Correlation Study of California Profilograph and K. J. Law Profilometer

SYLVESTER A. KALEVELA, ESTOMIH M. S. KOMBE, AND LARRY A. SCOFIELD

The Arizona Department of Transportation (ADOT) uses the California profilograph and the K. J. Law 690 DNC profilometer for measuring pavement roughness. However, ADOT has not used the K. J. Law profilometer on portland cement concrete (PCC) pavement construction contracts because the current smoothness specifications are given in terms of the California profilograph index (PRI). This study was initiated to determine the feasibility of including the K. J. Law profilometer as one of the principal devices for testing PCC pavement surface smoothness. To accomplish that objective (a) PCC pavement sections were selected for use in the testing of the K. J. Law profilometer and the California profilograph, (b) pavement roughness data were obtained from the selected sections by both the profilometer and profilograph, and (c) correlation analysis was conducted for the two types of devices. It was found from this study that (a) between three and five replicates are required to obtain a good estimate of the PRI and (b) a good linear relationship is obtainable for the mean values of profilometer Mays index and PRI and also between the profilometer international roughness index and PRI values. On the basis of this study, it was concluded that (a) the California profilograph and the K. J. Law profilometer can be linearly correlated, (b) it is feasible to calibrate the California profilograph by the profilometer, (c) the profilometer must be calibrated first before it can be used to calibrate profilographs, and (d) it is not practical to interchangeably use the profilometer and profilographs because each device is more suited for some jobs than others.

The most common devices used by Arizona Department of Transportation (ADOT) for measuring pavement profile roughness are the Maysmeter, the California profilograph, and the recently acquired K. J. Law 690 DNC profilometer. Pavement roughness measurements obtained with these devices are used for (a) quality control of pavement surface smoothness during construction, (b) pavement acceptance at project completion time, and (c) pavement condition monitoring for the implementation of pavement management systems.

The California profilograph and the K. J. Law profilometer are not equally suited for the various data collection needs and operating environments because of their different characteristics. For instance, the California profilograph is operated by pushing and steering it along a wheelpath. This profilograph is clearly not suited for large-scale data collection projects because of its speed limitations. The K. J. Law 690 DNC profilometer is much heavier but is operated at highway speeds. ADOT's current specification for the profilometer speed is 50 mph. The K. J. Law profilometer is not suited for use at project sites with inadequate acceleration or deceleration distances and on new PCC pavements that cannot support the weight of the profilometer system.

S. A. Kalevela and L. A. Scofield, Arizona Transportation Research Center, Arizona Department of Transportation, 7755 South Research Drive, Suite 106, Tempe, Ariz. 85284. E. M. S. Kombe, Department of Industrial and Management Systems Engineering, College of Engineering and Applied Sciences, Arizona State University, Tempe, Ariz. 85287-5906.

During the summer of 1992, ADOT successfully introduced its new asphalt concrete (AC) smoothness specifications. The specifications provide for performance-based bonuses and penalties and call for the use, in the measurement of pavement roughness, of either the General Motors Research (GMR) profilometer or the Maysmeter that has been calibrated by the GMR profilometer. During the 1992–1993 fiscal year, construction projects were built according to these specifications. None of the construction projects resulted in large bonuses because the attained overall pavement smoothness levels were just slightly better than the standard specified by ADOT. In this case, pavement roughness was measured with a K. J. Law 690 DNC profilometer.

At the same time, concern was expressed about the reproducibility of profilograph test results for portland cement concrete pavement (PCCP) acceptance. Subsequently, ADOT began evaluating the feasibility of performing final acceptance of PCCP smoothness with a K. J. Law 690 DNC profilometer.

ADOT currently has an incentive/disincentive scheme in place for its PCCP construction contracts. Upon completion of PCCP construction, contractors are rewarded with a bonus for PCCP roughness that is lower than the specified standard. Similarly if the roughness is higher than this standard, the contractor is penalized. Current PCCP construction specifications are in California profilograph index (PRI) units.

It was ADOT's goal to have the specifications in both PRI and profilometer equivalent measures so that the two types of devices could interchangeably be used during the different phases of a PCCP construction contract. Since the PCCP smoothness specifications exist and are based on the PRI values, it was decided to study how profilograph measurements correlate with profilometer measurements.

ROUGHNESS INDEX UNITS

Apart from the different physical characteristics and speed of operation, the California profilograph and the profilometer produce different pavement roughness indexes. The California profilograph computes a profilograph index (PRI) for the full length of the run in inches per mile. Typically these values are between 0 and 15 in./mi. On the other hand, the profilometer can be set to compute either a Mays index or an international roughness index (IRI) or both. Both IRI and Mays are given in inches per mile and can be reported for desired section lengths irrespective of the actual total length of the test run. The Mays index is based on profile measurements from both of the wheelpaths traversed by the profilometer vehicle. The measurements are computed simultaneously to obtain the Mays index. IRI is an index computed by the computer system for each wheelpath. If desired, a mean IRI for the lane can also be computed by averaging the individual IRIs from the wheelpaths for that lane.

PROJECT OBJECTIVE AND SCOPE

In a preliminary investigation of the correlation between profilometer roughness index values (Mays/IRI) and California profilograph index (PRI) values, roughness data using California profilograph devices were sampled from project measurements taken a few months earlier. The results of this exercise showed very poor correlation between the two devices. It was strongly felt that the problem was caused by the variability of California profilograph roughness measurements and the fact that the profilograph roughness index values had been computed on the basis of unreplicated tests using the California profilograph.

The low precision of the California profilograph made the use of single measurements from the device for correlation analysis statistically inappropriate. However, it was believed that if both devices were measuring the same physical quantity, there was reason to expect correlation between the measurements obtained with the two devices. Previous studies (*1,2*) showed that indeed there was correlation between profilometer and profilograph roughness indexes.

The principal objectives of the study were (a) to review the feasibility of correlating the California profilograph PCCP smoothness measurements with profilometer measurements and (b) to establish whether the profilometer can be used to calibrate the profilograph. To accomplish this objective, the following tasks were proposed:

- Review relevant literature about profilograph calibration methodologies and determine their suitability for this study;
- Review historical data obtained during acceptance testing of PCCP constructed for ADOT since 1986 in the Phoenix metropolitan area;
- Select, on the basis of historical data, concrete pavement sections that represent the roughness levels typically encountered during new construction;
- Test the pavement sections with both the profilograph and profilometer devices; and
- Develop a model for the relationship between profilograph and profilometer measurements of PCCP surface roughness.

REVIEW OF PROFILOGRAPH CALIBRATION PROCEDURES

The calibration of a measuring device assumes that one has a means of determining the true value of the parameter being measured. The true value can then be compared to the value obtained with the measuring device. Depending on the nature of this measurement, and the established cause of the observed difference from the true value, appropriate corrective measures may be taken. Alternatively, if an observed deficiency on the device(s) is known to result in systematic errors, a correction factor can be applied to the output from the device. In this study, the following procedures were reviewed to determine possible use for profilograph calibration:

- Use of a test section in conjunction with the Pennsylvania Transportation Institute (PTI) program for the computation of a California profilograph index,
- Use of profilometer profile data with the PTI program for the computation of a California profilograph index, and
- Calibration of profilograph by a linear regression model for the relationship between profilograph and profilometer indexes.

The procedures, their underlying assumptions, limitations, observed problems, and the results of test runs are described next.

PTI Program for Computation of Profilograph Roughness Index

The program, written in Microsoft FORTRAN for the IBM personal computer (PC) and compatible computers, was developed by Meau-Fuh Pong and reported by Kulakowski and Wambold (*3*). Its function is to calculate profile roughness index for a given set of profile elevation data obtained with a California or Rainhart procedure. The computer program requires input of profile elevations data collected at 2-in. intervals.

Test Section for Index Computation

The profilograph roughness index computation program was developed for use where a test section of known elevations exists. The known elevations are input to the program, which computes the appropriate profilograph index. The profilograph to be calibrated is used on this section, and the resulting index is compared with the computed value. Typical examples for such test sections are suggested by the authors as (a) a sinusoidal profile and (b) a horizontal section with rectangular bumps at particular locations. Because of the difficulty in the construction of a sinuosoidal section, the rectangular bumps are a more practical alternative.

LINEAR REGRESSION ANALYSIS

The following needed to be determined to conduct the regression analysis: (a) determination of the testing devices and operators; (b) identification of pavement roughness levels; (c) determination of measurements used in the analysis and of regression model and formulation of a hypothesis; and (d) procedure for data collection.

Test Devices

The correlation study investigated the correlation between profilometer pavement roughness index values (Mays and IRI) and profilograph PRI values. It was decided to initially use one profilometer (the only one available) and one automated profilograph at a filter setting of 8000. An automated profilograph is one that processes the profile readings and automatically computes the roughness index at the end of a test run.

Pavement roughness index values obtained with the profilograph and the profilometer are both expressed in inches per mile. The former is referred to as a California profilograph index (PRI) whereas the latter is computed as either a Mays index or an IRI. Although the units for these indexes are the same (inches/mile),

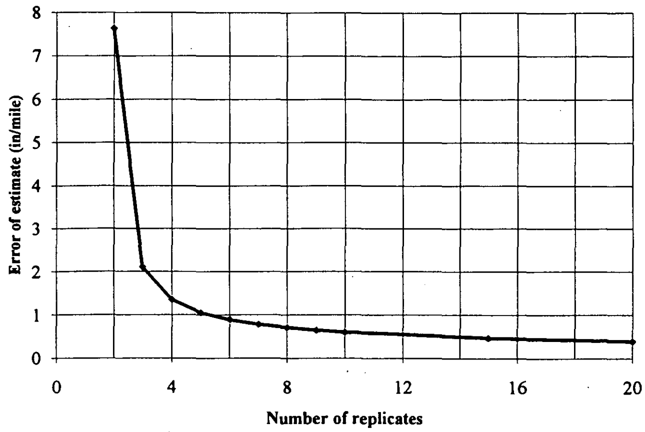

FIGURE 1 Plot of error of estimate for profilograph roughness index versus number of replications.

the magnitudes are different. Typically, PRI values for new PCCP have been found to lie in the range between 0.0 and 15.0 in./mi. The corresponding Mays index values have been found to lie in the range between 40 to 120 in./mi. Corresponding IRI values are only slightly larger than Mays index values.

Pavement Roughness Levels and Number of Test Sections

The importance of identifying the possible range of roughness values was based on how the results of the analysis can be generalized over this range. For the purpose of this study, it was believed that satisfactory results could be obtained by sampling highway pavement sections that were representative of low (PRI = 0 to 5 in./mi), moderate (PRI = 5 to 10 in./mi), and high (PRI = 10 to 15 in./mi) pavement roughness. The selection of pavement sections and the execution of the data collection task for the study were performed as follows:

- Twelve sections 0.1 mi representing three levels of pavement surface roughness were included. The roughness levels were (a) low, (b) moderate and (c) high, as described earlier.
- Five roughness measurements (replicates) were made for each wheelpath for each selected 0.1-mi section of a project. The mean of the replicate values for the 0.1-mi section constituted one data point for the analysis.
- It was initially considered desirable that more than one operator take part in the data collection, using the profilograph devices. The decision to use only one profilograph device was based on the preliminary nature of this phase of the study. For the same reason, a single profilograph operator was used.

Number of Replicates for Regression Data

The determination of a desirable number of replicates is an important consideration in influencing the quality and usefulness of the results of the analysis. There are a number of ways of obtaining the number of data points to be used in the regression. The most common of these are (a) data points based on a single measurement value from each test section for each device, and (b) data points based on average values from several replicate measurements from each test section for each device. The first case would be appropriate only in a situation in which measurements are obtained with very precise devices.

Because profilograph and profilometer measurements are not easily repeatable, a single measurement does not provide a good estimate of the true value of the roughness index. A good estimate of the value can be obtained by averaging a large number of replications. However, it is usually not practical or economical to obtain large numbers of replications. Therefore, a compromise that allows some degree of error in the estimate is normally adopted. The compromise provides for the use of a feasible number of replicates. For example, Figure 1 shows how the magnitude of the error of estimate (E) for the mean PRI value varies with the number of replications. The calculation of the error of estimate was based on a 95 percent confidence level and a repeatability standard deviation of 0.85 in./mi obtained during an earlier study.

The student t-distribution approximates the distribution of the measurement values for each individual section in this experiment. The mean is the theoretical average measurement for a 0.1-mi section, assuming a very large number of replicate measurements. An individual measurement can therefore lie within the range between $-E$ and $+E$ 95 percent of the time. The width of the con-

TABLE 1 Regression Equations for Index Variables

Response Variable (index)	Independent Variable (index)	Regression Equation	Coefficient of Determination (R^2)
Mays	PRI (both wp)	Mays = 43.3 + 5.7 * PRI	0.95
IRI (both wp)	PRI (both wp)	IRI = 52.9 + 6.1 * PRI	0.93
IRI (left wp)	PRI (left wp)	IRI = 53.5 + 6.6 * PRI	0.95
IRI (right wp)	PRI (right wp)	IRI = 54.5 + 5.0 * PRI	0.68

Note: '**wp**' used for "wheel path".

fidence interval narrows with an increasing number of replications, approximately according to the following expression:

$$E = \frac{(t_{(a/2,n-1)}) * S}{\sqrt{n}}$$

where

E = half width of confidence interval, permitted error for estimate of mean;
S = pooled standard deviation (for one data set it is standard deviation of applicable measurements);
t = value from student t-distribution for significance level and degrees of freedom $(n - 1)$ given;
n = number of replicates used to estimate parameter; and
a = significance level for desired confidence interval.

During an earlier study on the precision of profilograph measurements, it was determined that the pooled standard deviation (S) was approximately equal to 0.85 in./mi. In the above expression both the numerator and denominator vary as the number of replicates change. In this case, the values of error of estimate (E) at the 95 percent confidence level were computed as

- $E = 2.11$ for $n = 3$,
- $E = 1.0$ for $n = 5$,
- $E = 0.6$ for $n = 10$, and
- $E = 0.4$ for $n = 20$.

As the number of runs are increased beyond 10, the benefit per additional run in terms of the reduction in the error of estimate diminishes. At the same time the ratio of the error of estimate to the mean would be about 31.0 percent for $n = 3$, and 14.0 percent for $n = 5$, if the mean of pavement roughness index value were 7 in./mi. The profilograph roughness index of 7 in./mi is the target roughness index value for ADOT construction projects.

The research team decided that a relative error of 14 percent could be tolerated. Therefore, it was recommended that at least five replicate profilograph runs be made on each wheelpath and that the mean value obtained from the five runs be used as one data point during correlation analysis. In addition, it was recommended that project sections be picked from several levels of pavement roughness so that the results of the correlation could be generalized over a wide range of pavement roughness.

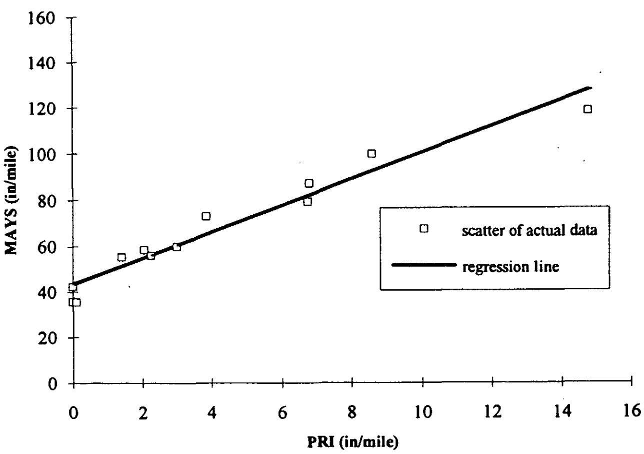

FIGURE 2 Plot of Mays index versus profilograph roughness index (both wheelpaths).

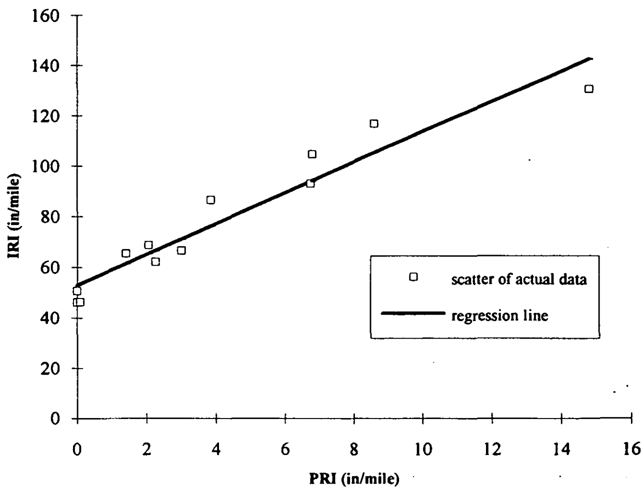

FIGURE 3 Plot of profilometer IRI versus profilograph roughness index (both wheelpaths).

Although desirable, the use of more than one profilograph was deemed unnecessary because results from an earlier study had indicated that variability between ADOT profilographs was not statistically significant.

To make a valid comparison between the variability of profilometer and profilograph measurements, it was decided to compare the coefficients of variation computed from data collected with the two devices. The coefficient of variation is used to express the standard deviation as a percentage of the mean. From the mean values for the data used in this study, which were 4.13 in./mi for profilograph roughness index and 66.5 in./mi for profilometer Mays index, the respective coefficients of variation were 13.0 percent for the profilograph and 3.0 percent for the profilometer. These coefficients of variation were computed on the basis of standard deviation values of 0.53 in./mi for the California profilograph and 2.0 in./mi for the K. J. Law profilometer.

Data Collection

A total of 120 tests were conducted with the profilograph on recently built PCCP sections in Phoenix, Arizona. The data collection plan was based on three levels of pavement roughness, four sections for each level of roughness, two wheelpaths for each section, and five replicate tests for each wheelpath (three roughness levels × four sections × two wheelpaths × five replicates = 120 total number of tests). Although the 12 sections did not constitute a large number of data sets for statistical purposes, it was considered sufficient for the preliminary task of establishing whether a linear model could indeed describe the relationship between the profilometer and profilograph indexes.

The majority of the data for the study were collected between July 9, 1992, and August 20, 1992. Additional data were collected in mid-September 1992 to replace some data that were inadvertently collected with a faulty profilometer. In most cases California profilograph measurements and profilometer measurements were made on the same day or within a few days. The final breakdown of projects included in the data collection and the number of sections used from each project are as shown. Details about the actual locations of the tested sections are given in a report (*4*) that was prepared for the correlation study.

- Loop 101: University Dr.–Southern Ave., 4 sections;
- SR-360 at Ellsworth, 3 sections;
- SR-51: Glendale Ave.–Northern Ave., 2 sections;
- I-10: 99th Ave.–115th Ave., 2 sections; and
- SR-143: Washington St.–Sky Harbor Blvd., 1 section.

For each section, 10 measurements were taken using the California profilograph (5 for each wheelpath). The average of set of five replicate measurements was computed and used in the development of the regression model.

Three replicate measurements were made on each section with the profilometer. The average of the three replicates was then computed and used as the measured Mays index or IRI index for the correlation. Therefore, only 36 profilometer tests were needed during the study.

A preliminary inspection of the profilometer data raised serious concerns on three sets of profilometer roughness measurements because

- The differences in the readings between the right and left wheelpaths were uncharacteristically high.
- When compared to profilometer readings taken 4 months earlier on the same highway sections, there were about 50 to 100 percent differences in the observed Mays/IRI index values. This was in contrast to most of the other sections for which the differences in magnitudes between the data sets were less than 5 percent.

After a careful review of all data and the historical records of the profilometer performance, it was determined that the sensor on the left wheel of the profilometer had malfunctioned during the collection of the suspect data sets. Therefore, the three sets of bad data were discarded and, to replace them, new profilometer

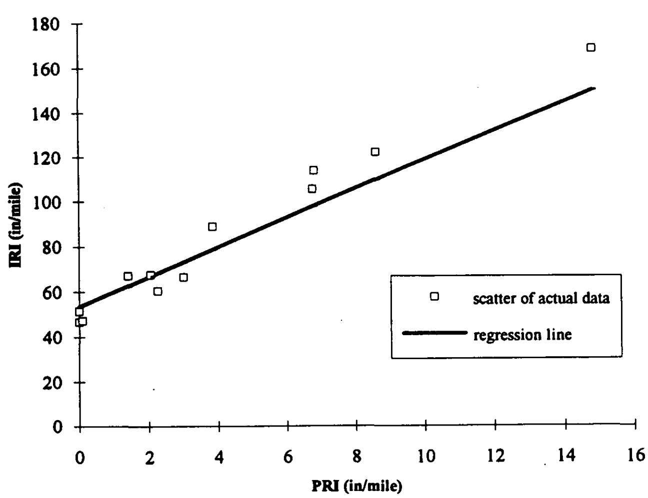

FIGURE 4 Plot of profilometer IRI versus profilograph roughness index (left wheelpath).

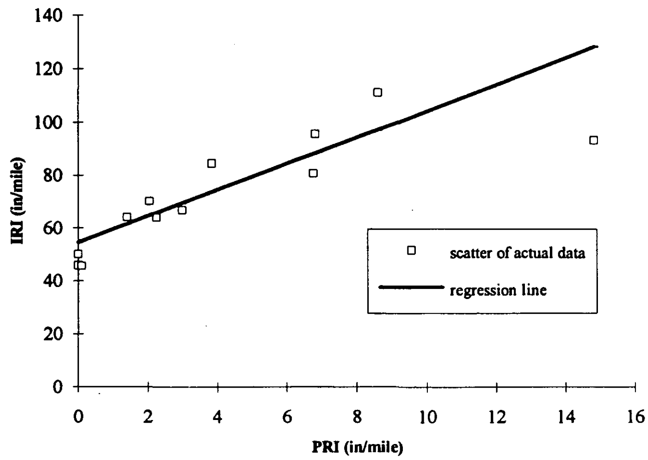

FIGURE 5 Plot of profilometer IRI versus profilograph roughness index (right wheelpath).

data sets were collected from the same sections. The new data showed no major discrepancy between the two wheelpaths and were similar to the values obtained 4 months earlier.

DATA ANALYSIS AND RESULTS

Data analysis was conducted to establish correlation and to develop regression models for the following pavement roughness variables: (a) Mays index with PRI (average of two wheelpaths in one lane), (b) IRI with PRI (based on the average of two wheelpaths in one lane), and (c) IRI with PRI (based on individual IRI and PRI for each wheelpath).

Scatter plots of the respective data suggested a linear relationship between the variables. In particular, the scatter plots for Mays against PRI, IRI against PRI (both wheelpaths) and IRI against PRI (left wheelpath) had a distinctive linear trend, with the data points falling within a very narrow band on the trend line. The scatter plot for IRI against PRI (right wheelpaths) was more spread out in comparison to the other three.

Simple linear regression models were developed for each pair of correlated variables. Statistical tests were conducted to determine if inclusion of x^2 and $x^{1/2}$ terms in the model would improve the regression model. The test results showed that the addition of one or both terms did not significantly improve the model. Therefore, the nonlinear terms were not included in the final regression equations. Table 1 gives the summary of the simple linear regression equations from the analysis. Plots of profilometer index values (Mays or IRI) against profilograph roughness index values, showing the respective regression lines are shown in Figures 2 through 5. The 95 percent prediction confidence intervals for Mays index values, based on three and five profilograph replicates, are shown in Table 2.

SUMMARY AND CONCLUSIONS

The principal objectives of the study were (a) to review the feasibility of correlating the California profilograph concrete pavement smoothness measurements with profilometer measurements

TABLE 2 Mays Index Prediction Confidence Intervals for Three and Five Profilograph Replicates

PRI in/mile	Predicted Mays Index (in/mile)	95% Confidence Limits for Mays Index Prediction			
		Limits from three Replicates		Limits from five Replicates	
		Lower	Upper	Lower	Upper
0	43.3	33.5	53.1	34.9	51.7
1	49.0	39.6	58.4	41.0	57.0
2	54.7	45.5	63.9	47.0	62.4
3	60.4	51.4	69.4	52.9	67.9
4	66.1	57.1	75.1	58.7	73.5
5	71.8	62.8	80.8	64.4	79.2
6	77.5	68.4	86.6	69.9	85.1
7	83.2	73.8	92.6	75.3	91.1
8	88.9	79.2	98.6	80.6	97.2
9	94.6	84.5	104.7	85.9	103.3
10	100.3	89.7	110.9	91.0	109.6
11	106.0	94.9	117.1	96.1	115.9
12	111.7	100.0	123.4	101.2	122.2
13	117.4	105.1	129.7	106.2	128.6
14	123.1	110.1	136.1	111.2	135.0
15	128.8	115.1	142.5	116.1	141.5

and (b) to establish whether the profilometer can be used to calibrate the profilograph. To accomplish this objective, the following principal tasks were done: (a) identification and selection of pavement sections that represent the roughness levels typically encountered during new construction, (b) testing of pavement sections with both the profilograph and profilometer, and (c) development of a model for the relationship between profilograph and profilometer profile roughness indexes.

This study showed that a linear model can be used to describe the relationship between California profilograph index values and profilometer Mays or IRI index values. It was demonstrated that a good regression model can be obtained if it is developed on the basis of mean values of the respective indexes, averaged from several replicates. It was also found that between three and five replicates are required to obtain a good estimate of the profilograph index.

On the basis of this study, it was concluded that (a) the California profilograph and the K. J. Law profilometer can be linearly correlated, (b) it was feasible to calibrate the California profilograph by the K. J. Law profilometer, (c) the profilometer must first be calibrated before it can be used to calibrate profilographs, and (d) it is not practical to interchangeably use the profilometer and profilographs because each device is more suited for some jobs than for others.

REFERENCES

1. Walker, R. S., and H. T. Lin. *Profilograph Correlation Study with Present Serviceability Index: Automated Pavement Data Collection Equipment.* University of Texas at Arlington, March 1988.
2. Uddin, W., G. E. Elkins, and W. R. Hudson. *Measurement of Pavement Roughness.* Interim Report. Arizona Department of Highways, Phoenix, Sept. 1986.
3. Kulakowski, B. T., and J. C. Wambold. *Development of Procedures for the Calibration of Profilographs.* Pennsylvania Transportation Institute, Pennsylvania State University, University Park, Aug. 1989.
4. Kombe, E. M., and S. A. Kalevela. *Evaluation of Initial Pavement Smoothness for the Development of PCCP Construction Specifications.* Special Report AZ-SP-9302. Arizona Department of Transportation, Phoenix, March 1993.

Publication of this paper sponsored by Committee on Surface Properties–Vehicle Interaction.