

# Evaluation of Roughness System of Automatic Road Analyzer

JIAN LU, W. RONALD HUDSON, AND CARL BERTRAND

The automatic road analyzer (ARAN) is a multifunction road-quality surveying instrument. The roughness measuring system is one of the subsystems of the ARAN unit. To enhance the understanding of the response of this instrument (so as to apply it more efficiently to pavement management), a research study was conducted by the Center for Transportation Research, University of Texas at Austin, to comprehensively evaluate this instrument. The results of evaluating the roughness subsystem of the ARAN unit, including roughness correlation analysis and development of a new present serviceability index (PSI) model, are presented. In the correlation analysis, roughness data were collected in Texas by the ARAN unit and the Texas Department of Transportation modified K. J. Law profilometer that was used as a standard reference. The evaluated roughness statistics of the ARAN unit were root mean square vertical acceleration (RMSVA), mean absolute slope (MAS), and TEXTURE. These roughness statistics were correlated with the roughness statistics of the profilometer Maysmeter output, serviceability index (SI), and international roughness index. The PSI model developed in this study is based on the roughness statistic SI of the modified K. J. Law profilometer. This PSI model, including RMSVA and MAS that are independent variables, shows good correlation with SI of the profilometer.

Research leading to the development of roughness measuring equipment dates back more than 60 years (1). As a result of the AASHO Road Test in particular, increasing attention has focused on this research area, leading to the development of many types of pavement roughness surveying instruments. Gradually the use of these instruments to evaluate the ride quality of pavement surface grew more widespread such that now the evaluation of the relative smoothness of pavement surfaces has become an important factor affecting decisions about maintenance and the classification of pavement inventories.

Existing pavement roughness instruments generally can be divided into three classes, with each class defined by measurement techniques and the associated measurement errors (2,3).

Class 1. Manually operated instruments that accurately measure short wavelength profiles of the roads. Examples of such instruments include the rod and level, the face dipstick, and the TRRL beam.

Class 2. Dynamic direct profiling instruments that employ a variety of methods to produce elevation data from the road surface. Examples of these instruments include the APL trailer, GM profilometer, K. J. Law profilometer, and South Dakota profiler.

Class 3. Response-type road roughness measuring (RTRRM) systems, which accumulate suspension deflections (axle to body

or acceleration values) from the roadway surfaces. Examples of these instruments include the Mays ride meter, Cox meter, BPR roughmeter, and the automatic road analyzer (ARAN) unit.

The basic concept of the Class 1 and Class 2 categories is the measurement of the shorter wavelengths contained in the pavement surface profiles. These categories and the associated instruments possess the highest resolutions and the least acceptable error associated with their operation.

The pavement surface ride quality can be directly related to the passenger's perception of the vehicle's vibrations in a certain frequency band rather than the absolute surface profiles. The passengers are more sensitive to the vertical acceleration of the vehicle body caused by the transfer of pavement surface smoothness through the suspension system of the vehicle than to the elevation of the pavement surface. This is the basic concept behind the instruments contained in Class 3.

The ARAN unit is classified as a Class 3 instrument. The vertical accelerations of the body and the axle of the unit are sampled and processed to produce the roughness indexes: root mean square vertical acceleration (RMSVA), mean absolute slope (MAS), and TEXTURE. Relatively speaking, the smaller the values of the reported roughness indexes, the better the corresponding pavement surface ride quality. In addition to the three indexes, the Texas Department of Transportation (DOT) is interested in also obtaining the serviceability index (SI), which is another roughness index. This roughness index can be obtained through a regression model with the variables RMSVA and MAS. The concept behind the SI is the same as that of the present serviceability index (PSI) (4).

The multiple functioning and high operating speed of the ARAN unit commend it as an important instrument in pavement management. In addition, a comprehensive evaluation of this unit, as provided in this study, will benefit the Texas DOT in the following ways:

1. The results of the research will provide useful information about the ARAN unit with respect to the performance of the subsystems.
2. The models developed and implemented for the ARAN unit will render it a more powerful instrument; moreover, the methodologies of the modeling and evaluation can be used for future application on other instruments of this type.

This paper presents the results of evaluating the correlation between the roughness statistics from the ARAN unit and the roughness statistics generated by the Texas DOT modified K. J. Law profilometer. The reference statistics from the profilometer are SI (5), Maysmeter output (MO) (5,6), and international roughness index (IRI) (7). The model providing RMSVA at various wave-

J. Lu, Transportation Research Center, University of Alaska Fairbanks, P.O. Box 755900, Fairbanks, Alaska 99775-5900. W. R. Hudson, Department of Civil Engineering, University of Texas at Austin, Austin, Tex. 78712-1001. C. Bertrand, Texas Department of Transportation, D-18, 125 East 11th Street, Austin, Tex. 78701.

lengths from the profilometer is also available. However, MO and SI are functions of RMSVA at the 4- and 16-ft wavelengths (6). It was considered unnecessary to use these three roughness statistics together for the correlation analysis. In this research effort, the researchers chose SI and MO, instead of RMSVA. As another research effort, a new present service ability index (PSI) model is presented that includes the independent variables RMSVA and MAS and is based on the roughness statistic SI of the K. J. Law profilometer.

## DESCRIPTION OF ROUGHNESS SYSTEM OF ARAN UNIT

The ARAN unit is a van-mounted system that measures and records a wide variety of pavement performance parameters. The entire system is mounted inside a 1986 Ford 1-ton van with a modified motorhome chassis to facilitate its operation; enlarged windows enhance operator observation, while a raised roof provides more space for equipment. As a multifunction system, the ARAN unit is equipped with the following subsystems (8):

1. Pavement surface roughness measurement,
2. Rut depth and transverse profile measurement,
3. Gyro,
4. Right-of-way videologging,
5. Pavement condition videologging, and
6. Pavement rating.

The individual subsystems have specialized functions. Detailed description and evaluation results of these subsystems can be found elsewhere (9,10).

The roughness measuring subsystem block diagram is shown in Figure 1. This two-part subsystem is divided according to its hardware or its software. The hardware consists of axle and body accelerometers, analog signal amplifiers, analog low-pass filters, and a 12-bit analog to digital (A/D) converter. The software consists of digital band-pass filters passing wavelengths of 1 to 300 ft, digital high-pass filters passing wavelengths of 2 ft or less, and statistical models generating the reported roughness statistics (RMSVA, MAS, and TEXTURE). These roughness statistics are described as follows. RMSVA is defined by

$$\text{RMSVA} = \sqrt{\frac{1}{N} \sum_{i=1}^N [a(i)]^2}$$

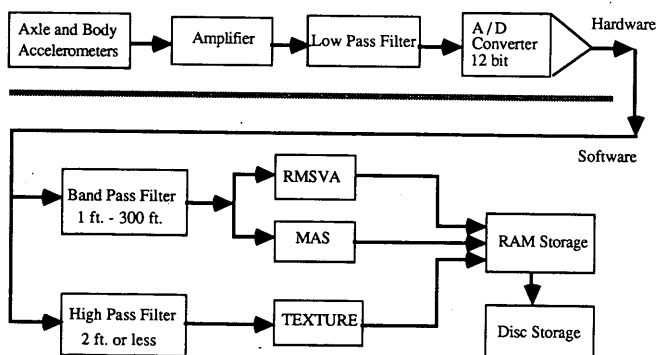


FIGURE 1 Roughness measuring subsystem.

where

$a(i)$  =  $i$ th discrete value of filtered acceleration that must be spatially filtered to remove any dc bias;

$N$  = number of samples taken in the given pavement section; and

MAS = cumulative value of the absolute vertical axle or body displacement divided by the vehicle's traveled distance. Mathematically,

$$\text{MAS} = \frac{1}{2N} \left( \frac{T}{L} \right)^2 (\Delta X) \sum_{i=1}^N |Z(i)|$$

where

$T$  = elapsed time in a test section (station) (sec);

$L$  = station length (mi);

$\Delta X$  = sample interval of raw acceleration values; and

$Z(i)$  = height calculated by double integrating with this equation; thus  $Z(i) = Z(i-1) + a(i) + a(i-1)$ .

The acceleration signal, once it passes through an A/D converter, follows one of two signal paths. One signal path is through the high-pass filter, whereas the other is through the band-pass filter. The output of the high-pass filter allows more high-frequency (short wavelength) components of the input signal to pass, in the process eliminating the low-frequency signal (long wavelength) components. The high-frequency components of acceleration signal represent the detailed characteristics of surface roughness, such as texturing and cracking. The output signals of the high-pass filter go through the same mathematical model used to calculate RMSVA. The result of the model is TEXTURE.

## FIELD DATA COLLECTION

Because most of the evaluation and modeling in this research effort were based on field testing and data collection, these activities were necessarily assigned a higher priority. In this study the ARAN unit had to be considered a "black box," that is, its performance had to be judged by its response (output) to a known input. The known input for the evaluation of correlation of the roughness subsystem was the Texas DOT modified K. J. Law profilometer—an instrument whose output had been verified using FHWA HPMS Appendix J procedures (2,11).

To obtain reliable correlation for the ARAN unit, 29 test sections were chosen for the field tests. With the exception of three rigid pavement sites, test sites were located in the Austin, Texas, area. Because no rigid pavements were accessible near Austin, three rigid pavement test sections near LaGrange, Texas, were chosen. The data collected from the flexible and the rigid pavements were combined without consideration of the type of pavement in the study.

The Texas DOT-modified K. J. Law profilometer, defined as a Class 2 pavement roughness monitoring instrument, was chosen as the standard reference instrument for correlation with the ARAN unit. From the standpoint of correlation analysis, it is better to correlate a Class 3 instrument with a Class 1 or Class 2 instrument. Class 1 and 2 instruments directly reflect the surface characteristics of a pavement, whereas Class 3 instruments reflect the response of a vehicle to, or the perception of the vehicle passengers of, the pavement surface roughness.

**TABLE 1** Summary of Correlation Analysis of Roughness Statistics for ARAN Versus the Profilometer

		Profilometer					
		SI		MO (counts/.2mi.)		IRI (in./mi.)	
		20 mph	50 mph	20 mph	50 mph	20 mph	50 mph
ARAN - RMSVA (MG)	30mph	A=4.9065 B=-7.0212E-3 R <sup>2</sup> =0.521 RMSE=0.763	A=4.9190 B=-7.3044E-3 R <sup>2</sup> =0.514 RMSE=0.778	A=4.8636 B=0.36917 R <sup>2</sup> =0.461 RMSE=43.64	A=6.5906 B=0.39226 R <sup>2</sup> =0.436 RMSE=48.76	A=18.688 B=0.53548 R <sup>2</sup> =0.504 RMSE=58.13	A=19.625 B=0.56516 R <sup>2</sup> =0.455 RMSE=67.72
	40mph	A=5.1249 B=-5.5126E-3 R <sup>2</sup> =0.577 RMSE=0.692	A=5.1435 B=-5.7276E-3 R <sup>2</sup> =0.568 RMSE=0.733	A=-18.579 B=0.29593 R <sup>2</sup> =0.533 RMSE=40.64	A=-21.563 B=0.31553 R <sup>2</sup> =0.508 RMSE=45.58	A=-1.3517 B=0.42964 R <sup>2</sup> =0.583 RMSE=53.30	A=-2.8514 B=0.45707 R <sup>2</sup> =0.534 RMSE=62.57
	50mph	A=5.2972 B=-4.7422E-3 R <sup>2</sup> =0.669 RMSE=0.612	A=5.3222 B=-4.9264E-3 R <sup>2</sup> =0.657 RMSE=0.653	A=-30.730 B=0.26084 R <sup>2</sup> =0.648 RMSE=35.27	A=-35.607 B=0.28046 R <sup>2</sup> =0.628 RMSE=39.62	A=-17.375 B=0.37520 R <sup>2</sup> =0.696 RMSE=45.50	A=-21.563 B=0.40275 R <sup>2</sup> =0.650 RMSE=54.27
ARAN - MAS (Slope*1000)	30mph	A=5.4152 B=-0.94085 R <sup>2</sup> =0.900 RMSE=0.337	A=5.4761 B=-0.99013 R <sup>2</sup> =0.907 RMSE=0.339	A=-42.140 B=53.749 R <sup>2</sup> =0.940 RMSE=14.52	A=-50.653 B=58.922 R <sup>2</sup> =0.947 RMSE=14.95	A=-27.190 B=74.634 R <sup>2</sup> =0.941 RMSE=20.23	A=-39.584 B=83.156 R <sup>2</sup> =0.946 RMSE=21.23
	40mph	A=5.3098 B=-0.93483 R <sup>2</sup> =0.891 RMSE=0.351	A=5.3698 B=-0.98577 R <sup>2</sup> =0.902 RMSE=0.349	A=-35.778 B=53.261 R <sup>2</sup> =0.926 RMSE=16.16	A=-44.199 B=58.607 R <sup>2</sup> =0.940 RMSE=15.94	A=-18.783 B=74.136 R <sup>2</sup> =0.931 RMSE=21.61	A=-30.764 B=82.833 R <sup>2</sup> =0.942 RMSE=22.10
	50mph	A=5.2116 B=-0.91685 R <sup>2</sup> =0.886 RMSE=0.360	A=5.2686 B=-0.96777 R <sup>2</sup> =0.899 RMSE=0.355	A=-30.299 B=52.285 R <sup>2</sup> =0.922 RMSE=16.58	A=-38.338 B=57.606 R <sup>2</sup> =0.938 RMSE=16.16	A=-10.882 B=72.659 R <sup>2</sup> =0.924 RMSE=22.69	A=-22.322 B=81.351 R <sup>2</sup> =0.939 RMSE=22.70
ARAN - TEXTURE (MG)	30mph	A=4.5438 B=-1.5897E-2 R <sup>2</sup> =0.451 RMSE=0.788	A=4.5362 B=-1.6478E-2 R <sup>2</sup> =0.442 RMSE=0.833	A=13.589 B=0.84265 R <sup>2</sup> =0.406 RMSE=45.83	A=12.638 B=0.89953 R <sup>2</sup> =0.388 RMSE=50.82	A=44.024 B=1.2380 R <sup>2</sup> =0.455 RMSE=60.93	A=46.320 B=1.3071 R <sup>2</sup> =0.411 RMSE=70.38
	40mph	A=4.6382 B=-1.4275E-2 R <sup>2</sup> =0.478 RMSE=0.769	A=4.6233 B=-1.4697E-2 R <sup>2</sup> =0.462 RMSE=0.818	A=7.2714 B=0.76888 R <sup>2</sup> =0.444 RMSE=44.33	A=6.2754 B=0.81724 R <sup>2</sup> =0.421 RMSE=49.44	A=34.423 B=1.1326 R <sup>2</sup> =0.500 RMSE=58.34	A=35.684 B=1.2005 R <sup>2</sup> =0.455 RMSE=67.68
	50mph	A=4.6590 B=-1.0636E-2 R <sup>2</sup> =0.448 RMSE=0.791	A=4.6434 B=-1.0942E-2 R <sup>2</sup> =0.432 RMSE=0.841	A=6.2946 B=0.57190 R <sup>2</sup> =0.415 RMSE=45.49	A=5.0451 B=0.60918 R <sup>2</sup> =0.394 RMSE=50.55	A=32.773 B=0.84387 R <sup>2</sup> =0.469 RMSE=60.16	A=34.498 B=0.89060 R <sup>2</sup> =0.432 RMSE=69.66

Model: Index (Prof.) = A + B Index (ARAN)

To evaluate the effect of the operational speed on the reported roughness statistics, different testing speeds were used. Because the response of the ARAN unit with respect to speed could be nonlinear, more than two different testing speeds had to be considered. Thus three testing speeds—30, 40, and 50 mph—were selected for use in this evaluation effort.

Three different groups of test sections were chosen to provide a range of surface roughness. These test groups include pavements with smooth surfaces (PSI = 3.5 to 5.0), pavements with medium smooth surfaces (PSI = 2.0 to 3.5), and pavements with rough surfaces (PSI = 0 to 2.0). The relative smoothness of these sections was ranked on the basis of the profilometer's output. The test sections chosen covered a full range of pavement conditions in terms of PSI. In addition, for each combination of the above factors, three runs were made.

		Profilometer	
		20 mph	50 mph
ARAN	30 mph	Model 1	Model 2
	40 mph	Model 3	Model 4
	50 mph	Model 5	Model 6

**FIGURE 2** PSI modeling factorial.

## ROUGHNESS CORRELATION ANALYSIS

From the standpoint of instrumentation, three factors—repeatability, correlativity, and accuracy—indicate the performance of an instrument. The repeatability of an instrument can be evaluated by observing outputs on repeated runs on the same pavement surface, whereas the evaluation of an instrument's correlativity and accuracy must be quantified by using a standard instrument such as that described previously (12). The roughness measuring subsystem of the ARAN unit, classified as a response-type road roughness measuring system, provides the statistics—RMSVA, MAS, and TEXTURE—as described earlier. The accuracy of these statistics could not be evaluated directly because the researchers did not have access to a reference instrument that provides the same roughness statistics as the ARAN unit. Accordingly, the measurement accuracy of the roughness statistics is not considered in this evaluation of the ARAN roughness subsystem. Instead, a calibration model was developed through correlation analysis with the profilometer.

### Choice of Reference

The profilometer must meet two basic requirements before it can be used as a reference instrument for correlation. The output statistics of the reference should be based on the results of an objective measurement and should not be vehicle dependent. If the reference instrument is vehicle independent, the models for correlation and calibration are stable in terms of time and the vehicle suspension system.

Two alternative approaches are available for developing the roughness statistics used in the correlation analysis and calibration of the roughness measuring subsystem of the ARAN unit. The first one is a dynamic modeling of a hypothetical device simulating the dynamic response of a vehicle with certain physical constants predefined. The dynamic model must have a sequence of pavement surface profiles used as the input. For example, a typical hypothetical device, called the reference quarter-car simulation (RQCS) (7), has been used as a standard reference for correlation and calibration. The corresponding statistical output of the RQCS, the quarter-car index (QI), was used for Maysmeter calibration in Brazil (7). Using RQCS makes it necessary to input the sequences of profile elevation measured by either a Class 1 or Class 2 in-

**TABLE 3 Values of Correlation Between New PSI Including TEXTURE (ARAN) and SI (Profilometer)**

		Profilometer	
		20 mph	50 mph
ARAN	30 mph	0.904	0.915
	40 mph	0.896	0.907
	50 mph	0.895	0.904

strument to the simulating model to develop a standard statistical output. This indirect procedure for obtaining reference standard statistical output is relatively complicated. The second approach uses the Class 2 profilometric method, directly developing roughness statistics from the relatively accurate measurement of the pavement surface elevations. This method, which measures the profile elevations and directly transfers elevations into roughness statistics, is comparatively simple, with the resulting roughness statistics relatively vehicle independent.

The modified K. J. Law profilometer provided by Texas DOT for the purpose of making comparisons in this test has been chosen as the reference for the correlation analysis and calibration of the ARAN unit's roughness subsystem. The selection of this instrument was based on the following:

1. The modified K. J. Law profilometer is classified as a Class 2 pavement surface ride quality surveying instrument (5). This instrument automatically measures the pavement profile elevations at high operating speed with good accuracy and repeatability.
2. The profilometer is equipped with the software to compute the roughness statistics, RMSVA, SI, MO, and IRI. These statistics have been carefully evaluated (5) and are widely used in pavement surface ride quality surveys.
3. Because the profilometer belongs to Texas DOT, it was accessible for this evaluation effort.

### Roughness Statistics of Modified K. J. Law Profilometer

The modified K. J. Law profilometer develops the roughness statistics SI, MO, and IRI. These statistics, which summarize the pavement roughness characteristics from different approaches, are relatively vehicle independent in principle because they are obtained through the processing of the raw profile elevations sequences. An explanation of each of these statistics follows:

#### Maysmeter Output

As explained previously (5) MO is the calibrated Maysmeter output value given in counts per 0.2 mi. This Maysmeter estimate is developed using the RMSVA values calculated for the 4- and 16-ft base wavelengths from profilometer, using the following equation.

**TABLE 2 Resulting Models of Equation 6 from Figure 2**

Model	Coefficients				R <sup>2</sup> Value
	A	B	C	D	
1	5.4898	-0.001007	-0.873430	0.000206	0.904
2	5.5465	-0.001126	-0.930580	0.000801	0.915
3	5.4323	-0.001702	-0.855272	0.002919	0.896
4	5.4979	-0.002143	-0.917207	0.004613	0.907
5	5.3507	-0.000795	-0.795375	-0.000344	0.895
6	5.3837	-0.000722	-0.865102	-0.000118	0.904

$$MO = A_1 + A_2 \text{ RMSVA}_4 + A_3 \text{ RMSVA}_{16} \quad (1)$$

where  $\text{RMSVA}_4$  and  $\text{RMSVA}_{16}$  are the RMSVA values of the profilometer for the 4- and 16-ft base wavelengths, respectively. The constants  $A_1$ ,  $A_2$ , and  $A_3$  are different for various types of pavement (rigid or flexible).

### Serviceability Index

The measure of riding quality with which engineers are most familiar is the SI. Representing the user's perception of pavement roughness, SI is given as a number between 0 and 5. Such unitless index can be developed on the basis of MO or RMSVA. The model for calculating SI in the profilometer (6) is

$$SI = 5 e^{-\left(\frac{\ln(32 \text{ MO})}{8.4933}\right)^{9.3566}} \quad (2)$$

where MO is calculated by Equation 1. The index SI is a measure of roughness primarily in the 8- to 35-ft wavelength range.

### International Roughness Index

IRI (7) is a well-known measure of roughness. IRI is reported in inches per mile, as measured with a Class 1 or Class 2 instrument or as computed with a quarter-car simulation. IRI values from the profilometer are calculated from the profiles for both the left wheelpath and the right wheelpath. The reported IRI is the mean value of the left wheelpath IRI and the right wheelpath IRI.

### Field Tests

To obtain the correlation and calibration models for the roughness measuring subsystem of the ARAN unit, 29 test sections were selected. These sections consisted of both rigid and flexible pavements and were evaluated with both the modified K. J. Law profilometer and the ARAN unit. The models developed for this research are based on the combined data collected from both the flexible and the rigid pavement test sections. The test sites were selected because they could provide the broadest range of roughness levels and could be safely run at the 50-mph test speed. The smooth sites were needed to ensure that the subsystem had the resolution necessary to correctly measure smooth pavements,

TABLE 4 Values of Correlation Between Original SI (ARAN) and SI (Profilometer)

		Profilometer	
		20 mph	50 mph
ARAN	30 mph	0.903	0.908
	40 mph	0.890	0.897
	50 mph	0.894	0.901

TABLE 5 Correlations Between New PSI Using TEXTURE and SI from Profilometer

Model	Coefficients		
	a	b	R <sup>2</sup> Value
1	-3.1604e-4	1.0001	0.904
2	-3.8273e-2	1.0115	0.915
3	-1.5422e-5	1.0000	0.896
4	-1.5556e-5	1.0000	0.907
5	-1.9383e-4	1.0000	0.895
6	3.6650e-4	0.99994	0.904

whereas the rough sites ensured that the subsystem could handle the large amplitudes generated when traveling down rough pavement. The medium sections allowed data points to be located between the two extremes. This wide roughness distribution makes the correlation analysis results suitable across the wide roughness levels that are normally found in the Texas highway network.

Three repeat runs were made for each test section, testing speed, and both K. J. Law profilometer and the ARAN unit. The mean values of the reported roughness statistics were calculated and used as the summarized statistic. This was done to cancel the operational bias. The ARAN unit is designed for operation in the normal traffic speed range. The field tests were conducted at speeds of 30, 40, and 50 mph for each test section. The most frequently used operational speeds of the K. J. Law profilometer are 20 and 50 mph. Therefore, each test section was run at the testing speed of 20 and 50 mph for the K. J. Law profilometer.

### Results

The linear correlation model proposed for the research evaluation effort is

$$\text{Roughness (profilometer)} = A + B \text{ roughness (ARAN)} \quad (3)$$

where  $A$  and  $B$  are constants, and Roughness (profilometer) is the estimation of the roughness statistic corresponding to one of the profilometer outputs: SI, MO, or IRI. Roughness (ARAN) is the roughness statistic (RMSVA, MAS, TEXTURE) measured and generated by the ARAN unit. Two statistical indexes showing the correlativity of the two instruments are used. One is the  $R^2$  value and the other is the root mean square error (RMSE) defined by

$$\text{RMSE} = \sqrt{\frac{1}{N} \sum_{i=1}^N (x_i - y_i)^2} \quad (4)$$

where

$N$  = number of test sections ( $N = 29$ );

$x_i$  = estimation of the roughness statistic of the profilometer at  $i$ th test section; and

$y_i$  is the roughness statistic measured by the ARAN unit and generated by Equation 3 at  $i$ th test section. The comprehensive correlation analysis results with different operational speeds are shown in Table 1. From this table, it can be said that MAS has relatively good correlation with the roughness statistics of the K. J. Law profilometer. Research results also show that the roughness statistics of the ARAN unit are speed dependent; that is, the reporting statistics on the same road surface will be different if the operational speed differs. Models used to cancel speed effect were developed in the same research project but not reported in this paper. Detailed analysis and models regarding speed effect were reported previously (9,13).

### PRESENT SERVICEABILITY INDEX MODEL FOR ARAN

HPI, the manufacturer of the ARAN unit, provided an SI model to the Texas DOT. This SI model has the following form:

$$SI = 5.6797 - 0.00134 \text{ RMSVA} - 0.7553 \text{ MAS} \quad (5)$$

Because the modified K. J. Law profilometer is considered by the Texas DOT to be the reference instrument for calibration of all of its roughness monitoring equipment, it is necessary that the SI model obtained from the ARAN unit be directly calibrated to the SI from the profilometer. In addition it can be expected that the operational speeds of the ARAN unit significantly affect its roughness statistics. The model estimating SI values should be used for a given operational speed. Because of these disadvantages a new PSI model, including TEXTURE, was proposed by research staff. This new model is

$$PSI = A + B \text{ RMSVA} + C \text{ MAS} + D \text{ TEXTURE} \quad (6)$$

where  $A$ ,  $B$ ,  $C$ , and  $D$  are constant coefficients. These constant coefficients were obtained through a linear regression analysis of the ARAN unit's roughness output and that of the modified K. J. Law profilometer. Therefore, the PSI value resulting from this model is an estimate of the PSI values corresponding to the profilometer. According to the definitions of RMSVA, MAS, and TEXTURE, these variables are independent of each other. Con-

ceptually, the more independent variables the model includes, the better the model will be.

As another alternative, a model that excludes the TEXTURE statistic was also generated. The model has the following form:

$$PSI = A + B \text{ RMSVA} + C \text{ MAS} \quad (7)$$

This new PSI model has the same form as the original SI model. The new model has the advantage of being obtained through the regression analysis of the ARAN unit and the modified K. J. Law profilometer. The data were collected in Texas.

### New PSI Model Including TEXTURE

The factorial used in the modeling of the new PSI is shown in Figure 2. A FORTRAN program (MULT REGRESSION) developed by research staff was used to process the data collected from field tests. The resulting models correspond to the regression models seen in Figure 2.

Table 2 shows the linear correlation results representing the models shown in Figure 2. The  $R^2$  values of the linear fits are also included in the table.

The sensitivities of PSI to each roughness statistic can be compared in terms of the absolute value level of each coefficient. In the resulting models, the absolute value level of Coefficient  $C$  is much higher than that of either  $B$  or  $D$ . Coefficients  $B$  and  $D$  are at the same relative level. Because Coefficient  $C$  was defined for MAS it can be said that PSI is more sensitive to MAS than to either RMSVA or TEXTURE. In fact, from the correlation analysis results, the  $R^2$  values for MAS are much higher than those for either RMSVA or TEXTURE. This means that the correlation of MAS with the profilometer SI is better than that of RMSVA or TEXTURE.

Greater RMSVA or MAS values for the ARAN unit represent poorer serviceability or smaller PSI values. Mathematically, this relationship requires that the signs of Coefficients  $B$  and  $C$  be negative. Because TEXTURE reflects only the detail (short wavelength) characteristics of a pavement surface, it does not have an obvious direct relationship with PSI. Therefore, the sign of the coefficient of TEXTURE could be either positive or negative. From the resulting models shown in Table 2 it can be seen that the signs for Coefficients  $B$  and  $C$  are negative. Coefficient  $D$  is both positive and negative.

A comparison can be made between the new PSI model including TEXTURE and the original SI equation by considering the  $R^2$  values resulting from the correlation analysis. The  $R^2$  values resulting from the new PSI model are listed in Table 3 and correspond to the factorial shown in Figure 2. The  $R^2$  values of the correlation between original SI for the ARAN unit and SI from the profilometer are shown in Table 4. All of the  $R^2$  values from the new PSI model are greater than those from the original SI equation. It can be concluded that the new PSI equation fits the profilometer output better than the original SI equation.

The correlations of the new PSI equation using TEXTURE from the ARAN unit and SI from the profilometer at different speeds are presented in Table 5. The equation for those correlations is

$$SI (\text{profilometer}) = a + b \text{ PSI(ARAN)} \quad (8)$$

TABLE 6 Models from Equation 7 and Figure 2

Model	Coefficients			$R^2$ Value
	A	B	C	
1	5.4879	-0.000924	-0.873794	0.904
2	5.5391	-0.000801	-0.931996	0.916
3	5.3875	-0.000647	-0.867200	0.894
4	5.4269	-0.000475	-0.936057	0.904
5	5.3546	-0.000951	-0.787525	0.895
6	5.3850	-0.000775	-0.862404	0.904

From these figures and the resulting linear equations, it can be seen that

$$a \approx 0, b \approx 1$$

Therefore, the six new PSI models, including TEXTURE, that correspond to the various speeds of operations can be used effectively to estimate the SI values from the profilometer.

### New PSI Model Excluding TEXTURE

The second set of PSI equations does not include TEXTURE. These equations have the same form as the PSI model shown in Equation 7. The factorial equations that omit TEXTURE are the same as those that include TEXTURE (Figure 2).

Table 6 represents the coefficients from the new PSI equations excluding TEXTURE, which have the form of Equation 7. The program MULT REGRESSION was again used with the data from the test sections.

As shown in Table 6 and discussed in the previous section, the second new PSI equation excluding TEXTURE has the same sign and sensitivity qualities as does the equation including TEXTURE. It can also be seen that the new PSI equations excluding TEXTURE are not significantly different from the ones that include TEXTURE. In this case, it is reasonable to use the equations without TEXTURE because they are similar and just as valid.

### CONCLUSIONS

The correlation analysis compared the Texas DOT ARAN unit and the modified K. J. Law profilometer with the results showing good correlation between the outputs of these two instruments. However, because the correlation models developed are speed dependent, the correlation models must be used for a given operational speed if no speed-effect-canceling model is implemented. It is recommended that MAS be used to estimate the roughness outputs corresponding to the profilometer. Unfortunately, RMSVA and TEXTURE do not correlate well with any of the profilometer's outputs.

Two PSI models, developed as a result of this research effort, are reported in this paper: (a) the model including the roughness output TEXTURE, and (b) the model excluding TEXTURE. The test results demonstrated that the new PSI models developed are better than the original SI model. The new PSI model excluding TEXTURE has been implemented with the personal computer program presented previously (9).

The operational speed of the ARAN unit has a significant impact on its roughness outputs. The impact of the operational speed on the roughness outputs also depends on the roughness level of

the pavement surface being evaluated. With respect to the operational speed, it was found that RMSVA and TEXTURE are more sensitive than MAS (9,13).

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