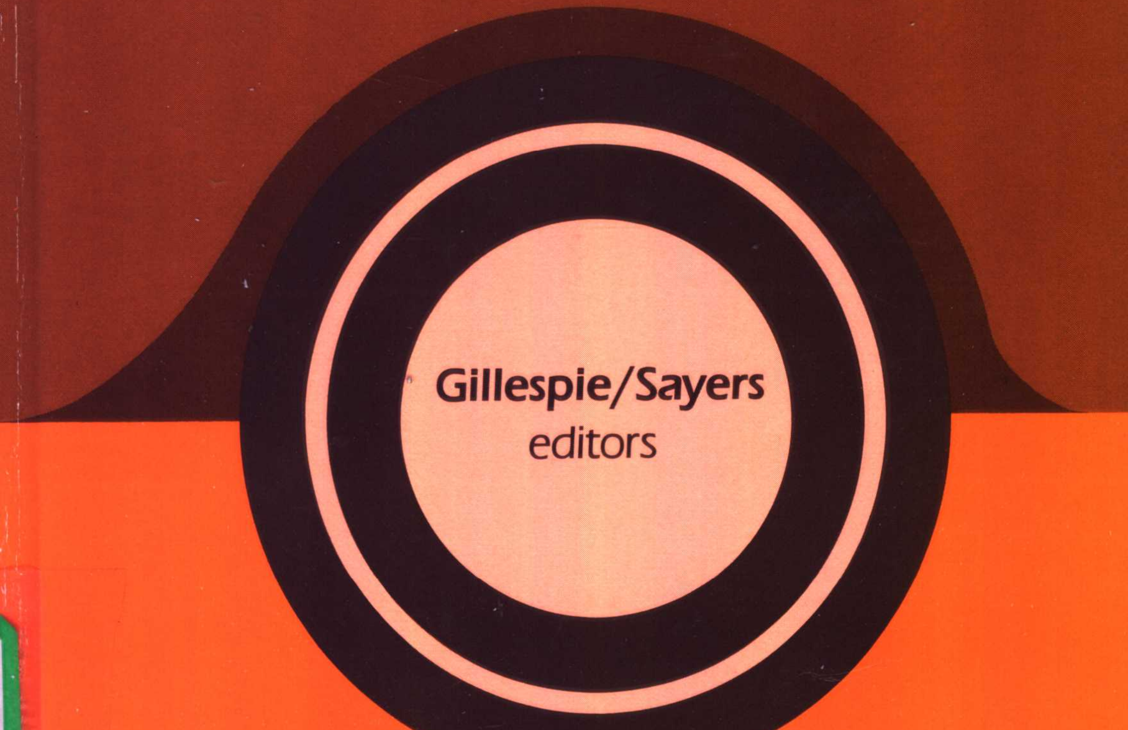
Measuring **Road Roughness** and Its Effects on User Cost and Comfort



Gillespie/Sayers
editors

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Foreword

This publication, *Measuring Road Roughness and Its Effects on User Cost and Comfort*, contains papers presented at the symposium on Roughness Methodology, which was held on 7 Dec. 1983 in Bal Harbour, Florida. The event was sponsored by ASTM Committee E-17 on Traveled Surface Characteristics. Thomas D. Gillespie and Michael Sayers, both of the University of Michigan Transportation Research Institute, presided as cochairmen of the symposium and also served as editors of this publication.

A Note of Appreciation to Reviewers

The quality of the papers that appear in this publication reflects not only the obvious efforts of the authors but also the unheralded, though essential, work of the reviewers. On behalf of ASTM we acknowledge with appreciation their dedication to high professional standards and their sacrifice of time and effort.

ASTM Committee on Publications

Contents

Overview 1

Root-Mean-Square Vertical Acceleration as a Summary Roughness Statistic—W. RONALD HUDSON, DAN HALBACH, JOHN P. ZANIEWSKI, AND LEN MOSER 3

Development, Implementation, and Application of the Reference Quarter-Car Simulation—MICHAEL SAYERS 25

Simulation of Road Meters by Separate Analysis of Accelerometer and Height Sensor Data—GAMAGE K. WATUGALA AND GORDON F. HAYHOE 48

Accuracy of Calibrated Roughness Surveys—WILLIAM D. O. PATERSON 66

Relationships Between Vehicle Speed, Ride Quality, and Road Roughness—WILLIAM D. O. PATERSON AND THAWAT WATANATADA 89

Effects of Vehicle and Driver Characteristics on the Subjective Evaluation of Road Roughness—MICHAEL S. JANOFF AND JAMES B. NICK 111

Vehicle Operating Costs Related to Operating Mode, Road Design, and Pavement Condition—JOHN P. ZANIEWSKI AND BERT C. BUTLER 127

Effects of Road Roughness on Vehicular Rolling Resistance—XIAO-PEI LU 143

Analytical Determination of Normal Contact Stresses for Arbitrary Geometries with Application to the Tire/Pavement Interaction Mechanism—TIMOTHY G. CLAPP, CARL T. KELLEY, AND ALLEN C. EBERHARDT 162

Road Roughness Effects on Vehicle Dynamics—JAMES C. WAMBOLD 179

Index 000

Overview

In order to develop better methods for managing our highway systems, the highway engineers, administrators, and economists responsible for those systems need clear and meaningful information about the pavement surface conditions. Among the numerous properties indicative of pavement condition, a measurement of the roughness provides a rich source of information to aid in the management process.

From the beginning, road roughness was viewed as a subjective quality. Thus, early efforts to develop ways to measure roughness resulted in hardware that could generate a measurement closely correlated to subjective judgements. The rolling straightedge, the Bureau of Public Roads (BPR) roughometer, CHLOE, and other devices were inventions conceived from an intuitive understanding of the physical properties of interest. As more roughness measuring devices have been developed, the focus has shifted toward objective measurements of road roughness.

Current practice in the United States concentrates primarily on two types of equipment—road meters and profilometers. Road meters, measuring the vehicle's dynamic response to the road, have a clear intuitive link to the roughness directly encountered by the road user. They reduce roughness to the simple concept of a numerical index indicative of the average level of vibration produced on a motor vehicle. Though profilometers measure a much broader range of properties by means of a recorded profile, they, too, are capable of reducing the roughness information to a single index.

The highway community is at a juncture. With the widespread practice of reducing roughness to a single index, there is need for acceptance of a common roughness index as a basis for communication and understanding. The choice of such an index must be made from those used in past practice if data bases are to be maintained. At the same time, a rational choice must weigh all the utilitarian advantages and disadvantages associated with each of the available alternatives.

On 7 Dec. 1983 an ASTM symposium on Roughness Methodology was held as a forum for presenting recent technical findings relevant to the objective measurement of road roughness. This publication contains the papers from that symposium. The first few papers describe two alternative conceptual approaches to a roughness index, both anchored in past practice. The root-mean-square vertical acceleration (RMSVA) technique described in the paper by *Hudson et al* represents the viewpoint that roughness should be quantified by an index derived from geometrical properties that have been empirically linked to effects on road-user vehicles. The approach is attractive for its simplicity in that a road has a unique roughness value, but it does not recognize that the roughness effects on vehicles are dependent on the speed. The other papers examine the alternative approach of using a quarter-car simulation (QCS) to calculate an index based directly on vehicle response to roughness. The QCS directly replicates the behavior of road meters, such as the Mays meter on cars and trailers and the BPR roughometer. The paper by *Sayers* provides an overview of the QCS, including its history and details for performing the QCS calculations. Results are presented that link the QCS index to the ride quality of passenger cars and trucks and to the dynamic loading on pavement caused by the wheels of heavy trucks. The paper by *Watugala and Hayhoe* presents recent developments relating to an alternative means for performing calculations in a QCS that are well suited for automated profilometers. Additional background on the QCS modeling of vehicle dynamics is provided in the last paper, by *Wambold*, which is based on the 1982 Kummer Lecture.

The practical side of measuring and using roughness information is addressed in three of the papers. *Paterson and Watanatada* examine the relationships between roughness measurements from the QCS and the operating speed, with interesting findings on the limitations of travel speed because of roughness. The second paper by *Paterson* addresses the practical problems of obtaining accurate measurements of a QCS-based roughness index using road meter vehicles. The subjective evaluation of roughness is the subject of the paper by *Janoff and Nick*, which concludes that vehicle size and speed do not significantly affect subjective ratings of roads in a properly designed experiment.

The remainder of the papers address the impact of road roughness on vehicles using the roads. *Zaniewski and Butler* report on a correlation study dealing with roughness and vehicle operating costs by consideration of the fuel, oil, and tire consumption and the maintenance, repair, and depreciation costs. The effect of roughness on vehicle rolling resistance is addressed by *Lu* in a theoretical study that defines the various mechanisms by which additional energy dissipation arises from road surface roughness. Finally, the influence of roughness on the pressure distribution under a tire is analyzed in the paper by *Clapp et al.*

The technical papers published here provide additional reference material for those in the highway community concerned with roughness measurement and characterization. The editors hope that this publication will help to clarify the issues and to speed the day that a common language for roughness can be achieved. To this end, the editors acknowledge each of the authors for his contribution and the staff within ASTM responsible for organization of the symposium and publication of this volume.

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Root-Mean-Square Vertical Acceleration as a Summary Roughness Statistic

REFERENCE: Hudson, W. R., Halbach, D., Zaniewski, J. P., and Moser, L., "**Root-Mean-Square Vertical Acceleration as a Summary Roughness Statistic,**" *Measuring Road Roughness and Its Effects on User Cost and Comfort, ASTM STP 884*, T. D. Gillespie and Michael Sayers, Eds., American Society for Testing and Materials, Philadelphia, 1985, pp. 3-24.

ABSTRACT: Much has been done in recent years to relate various roughness statistics to rider comfort in terms of a serviceability index (developed by Carey and Irick). Much less has been done on correct evaluation of a true profile in terms of summary statistics for field comparison of vehicle operating costs and user comfort. Important work in this area has been done by Gillespie and Sayers at the University of Michigan, and additional work has been done by Hudson, Williamson, and McKenzie at the University of Texas. Work has also been done in Brazil by Queiroz and others. At least two statistics have been offered for summarizing roughness information:

(*a*) the average rectified velocity, by Gillespie and Sayers, and
(*b*) the root-mean-square vertical acceleration, by Hudson et al.

The purpose of this paper is to examine and compare these statistics with particular emphasis on their potential effects on rider comfort and their use as standard calibration statistics for response-type road roughness meters.

A complete parameter study is reported comparing these two statistics. The results of the study will be helpful in selecting useful analytical techniques for routine applications.

KEY WORDS: roughness, ride meter calibration, average rectified velocity, root-mean-square vertical acceleration, quarter-car simulation

Road roughness is a very important consideration in evaluating the condition of a given roadway, as it affects the ride quality for the user and the vehicle operating cost. Because of this importance, numerous devices have been developed which either measure the actual longitudinal profile of the road, such as the surface dynamic profilometer (SDP), or summarize the vehicular response

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to roughness, such as the Mays ride meter (MRM). Each device generates its own individual measurement of pavement roughness. Unfortunately, there has not been common acceptance in the highway engineering community of a standardized method for relating these individual measurements to a common scale. A variety of roughness summary statistics can be computed from the profile data. Instruments that summarize the response of a vehicle to road roughness, designated response-type road roughness meters (RTRRMs), are sensitive to both vehicle parameters and operating speed. The output from these instruments must be transcribed onto a common scale if the data are to be used for anything but a direct comparison of the relative roughness of sections over a short time period. In order to standardize the output of the many devices, a generalized roughness index (GRI) can be used as a standard to which all roughness measurements may be correlated. A useful GRI must satisfy the following criteria:

1. The output should correlate well with a variety of RTRRM systems.
2. The computations should be fast, simple, and easily understood.
3. The GRI must be repeatable and stable over time.
4. It should have a relatively low sensitivity to error in the input data.
5. It should correlate highly with other roughness statistics.

The major objective of this paper is to evaluate the effectiveness of various common roughness summary statistics and recommend one to be used as a generalized roughness index (GRI). The techniques for defining a GRI require the analysis of profile data. Since these data are difficult and expensive to obtain, the sensitivity of these statistics to the quality and quantity of the profile data was analyzed to determine the precision and sampling interval required for each of the statistics.

Techniques for Developing Roughness Statistics

A review of the state of the art in roughness device calibration was undertaken to ensure that the most recent procedures would be included in this research. Based on this review, calibration procedures and computer models developed at the University of Texas and Michigan and at Penn State University were obtained [*1–3*]. In general, two types of roughness calibration statistics are currently recommended:

(*a*) quarter-car simulation and
(*b*) root-mean-square vertical acceleration (RMSVA).

Queiroz [*4*] has proposed a combination of the quarter-car simulation and RMSVA techniques. Under this approach, the RMSVA procedure is used to analyze the profile data, and the results are correlated with a quarter-car index value.

Quarter-Car Simulation

Historically, the Bureau of Public Roads (BPR) roughometer was one of the first devices developed to measure road roughness at normal highway speeds. This instrument was mounted on a single-wheel trailer and was designed to respond to roughness in a manner similar to the response of one quarter of a passenger vehicle. This device was widely used to measure roughness, and since that time, mathematical models that simulate the response of one fourth of a vehicle "traveling" over pavement profile data have been developed and used as roughness summary statistics for calibrating RTRRM systems.

A quarter car can be described mathematically with two second-order differential equations

$$M_s\ddot{Z}_s + C_s(\dot{Z}_s - \dot{Z}_u) + K_s(Z_s - Z_u) = 0 \quad (1)$$

$$M_s\ddot{Z}_s + M_u\ddot{Z}_u + K_t(Z_u - Z) = 0 \quad (2)$$

where the variables are defined in Fig. 1.

Computer algorithms have been developed to produce quarter-car simulation (QCS) statistics using this model. The QCS statistics derived from this quarter car may be one of two types. The first is in the form

$$\text{QCS}_1 = \frac{1}{T}\int_0^T \left|(\dot{Z}_s - \dot{Z}_u)\right| dt \quad (3)$$

where T is the time required to traverse the section of road being tested. The second is in the form

$$\text{QCS}_2 = \frac{1}{L}\int_0^T \left|(\dot{Z}_s - \dot{Z}_u)\right| dt \quad (4)$$

where L is the length of the road section. Furthermore, $\text{QCS}_1/\text{QCS}_2 = L/T = V$, the velocity of the quarter car. In other words

$$\text{QCS}_1 = \text{QCS}_2 \times V \quad (5)$$

A constant may be used in Eq 5 to maintain consistent units between the quarter-car statistics. Because the differential equations are linear, exact solutions can be calculated, thereby avoiding the errors in numerical methods. This method is known as the transition matrix method and is presented in Ref *3*. For this study, three QCS statistics were examined:

1. QI—a quarter-car index using the vehicle parameter values from a BPR roughometer (Fig. 1). A modified version of a program developed by Maitree

Vehicle Parameters	K_t/M_s	K_s/M_s	M_u/M_s	C_s/M_s
HSRI	667	62.3	0.150	6.0
BPR	667	133.3	0.167	5.0

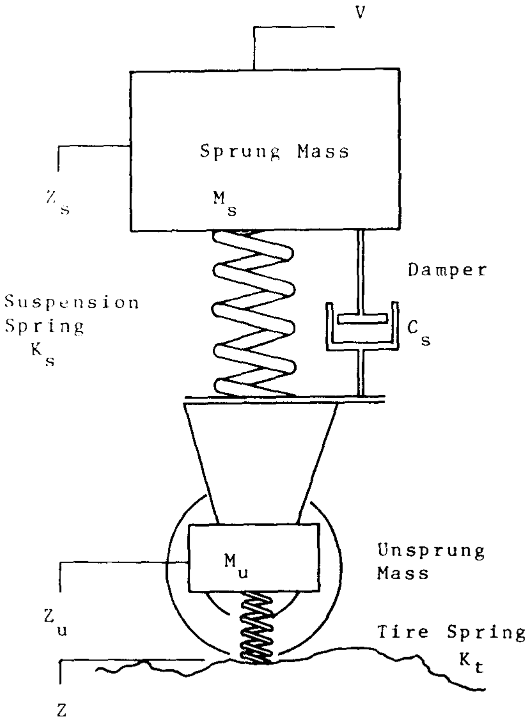

FIG. 1—*Quarter-car model.*

Srinarawat [5] was used to compute the QI statistic. The QI is in the form of QCS_2 (Eq 4), and it is in units of inches per mile.

2. Average rectified velocity (ARV)—a statistic developed by Gillespie, Sayers, and Segel [6], which is a QCS_1 derivation (Eq 3) using reference parameters developed by the Highway Safety Research Institute (HSRI) (Fig. 1) for the calculation of the index. The units for ARV are feet per second.

3. Average rectified slope (ARS)—a QCS_2 statistic also developed using HSRI parameters. It is related to ARV through the velocity term, as shown in Eq. 5.

Derivation of RMSVA

This method was named the root-mean-square vertical acceleration (RMSVA) for two reasons. First, the computation is equivalent to the second derivative of the height with respect to time of an object in contact with a profile moving at a constant horizontal speed. Such computation yields a vertical acceleration of the object. Second, a series of vertical acceleration values results from the discrete elevation points; therefore, a root mean square of these values is computed to arrive at a single value.

Let $Y_1, Y_2, \ldots Y_n$ represent elevations of equally spaced points along one wheel path of the profile. If s is the horizontal distance between adjacent points (the sampling interval), then a simple estimate of the second derivative of Y at Point i with respect to distance is

$$(S_b)_i = \frac{Y_{i+k} - Y_i}{ks} - \frac{Y_i - Y_{i-k}}{ks}$$

$$(S_b)_i = \frac{Y_{i+k} - 2Y_i + Y_{i-k}}{ks^2} \qquad (6)$$

where

$(S_b)_i$ = second derivative of Y at Point i with respect to the base length distance, b;
b = base length $= ks$;
k = an arbitrary integer used to define b as a multiple of s (sampling interval); and
s = data sampling interval, i.e., the horizontal distance between adjacent elevation points at which the profile data were taken.

and

$$VA_b = c \left[\sum_{i=k+1}^{n-k} \frac{(S_b)_i^2}{n - 2k} \right]^{1/2} \qquad (7)$$

where

VA_b = root-mean-square vertical acceleration corresponding to the base length, b,
n = total number of elevation points, and
c = a constant required for unit conversion from a spatial acceleration to a frequency domain acceleration.

The RMSVA statistic can be computed for any base length. This capability provides the technique with a strong ability to distinguish between the various components of roughness that exist in a roadway profile. The profiles of the

Texas calibration sections were analyzed for base lengths ranging from 0.15 to 19.8 m (0.5 to 64 ft), and the results of this analysis were statistically compared with the output from nine Mays meters [5]. Multiple regression analysis showed that a combination of VA_4 and VA_{16} correlated quite well with the data from the various Mays meters, with an average R^2 of 0.96. Regression analysis yielded the equation for a reference Mays meter

$$\text{MO} = -20 + 23VA_4 + 58VA_{16} \tag{8}$$

Through the correlation process described in this paper, the MO statistic will be in units of inches per mile for VA values in feet per second squared. Since the MO statistic is used for calibration of the Texas Mays meters, it has been related to the present serviceability index (PSI). The relationship between PSI and MO is

$$\begin{aligned} \text{PSI} &= 5e^b \\ b &= -\left[\frac{\ln(a\text{MO})}{d}\right]^c \end{aligned} \tag{9}$$

where e is the basis of the natural logarithm, and a, c, and d are constants derived from regression analysis and independent of any particular Mays meter. In a study done by McKenzie and Hudson [7] these constants were found to be

$a = 32$,
$c = 9.387$, and
$d = 8.493$.

Comparison of the Statistics

A primary objective of this research was to evaluate carefully the statistics with respect to their stability and response to various road profiles. The first step in the analysis was to test the sensitivity of the statistics to simulated road profiles. By controlling the profiles, the authors could test the computer programs to ensure that they were working correctly. In addition, extremely rough and smooth profiles could be generated so the behavior of the statistics to extreme conditions could be tested. We then obtained real road profile data, collected with the General Motors (GM) profilometer used by the Texas State Department of Highways and Public Transportation (SDHPT). The sensitivity of the statistics was then studied with respect to the response to random variations in the elevation measurements and the sampling interval of the profile points. The method used in the statistics to combine the information from two wheel paths and the effect of different frequency bands were evaluated. Finally, correlation equations were developed between the various statistics.

Simulated Profiles

The statistics described in this paper were tested for sensitivity to random error and sampling interval on both real profile data and simulated profiles. The nine simulated profiles used as examples consisted of three sine waves, three sawtooth waves, and three potholed surfaces, as shown in Fig. 2. The sawtooth, sinusoidal, and potholed surfaces, ranging in wavelength from 0.15 to 61 m (0.5 to 200 ft), were used to test the statistics, and it was found that for a given wavelength the roughness of a waveform varied directly with the amplitude. It was also found that the roughness of a potholed section did not vary significantly when the spacing between consecutive potholes was varied ran-

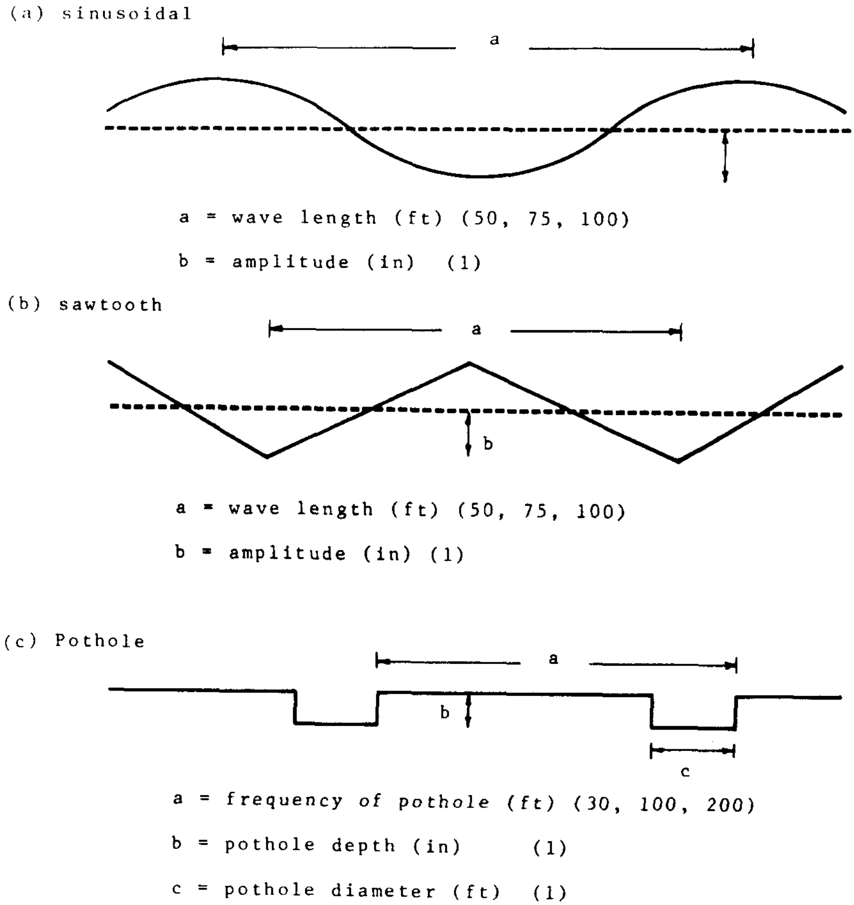

FIG. 2—*Profiles generated by the Highway Safety Research Institute for testing the statistics in the aggregate.*

domly, so long as the average spacing, and thus the total number of potholes over the entire section, remained the same. Hence, the profile examples given in Table 1 are representative of the most prominent profile characteristics, the wavelengths and pothole frequency.

In April 1983 the Texas SDHPT obtained profile data for 26 MRM calibration sections located in Austin, Texas, using a GM profilometer [*8*]. These data were made available for testing the roughness summary statistics, and the five representative sections listed in Table 2 are used here for the purpose of demonstration. The values in Tables 1 and 2 are the results of using the elevation data at 0.15-m (6-in.) sampling intervals in the computer programs.

Sensitivity Studies

The statistics were tested to determine their sensitivity to variations in the elevation measurement and to the frequency or spacing of the elevation measurement.

Random Variations—In this analysis, the sensitivity of the statistics to small random variations was tested on the simulated profiles. A random number selected within the ranges of ±0.0254, ±0.254, and ±2.54 mm (±0.001, ±0.01, and ±0.1 in.) was added to the computed elevations. All of the statistics behaved in a manner similar to that shown in Table 3. Random variations of ±0.0254 mm did not affect any of the summary statistics in a significant manner. A random variation of ±0.254 mm did cause some minor but insignificant changes in the summary statistics for some profiles. A random variation of ±2.54 mm significantly influenced the results of all the pavement statistics. In general, each of the pavement statistics changed about the same on a percentage basis.

The analysis was repeated on the real pavement profile, except the maximum variance was ±0.76 mm, with the results shown in Table 4. A variation of ±0.254 mm affected the statistics by less than 2%, except for the extremely smooth section, where the effect was approximately 8%. A random variation of ±0.76 mm affected the statistics by approximately 1% for the rough sections and almost 70% on the very smooth sections.

Data Requirements—Because of the expense of obtaining pavement profile data for a 300-m section at 0.15-m intervals, an evaluation was performed to determine the effect on the statistics of using shorter sections and reducing the data intensity. Table 5 summarizes the various statistical values for a sine wave with a 15.2-m wavelength and 25.4-mm amplitude for several section lengths and sampling intervals. From this table it is apparent that values of MO are not substantially changed by changes in either the distance between profile points or the section length. The effect of section length on QI and on ARV and ARS is very pronounced. The algorithm appears unable to produce a believable QI for 0.61-m (2-ft) intervals. Although Table 5 is for a 15.2-m sine wave

TABLE 1—*Roughness summary statistics data by profile type, using sine and sawtooth waves of 1-in. amplitude, potholes of 1-in. depth and 1-ft width, 1000-ft sections, and 6-in. sampling intervals.*[a]

Profile Type	Wavelength or Spacing	VA_4, ft/s^2	VA_{16}, ft/s^2	MO, in./mile	QI, in./mile	ARS, in./mile	ARV, ft/s
Sine wave	50	4.89	3.54	297.79	806.28	631.62	0.7310
	75	2.21	1.92	142.19	121.11	254.99	0.2951
	100	1.25	1.14	74.87	43.19	95.34	0.1103
Sawtooth wave	50	5.83	2.88	281.13	699.42	477.53	0.5527
	75	3.17	1.60	145.22	154.22	227.95	0.2638
	100	2.03	1.03	86.43	123.55	102.99	0.1192
Pothole	30	12.32	0.77	308.02	460.02	311.46	0.3605
	100	6.53	0.41	153.97	141.69	91.23	0.1056
	200	4.36	0.28	96.52	64.88	40.72	0.0471

[a] Metric equivalents:
1 in. = 2.54 cm
1 ft = 0.3048 m
1 mile = 1.61 km