no repair at all. Hence, from a practical viewpoint (e.g., to make a decision concerning whether a specific road should be repaired), only the range from 1.0 to 4.5 is important; what happens outside this range is not important.

2. Extrapolation to predict values (of RN) outside the range of the empirical data can lead to inaccuracies; none of us knows how the data will behave outside the (RN) range of 1.0 to 4.5. Although their assumptions concerning behavior at the extremes of the curve appear reasonable, neither they, nor I, have any validation of them.

3. Their point concerning application by unfamiliar users is well taken. However, there are methods other than nonlinear that are far simpler to apply to alleviate this problem. Restricting the range of the equation (a simple "if" statement, for example) is one of them.

I believe that the analysis accomplished by Weed and Barros is important in providing more insight into the entire process that describes the relationship between psychological ride quality and physical roughness. However, their results, like mine, still leave questions to be answered. I hope that additional research will be undertaken to answer these questions.

Critical Evaluation of the Calibration Procedure for Mays Meters

BOHDAN T. KULAKOWSKI

ABSTRACT

A procedure for calibrating Mays meters using a standard quarter-car model is reviewed. Uncertainties of the calibration method caused by lateral nonuniformity of the road surface and differences between the dynamics of calibrated and standard vehicles are discussed. The results of a statistical analysis of experimental data used for Mays meter calibration are presented. Investigation of the effects of the number of raw data on the accuracy of calibration leads to some practical recommendations for the number and length of the calibration test sites.

Mays meters are the most common equipment used by state transportation agencies to measure road roughness. The output generated by the Mays meter represents an accumulated displacement between the rear axle and the body of the vehicle. In order to calibrate the system, the scale of the output signal in terms of road roughness has to be determined by comparison with a standard. The calibration procedure for Mays meters was the subject of an extensive study conducted by Gillespie et al. (1). In the study a reference standard system--a quarter-car model of specified parameters--was introduced, and various calibration methods were evaluated. The research findings reported (1) provided the basis for the new standard calibration procedure that will be introduced by ASTM in the near future. The results presented by Gillespie et al. have undoubtedly been very helpful to the transportation agencies now developing reliable and accurate calibration procedures, yet many important questions remain unanswered.

The objective of this paper is to address some of these questions: How good or how certain is the standard system used in Mays meter calibration? Are there any important uncertainties affecting the accuracy of calibration? How extensive should the raw data set be to assure good correlation with the standard system, and, in particular, how many test sites should be used and of what length? Are multiple tests on each road site necessary? Although definite answers to some of these questions have not been found at this point, raising them should bring researchers closer to a better, more accurate calibration procedure.

UNCERTAINTIES OF THE STANDARD QUARTER-CAR MODEL

Every calibration procedure requires a standard (reference) against which a calibrated system may be compared. It is necessary that the uncertainties of the standard be considerably less than those of the system to be calibrated in order to assure high ac-

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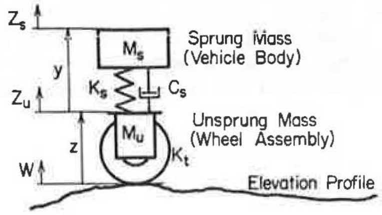
curacy of measurement. In the calibration of Mays meters, a model of a quarter-car, shown in Figure 1, is used as a standard. The model is well defined and probably as certain as a mathematical model can be. However, it is not the quarter-car model itself but the model-generated roughness data that are used as the reference in calibrating Mays meters.



$K_s/M_s = 62.3\ s^{-2}$ $M_u/M_s = 0.15$

$K_t/M_s = 653.0\ s^{-2}$ $C_s/M_s = 6.0\ s^{-1}$

FIGURE 1 Standard quarter-car model.

The quarter-car roughness index values are calculated for a given input signal representing a road profile. It is assumed that exactly the same input signal is applied to the calibrated and calibrating vehicles. This in general is not quite true, but it is hoped, at least, that the difference between the two signals is insignificant.

Is it insignificant? Consider the structure of the calibration system. The idealized and actual system structures are shown in Figure 2. The wheelpaths of the calibrating and calibrated vehicles are never exactly the same. The differences between the profiles are represented in Figure 2 by random signals v' and v" for the left and right wheelpaths, respectively. Mathematically the relationship between the profiles can be described by Equations 1 and 2

$$w'_{MM} = w'_{QC} + v' \quad (1)$$

$$w''_{MM} = w''_{QC} + v'' \quad (2)$$

where

- w_{MM} = road profile in Mays meter wheelpath,
- w_{QC} = road profile in profilometer wheelpath, and
- v = signal representing difference in profiles between the two paths.

Superscripts ' and " are used to denote the left and right wheel signals, respectively. The disturbances v' and v" appear to be a result of the lateral nonuniformity of the road surface. In order to evaluate the extent of this lateral nonuniformity, actual roughness index values for the left and right wheelpaths on 20 road sites, each 0.6 mi long, were compared. The height sensor and accelerometer data for the left and right wheels were collected with the Pennsylvania Transportation Institute (PTI) profilometer, and the roughness index values for the two wheels, R'_{QC} and R''_{QC}, were calculated. The roughness index is defined as

$$R_{QC} = 1/L \int_0^L |z(x)|\ dx \quad (3)$$

where

- $z(x)$ = axle-body displacement of the quarter-car model, inches;
- x = longitudinal distance variable, miles; and
- L = length of the road site, miles.

The values of R'_{QC} and R''_{QC} were obtained for 0.05-mi increments from the computer program developed by Watugala (2) on a DEC LSI 11/23 computer. Two conclusions, shown graphically in Figure 3, can be drawn from the results. First, the lateral nonuniformity of road roughness is considerable as is indicated by large differences between the right and left wheelpath values on many sites. This means that the inputs to the calibrated and calibrating systems may be significantly different because they never follow exactly the same path. One of the most important requirements for a highly accurate calibration, namely, that inputs to the two systems be identical, is therefore not met. The magnitude of the error caused by the lateral nonuniformity of the road surface, however, is difficult to assess.

The second conclusion from a comparison of the roughness data for the two wheels is that the values for the right wheel are higher than those for the left wheel on most road sites, as is indicated by the clustering of the data points below the line of unity slope in Figure 3. It was found that the average roughness index value in the right wheelpath was 83.37 in./mi, whereas in the left wheelpath it was only 75.60 in./mi, about 10 percent lower. The difference was more pronounced for rougher roads having a roughness index value greater than 50 in./mi. The high value of the correlation coefficient, r = 0.96,

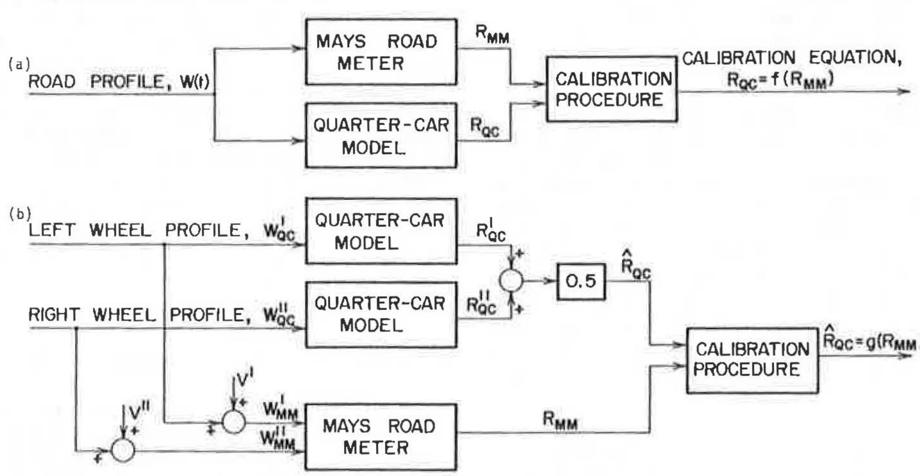


FIGURE 2 Idealized (a) and actual (b) structures of the calibration system.

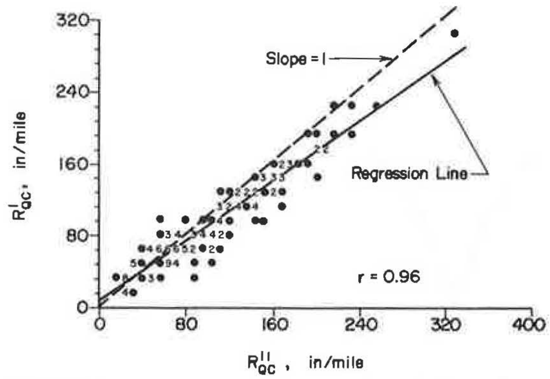


FIGURE 3 Comparison of road roughness index values calculated with a standard quarter-car model from left, R'_{QC}, and right, R''_{QC}, wheelpath data.

confirms that the relationship is not coincidental. In fact, a statistically meaningful linear regression model was obtained relating roughness index values in two wheelpaths:

$$R'_{QC} = 5.83 + 0.837\ R''_{QC} \tag{4}$$

The standard deviation between the model (Equation 4) and the raw data was relatively low--12.55 in./mi. As mentioned before, the magnitude of the inaccuracy of the calibration formula caused by the lateral nonuniformity of the road is difficult to evaluate, but it can be as much as 5 to 10 percent. The closer are the wheelpaths of the calibrated and calibrating vehicles, the smaller is the effect of the lateral nonuniformity. The error can be entirely eliminated only if calibration is conducted on test facilities closed to road traffic.

PHYSICAL VERSUS STATISTICAL VALIDITY OF THE LINEAR CALIBRATION FORMULA

A linear regression equation is commonly used as a calibration formula relating road roughness index values obtained with Mays meters and with the standard quarter-car model. The form of this equation is

$$R_{QC} = \alpha_0 + \alpha_1 R_{MM} \tag{5}$$

where

- R_{QC} = roughness index value calculated using standard quarter-car model,
- R_{MM} = roughness index value measured with Mays meter, and
- α_0, α_1 = constant parameters.

Both R_{QC} and R_{MM} are numerical measures associated with the responses of two dynamic systems, the quarter-car model and the Mays meter, to a dynamic road profile input. Therefore, the relationship between the two system outputs is dynamic, depending on the frequency spectrum of the input signal, and can only be approximated by the static formula (Equation 5) with a limited accuracy.

Consider the dynamics of the Mays meter-quarter-car relationship in more detail. First of all, assume that both the Mays meter and the standard quarter-car model are described by the set of two linear differential equations

$$M_s\ddot{z}_s + C_s(\dot{z}_s - \dot{z}_u) + K_s\ (z_s - z_u) = 0 \tag{6}$$

$$M_u\ddot{z}_u - C_s\ (\dot{z}_s - \dot{z}_u) - K_s\ (z_s - z_u) = K_t(w - z_u) \tag{7}$$

where the meaning of the symbols used in these equations is explained in Figure 1. By applying a Fourier transformation and rearranging Equations 6 and 7, the relative axle-body displacement, $z = z_s - z_u$ can be expressed in terms of model parameters, profile w, and frequency ω as follows:

$$z(j\omega) = M_sK_t\omega^2/[M_uM_s\omega^4 - j(M_u + M_s)C_s\omega^3 - (M_uK_s + M_sK_s + M_sK_t)\omega^2 + jC_sK_t\omega + K_sK_t]\ w(j\omega) \tag{8}$$

The magnitude of the axle-body displacement, which is used to calculate the road roughness index from Equation 3 can be derived from Equation 8 as

$$|z(j\omega)| = b_2\omega^2/(a_8\omega^8 + a_6\omega^6 + a_4\omega^4 + a_2\omega^2 + a_0) \tag{9}$$

where

$$b_2 = K_t/M_u$$
$$a_0 = K_sK_t/M_sM_u$$
$$a_2 = (C_sK_t/M_sM_u)^2 - 2(K_sK_t/M_sM_u)[K_s/M_s + (K_s + K_t)/M_u]$$
$$a_4 = [K_s/M_s + (K_s + K_t)/M_u]^2 + 2K_sK_t/M_sM_u - 2(C_sK_t/M_sM_u)(C_s/M_s + C_s/M_u)$$
$$a_6 = (C_s/M_s + C_s/M_u)^2$$
$$a_8 = 1.0$$

It can be seen that the relationship between the two measures of roughness determined by the ratio of magnitudes $|z(j\omega)|$ integrated and averaged over the road length is a complex function of frequency. The problem is illustrated in Figure 4, which shows how the ratio of the magnitude of the axle-body displacement of the standard quarter-car model versus that of the Mays meter quarter-car model represented by the 1962 Chevrolet Impala varies with the frequency of the road profile. An attempt to approximate the relationship between the roughness indices generated with the two models by the linear calibration formula (Equation 5) is hardly justified if roads of different frequency spectra are to be analyzed.

On the other hand, the statistical parameters of linear calibration equations are usually rather encouraging: high correlation coefficient, relatively small standard deviations. This happens because most roads have similar frequency spectra of their profiles. However, great care should be exercised if roads of unusual frequency characteristics are to be tested.

The frequency spectrum of the profile, as observed by a vehicle, changes not only from site-to-site but it also changes with the vehicle speed on the same site. It can thus be concluded from the earlier discussion that the road roughness index is a speed-related quantity. It is therefore proposed that the speed at which the roughness measurements are made always be indicated; for example, I/M_{40} or I/M_{25} would denote the road roughness index values at 40 and 25 mph, respectively.

SELECTION OF THE NUMBER AND LENGTH OF ROAD TEST SITES

Calibration of Mays road meters is a statistical procedure designed to produce the best mathematical model of the relationship between a calibrated system subject to random disturbances and a standard. The form of the model is assumed a priori to be linear with constant coefficients as shown in Equation 5. With the specified form (Equation 5) the problem reduces to an estimation of the parameters α_0, α_1, which is commonly accomplished by using a linear regression method. It is usually considered that the number of raw data must be sufficiently

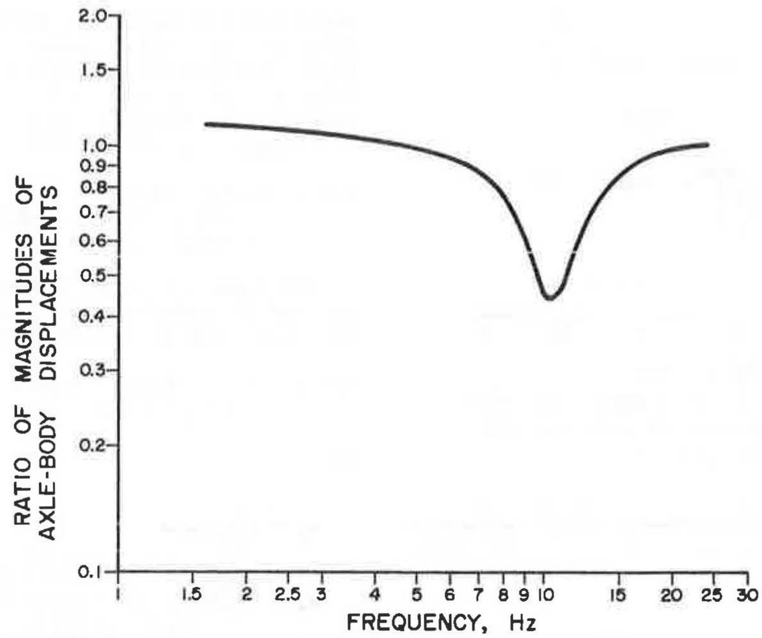


FIGURE 4 Ratio of magnitudes of axle-body displacement of the standard quarter-car model versus Mays meter quarter-car model represented by a 1962 Chevrolet Impala.

large, whatever that means, in order to ensure accurate results. The term sufficiently large, is usually interpreted as the larger the better, which essentially is true if the cost of calibration is not taken into account. Some state transportation agencies have developed extensive (and expensive) data collection procedures for calibrating their Mays meters. The effect of the number of data on the accuracy of Mays meter calibration was investigated in a study sponsored by the Pennsylvania Department of Transportation (3). The raw data base used in this study contained road roughness index values measured in 0.05-mi increments on 20 road sites, each 0.6 mi long. The calibrated Mays meter was run five times on each site. A total of 1,200 data were therefore collected. The calibration formula obtained from the original set of data was

$$R_{QC} = 14.3 + 0.693\ R_{MM} \quad (10)$$

Next, the raw data were averaged over 0.10, 0.20, 0.30, and 0.60-mi increments. The results of the calibration for the different distance increments are given in Table 1. Increasing the distance increment eliminates high frequency noise and thus has a smoothing effect on the data, which causes the standard deviation to decrease. On the other hand, with an increased distance increment, the range of the roughness data is narrowed; as a result the regression line fits the data better around the center of the range, but the accuracy for extreme values of roughness gets worse. A compromise selection of a distance increment between 0.2 and 0.3 mi appears to be the best choice.

TABLE 1 Effect of Distance Increment on the Results of Calibration

Distance Increment, Mile	Calibration Formula, Equation 5: Intercept, α_0	Slope, α_1	Correlation Coefficient	Standard Deviation, in./Mile
0.05	17.5	0.629	0.91	19.3
0.10	15.8	0.647	0.94	14.7
0.20	14.4	0.659	0.96	12.1
0.30	14.4	0.660	0.97	10.4
0.60	14.6	0.658	0.98	9.1

As mentioned earlier, the data were collected five times on each site in order to eliminate random measuring errors. Additional computations were performed to determine calibration equations based on data obtained after one, two, three, and four repetitions. The results are given in Table 2 where it can be seen that the calibration parameters are almost totally independent of the number of repetitions. This observation can be explained by the fact that even with a single test on each road site, the total number of data collected was sufficiently large to ensure good accuracy of calibration. It should be noted that by reducing the number of runs from five to one, the extent of the calibration testing program is reduced by 80 percent without loss of accuracy.

Next, the problem of test site selection was examined. Calibration computations initially made for 20 sites were repeated for 15, 10, and 5 sites selected from the original set of 20. The data were averaged over 0.25 mi, which gives two data points from each 0.5-mi section. The distribution of raw data and the calibration lines of the standard quarter-car, R_{QC}, versus Mays meter roughness index, R_{MM}, are shown in graphical form in Figures 5 through 8. The numerical results are given in Table 3. In addition to the data presented here, the same experiment was conducted for three other Mays road meters yielding very similar results (3). It can, therefore, be concluded that as few as 5 sites can be used instead of 20 to obtain sufficient accuracy of calibration.

Finally, the conclusions regarding the number of sites and the number of repetitions were combined, and the calibration was conducted for the drastically reduced set of data containing roughness index values from five sites, each obtained in a single test. The sites selected were 0.5 mi long and the distance increment was 0.25 mi, which gives a total of 200 data points in the full set against 10 data points

TABLE 2 Results of Calibration for Different Numbers of Test Runs on Each Site

Speed	Parameter	No. of Repetitions 5	4	3	2	1
25 mph	Intercept, α_0	14.3	14.4	14.3	14.4	14.3
	Slope, α_1	0.693	0.693	0.693	0.693	0.698

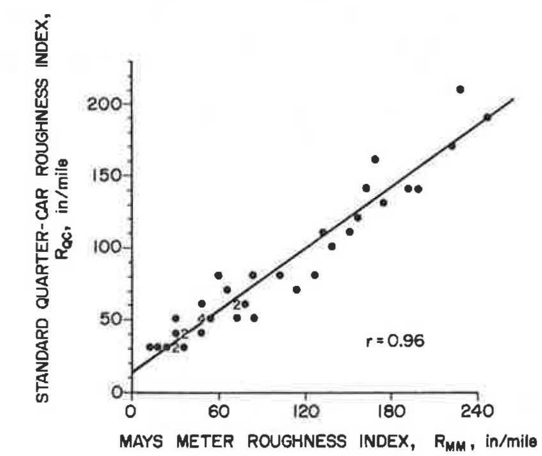


FIGURE 5 Calibration data for 20 sites.

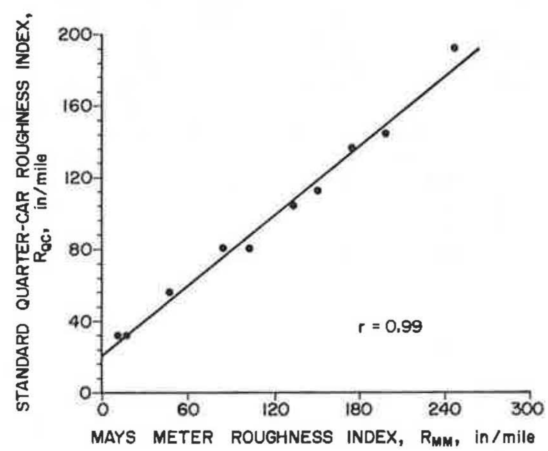


FIGURE 8 Calibration data for 5 sites.

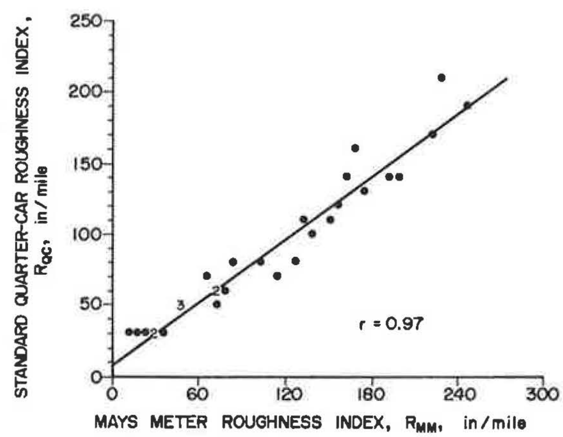


FIGURE 6 Calibration data for 15 sites.

TABLE 3 Results of Calibration for Different Number of Test Sites

Speed	Parameter	No. of Test Sites 20	15	10	5
25 mph	Intercept, α_0	12.8	8.61	10.3	20.1
	Slope, α_1	0.708	0.734	0.719	0.649

in the reduced data set. The calibration lines obtained for the reduced and full sets of data at 25 mph are shown in Figure 9. A rule of thumb often used in least-squares parameter estimation states that a minimum of 5 to 10 raw data points per estimated parameter are needed to ensure meaningful results. Thus at least 10 to 20 raw data points are necessary for Mays meter calibration because two parameters, α_0 and α_1, are being estimated, which roughly agrees with the conclusions set forth.

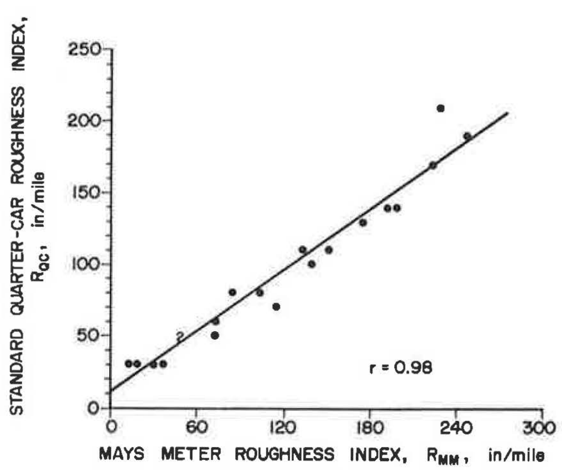


FIGURE 7 Calibration data for 10 sites.

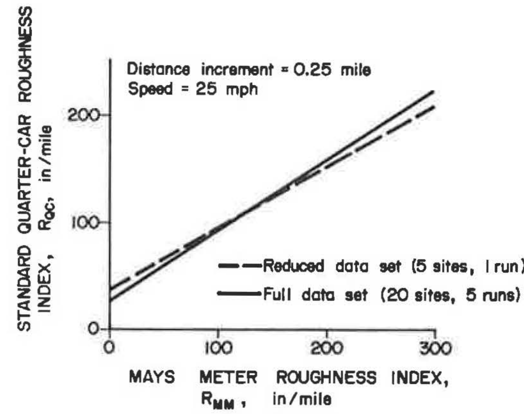


FIGURE 9 Calibration lines obtained from the full set of data and from the reduced set of data.

SUMMARY

Mays meter users, in their efforts aimed toward obtaining maximum accuracy of calibration, should be aware of the fundamental conceptual and technical problems associated with the calibration of the Mays meters against a standard quarter-car model. These problems include lateral nonuniformity of the road surface, which means that the input signals applied to the calibrated and calibrating systems are never identical. The difference between the dynamic characteristics of the Mays meter and those of the standard quarter-car is another problem limiting the accuracy of calibration. The lateral nonuniformity of road surface and the differences between the dynamic behavior of the calibrated and the calibrating vehicles cause inherent uncertainties in the calibration procedure that cannot be eliminated by increasing the amount of test data. The results of the statistical analysis presented in this paper should be useful in developing accurate, low-cost testing procedures for the calibration of Mays road meters.

ACKNOWLEDGMENTS

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