Use of the Inertial Profilometer To Calibrate Kentucky Department of Highways Mays Ride Meter Systems

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The National Bureau of Standards (NBS), the Commonwealth of Kentucky Department of Highways (DOH), and Surface Dynamics, Inc. joined in a project in the Commonwealth of Kentucky to calibrate five Kentucky DOH vehicle-mounted Mays Ride Meter (MRM) systems. In this project, an NBS-operated inertial profilometer system was used to measure the elevation profiles of selected pavement test sections. The measured elevation profiles were used to compute the Standard Mays Ride Meter Index (SMRMI) values for each pavement test section. The computed SMRMI values were then used as reference values for the calibration of the actual Kentucky DOH MRM systems. The profilometer was used to identify suitable pavement sections from test sites selected by the Kentucky DOH using an MRM system. The site selection process included sufficient repeat runs to establish a mean SMRMI value for each pavement and a standard deviation from that mean for the repeat runs. Six pavement test sites with the desired SMRMI values and low standard deviations were selected. The five Kentucky DOH MRM systems were then driven over the selected test sites a number of times to determine a mean measured value and a standard deviation about that measured mean value for each system on each pavement test site. The test data from the profilometer and the five Kentucky DOH MRM systems were used to develop a calibration equation and expected standard deviation for each of the MRM systems. The resulting calibration equations will be used by the Kentucky DOH to compute SMRMI values for each system. Included in the project was a correlation of the Ohio Department of Transportation inertial profilometer with the NBS-operated inertial profilometer to establish the validity of using another identically constructed inertial profilometer for the same calibration procedure.

The inertial profilometer was developed in the early 1960s by Elson Spangler and William Kelly at the General Motors Research Laboratory in Warren, Michigan. The profilometer was designed to be a research tool that would allow pavement profiles to be brought into the laboratory for use as computer input data for vehicle suspension studies. The first presentation of the inertial profilometer was made by Spangler and Kelly (*1*) at the Transportation Research Board Annual Meeting in Washington, D.C., in 1965. Through the efforts of the General Motors Corporation, the technology associated with the inertial profilometer has been made available for use in the highway testing community. Early inertial profilometer implementations were used by Michigan (*2*), Pennsylvania, Kentucky (*3*), and Texas (*4*) and by Brazil as part of a World Bank project. More recent implementations are in use in five states including Texas, West Virginia, Minnesota, Michigan, and Ohio and in Chile, as part of a World Bank project.

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INTRODUCTION

The most recent implementation is an inertial profilometer purchased by the Federal Highway Administration (FHWA) from K. J. Law Engineers, Inc., and was being evaluated by the National Bureau of Standards (NBS) for the FHWA during the work reported in this paper. In May 1987, the NBS, the Commonwealth of Kentucky Department of Highways (DOH), the Ohio Department of Transportation (DOT) and Surface Dynamics, Inc. joined in a project in the Commonwealth of Kentucky to calibrate five Kentucky DOH vehicle-mounted MRM systems using an NBS-operated inertial profilometer to perform this calibration. Fourteen pavement test sections in the vicinity of Frankfort, Kentucky, were selected as candidate sites for the calibration of Kentucky DOH MRM systems. Seven of the pavement test sections were portland cement concrete and seven were bituminous concrete.

PROFILOMETER MEASUREMENTS AND ANALYSIS

The elevation profiles of all the pavement test sections were measured with an NBS-operated inertial profilometer multiple times to evaluate the precision of the measuring method. After the multiple measurements of the elevation profiles of the fourteen pavement test sections, a SMRMI value was computed for each test section.

The SMRMI value is a computed output of a computer simulation of an MRM system including the vehicle and the MRM measuring instrument. The MRM vehicle parameters ("Golden Car") used in the computer simulation are those proposed in NCHRP Project 1-18 (*5*), which are being defined further in a new proposed ASTM standard. The inputs to the computer simulation are the elevation profile measurements

TABLE 1 INERTIAL PROFILOMETER MEASUREMENTS

Kentucky DOH Test Site No.	Number of Repeat Measurements	Standard Mean MRM Index Value (in/mi)	Standard Deviation (in/mi)
PCC			
101*	9	75.0	0.34
102	5	82.4	2.52
103	6	100.5	0.82
104*	5	103.0	0.57
105*	9	144.1	1.38
106	5	151.4	1.57
107	5	160.7	2.71
BC			
201	20	47.1	0.56
202*	5	49.4	0.45
203	5	63.3	0.42
204	6	57.5	1.04
205	5	83.5	0.93
216*	10	111.4	1.03
207*	6	133.9	1.38

made with the inertial profilometer. Using this computer simulation, the SMRMI value was computed for each of the multiple profile measurements. The computed mean SMRMI value and standard deviation for the multiple measurements for each of the fourteen Kentucky DOH test sites are shown in Table 1.

Although readings were taken every 0.1 mile, it was found that averaging readings over a longer test section improved the precision of SMRMI values computed from the profilometer measurements. It was determined that the precision of the measurements improved significantly as the length of the test section was increased from 0.1 mile to 0.5 mile and continued to improve as the test section length was increased to one mile. Where possible, all measurements were made over a test section length of one mile.

The asterisks beside the test site numbers in Table 1 indicate the final six test pavements selected for the calibration study. Three of those sites were constructed with portland cement and the other three with bituminous concrete pavement. These six pavement test sites were chosen because they represented a range of desired SMRMI values and because they exhibited low standard deviations. Although there is a wide range of standard deviations for each test site, it is important to note that the six calibration test pavements selected exhibited about a 1 percent maximum standard deviation.

Test site 201, a smooth bituminous concrete pavement, was the site where the precision or repeatability of the NBS-operated profilometer was evaluated in detail. Twenty test runs were conducted on this particular site. The results of twenty tests runs are shown in Figure 1 as a plot of the computed SMRMI value (inches/mile) for each of the twenty runs. The variation in the computed SMRMI values can be attributed to three factors:

- Variation in the profilometer's elevation profile measuring performance,
- Variation in the path driven by the profilometer driver, and
- Transverse variations in the elevation profile of the test site pavement.

It is suggested that a test site with little variation in computed SMRMI values (low standard deviation) would be a test site with little transverse variation in the elevation profile, and the computed SMRMI values would be less affected by the path driven by the profilometer driver.

The computed cumulative mean SMRMI value (inches/mile) is shown in Figure 2 as a function of the number of test runs included in the computation. As would be expected, the computed mean becomes more stable as the number of included tests runs increases. The computed standard deviation of the computed SMRMI values (inches/mile) as a function of the number of test runs is shown in Figure 3. Again, as would be expected, the standard deviation is reduced as the number of runs increases. Although some improvement is still occurring at test run twenty, the majority of the improvement has occurred by run ten and on the less variable sites, measuring stability appears possible with five test runs with the profilometer.

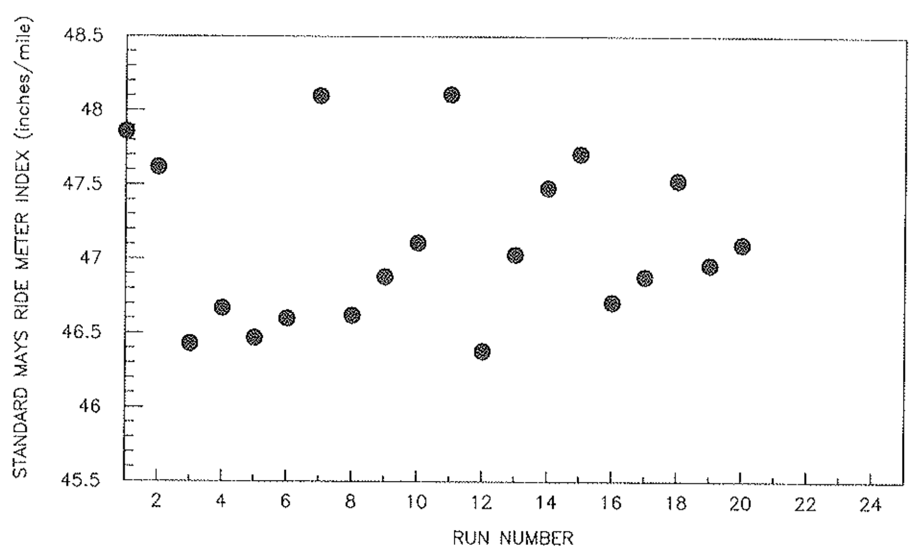

FIGURE 1 Computed standard MRM index value by run number.

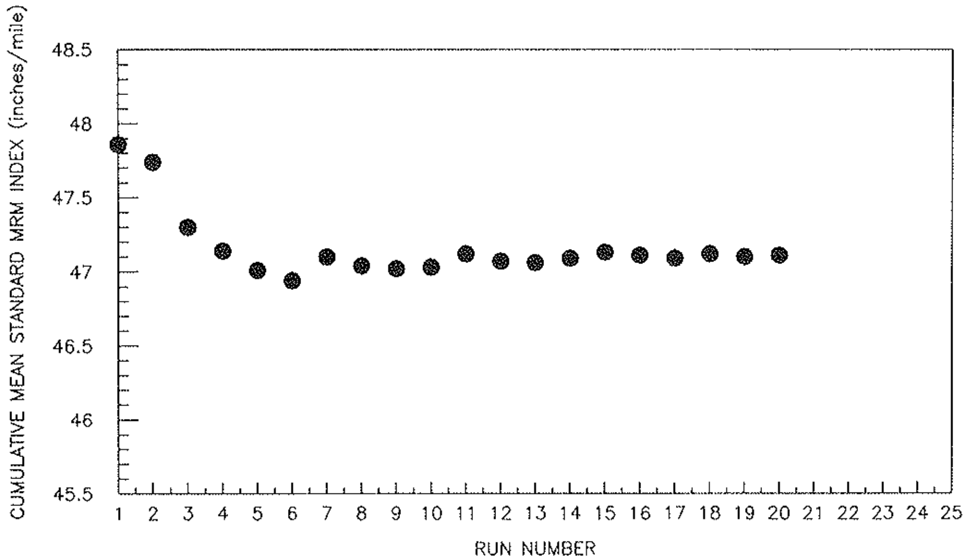

FIGURE 2 Computed mean standard MRM index value by run number.

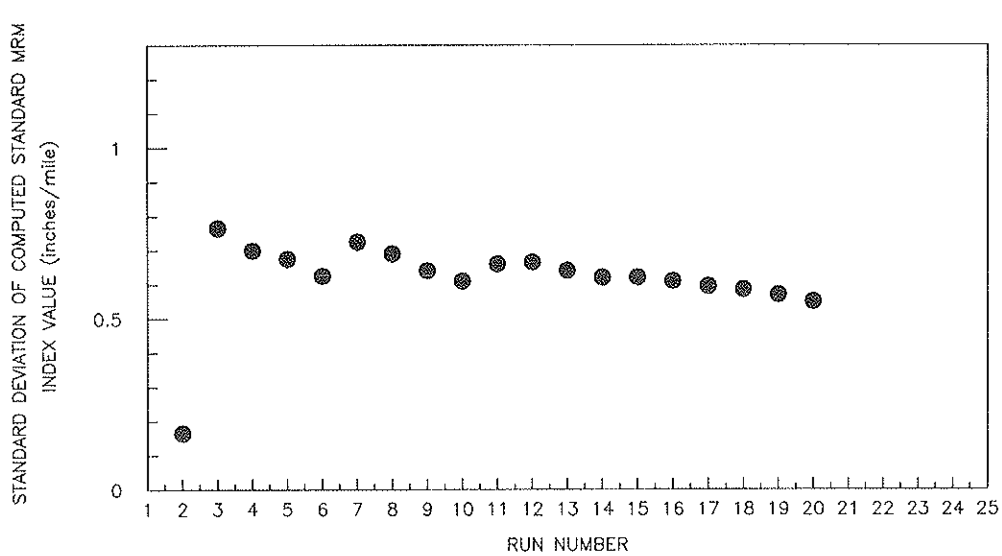

FIGURE 3 Standard deviation of the mean standard MRM index value by run number.

Simultaneous to measuring the Kentucky DOH test sites with the inertial profilometer, the five Kentucky DOH MRM vehicles were used to obtain MRM index values for each of the six test sites. Each of the test sites was measured at least ten times by each Kentucky DOH MRM system. The repeat measurements were made to compute a mean MRM index value and standard deviation about the mean for each MRM system for each test site. The computed mean MRM index value ($\bar{x}$) and standard deviation (σ) in inches/mile for each Kentucky DOH MRM system for each of the six Kentucky DOH test sites are shown in Table 2. Also shown in Table 2 are the computed SMRMI values (from Table 1) computed from elevation profile measured with the inertial profilometer.

The MRM index values in Table 2 show a wide range values for the different MRM vehicles. For example, Kentucky DOH vehicle 2678 had a mean MRM index value of 136.2 inches/mile on test site No. 105 while vehicle 3664 had a mean MRM index value of 184.8 inches/mile for the same site. Since the SMRMI value as established by the NBS inertial profilometer was 144.1 inches/mile, vehicle 2678 was measuring 5 percent too low, and vehicle 3664 was measuring 28 percent too high. The measurements shown in Table 2 clearly show the problem associated with using uncalibrated MRM measurements and emphasizes the need for good MRM calibration procedures.

The computed SMRMI values from the inertial profilometer were then used with the computed mean MRM index value for each Kentucky DOH MRM system to compute the least-squares best fit straight line relationship between the two data sets. This relationship is shown graphically in Figure 4 for Kentucky DOH MRM vehicle No. 2678. For the data set shown in Figure 4, we can compute the slope and y-

TABLE 2 MEAN MAYS RIDE METER INDEX VALUES FOR KENTUCKY DOH MRM SYSTEMS

Kentucky DOH Test Site No.	Standard* Mean MRM Index Value (in/mi)	Mean MRM Index Value ($\bar{x}$) and Standard Deviation (σ) by Kentucky DOH Vehicle No. 2678		3664		3665		4323		4325	
		$\bar{x}$	σ	$\bar{x}$	σ	$\bar{x}$	σ	$\bar{x}$	σ	$\bar{x}$	σ
PCC											
101	75.0	70.3	3.98	98.3	2.83	72.9	1.47	76.2	0.85	77.7	2.78
104	103.0	98.1	4.22	139.3	1.44	108.9	2.45	107.8	1.64	104.1	3.19
105	144.1	136.2	4.25	184.8	2.59	154.1	2.42	150.3	1.73	142.4	3.75
BC											
202	49.4	40.6	3.14	69.2	4.51	41.0	2.18	43.7	0.83	47.0	3.26
216	111.4	108.4	4.95	143.0	6.61	115.5	3.36	101.1	1.90	109.9	4.61
207	133.9	128.0	2.84	163.0	3.53	139.6	3.77	127.4	2.34	127.8	2.34
Average Std. Dev.			3.90		3.58		2.61		1.55		3.32

* Computed from Profilometer Measurements

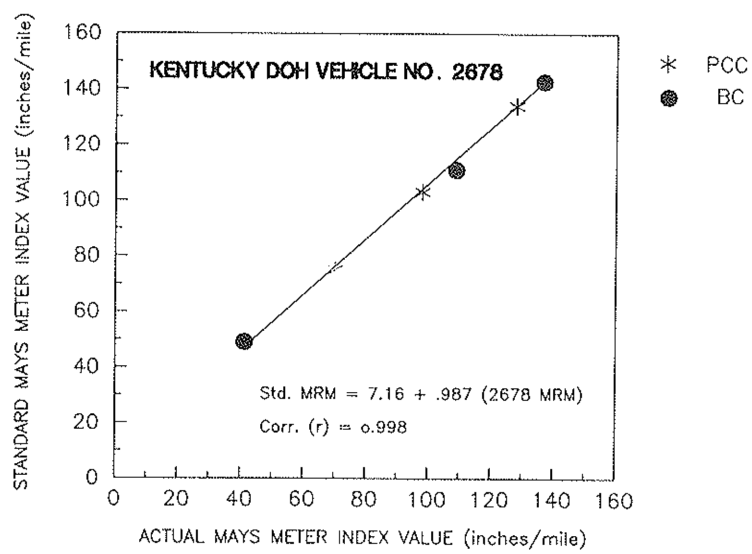

FIGURE 4 Calibration curve for Kentucky Mays Meter Vehicle No. 2678.

intercept for the least-squares best fit line through the data points. The computed line slope and y-intercept can then be used to develop a transform or calibration equation between the MRM Index values obtained with the Kentucky DOH MRM system and the SMRMI values computed from the inertial profilometer elevation profile measurements. The calibration equation and the data set correlation coefficient (r) for Kentucky DOH MRM vehicle No. 2678 are shown in Figure 4.

Calibration equations and correlation coefficients for Kentucky DOH MRM vehicles Number 3664, 3665, 4323, and 4325 were developed using the same procedure shown in Figure 4. The results for these four MRM systems are shown in Figures 5 through 8. The high correlation coefficients for the five Kentucky DOH MRM systems is an indication that the "Golden Car" computer model used to compute the SMRMI values is an accurate representation of the actual MRM systems. It is also an indication that the Kentucky DOH MRM systems are in good condition and are functioning as expected.

The calibration equations for each of the five Kentucky DOH MRM systems are summarized in Table 3. Also shown in Table 3 are the average standard deviation for each of the

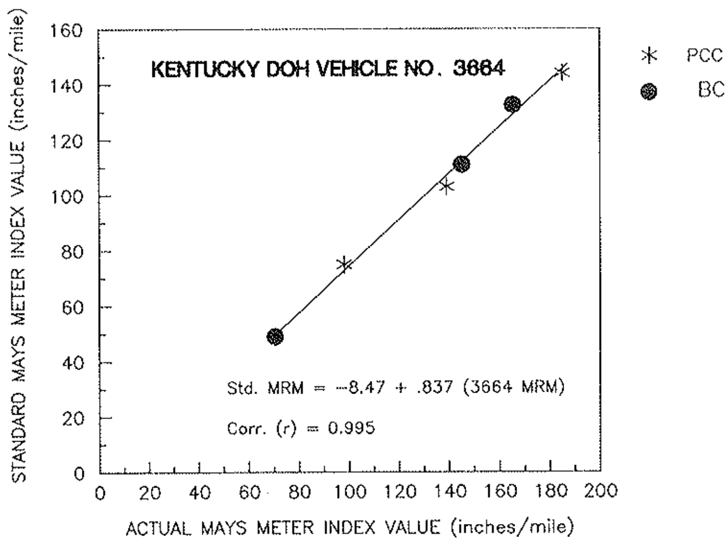

FIGURE 5 Calibration curve for Kentucky Mays Meter Vehicle No. 3664.

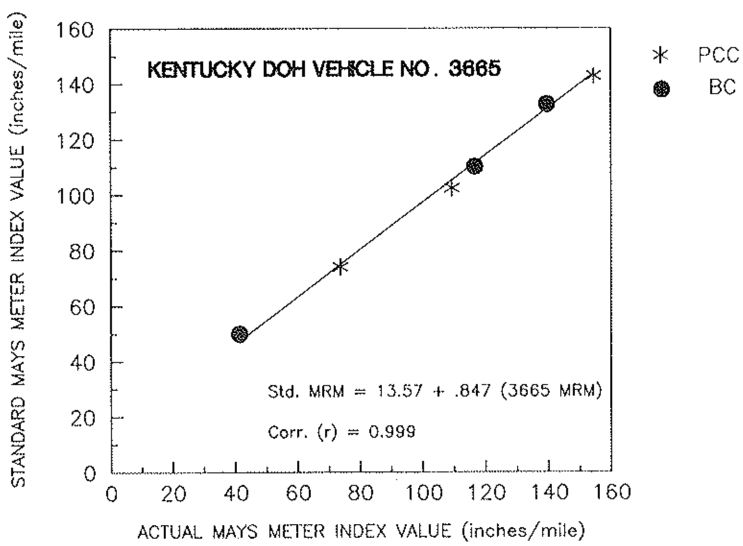

FIGURE 6 Calibration curve for Kentucky Mays Meter Vehicle No. 3665.

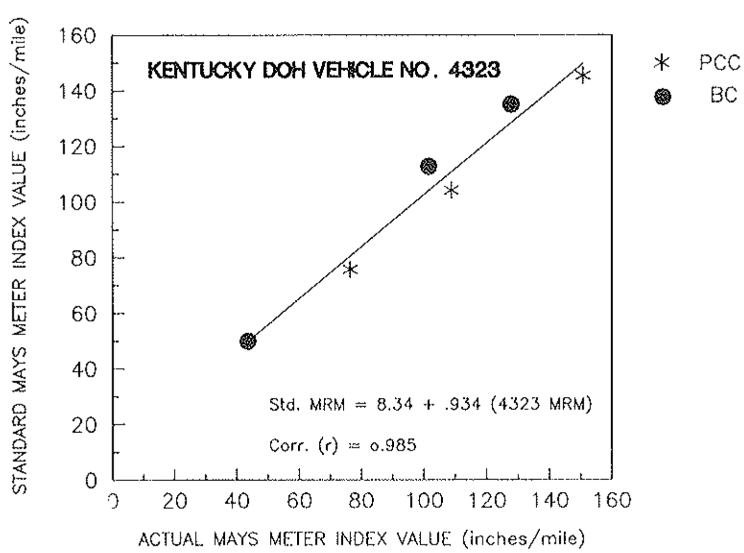

FIGURE 7 Calibration curve for Kentucky Mays Meter Vehicle No. 4323.

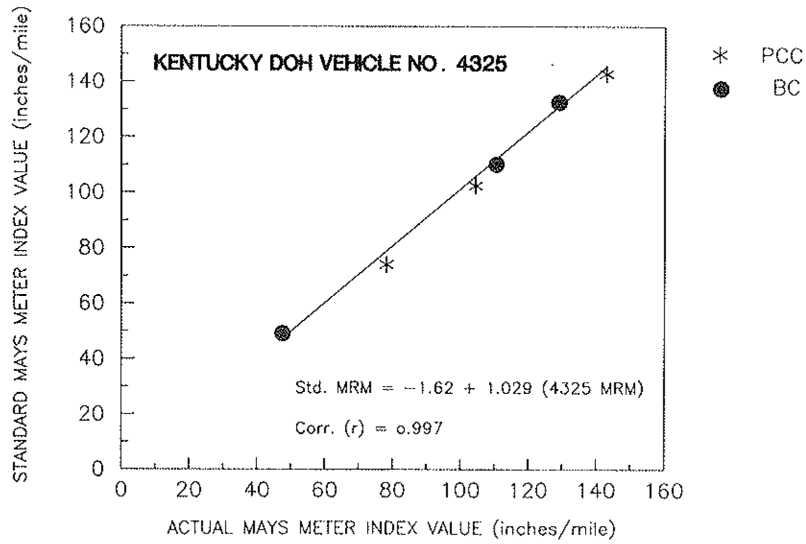

FIGURE 8 Calibration curve for Kentucky Mays Meter Vehicle No. 4325.

TABLE 3 CALIBRATION EQUATIONS FOR KENTUCKY DOH MAYS RIDE METER VEHICLES

Kentucky DOH MRM Vehicle No.	Calibration Equations
2678	Standard MRM = 7.16 + .987 (vehicle MRM) Average Std. Dev. = 3.90
3664	Standard MRM = −8.47 + .837 (vehicle MRM) Average Std. Dev. = 3.58
3665	Standard MRM = 13.57 + .847 (vehicle MRM) Average Std. Dev. = 2.61
4323	Standard MRM = 8.34 + .934 (vehicle MRM) Average Std. Dev. = 1.55
4325	Standard MRM = −1.62 = 1.029 (vehicle MRM) Average Std. Dev. = 3.32

five Kentucky DOH MRM systems (from Table 2). This average standard deviation is probably the best that might be expected for each system, since these values were computed for pavement test sites that were initially selected for their low standard deviations when measured with the inertial profilometer.

PROFILOMETER CORRELATION

Although the NBS-operated inertial profilometer was used to establish the SMRMI values for the Kentucky DOH calibration test sites, a second K. J. Law Engineers, Inc., inertial profilometer, owned and operated by the Ohio Department of Transportation, was used to measure and compute the SMRMI values for seven of the Kentucky DOH test sites used in the calibration project. This simultaneous measurement of seven test sites provided an excellent opportunity to compare the measuring performance of the two inertial profilometers manufactured by K. J. Law Engineers, Inc., and to determine if equivalent MRM calibrations can be obtained from two identical inertial profilometers.

The measuring results for the NBS and Ohio DOT profilometers are shown in Table 4 for the seven Kentucky DOH test sites. The SMRMI values for each profilometer are plotted in Figure 9 for each of the seven sites. Also shown in Figure 9 is the best fit straight line for the data point pairs, and the y-intercept, slope, and the correlation coefficient (r) for the best fit straight line. The high correlation coefficient of 0.99934 would support the interchangeable use of identical inertial profilometers for the calibration of MRM systems.

DISCUSSION

The calibration procedure developed in this project provides a method that can be used to convert MRM measurements

TABLE 4 COMPUTED STANDARD MAYS RIDE METER DATA

Kentucky DOH Test Site No.	NBS Profilometer Number of Runs	NBS Profilometer $\bar{x}$ in/mi	NBS Profilometer σ in/mi	Ohio DOT Profilometer Number of Runs	Ohio DOT Profilometer $\bar{x}$ in/mi	Ohio DOT Profilometer σ in/mi
PCC						
101	7	75.1	0.15	4	75.1	0.35
102	5	85.7	0.49	5	82.8	0.78
105	9	143.1	0.26	4	141.1	0.78
BC						
201	20	47.1	0.79	20	46.8	0.60
202	5	48.6	0.39	4	49.4	0.44
203	5	63.7	0.23	4	64.7	0.60
205	5	84.7	1.32	4	83.5	0.92

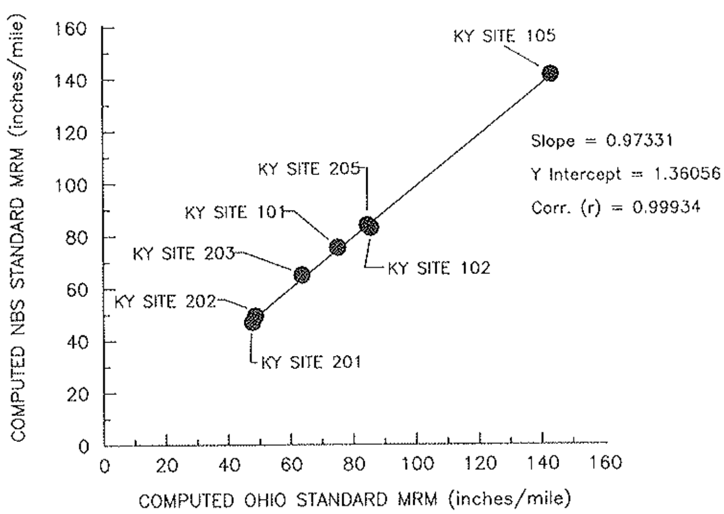

FIGURE 9 Correlation of identical inertial profilometers.

made with individual MRM systems into SMRMI values. The experiences gained in developing calibration procedure suggest the following recommendations related to the calibration and use of MRM systems, in particular, and to response-type ride meters, in general:

- Due to the higher standard deviation values for MRM systems compared to the profilometer, measurements should be made by averaging multiple repeat measurements for each test site. Ten repeat measurements would be desirable.
- One calibration site for each pavement type should be used periodically to confirm the calibration of individual MRM systems. The confirmation would consist of computing the standard mean MRM index value for ten repeat measurements at each site. A deviation from the expected SMRMI value would indicate a change in the system and the need for recalibration.
- A change in the measuring characteristics of an individual MRM system would indicate the need for a full calibration on all calibration sites. As in the original calibration, the mean of ten repeat measurements would be used with the SMRMI value to compute a new calibration equation and correlation coefficient.
- A reduction in the correlation coefficient computed in the recalibration process might be an indication that the SMRMI value for one or more of the established calibration test sites has changed. A significant reduction in the computed correlation coefficient would be an indication that the SMRMI values for the calibration test sites should be reestablished using an inertial profilometer.

Although it would be a significant task, it would be desirable to monitor the time stability of calibration sites with an inertial profilometer to develop a short-term (24-hour) and long-term (daily, monthly and annually) time history for each site. A research project in this area may be highly desirable.

CONCLUSION

- MRM systems can be effectively calibrated using an inertial profilometer.
- The observed variability between MRM systems supports the need for an accurate system calibration.
- Additional research is required to investigate the time stability of both the MRM systems and the pavement sections used in calibration.

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