Comparative Testing of Profilometers

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A comparative testing experiment between the four K.J. Law profilometers that are used to collect data for the Long-Term Pavement Performance program was conducted in Ames, Iowa, in August 1992. The objectives of the comparison were to (a) determine whether the profilometers collect similar data, (b) determine whether the profilometers can collect repeatable data at a section, and (c) compare data collected by the profilometers with data collected by the Dipstick and the rod and level. Four asphalt concrete and four portland cement concrete sections were selected for testing. All profilometers obtained six replicate runs at 65 km/hr (40 mph) and 80 km/hr (50 mph) at all test sections. The international roughness index (IRI) computed from the profile data was used as the statistic to analyze profiles. An analysis of variance was separately conducted on the left and right wheelpath IRI. This analysis showed that similar profile data are being collected by the profilometers in both wheelpaths. All profilometers showed good repeatability in collecting data. Generally good agreement was obtained between the IRI computed from profiles measured by the Dipstick and the profilometers. A study of random measuring errors showed that they can have a considerable effect on IRI of smooth pavements. Generally, for pavements that had IRI values less than 1.6 m/km (100 in./mi), poor agreement was obtained between IRI computed from rod and level and profilometer profiles. This was attributed to random measuring errors during rod and level measurements. Better agreement was obtained between rod and level and profilometer IRI for profiles that had an IRI greater than 1.6 m/km (100 in./mi).

As a part of the Long-Term Pavement Performance (LTPP) program, pavement profile data are being collected annually at approximately 800 general pavement study and 100 specific pavement study sites in the United States and Canada. Profile data collection is a primary task of the LTPP program. These profile data will be used to develop pavement performance models. The profile data are being collected by regional contractors from four regions: North Central, Western, North Atlantic, and Southern. Each region employs its own K.J. Law profilometer to collect data within the region. Three of these profilometers are identical, with the distance between the sensors being 168 cm (66 in.). The fourth profilometer contains the same electromechanical equipment as the other profilometers, but the distance between the sensors in this unit is 137 cm (54 in.). This profilometer with the shorter distance between the sensors is being used by the North Central region. The profilometers record both the left and the right wheelpath profiles. The recorded profile data are used to compute the IRI of each wheelpath. Other statistical summaries such as root mean square vertical acceleration (RMSVA) and slope variance are also computed using the profile measurements. The profile data and computed indexes are stored in the LTPP information management system data base.

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A comparative study between the profilometers from the four regions was conducted in August 1992 in Ames, Iowa. The objectives of this profilometer comparison were to

1. Determine whether the profilometers can collect similar data,
2. Determine whether repeatable data can be obtained by each profilometer at a given section,
3. Determine whether accurate data are being collected by the profilometers by comparing the IRI computed from profilometer data with IRI computed from Dipstick as well as rod and level data.

DESIGN OF EXPERIMENT

The following factors were identified as having a potential influence on the measurements collected by the profilometers: type of profilometer, speed of testing, surface type, and level of roughness. The experimental plan designed for this study is shown in Figure 1. Eight pavement sections were used for this study, with four of the pavement sections being asphalt concrete and the other four being portland cement concrete. For each pavement type, two levels of roughness were considered. A pavement was categorized as smooth if both wheelpath IRI values (average of right and left wheelpath IRI) were less than 2 m/km (125 in./mi) and as medium if both wheelpath IRI values were between 2 m/km (125 in./mi) and 4.7 m/km (300 in./mi). This experimental plan was intended to cover the range of conditions present in the LTPP test sections. At each section, all profilometers were scheduled to make six error-free runs at two test speeds of 65 km/hr (40 mph) and 80 km/hr (50 mph). The IRI computed from the profile data was used as the statistic in all analyses.

SELECTION OF TEST SECTIONS AND DATA COLLECTION

Selection of Test Sections

The test sections were selected such that they were similar to typical Strategic Highway Research Program test sections. Each test section was 152 m (500 ft) long with similar profile characteristics throughout its length, as well as immediately before and after the test section. The cross profile was uniform over the length of these sections, which were located on straight sections of roadway.

Profilometer Data Collection

A schedule was prepared for each profilometer giving the order in which they were to test the asphalt concrete pavements and the portland cement concrete pavements. This schedule was prepared using a random number generating table. The portland cement concrete pavements were to be tested after 12:00 p.m. to minimize the effect of slab curling on profile measurements. Each test section was tested at two speeds, 65 km/hr (40 mph) and 80 km/hr (50 mph). All profilometer crews were instructed to align their vehicles along the wheelpaths when collecting data. Each crew was instructed to perform six error-free runs at both test speeds at all sections (for a total of 12 runs for a section).

Data Collection by Manual Devices

Profile measurements along the wheelpaths of the test sections using the Dipstick and the rod and level were completed in July 1992 before the profilometer comparison. In all sections, the left and right wheelpaths were marked by a chalk line, and markings were made along the wheelpaths at 0.3-m (1-ft) intervals. Profile measurements were performed using the Dipstick and the rod and level at 0.3-m (1-ft) intervals.

COMPARISON BETWEEN PROFILOMETERS

Computation of IRI

During a profilometer run, profile data on the left and right wheelpaths are collected. The IRI for each wheelpath was computed from the profile data using the Profscan program (*1*), which uses the algorithm given in a World Bank technical report (*2*). The average left wheelpath and right wheelpath IRI computed from the six profilometer runs at each section for both test speeds are shown in Table 1. As seen from these IRI values, the test sections did not completely satisfy the requirements for pavement roughness shown in the experimental design. This occurred because of difficulties in selecting suitable sites, which had to be close to each other so that the experimental testing could be completed in the shortest possible time.

Analysis of Variance

The main objective in this profilometer comparison experiment was to determine whether the IRI of the left and right wheelpaths computed from the measured profiles are similar between the profilometers. In addition, the effect of speed of testing on the computed IRI was also to be studied. The effect of the different profilometers and test speeds on the computed IRI can be determined by conducting a factorial analysis of variance (ANOVA) on the IRI.

The factors profilometer, speed, and sections were considered for the factorial ANOVA. In this design, the factors profilometer and speed are fixed whereas the factor section is random. Each cell in this design had six replicates. As the design consists of fixed and random factors, a mixed model analysis has to be performed (*3*). The SPSS program (*4*) was used to perform ANOVA. ANOVA was carried out separately for IRI of the left and right wheelpaths for the following profilometer combinations:

1. North Central, Western, North Atlantic, and Southern;
2. North Central, Western, and North Atlantic;
3. North Central, Western, and Southern;
4. North Central, North Atlantic, and Southern; and
5. Western, North Atlantic, and Southern.

The effects that were of importance in this study were type of profilometer, speed, and the interaction between profilometer and speed. The significance of each factor was tested at a significance level of 0.05. After performing ANOVA, the adequacy of the model was checked by plotting the residuals against the fitted values. An important assumption in ANOVA is the equality of variances. If this assumption is satisfied, the residuals should be structureless. Although the residual plot for the left wheelpath was structureless, the residual plot for the right wheelpath was not structureless, with a wide scatter in the residuals for the IRI values corresponding to Section 7. In Section 7, the right wheelpath area had severe cracking, which caused high variability between runs for all profilometers. Because the inclusion of Section 7 could influence the results of ANOVA in the right wheelpath, another series of ANOVA were conducted omitting Section 7. All procedures followed when conducting ANOVA were identical to those used in the earlier ANOVA. The residual plots from this analysis were structureless.

Results from ANOVA

Left Wheelpath IRI

The factors profilometer, speed, and the interaction between profilometer and speed were not significant for all profilometer com-

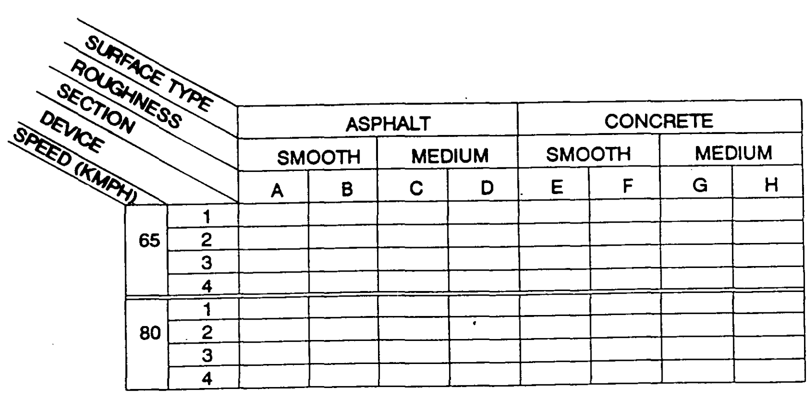


FIGURE 1 Experimental plan.

binations considered (α = 0.05). These results show that there is no significant difference in the profiles measured in the left wheelpath by all profilometers. In addition, the results indicated that there was no difference in the profiles measured in the left wheelpath at test speeds of 65 km/hr (40 mph) and 80 km/hr (50 mph) for all profilometers.

Right Wheelpath IRI

Speed or the interaction between speed and profilometer were not significant for all profilometer combinations (significance level, 0.05). The factor profilometer was not significant (α = 0.05) for the following profilometer combinations: (a) North Central, Western, and North Atlantic; and (b) North Central, Western, and Southern. However, the factor profilometer was significant (α = 0.05) for the following profilometer combinations: (a) North Central, Western, North Atlantic, and Southern; (b) North Central, North Atlantic, and Southern; and (c) Western, North Atlantic, and Southern.

This analysis shows that the profiles measured by the four profilometers in the right wheelpath are not the same. But when the North Central and Western profilometers are combined separately with the North Atlantic and Southern Profilometers, the factor profilometer for the combination of the three profilometers is not significant. These results indicate that there is a difference in the IRI values computed from profiles measured by the North Atlantic and Southern profilometers.

At each section, the SPSS program (*4*) was used with the IRI values from the right wheelpath to perform a multiple comparison of the means using the Duncan procedure and to determine homogeneous subsets of data. The purpose of this analysis was to identify profilometers that are similar. A clear conclusion could not be obtained from this analysis. An examination of the average right wheelpath IRI values (see Table 1) showed that for most sections the IRI of the Southern profilometer was lower than the average for all profilometers, whereas the IRI of the North Atlantic profilometer was higher than the average for all profilometers. The cause for the factor profilometer to be significant for any profilometer combination that included the Southern profilometer and the North Atlantic profilometer can be attributed to this difference.

From this analysis it was not possible to clearly identify which profilometer was different. However, for all practical purposes the four profilometers can be assumed to be similar for two reasons. First, the factor profilometer was not significant for profilometer combinations of (a) North Central, Western, and North Atlantic and (b) North Central, Western, and Southern regions. Second, the right wheelpath IRI values shown in Table 1 for all four profilometers are close to each other for all sections, except for Section 7, which had cracking in the wheelpath.

REPEATABILITY OF PROFILOMETERS

Table 2 shows the standard deviations of the left wheelpath IRI for all test sections at both test speeds. The values shown in this table had the following distribution: 33 percent of the values were less than 0.015 m/km (1.0 in./mi); 30 percent of values were between 0.015 and 0.03 m/km (1.0 and 2.0 in./mi); 30 percent of the values were between 0.03 and 0.045 m/km (2.0 and 3.0 in./mi); and 7 percent of the values were greater than 0.045 m/km (3.0 in./mi). Generally in sections with low IRI values, the standard deviations were less when compared with sections with higher IRI values. Similar results were obtained for the standard

TABLE 1 Average Left and Right Wheelpath IRI

			Average IRI (m/km)								Average IRI
	Test		Asphalt Sections				Concrete Sections				for all
Wheel	Speed		Section Number				Section Number				Sections
Path	(kmph)	Profilometer	3	5	6	7	1	2	4	8	(m/km)
Left	65	North Central	1.39	1.23	0.63	1.74	1.61	2.15	4.59	1.26	1.82
Left	65	Western	1.37	1.23	0.58	1.55	1.69	2.35	4.34	1.42	1.82
Left	65	North Atlantic	1.39	1.22	0.66	1.53	1.59	2.18	4.17	1.40	1.77
Left	65	Southern	1.37	1.23	0.60	1.53	1.70	2.38	4.34	1.44	1.82
Left	80	North Central	1.39	1.25	0.65	1.77	1.64	2.11	4.59	1.28	1.83
Left	80	Western	1.39	1.23	0.60	1.52	1.69	2.32	4.34	1.45	1.82
Left	80	North Atlantic	1.44	1.15	0.65	1.52	1.58	2.23	4.28	1.44	1.78
Left	80	Southern	1.39	1.22	0.60	1.56	1.77	2.34	4.40	1.48	1.84
Average Left Wheel Path IRI for Section			1.39	1.22	0.62	1.59	1.66	2.26	4.38	1.40	
Right	65	North Central	1.34	0.87	0.74	3.74	1.99	1.64	5.67	1.07	2.13
Right	65	Western	1.45	0.90	0.74	3.50	2.00	1.61	5.73	1.07	2.13
Right	65	North Atlantic	1.39	0.93	0.79	3.25	2.02	1.67	5.68	1.09	2.10
Right	65	Southern	1.31	0.90	0.74	3.06	1.97	1.66	5.62	1.07	2.04
Right	80	North Central	1.36	0.85	0.74	3.65	1.97	1.59	5.74	1.09	2.12
Right	80	Western	1.45	0.93	0.76	3.61	2.02	1.61	5.68	1.12	2.15
Right	80	North Atlantic	1.39	0.93	0.79	3.50	2.02	1.67	5.68	1.09	2.13
Right	80	Southern	1.33	0.88	0.74	3.08	1.97	1.59	5.56	1.09	2.03
Average Right Wheel Path IRI for Section			1.38	0.90	0.76	3.42	2.00	1.63	5.67	1.09	

Note: 1 m/km = 63 in/mile, 1 kmph = 0.62 mph deviation of the right wheelpath IRI, except for Section 7. In Section 7, which had cracking along the right wheelpath, the standard deviation in IRI of the right wheelpath for the profilometers ranged from 0.06 to 0.22 m/km (4 to 14 in./mi). The following conclusions can be drawn from the analysis of standard deviations.

1. Because the standard deviation of IRI for the left and right wheelpaths in all sections was low for all profilometers, it can be concluded that the profilometers collect repeatable data.
2. There was no observed difference in the standard deviation of IRI for the left and right wheelpaths because of the difference in test speeds.
3. There was no observed difference in the standard deviation of IRI between the asphalt concrete and portland cement concrete pavements.

COMPARISON BETWEEN PROFILOMETERS AND MANUAL DEVICES

Manual Devices Used

Profile measurements were obtained using the Dipstick as well as the rod and level. The Dipstick measures the difference in elevation between two points that are 0.3 m (12 in.) apart. The Dipstick used was an autorecording device, which recorded elevations to the nearest 0.025 mm (0.001 in.). Rod and level measurements were performed at 0.3-m (1-ft) intervals using an autorecording Wild NA 2000 level. The elevations were measured using the feet option, which recorded each reading to the nearest 0.25 mm (0.01 in.). The rod was equipped with a circular bubble. For a single reading this instrument typically has a standard deviation of 0.3 mm (0.012 in.) at a distance of 50 m (164 ft) and a standard deviation of 0.5 mm (0.02 in.) at a distance of 100 m (328 ft) (*5*).

IRI from Manual Devices

The profile data obtained from the Dipstick and the rod and level were used to compute the IRI of the left and right wheelpaths. Dipstick measurements were available on both wheelpaths in all sections. Except for one section, two replicate runs of the Dipstick were available. Rod and level measurements were not performed in some sections. The IRI computed from the data collected by the manual devices are given in Table 3.

TABLE 3 IRI from Manual Devices

		IRI (m/km)		
Section	Wheel Path	Dipstick Run 1	Dipstick Run 2	Rod & Level
1	Left	1.82	–	–
2	Left	2.34	2.30	2.35
3	Left	1.45	1.47	–
4	Left	4.14	4.06	4.15
5	Left	1.31	1.45	1.45
6	Left	0.68	0.63	–
7	Left	1.89	1.78	–
8	Left	1.39	1.37	–
1	Right	2.13	–	–
2	Right	1.67	1.70	1.66
3	Right	1.39	1.34	–
4	Right	5.67	5.57	5.57
5	Right	0.93	0.93	–
6	Right	0.77	0.74	0.95
7	Right	3.60	3.42	–
8	Right	1.10	1.10	1.20

Note: – No tests performed
1 m/km = 63 in/mile

Comparison of IRI from Profilometers and Dipstick

The ratio between average profilometer IRI at 80 km/hr (50 mph) and average Dipstick IRI (profilometer IRI/Dipstick IRI) are shown in Table 4. The ratios shown in this table have the following distribution: 4 percent between 0.8 and 0.85, 9 percent between 0.85 and 0.9, 31 percent between 0.9 and 0.95, 27 percent between 0.95 and 1.00, 22 percent between 1.00 and 1.05, 6 percent between 1.05 and 1.10, and 1 percent between 1.10 and 1.15. These results indicate that in general there is good agreement between the Dipstick IRI and the profilometer IRI. A typical relationship between IRI computed from profilometer and Dipstick profiles is shown in Figure 2.

The differences between the IRI computed from profilometer and Dipstick profiles can be attributed to the following:

1. There are differences in the paths measured by the two devices.

TABLE 2 Standard Deviation of Left Wheelpath IRI

		Standard Deviation (m/km)							
		Asphalt Sections				Concrete Sections			
Test Speed		Section Numbers				Section Numbers			
(kmph)	Profilometer	3	5	6	7	1	2	4	8
65	North Central	0.030	0.009	0.013	0.021	0.041	0.038	0.071	0.036
65	Western	0.011	0.006	0.011	0.035	0.041	0.017	0.038	0.024
65	North Atlantic	0.043	0.051	0.013	0.036	0.027	0.038	0.017	0.039
65	Southern	0.014	0.016	0.011	0.032	0.044	0.032	0.011	0.011
80	North Central	0.016	0.024	0.016	0.036	0.038	0.016	0.106	0.025
80	Western	0.022	0.014	0.013	0.041	0.039	0.022	0.035	0.030
80	North Atlantic	0.052	0.022	0.022	0.047	0.054	0.033	0.028	0.025
80	Southern	0.014	0.011	0.009	0.036	0.017	0.017	0.016	0.008

Note: 1m/km = 63 in/mile, 1 kmph = 0.62 mph

2. The profilometers take measurements at every 2.5 cm (1 in.) and these data points are averaged over a 30-cm (12-in.) moving average and recorded as profile points every 15 cm (6 in.). The Dipstick records the elevation difference between two points that are 30 cm (12 in.) apart.

Figure 3 shows the relationship between the ratio profilometer IRI/Dipstick IRI with the IRI of the wheelpath. In this figure, the ratio profilometer IRI/Dipstick IRI is the average value of this ratio for all four profilometers for a wheelpath, whereas the IRI of a wheelpath corresponds to the average IRI obtained from all profilometer runs at 80 km/hr (50 mph) in that section. Results for the left and right wheelpaths of all sections are shown in this figure. This figure shows that most of the values fall within the range of 0.95 to 1.05.

Comparison of IRI from Profilometers and Rod and Level

The ratio between average profilometer IRI and rod and level IRI (profilometer IRI/rod and level IRI) is shown in Table 5. Figure 4 shows the relationship between the ratio profilometer IRI/rod and level IRI of a wheelpath and the IRI of that wheelpath. The ratio profilometer IRI/rod and level IRI in this figure is the average value of this ratio for all four profilometers for a wheelpath in a section. The IRI of a wheelpath corresponds to the average IRI obtained by considering all profilometer runs at 80 km/hr (50 mph) in a section for that wheelpath. Figure 4 includes data for both the left and right wheelpaths.

An examination of Figure 4 shows that poor agreement between the two devices was obtained at several wheelpaths, whereas good agreement was obtained at other wheelpaths. Poor agreement occurred in wheelpaths that had IRI values less than 1.6 m/km (100 in./mi). In all these instances the rod and level IRI values were greater than profilometer IRI values. Reasonable agreement between IRI computed from rod and level and profilometer profile data was generally obtained at IRI values greater than 1.6 m/km (100 in./mi).

ANALYSIS OF ROD AND LEVEL MEASUREMENTS

The resolution requirements for profile measurements given in an ASTM standard (E1364-90) are as follows:

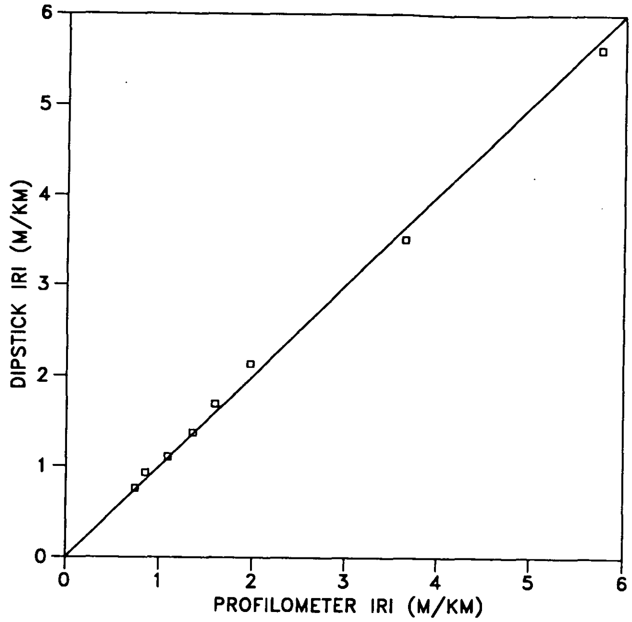


FIGURE 2 Comparison between Dipstick and North Central profilometer (right wheelpath).

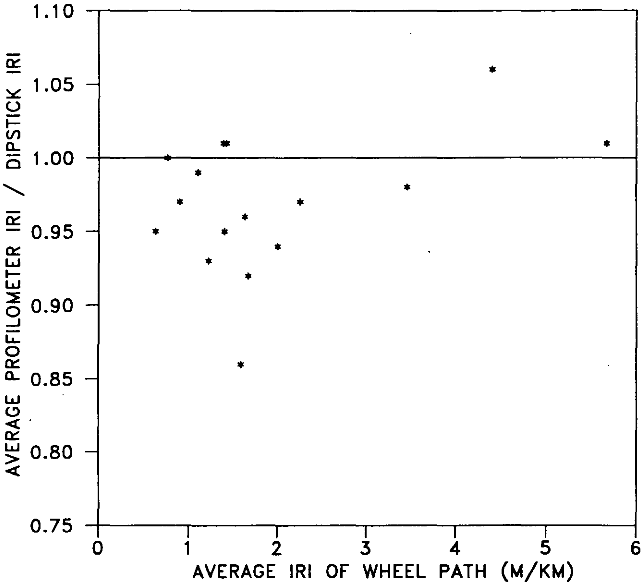
1. IRI less than 0.5 m/km (32 in./mi); resolution = 0.125 mm (0.005 in.).
2. IRI between 0.5 and 1 m/km (30 and 63 in./mi); resolution = 0.25 mm (0.01 in.).
3. IRI between 1 and 3 m/km (63 and 190 in./mi); resolution = 0.5 mm (0.02 in.).
4. IRI between 3 and 5 m/km (190 and 317 in./mi); resolution = 1.0 mm (0.04 in.).

For the sections measured, the device used for rod and level measurements satisfied these resolution requirements. Errors that occur during rod and level measurements can be classified into the following categories:

1. Error caused by the rod not being truly vertical; and
2. Random error associated with each reading, which includes all errors except the error caused by the rod being not truly vertical

TABLE 4 Ratio Between Average Profilometer IRI and Average Dipstick IRI

		Average Profilometer IRI / Average Dipstick IRI							
		Asphalt Sections				Concrete Sections			
	Wheel	Section Number				Section Number			
Profilometer	Path	3	5	6	7	1	2	4	8
North Central	Left	0.95	0.95	0.98	0.95	0.90	0.92	1.11	0.92
Western	Left	0.95	0.94	0.90	0.83	0.93	1.01	1.05	1.03
North Atlantic	Left	0.97	0.90	1.00	0.83	0.88	0.95	1.03	1.02
Southern	Left	0.95	0.94	0.90	0.84	0.96	1.02	1.06	1.06
North Central	Right	0.99	0.92	0.98	1.04	0.93	0.94	1.02	0.99
Western	Right	1.06	1.00	1.00	1.03	0.95	0.95	1.01	1.01
North Atlantic	Right	1.01	1.00	1.04	1.00	0.95	0.99	1.01	0.99
Southern	Right	0.97	0.95	0.98	0.87	0.93	0.94	0.99	0.99



Note: 1 m/km = 63 in/mile

FIGURE 3 Ratio between profilometer and Dipstick IRI versus IRI of wheelpath.

For the autorecording level the standard deviation of a single measurement is typically 0.3 mm (0.012 in.) at a distance of 50 m (164 ft) and 0.5 mm (0.02 in.) at a distance of 100 m (328 ft) (*5*). Therefore, there is an error associated with each reading recorded by the instrument. During profile measurements, the maximum distance between the rod and the level was always less than 40 m (130 ft). Therefore, assuming that the readings at a point are normally distributed, there is a 68 percent probability for a reading to lie within the mean plus or minus a standard deviation and a 95 percent probability for the value to lie within the mean plus or minus two standard deviations (*6*).

Table 6 shows the error in reading the rod as a result of the deviation of the rod from the vertical when viewed along the line of sight of the level, for different rod reading heights. When compared with the ASTM resolution requirements of the level for profile measurements, a considerable error can occur when the rod is not truly vertical. The deviation of the rod from the vertical will always cause the value read to be greater than the true value.

The effect of random errors during leveling on the computer IRI was studied using the following scheme. A profilometer run was selected from one of the sections, and the IRI was computed for one wheelpath. Then a random error between −0.25 and 0.25 mm (−0.01 and +0.01 in.) was added to each point recorded by the profilometer. The random numbers between −0.25 and +0.25 mm (−0.01 and +0.01 in.) were generated using a random number generator. The IRI of this new profile containing the random error was then computed. The procedure was repeated using the original profilometer profile and random numbers between −0.5 and +0.5 mm (−0.02 and +0.02 in.), −0.75 and +0.75 mm (−0.03 and +0.03 in.), and −1 and + 1 mm (−0.04 in. and +0.04 in.), respectively. The results of these computations for five profiles are given in Table 7. This analysis shows that in general, a random error in a profile having a high IRI value does not have much effect on the computed IRI. However, for profiles that have relatively low IRI values, introduction of a random error can have a large effect on IRI, depending on the magnitude of the error.

The effect on IRI caused by the rod's not being held exactly vertical was studied using the same scheme outlined in the previous paragraph. The same wheelpaths that were used earlier were used for this study too. However, in this case the random numbers generated were all positive as an error because the rod is not vertical and thus is always positive. Random numbers between 0 and 0.25, 0 and 0.5, 0 and 0.75, and 0 and 1 were generated for this analysis. These numbers were added separately to the original profile recorded by the profilometer, and the IRI of each profile was computed. The results of this analysis are shown in Table 8. The conclusions arrived at in the earlier study described in the previous paragraph are true for this analysis too. A comparison of Tables 7 and 8 shows that the effect on IRI was greater because of random error associated with each reading than because of the error caused by the rod's being not exactly vertical. The reason for this is that an introduction of a random error that varies between positive and negative values will make a profile rougher than a random error that always is positive.

The error in a reading obtained by the level is a combination of random error associated with that reading and the error caused by the rod's not being vertical. For each reading obtained by the level, a combination of these two errors will cause an error in the recorded value. The results in Tables 7 and 8 show that errors during leveling can have an appreciable effect on the computed IRI of pavements having a low IRI value, whereas their effect is not very significant in pavement profiles having a high IRI.

TABLE 5 Ratio Between Average Profilometer IRI and Rod and Level IRI

		Average Profilometer IRI / Rod & Level IRI							
		Asphalt Sections				Concrete Sections			
	Wheel	Section Number				Section Number			
Profilometer	Path	3	5	6	7	1	2	4	8
North Central	Left	–	0.86	–	–	–	0.91	1.11	–
Western	Left	–	0.85	–	–	–	0.99	1.05	–
North Atlantic	Left	–	0.82	–	–	–	0.94	1.02	–
Southern	Left	–	0.85	–	–	–	1.01	1.05	–
North Central	Right	–	–	0.78	–	–	0.96	1.03	0.91
Western	Right	–	–	0.80	–	–	0.97	1.02	0.93
North Atlantic	Right	–	–	0.83	–	–	1.01	1.02	0.91
Southern	Right	–	–	0.78	–	–	0.96	1.00	0.91

Note: – Not measured by rod and level

The poor agreement between IRI computed from profiles measured with rod and level and profilometers on very smooth pavements can be explained by the effect of leveling errors on measured profiles. In addition, as described in the comparison between IRI values from the Dipstick and the profilometers, differences can also occur because of the differences in measured paths and the averaging of readings by the profilometers.

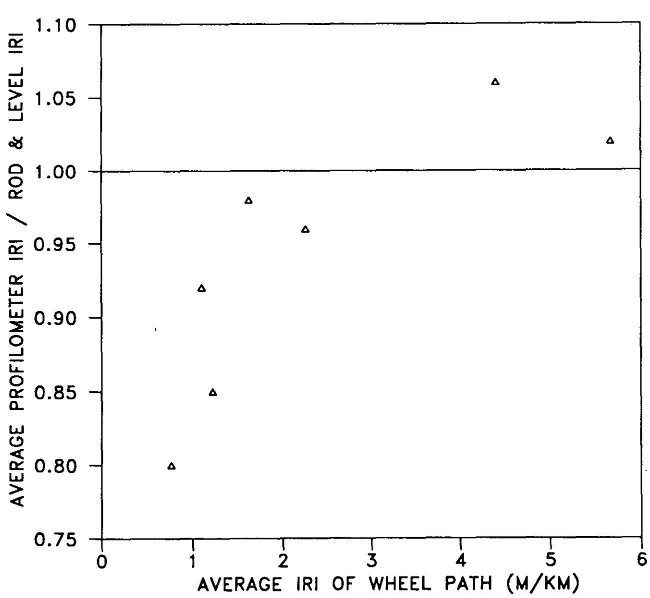
COMPARISON OF DISTANCE-MEASURING SYSTEMS OF PROFILOMETERS

An important factor in a profilometer comparison is to determine whether the distance-measuring systems of the profilometers are measuring the distance accurately so that measurements are obtained at specified intervals. This was investigated by placing a reflective tape at the beginning and the end of the test sections. This reflective tape is detected by the photo cell in the profilometer and is recorded as an event mark in the data file. The distance between the event marks in the data files was analyzed to determine the accuracy of the distance-measuring systems. The analysis showed that the distance-measuring systems of all profilometers were within the acceptable error.

CONCLUSIONS

The following conclusions are drawn from this analysis:

1. The profilometers are recording similar data in the left and right wheelpaths.
2. Profile measurements by the profilometers are independent of test speed at test speeds of 65 km/hr (40 mph) and 80 km/hr (50 mph).



Note: 1m/km = 63 in/mile

FIGURE 4 Ratio between profilometer and rod and level IRI versus IRI of wheelpath.

TABLE 6 Error Caused by Deviation of Rod from Vertical

Deviation of Rod from Vertical (Degrees)	Error in Rod Reading (mm) Rod Height 0.9 m	1.20 m	1.50 m
1	0.14	0.19	0.23
1.5	0.31	0.42	0.52
2	0.56	0.74	0.93
2.5	0.87	1.16	1.45
3	1.25	1.67	2.09
3.5	1.71	2.28	2.84
4	2.23	2.97	3.72
4.5	2.82	3.76	4.70
5	3.48	4.64	5.80

Note: 1 mm = 0.04 in

3. All profilometers generally showed excellent repeatability at a section in the left and the right wheelpaths. It was observed that the repeatability of the profilometers was not affected by speed of testing (65 km/hr versus 80 km/hr) or the surface type (asphalt concrete versus portland cement concrete).
4. Reasonable agreement was found between the IRI computed from Dipstick profile data and profilometer profile data for all four profilometers in the left and right wheelpath, for IRI values ranging from 0.8 to 5.6 m/km (50 to 360 in./mi). Exact agreement between IRI computed from Dipstick and profilometer data is unlikely because of the variations between the wheelpaths measured by the devices and because of different sampling and recording intervals of the two devices.
5. Random errors in a profile having a low IRI value can cause a considerable error on the computed IRI. The magnitude of the error depends on the magnitude of the random error. Random errors on a profile having a medium to high IRI value do not have much effect on the IRI.
6. The IRI computed from profiles measured using a level meeting the resolution requirements in ASTM E1364-90 for profile measurements generally showed good agreement with the IRI computed from the profilometer profiles for IRI values greater than 1.6 m/km (100 in./mi). There was generally poor agreement between the devices for profiles with IRI values less than 1.6 m/km (100 in./mi). Some difference in IRI between these two devices is expected because of the variations in wheelpath measured by the devices and because of the different sampling and recording interval of the two devices. However, it was seen that random errors in a rod and level survey can introduce considerable errors in the calculated IRI for pavements whose IRI value is generally less than 1.6 m/km (100 in./mi).
7. The following procedures should be followed when measuring profiles with the rod and level to minimize errors: (a) use a level having the resolution specified in ASTM E1364-90; (b) set up the instrument in such a way that only low readings are taken on the rod, which will minimize the error caused by deviations of the rod from the vertical; and (c) use a rod having a circular bubble and allow the rod person sufficient time to hold the rod vertical at a location before taking a reading.
8. IRI computed from rod and level measurements are generally taken as the "correct" measurement to validate other profile-measuring devices. This analysis indicates that on profiles having low IRI values leveling errors could influence the IRI considerably. Therefore, IRI from rod and level data of profiles having low IRI values should be examined with caution. When using the

TABLE 7 Effect on IRI Caused by Random Variations in Profile

IRI of Original Profile (m/km)	IRI of Profile with Random Variations (m/km)				Percentage Change in IRI Due to Random Variations			
	Range of Random Variation (mm)				Range of Random Variation (mm)			
	−0.25 to +0.25	−0.5 to +0.5	−0.75 to +0.75	−1 to +1	−0.25 to +0.25	−0.5 to +0.5	−0.75 to +0.75	−1 to +1
0.76	0.78	0.90	0.97	1.19	3.3	19.0	28.5	56.9
1.07	1.10	1.16	1.26	1.37	2.8	8.3	18.3	28.2
1.64	1.65	1.68	1.77	1.79	0.4	2.5	8.1	8.8
2.35	2.35	2.40	2.37	2.55	−0.2	1.9	0.8	8.2
4.43	4.43	4.44	4.44	4.51	−0.1	0.2	0.2	1.8

Note : 1 m/km = 63 in/mile, 1 mm = 0.04 in.

TABLE 8 Effect on IRI Caused by Positive Random Variations in Profile

IRI of Original Profile (m/km)	IRI of Profile with Random Variations (m/km)				Percentage Change in IRI Due to Random Variations			
	Range of Random Variation (mm)				Range of Random Variation (mm)			
	0 to +0.25	0 to +0.5	0 to +0.75	0 to +1	0 to +0.25	0 to +0.5	0 to +0.75	0 to +1
0.76	0.77	0.78	0.83	0.88	1.0	2.7	9.2	16.0
1.07	1.08	1.06	1.13	1.14	0.7	−0.6	5.5	6.9
1.64	1.64	1.66	1.67	1.82	−0.3	1.2	1.5	10.9
2.35	2.35	2.37	2.37	2.37	0.1	0.5	0.5	0.8
4.43	4.43	4.44	4.46	4.49	−0.1	0.1	0.5	1.2

Note: 1m/km = 63 in/mile, 1 mm = 0.04 mm

IRI computed from profiles measured with the rod and level for validating profile-measuring devices, it is recommended that pavements with a wide range of IRI be considered.

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