Factors Affecting Repeatability of Pavement Longitudinal Profile Measurements

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When looking at the accuracy of profilometers, most agencies are mainly concerned with hardware precision rather than the errors caused by the human operators or environmental factors. The Wyoming Transportation Department and the University of Wyoming conducted a joint research project to determine the effect of these two factors on the accuracy and repeatability of roughness and rut depth measurements. The Wyoming Transportation Department's road profiler, which is a duplicate of the South Dakota road profiler, was used in this study. A total of 36 test sections were tested by three different operators to determine the effect of human factors on measurement repeatability. In addition, a concrete test section was monitored and tested several times in the 1991 testing season to examine the effect of various combinations of environmental factors on the measured roughness. The data collected were then tabulated and statistically analyzed. The design of the experiment is summarized, the data that were collected are described, and specific conclusions with regard to the effect of human and environmental factors on the accuracy of roughness and rut depth measurements are discussed.

One of the primary operating characteristics of a road, whether paved or unpaved, is the level of service that it provides to its users. In turn, the variation of this level of service or serviceability with time provides one measure of the road's performance. This performance can be quantified by calculating pavement serviceability index (PSI) on the basis of roughness measurements.

Surface roughness of any pavement can be defined simply as the vertical surface undulations that affect the vehicle operating costs and the riding quality of that pavement as perceived by the user. Immediately after pavements are laid, deterioration starts as a result of continuous dynamic traffic loads and several environmental factors. Road surfaces start developing cracks, potholes, ruts, and so on. As road surfaces become rougher and if maintenance is not performed in a timely manner, roads will become uncomfortable to their users.

In the past few decades, roughness response devices were the primary instruments for estimating the roughness of a roadway section. However, several drawbacks involved in the use of such instruments made them unpopular, and the need was felt to develop a more effective way to measure roughness.

Profilometers were designed to measure the actual pavement profile instead of a vehicle's response to the profile. Measurements obtained with profilometers are essentially independent of the test vehicle's suspension characteristics. Approximately 15 different types of road profilometers are in existence throughout the world. The first modern profilometer was developed in the early 1960s at the General Motors Corporation Research Laboratories (GMR) (*1*). The GMR profilometer, a contact-type device, used a high-quality potentiometer with several accelerometers to measure the road profiles. Since then several noncontact sensors were introduced to the market. K.J. Law Engineers, Inc., utilized the noncontact light beam measuring system in the 690 digital noncontact profilometers (*2,3*). In England, the Transportation Road Research Laboratory developed a high-speed, laser-based profilometer in the late 1970s. The South Dakota Department of Transportation (SDDOT) developed a profilometer that utilized ultrasonic (acoustic) sensors (*2–4*). This equipment, referred to as a road profiler, operates at highway speeds and measures pavement profiles only in the left wheelpath. 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, and about 25 others have bought commercially built systems. Two factors encouraged the fast spread of this technology:

1. FHWA requires that pavement roughness be reported in international roughness index (IRI) units.
2. The road profiler is relatively low cost compared with other available technologies.

Although quantifying roughness from pavement profiles proved to be much more accurate and reliable than depending on the point response of a vehicle, certain factors must be addressed when dealing with the measurements of pavement longitudinal profiles:

1. Effect of human operators on accuracy and repeatability of road profiler measurements;
2. Effect of environmental variations on pavement profiles; and
3. Importance of road profiler calibration.

The Wyoming Transportation Department and the University of Wyoming conducted a joint research project to examine the effect of these factors. The findings from the first two factors are discussed in this paper. The importance of calibration is discussed in detail by Asnani et al. in another paper in this Record.

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BACKGROUND

When an agency is considering the purchase of a profilometer, factors related to the hardware accuracy normally are considered. Other important factors such as the effect of human operator on measurement repeatability or the effect of fluctuations in environmental factors on changing road profiles seldom are taken into account.

Operators' ability and experience can be one of the major factors contributing to the inaccuracy of the collected roughness data. The human profilometer operator has a limited ability to concentrate on the job of profiling. The ability to concentrate is somewhat time dependent. The operator will probably do a better job testing short control sections, where the required attention span is short, than longer inventory sections. Also, every operator has a particular style of driving and reaction to particular situations. For example, if an operator is familiar with the profile of the section being tested, he or she may tend to avoid driving over rough spots by deliberately swerving to the left or the right. This type of behavior will result in inaccuracies in measuring longitudinal road profiles. Thus, the very fact that a human is required to operate the profiling equipment may limit the accuracy and repeatability of the profilometer data.

Variations in environmental conditions can also have a significant impact on pavement longitudinal profiles. Road profile characteristics can change significantly as a result of the daily cycle of heating and cooling, seasonal cycles of heating and cooling, and wetting and drying. As an example, excess rainfall will change the moisture conditions in the subgrade and the pavement layers. Variation in water content may cause shrinkage or swelling of subgrade soils, contributing to change in the profile pattern of a pavement. Also, wide variations in temperature may cause the profile of a concrete pavement to change. During the day, the top of the pavement slab heats under the sunlight while the bottom of the slab remains relatively cooler. The maximum difference in temperature between the top and bottom of the pavement slab may occur sometime after noon. This may cause the slab to warp or bend downward, developing stresses (See Figure 1, *top*). Late in the evening, there may be reversal of warping stresses because of the heat transfer from top to bottom, making the top surface colder than the bottom surface (See Figure 1, *bottom*). Seasonal variation in temperature may also contribute to the change in road profile of concrete sections. During summer, as the mean temperature of the slab increases, the concrete pavement expands. As the slab tends to expand, compressive stress is developed at its bottom. Similarly, during winter the slab contracts, causing tensile stresses at the bottom (*5,6*). If the profile of a road changes from day to day and season to season, it raises the question about the value of acquiring highly accurate and repeatable profilometer data.

Lack of calibration among presently existing profiling systems may also lead to noncomparable data collected by various states across the United States. Research was recently completed by Asnani et al. (and is reported in this Record) to investigate the effect of lack of calibration among some of the existing systems. Eleven road profilers participated in that experiment in which IRI and rut depth data were collected on eight pavement test sections. The major findings of that experiment were as follows:

1. Roughness and rut depth measurements obtained with any single system are repeatable.
2. Most roughness and rut depth measurements with all the systems are statistically different, but there exist strong relationships among the systems. This indicates the need for calibrating road profilers against each other.

DESIGN OF EXPERIMENT

A detailed plan was prepared to determine the effect of human factors and the environmental variations on the accuracy of pavement longitudinal profile measurements. This testing plan involved the creation of two data bases. The first data set was used to examine the effect of human operators on the accuracy of profile measurements, whereas the second data set was used to determine the magnitude of changes in pavement profiles (roughness) caused by changes in environmental factors. Figure 2 shows the data collection and analysis strategies for this experiment. The road profiler of the Wyoming Transportation Department was used to measure the roughness of all test sections included in the experiment.

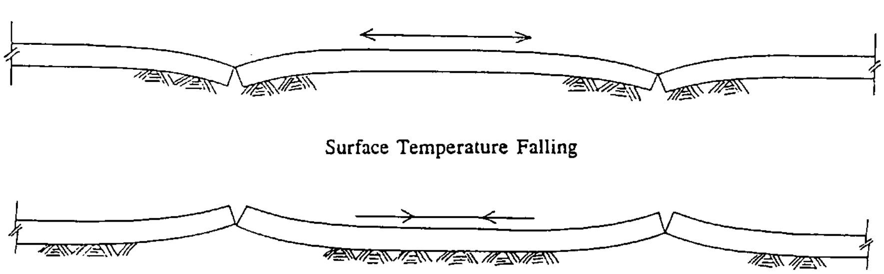

FIGURE 1 Temperature effects on concrete slabs: *top*, surface temperature is higher than temperature at bottom of slab; *bottom*, surface temperature is lower than temperature at bottom of slab.

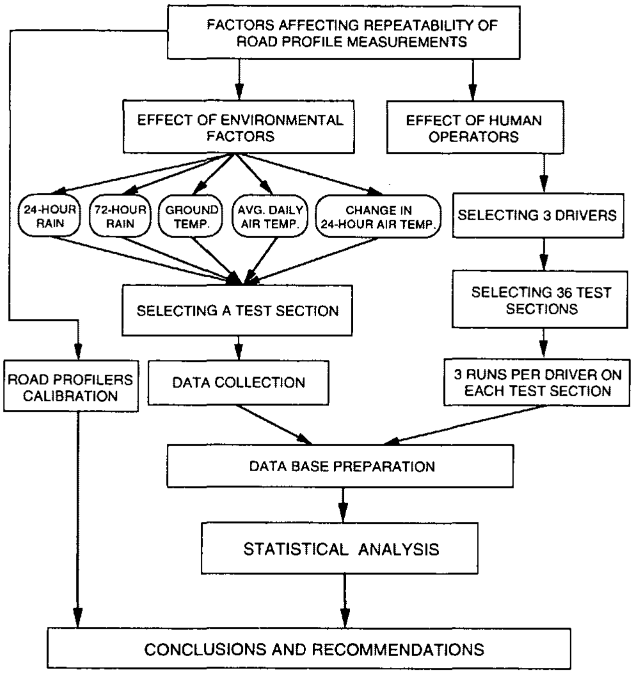

FIGURE 2 Data collection and analysis strategies.

To examine the effect of human operator on the repeatability of road profiler measurements, 36 sections were included in the experiment. A total of 27 pavements were flexible and 9 were rigid. The sections were selected to represent all possible ranges of roughness and rut depth values. These ranges were as follows:

- Low IRI: $0 \leq \text{IRI} \leq 2.0$ mm/m
- Medium IRI: 2.0 mm/m $< \text{IRI} \leq$ 3.0 mm/m
- High IRI: 3.0 mm/m $< \text{IRI}$

- Low rut depth: $0 \leq$ rut depth ≤ 2.54 mm
- Medium rut depth: $2.54 <$ rut depth ≤ 6.35 mm
- High rut depth: 6.35 mm $<$ rut depth

The test sections were located on I-25, SR-96, and SR-211 in the southeastern corner of Wyoming. Table 1 presents the testing matrix for this experiment. Three operators were selected to operate the road profiler. The regular operator who normally conducts the routine inventory testing for the Wyoming Transportation Department was included in this study. The other two operators had no prior experience in driving the road profiler. Each operator drove the road profiler three times on each test section. The operators were not told the exact locations of test sections. Instead, they were asked to cover long test segments on different highways. This was done to simulate regular field operating conditions when the operators are collecting routine data for inventory purposes. After the data on all the sections were collected, IRI and rut depth measurements for test sections 0.2 mi (0.12 km) long were extracted from the long segments. The means, standard deviations, and coefficients of variations of IRI and rut depth observations were then calculated. Tables 2, 3, and 4 summarize these values for the flexible and rigid test sections.

To examine the effect of environmental factors on pavement longitudinal profiles, one test section was monitored in 1991 for 3 consecutive months. This test section was located on a stretch of I-25 4 mi (2.5 km) long between Mileposts 13.8 and 16.2. The wearing surface of the test section consisted of a 9-in. (23-cm) jointed unreinforced portland cement concrete underlain by 6 in. (15.2 cm) of crushed gravel. Roughness data were collected on the test section under various combinations of environmental conditions, such as

1. 24-hr rainfall, in millimeters;
2. 72-hr rainfall, in millimeters;
3. Ground temperature at bottom of the slab, in degrees Celsius;

TABLE 1 Locations of Test Sections Used to Evaluate Operators' Effect on Roughness Measurement Accuracy

ROAD PROFILER PROJECT		PAVEMENT TYPE											
		FLEXIBLE									RIGID		
		PERFORMANCE INDEX									PERFORMANCE INDEX		
		IRI									IRI		
		LOW			MEDIUM			HIGH			L	M	H
		RUT			RUT			RUT					
		L	M	H	L	M	H	L	M	H			
SECTIONS	1	25N MP 5.0	25N MP 6.2	25N MP 18.0	25N MP 9.7	25N MP 14.9	25N MP 14.3	211 MP 39.0	25N MP 15.1	96W MP 2.1	25N MP 11.3	25N MP 11.0	25S MP 9.5
	2	25N MP 4.1	25N MP 6.5	25N MP 18.3	25N MP 9.2	25N MP 16.3	25N MP 14.6	211 MP 40.2	25N MP 15.9	96W MP 1.7	25N MP 11.5	25N MP 12.4	25S MP 10.3
	3	25N MP 9.4	25N MP 7.0	25N MP 18.6	25N MP 4.0	25N MP 28.3	W96 MP 1.0	211 MP 40.9	25N MP 16.1	96W MP 0.1	25N MP 11.7	25N MP 12.9	25S MP 12.1

TABLE 2 Means and Standard Deviations of IRI Values for Flexible Test Sections

			LOW IRI								
			RUT								
			LOW			MEDIUM			HIGH		
			SECTIONS								
			1	2	3	1	2	3	1	2	3
DRIVERS	1	AVG.	2.27	1.52	1.39	1.50	1.63	1.69	1.97	2.09	1.51
		S.D.	0.27	0.11	0.13	0.17	0.14	0.13	0.05	0.15	0.09
		C.V.	11.89	7.24	9.35	11.33	8.59	7.69	2.54	7.18	5.96
	2	AVG.	2.08	1.44	1.74	1.51	1.61	1.54	1.68	2.08	1.21
		S.D.	0.16	0.07	0.30	0.05	0.16	0.14	0.06	0.11	0.05
		C.V.	7.69	4.86	17.24	3.31	9.94	9.09	3.57	5.29	4.13
	3	AVG.	2.24	1.45	1.53	1.69	1.87	1.74	1.84	2.05	1.36
		S.D.	0.12	0.10	0.18	0.08	0.15	0.12	0.11	0.15	0.06
		C.V.	5.36	6.90	11.76	4.73	8.02	6.90	5.98	7.32	4.41

TABLE 3 Means and Standard Deviations of IRI Values for Rigid Test Sections

			LOW IRI			MEDIUM IRI			HIGH IRI		
			SECTION			SECTION			SECTION		
			1	2	3	1	2	3	1	2	3
DRIVERS	1	AVG.	2.12	1.86	1.81	2.08	2.34	2.42	2.33	2.80	3.10
		S.D.	0.09	0.08	0.11	0.12	0.13	0.16	0.04	0.21	0.01
		C.V.	4.25	4.30	6.08	5.77	5.56	6.61	1.72	7.50	0.32
	2	AVG.	2.31	2.06	1.99	2.24	2.37	2.50	2.44	2.83	3.30
		S.D.	0.10	0.28	0.21	0.10	0.07	0.06	0.17	0.16	0.06
		C.V.	4.33	13.59	10.55	4.46	2.95	2.40	6.97	5.65	1.82
	3	AVG.	2.26	1.90	1.79	2.06	2.20	2.55	2.26	3.00	3.26
		S.D.	0.17	0.06	0.03	0.10	0.08	0.09	0.10	0.43	0.11
		C.V.	7.52	3.16	1.68	4.85	3.64	3.53	4.42	14.33	3.37

4. Average daily air temperature, in degrees Celsius; and
5. Change in 24-hr air temperature, in degrees Celsius.

Table 5 summarizes all roughness and environmental data collected on the test section.

DATA ANALYSIS

All collected data were reduced and compiled in computer files. Data analysis was later conducted by using regular statistical tools. The main objectives of the analysis were to investigate the repeatability of roughness and rut depth measurements obtained by each operator, compare the results obtained from three operators, and study the effect of environmental factors on pavement roughness.

Repeatability of Roughness Measurements by Each Operator

Each operator drove the road profiler 3 times on all 36 test sections. The averages, standard deviations, and coefficients of variation were then calculated for IRI and rut depth data

TABLE 4 Means and Standard Deviations of Rut Depth Values for Flexible Test Sections

			LOW IRI								
			RUT								
			LOW			MEDIUM			HIGH		
			SECTIONS								
			1	2	3	1	2	3	1	2	3
DRIVERS	1	AVG.	0.10	0.10	0.08	0.15	0.13	0.10	0.33	0.46	0.52
		S.D.	0.04	0.01	0.01	0.06	0.04	0.06	0.11	0.02	0.03
		C.V.	40.00	10.00	12.50	40.00	30.77	60.00	33.33	4.35	5.77
	2	AVG.	0.13	0.11	0.09	0.11	0.13	0.07	0.40	0.47	0.49
		S.D.	0.05	0.01	0.00	0.02	0.05	0.04	0.06	0.02	0.07
		C.V.	38.46	9.09	0.00	18.18	38.46	57.14	15.00	4.26	14.29
	3	AVG.	0.09	0.07	0.09	0.19	0.21	0.17	0.39	0.45	0.52
		S.D.	0.07	0.02	0.00	0.01	0.02	0.02	0.06	0.02	0.02
		C.V.	77.78	28.57	0.00	5.26	9.52	11.76	15.38	4.44	3.85

TABLE 5 Data Collected for IRI and Other Environmental Factors

TEST NO.	IRI (mm/m)	GROUND TEMPERATURE (°C)	AVERAGE DAILY AIR TEMPERATURE (°C)	CHANGE IN 24-HOUR AIR TEMPERATURE (°C)	TOTAL 24-HOUR RAIN (mm)	TOTAL 72-HOUR RAIN (mm)	CHANGE IN AIR v GROUND TEMPERATURE (°C)
1	2.76	13	13	+2.8	0.00	2.03	0.6
2	2.75	12	13	0	0.00	3.64	1.1
3	3.04	15	11	-2.2	18.54	73.15	3.9
4	2.76	14	15	-1.7	0.00	5.33	0.6
5	2.72	20	19	+1.1	0.00	0.51	1.1
6	2.70	21	22	+3.9	0.00	1.27	1.1
7	2.75	22	21	+0.6	2.30	15.55	1.1
8	2.68	21	16	-1.1	0.00	0.00	5.0
9	2.71	22	21	-0.6	3.30	3.81	0.6
10	2.81	24	22	+1.7	0.00	4.06	2.2
11	2.69	16	21	+2.2	0.00	4.06	5.0
12	2.77	20	22	+1.1	0.00	0.00	1.7

on all test sections (see Tables 2 through 4). The coefficient of variation, the ratio of standard deviation to the mean expressed as a percent, is normally used to measure the relative variability of any factor. In this analysis, the coefficient of variation for IRI ranged from 0.32 to 14.33 on concrete sections and from 0.92 to 17.74 on bituminous sections. These coefficients of variation indicate acceptable variability of IRI measurements. In other words, IRI measurements obtained by any operator were repeatable. On the other hand, the coefficients of variation for rut depth measurements ranged from 0 to 77.78, indicating high relative variability for rut depth measurements.

Comparison Among Three Operators

Pavement longitudinal profiles obtained by the three drivers were first plotted and compared visually. Figure 3 shows some of these profiles on a selected test section. Because no definite conclusions could be obtained by the visual comparison, IRI and rut depth measurements were calculated and averaged on each test section. The two-sample *t*-test was then used to conduct paired comparisons between the means. Basically, average measurements from any two operators were compared to determine whether they were statistically different at 95 percent confidence level.

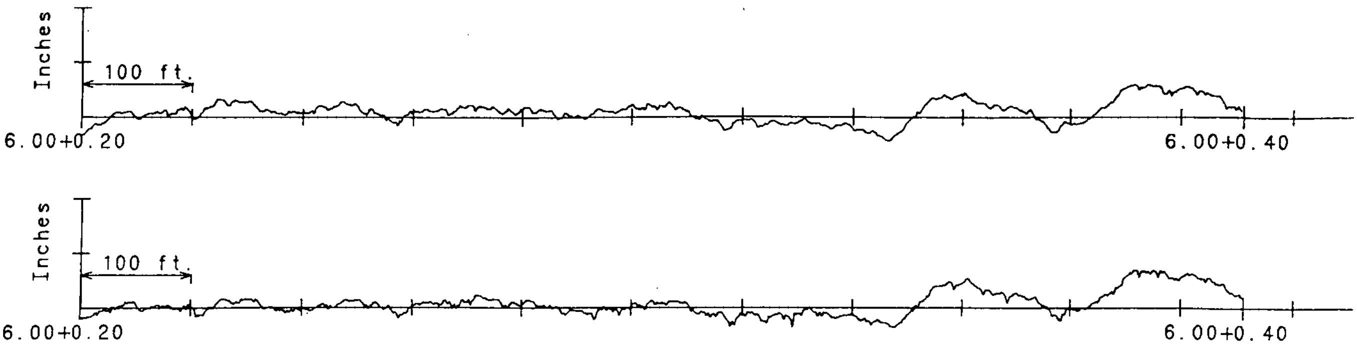

FIGURE 3 Profile of test section between Mileposts 6.2 and 6.4 for Run 3 by Drivers 2 (*top*) and 3 (*bottom*).

The t-statistic used in the analysis was calculated with the following equation:

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

where

Y_1, Y_2 = sample means,
n_1, n_2 = sample sizes (three in this case),
S_p^2 = estimate of common variance computed with the following equation:

$$S_p^2 = \frac{(n_1 - 1)S_1^2 + (n_2 - 1)S_2^2}{n_1 + n_2 - 2},$$

and

S_1^2, S_2^2 = two individual sample variances.

The calculated t-value was compared with $t_{\alpha/2,n_1+n_2-2}$ = 2.776 (for $\alpha = 0.05$ and 4 degrees of freedom). If ABS (t) > $t_{\alpha/2,n_1+n_2-2}$, it would be concluded that the two means are statistically different.

Using this two-sample t-test, a large number of paired comparisons were conducted on IRI and rut depth data. Measurements obtained with each operator were compared with measurements from the other two operators on all 36 test sections. The results of the statistical analysis are summarized in Tables 6 and 7 for IRI and rut depth data, respectively. Table 6 indicates that the IRI measurements obtained with the three operators were equal in all cases except five. It is interesting that three of the five cases were on flexible sections with low roughness levels. On the other hand, Table 7 shows how the disagreement among operators was much higher when dealing with rut depth measurements. In this case, more differences were detected on sections with high roughness level.

Effect of Environmental Factors on Pavement Roughness

The environmental data collected on the concrete test section were analyzed statistically. The main objectives of the analysis were first to determine which environmental factors cause changes in pavement profiles and second to develop a regression relationship that can predict IRI on the basis of these important factors. The following regression model was initially used:

$$Y_i = B_0 + B_1X_1 + B_2X_2 + B_3X_3 + E_i$$

where

Y_i = value of response variable IRI;
X_1, X_2, X_3 = independent variables (environmental factors such as temperature and rain); and
B_0, B_1, B_3 = regression constants.

On the basis of the regression model, relationships were established by using the MINITAB software package. All factors were linearly correlated with IRI, and the resulting R-squares were examined. None of the linear models seemed to fit adequately. Graphs were then drawn to determine the general shape of the relationship between each environmental factor and IRI. The relationship between IRI and the variation in air temperature during 24 hr is shown in Figure 4. It is clear from this figure that a nonlinear rather than a linear relationship should be established between these two factors. After considering this fact, the following regression model was obtained with $R^2 = 0.849$:

$$\text{IRI} = 2.72 + 0.117A + 0.00357B - 0.00065B^2$$

where

IRI = international roughness index;
A = 72-hr rainfall before testing; and
B = change in 24-hr air temperature.

This relationship indicates clearly that IRI is influenced by environmental factors. Specifically, the higher the amount of rain falling on the section within 72 hr before testing the higher the measured IRI value. Also, the roughness (IRI) of a concrete section will vary depending on air temperature fluctuation before testing. Some other relationships were developed with the factor 24-hr rainfall. However, these relationships produced a lower R^2.

CONCLUSIONS

In this research, an attempt was made to identify the effect of human and environmental factors on the accuracy of pave-

TABLE 6 Results from IRI-Paired Comparisons

ROAD PROFILER PROJECT			PAVEMENT TYPE											
			FLEXIBLE									RIGID		
			PERFORMANCE INDEX									PERFORMANCE INDEX		
			IRI									IRI		
			LOW			MEDIUM			HIGH			L	M	H
			RUT			RUT			RUT					
			L	M	H	L	M	H	L	M	H			
DRIVERS (1) AND (2)	SECTIONS	1	E*	E	NE**	E	E	E	E	E	E	E	E	E
		2	E	E	E	E	E	E	E	E	E	E	E	E
		3	E	E	NE	E	E	E	E	E	E	E	E	NE
DRIVERS (1) AND (3)	SECTIONS	1	E	E	E	E	E	E	E	E	E	E	E	E
		2	E	E	E	E	E	E	E	E	E	E	E	E
		3	E	E	E	NE	E	E	E	E	E	E	E	E
DRIVERS (2) AND (3)	SECTIONS	1	E	NE	E	E	E	E	E	E	E	E	E	E
		2	E	E	E	E	E	E	E	E	E	E	E	E
		3	E	E	E	E	E	E	E	E	E	E	E	E

* E: IRI DATA OBTAINED WITH RESPECTIVE DRIVERS ARE STATISTICALLY EQUAL.
** NE: IRI DATA OBTAINED WITH RESPECTIVE DRIVERS ARE STATISTICALLY DIFFERENT.

TABLE 7 Results from Rut Depth-Paired Comparisons

ROAD PROFILER PROJECT			PAVEMENT TYPE								
			FLEXIBLE								
			PERFORMANCE INDEX								
			IRI								
			LOW			MEDIUM			HIGH		
			RUT			RUT			RUT		
			L	M	H	L	M	H	L	M	H
DRIVERS (1) AND (2)	SECTIONS	1	E*	E	E	E	E	E	NE	E	E
		2	E	E	E	E	E	E	E	E	E
		3	E	E	E	E	NE	E	E	E	E
DRIVERS (1) AND (3)	SECTIONS	1	E	E	E	E	E	E	NE	E	NE
		2	E	NE**	E	E	NE	E	E	NE	E
		3	E	E	E	E	E	E	E	NE	E
DRIVERS (2) AND (3)	SECTIONS	1	E	NE	E	E	E	E	E	E	NE
		2	NE	E	E	E	E	E	E	E	NE
		3	E	NE	E	E	NE	E	NE	NE	E

* E: RUT DEPTH DATA OBTAINED WITH RESPECTIVE DRIVERS ARE STATISTICALLY EQUAL.
** NE: RUT DEPTH DATA OBTAINED WITH RESPECTIVE DRIVERS ARE STATISTICALLY DIFFERENT.

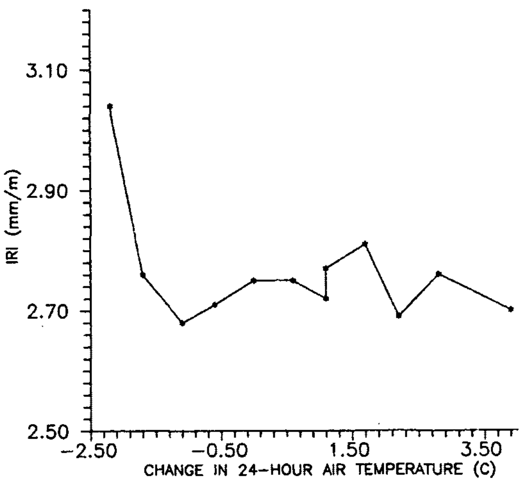

FIGURE 4 IRI versus change in 24-hr air temperature.

ment roughness and rut depth measurements. An extensive testing program was performed. The collected data were then reduced, tabulated, and analyzed statistically. This analysis leads to the following conclusions:

1. When considering measurements obtained by any single road profiler operator, the coefficient of variation of rut measurements is much higher than the coefficient of variation of roughness measurements. In other words, the roughness measuring capability of the road profiler is much better than its rut depth-measuring capability.

2. The *t*-test results indicate that roughness measurements obtained by the three operators were statistically equal in all but five cases. Three of these five cases were on sections with low roughness level. These results indicate that road profiler operators should give more attention when measuring roughness of smooth pavements. On the other hand, rut depth measurements obtained by different operators were statistically different in 20 percent of the cases. More differences were detected on sections with a high roughness level where it is harder for the operator to drive in the wheelpaths.

3. The regression analysis yielded a good nonlinear relationship between IRI and two environmental factors. R^2 for this relationship was almost 85 percent, which indicates that pavement roughness does fluctuate as a result of changes in environmental conditions.

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