Consistency of Roughness and Rut Depth Measurement Collected with 11 South Dakota Road Profilers

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Pavement roughness has long been recognized as a primary indicator of pavement performance. To provide accurate and reliable roughness measurements, the South Dakota Department of Transportation (SDDOT) designed and constructed a profilometer system in 1982. This system was later improved and enhanced by adding more sensors for rut measurements. The increased interest in the road profiler resulted in the establishment in 1989 of the South Dakota Road Profiler User's Group (SDRPUG). During the Third Annual SDRPUG meeting in Minnesota in 1991, international roughness index and rut depth data were collected with 11 road profilers on 4 different pavement surfaces. These selected pavement types were concrete, bituminous, concrete-bituminous over concrete, and bituminous over concrete. Each road profiler was run three times over each test section. The collected data were then reduced and analyzed statistically. The main objective of the statistical analysis was to determine whether the differences in roughness and rut measurements obtained with the 11 road profilers were statistically significant. The experiment and the statistical analysis are described in detail. In addition, specific recommendations are provided for the need to establish calibration procedures to ensure consistency in roughness and rut depth measurements obtained nationwide.

AASHTO pavement design procedure is based on the functional performance of pavements. Functional performance is measured by the serviceability index that incorporates a number of parameters such as pavement roughness, cracking, rutting, and patching. Because roughness is an indicator of all other parameters, some highway agencies calculate pavement serviceability index (PSI) on the basis of roughness measurements only.

Highway agencies use roughness to monitor the condition and performance of their pavement networks. The existing conditions of pavements, measured by roughness, determine the distribution of available funds for highway allocation such as providing routine maintenance, major maintenance, or reconstruction of a pavement section. In addition, roughness measurements often are employed as the dependent factor relative to the evaluation of new or modified pavements, pavement maintenance, materials, or construction techniques.

During the past few decades, roughness response devices were the primary instruments for measuring roughness. Results from these devices were known to be affected by the condition of shock absorbers, wear and pressure of tires, and vehicles. These uncertainties greatly reduced the level of confidence in the data and demanded that consideration be given to the development of a more accurate and positive apparatus.

In the early 1980s the South Dakota Department of Transportation (SDDOT) developed and built a highway profiling and rut depth measurement system (*1*). This equipment, referred to as a road profiler, operates at highway speeds and measures pavement profile only in the left wheelpath. Pavement profile can be converted to any computerized roughness statistic. Over the years, quantifying roughness from pavement profiles proved to be much more accurate and reliable than depending on the point response of a vehicle.

SDDOT shared the road profiler technology with several other highway agencies. The demand for road profilers has become so great that they are now manufactured commercially. Today 8 states have duplicated the road profiler in house and about 20 others have purchased commercially manufactured systems (*2*). The following two reasons are behind the fast spread of this technology:

1. The FHWA requirement that pavement roughness measurements be reported in international roughness index (IRI) units.
2. The relatively low cost of the road profiler when compared with other available technologies.

Because of the increasing interest in measuring road profile, users of the road profiler began meeting annually to discuss feasible system enhancements. The first meeting was held in South Dakota in 1989, the second was held in Wyoming in 1991, and the last meeting was held in Minnesota in 1991. Eleven road profilers from 11 states participated in the meeting in Minnesota. The main objective of this paper is to investigate repeatability and consistency of roughness and rut depth measurements obtained with these 11 road profilers.

DESIGN OF EXPERIMENT

One major objective of the Minnesota experiment was to run the participating road profilers on several pavement test sections and then conduct statistical analysis on the collected IRI and rut depth measurements. Figure 1 graphically shows the data gathering and analysis strategies for the experiment. Pavement sites used in this study were selected to represent the range of surface types encountered in Minnesota. These

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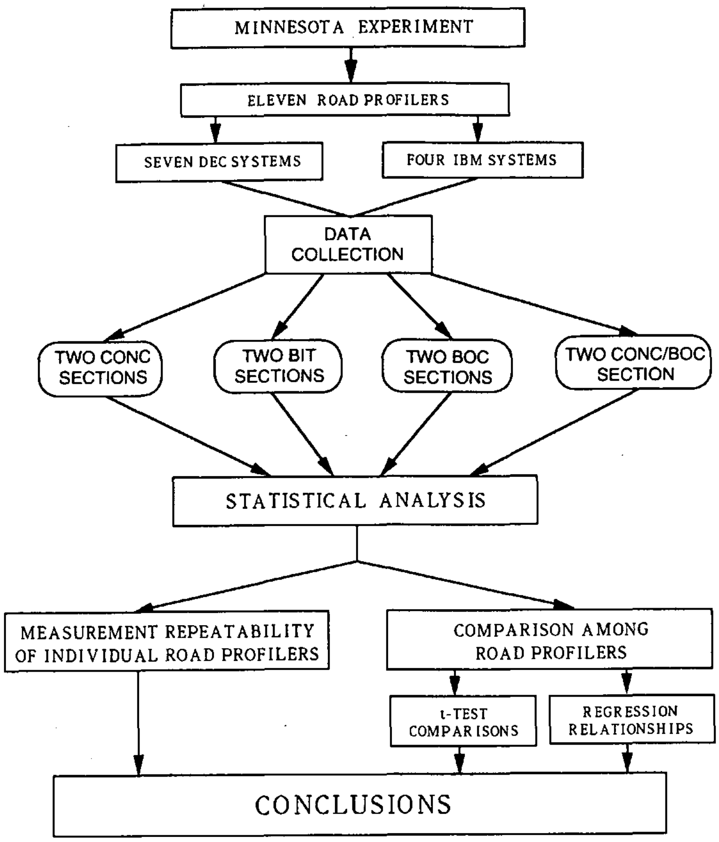

FIGURE 1 Data gathering and analysis strategies.

pavement types were concrete, bituminous, bituminous over concrete, and concrete-bituminous over concrete. All test sections were 0.2 mi long and selected to represent a wide range of roughness and rut depths of pavements in Minnesota. The test sections were conveniently located around the St. Paul area. Table 1 shows the locations and types of the selected eight test sections.

Seven participating road profilers were Digital Equipment Corporation (DEC)-based and four were IBM-based. The original South Dakota road profiler is DEC based whereas the IBM-based road profilers are commercially manufactured with slight hardware and software modifications. Table 2 provides a list of the participating road profilers and their types.

DATA COLLECTION

On the second day of the Minnesota meeting, all road profilers' operators were given detailed information about the locations of the test sections. Data were then collected by all

TABLE 1 Test Section Types and Locations

TEST SECTION NO.	PAVEMENT TYPE	LOCATION
1	CONCRETE	I-94 EAST
2	CONCRETE	I-94 WEST
3	BITUMINOUS	CO-10 WEST
4	BITUMINOUS	CO-10 EAST
5	BITUMINOUS OVER CONCRETE	IS-694 NORTH
6	BITUMINOUS OVER CONCRETE	IS-694 SOUTH
7	CONC/BOC	MN-5 EAST
8	CONC/BOC	MN-5 WEST

TABLE 2 Road Profilers That Participated in Minnesota Experiment

ROAD PROFILER NUMBER	STATE	TYPE
1	WYOMING (WY)	DEC
2	NEBRASKA (NE)	DEC
3	MINNESOTA (MN)	DEC
4	WISCONSIN (WI)	DEC
5	ILLINOIS (IL)	DEC
6	NORTH DAKOTA (ND)	DEC
7	SOUTH DAKOTA (SD)	DEC
8	IOWA (IA)	IBM
9	ALABAMA (AL)	IBM
10	MONTANA (MT)	IBM
11	IDAHO (ID)	IBM

11 road profilers at the same time. The collected data included pavement roughness expressed in IRI and rut depth measurements. Each road profiler was run three times on each test section. In total, each road profiler made 24 runs. Tables 3 and 4 summarize in tabular form the collected roughness and rut depth data respectively.

DATA ANALYSIS

The main objectives of the statistical analysis were to

1. Investigate the repeatability of measurements for individual road profilers,
2. Compare results from different road profilers, and
3. Determine the effect of pavement type on the repeatability of road profilers.

The data collected during the experiment were adequate to satisfy the first two objectives only.

Repeatability of Measurements of Individual Devices

Each road profiler was run three times on each test section. Roughness and rut depth measurements from all three runs were then averaged, and the standard deviations were calculated. Table 3 summarizes the averages and standard deviations for all systems on all test sections. It is clear from Table 3 that the standard deviations for all measurements were extremely low, which indicates that the overall repeatability of measurements for all road profilers is very good.

Comparisons Among Road Profilers

Roughness and rut depth measurements from all 11 road profilers were first examined visually without conducting any analysis. This preliminary examination indicated some variations in the results from various road profilers. As an example, Table 3 shows that the roughness of Test Section 1 is 1.41 when measured with the South Dakota road profiler and 1.11 when measured with the Idaho road profiler. Therefore, it was necessary to determine the statistical significance of these differences. The two-sample t-test was used in the comparison among the means. Basically, the measurements from any two road profilers were compared to see whether they were statistically equal. A 95 percent confidence level was used in the whole analysis to be within practical limits. To conduct the t-test the following assumptions were made:

1. The population samples are small.
2. Both the populations are normal with $\sigma_1 = \sigma_2 = \sigma$, and the design is completely randomized.

The t-value was calculated with the following equation:

$$t = \frac{(\overline{Y}_1 - \overline{Y}_2)}{S_p\sqrt{\frac{1}{n_1} + \frac{1}{n_2}}} \quad (1)$$

where

Y_1, Y_2 = sample means,
n_1, n_2 = sample sizes, and
S_p = estimate of common variance $\sigma_1^2 = \sigma_2^2 = \sigma^2$.

The common variance S_p was computed with the following equation:

$$S_p^2 = \frac{(n_1 - 1)\sigma_1^2 + (n_2 - 1)\sigma_2^2}{n_1 + n_2 - 2} \quad (2)$$

where S_1^2 and S_2^2 are the two individual sample variances.

In the analysis of IRI and rut depth data, the previously described two-sample t-test was used. Means of IRI and rut

TABLE 3 IRI Data Collected at Minnesota Experiment

CONC	MN	SD	IA	AL	ND	MT	ID	WY	NE	WI	IL
TEST #1 IS 94 (EB)											
RUN 1	1.26	1.36	1.20	1.19	1.21	1.14	1.11	1.28	1.37	1.26	1.34
RUN 2	1.27	1.42	1.18	1.18	1.19	1.14	1.10	1.37	1.49	1.31	1.37
RUN 3	1.26	1.45	1.19	1.18	1.22	1.08	1.13	1.38	1.35	1.25	1.35
AVERAGE	1.26	1.41	1.19	1.18	1.21	1.12	1.11	1.34	1.40	1.27	1.35
STD. DEVIATION	0.01	0.05	0.01	0.01	0.02	0.03	0.02	0.055	0.08	0.03	0.02
CONC	**MN**	**SD**	**IA**	**AL**	**ND**	**MT**	**ID**	**WY**	**NE**	**WI**	**IL**
TEST #2 IS 94 (WB)											
RUN 1	1.50	1.56	1.40	1.46	1.38	1.31	1.53	1.51	1.53	1.38	1.45
RUN 2	1.44	1.64	1.42	1.46	1.39	1.26	1.53	1.60	1.45	1.37	1.47
RUN 3	1.49	1.59	1.41	1.43	1.39	1.27	1.38	1.53	1.46	1.37	1.49
AVERAGE	1.48	1.60	1.41	1.45	1.39	1.28	1.48	1.55	1.48	1.37	1.47
STD. DEVIATION	0.03	0.04	0.01	0.02	0.01	0.03	0.09	0.047	0.04	0.01	0.02
BIT	**MN**	**SD**	**IA**	**AL**	**ND**	**MT**	**ID**	**WY**	**NE**	**WI**	**IL**
TEST #3 CO 10 (WB)											
RUN 1	4.47	4.38	4.30	4.43	4.53	3.88	4.21	4.58	4.23	4.51	4.53
RUN 2	4.56	4.31	4.27	4.54	4.36	3.93	4.24	4.51	4.44	4.46	4.43
RUN 3	4.54	4.28	4.34	4.32	4.41	3.97	4.24	4.48	4.43	4.53	4.38
AVERAGE	4.52	4.32	4.30	4.43	4.43	3.93	4.23	4.52	4.37	4.50	4.45
STD. DEVIATION	0.05	0.05	0.04	0.11	0.09	0.05	0.02	0.051	0.12	0.04	0.08
BIT	**MN**	**SD**	**IA**	**AL**	**ND**	**MT**	**ID**	**WY**	**NE**	**WI**	**IL**
TEST #4 CO 10 (EB)											
RUN 1	4.53	4.42	4.39	4.48	4.52	3.73	4.18	4.70	4.47	4.45	4.43
RUN 2	4.81	4.27	4.36	4.25	4.55	3.72	4.14	4.54	4.51	4.56	4.44
RUN 3	5.13	4.27	4.39	4.21	4.54	3.74	4.05	4.54	4.51	4.40	4.45
AVERAGE	4.82	4.32	4.38	4.31	4.54	3.73	4.12	4.59	4.50	4.47	4.44
STD. DEVIATION	0.3	0.09	0.02	0.15	0.02	0.01	0.07	0.092	0.02	0.08	0.01
BOC	**MN**	**SD**	**IA**	**AL**	**ND**	**MT**	**ID**	**WY**	**NE**	**WI**	**IL**
TEST #5 IS 694 (NB)											
RUN 1	1.07	1.10	0.99	0.95	1.25	0.86	0.87	1.03	1.03	0.99	1.05
RUN 2	1.09	0.98	0.99	0.89	1.19	0.86	0.91	1.03	1.06	1.02	1.09
RUN 3	1.07	1.04	0.99	0.93	1.03	0.85	0.89	1.01	1.05	1.01	1.14
AVERAGE	1.08	1.04	0.99	0.92	1.16	0.86	0.89	1.02	1.05	1.01	1.09
STD. DEVIATION	0.01	0.06	0	0.03	0.11	0.01	0.02	0.012	0.02	0.02	0.05
BOC	**MN**	**SD**	**IA**	**AL**	**ND**	**MT**	**ID**	**WY**	**NE**	**WI**	**IL**
TEST #6 IS 694 (SB)											
RUN 1	1.16	1.08	1.00	0.88	0.97	0.87	0.90	1.05	1.07	1.05	1.09
RUN 2	1.11	1.04	1.00	0.87	0.95	0.85	0.89	1.07	1.15	1.08	1.07
RUN 3	1.04	1.03	1.02	0.88	0.95	0.88	0.85	1.10	1.13	1.07	1.07
AVERAGE	1.10	1.05	1.01	0.88	0.96	0.87	0.88	1.07	1.12	1.07	1.08
STD. DEVIATION	0.06	0.03	0.01	0.01	0.01	0.02	0.03	0.025	0.04	0.02	0.01
CONC/BOC	**MN**	**SD**	**IA**	**AL**	**ND**	**MT**	**ID**	**WY**	**NE**	**WI**	**IL**
TEST #7 MN 5 (EB)											
RUN 1	2.23	2.63	1.99	2.08	2.07	1.84	1.95	2.10	2.23	2.16	2.28
RUN 2	2.22	2.55	1.96	2.08	2.09	1.86	1.98	2.20	2.25	2.02	2.26
RUN 3	2.24	2.53	2.03	2.01	2.11	1.84	1.98	2.19	2.23	2.15	2.29
AVERAGE	2.23	2.57	1.99	2.06	2.09	1.85	1.97	2.16	2.24	2.11	2.28
STD. DEVIATION	0.01	0.05	0.04	0.04	0.02	0.01	0.02	0.055	0.01	0.08	0.02
CONC/BOC	**MN**	**SD**	**IA**	**AL**	**ND**	**MT**	**ID**	**WY**	**NE**	**WI**	**IL**
TEST #8 MN 5 (WB)											
RUN 1	2.15	2.16	1.92	2.07	2.03	1.72	2.02	2.30	2.11	2.04	2.19
RUN 2	2.27	2.12	1.95	1.98	2.06	1.74	2.04	2.37	2.11	2.06	2.18
RUN 3	2.19	2.16	1.97	2.09	2.02	1.73	2.00	2.33	2.09	2.03	2.15
AVERAGE	2.20	2.15	1.95	2.05	2.04	1.73	2.02	2.33	2.10	2.04	2.17
STD. DEVIATION	0.06	0.02	0.03	0.06	0.02	0.01	0.02	0.035	0.01	0.02	0.02

TABLE 4 Rut Depth Data Collected at Minnesota Experiment

BIT	MN	SD	ND	WY	NE	WI	IL	IA	AL	MT	ID
TEST #1 CO 10 (WB)											
RUN 1	0.64	0.54	0.67	0.65	0.58	0.63	0.63	0.72	0.65	0.58	0.59
RUN 2	0.64	0.49	0.71	0.64	0.60	0.64	0.60	0.70	0.66	0.58	0.58
RUN 3	0.63	0.49	0.66	0.64	0.60	0.65	0.61	0.72	0.66	0.60	0.56
AVERAGE	0.63	0.51	0.68	0.64	0.59	0.64	0.61	0.71	0.66	0.59	0.58
STD. DEVIATION	0.01	0.03	0.03	0.01	0.01	0.01	0.02	0.012	0.01	0.01	0.02
BIT	MN	SD	ND	WY	NE	WI	IL	IA	AL	MT	ID
TEST #2 CO 10 (EB)											
RUN 1	0.53	0.43	0.62	0.59	0.50	0.51	0.55	0.61	0.57	0.43	0.48
RUN 2	0.55	0.41	0.64	0.58	0.49	0.52	0.54	0.62	0.53	0.43	0.48
RUN 3	0.55	0.36	0.63	0.58	0.47	0.51	0.54	0.61	0.54	0.42	0.44
AVERAGE	0.54	0.40	0.63	0.58	0.49	0.51	0.54	0.61	0.55	0.43	0.47
STD. DEVIATION	0.01	0.04	0.01	0.01	0.02	0.01	0.01	0.007	0.02	0.01	0.02
BOC	MN	SD	ND	WY	NE	WI	IL	IA	AL	MT	ID
TEST #3 IS 694 (NB)											
RUN 1	0.11	0.05	0.17	0.16	0.05	0.11	0.12	0.11	0.09	0.01	0.01
RUN 2	0.11	0.02	0.17	0.16	0.05	0.11	0.12	0.11	0.09	0.02	0.00
RUN 3	0.12	0.02	0.17	0.17	0.05	0.12	0.12	0.12	0.10	0.02	0.00
AVERAGE	0.11	0.03	0.17	0.16	0.05	0.11	0.12	0.11	0.09	0.02	0.00
STD. DEVIATION	0.01	0.02	0	0.01	0	0.01	0	0.007	0.01	0.01	0.01
BOC	MN	SD	ND	WY	NE	WI	IL	IA	AL	MT	ID
TEST #4 S 694 (SB)											
RUN 1	0.09	0.02	0.12	0.11	0.03	0.07	0.06	0.08	0.05	0.00	0.00
RUN 2	0.08	0.01	0.13	0.12	0.03	0.08	0.06	0.08	0.05	0.00	0.00
RUN 3	0.09	0.03	0.13	0.12	0.03	0.08	0.06	0.08	0.05	0.00	0.00
AVERAGE	0.09	0.02	0.13	0.12	0.03	0.08	0.06	0.08	0.05	0.00	0.00
STD. DEVIATION	0.01	0.01	0.01	0.01	0	0.01	0	0	0	0	0

depths for all three runs on each test section were calculated and compared with each other. The test statistic t was then determined by using Equation 1, and finally its absolute value was compared with $t_{\alpha/2,n_1+n_2-2} = 2.776$ (for $\alpha = 0.05$ and 4 degrees of freedom since $n_1 = n_2 = 3$). If $\text{ABS}(t) > t_{\alpha/2,n_1+n_2-2}$, it would be concluded that the two means are statistically different. A large number of paired comparisons were made. As an example, roughness measurements from each road profiler were compared with the measurements from 10 other road profilers on eight test sections, which would result in 80 possible comparisons. The results from all of these comparisons are summarized in Tables 5 and 6 for roughness and rut depth measurements, respectively. It is clear from examining these tables that the road profilers produced equal IRI measurements in 35.5 percent of the cases and equal rut depth measurements in only 25.7 percent of the cases. These extremely low percentages are alarming because all the systems are similar in design.

To find the reason behind the differences in measurements from the 11 road profilers, an additional statistical analysis was conducted. This analysis aimed at determining whether there are any linear relationships among IRI and rut depth data collected with different road profilers. A regular regression approach was used to establish these relationships. The following basic regression model (i.e., simple linear parameters) was used in the analysis:

$$Y_i = B_0 + B_1 X_i \tag{3}$$

where

Y_i = mean of IRI or rut depth for three runs by one profiler,
X_i = mean of IRI or rut depth by another road profiler, and
B_0, B_1 = regression constants.

Tables 7 and 8 present summaries of the regression equations for IRI and rut depth measurements, respectively. These regression equations yield very high R-square (100% in some cases), which indicate almost perfect agreement among systems. Sample plots of the raw data used in the regression analysis are shown in Figures 2 and 3.

The t-test results can be now explained on the basis of the results from the regression analysis. Although all participating road profilers are similar in design, they should be calibrated against each other before making any attempts for comparisons. Unfortunately, the South Dakota–type road profilers are used by different highway agencies to create a national roughness data base without calibration. This national data base can be used to compare roughness measurements within any individual state. However, roughness measurement comparison for sections in various states will not be accurate without calibration.

TABLE 5 Results from IRI Comparisons

SYSTEM	SECTION	POSSIBLE COMPARISONS	GOOD COMPARISONS	% GOOD COMAPRISONS
MN	CONC	20	8	40
	BIT	20	13	65
	BOC	20	10	50
	CONC/BOC	20	5	25
	ALL SECTIONS	80	36	45
SD	CONC	20	5	25
	BIT	20	9	45
	BOC	20	10	50
	CONC/BOC	20	3	15
	ALL SECTIONS	80	27	33.8
IA	CONC	20	4	20
	BIT	20	8	40
	BOC	20	5	25
	CONC/BOC	20	4	20
	ALL SECTIONS	80	21	26.3
AL	CONC	20	6	30
	BIT	20	16	80
	BOC	20	3	15
	CONC/BOC	20	10	50
	ALL SECTIONS	80	35	43.8
ND	CONC	20	3	15
	BIT	20	13	65
	BOC	20	7	35
	CONC/BOC	20	6	30
	ALL SECTIONS	80	29	36.3
MT	CONC	20	2	10
	BIT	20	0	0
	BOC	20	3	15
	CONC/BOC	20	0	0
	ALL SECTIONS	80	5	6.25
ID	CONC	20	10	50
	BIT	20	2	10
	BOC	20	4	20
	CONC/BOC	20	5	25
	ALL SECTIONS	80	21	26.3
WY	CONC	20	10	50
	BIT	20	10	50
	BOC	20	10	50
	CONC/BOC	20	5	25
	ALL SECTIONS	80	35	43.8
NE	CONC	20	10	50
	BIT	20	14	70
	BOC	20	9	45
	CONC/BOC	20	3	15
	ALL SECTIONS	80	36	45
WI	CONC	20	4	20
	BIT	20	14	70
	BOC	20	8	40
	CONC/BOC	20	9	45
	ALL SECTIONS	80	35	43.8
IL	CONC	20	8	40
	BIT	20	11	55
	BOC	20	9	45
	CONC/BOC	20	3	15
	ALL SECTIONS	80	31	38.8
ALL SYSTEMS	CONC	220	70	31.8
	BIT	220	110	50
	BOC	220	78	35.5
	CONC/BOC	220	53	24.1
	ALL SECTIONS	880	311	35.3

TABLE 6 Results from Rut Depth Comparisons

SYSTEM	SECTION	POSSIBLE COMPARISONS	GOOD COMPARISONS	% GOOD COMPARISONS
MN	BIT	20	6	30
	BOC	20	7	35
	BOTH BIT & BOC	40	13	32.5
SD	BIT	20	2	10
	BOC	20	7	35
	BOTH BIT & BOC	40	9	22.5
IA	BIT	20	2	10
	BOC	15	5	33.3
	BOTH BIT & BOC	35	7	20
AL	BIT	20	10	50
	BOC	15	2	13.3
	BOTH BIT & BOC	35	12	34.3
ND	BIT	20	6	30
	BOC	19	2	10.5
	BOTH BIT & BOC	39	8	20.5
MT	BIT	20	7	35
	BOC	15	4	26.7
	BOTH BIT & BOC	35	11	31.4
ID	BIT	20	7	35
	BOC	15	3	20
	BOTH BIT & BOC	35	10	28.6
WY	BIT	20	4	20
	BOC	20	2	10
	BOTH BIT & BOC	40	6	15
NE	BIT	20	4	20
	BOC	15	3	20
	BOTH BIT & BOC	35	7	20
WI	BIT	20	6	30
	BOC	20	7	35
	BOTH BIT & BOC	40	13	32.5
MN	BIT	20	6	30
	BOC	14	3	21.4
	BOTH BIT & BOC	34	9	26.6
ALL SYSTEMS	BIT	220	60	27.3
	BOC	188	45	24
	BOTH BIT & BOC	408	105	25.7

Effect of Pavement Type on Repeatability of Measurements

As shown in Table 5, the percentages of good IRI comparisons were 50 and 31.8 percent on bituminous and concrete sections, respectively. These percentages may lead someone to believe that measurements on bituminous surfaces are more repeatable than measurements on concrete sections. But since all bituminous sections were rough and all concrete sections were smooth, the factor roughness level should be taken into consideration. In other words, the encountered differences could be due to the effect of roughness level rather than pavement type. In this experiment, the selected sections did not reflect all roughness ranges. Therefore, no conclusive conclusions could be obtained with respect to the effect of pavement type on the repeatability of measurements.

CONCLUSIONS AND RECOMMENDATION

In this research, 11 South Dakota–type road profilers participated in collecting roughness and rut depth data in Min-

TABLE 7 IRI Calibration Equations

SYSTEMS		REGRESSION EQUATION	R-SQUARE(%)
MN	SD	$IRI_{MN} = -0.229 + 1.11\ IRI_{SD}$	98.2
MN	IA	$IRI_{MN} = 0.0218 + 1.08\ IRI_{IA}$	99.7
MN	AL	$IRI_{MN} = 0.0734 + 1.05\ IRI_{AL}$	99.3
MN	ND	$IRI_{MN} = 0.0214 + 1.04\ IRI_{ND}$	99.7
MN	MT	$IRI_{MN} = -0.015 + 1.23\ IRI_{MT}$	99.0
MN	ID	$IRI_{MN} = 0.029 + 1.11\ IRI_{ID}$	99.1
MN	WY	$IRI_{MN} = -0.0687 + 1.04\ IRI_{WY}$	99.6
MN	NE	$IRI_{MN} = -0.133 + 1.08\ IRI_{NE}$	99.7
MN	WI	$IRI_{MN} = 0.0185 + 1.04\ IRI_{WI}$	99.6
MN	IL	$IRI_{MN} = -0.126 + 1.07\ IRI_{IL}$	99.6
SD	IA	$IRI_{SD} = 0.262 + 0.95\ IRI_{IA}$	98.1
SD	AL	$IRI_{SD} = 0.295 + 0.932\ IRI_{AL}$	98.7
SD	ND	$IRI_{SD} = 0.262 + 0.918\ IRI_{ND}$	97.9
SD	MT	$IRI_{SD} = 0.215 + 1.09\ IRI_{MT}$	98.7
SD	ID	$IRI_{SD} = 0.257 + 0.982\ IRI_{ID}$	98.5
SD	WY	$IRI_{SD} = 0.177 + 0.917\ IRI_{WY}$	98.3
SD	NE	$IRI_{SD} = 0.115 + 0.96\ IRI_{NE}$	98.9
SD	WI	$IRI_{SD} = 0.254 + 0.921\ IRI_{WI}$	98.3
SD	IL	$IRI_{SD} = 0.117 + 0.956\ IRI_{IL}$	99.1
IA	AL	$IRI_{IA} = 0.0465 + 0.975\ IRI_{AL}$	99.6
IA	ND	$IRI_{IA} = 0.0012 + 0.966\ IRI_{ND}$	99.8
IA	MT	$IRI_{IA} = -0.0381 + 1.14\ IRI_{MT}$	99.6
IA	ID	$IRI_{IA} = 0.0056 + 1.03\ IRI_{ID}$	99.5
IA	WY	$IRI_{IA} = -0.082 + 0.962\ IRI_{WY}$	99.6
IA	NE	$IRI_{IA} = -0.142 + 1.01\ IRI_{NE}$	99.8
IA	WI	$IRI_{IA} = -0.004 + 0.967\ IRI_{WI}$	99.9
IA	IL	$IRI_{IA} = -0.136 + 0.999\ IRI_{IL}$	99.6
AL	ND	$IRI_{AL} = -0.0385 + 0.987\ IRI_{ND}$	99.4
AL	MT	$IRI_{AL} = -0.085 + 1.17\ IRI_{MT}$	99.8
AL	ID	$IRI_{AL} = -0.0429 + 1.06\ IRI_{ID}$	99.9
AL	WY	$IRI_{AL} = 0.129 + 0.985\ IRI_{WY}$	99.7
AL	NE	$IRI_{AL} = -0.186 + 1.03\ IRI_{NE}$	99.5
AL	WI	$IRI_{AL} = -0.045 + 0.989\ IRI_{WI}$	99.6
AL	IL	$IRI_{AL} = -0.184 + 1.02\ IRI_{IL}$	99.8
ND	MT	$IRI_{ND} = -0.0349 + 1.18\ IRI_{MT}$	99.3
ND	ID	$IRI_{ND} = 0.0105 + 1.06\ IRI_{ID}$	99.2
ND	WY	$IRI_{ND} = -0.08 + 0.994\ IRI_{WY}$	99.3
ND	NE	$IRI_{ND} = -0.143 + 1.04\ IRI_{NE}$	99.5
ND	WI	$IRI_{ND} = -0.0003 + 0.999\ IRI_{WI}$	99.7
ND	IL	$IRI_{ND} = -0.138 + 1.03\ IRI_{IL}$	99.6
MT	ID	$IRI_{MT} = 0.0405 + 0.899\ IRI_{ID}$	99.6
MT	WY	$IRI_{MT} = -0.0317 + 0.893\ IRI_{WY}$	99.3
MT	NE	$IRI_{MT} = -0.0844 + 0.877\ IRI_{NE}$	99.5
MT	WI	$IRI_{MT} = 0.035 + 0.844\ IRI_{WI}$	99.8
MT	IL	$IRI_{MT} = -0.0821 + 0.873\ IRI_{IL}$	99.7
ID	WY	$IRI_{ID} = -0.0804 + 0.933\ IRI_{WY}$	99.7
ID	NE	$IRI_{ID} = -0.132 + 0.972\ IRI_{NE}$	99.3
ID	WI	$IRI_{ID} = 0.0015 + 0.935\ IRI_{WI}$	99.4
ID	IL	$IRI_{ID} = -0.13 + 0.968\ IRI_{IL}$	99.5
WY	NE	$IRI_{WY} = -0.055 + 1.04\ IRI_{NE}$	99.6

(continued on next page)

TABLE 7 *(continued)*

SYSTEMS		REGRESSION EQUATION	R-SQUARE(%)
WY	WI	$IRI_{WY} = 0.0896 + 1.0\ IRI_{WI}$	99.5
WY	IL	$IRI_{WY} = -0.0512 + 1.04\ IRI_{IL}$	99.6
NE	WI	$IRI_{NE} = 0.141 + 0.961\ IRI_{WI}$	99.8
NE	IL	$IRI_{NE} = 0.0063 + 0.993\ IRI_{IL}$	99.8
WI	IL	$IRI_{WI} = -0.137 + 1.03\ IRI_{IL}$	99.8

TABLE 8 Rut Depth Calibration Equation

SYSTEMS		REGRESSION EQUATION	R-SQUARE(%)
MN	SD	$RUT_{MN} = 0.0685 + 1.32\ RUT_{SD}$	97.2
MN	ND	$RUT_{MN} = -0.045 + 0.963\ RUT_{ND}$	99.6
MN	WY	$RUT_{MN} = -0.0452 + 1.03\ RUT_{WY}$	99.7
MN	NE	$RUT_{MN} = 0.0616 + 0.969\ RUT_{NE}$	100.0
MN	WI	$RUT_{MN} = 0.008 + 0.999\ RUT_{WI}$	99.6
MN	IL	$RUT_{MN} = 0.0107 + 0.998\ RUT_{IL}$	99.6
MN	IA	$RUT_{MN} = 0.0123 + 0.986\ RUT_{IA}$	94.6
MN	AL	$RUT_{MN} = 0.0319 + 1.05\ RUT_{AL}$	94.9
MN	MT	$RUT_{MN} = 0.0955 + 0.95\ RUT_{MT}$	99.2
MN	ID	$RUT_{MN} = 0.101 + 0.922\ RUT_{ID}$	99.9
SD	ND	$RUT_{SD} = -0.0806 + 0.716\ RUT_{ND}$	98.7
SD	WY	$RUT_{SD} = -0.0797 + 0.766\ RUT_{WY}$	98.2
SD	NE	$RUT_{SD} = 0.0011 + 0.712\ RUT_{NE}$	96.8
SD	WI	$RUT_{SD} = -0.036 + 0.727\ RUT_{WI}$	94.8
SD	IL	$RUT_{SD} = -0.038 + 0.738\ RUT_{IL}$	97.6
SD	IA	$RUT_{SD} = -0.0453 + 0.755\ RUT_{IA}$	99.5
SD	AL	$RUT_{SD} = -0.03 + 0.805\ RUT_{AL}$	99.5
SD	MT	$RUT_{SD} = 0.0286 + 0.688\ RUT_{MT}$	93.3
SD	ID	$RUT_{SD} = 0.03 + 0.676\ RUT_{ID}$	96.6
ND	WY	$RUT_{ND} = 0.0004 + 1.07\ RUT_{WY}$	100.0
ND	NE	$RUT_{ND} = 0.112 + 1.0\ RUT_{NE}$	99.4
ND	WI	$RUT_{ND} = 0.0578 + 1.03\ RUT_{WI}$	98.6
ND	IL	$RUT_{ND} = 0.0583 + 1.04\ RUT_{IL}$	99.8
ND	IA	$RUT_{ND} = 0.0561 + 1.03\ RUT_{IA}$	97.0
ND	AL	$RUT_{ND} = 0.0776 + 1.1\ RUT_{AL}$	97.3
ND	MT	$RUT_{ND} = 0.149 + 0.977\ RUT_{MT}$	97.6
ND	ID	$RUT_{ND} = 0.153 + 0.951\ RUT_{ID}$	99.1
WY	NE	$RUT_{WY} = 0.104 + 0.934\ RUT_{NE}$	99.6
WY	WI	$RUT_{WY} = 0.0529 + 0.962\ RUT_{WI}$	99.0
WY	IL	$RUT_{WY} = 0.0539 + 0.966\ RUT_{IL}$	99.9
WY	IA	$RUT_{WY} = 0.0532 + 0.961\ RUT_{IA}$	96.3
WY	AL	$RUT_{WY} = 0.0722 + 1.03\ RUT_{AL}$	96.7
WY	MT	$RUT_{WY} = 0.138 + 0.913\ RUT_{MT}$	98.2
WY	ID	$RUT_{WY} = 0.142 + 0.888\ RUT_{ID}$	99.3
NE	WI	$RUT_{NE} = -0.0555 + 1.03\ RUT_{WI}$	99.7
NE	IL	$RUT_{NE} = -0.0524 + 1.03\ RUT_{IL}$	99.5
NE	IA	$RUT_{NE} = -0.05 + 1.02\ RUT_{IA}$	94.2
NE	AL	$RUT_{NE} = -0.0299 + 1.08\ RUT_{AL}$	94.5
NE	MT	$RUT_{NE} = 0.0347 + 0.982\ RUT_{MT}$	99.3
NE	ID	$RUT_{NE} = 0.0402 + 0.951\ RUT_{ID}$	99.9
WI	IL	$RUT_{WI} = 0.0042 + 0.995\ RUT_{IL}$	99.1

(continued on next page)

TABLE 8 *(continued)*

SYSTEMS		REGRESSION EQUATION	R-SQUARE(%)
WI	IA	$RUT_{WI} = 0.0101 + 0.970\ RUT_{IA}$	91.7
WI	AL	$RUT_{WI} = 0.0291 + 1.04\ RUT_{AL}$	92.2
WI	MT	$RUT_{WI} = 0.0872 + 0.953\ RUT_{MT}$	99.9
WI	ID	$RUT_{WI} = 0.0935 + 0.92\ RUT_{ID}$	99.6
IL	IA	$RUT_{IL} = 0.0004 + 0.991\ RUT_{IA}$	95.7
IL	AL	$RUT_{IL} = 0.0199 + 1.06\ RUT_{AL}$	96.2
IL	MT	$RUT_{IL} = 0.0866 + 0.946\ RUT_{MT}$	99.2
IL	ID	$RUT_{IL} = 0.0916 + 0.918\ RUT_{ID}$	99.0
IA	AL	$RUT_{IA} = 0.0204 + 1.07\ RUT_{AL}$	100.0
IA	MT	$RUT_{IA} = 0.103 + 0.892\ RUT_{MT}$	89.8
IA	ID	$RUT_{IA} = 0.104 + 0.881\ RUT_{ID}$	93.7
AL	MT	$RUT_{AL} = 0.0769 + 0.839\ RUT_{MT}$	90.2
AL	ID	$RUT_{AL} = 0.0779 + 0.827\ RUT_{ID}$	93.9
MT	ID	$RUT_{MT} = 0.0072 + 0.963\ RUT_{ID}$	99.4

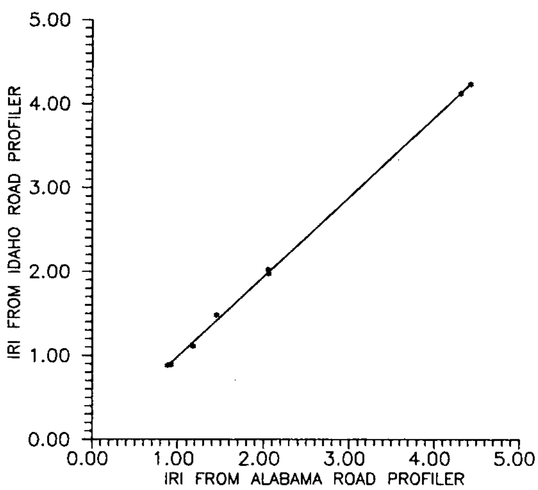

FIGURE 2 IRI correlation between Idaho and Alabama road profilers (R^2 = 99.9 percent)

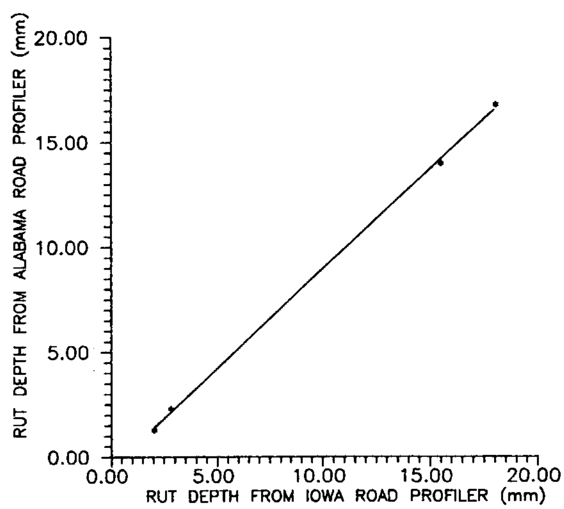

FIGURE 3 Rut depth correlation between Iowa and Alabama road profilers (R^2 = 100.0 percent).

nesota. Eight pavement test sections were included in the experiment to reflect the various pavement types encountered in Minnesota. Each road profiler was run three times on all test sections. The collected data were then reduced, tabulated, and analyzed statistically. This analysis leads to the following conclusions:

1. Roughness and rut depth measurements obtained with any single system seem to be repeatable.
2. The *t*-test results indicate that roughness measurements obtained with all systems were statistically different in 64.5 percent of the cases. On the other hand, rut depth measurements were statistically different in 74.3 percent of the cases.
3. The regression analysis yielded very strong linear relationships among systems. *R*-squares were in the upper 90s for almost all relationships. These relationships indicate that the systems do correlate among each other.
4. There is no conflict in the findings stated in Items 1 and 2. They simply reflect the fact that road profilers should be calibrated before any comparisons are conducted. Calibration will ensure the validity of the comparison.
5. The data collected were not adequate to determine whether pavement type influenced the repeatability of measurements of road profilers.

Finally, the urgency for establishing calibration procedures for South Dakota–type road profilers cannot be overemphasized. Highway agencies invest a huge amount of resources in collecting roughness data every year. Roughness data from all states are used by FHWA to determine the level of deterioration for the pavement network nationwide. For the FHWA and different states to use roughness data effectively, all states using the South Dakota–type road profiler should calibrate their devices to ensure data consistency. Calibration could be done by establishing regional calibration sites that could be used in establishing calibration factors that would ensure that roughness devices operating across the United States produce comparable results.

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