit.

Minnesota

Minnesota contributed a Rainhart Mays ride meter and a Minnesota designed PCA roadmeter mounted in a 1980 Ford Fairmont to the correlation. Each system connected and measured response from the axle differential. The Mays meter used an International Cybernetics, Inc. pavement condition recorder Model 2001 for data collection and the PCA meter used electrical counters for measuring roughness (Figure 5). Speed is controlled and measured by the vehicle speedometer.

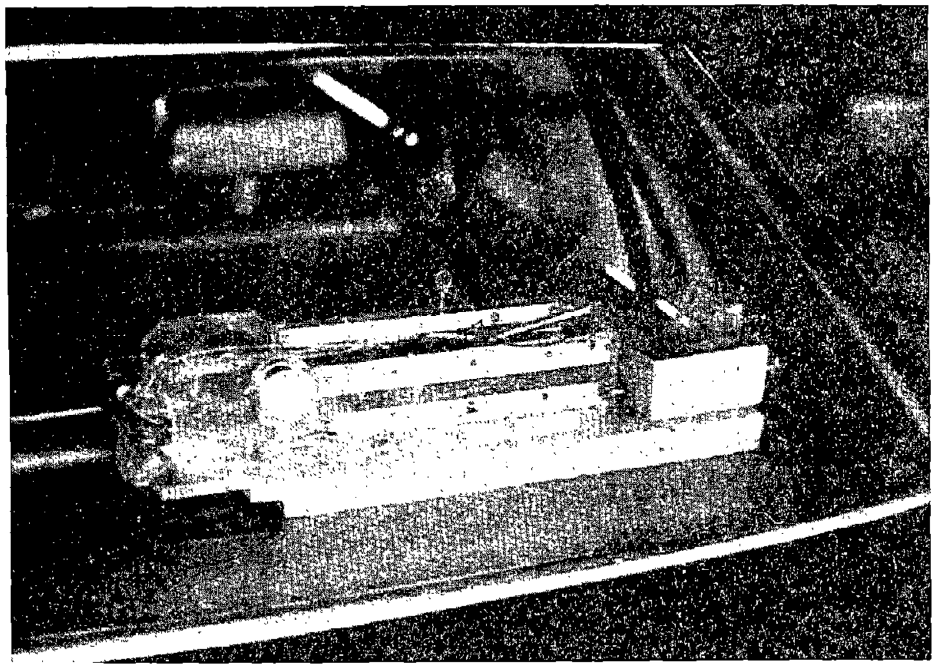


Figure 5. PCA Meter - Minnesota.

Ohio

Ohio furnished the non-contact inertial profilometer to determine the longitudinal roadway profiles (Figure 6). The first highway use of the profilometer was reported by Elson Spangler in 1965 (11) and the current model profilometers meet the requirements of ASTM Standard E 950. Current inertial profilometers have a non-contact displacement sensor and make measurements at highway speeds. Roughness output from the profilometer for this study was in Mays, PCA, RMS, and PSR numbers. The reference vehicle model used to derive the roughness numbers from the profile was the quarter-car model developed by Gillespie & Sayers under NCHRP 1-18 (6) which is also referred to sometimes as the "golden car." The PSR value derived with the profilometer is based on a correlation between measured pavement profile and a panel rating utilizing Ohio drivers conducted in 1983 (12).

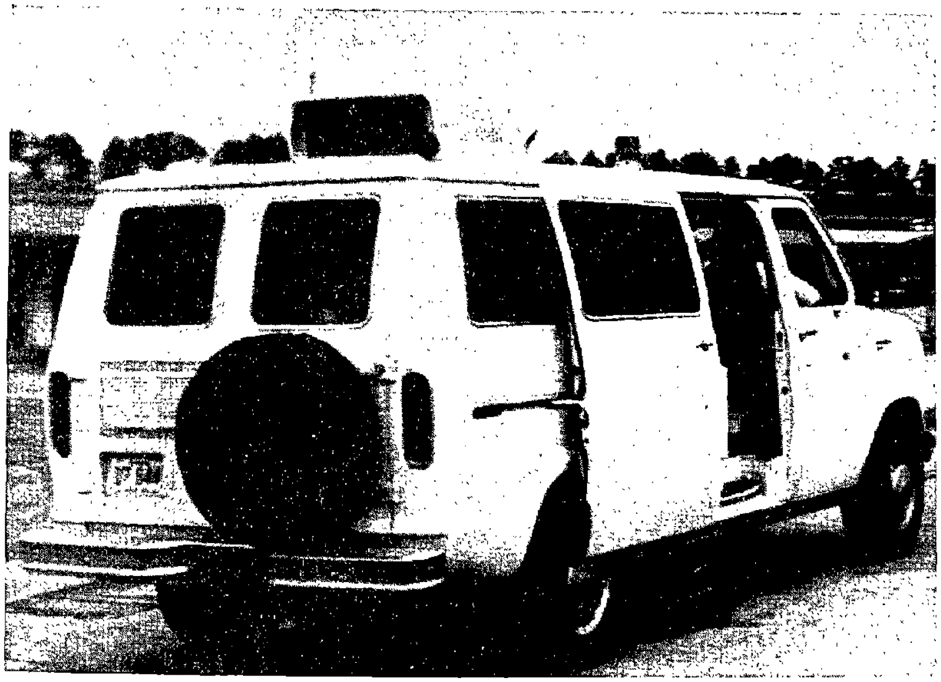


Figure 6. Ohio Inertial Profilometer.

Longitudinal profile measurements were being obtained in both the right and left wheelpaths and then averaged for the calculations of the simulated roughness output.

South Dakota

The South Dakota profilometer was designed and constructed by the South Dakota Department of Transportation personnel in 1981-1982. The system consists of a linear accelerometer and a non-contact ultrasonic ranging device mounted inside the left front fender of a 1977 Plymouth Fury (Figure 7). The ultrasonic device is an instrument grade transducer similar to the version used on auto focusing cameras. The transducer is mounted in a 1 1/2-inch PVC pipe fitting. The distance is measured by means of an electro-magnetic sensor attached to the left front wheel of the vehicle. A Digital Equipment Corporation LSI -11/23 microcomputer, contained in the back seat, controls the devices that measure the vehicle's horizontal distance, vertical position, and height above pavement. The computer also computes and records the highway profile. The roughness output is presented as a roughness rating similar to a PSR type number and is based upon a panel's subjective roughness rating correlated to the mean square power present in the measured profile for wavelengths less than 50 ft. A more complete description of South Dakota's profilometer can be found in Transportation Research Record 1000 (13).

Figure 7. Non-Contact Profilometer - South Dakota.

Georgia - Roughness Surveyor

The K. J. Law Model 8300 Roughness Surveyor is an ultrasonic non-contact profile measuring system which operates on the same principles as the inertial profilometer. The unit consists of a cannister which contains the accoustic probe, receiver, and an accelerometer. The cannister is mounted at the rear of the vehicle behind either the left or right wheel (Figure 8).

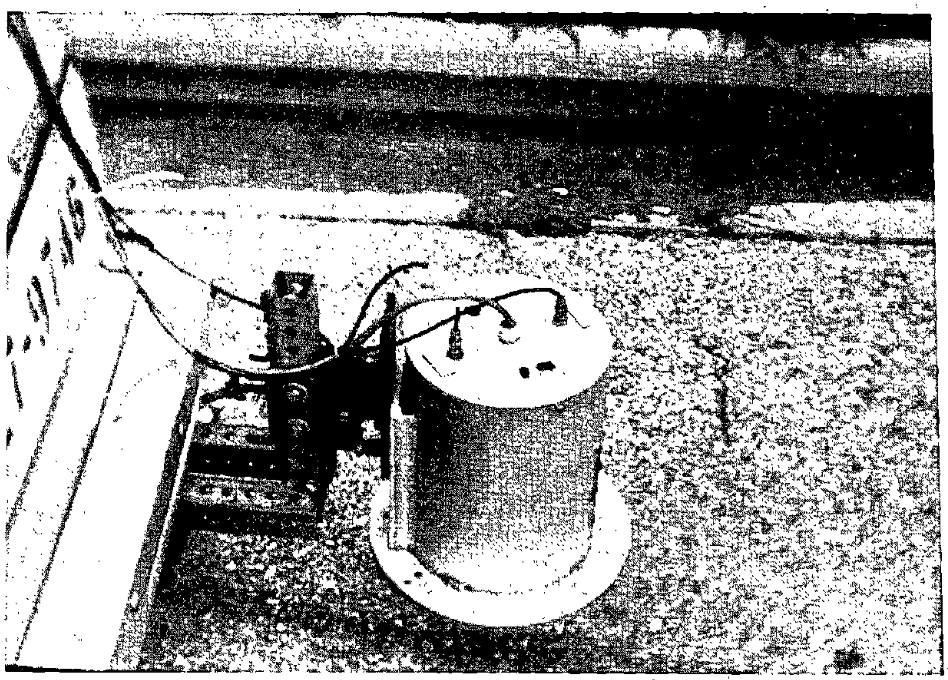


Figure 8. Roughness Surveyor Mounted on Vehicle.

The ultrasonic probe measures the displacement between the vehicle and the surface. The accelerometer measures the displacement of the vehicle only Both signals are fed into a digital microprocessor computer system placed in the vehicle. A computer program processes the signals, removes the vehicle motion from the total motion and calculates the profile measured by the Roughness Surveyor. The speed and distance is measured by an encoder mounted on the rear wheel and this data is also sent to the computer to be used in the computations. The computer can be programmed to provide Mays meter, PCA meter, RMS, and other vehicle response parameters. The "Golden Car" quarter-car systems is used to derive a simulated RTRRM systems output. The user has the option to select one RTRRM output and RMS output is always provided. The Mays meter output was selected for this project. The Root Mean Square (RMS) output provided by the Roughness Surveyor and the Inertial Profilometer is the RMS of the vertical movement of the sprung mass of the Quarter-Car Model. The Roughness Surveyor was mounted on the right rear framing of a 1979 Chevrolet Malibu Stationwagon. It was determined that since the right wheelpath of the pavement is normally rougher than the left wheelpath that a better evaluation of the device would be obtained by mounting the cannister on the right side.

It was also determined, through trial set ups, that the cannister should be frame mounted rather than bumper mounted. Most bumpers are shock mounted which allows too much vibration on the cannister. The earlier trials indicated that the accelerometer would not compensate for some of the additional vibration transmitted by the vehicle.

VI. RESULTS OF CORRELATION PROGRAM

The major objective of the correlation program was to determine how the various response-type roughness devices related to the profilometers and to determine if they could be calibrated and yield similar roughness values on identical pavement sections through calibration. All testing was done at a speed of 50 mph.

All test sections were used in the linear regression analysis of each response-type device against the profilometers to determine if a reasonable correlation existed between the profilometers and the roadmeters. The results of the correlation are shown for the Ohio Profilometer graphically in Figure 9 for the Maysmeter statistic. The linear regression equations for all the interactions are found in Table 3.

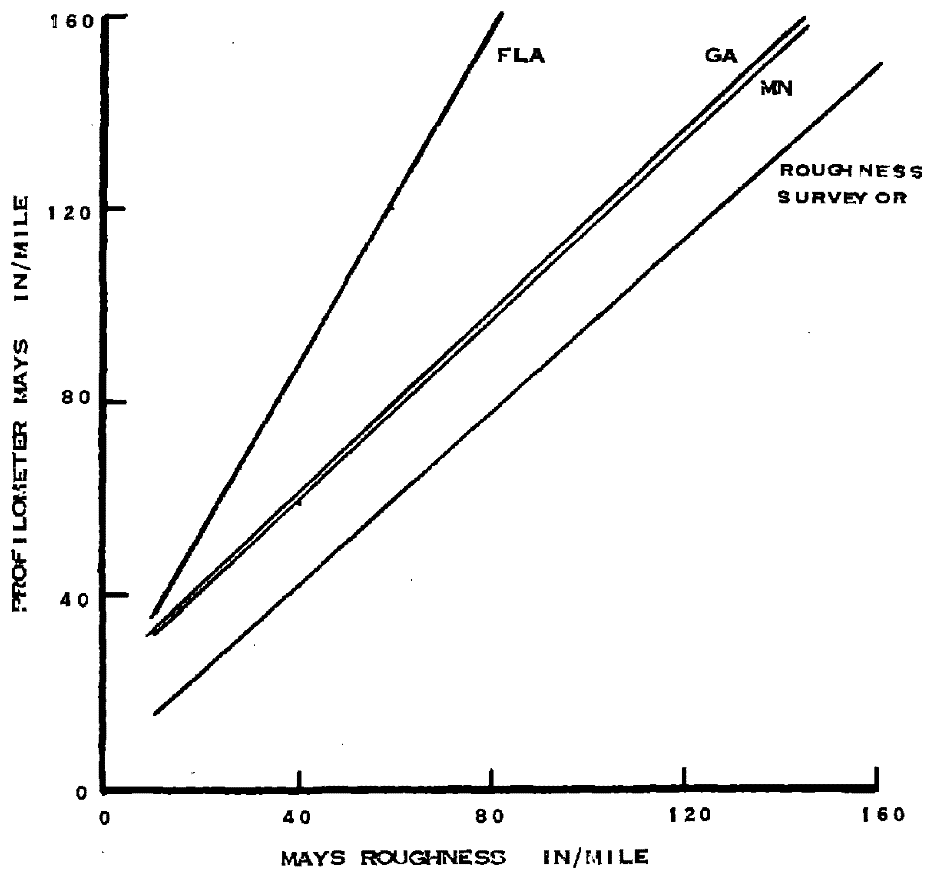


Figure 9. Ohio Profilometer Mays Compared to Other Roughness Meters.

TABLE 3. CORRELATION RESULTS.

RELATIONSHIP X vs Y	EQUATION	STANDARD ERROR OF ESTIMATE	CORRELATION COEFFICIENT
Ohio Mays vs Florida Mays	Y = 0.57X-10.32	3.9	.99
Ohio Mays vs 8300 Mays	Y = 1.09X- 5.39	33.2	.96
Ohio Mays vs Georgia Mays	Y = 1.04X-22.90	7.6	.98
Ohio Mays vs Minnesota Mays	Y = 1.08X-23.65	4.9	.99
Ohio PCA vs Minnesota PCA	Y = 0.25X-82.43	85.0	.97
Ohio RMS vs 8300 RMS	Y = 0.72X+ 1.64	6.55	.89
8300 Mays vs Georgia Mays	Y = 0.88X-11.9	13.3	.95
8300 Mays vs Florida Mays	Y = 0.48X- 4.32	7.4	.94
8300 Mays vs Minnesota Mays	Y = 0.9 X-10.84	12.7	.95
Florida Mays vs Minnesota Mays	Y = 1.87X- 2.82	6.0	.99
Georgia Mays vs Florida Mays	Y = 0.54X+ 2.84	4.2	.98
Georgia Mays vs Minnesota Mays	Y = 1.01X+ 2.11	8.7	.98
Ohio PSI vs Florida PSI	Y = 0.96X+ 0.69	0.15	.95
Ohio PSI vs South Dakota PSI	Y = 1.01X+ 0.13	0.50	.72
Florida PSI vs South Dakota PSI	Y = 1.12X- 0.85	0.43	.80

The Mays data obtained with the Florida and Minnesota meters is recorded in units of 0.1 inch/mile which was corrected to 1 inch/mile units in arriving at the above equations to correspond to the Mays units being calculated with the profilometer.

The results indicate that a good correlation exists between all the units in their ability to measure relative road roughness levels using the Mays and PCA measuring statistics. The correlation coefficients were somewhat less for the PSI comparisons involving the South Dakota unit.

The slopes of the lines for the correlation between the Profilometer Mays and the Georgia, Minnesota, and Roughness Surveyor Mays are close to 1:1, although there is a residual value for all the correlations.

The equations are nearly identical for the Georgia trailer mounted Mays and the Minnesota vehicle-mounted Mays. This result is probably due to the fact that the Georgia Mays meter values were calibrated to correspond to the response that was being obtained with Ford Torino stationwagon in use by Georgia at the time the Mays meters were transferred to trailers. The Minnesota vehicle used in the correlation, a Ford Fairmont, has a suspension system similar to the Ford Torino.

The variability in the correlation between the Inertial Profilometer and the Roughness Surveyor is much larger than the variability for the response-type meters as shown in Figures 10 through 12. This is a detriment to the use of the Roughness Surveyor as a calibration device.

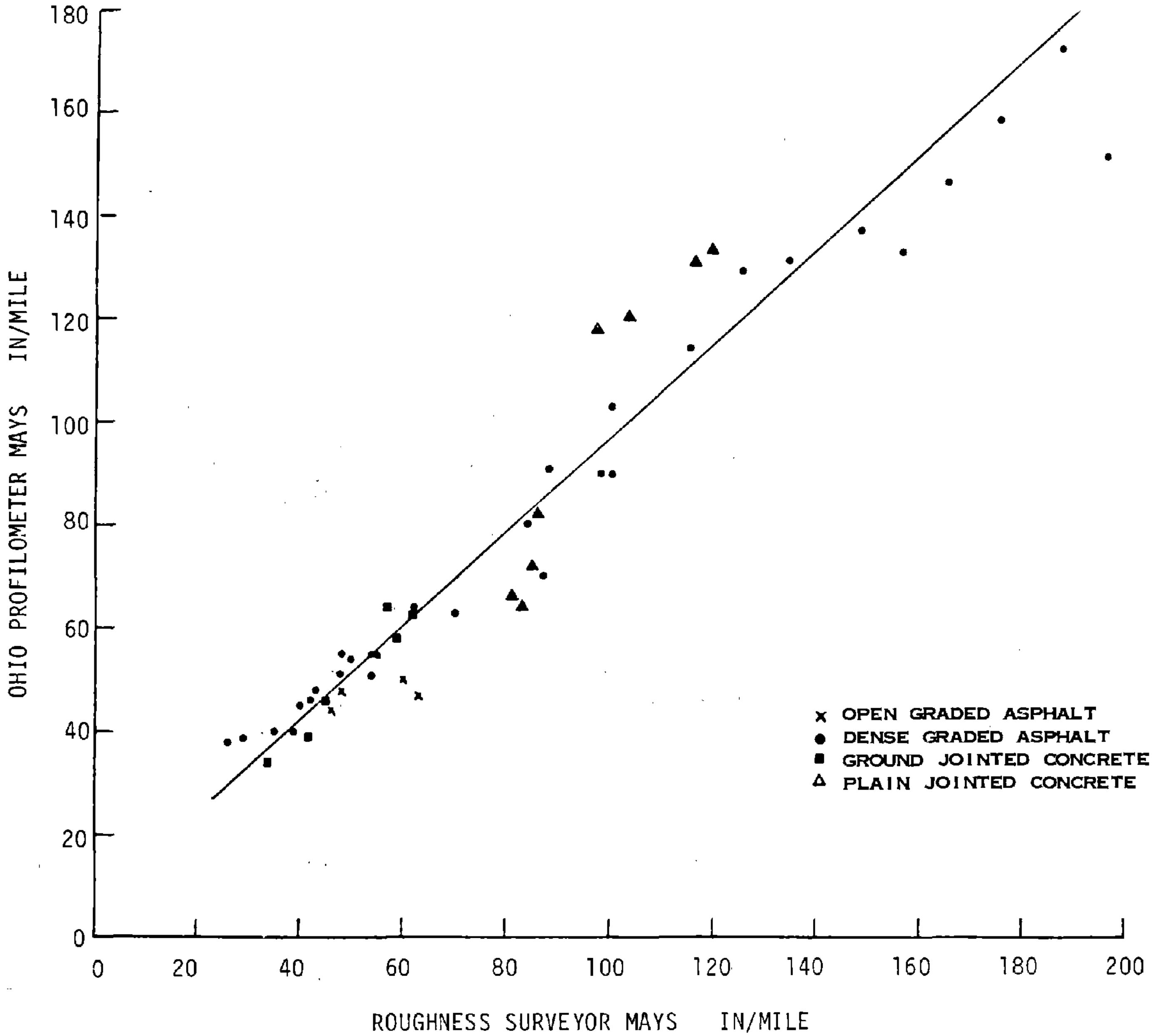
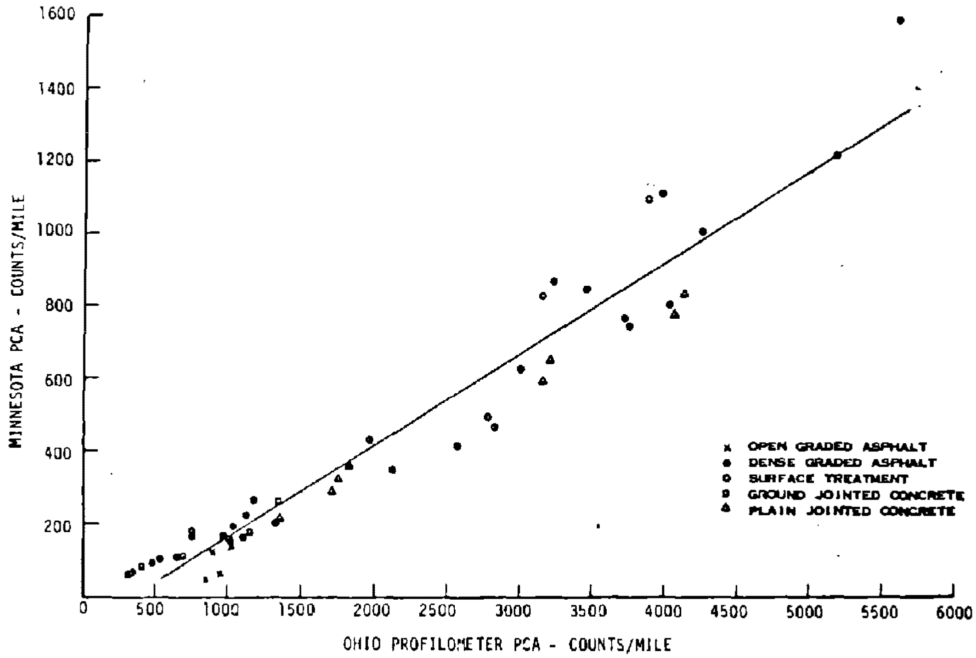


Figure 10. Correlation Between Roughness Surveyor and Ohio Profilometer.



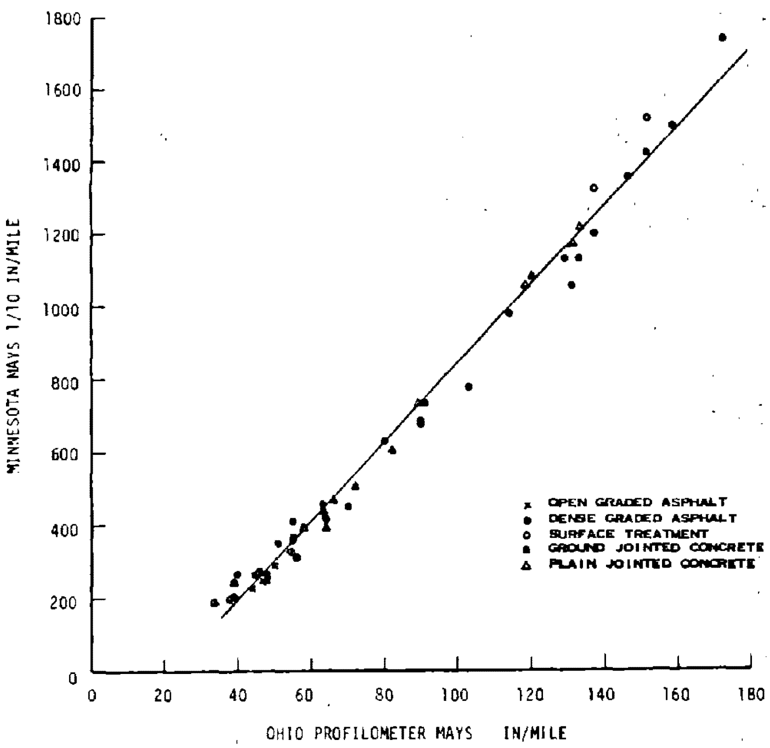
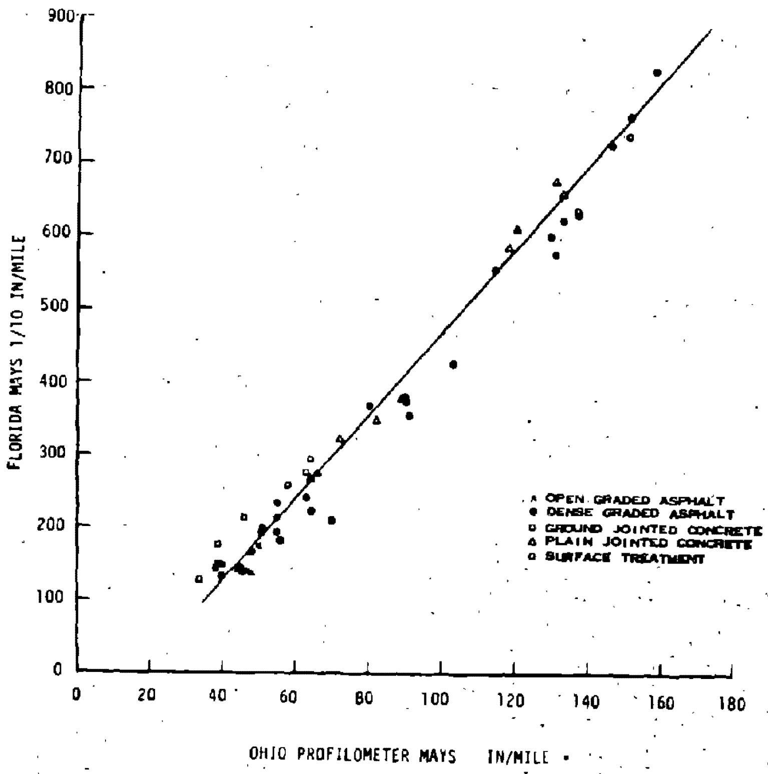


Figure 11. Correlation Between Ohio Profilometer and Minnesota Roughness Meters.



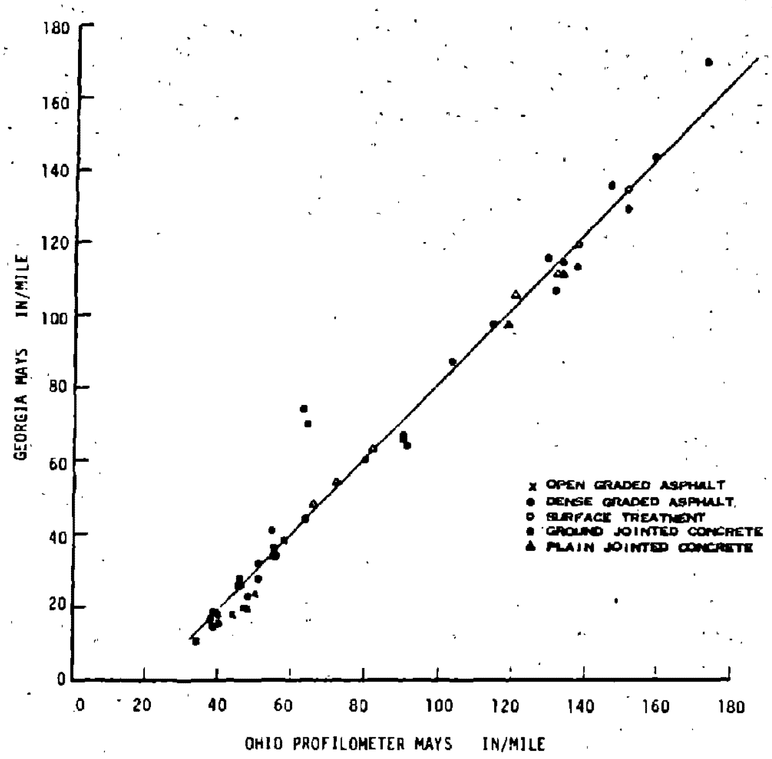


Figure 12. Correlation Between Ohio Profilometer and Georgia and Florida Mays Meters.

Comparison of Present Serviceability Index (PSI) Values

The Florida, Ohio, and South Dakota units all produced PSI values from the roughness measurements. The PSI values obtained by Florida are derived from a periodic correlation between the Mays meter and CHLOE. The South Dakota unit produces a roughness rating on a scale from 0 to 5 which can be considered comparable to the PSI scale. The roughness ratings is a function of the mean square power P found in the measured profile for wavelengths of less than 50 ft. The values of P have been related to a panel's subjective ratings of road roughness (13). The PSI rating from the Ohio Inertial Profilometer was based on a relationship between profile data and the mean subjective ratings of a thirty-six member panel on fifty-two Ohio test sections obtained in 1983 (12).

The serviceability values for the test sections in the Georgia correlation study are shown in Table 4 for the three devices. The serviceability values obtained with the Florida unit were higher for every test section when compared to the values obtained with the Ohio unit. The average difference between the two units was 0.55 with the differences ranging from 0.19 to 0.96. The distribution of the serviceability values were similar for the Ohio and Florida units as seen in Figure 13 with a shift of 0.5 units in serviceability level. This shift could possibly be due to the fact that the Ohio formula in reference 12 which calculates PSI values from the profilometer data uses a value of 4.54 as the upper end of the rating scale rather than 5.0 as is customary on the AASHTO PSI scale. The serviceability values obtained with the South Dakota profilometer were more uniformly distributed over a range from 2.5 to 5.0 as shown in Figure 13 which is in sharp contrast to the distributions obtained with the Florida and Ohio units. A comparison of the South Dakota and Ohio units show that approximately two-thirds of the

TABLE 4. COMPARISON OF PSI VALUES OF CORRELATION TEST SECTIONS.

TEST SITE	TEST SECTION NO.	TYPE PAVEMENT	PSI			Δ PSI		
			OH	FL	SD	FL OH	SD OH	SD FL
1	1	OG	3.88	4.39	4.03	.51	.15	- .36
	2		3.83	4.39	4.07	.56	.24	- .32
2	3	AC	3.67	3.88	3.27	.19	- .42	- .61
	4		3.56	3.85	3.28	.29	- .28	- .57
3	5	AC	3.45	3.91	3.06	.46	- .39	- .85
	6		3.51	3.79	2.91	.28	- .60	- .88
4	7	OG	3.89	4.31	4.19	.42	.30	- .12
	8		3.89	4.39	4.12	.50	.23	- .27
5	9	ST	2.62	3.20	2.74	.58	.12	- .46
	10		2.63	3.02	2.73	.39	.10	- .27
6	11	PCC GND.	3.61	4.28	3.97	.67	.36	- .31
	12		3.65	4.35	4.75	.70	1.10	.40
	13		3.81	4.40	4.51	.59	.70	.11
	14		3.88	4.47	4.67	.59	.79	.20
7	15	AC	3.68	4.22	3.56	.54	- .12	- .66
	16		3.87	4.41	3.96	.54	.09	- .45
	17		3.91	4.37	3.92	.46	.01	- .45
	18		3.76	4.27	3.54	.51	- .22	- .73
8	19	AC	2.93	3.44	2.83	.51	- .10	- .61
	20		2.99	3.73	3.24	.74	.25	- .49
9	21		2.73	3.28	2.79	.55	.06	- .49
	22		2.82	3.39	2.63	.57	- .19	- .76
	23		2.81	3.26	2.65	.45	- .16	- .61
	24		2.71	2.96	2.46	.25	- .25	- .50

TABLE 4 (CONTINUED)

TEST SITE	TEST SECTION NO.	TYPE PAVEMENT	PSI OH	PSI FL	PSI SD	Δ PSI FL/OH	Δ PSI SD/OH	Δ PSI SD/FL
10	25	AC	3.67	4.30	3.40	.63	- .27	-1.00
	26		3.66	4.27	2.70	.61	- .96	-1.57
	27		3.70	4.20	2.70	.50	-1.00	-1.50
	28		3.71	4.17	3.55	.46	- .16	- .62
11	29	AC	3.81	4.27	4.49	.46	.68	.22
	30		3.80	4.38	4.02	.58	.22	- .36
	31		3.83	4.39	3.94	.56	.11	- .45
	32		3.84	4.33	4.56	.49	.72	.23
12	33	AC	2.13	2.84	2.77	.71	.64	- .07
	34		2.57	3.33	2.66	.76	.09	- .67
	35		2.20	3.05	2.52	.85	.32	- .53
	36		1.98	2.37	2.57	.39	.59	.20
13	37	PCC	3.41	4.12	3.96	.71	.55	- .16
	38		3.41	4.09	3.86	.68	.45	- .23
	39	PCC GND.	3.35	4.26	4.20	.91	.85	- .06
	40		3.27	4.23	4.43	.96	1.16	.20
14	41	AC MILL	3.70	4.16	4.09	.46	.39	- .07
	42		3.62	4.23	4.24	.61	.62	.01
	43	AC	3.77	4.36	4.63	.59	.86	.30
	44		3.69	4.38	4.62	.69	.93	.24
15	45	PCC NEW	3.61	4.27	-	.66	-	-
	46		3.71	4.26	-	.55	-	-
	47		3.51	4.16	-	.65	-	-
	48		3.70	4.19	-	.49	-	-
16	49	PCC	3.25	3.72	2.73	.47	- .52	- .99
	50		3.31	3.83	3.21	.52	- .10	- .62
	51		3.32	3.70	3.08	.38	- .24	- .62
	52		3.35	3.79	3.03	.44	- .32	- .76

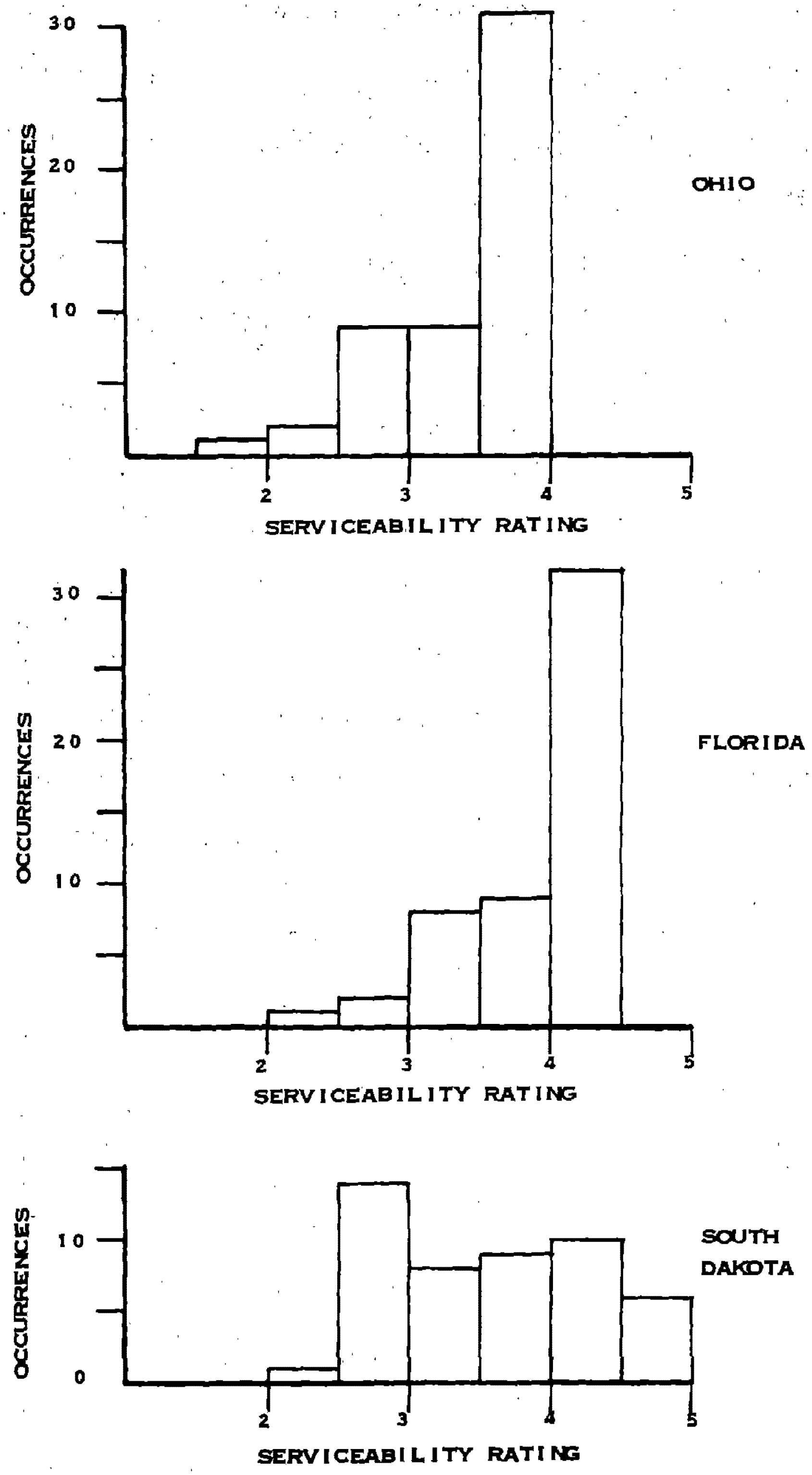


Figure 13. Distribution of Serviceability Ratings of Test Sections.

sections were rated higher by South Dakota and one-third were rated higher by Ohio. The mean difference was 0.46 units for the higher rated sections by South Dakota and 0.30 units for the lower rated sections by South Dakota.

The differences in the serviceability values obtained on the same test sections at the same time with different measuring units point out the problems associated with utilizing serviceability values as a common reference.

VII. EVALUATION OF MODEL 8300 ROUGHNESS SURVEYOR

One of the objectives of the research project was to determine the accuracy and repeatability of the Roughness Surveyor. A second objective was to determine the feasibility of using the device as a calibration reference for response-type roughness meters. The evaluation included investigations into effects of speed variation, testing repeatability, day-to-day repeatability, and a correlation against the Surface Dynamics Profilometer. The device was tested over time on a variety of road surfaces, pavement textures, and roughness levels as previously outlined in this report.

Speed Dependency

One of the advantages of a roughness measuring system with an inertial reference is that speed variations do not effect the test results. This feature eliminates a variable which must be tightly controlled with response-type meters. Such a system is also useful in urban areas where a constant test speed can generally not be maintained. The vehicle motion, generally measured by an accelerometer, is subtracted electronically from the total motion to establish the changes in pavement profile.

Roughness tests were made on a selected number of sections with the Roughness Surveyor at three test speeds, 30 mph, 40 mph, and 50 mph. The results of these tests are shown in Table 5 and indicate that the test speed generally has no effect on the roughness results.

Test Repeatability

To determine the variability of the test results, obtained with the 8300 Roughness Surveyor in comparison to the other devices, five repeat runs were made on six test sites with a total of fourteen (14) test

TABLE 5. RESULTS OF SPEED VARIATION TESTING WITH ROUGHNESS SURVEYOR.

LOCATION			SURFACE TYPE	DATE	TESTING SPEED (MPH)		
					30	40	50
SR-7	MP 1-2	N	O.G.	4-8-85	-	54	52
		S	O.G.		-	50	47
SR-7	MP 1-2	N	O.G.	4-9-85	46	-	47
		S	O.G.		39	-	42
Camp Calvin		E	A.C.	4-9-85	93	94	112
		W	A.C.		109	110	125
SR-16	MP 2-3	E	A.C.	4-10-85	53	53	53
		W	A.C.		51	56	57
High Falls Rd.		N	A.C.	4-10-85	85	89	89
		S	A.C.		95	97	98
SR-16	MP 0-1	E	A.C.	4-10-85	51	52	52
		W	A.C.		47	47	48

sections. Surface types included open graded friction courses, dense graded mixes, surface treatment, and ground portland cement concrete pavements. The coefficient of variation (c.v.) was calculated for each test site for each device with the results shown in Table 6. The repeatability was excellent for the Ohio Profilometer with a coefficient of variation of about 1 percent. The results obtained with the other devices also were good with average values of less than 5 percent.

TABLE 6. TESTING REPEATABILITY OF ROUGHNESS DEVICES.

TEST SECTION	TYPE SURFACE	COEFFICIENT OF VARIATION						
		OHIO MAYS	8300 Mays	GA Mays	MINN Mays	FLA MAYS	OHIO RMS	8300 RMS
1	Open Graded	0.8	2.1	1.5	4.8	2.6	0.6	3.3
		1.2	2.5	4.4	5.3	2.2	2.2	5.1
2	Dense Graded	1.2	3.9	1.9	2.4	2.3	1.2	3.3
		1.5	1.7	3.1	3.4	1.4	1.9	4.5
3	Dense Graded	0.4	1.7	1.9	2.2	2.0	-	1.3
		0.6	3.2	4.3	2.7	0.8	-	4.0
4	Open Graded	0.6	2.3	1.5	7.1	3.9	-	1.8
		1.3	3.1	4.3	7.2	3.7	-	2.6
5	Surface Treatment	1.5	-	0.7	0.9	4.8	-	-
		1.4	-	1.3	2.4	4.3	-	-
6	Ground Concrete	-	3.4	2.2	4.9	2.4	-	4.0
		-	4.3	3.1	7.3	4.3	-	2.8
		-	2.7	4.0	6.0	9.3	-	4.0
		-	-	2.9	4.3	10.4	-	-
Average		1.1	2.8	2.7	4.3	3.9	1.5	3.3

DAY-TO-DAY REPEATABILITY

Any device that is to be used as a calibration tool for road roughness meters must be able to give accurate repeat measurements on a day-to-day basis. When a change in roughness level of a roadway is indicated by a calibration device it must be due to a change in the roadway profile and not due to random testing variation from the calibration standard. To determine the day-to-day variability of the Model 8300 Roughness Surveyor, a number of test sites were measured on two different days (2 1/2 to 4 1/2 days apart). Due to rain during one of the testing days, repeat data was obtained only on ten of the sixteen test areas with a total of thirty (30) test sections. The Mays and RMS statistics obtained on these sites were compared for day-to-day repeatability to determine the reliability of the Roughness Surveyor in measuring actual changes in roadway roughness levels. The degree of change between the repeat runs was calculated and expressed as a percentage of the initial test values with the results shown in Table 7. The actual test values are shown in Appendix A with each value representing the average of three to five actual test runs made in succession on each day. Only the Mays and RMS values are being compared since the PCA statistic was not being obtained with the Roughness Surveyor.

An examination of the data indicates that the degree of change was not related to the level of roughness as might have been expected. The percent of change of course is affected by the initial roughness level. For instance, a change in roughness level of 2 units would translate into a larger percentage change for a smooth road than for a rough road. A comparison of actual changes in roughness level between the units producing a Mays statistic is shown in Table 8. This comparison clearly indicates the reliability of the Inertial Profilometer in obtaining repeatable profile data from day-to-day.

TABLE 7. DAY-TO-DAY REPEATABILITY.

ROUGHNESS OUTPUT	AVERAGE PERCENT OF DAY-TO-DAY VARIABILITY
Profilometer Mays	2.2
Roughness Surveyor Mays	17.6
Georgia Trailer Mays	4.8
Florida Trailer Mays	5.8
Minnesota Vehicle Mays	10.3
Profilometer RMS	2.4
Roughness Surveyor RMS	17.4

The data also shows that the day-to-day repeatability for the trailer-mounted Mays meters was very acceptable with the roughness levels for 28 out of 30 sections repeating within 3 or less Mays units (in/mile). By comparison, the results from the Roughness Surveyor only showed 4 out of 30 test sections to be within 3 Mays units. A direct comparison of Mays numbers can be considered valid since the Mays meter results from the roughness equipment are generally of equal order of magnitude. The results of the testing to determine day-to-day repeatability indicates that the Roughness Surveyor has too much variability to be used as a calibration reference.

TABLE 8. COMPARISON OF DAY-TO-DAY VARIABILITY FOR MAYS ROUGHNESS STATISTIC.

MAYS NUMERICAL CHANGE	PROFILOMETER	ROUGHNESS SURVEYOR	GEORGIA TRAILER	FLORIDA TRAILER	MINNESOTA VEHICLE
0	13	2	7	10	2
1	8	1	11	7	5
2	5	1	4	7	2
3	3	0	6	4	5
4	1	3	1	1	4
5		1	1	1	4
6-9		10			6
≥10					

WHEELPATH BIAS

The Roughness Surveyor measures the roughness in one wheelpath only; therefore, the simulated RTRRM output does not represent the effects of the other wheelpath. The inertial profilometer obtains profiles in both wheelpaths and the computer combines the effects of both wheelpaths in calculating the selected RTRRM output. It was desirable to determine the possible effect of wheelpath roughness on the various analysis and comparisons made between the devices which measure the combined roughness from both wheelpaths and the roughness surveyor. The roughness in the right wheelpath only was also calculated from the inertial profilometer data to correspond to the roughness actually measured by the Roughness Surveyor.

A linear regression analysis was performed on the data comparing the right wheelpath roughness from the inertial profilometer against the roughness obtained from combining the left and right wheelpaths. Comparisons were also made against the data from the Roughness Surveyor. The analysis clearly indicates that the right wheelpath was substantially higher in roughness level than the average roughness obtained from both wheelpaths. The difference in roughness level also increased with increasing magnitude of roughness of the roadway, especially for asphaltic concrete surfaces (Figure 15). The linear regression showed a high degree of correlation for both the asphaltic and portland cement concrete surfaces with the following equations:

Asphaltic Concrete Mays RWP = 0.72 (Mays BWP)+5.5 r = 0.996 SEE = 4.1

Portland Cement Concrete Mays RWP = 0.89 (Mays BWP)-2.0 r = 0.977 SEE = 6.6

where: RWP = Right Wheelpath

BWP = Both Wheelpath

r = Correlation Coefficient

SEE = Standard Error of Estimate

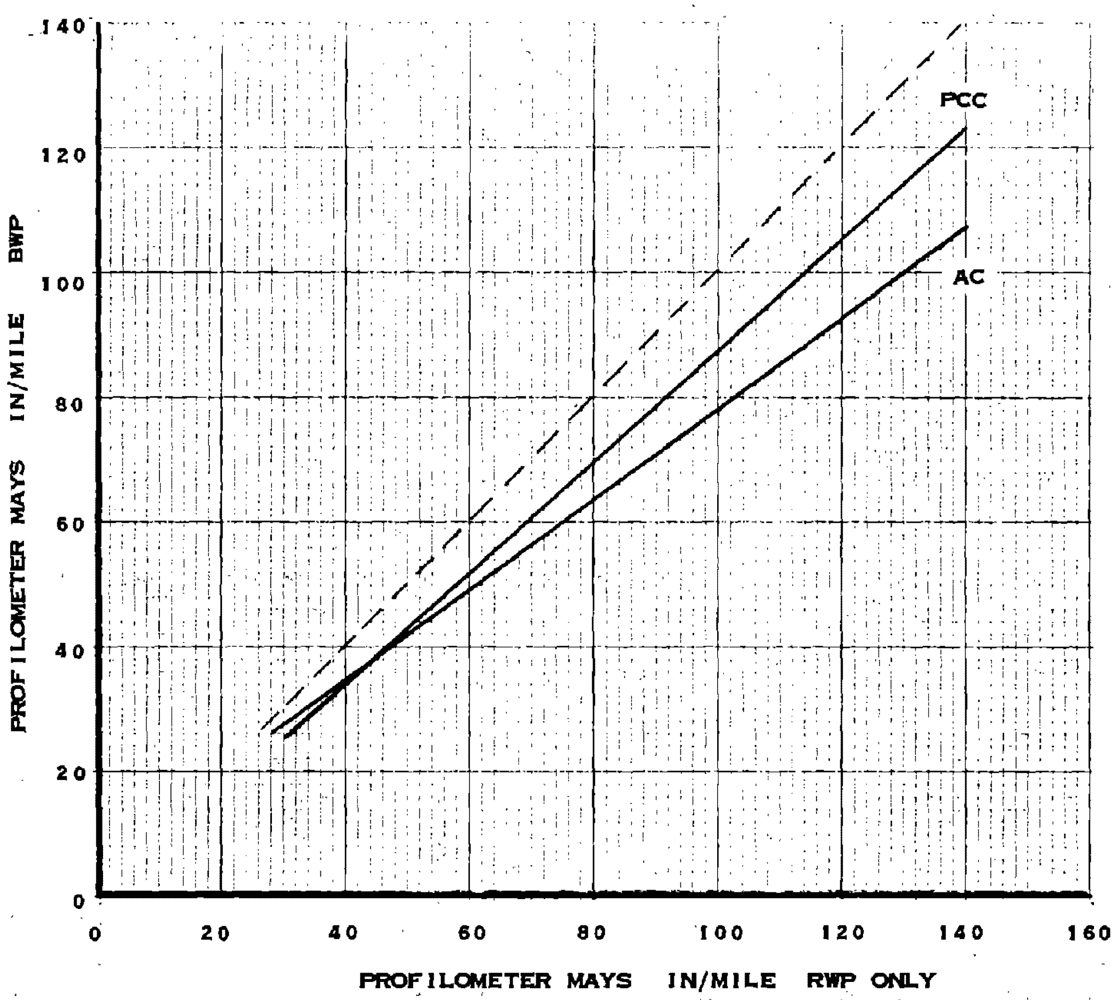


Figure 14. Comparison of Right Wheelpath Roughness to Total Roughness.

A linear regression analysis was also performed comparing the Mays roughness results from the inertial profilometer's right wheelpath and the Roughness Surveyor Mays output. This comparison should give an indication of the accuracy of the Roughness Surveyor in obtaining the longitudinal profile since the simulation programs which "drive" the quarter-car model over the profile are the same for both devices. The result of the analysis is shown in Figure 15.

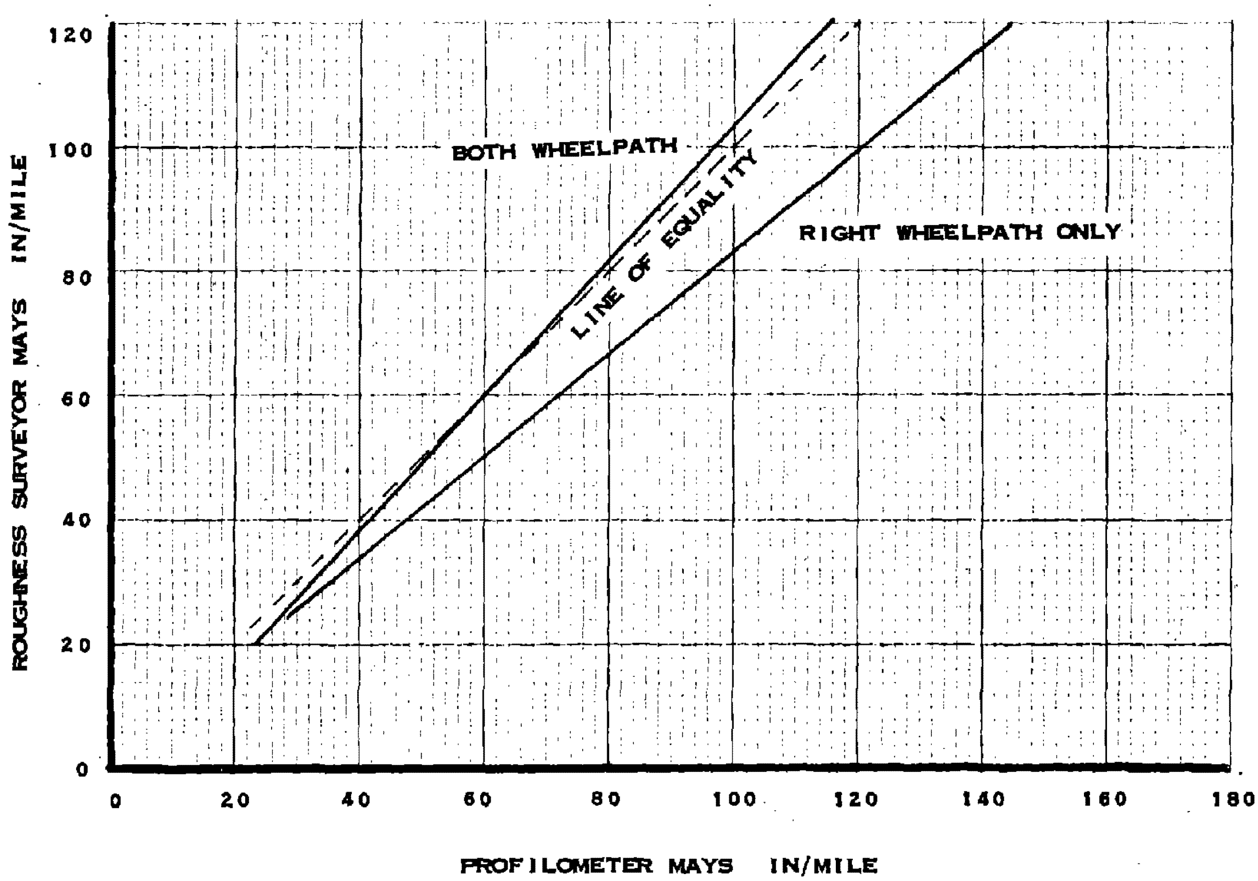


Figure 15. Comparison of Roughness Level for Right Wheelpath Only.

The resulting equation is as follows:

Mays Roughness Surveyor = 0.81 (Ohio RW) Mays) +1.7

$r = 0.957$ SEE = 17.8

The results in Figure 15 clearly indicate that the Roughness Surveyor shows a lower roughness level than the inertial profilometer for the right wheelpath. The difference in roughness levels also increases as the magnitude of the road roughness increases. A comparison of the results from the Roughness Surveyor to the combined roughness levels from both wheelpaths as measured by the profilometer indicates that these roughness levels are nearly identical.

The data for the repeat runs made with the inertial profilometer several days apart were available for 28 test sections only. The comparison of the results of the repeat runs for the right wheelpath obtained with the profilometer showed that the average difference in roughness levels was 1.6 percent which again indicates excellent repeatability for the inertial profilometer.

VIII. CALIBRATION OF RTRRM SYSTEMS

Calibration Methods

Ever since the response-type road roughness meters (RTRRM) came into use in the late 60's, the calibration and correlation of these devices has been of concern. RTRRM systems are attractive to highway agencies for measuring roughness because of the relatively low initial and operating cost, simplicity of operation and maintenance, and ease of data reduction. These systems, however, also have vehicle and instrumentation characteristics which can drastically affect the test results if not properly accounted for. Some of these variables are speed, tire pressure, vehicle weight, type of tire, fluctuations in amounts of gasoline, springs, shocks, wind, etc. Many of the variables can be minimized through standardization of the test procedure and by the use of standard equipment such as trailers, but the fact remains that there is a potential problem with time stability of the system. Frequent calibration checks are necessary to insure the proper operation of any RTRRM system. The degree of accuracy desired in the calibration of roughness measuring systems depends upon the purpose of the data being collected.

Until recently most agencies obtained roughness measurements for inventory purposes or as a means of obtaining the Present Serviceability Index (PSI) value of a roadway. In recent years, more and more emphasis has been placed on obtaining rideability standards during construction utilizing RTRRM and profilograph requirements instead of straightedge results. The use of RTRRM systems in construction control requires calibrations which show sensitivity to relative small changes in the measuring system.

Some of the calibration methods that have been used are:

1. Periodic calibration against rating panels.
2. Use of a "Standard Meter" which is only used for calibration purposes.
3. Artificial Reference Surfaces.
4. In-Service Roughness Calibration Sections.
5. Correlations against Profilometers.

The use of rating panels for calibration of roughness meters was a logical extension of AASHO road test results where pavement performance was rated in terms of PSI values. Shortcomings in this method, however, were realized due to the large standard deviations of the mean ratings, the need for a large number of sections, and the use of large panels (15) (16).

The use of artificial reference surfaces would appear to be a logical method for calibration since a "known" roughness could be induced and any changes in the measured roughness could therefore be attributed to the RTRRM system. The use of artificial reference surfaces was recommended as an alternate calibration procedure in NCHRP Report 228 which deals with the calibration of RTRRM systems (6). The procedure called for the placement of four artificial "bumps" in each wheelpath over a distance of 131 ft. Two of the elements were 25 ft in length and 1 1/2 in high, and the other two were 22 1/2 ft long and 1 1/4 in. high. The elements were stair-stepped to the maximum height. A similar system using rubber pads was recommended in a Canadian study (8).

The use of one-inch by one-inch boards placed across the road was recommended as a calibration procedure in a study conducted by Clemson University in 1981 (18). The artificial reference surfaces all require a relatively smooth section of pavement to reduce latent roughness. Some of the problems with the use of artificial reference surfaces were described in the NCHRP report. Generally, the calibration has to be conducted at low speeds due to the short length, thereby eliminating any effects of tire/wheel non-uniformities. In addition, the full spectrum of roughness contained in a roadway cannot be duplicated, and only the large axle-body movements are generated by the artificial bumps masking any potential problems which may affect the roughness measured on smooth roads. These problems were observed in a study performed by the Georgia Department of Transportation using the NCHRP reference surfaces. Nine trailer-mounted Mays meters were calibrated using the procedure and then tested on smooth and rough in-service test sections. The test results indicated a wide range in measured roughness levels between the trailers, especially on the smooth sections (19).

The use of in-service test sections for calibration of RTRRM systems is typically used by many agencies. Often a large number of test sections are selected over a wide range of roughness levels. Roughness levels are established for the sections by rating panels, CHLOE Profilometer, a "standard" roughness vehicle or simply the initial roughness output of the device at some point in time may be considered as the calibration standard. The concern with in-service sections is the large amount of time required for calibration if many sections have to be checked, the expense involved if rating panels are used, the accuracy of the roughness values used as calibration standards, and the long-term stability of the pavement surfaces. If the output of a RTRRM system is used as a standard, frequent checks and the use of control charts is needed to be able to detect and minimize the effects of long-term changes in the roughness levels of the control sections (9)(19).

The Texas Department of Highways and Public Transportation (SDHPT) has been using the GMR Profilometer for a number of years to produce a stable reference statistic for calibrating its Mays meters (7). The CHLOE Profilometer is being used in Florida to establish PSI values on a number of test sections for calibration of Mays meters (20). High speed non-contact profilometers capable of measuring and storing the longitudinal profiles are relatively expensive to purchase and to operate prohibiting its use as a calibration tool for RTRRM systems for many agencies.

Rod and level procedures have been developed to obtain roadway profiles that can be used for analysis and from which a calibration statistic can be derived (10). South Dakota also developed an inexpensive profilometer using accoustic techniques which gives a roughness rating equivalent to a PSI scale (13).

Roughness Statistic for Calibration

The selection of a roughness statistic to be used as a calibration reference is an important consideration in the calibration procedure. Several roughness statistics have been used or have been recommended by various agencies and researchers. Some of these statistics are as follows:

1. Present Serviceability Index, PSI.
2. CHLOE Slope Variance, SV.
3. Quarter-Car Simulation Index QI.
4. Average Rectified Velocity ARV.
5. Root Mean Square Vertical Acceleration, RMSVA.

A complete description and comparison of these statistics can be found in reference (10). All these statistics can be generated from the roadway longitudinal profiles by computer analysis. With the increasing use of the

RTRRM systems for construction control, any calibration reference statistic must be sensitive to relatively small changes in the response of the RTRRM system.

Studies done by McKenzie and Hudson compared the serviceability statistic to the RMSVA statistic and concluded that the RMSVA statistic more accurately represent the pavement roughness as determined by the Mays meter (7). The PSI or SV statistic is also not very sensitive to relatively small changes in RTRRM statistics produced by Mays meters and PCA meters. Hudson et al in reference (10) recommended the use of the RMSVA statistic as the reference roughness statistic for calibration because the value is based solely on profile data and not a simulation of a standard vehicle transversing the profile.

A significant amount of information has been reported in the literature dealing with relating pavement profile characteristics to user opinion of the roughness of a road (6)(7)(21-27). It is generally accepted that the vertical acceleration experienced by the vehicle mass relates to the driver's opinion of the roughness level of the roadway. The standard roughness statistics, MO, recommended by Hudson in reference (10) is based on the best correlation between Mays meter response and RMSVA with a 4 ft and 16 ft base lengths.

The main purpose in calibrating a RTRRM system is to ensure that the system response to a profile has not changed and to determine the corrective factor to be applied to the output if a change has taken place and cannot be corrected by replacement or repair of suspension components.

The use of the Quarter-Car Simulation statistic utilizing the "Golden Car" parameters developed by Gillespie in a NCHRP study and contained in reference (6) may be more attractive to highway agencies as a calibration reference than the other roughness parameters discussed in this section.

The Q.I. statistic can be simulated for any RTRRM statistic producing values which are of the same magnitude as the values obtained by the agencies from the RTRRM systems. In addition, the concept of simulation can be readily explained and understood by agency and contracting personnel.

IX. DISCUSSION OF CALIBRATION PROCEDURES

The results that have been obtained in the test program with the Model 8300 Roughness Surveyor indicate that the device is unsuitable to be used as a calibration reference. The test program also showed that the inertial profilometer is highly suitable as a calibration reference for road roughness meters and the device is being used in Texas for calibration of Mays meters.

The profilometer can be used to obtain a correlation with a response-type meter using a number of roads. This correlation can then be used to convert the roughness number from the response-type meter to a standard roughness number obtained with the profilometer. Another approach would be to use the profilometer to detect changes in the road profile of test sections or changes in the response-type meter so that the readings from the response-type meter can be corrected to account for the changes in roughness meter's response.

Both approaches would require periodic visits by a profilometer and the use of road tests sections for calibration control between profilometer visits.

Use of Profilometer Generated Roughness Number

The use of a generalized roughness index is of interest in that it would give comparable roughness readings regardless of the response-type roughness system which was used to obtain the data. Hudson et al has reported on a study sponsored by FHWA which examined the various roughness statistics and recommended a statistic based upon root mean square vertical acceleration (RMSVA) called MO (1) as discussed previously in this report.

Any statistic produced by the profilometer can be used by an agency in calibrating its response-type meter since the profilometer only represents a stable reference plane in the calibration process.

Test sections encompassing several pavement types and roughness levels must be selected by the agency to establish a correlation between the chosen profilometer statistic and the response-type meter(s). The number of sections needed for correlation that has been recommended in some of the literature range from 10 to 30 (1)(2). In this study, comparisons were made using 52 test sites and 14 test sites and no significant differences were found between the correlation equations for any of the devices included in the testing program.

Prior to establishing a correlation with the profilometer, the response-type meter should be operated on some of the smooth and rough test sites to determine the variability in the testing device. Any variability of more than 10% may indicate mechanical problems such as shocks, tires, springs, wheelbearings, etc. which must be corrected prior to a correlation. It may also indicate that the vehicle or trailer is unsuitable for use as a roadmeter due to a poor suspension system for instance.

Once the initial correlation has been obtained, the test sites should be established as control sections to check the calibration of the response meter between visits by the profilometer. Variability limits must be established on each control site to account for the variability in the testing device.

By examining the results of the calibration checks on the various control sections it can be determined if a problem exists with the response-type meter. Changes in road profiles generally do not occur over relatively short periods of time unless repair work has been done within the control sections. Any drastic changes in roughness levels therefore would indicate a mechanical problem and the roadmeter should be examined and the problem corrected. If no mechanical problems exist recalibration with the profilometer will be necessary. Experience in Georgia has indicated that four to six control sections are adequate for calibration checks as long as the sites are placed equally on smooth, medium, and rough roads.

Use of Response-Type Meter Statistic

Many agencies have been obtaining roughness numbers with a Mays or PCA-type meter for several years and only wish to calibrate their roadmeters without changing the magnitude or type of their roughness statistic. The calibration procedure would be similar to the method described previously in that test sections must be established for a correlation with the profilometer. Also, the response-type system must be checked for system variability and mechanical problems corrected prior to a correlation.

The existing magnitude of the roughness levels of the response meter will become the benchmark level for that system. If more than one response-type system is being used by an agency, the output from one system must be selected as the benchmark or standard roughness level initially.

The initial correlation with the profilometer will relate the benchmark roughness levels to a profilometer reference statistic. Subsequent regular visits by the profilometer will then establish the current benchmark roughness level for each control section. If no significant profile changes have taken place, the roughness level would be the same as the value previously established. The output from the response-type meter would then be correlated against the calculated value from the profilometer for the control sections. If the values fall within an established range for each control section, no change in the calibration will be necessary. If there are significant differences, it will be necessary to develop a transform function for the response meter(s) assuming mechanical problems were not the cause of the discrepancy. This transform function would correct the measured roughness value to the benchmark or calibrated roughness value. The roughness corrections are then made using the equation developed during correlation.

This calibration may be preferable to agencies which already have existing data bases. The procedure also provides for the capability of relating the response meter output to a generalized roughness index obtained with the profilometer when necessary.

The discussion so far has been concerned with calibration through correlation. There are inherent problems with calibration accuracy utilizing this approach since the calibration will only be as precise as the correlation allows. The standard error of estimate values can be and are significant for some correlations even with the best RTRRM systems due to inherent random variations.

The calibration can also be accomplished by mechanically amplifying or reducing the response of the roughness meter so that the meter's output will produce the values that are indicated by the profilometer based on the original correlation which established the benchmark roughness levels. The mechanical adjustments allows the fine-tuning of the response of a RTRRM system to an acceptable tolerance.

The mechanical adjustment arm is shown schematically in Figure 16 and as installed on the Georgia Mays trailer in Figure 17. This concept was originally used in Georgia with the car mounted PCA-type meter.

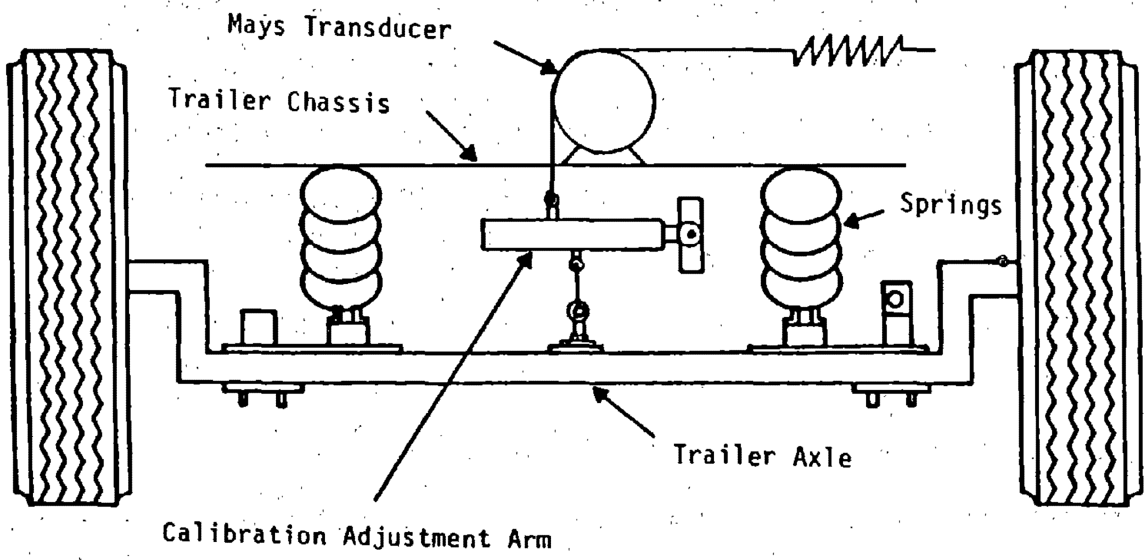


Figure 16. Conceptual View of Mechanical Calibration Arm.

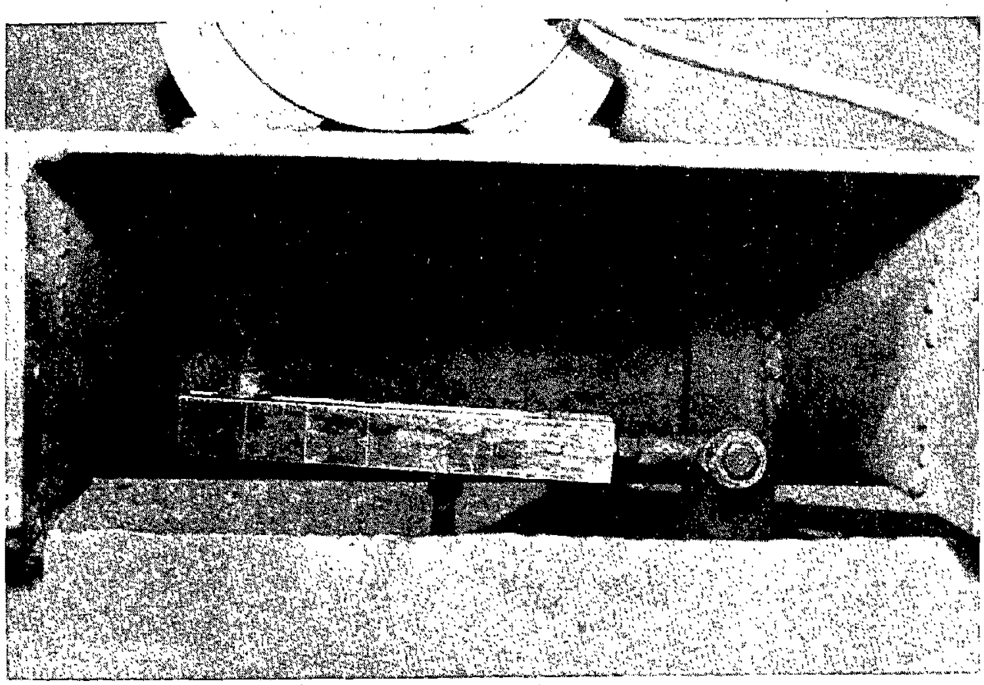


Figure 17. Mechanical Calibration Arm Installed on Roughness Trailer.

X. FRAMEWORK FOR A CALIBRATION PROGRAM

The calibration program discussed in this section of the report is based on the flow chart shown in Figure 18.

Initial Calibration

A. Selection of Roadway Sections

Select road sections between 1/2 mile and one mile in length to be used for calibration and correlation sections. The selected sections should not contain bridges or intersections and should be on a tangent section as much as possible. Sharp horizontal curves and steep grades should be avoided. Two roads at each of three roughness levels (low, medium, high) should be chosen with a minimum of two test sections in each travel direction for each roadway selected. This procedure will give a total of twelve sections minimum for correlation and calibration.

B. Establish Roadmeter System Variability

Prior to conducting any initial calibration, the variability of the roadmeter system must be checked. A minimum of 10 repeat runs should be made initially on a smooth, medium, and rough test section to determine the repeatability of the system. Extreme variability ($\geq$10%) is likely caused by mechanical problems such as weak suspension, leaking shocks, tire unbalance and roundness, worn wheelbearings, etc. Any such problems should be checked and corrected prior to any calibration and correlation. Any system with extreme variability cannot possibly be calibrated with any accuracy.

C. Establish Initial Roughness Levels

The initial or benchmark roughness levels can be established on all the test sections once it has been determined that the roadmeter

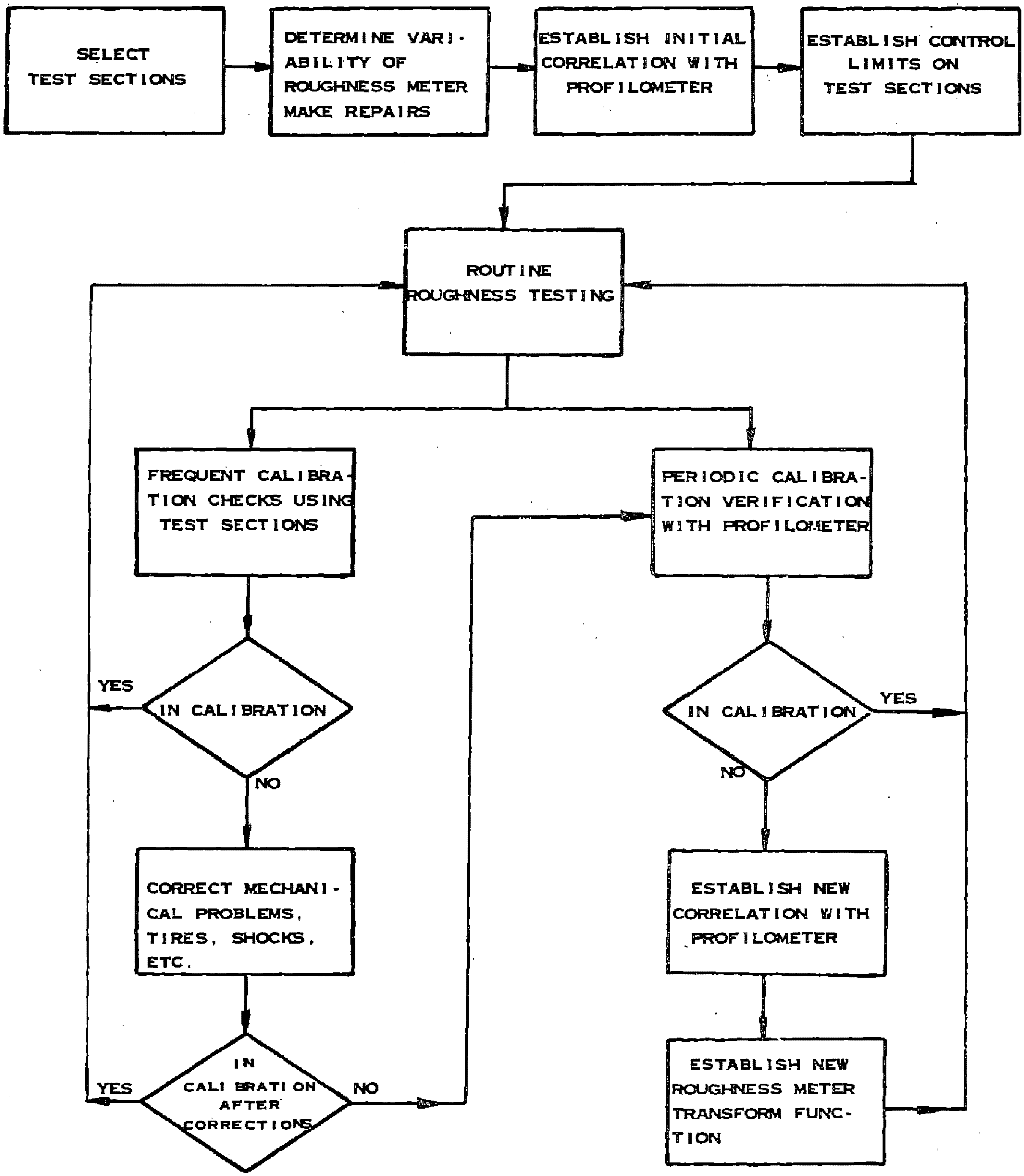


Figure 18. Flow Chart for RTRRM Calibration Procedures.

system is operating satisfactorily. A correlation is established with the profilometer using the test sites selected in Step A. The agency can select to use a profilometer statistic such as the Quarter-Car Mays Index or Root Mean Square Statistic (RMS) by using the transform function derived from the correlation as the roughness statistic or can merely use the profilometer as a reference for calibration procedures. In the latter case the actual output from the response meter would be used for testing purposes and the profilometer data would be used for future reference.

Maintaining Calibration

Once the initial calibration of the roadmeter system has been accomplished and the benchmark roughness levels have been established, calibration checks must be made at periodic intervals. Several potential problem areas exist with maintaining calibration of response-type meters and the use of in-service roads for control sections. Mechanical problems can drastically alter the response of the roadmeter and changes in roughness levels of the control sections can change the calibration reference levels. If a profilometer is readily available, calibration checks can simply be made by validating the latest correlation or transform function on two smooth and two rough test sections and re-establishing a new correlation if necessary. If a profilometer is not readily available, in-service test sections must be used for calibration checks. The following procedure is recommended for maintaining calibration.

A. Checking Calibration

For calibration checks, it is not necessary that all control sections used in the correlation be tested again. Calibration checks can be made by obtaining the roughness levels on two smooth test sections and two rough test sections. If the average of three repeat runs are fully within the control limits previously established for those test sections, the roadmeter can be considered in calibration. If the readings on one or more sections fall outside the control limits it may be desirable to check additional control sections. Generally, a mechanical problem will cause the response meter to be out of calibration. Changes in the roughness level of the control section will generally only occur over extended periods of time. Sudden changes in the roughness level of a control section are usually caused by maintenance activities of the roadway or a rapid deterioration in the service level of the roadway which can easily be noticed.

B. Re-establishing Calibration

If a roadmeter is found to be out of calibration, it must be checked for mechanical problems such as shocks etc. and corrections made. The roadmeter must then be checked again on the calibration control sections. If it be visually determined that the roadway has changed due to rapid deterioration, the section should be abandoned and a new control section established.

The roughness levels of the test section should be checked on a yearly or twice a year basis with a profilometer and calibration checks run against the response roadmeter to prevent long-term drift of the calibrated roughness levels.

If the agency has been using the original correlation to transform the roadmeter output to a profilometer generated statistic, this correlation is checked during the re-calibration procedure and a new correlation established if necessary using the calibration control sections. New sections would also be establsihed at this time if necessary and the average roughness levels and control limits would be re-established on all calibration control sections.

If the agency has been using the statistic generated by the response meter, the profilometer must be used to check the current roughness level of the control sections and to verify or re-establish the original correlation so that the response meter output can be related to a standard roughness statistic for comparison purposes. The original correlation between the profilometer and the response meter would be used to establish the current roughness level and control limits of the test sections. If the roadmeter is still in calibration, the roughness runs obtained with the roadmeter should produce an average roughness value within the control limits. If the roadmeter is found to be out of calibration by not being able to produce the roughness values indicated by the profilometer, a transform function must be obtained to relate measured roughness value to actual roughness values of the test sections assuming problems with the roadmeter testing equipment are not the cause of the differences.

The transform can be done mechanically using the device shown in Figure 16 or a transform equation can be established by correlating the measured roughness values of the test sections to the predicted roughness values from the profilometer data. This latter procedure is shown graphically in Figure 19.

In this procedure the profilometer is used to establish the roughness level of a roadway in terms of the response meter statistic utilizing the roughness benchmark levels established during the original correlation. In the hypothetical example shown in Figure 19, the correlation between the profilometer and the response meter was established using the initial calibration procedures. A subsequent calibration check indicated that for a profilometer value of 5 the response meter value for the section was 14 rather than 10 as it should have been based on the original calibration procedures. The correlation between the actual roughness level as indicated by the profilometer and the measured value would then be used to reduce the measured value of 14 to a corrected value of 10 according to the current calibration functions for the roadmeter.

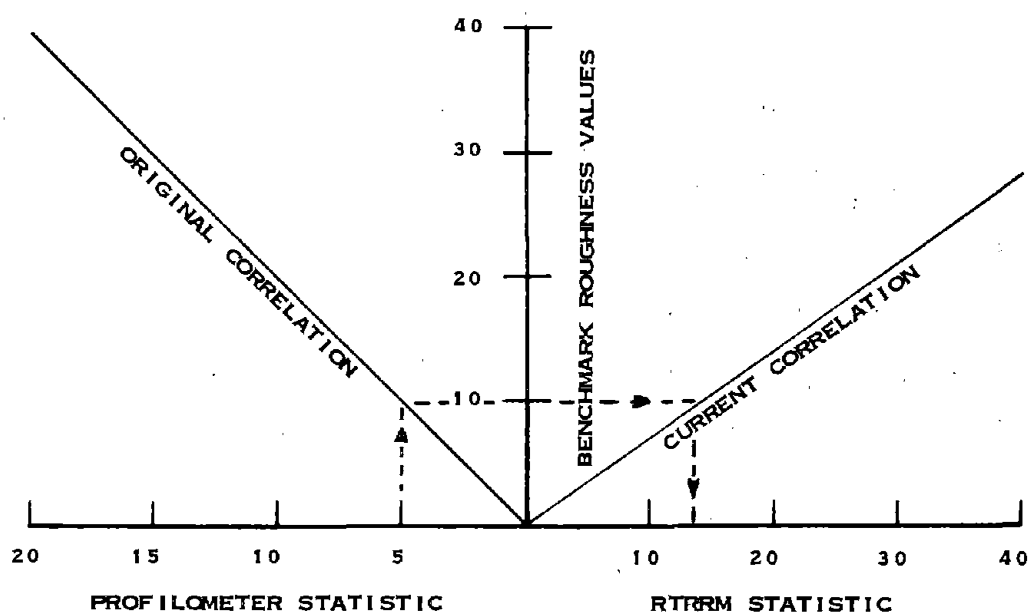


Figure 19. Graphical Method For Calibrating Roughness Meters.

In many roadmeter units with digital output the calibration function can be entered into the equipment and the measured roughness value will be corrected internally. The preferred method is to utilize the mechanical calibration device to eliminate the variability inherent with any calibration by correlation procedure.

The calibration procedure described in this chapter is contained in ASTM format in Appendix B of this report.

XI. EVALUATION OF CALIBRATION PROCEDURES

In order to determine the accuracy that can be expected with the calibration procedure, the standard control sections used by the Georgia DOT were used as calibration sections (Test Sites 1-6). The remainder of the test sections used in the correlation program were then used to determine the accuracy of the calibration process. Only the data from the profilometer was used as the calibration reference standard. One of the objectives of this research project was to determine the feasibility of the Roughness Surveyor as a calibration reference. The data presented in previous sections in this report has clearly indicated that this device should not be used as a calibration tool and therefore is not included in this analysis.

The procedure outlined in the previous chapter was followed in establishing the initial calibration and the evaluation of this procedure will be done utilizing the profilometer Quarter-Car Mays and RMS statistics as the standard roughness numbers and the Georgia Mays statistics as the standard roughness number.

Regression equations were obtained between the response-type roughness meters and the Quarter-Car Mays and RMS statistics obtained from the profilometer data. These relationships are shown in Table 9. Utilizing these calibration equations the roughness readings obtained with the response meters on the test sites not used in establishing the calibration equations were then transformed to the profilometer statistics of Quarter-Car Mays (QCI Mays) and Root Mean Square (RMS). The results of these calculations are shown in Table 10. The results indicate that response meters calibrated in this manner will give roughness results that are comparable to a certain degree. The results certainly indicate that the roughness statistics of

TABLE 9. PROFILOMETER CALIBRATION EQUATIONS FOR RESPONSE-TYPE ROUGHNESS METERS.

EQUATION	CORRELATION COEFFICIENT r	STANDARD ERROR OF ESTIMATE (y) S.E.E.y
RMS = 0.24 GA Mays + 4.04	0.996	0.83
RMS = 0.05 FL Mays + 1.09	0.992	1.27
RMS = 0.02 MN Mays + 3.60	0.997	0.78
RMS = 0.03 MN PCA + 6.17	0.989	1.45
QCI Mays = 0.941 GA Mays + 25.9	0.997	2.94
QCI Mays = 0.190 FL Mays + 14.7	0.987	6.14
QCI Mays = 0.087 MN Mays + 24.3	0.993	4.36
QCI Mays = 0.115 MN PCA + 34.3	0.987	6.13

various magnitudes produced by the response meters used in this study can be brought to a common level for comparison purposes utilizing the inertial profilometer as the calibration instrument. The average variation between the calibrated roughness Quarter-Car Mays statistic from the Georgia trailer and the Florida trailer was 6.6% with the date from Section 13 being excluded because of apparent erroneous test data from the Georgia Mays. In addition, 50% of the calibrated roughness numbers from the two trailers were within 5% percent.

The second method of calibration discussed in the previous chapter utilizes the profilometer to establish the roughness levels of the test sections in terms of the response-type meter's output.

Calculations were also made to evaluate the calibration results utilizing this procedure. The result from the Georgia trailer were used as the standard roughness output. The regression equation between the

TABLE 10. RESULTS OF CALIBRATING ROUGHNESS METERS TO QUARTER-CAR MAYS INDEX.

		EQUIV. QUARTER CAR MAYS					EQUIV. ROOT MEAN SQUARE				
TEST SITE	TYPE PAVEMENT	GA MAYS	FL MAYS	MN MAYS	MN PCA	OHIO MAYS	GA MAYS	FL MAYS	MN MAYS	MN PCA	OHIO RMS
7	AC	58	55	60	65	55	12.2	11.7	11.9	14.2	15.7
		41	40	48	47	40	7.9	7.7	9.0	9.4	9.3
		43	43	47	45	40	8.4	8.5	8.9	8.1	9.2
		52	51	55	61	51	10.8	10.7	10.7	13.0	14.2
8	AC	117	120	109	106	114	27.3	28.8	23.1	24.9	26.9
		108	95	91	84	103	24.9	22.3	19.0	19.2	24.5
9	AC	133	133	122	122	133	31.4	32.3	26.1	29.2	32.0
		126	124	115	120	131	29.5	29.7	24.6	28.4	30.8
		132	134	128	126	137	31.2	32.6	27.5	30.2	33.5
		147	160	148	174	151	35.0	39.3	32.0	42.6	37.4
10	AC	58	49	52	52	56	12.2	10.1	9.9	10.7	12.8
		60	51	56	53	55	12.7	10.7	10.8	11.2	12.1
		67	57	60	57	64	14.6	12.1	11.9	12.2	13.5
		64	60	56	57	55	13.9	12.9	11.0	12.1	12.2
11	AC	56	53	53	52	51	11.7	11.0	10.2	10.9	11.4
		50	42	47	47	45	10.3	8.3	8.9	9.5	9.7
		50	41	48	53	46	10.3	8.0	9.0	11.2	10.6
		48	47	47	52	48	9.6	9.5	8.9	10.8	10.5
12	AC	160	171	154	161	158	38.4	42.3	33.3	39.2	36.8
		134	129	122	131	129	31.6	31.1	26.1	31.5	29.7
		153	152	141	150	146	36.4	37.3	30.5	36.2	34.4
		185	211	174	216	172	44.6	52.6	38.0	53.6	41.9
13	PCC	81	86	88	72	89	18.2	19.8	18.2	16.0	20.6
		75	87	88	75	90	16.5	20.2	18.3	16.9	22.0
		96	67	62	55	63	21.8	14.9	12.4	11.5	13.2
		92	71	61	53	64	20.8	15.8	12.1	11.0	14.3
14	AC	65	60	64	55	63	14.1	13.1	12.8	11.6	14.5
		67	55	64	55	70	14.6	11.6	12.7	11.6	15.6
		44	43	42	43	39	8.6	8.6	7.7	8.4	9.1
		42	42	42	41	38	8.1	8.4	7.6	8.0	8.3
15	PCC	67	66	59	55	64	14.6	14.5	11.6	11.7	13.8
		71	67	65	54	66	15.6	14.7	12.9	11.4	14.2
		85	81	77	67	82	19.2	18.5	15.7	14.8	17.7
		77	76	69	59	72	17.0	17.2	13.8	12.7	16.0
16	PCC	130	140	130	130	133	30.7	34.0	27.9	31.1	30.7
		117	125	116	102	118	27.3	30.2	24.7	23.9	28.4
		130	143	125	124	131	30.7	34.8	26.9	29.5	30.9
		125	131	118	109	120	29.2	31.6	25.2	25.6	28.9

Georgia Mays data and the profilometer data was used to establish the "standard" roughness level of each of the calibration control sections (Sections 1 through 7). Regression analysis was then performed between the Florida and Minnesota roughness meters and the reference Mays roughness levels of the control sections. This procedure calibrated the Florida and Minnesota roughness output to the same magnitude of roughness values obtained with the Georgia roughness meter. The results of the linear regression analysis gave the following calibration equations for the Florida and Minnesota roughness meters.

Cal. Mays = 0.20 FL Mays - 12   r = 0.99 SEE 6.5

Cal. Mays = 0.093 MN Mays - 2   r = 0.99 SEE 5.1

These calibration equations were than used to calculate the calibrated roughness values for the Florida and Minnesota response meters on the test sites not used as calibration sites. The results of these calculations which represent the "calibrated Mays roughness values" for the sites are shown in Table 11.

An examination of the data in Table 11 indicates that the uncalibrated roughness values have been brought to comparable roughness levels through the calibration equations. The differences between the calibrated values would probably be acceptable for routine inventory testing, but are too large in many instances for construction control.

Discussion on Results

The differences in the calibrated values presented in this section are to be expected since the procedure is based on regression analysis. There is a certain amount of random variation about the line of best fit, and any calibrated value obtained from the regression represents only an estimated

TABLE 11. ROUGHNESS VALUES CALIBRATED TO GEORGIA STANDARD ROUGHNESS LEVEL.

SECTION NO.	PAVEMENT TYPE	ORIGINAL MAYS FL	ORIGINAL MAYS MN	CALIBRATED MAYS FL	CALIBRATED MAYS MN	ACTUAL MAYS GA
8	AC	554	976	99	89	97
		425	772	73	70	87
9	AC	624	1127	113	103	114
		573	1048	103	95	106
		630	1195	114	109	113
		764	1418	141	130	129
10	AC	181	317	24	27	34
		192	359	26	31	36
		221	414	32	37	44
		236	368	35	32	41
11	AC	199	332	28	29	32
		145	264	17	23	26
		139	270	16	23	26
		168	264	22	23	23
12	AC	824	1486	153	136	143
		600	1127	108	103	115
		724	1345	133	123	135
		1031	1722	194	158	169
13	PCC	375	728	63	66	59
		382	736	64	66	52
	PCC Gnd	277	438	43	39	74
		295	424	47	37	70
14	PM Milled	241	459	36	41	42
		210	454	30	40	44
		150	204	18	17	19
		146	200	17	17	17
15	New PCC	268	398	42	35	44
		273	466	43	41	48
		349	604	58	54	63
		322	509	52	45	54
16	PCC	659	1214	120	111	111
		582	1054	104	96	97
		674	1163	123	106	111
		610	1078	110	98	105

value. In addition, the Mays meter is measuring the response of three different suspension systems to the profile; therefore, an exact identical response should not be expected. Another major variable is the tracking variation of the three vehicles. Any procedure that is used to calibrate response meters utilizing different host vehicles will only produce comparable values, not identical values.

In order for an agency with multiple response meters to obtain a more precise agreement, it must insure that all the measuring systems are identical in design and suspension components. It is also useful to "fine-tune" the response from identical systems or nearly identical systems utilizing the mechanical adjustment shown in Figures 16 and 17. This device allows for the correction of changes in suspension characteristics with time, as well as for differences between similar roadmeters. It eliminates the need for regression equations, providing the roadmeters have similar response characteristics to the road profile. The value of the profilometer in this calibration process is that it determines the roughness value that a calibrated response meter should be measuring on the control sections. The roughness value would include an upper and lower limit at the 95% confidence level to account for random variations.

XII. SUMMARY AND CONCLUSIONS

The research project was conducted to evaluate the performance of an inexpensive non-contact roughness measuring device, Roughness Surveyor, as well as the potential use of this device as a calibration reference for Response-Type Road Roughness Measuring (RTRRM) systems. A correlation was also conducted between RTRRM systems from three different States (Georgia, Florida, and Minnesota) against the Roughness Surveyor, the inertial profilometer owned by the Ohio DOT, and the profilometer designed and operated by the South Dakota DOT.

A total of sixteen test sites were selected for the correlation and calibration study with a total of 52 individual test sections encompassing a variety of roughness levels and pavement surface types. The results of the roughness testing showed an excellent correlation between all the devices. The standard error of estimate, however, was rather large for some of the linear regression equations. The units from Florida, Ohio, and South Dakota provided serviceability index ratings. An analysis of these ratings indicated that different values were obtained between the units on the same test sections.

The evaluation of the Roughness Surveyor indicated that the roughness results obtained were insensitive to speed variations. Problems were encountered with obtaining valid roughness readings on extremely rough textured surfaces, such as surface treatment. The testing repeatability of the Roughness Surveyor was not as good as that obtained with the Ohio Profilometer and slightly better than two of the three RTRRM systems. The day-to-day variability was much higher for the Roughness Surveyor than for the Ohio Profilometer and the RTRRM systems.

An examination of the roughness levels of the right wheelpath only from the Ohio Profilometer against the Roughness Surveyor indicated that the Profilometer measured consistently higher roughness levels. The difference in the roughness levels also increased as the roughness level of the roadway increased, especially for asphaltic concrete surfaces. These results indicated a potential loss of return signal to the accoustic sensor used on the Roughness Surveyor.

The evaluation of the Roughness Surveyor indicated that the device would be suitable as a roughness measuring device, similar to the RTRRM systems in test result variability. One advantage would be the fact that a standard test speed is not necessary which makes the Roughness Surveyor extremely useful in obtaining roughness measurements in urban areas. The evaluation also indicated that the Roughness Surveyor is not suitable as a calibration reference device for RTRRM systems because of the degree of test variability. The inertial profilometer was found to provide extremely stable calibration reference values for RTRRM systems.

An analysis was also conducted utilizing the profilometer as a calibration reference. Principally the "calibration through correlation" method was used in the analysis by utilizing six test sites to establish calibration equations. The roughness of the remaining test sites were then adjusted according to the calibration equations to a common roughness statistic produced by the profilometer from the longitudinal profiles. The results of this analysis produced roughness values for the RTRRM systems which were generally comparable, but probably would not provide sufficient accuracy for construction quality control. A better procedure for calibration would be to utilize the profilometer to determine if changes in the in-service test sections have occurred and to utilize a mechanical calibration adjustment system to fine-tune the RTRRM system to measure the correct roughness level.

The results of the study also indicated that the concept of the "Golden Car" as described in NCHRP Report 228 would be an acceptable calibration reference value and a standard roughness index that can easily be understood by agency and contracting personnel.

XIII. RECOMMENDATIONS

The major objectives of the research project were to evaluate calibration procedures for RTRRM systems and to evaluate the use of the Roughness Surveyor as a calibration reference. The recommendations from the study are concerned with calibration in general as follows:

1. The evaluation of the Roughness Surveyor has indicated that the model of the device used in the study should not be used as a calibration reference. The performance of the inertial profilometer was excellent and will provide a reliable reference for calibration of RTRRM systems.
2. The roughness measured by a RTRRM system depends to a large extent on the characteristics of the host vehicle. In order to minimize the effect of the performance and condition of the host vehicle on roughness measurements, it is recommended that RTRRM systems are placed on trailers specifically designed for road roughness testing. The design of the trailers should conform to the proposed ASTM roughness trailer specifications.
3. The Quarter Car RTRRM simulation model presented in NCHRP Report 228 should be adopted as a calibration reference system. The concept of this model being "driven" over the longitudinal roadway profile simulates the operation of an actual RTRRM system, provides roughness values which are comparable to actual values obtained with RTRRM systems and the concept is easily understood by agency and contracting personnel.
4. Any agency with multiple RTRRM units should adopt the use of a mechanical calibration adjustment arm to fine-tune the response of each unit to the calibration reference values established by the

agency. The use of the mechanical calibration device will reduce the variations between individual units which are inherent in any "calibration through correlation" method. The reduction in variability between units is extremely important when the RTRRM systems are used as in construction quality control.

5. The calibration of RTRRM systems can be successfully done utilizing in-service test sections, providing sections are chosen to provide roads in the smooth, medium, and rough range. The long-term stability of the in-service roads should be checked by obtaining the longitudinal profile and calculating the calibration reference numbers for the sections.

REFERENCES

(1) Shah, S.C. "A Correlation of Various Smoothness Measuring Systems for Asphaltic Concrete Surfaces," Research Report No. 80, Louisiana Department of Highways, June 1974.

(2) Hudson, W.R. "Road Roughness: Its Elements and Measurements," TRR 836, 1981, pp. 1-7.

(3) "State of the Art of Pavement Condition Evaluation," HRB Special Report 95, 1968, pp.49-68.

(4) "Pavement Evaluation Using Roadmeters," HRB Special Report 133, 1973.

(5) TRR 836 "Pavement Roughness and Skid Properties," 1981.

(6) Gillespie, T.D., Sayers, M.W., Segal L. "Calibration of Response-Type Road Roughness Measuring Systems," NCHRP 228, 1980.

(7) McKenzie, D.W., Hudson, W.R. , Lee, C.E. "The Use of Road Profile Statistics For Maysmeter Calibration," Research Report 251-1, Center for Transportation Research, University of Texas at Austin, 1982.

(8) Keyser, J.H., Tessier, G., Bisaillon, A. "Development of a Car Meter Calibration Method," Committee A2B05, TRB Annual Meeting, January 1976.

(9) Croteau, J. "Ensuring Reliability of Mays Roughness Measurements" Report 76-005-7776, New Jersey Department of Transportation, March 1976.

(10) Hudson, W.R. et al "Pavement Performance Model Development, Vol. IV FHWA/RD-84/106, January 1985.

(11) Spangler, E.B. and Kelly, W.J. "GMC Road Profilometer - A Method for Measuring Road Profile," HRR 121, Washington, D.C., 1966.

(12) McQuirt, J.E. and Spangler, E.B. "Use of the Inertial Profilometer in the Ohio DOT Pavement Management System," Paper presented at ASTM E-17 meeting, Columbus, Ohio, June 1985.

(13) Huft, David L. "South Dakota Profilometer," TRR 1000, pp. 1-8, Washington, D.C., 1984.

(14) "Pavement Evaluation Using Road Meters," HRB Special Report 133, Washington, D.C., 1973.

(15) Brokaw, M. P. "Development of the Roadmeter: 1964-1972," HRB Special Report 133, pp. 17-19, Washington, D.C., 1973.

(16) Argue, G. H. "A Canadian Evaluation Study of Roadmeters," HRB Special Report 133, pp. 41-48, Washington, D.C., 1973.

(17) "Survey of Roughness Equipment," Massachusetts Department of Public Works, 1985.

(18) Josey, J. L. "Evaluation of a Pavement Roughness Measuring Devices (Mays Ride Meter)," Research Project 530, South Carolina Department of Highways and Public Transportation, 1981.

(19) Gulden, W. et al "Use of Response-Type Roughness Meters For Pavement Smoothness Acceptance in Georgia," TRR 946, Washington, D.C., 1983.

(20) Page, G. C. "Overview of Pavement Roughness Measurements in Florida," Study 82-5, Florida Department of Transportation, March 1982.

(21) Walker, R. S. and Hudson, W. R. "Use of Profile Wave Amplitude Estimates For Pavement Serviceability Measures," HRR 471, Washington, D.C., 1973.

(22) Lenke, L. R. "Suggested Improved Methodology for Relating Objective Profile Measurement with Subjective User Evaluation," TRR 893, Washington, D.C.,1982.

(23) Quinn, B. E. and Kelly, S. R. "Tentative Road Roughness Criteria Based Upon Vehicle Performance," Report FHWA-RD-75-3, Federal Highway Administration, 1975.

(24) Healey, A. J. and Stearman, R. O. "Measurement of Roadway Roughness and Automobile Ride Acceleration Spectra," Research Report 13, University of Texas at Austin, July 1974.

(25) Wambold, J. C. et al "State of the Art of Measurement and Analysis of Road Roughness," TRR 836, Washington, D.C., 1981.

(26) Quinn, B. E. "Problems Encountered in Using Vehicle Ride as a Criterion of Pavement Roughness," TRR 946, Washington, D.C., 1983.

(27) Holbrook, L. F. and Darlington, J. R. "Analytical Problems Encountered in the Correlation of Subjective Response and Pavement Power Spectral Density Functions," HRR 471, Washington, D.C., 1973.

APPENDIX A

TEST VALUES FOR ROUGHNESS SURVEYOR REPEATABILITY TESTS

		Model 8300 Mays				Ohio Profilometer Mays			
SURFACE TYPE	SECTION NO.	FIRST TEST	SECOND TEST	CHANGE	%	FIRST TEST	SECOND TEST	CHANGE	%
OG	1 N	48	54	6	12.5	48	48	0	0
	S	46	46	0	0	44	44	0	0
AC	2 E	84	92	8	9.5	80	81	1	1.3
	W	100	112	12	12.0	90	90	0	0
AC	3 N	88	83	-5	-5.7	91	89	-2	-2.2
	S	98	92	-6	-6.1	90	92	2	2.2
OG	4 E	60	52	-8	-13.3	50	51	1	2.0
	W	63	46	-17	-27.0	47	46	-1	-2.1
PCC Gnd.	6 S 204-203	59	66	7	11.9	58	58	0	0
	S 202-201	45	49	4	8.9	46	45	-1	-2.2
	N 200-201	42	46	4	9.5	39	39	0	0
	N 202-203	34	42	8	23.5	34	34	0	0
AC	7 E 2-3	48	67	19	39.6	55	52	-3	-5.5
	E 4-5	35	56	21	60.0	40	40	0	0
	W 5-4	39	58	19	48.7	40	40	0	0
	W 3-2	48	65	17	35.4	51	51	0	0
AC	8 N	115	134	19	16.4	114	114	0	0
	S	100	131	31	31.0	103	100	-3	-2.9
AC	9 N 0-1	156	140	-16	-10.3	133	134	1	0.8
	N 2-3	134	127	-7	-5.2	131	131	0	0
	S 3-2	148	141	-7	-4.7	137	139	2	1.5
	S 1-0	196	175	-21	-10.7	151	153	2	1.3
AC	10 E 5-6	50	48	-2	-4.0	56	55	-1	-1.8
	E 7-8	55	55	0	0	55	57	2	3.6
	W 8-7	62	66	4	6.5	64	61	-3	-4.7
	W 6-5	56	57	1	1.8	55	51	-4	-7.3
AC	11 E 15-14	46	65	19	41.3	51	52	1	1.9
	E 13-12	40	48	8	20.0	45	44	-1	2.2
	W 12-13	42	50	8	19.0	46	46	0	0
	W 14-15	43	57	14	32.6	48	48	0	0

		Georgia Mays				Florida Mays			
SURFACE TYPE	SECTION NO.	FIRST TEST	SECOND TEST	CHANGE	%	FIRST TEST	SECOND TEST	CHANGE	%
OG	1 N	20	23	3	15.0	14	14	0	0
	S	18	19	1	5.5	14	14	0	0
AC	2 E	60	63	3	5.0	37	37	0	0
	W	67	67	0	0	38	40	2	5.3
AC	3 N	64	62	-2	3.1	35	31	-4	11.4
	S	66	64	-2	3.0	37	32	-5	13.5
OG	4 E	24	25	1	4.2	17	15	-2	11.8
	W	20	23	3	15.0	14	12	-2	14.3
PCC Gnd.	6 S 204-203	38	34	-4	10.5	26	24	-2	7.7
	S 202-201	27	24	-3	11.1	21	18	-3	14.3
	N 200-201	15	14	-1	6.7	17	16	-1	5.9
	N 202-203	11	12	1	9.1	13	13	0	0
AC	7 E 2-3	34	36	2	5.9	21	20	-1	4.8
	E 4-5	16	19	3	18.8	13	11	-2	15.4
	W 5-4	18	19	1	5.6	15	12	-3	20.0
	W 3-2	28	28	0	0	19	19	0	0
AC	8 N	97	102	5	5.2	55	58	3	5.5
	S	87	84	-3	3.4	43	41	-2	4.7
AC	9 N 0-1	114	112	-2	1.8	62	65	3	4.8
	N 2-3	106	107	1	0.9	57	57	0	0
	S 3-2	113	113	0	0	63	63	0	0
	S 1-0	129	129	0	0	76	77	1	1.3
AC	10 E 5-6	33	32	-1	3.0	18	19	1	5.6
	E 7-8	36	37	1	2.8	19	20	1	5.3
	W 8-7	44	43	-1	2.3	22	22	0	0
	W 6-5	41	40	-1	2.4	24	23	-1	4.2
AC	11 E 15-14	32	32	0	0	20	22	2	10.0
	E 13-12	26	25	-1	3.8	15	15	0	0
	W 12-13	26	26	0	0	14	15	1	7.1
	W 14-15	23	23	0	0	17	17	0	0

Minnesota Mays

SURFACE TYPE	SECTION NO.	FIRST TEST	SECOND TEST	CHANGE	%	FIRST TEST	SECOND TEST	CHANGE	%
OG	1 N	25	26	1	4.0				
	S	22	23	1	4.5				
AC	2 E	63	64	1	1.6				
	W	68	73	5	7.4				
AC	3 N	73	73	0	0				
	S	68	69	1	1.5				
OG	4 E	29	26	-3	1.0				
	W	25	22	-3	12.0				
PCC Gnd.	6 S 204-203	40	35	-5	12.5				
	S 202-201	27	23	-4	14.8				
	N 200-201	24	19	-5	20.8				
	N 202-203	19	15	-4	21.1				
AC	7 E 2-3	42	35	-7	16.7				
	E 4-5	27	19	-8	29.6				
	W 5-4	26	20	-6	23.1				
	W 3-2	36	33	-3	8.3				
AC	8 N	98	108	10	10.2				
	S	77	78	1	13.0				
AC	9 N 0-1	113	122	9	8.0				
	N 2-3	105	117	12	11.4				
	S 3-2	120	125	5	4.2				
	S 1-0	142	149	7	4.9				
AC	10 E 5-6	32	34	2	6.3				
	E 7-8	36	40	4	11.1				
	W 8-7	41	45	4	9.8				
	W 6-5	37	45	8	21.6				
AC	11 E 15-14	33	35	2	6.1				
	E 13-12	26	26	0	0				
	W 12-13	27	30	3	11.1				
	W 14-15	26	29	3	11.5				

		Model 8300 RMS				Ohio Profilometer RMS			
SURFACE TYPE	SECTION NO.	FIRST TEST	SECOND TEST	CHANGE	%	FIRST TEST	SECOND TEST	CHANGE	%
OG	1 N	9.6	11.0	2.4	25.0	9.0	9.2	0.2	2.2
	S	9.8	10.2	1.4	14.3	9.0	9.3	0.3	3.3
AC	2 E	15.2	16.4	1.2	7.9	17.7	18.1	0.4	2.3
	W	17.7	19.1	1.4	7.9	20.2	20.6	0.4	2.0
AC	3 N	16.0	15.3	-0.7	4.4	19.8	19.3	-0.5	2.5
	S	17.8	16.4	-1.4	7.9	18.0	18.3	0.3	1.7
OG	4 E	11.8	10.3	-1.5	12.7	9.8	9.8	0	0
	W	12.2	9.4	-2.8	23.0	9.3	8.8	-0.5	5.4
PCC Gnd.	6 S 204-203	12.4	13.5	1.1	8.9	13.9	16.8	2.9	20.9
	S 202-201	8.2	9.2	1.0	12.2	9.4	9.3	-0.1	1.1
	N 200-201	8.4	8.9	0.5	6.0	7.9	8.1	0.2	2.5
	N 202-203	7.1	8.4	1.3	18.3	7.3	7.4	0.1	1.4
AC	7 E 2-3	10.5	13.8	3.3	31.4	15.7	16.0	0.3	1.9
	E 4-5	7.2	10.9	3.7	51.4	9.3	9.4	0.1	1.1
	W 5-4	7.4	11.0	3.6	48.6	9.2	9.0	-0.2	2.2
	W 3-2	10.6	12.9	2.3	21.7	14.2	14.2	0	0
AC	8 N	19.6	21.3	1.7	8.7	26.9	27.3	0.4	1.5
	S	17.2	21.1	3.9	22.7	24.5	23.8	-0.7	2.9
AC	9 N 0-1	30.0	25.5	-4.5	15.0	32.0	32.2	0.2	0.6
	N 2-3	21.8	21.2	-0.6	2.8	30.8	31.1	0.3	1.0
	S 3-2	24.6	23.3	-1.3	5.3	33.5	34.0	0.5	1.5
	S 1-0	43.0	34.4	-8.6	20.0	37.4	37.8	0.4	1.1
AC	10 E 5-6	9.8	9.4	-0.4	4.1	12.8	12.5	-0.3	2.3
	E 7-8	11.2	13.2	2.0	17.9	12.1	12.5	0.4	3.3
	W 8-7	13.1	16.0	2.9	22.1	13.5	13.0	-0.5	3.7
	W 6-5	11.7	12.2	0.5	4.3	12.2	12.2	0	0
AC	11 E 15-14	9.4	12.2	2.8	29.8	11.4	11.5	0.1	0.9
	E 13-12	7.8	9.5	1.7	21.8	9.7	9.6	-0.1	1.0
	W 12-13	8.4	10.2	1.8	21.4	10.6	10.6	0	0
	W 14-15	9.2	11.4	2.2	23.9	10.5	10.6	0.1	1.0

APPENDIX B
PROPOSED METHOD FOR CALIBRATION OF RTRRM SYSTEMS

1. Scope

   1.1 This method describes the procedures and equipment necessary for the calibration of Response-Type Road Roughness Measuring (RTRRM) systems.

   1.2 A RTRRM system is defined as any device which measures the relative motion of a sprung mass system in response to traveled surface roughness where the mass is supported by an automotive-type suspension and tires.

2. Applicable Documents

   2.1 ASTM Standard:

   E-1082-85 Standard Test Method for Measurement of Vehicular Response to Traveled Surface Roughness

   2.2 ASTM Standard:

   Under Development Trailers Used For Measuring Vehicle Response to Road Roughness

   2.3 ASTM Standard:

   E-950-83 Standard Test Method For Measuring the Longitudinal Profile of Vehicular Traveled Surface with an Inertial Profilometer

3. Summary of Method

   3.1 A number of in-service test sections are selected as calibration reference section encompassing a wide range of roughness levels.

   3.2 The RTRRM system(s) is then operated over the test sites to establish benchmark roughness levels for the test sites.

   3.3 Longitudinal profiles are obtained on the test sites and the calibration reference values are obtained utilizing the Quarter-Car model from NCHRP 228. An inertial profilometer is the preferred method for obtaining the profiles.

3.4 A correlation is then obtained between the RTRRM roughness values and the calibration reference values. This correlation can be used (1) to adjust the RTRRM output to the standard roughness value obtained from the profile measurements, (2) as a reference to establish the benchmark roughness levels in subsequent calibration checks.

3.5 The in-service test sections are used for frequent calibration checks. Longitudinal profile data is obtained on a yearly basis, or more frequently if necessary, to re-establish the correlation or benchmark roughness levels for the RTRRM system(s).

4. Apparatus

4.1 Roughness Trailer - The roughness trailer shall be designed to house the roughness measuring displacement sensor and be capable of being towed at highway speed. The trailer shall in conformance with all the specifications and provisions of ASTM E 17 .

4.2 Profilometer - The profilometer shall be capable of measuring the road profile in the left and right wheel tracks over a frequency band of 0.5 to 25 Hz at highway speeds. The profile measurements in this band width shall be obtained with a resolution of 0.01 in and a hysteresis not to exceed 0.001 in.

4.3 Simulation Model - The simulation of the RTRRM system shall be the Quarter-Car model from NCHRP Report 228. The simulated speed shall be 50 mph. Output shall be the calculated accumulation of the axle-body displacement in RTRRM system units.

4.4 Test Sections - A minimum of 20 test sections must be selected to establish the initial correlation of the RTRRM system response to the Quarter-Car reference roughness level. The test sections must be selected to cover the various pavement types and a broad range of roughness levels that will be encountered during the normal operation of the RTRRM system. Once the initial calibration has been established, a minimum of six sites will be sufficient for periodic calibration checks and recalibration. These six sites (minimum) must be chosen to represent a smooth, medium, and rough road in accordance with each agency's roughness standards.

The test sections should be from 0.5 to 1 mile in length, not contain bridges and intersections, and be on a tangent as much as possible. Sharp horizontal curves, steep grades, and areas with heavy traffic must be avoided.

5. Calibration Procedure

5.1 Testing Speed

All calibration testing of RTRRM systems will be performed at a speed of 50 mph.

5.2 Initial Calibration and Correlation

5.2.1 Select in-service test sections in accordance with the criteria of Section 4.4. Select a smooth and rough test section and obtain ten (10) repeat runs on each section and determine the repeatability of the RTRRM system. A variation of more than 10% may indicate mechanical problems such as shocks, tires, wheelbearings, etc. and correction must be made.

5.2.2 Obtain two repeat runs with the RTRRM system on each test section selected in 5.2.1 and obtain the longitudinal profile using a profilometer or by rod and level method. Calculate the quarter-car calibration reference values at a simulated speed of 50 mph using the simulation model of Section 4.3.

5.2.3 Calculate the regression equation between the roughness results obtained with the RTRRM system and the simulated calibration reference values. The average of the two repeat runs on each section should be used as the roughness value for each section. If the two values are more than 15% apart on smooth sections and more than 10% apart on rough sections, a third repeat test should be made. If no two runs are within the 10% or 15% as applicables, the RTRRM system must be examined for mechanical or other problems.

5.2.4 Select a minimum of 3 test sites with a total of 6 test sections from the sites used in the correlation to serve as calibration test sites. The selected sites must represent a smooth, medium, and rough road. The simulated roughness index or the benchmark roughness level from the RTRRM system obtained in Section 5.2.3 will serve as the calibration reference roughness level for periodic calibration checks. Establish control limits for each of the sites by obtaining 10 repeat runs with the RTRRM system and using the following formula to establish the upper and lower control limit.

$\overline{X}$ = Target Roughness Value

= Standard Deviation of X

Upper Control Limit = $\overline{X} + 1.73 \times \sigma$

Lower Control Limit = $\overline{X} - 1.73 \times \sigma$

5.3 Periodic Calibration

5.3.1 Conduct calibration checks of the RTRRM system on a monthly or more frequent cycle by obtaining 3 repeat test on each of the 6 test sites selected in Section 5.2.4. The average of the three runs must fall within the control limits on five of the six sites.

5.3.2 Mechanical checks must be made of the RTRRM system if the unit is not in calibration and the unit must be recalibrated after appropriate repairs are made. The mechanical adjustment arm is used to fine-tune the RTRRM system so that the roughness readings fall within the control limits on all six test sites. If the adjustment arm is not available on the RTRRM unit, new calibration values must be established using the procedures of Section 5.2.

5.4 Yearly Calibration Checks

5.4.1 In order to detect long-term changes in the calibration reference test sections, the longitudinal profiles of the six test sites must be obtained on a yearly basis. The calibration reference values are calculated from the profile using the simulation model of Section 4.1.3 and compared to the previously established calibration values. The calibration values can be the generalized roughness index from the simulated RTRRM system or can be reduced to the benchmark roughness values utilizing the correlation established in Section 5.2.3.

5.4.2 A new target value must be established in the new calibration reference value is not within ± 5 percent of the exisiting reference value. The output from the RTRRM system on the six test sites is then checked to determine if the roughness value falls near the new target value and within the control limits and no calibration adjustments will be necessary. A new correlation or a mechanical adjustment need to be made if the output of the RTRRM system does not conform to the target value calculated from the current longitudinal profile. The procedures from Section 5.2 must be followed to recalibrate the RTRRM system.

6. Data Reduction

6.1 Initial Calibration

6.1.1 Calculate mean, standard deviation, and coefficient of variation for the 10 initial runs on smooth and rough test sections to determine the variability of the RTRRM system.

6.1.2 Calculate average roughness of the two tests on each test section for RTRRM system and Quarter-Car simulated roughness index.

6.1.3 Determine regression equation between RTRRM roughness and Quarter-Car simulated roughness.

$$y = a + bx$$

6.1.4 Establish control limits on six calibration test sites. Calculate average roughness value and standard deviation of 10 repeat tests for each site and calculate control limits as follows:

$$U.C.L. = \overline{X} + 1.73 \times \sigma$$

$$L.C.L. = \overline{X} - 1.73 \times \sigma$$

6.2 Periodic Calibration

Calculate average roughness level of three tests on each site during calibration checks.

6.3 Yearly Calibrations

6.3.1 Calculate the average RTRRM roughness values of three repeat runs on each calibration test site.

6.3.2 Calculate the Quarter-Car simulated roughness value from the longitudinal profile for each calibration test site.

6.3.3 Compare new calibration reference value to previously established values.

6.3.4 If re-calibration is necessary, refer to data reduction procedures in Section 6.1.

APPENDIX C

SUMMARY OF ROUGHNESS DATA FROM CORRELATION STUDY

DATA FROM CORRELATION TESTS
FIRST RUNS

TEST SECTION	LOCATION	TYPE PAVEMENT	GA TRAILER MAYS	8300 MAYS	8300 RMS	FL MAYS	FL PSI	MN MAYS	MN PCA	OH MAYS	OH PCA	OH PSI	OH RMS	SD PSI	SD RMS
1	SR-7 N	OG	20	48	9.6	139	4.39	247	62	48	950	3.88	9.0	4.03	
	S	OG	18	46	9.8	141	4.39	224	51	44	845	3.83	9.0	4.07	
2	Camp Calvin E	AC	60	84	15.2	368	3.88	625	358	80	2134	3.69	17.7	3.27	
	W	AC	67	100	17.7	380	3.85	675	418	90	2576	3.56	20.2	3.28	
3	High Falls N	AC	64	88	16.0	354	3.91	729	496	91	2783	3.45	19.8	3.06	
	S	AC	66	98	17.8	373	3.79	682	466	90	2823	3.51	18.0	2.91	
4	SR-16 0-1 E	OG	24	60	11.8	174	4.31	286	140	50	1026	3.89	9.8	4.19	
	1-0 W	OG	20	63	12.2	140	4.39	251	126	47	908	3.89	9.3	4.12	
5	Bailey Jester N	ST	119	-	-	633	3.20	1317	827	137	3158	2.62	33.5	2.74	
	S	ST	134	-	-	739	3.02	1514	1097	151	3878	2.63	36.9	2.73	
6	I-75 203-204 S	PCC Gnd.	38	59	12.4	257	4.28	397	262	58	1354	3.61	13.9	3.97	
	201-202 S	PCC Gnd.	27	45	8.2	211	4.35	266	111	46	703	3.65	9.4	4.75	
	201-200 N	PCC Gnd.	15	42	8.4	174	4.40	242	86	39	509	3.81	7.9	4.51	
	202-203 N	PCC Gnd.	11	34	7.1	127	4.47	191	80	34	414	3.88	7.3	4.67	
7	SR-16 2-3 E	AC	34	48	10.5	213	4.22	415	269	55	1183	3.68	15.7	3.56	
	4-5 E	AC	16	35	7.2	132	4.41	271	107	40	543	3.87	9.3	3.96	
	5-4 W	AC	18	39	7.4	149	4.37	264	97	40	496	3.91	9.2	3.92	
	3-2 W	AC	28	48	10.6	192	4.27	357	228	51	1121	3.76	14.2	3.54	
8	CR-162 N	AC	97	115	19.6	554	3.44	976	625	114	3004	2.93	26.9	2.83	
	S	AC	87	100	17.2	425	3.73	772	435	103	1982	2.99	24.5	3.24	
9	CR-171 0-1 N	AC	114	156	30.0	624	3.28	1127	767	133	3715	2.73	32.0	2.79	
	2-3 N	AC	106	134	21.8	573	3.39	1048	742	131	3755	2.82	30.8	2.63	
	3-2 S	AC	113	148	24.6	630	3.26	1195	801	137	4020	2.81	33.5	2.65	
	1-0 S	AC	129	196	43.0	764	2.96	1418	1215	151	5174	2.71	37.4	2.46	
10	SR-16 5-6 E	AC	34	50	9.8	181	4.30	317	151	56	1020	3.67	12.8	3.40	
	7-8 E	AC	36	55	11.2	192	4.27	359	166	55	977	3.66	12.1	2.70	
	8-7 W	AC	44	62	13.1	221	4.20	414	200	64	1331	3.70	13.5	2.70	
	6-5 W	AC	41	56	11.7	236	4.17	368	197	55	1041	3.71	12.2	3.55	
11	SR-212 15-14 E	AC	32	46	9.4	199	4.27	332	158	51	1019	3.81	11.4	4.49	
	13-12 E	AC	26	40	7.8	145	4.38	264	112	45	664	3.80	9.7	4.02	
	12-13 W	AC	26	42	8.4	139	4.39	270	166	46	745	3.83	10.6	3.94	
	14-15 W	AC	23	43	9.2	168	4.33	264	153	48	1010	3.84	10.5	4.56	
12	Juliette 0-1 E	AC	143	175	31.2	824	2.84	1486	1101	158	4488	2.13	36.8	2.77	
	2-3 E	AC	115	125	20.6	600	3.33	1127	845	129	3467	2.57	29.7	2.66	
	3-2 W	AC	135	165	28.8	724	3.05	1345	1002	146	4246	2.20	34.4	2.52	
	1-0 W	AC	169	187	32.5	1031	2.37	1722	1581	172	5596	1.98	41.9	2.57	
13	I-475 14-13 N	PCC	59	69	12.0	375	4.12	728	329	89	1743	3.41	20.6	3.96	
	12-11 N	PCC	52	70	12.5	382	4.09	736	358	90	1825	3.41	22.0	3.86	
	11-12 S	PCC Gnd.	74	62	10.3	277	4.26	438	179	63	1160	3.35	13.2	4.20	
	13-14 S	PCC Gnd.	70	57	9.9	295	4.23	424	161	64	1096	3.27	14.3	4.43	
14	I-75 140-139 S	AC Mill	42	70	13.6	241	4.16	459	180	63	743	3.70	14.5	4.09	
	138-137 S	AC Mill	44	87	15.2	210	4.23	454	182	70	758	3.62	15.6	4.24	
	137-138 N	AC	19	29	5.7	150	4.36	204	73	39	358	3.77	9.1	4.63	
	139-140 N	AC	17	26	4.8	146	4.38	200	61	38	310	3.69	8.3	4.62	
15	Camp Creek 1-2 E	PCC New	44	83	18.7	268	4.27	398	184	64	1157	3.61	13.8	-	
	3-4 E	PCC New	48	81	14.0	273	4.26	466	174	66	1158	3.71	14.2	-	
	4-3 W	PCC New	63	86	14.5	349	4.16	604	288	82	1713	3.51	17.7	-	
	2-1 W	PCC New	54	85	14.5	322	4.19	509	216	72	1365	3.70	16.0	-	
16	SR-166 10-11 E	PCC	111	119	19.1	659	3.72	1214	831	133	4123	3.25	30.7	2.73	
	12-13 E	PCC	97	97	16.0	582	3.83	1054	591	118	3147	3.31	28.4	3.21	
	13-12 W	PCC	111	116	18.6	674	3.70	1163	776	131	4051	3.32	30.9	3.08	
	11-10 W	PCC	105	103	16.4	610	3.79	1078	648	120	3215	3.35	28.9	3.03	

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DATA FROM CORRELATION TESTS
REPEAT RUNS

TEST SECTION	LOCATION	TYPE PAVEMENT	GA TRAILER MAYS	[illegible]		FL		MN		OH				SD	
				MAYS	RMS	MAYS	PSI	MAYS	PCA	MAYS	PCA	PSI	RMS	PSI	RMS
1	SR-7 N	OG	23	54	11.0	142	4.38	260	122	48	945	3.85	9.2		
	S	OG	19	46	10.2	136	4.38	225	118	44	857	3.80	9.3		
2	Camp Calvin E	AC	63	92	16.4	374	3.87	640	398	81	2109	3.66	18.1		
	W	AC	67	112	19.1	395	3.82	727	452	90	2570	3.52	20.6		
3	High Falls N	AC	62	83	15.3	314	4.00	734	456	82	2720	3.51	19.3		
	S	AC	64	92	16.4	315	4.00	688	459	92	2922	3.58	18.3		
4	SR-16 0-1 E	OG	25	52	10.3	153	4.36	256	124	51	1064	3.90	9.8		
	W	OG	23	46	9.4	118	4.44	222	103	46	860	3.91	8.8		
5	Bailey Jester N	ST	105	-	-	592	3.33	1278	729	137	3206	2.58	33.7		
	S	ST	123	-	-	723	3.06	1451	1090	150	3917	2.63	36.2		
6	I-75 203-204 S	PCC Gnd.	34	66	13.5	237	4.31	345	223	58	1349	3.51	16.8		
	201-202 S	PCC Gnd.	24	49	9.2	183	4.39	225	80	45	683	3.61	9.3		
	201-200 N	PCC Gnd.	14	46	8.9	157	4.43	185	67	39	523	3.78	8.1		
	202-203 N	PCC Gnd.	12	42	8.4	126	4.47	150	70	34	413	3.84	7.4		
7	SR-16 2-3 E	AC	36	67	13.0	201	4.25	251	256	55	1212	3.71	16.0		
	4-5 E	AC	19	56	10.9	109	4.46	194	85	40	538	3.77	9.4		
	5-4 W	AC	19	58	11.0	116	4.45	201	95	40	445	3.90	9.0		
	3-2 W	AC	28	65	12.9	188	4.28	332	236	51	1128	3.76	14.2		
8	CR-162 N	AC	102	134	21.3	578	3.33	1042	692	114	3046	2.88	27.3		
	S	AC	84	131	21.1	414	3.76	781	436	100	1891	2.99	23.8		
9	CR-171 0-1 N	AC	112	140	25.5	651	3.21	1216	946	134	3722	2.72	32.2		
	2-3 N	AC	107	127	21.2	572	3.40	1165	781	131	3748	2.82	31.1		
	3-2 S	AC	113	141	23.3	631	3.26	1246	913	139	4100	2.76	34.0		
	1-0 S	AC	129	175	34.4	766	2.96	1495	1372	153	5308	2.71	37.8		
10	SR-16 5-6 E	AC	32	48	9.4	187	4.22	341	180	55	972	3.68	12.8		
	7-8 E	AC	37	55	13.2	200	4.25	396	204	57	1075	3.67	12.5		
	8-7 W	AC	43	66	16.0	222	4.20	450	222	61	1129	3.65	13.0		
	6-5 W	AC	40	57	12.2	225	4.20	447	248	51	846	3.70	12.2		
11	SR-212 15-14 E	AC	32	65	12.2	215	4.22	354	178	52	1050	3.81	11.5		
	13-12 E	AC	25	48	9.5	154	4.36	260	129	44	666	3.83	9.6		
	12-13 W	AC	26	50	10.2	152	4.37	295	120	46	768	3.84	10.6		
	14-15 W	AC	23	57	11.4	165	4.33	294	164	48	1029	3.86	10.6		
12	Juliette 0-1 E	AC													
	2-3 E	AC		No	second	run									
	3-2 W	AC													
	1-0 W	AC													
13	I-475 14-13 N	PCC													
	12-11 N	PCC		No	second	run									
	11-12 S	PCC Gnd.													
	13-14 S	PCC Gnd.													
14	I-75 140-139 S	AC Mill													
	138-137 S	AC Mill		No	second	run									
	137-138 N	AC													
	139-140 N	AC													

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