Abridgment

Road Profile Evaluation for Compatible Pavement Evaluation

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An important application of the Surface Dynamics profilometer is to provide a stable calibration reference for response-type road roughness measuring (RTRRM) instruments. The latter devices, of which the Mays meter is typical, are relatively inexpensive and are used by many agencies for routine pavement monitoring. A special class of profile statistics, termed root-mean-square vertical acceleration (RMSVA), has been shown to reveal many of the road surface properties normally associated with roughness, including those measured by Mays meters. An RMSVA-based roughness index, which was tailored to describe the behavior of eight Mays meters run on 29 pavement test sections, is now the basis of a large-scale calibration program by the Texas State Department of Highways and Public Transportation. Although the Mays meter calibration problem motivated the development of RMSVA roughness indices, careful monitoring of a set of calibration test sections and other pavements has revealed interesting surface properties that could never be detected by Mays meters or by other RTRRM devices that reduce roughness evaluations to a single number. The RMSVA indices computed from a road profile can provide a signature that reflects roughness over a broad range of profile wavelengths. Distinctive signatures that correspond to certain pavement classes, or types of deterioration, have been tentatively identified and are presented here. Their interpretation remains a promising subject for future research.

The availability of accurate road profiles makes it possible to isolate, or describe mathematically, certain features of road surfaces that a particular roughness measuring device responds to. The Mays meter, a primary means of evaluating roads in many states, detects profile irregularities in the 4- to 40-ft (1- to 12-m) wavelength range, depending on vehicle speed. However, it has been shown that human ratings of road roughness correlate significantly with wave components that are beyond this wavelength range (1,2). Walker and Hudson (3) have demonstrated that about 80 percent of the variance in ratings in one large rating session in Texas (1968) could be explained by a profile statistic that incorporates amplitude measures for wavelengths up to 83 ft.

Nevertheless, the basic requirement of a calibration standard is that it correlate highly with the actual measurements of the type of device being calibrated. A weak correlation would result in an unstable calibration method, the final effect being a loss of potentially useful information in measurement data.

DEVELOPMENT OF CALIBRATION STANDARD

For our work in attempting to simulate the Mays meter with road profile statistics we had available the results of a calibration session for eight devices. All measurements were obtained within a three-month period surrounding an October 1977 profilometer run on 29 asphalt concrete pavement (ACP) test sections near Austin. Each measurement was obtained by averaging the results of four runs on a 0.2-mile section. (A fifth run, which had deviated most from the overall mean, was excluded.) This redundancy provided a measure of the repeatability of the Mays meter for successive runs. The table below contains the average section mean, the standard deviation of the section means (SD), and the standard error of repeatability (SE) for each unit. The repeatability (although slightly optimistic because of the excluded run) is quite good when we consider that 100 ± 5 in/mile corresponds approximately to a serviceability index of 2.7 ± 0.1.

Mays Meter	Mean	SD	SE
M1	104.17	70.13	5.01
M2	93.73	56.02	3.88
M3	101.87	67.83	6.47
M4	90.46	60.05	3.94
M5	95.91	69.16	7.19
M6	128.67	54.17	6.33
M7	116.96	56.34	7.27
M8	174.02	125.27	16.05

Most relevant to the problem of calibration is the relations revealed to exist among the different units. The correlation matrix and plots for the calibration session data indicate that the Mays meter roughness readings are highly correlated and, in fact, plots show that the relations are linear. If we were to seek a simple linear calibration function, with one of the units selected as the reference device, then a good reference would be unit M3, whose measurements explain about 97 percent of the section-to-section variation in response in the other units.

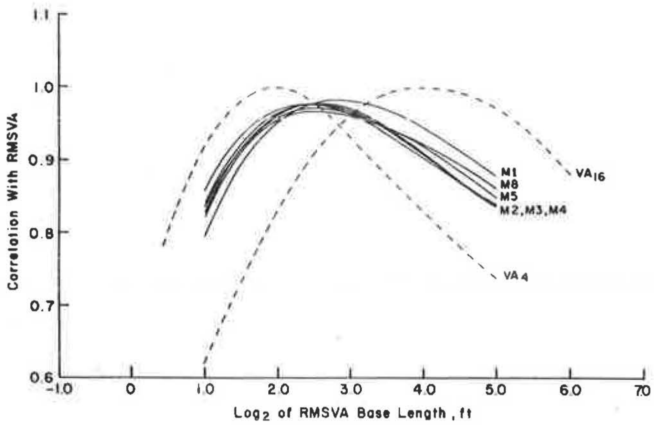
The results convinced us that a linear calibration model would be adequate provided a profile statistic could be found that would be effective in assuming the role of Mays meter M3. Unlike M3, of course, it must also have long-term stability, depending only on the profilometer or other instruments to obtain a reasonably accurate profile. Moreover, since calibration requires that measurements from all units be transferable to a common scale, we cannot expect to find a single statistic that agrees much better with the units than they do between themselves; hence, we can be satisfied if our candidate index, when statistically compared with Mays meter measurements in a linear regression, achieves a coefficient of determination (R^2) of approximately 0.97. This means that standard errors of estimate (SE) should be on the order of 10 in/mile or 0.2 serviceability units.

Correlation of Mays Meter with Root-Mean-Square Vertical Acceleration

A computer program was written that reads sequences of profile elevations (two profilometer wheelpaths) and computes a set of special summary statistics for each road section. These statistics, which are termed root-mean-square vertical acceleration (RMSVA) indices at base lengths 1 ft, 2 ft, 4 ft, etc., are proportional to the RMS difference between adjacent profile slopes. Each slope is measured over a fixed horizontal distance--the base length that corresponds to that index--and the numbers are scaled to have units of feet per square second, which corresponds to RMSVA of a hypothetical point in contact with the road and travels horizontally at 50 mph.

Some RMSVA indices are highly correlated with Mays meter roughness readings. In fact, different components of the profile wavelength are revealed in the indices obtained at different base lengths to provide a more complete description of road rough-

Figure 1. Correlation of Texas Mays meter measurements with RMSVA.



ness than could be obtained with a Mays meter. RMSVA is most sensitive to profile disturbances at wavelengths of approximately twice the base length. For example, if a pavement's RMSVA at base length 8 ft if unusually large, then the pavement is unusually rough in terms of its 16-ft-long waves.

For the purpose of analyzing the Mays meter data provided by the Texas State Department of Highways and Public Transportation (TSDHPT), the following indices were obtained from an October 1977 profilometer run of the 29 Austin test sections: $AV_{0.5}$, VA_1, VA_2, VA_4, VA_8, VA_{16}, VA_{32}, and VA_{65}.

The subscripts represent base length (b) in feet. VA_b was calibrated as the average RMSVA over both right and left wheelpaths and over two profilometer runs. In each case a sampling interval of 0.169 ft was used over a section length of 1050 ft. This particular sequence of base lengths was chosen in view of both the sampling interval and the correlation between indices. (For example, the correlation between VA_2 and VA_4 is about the same as that between VA_4 and VA_{16}.) The profilometer exhibited excellent repeatability with respect to these indices. The standard errors of duplication (SE), for example, can be compared with the standard deviation (SD) of the section means (see table below).

Base Length (ft)	Mean(VA_b)	SD(VA_b)	SE
0.51	82.52	29.71	2.60
1.01	28.48	10.56	0.83
2.03	9.13	3.73	0.28
4.06	3.43	1.77	0.07
8.11	1.38	0.86	0.13
16.22	0.64	0.43	0.008
32.45	0.23	0.19	0.017
64.85	0.13	0.075	0.005

When multiple regression procedures were applied to the Mays meter data, it was found that the two indices, VA_4 and VA_{16}, were sufficient to explain the response of each Mays meter on the 29 test sections. Furthermore, no significant improvement in the correlations came about by allowing different combinations, or functions, of RMSVA indices. Figure 1 shows that the correlations of the two indices, VA_4 and VA_{16}, with Mays meter roughness are large compared with their correlation with each other; hence, each statistic contains relevant information that is not contained in the opposing statistic. Such plots actually indicate that the peak response for most Mays meter units is at a base length smaller than 8 ft and that perhaps another pair, say VA_3 and VA_{12}, would have provided marginally better correlations. Comparison of the Mays meter data with VA_4 and VA_{16} produced regression equations that, with few exceptions, have markedly similar coefficients.

The method used for arriving at a single profile index was to fit each Mays meter Mi (run at the standard speed of 50 mph) to the nonlinear model

$$Mi \simeq \alpha_1 + \beta_1 (VA_4 + R\,VA_{16}) \quad (1)$$

where coefficient R is determined to provide an optimum calibration for the collection of Mays meter trailers as a whole. This nonlinear regression problem is easily solved by plotting the total regression sum of squares for Equation 1 at various values of R and interpolating the minimum. In this manner, $R^2 = 2.5$ was obtained.

Such considerations led us to the linear calibration model

$$Mi \simeq \alpha_1 + \beta_1\,MO \quad (2)$$

where

$$MO = 20 + 23\,VA_4 + 58\,VA_{16} \quad (3)$$

The coefficients in the RMSVA statistic MO were selected so that α_1 and β_1 are approximately 0 and 1, respectively, for the Mays meter trailers. Thus, MO will serve as our ideal Mays meter. The results of fitting this model to the Mays meter and RMSVA data are given in Table 1.

The regression results of Table 1, when plotted, reveal two distinct Mays roughness meter (MRM) groupings: trailers and cars. Although based on fewer data, the car-mounted Mays meters obviously differ from the trailers in their relation to MO. The five trailers, however, are so similar in their response that they would seem to be indistinguishable and thus be in no need of calibration. Yet, their correlation with MO is strong enough that units as similar to each other as M2 and M5 can be separated, as is shown in Figure 2. Ninety-five percent confidence intervals for their slope parameters (B and B) do not, in fact, overlap.

We summarize the Mays meter-RMSVA correlation study as follows: A profile statistic based on RMSVA at base lengths of 4 ft and 16 ft was successful in explaining approximately 97 percent of the response variation between five trailer-mounted Mays meters on 29 pavement test sections. This corresponds to a prediction standard error of about 10 percent of the Mays meter reading (in/mile), which compares favorably with what would be achieved if an actual Mays meter had been singled out as the reference device. Results for the three car-mounted Mays meters were not quite as favorable ($R^2 = 0.91$, 0.93, and 0.95); however, section data for the two units that deviated most were incomplete.

The correlation studies that produced the profile statistic MO (Equation 6) were carried out in early 1978 and since then the statistic has been used regularly by TSDHPT for the calibration of its Mays meters. Although MO was tailored to describe Mays meter data obtained around October 1977, subsequent Mays meter calibrations have continued to demonstrate the high correlations described above.

Rescaling of RMSVA Indices

The Mays meter simulation MO has proved to be an effective standard for Mays meter calibration; however, the individual RMSVA indices (base lengths 1, 2, 4, 8, 16, 32, 65, and 130 ft) are genuine roughness traits that have been useful for comparing pavements in other studies. Therefore, to make such

Table 1. Regression that results from fitting eight Mays meters to the linear model of Equation 5.

Item	M1	M2	M3	M4	M5	M6	M7	M8
α_i	-1.7	9.6	0.2	0.5	-7.9	28.6	8.9	-6.0
β_i	1.07	0.88	1.06	0.94	1.08	1.42	1.49	1.89
R^2	0.981	0.972	0.969	0.967	0.972	0.913	0.925	0.951
SE	9.7	9.5	12.2	11.1	11.9	16.4	15.8	27.9

Figure 2. Calibration results for two trailer-mounted Mays meters.

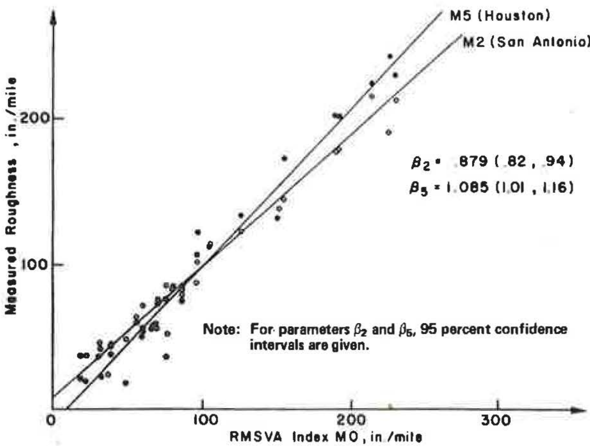
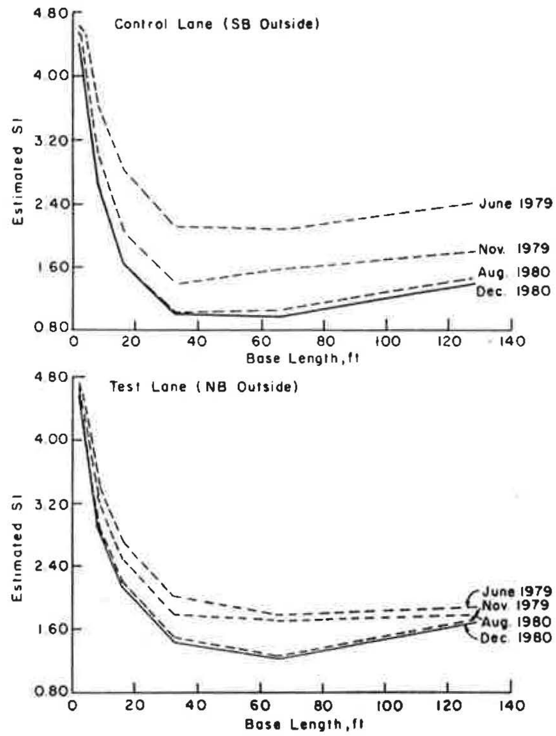


Figure 3. RMSVA signatures for untreated (top) and treated (bottom) ACP sections in a swelling clay environment—loop 410, San Antonio.



comparisons easier, rescaled versions of these indices are usually provided that resemble a sequence of serviceability ratings in the range 0-5.

The main advantage of such scalings is that their means, as determined on 31 ACP test sections near Austin (April 1981), are approximately the same, which makes it easier to judge their significance for other pavements. The test sections encompass a variety of roughness conditions, which exhibit a serviceability range of 0.63 to 4.83, with a mean of 3.12 and SD of 1.23.

The RMSVA data for two sections known to be subject to deterioration from expansive clays are shown in Figure 3 (SI versus base length), along with the corresponding values obtained periodically during the previous 18 months (dashed lines). Notice that the spectra of SI values form distinctive signatures that, in this case, changed very little during the last 4-month period. The test section (lower figure) shows the effect of treatment by a fabric moisture seal prior to the first profilometer run in June 1979. The differences, however, are confined to the longer RMSVA base lengths and would probably not be noticed in readings from a Mays meter. Data for these sections were provided by TSDHPT engineer Malcolm Steinberg.

CONCLUDING REMARKS

We must not confuse the problem of calibrating a group of instruments with the problem of interpreting their measurements. When the Texas Mays meter calibration method was first devised, the serviceability index (SI) was the best available estimate of present serviceability rating (PSR), a measure of roughness that is meaningful. Since serviceability estimates were desired from the Mays meters, SI was chosen as the standard against which different units were to be calibrated. This would have been a good approach, however, only if Mays meters were capable of measuring SI with as much accuracy as their precision would seem to indicate. Unfortunately, this is not the case. At best, Mays meters can be assigned scalings so that different units give comparable Mays meter roughness ratings. How the ratings should be used to predict other things, such as ride quality, is a problem to be considered apart from the calibration process itself.

Our study of the Texas Mays meters revealed that a simple profile statistic based on RMSVA could serve effectively as a calibration standard. When the statistic is rescaled by regression techniques to approximate a serviceability rating, we find that different Mays meters that are calibrated against it can measure roads and agree to within 0.1 or 0.2 serviceability unit. This precision, of course, says nothing about the accuracy of such measurements as predictors of subjective serviceability ratings because the Mays meter is necessarily limited in its response.

However, the Mays meter is capable of measuring a certain kind of roughness with good precision. The obvious benefit of this is in making comparisons; for example, in revealing differences between pavement sections and in showing trends in deterioration or the effects of rehabilitation on roughness. For this purpose, especially, a good calibration method based on a stable and valid reference is necessary.

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REFERENCES

1. J.R. Darlington. Evaluation and Application Study of the General Motors Corporation Rapid Travel Profilometer. Michigan Department of State Highways, Lansing, Rept. R-731, April 1973.
2. J.P. Guilford. Psychometric Methods. McGraw-Hill, New York, 1954.
3. R.S. Walker and W.R. Hudson. Use of Profile Wave Amplitude Estimate for Pavement Serviceability Measures. HRB, Highway Research Record 471, 1973, pp. 110-117.

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Inertial Profilometer Uses in the Pavement Management Process

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The inertial profilometer has the potential to become one of the most important tools in the pavement condition evaluation process. This paper discusses its continuing development, including a noncontact profile sensor, digital profile computation, and an array of computer software developments that will further enhance the inertial profilometer's contribution to the pavement management process. For historical purposes the paper also discusses the original development of the inertial profilometer at the General Motors Research Laboratories in the early 1960s and its introduction into the user community by K.J. Law Engineers, Inc.

The inertial profilometer was developed in the early 1960s at the General Motors Corporation Research Laboratories (GMR) (1). It was developed for the purpose of measuring, recording, and bringing a replica of a pavement surface profile into the laboratory for use in vehicle suspension computer simulations. The original development task was thought to be trivial but took four years and cost $0.5 million in 1960 dollars. This paper discusses that original development, its continued development as a commercial product under license from General Motors, and some future developments that will enhance the device as an important pavement management tool.

GMR PROFILOMETER

The development of the inertial profilometer at the General Motors Research Laboratories in the 1960s was made possible by the availability of high quality force balance accelerometers used in the Aerospace Industry for inertial guidance. Also important in the development was the availability of high quality analog computer components, including the integrators used in the profile computation. The GMR profilometer developed at that time (Figure 1) used a 6-in diameter wheel to follow the pavement surface (W), a high-quality potentiometer to measure the relative motion (W-Z) of the pavement-following wheel, and an accelerometer isolated from large pavement profile acceleration by being mounted on the vehicle's sprung mass. The accelerometer output ($\ddot{Z}$) and the potentiometer output (W-Z) were inputs to an analog computation that produced the measured pavement profile, W_m:

$$W_m = (W - Z) + \iint \ddot{Z}\,dt\,dt \quad (1)$$

The capability for measuring the spatial wavelength (Figure 2) was found to be more than adequate for vehicle ride studies. Measuring response remained flat for wavelengths up to 200 ft for even the low measuring velocities. The profilometer's short wavelength measuring capability was demonstrated by the ability of the pavement-following wheel to follow a wood shingle (Figure 3) placed on the pavement surface. The profilometer's overall measuring capability was demonstrated by its ability to measure (Figure 4) and isolate (Figure 5) pavement spatial wavelengths that caused ride quality problems in General Motors' cars on California highways.

Much of the work at the General Motors Research Laboratories was reported by Spangler and Kelly (1). Work that was not reported included the use of the GMR profilometer to measure airport runways and taxis strips, city streets traveled by General Motor's buses, and rail profiles (2) traveled by General Motor's locomotives. One of the more important results of this early effort was the ability to measure and record an accurate replica of many different pavement surfaces (Figure 6) for later examination, analysis, and processing by more-sophisticated engineering computer tools.

COMMERCIAL PROFILOMETER

After the 1965 TRB presentation on the GMR profilometer (1) the General Motors Corporation was requested by several transportation agencies to make the inertial profilometer technology available to the transportation community. K. J. Law Engineers, Inc., of Farmington Hills, Michigan, was granted a