Figure 11. Calibration of crude profilometer.

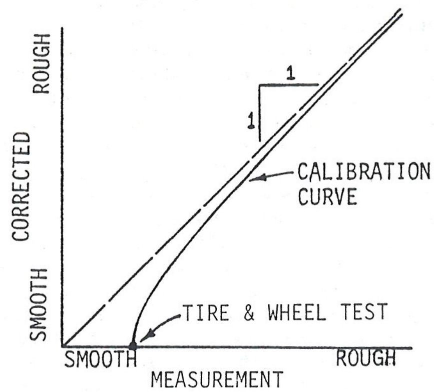
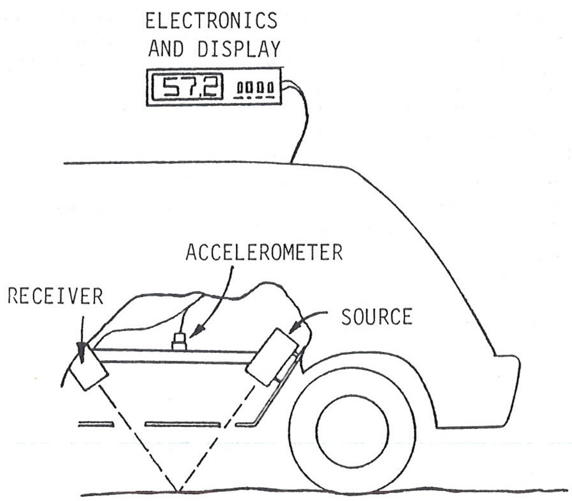


Figure 12. Noncontacting profilometer with quarter-car simulation.



sated by using a drum roller set-up or the inductive pick-up method.

Accelerometer and Noncontacting Probe

The final level of sophistication that can be achieved consists of an accelerometer together with a noncontacting probe that operates as shown in Figure 12. This system should be recognized as a GMR-type profilometer, although the actual instrumentation package would more resemble today's road meters. Note that the trimmings available on most profilometers are lacking. The system simply measures the body-to-ground distance with the probe, along with the body acceleration. After the acceleration is integrated twice, the two signals are added, which yields the profile, which is then input to a quarter-car simulation that provides the well-defined reference roughness statistic. No computers or tape recorders are needed. The calibration task is limited to the following:

1. Calibration of the probe,
2. Calibration of the accelerometer, and
3. Occasional checking of the electronic processor.

As Table 1 shows, all of the problems with existing road meter systems are eliminated.

SUMMARY AND CONCLUSIONS

The low cost and simplicity that make road meter systems so popular are offset by limited accuracy and the need for a difficult calibration, as demonstrated in the NCHRP 1-18 project (1). Means for overcoming these limitations by the addition of more complex and sophisticated instrumentation have been explored in this paper. At the level of instrumentation needed to allow calibration on something other than a known, random road surface, the system has actually become a simple profilometer. Thus, the development of improved road meter systems will lead to the development of simplified, low-cost road profilometer systems.

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Better Method for Measuring Pavement Roughness with Road Meters

M. SAYERS AND T.D. GILLESPIE

Recent research on methods for calibrating road roughness measuring systems has shed new light on improving the use of the currently popular Mays and Portland Cement Association (PCA) roadmeters. The measurement provided by these meters (accrued displacement between the rear axle and vehicle body) is discussed and shown to relate best to pavement serviceability when normalized by the time duration of the test, thus yielding a simple statistic called the average rectified velocity (ARV) of the axle-body motion. Unlike the inches per mile statistic that is commonly calculated, the ARV is shown to be valid for comparing pavements that are measured (and used) at different speeds. At the same time, the ARV concept provides a logical basis on which to establish calibration for roadmeter systems. In the absence of a universal calibration, the measurements obtained from different systems cannot be compared except in the special case where empirical correlations have been established. Accordingly, an absolute roughness scale is specified based on a refer-

ence ARV (RARV) statistic determined from a quarter-car simulation. RARV constitutes an absolute roughness statistic, rigorously defined at a given test speed, whose validity as a calibration reference has been established from field-test experience with in-use roadmeter systems. An appreciation for the ARV is important to highway engineers because the concept provides the link in understanding between current roughness measurement practice and serviceability of roads as seen by the public at normal traffic speeds.

National Cooperative Highway Research Program (NCHRP) Report 228 (1) has provided an opportunity to take an objective look at the road roughness measurement process with roadmeter systems. In so doing, it has become evident that their ultimate purpose--to assess pavement serviceability--is hampered by the choice of the measured statistic in common use. Specifically, the practice of normalizing inches of roadmeter roughness by the distance traveled (inches per mile statistic) is not appropriate to such systems because it implies that the statistic is a measure of the actual pavement properties, rather than the measure of vehicle response that it is. Further, the inches per mile statistic incorporates a speed dependence that confounds its relation to serviceability on roads that have different prevailing traffic speeds and complicates the calibration of these systems.

Roadmeter systems are subject to many other problems related to day-to-day reliability and calibration procedures, which are more visible to the user than the aforesaid limitations. Thus, it is no surprise that they would remain mostly unknown prior to a research effort that has the scope of the NCHRP project. But, once the performance and operation of roadmeter systems are well understood, we see that these systems are best used to measure the average rectified velocity (ARV) of the axle motion relative to the body.

ARV is obtained simply by normalizing the roadmeter roughness count by the time duration of the test. This statistic, which has units of length per time (e.g., inches per second), has a more direct relation to the dynamic response of vehicles to road roughness. Hence, it has more utility as a roughness measure related to serviceability. Similarly, it provides a more direct basis for calibrating roadmeter systems to a comparable roughness scale.

This paper reviews the concept of pavement serviceability and illustrates the differences between ARV and the inches per mile statistic as a measure of serviceability. A calibration reference for ARV measures is also presented.

PAVEMENT SERVICEABILITY

A primary result of the American Association of State Highway Officials (AASHO) road test was the development of the serviceability concept for evaluating the condition of the pavement surface (2). The proper measure of pavement serviceability, defined by AASHO, is an average of subjective opinions provided by a panel of judges by using a present serviceability rating (PSR) scale of 0-5, with a 5.0 being perfectly smooth and 0 being impassable. The PSR numbers were correlated with various objective measurements of pavement features through regression equations so that the objective measurements could be used later to estimate PSR. The estimate of PSR based on a measured pavement statistic is called present serviceability index (PSI). PSI values also vary from 0 to 5 and have the same physical interpretation.

At the time of the AASHO study (1955), the slope variance (SV) produced by the AASHO profilometer [the predecessor to the Carey, Huckins, Leathers, and other engineers (CHLOE) profilometer] was the objective measurement of roughness obtained on the pavement test sections, although some sections were also run with a Bureau of Public Roads (BPR) roughometer. Each of these devices produces only a single statistic, and thus the AASHO data cannot be used to provide a detailed understanding of exactly which road features influence PSR the most, other than the general conclusion that pavement roughness almost completely determined the PSI (2,3). Another finding from the AASHO study was that different regression equations were needed to relate the objective measures to PSR for different pavement types. This indicates that neither measure is truly related to serviceability; for if this were the case, a single regression equation would be valid for all pavement types. Analyses of the CHLOE and BPR roughometers have shown that they are sensitive to roughness features that are absorbed by the tires on a vehicle and have little effect on ride. At the same time, rigid pavements were found to have more of this type of roughness, and hence the measures are biased against rigid pavements (1).

The exact relation between pavement features and PSR has never been established, but by just considering the interaction among pavement, vehicle, and passenger we can be fairly certain that serviceability is a measure of the ride experienced by the users, as well as perceived wear and tear on the vehicles. A PSR of 5.0 would mean that no vibrations attributable to the road are detected by the panel member, and a PSR of 0.0 would mean damage to the vehicle. In this paper, we will proceed with the understanding that the exact nature of the PSR scale is unknown, but that equal PSR ratings are obtained for different pavements if both excite equivalent vehicle motions, in terms of both passenger vibrations (ride) and suspension and wheel motions (wear and tear). Thus, at a minimum, a single serviceability rating is a function of (a) pavement roughness features, (b) vehicle properties, (c) the individuality of the person making the rating judgment, and (d) speed.

Although the first three points were widely accepted, the speed factor is sometimes ignored, although virtually any section of pavement has a reasonable serviceability if very low speeds are maintained for reasons other than its roughness. For example, a section of pavement in a congested city area could have potholes, cracks, irregular settlement, and still be fair (PSR = 2.5) for the people it services if other conditions (e.g., children, intersections, and many driveways) restrict the speeds to less than 20 mph. Yet, if these other restrictions were removed, the same pavement might be impassable (PSR = 0) for most users at 45 mph, because the vehicle would be damaged by the roughness. Clearly, the serviceability cannot be defined by a physical measure of the pavement roughness alone, but also must take into account the average speed of the traveling public. This fact is not acknowledged in the original AASHO study, no doubt because the concern was in rating highways at high speed. Therefore, the equations provided for PSI do not include speed, and as a result, the validity of comparing PSI values for pavements that are traveled at different speeds is uncertain.

Although the above example might seem extreme, the same argument applies for highways that have close, but dissimilar, speed limits. A section of highway used at 45 mph can be a little rougher (and thus have a lower PSI as determined by the AASHO equations) than a section used at 55 mph, even though they both offer equivalent ride quality and thus equal serviceability.

Figure 1. Illustration of ABD and accumulated ABD on road 1 at 50 mph.

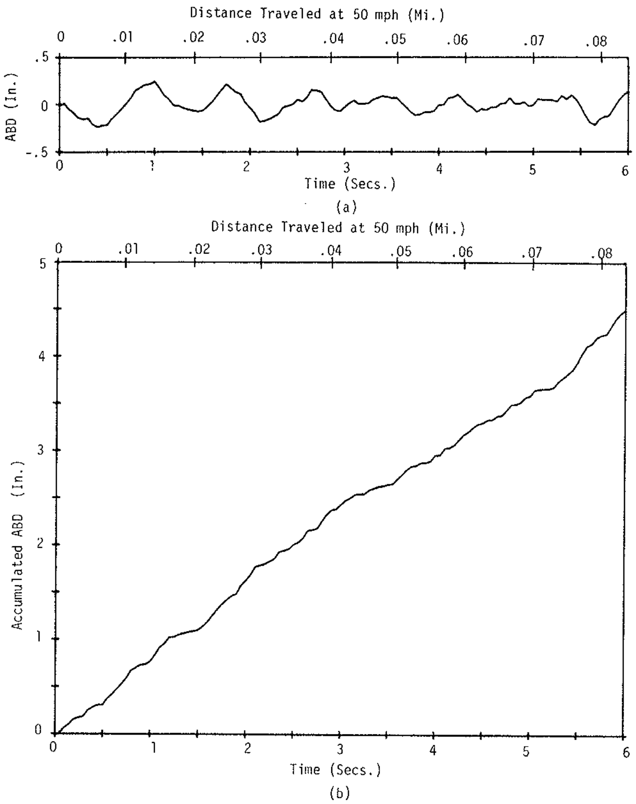
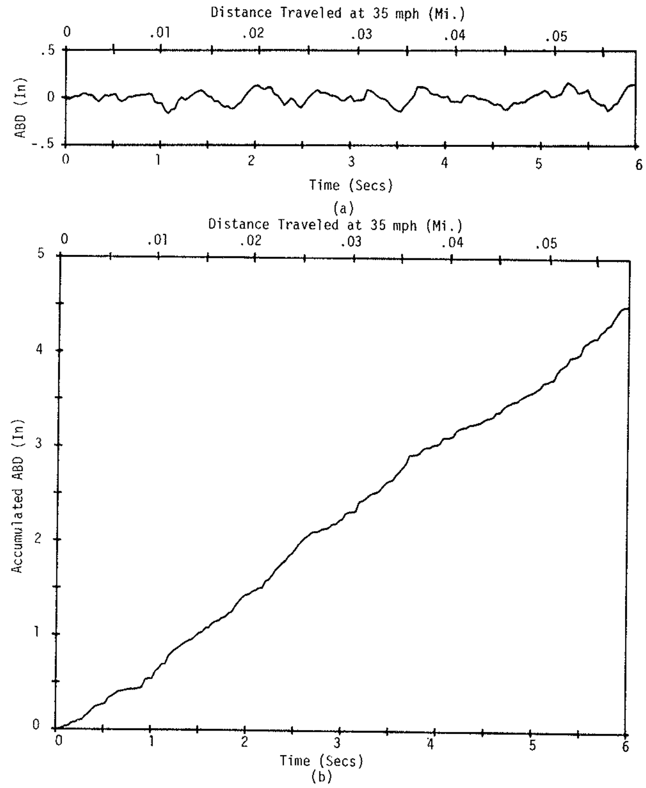


Figure 2. Illustration of ABD and accumulated ABD on road 2 at 35 mph.



RATING PAVEMENTS IN INCHES PER MILE

The CHLOE profilometer and the BPR roughometer are seldom used routinely for measuring pavement roughness anymore, mainly because they require low operating speeds that obstruct traffic and slow down the measurement process. Instead, the most popular type of system is that of a conventional passenger car instrumented with a roadmeter. Most roadmeters in use are either Mays meters manufactured by Rainhart Corporation (4) or Portland Cement Association (PCA)-Wisconsin meters (5), also available commercially from several manufacturers but sometimes fabricated by their users. Both types of meters transduce the rear-axle motion relative to the car body. Consider first the measurement process, which assumes that they transduce the motion perfectly and are perfect meters. In fact, they are not, and the resulting effects on the measurement are addressed later.

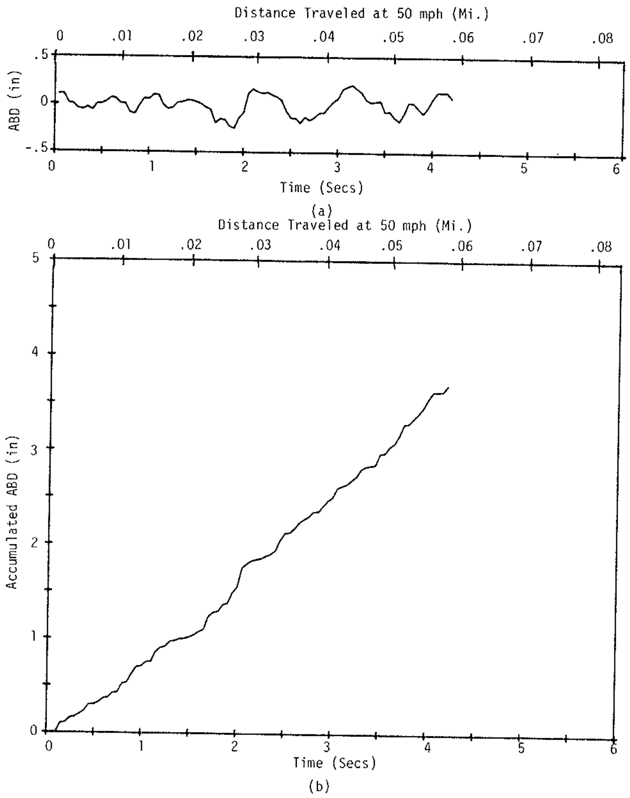
The axle-body motion is random, as illustrated in Figure 1a for a typical record of axle-body distance (ABD) versus time. Roadmeters are intended to accumulate this motion, as shown in Figure 1b for the same record. When ABD is increasing, which is to say it has a positive velocity, the two plots have identical shapes. But when the ABD is decreasing and has negative velocity, the accumulation on the meter is an inverted duplicate of the ABD plot that has a positive velocity. Therefore, the accumulation on the meter is a version of the ABD record that has the velocity rectified (i.e., unchanged when positive and inverted when negative).

[This figure and the following figures were generated on the computer for the convenience of illustrating certain effects of using a quarter-car simulation together with measured road profiles and a mathematical model of a ridemeter. The models were thoroughly validated with field tests in the NCHRP project (1) such that the results shown are indeed representative.]

Common practice in the past has been to normalize the total accumulated motion obtained by dividing it by the length of road section under test to obtain an inches per mile statistic. The measure obtained is supposedly an indication of vertical deviation per mile of length--a type of measurement that closely identifies with the engineer's notion of roughness in the roadway as seen by a vehicle. In fact, the value accumulated on the meter at any time is the product of the average rate of vehicle motion and the length of time the meter has been running. The rate of accumulation is directly related to the ride vibration amplitude at any speed. The rate normally increases with the speed, as does the level of ride vibration. However, the travel time over a given length of pavement diminishes with speed, so that the ratio (as reflected in the inches per mile statistic) varies with speed both according to the different level of ride vibration and to the different travel time. This behavior is illustrated here by some examples; a more rigorous treatment is presented elsewhere (1).

In the first example, the vehicle speed is 50 mph during the test illustrated in Figure 1 and thus, in the 6 s shown, 0.083 mile was traveled. The accumulated ABD is 4.5 in, which gives a roughness measurement of 54 in/mile. Figure 2 shows similar time histories, for a different pavement section, with a measurement speed of 35 mph. A comparison of Figures 1 and 2 reveals that both ABD plots are qualitatively similar and that the accumulated ABD in Figure 2b is also 4.5 in after 6 s. From the user's viewpoint, both pavements will cause the same wear and tear to the vehicle and produce the same intensity of vehicle vibration (ride), hence the serviceability of the pavements should be equivalent. But at 35 mph, 6 s is only 0.058 mile, and thus the 4.5

Figure 3. Illustration of ABD and accumulated ABD on road 2 at 50 mph.



in of accumulated ABD result is 77 in/mile. Therefore, judgment of roughness on the basis of the inches per mile statistic leads to the erroneous conclusion that road 2, used at 35 mph, is worse than road 1, used at 50 mph when, in fact, both roads appear equivalent to the user public.

Not only do the inches per mile numerics distort the underlying pavement serviceability, they do not relate to fixed physical features of the road as one might suppose from the implied meaning of the statistic. Regardless of the final units, the statistic is still based on the response of the vehicle to the road at the measurement speed. If the measuring speed on the second road (Figure 2) is increased to 50 mph, the ride is rougher, with more ABD motion, as shown in Figure 3. If the speed limit is raised for this road section, so that 50 mph would be representative of the typical user speed, the road would provide less service because there would be more wear and tear on the vehicle, along with a poorer ride. However, because of the decreased transit time, the accumulated ABD will decrease to 3.7 in, which results in a roughness of 65 in/mile. Thus, this measure would mislead the casual observer into thinking that the road offers better service at 50 mph than at 35 mph.

BETTER STATISTIC FOR RATING PAVEMENTS

Clearly, the problem in comparing roadmeter accumulated ABD measurements taken at different speeds results from the conversion of the measurement to the inches per mile statistic. A more useful statistic is obtained by dividing each accumulated ABD measurement by the time duration of the test. By using the same three examples, the data from Figure 1 would yield a measurement of 0.75 in/s. The data in Figure 2 would also give 0.75 in/s, and the data in Figure 3 would give 0.88 in/s. It is clear from these inch per second statistics that road 1, at 50 mph, provides the same service to its users as road 2 at 35 mph. The change in serviceability when the speed for road 2 is increased from 35 to 50 mph is equally clear from these numbers.

Division of the accumulated axle-body distance by a time interval results in an average velocity. Since the roadmeter rectifies the axle-body motion, the statistic being calculated is the average rectified velocity (ARV) of the axle-body motion. The conversion factor between ARV and inches per mile is the time needed to travel one mile at the test speed. For 50 mph, this factor is 72 s/mile when ARV is given the units inches per second. Thus, data recorded in inches per mile can be easily converted to ARV, after which measurements taken at different speeds can be compared directly. Note that the practice of converting the roughness measurements to an equivalent 50 mph test speed by multiplying the inches per mile figure by the ratio actual speed/50 results in the ARV, which has the units inches per 72 s. This measure is equally valid, but should be recognized for what it is--ARV represented with unconventional units.

Because the basic measure produced by a roadmeter depends on vehicle response, and is therefore speed dependent, measurements must be taken at speeds typical of the users of the pavement. Open highways should be run at 50 mph (or even 55 mph), but other roads should be run at normal prevailing speeds. Measurements made at other speeds (for example, 35 mph on an Interstate highway) are not valid and cannot be converted to an equivalent measure at the correct speed without a tedious correlation exercise. Although all roads have qualitatively similar roughness characteristics, any one section is unique and no universal relation between roughness at different speeds will accurately correct for speed on every road (1).

EFFECTS OF ROADMETER TRANSDUCER FEATURES ON MEASURED ROUGHNESS STATISTICS

Up until this point in the discussion, we have assumed that the roadmeters are capable of measuring ABD perfectly and continuously. In fact, current Mays and PCA meters employ transducers that have discrete steps that can only identify the ABD as being within a certain interval. The original PCA meter used switches 1/8-in on-center, and the Mays meter uses an optical pick-up that had 1/10-in steps. Although different versions of the roadmeters detect motion with different hardware setups, they all act to quantize the ABD, as illustrated in Figure 4. For the Mays meter, each step (as in the figure) corresponds to one incremental step in the advance of the strip chart; for the PCA meter, each step corresponds to a count in one of the registers. [Note that the paper length produced by the Mays meter must be multiplied by a scale factor of 6.4 in/in to relate paper displacement to ABD. Similarly, the unweighted sum of PCA meter counts must be multiplied by the quantization interval (typically 1/8 in/count). The practice of weighting the PCA meter counts before summing them is not considered in this paper. Although PCA meters can produce the same measurements as a Mays meter, and thus ARV, the converse is not true and therefore the simple accumulated ABD measure is seen to be of more universal interest.] Note that although the quantized version of the accumulated ABD plot is not a true representation (see Figure 1b), the fractional error in the resulting accumulated ABD is small if the measurement time is long enough. A statistical analysis, which employed random process theory, showed quantization effects to be negligible for

Figure 4. Illustration of accumulated ABD obtained by a meter with quantization.

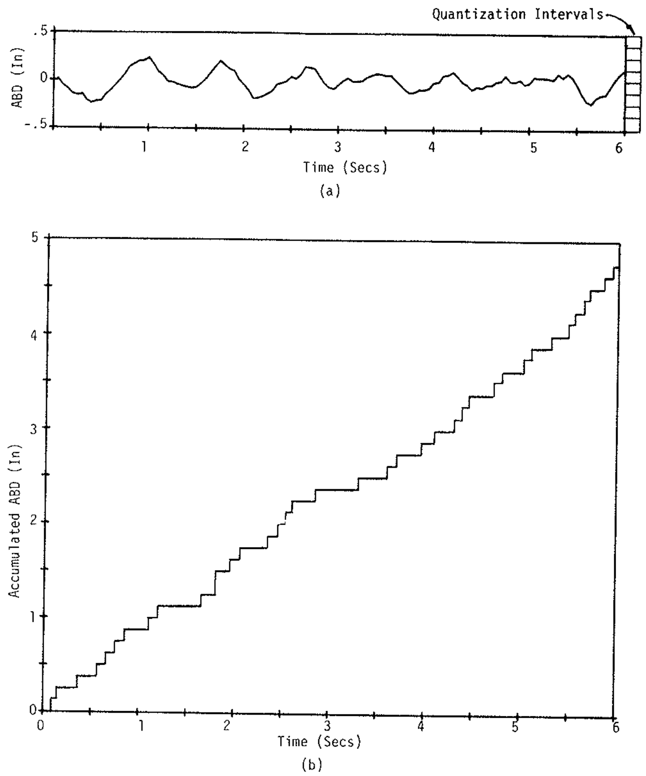
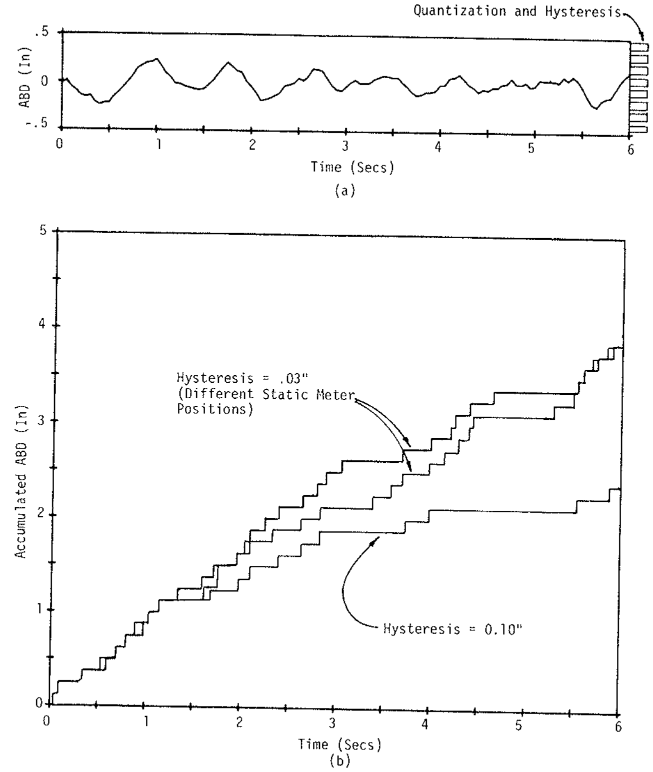


Figure 5. Illustration of accumulated ABD obtained from meters with different hysteresis levels and static positions.



reasonably long measurement times when the axle-body motion is fairly large compared with the quantization level (1). (The 6-s record length in the figures was selected to clearly illustrate roadmeter operation but is really too short for accurate measures with commercial meters.) In general, if four or more quantization intervals on a Mays or PCA meter are frequently activated in measurement, the quantization should not be a problem. But if the road is so smooth that only a few intervals are activated, a random error will be included in the measurement, depending on the equilibrium position of the axle relative to the switching intervals.

Commercial Mays and PCA meters also have hysteresis in the transducers. This is usually a result of spaces between the switches, as illustrated on the side of Figure 5a. But hysteresis can also be caused by free-play somewhere between the axle attachment and the position sensor, as, for example, with loose mountings or worn bearings. Figure 5b shows the accumulated ABD for two hysteresis levels and also for a second axle-body equilibrium position for one of the levels. The figure illustrates that (a) hysteresis acts to reduce the accumulated ABD from its true value (shown in Figure 1a) and (b) hysteresis, together with the quantization, introduces a random error that depends on the equilibrium ABD within the center switch interval. The practical importance of these two effects is apparent from Figure 6, which compares ARV measurements taken simultaneously from two commercial roadmeters that were installed in the same vehicle. The figure shows that the loss in measured ARV is more or less constant and not proportional to the true ARV. In addition, more scatter occurs with the high-hysteresis meter, which has a standard residual error of 0.140, than for the lower-hysteresis meter, which has a standard residual error of 0.097. The standard residual error used to compare these two measuring systems is the ratio of the range of scatter to the range of measured values and defines that portion of the standard deviation of one measurement not accounted for in the correlation with the second measurement.

In practice, hysteretic losses can be compensated, on the average, by calibration by using regression equations. However, the increased scatter cannot be reduced by any practice other than by reducing the hysteresis. The calibration, though imprecise, eliminates trends correctly if a large number of roads are included and all measurements are converted to ARV. If the calibration is to be used to relate measurements taken at different speeds, it is vital that all inches per mile measurements be converted to ARV. This is obvious from the figure and preceding discussions because the hysteretic effect is a constant loss of ARV and, therefore, corresponds to a different inches per mile value at each speed. Thus, a calibration obtained from inches per mile statistics measured at different speeds will have even greater scatter. Figure 7 illustrates the scatter effect by showing the same data used in Figure 6 plotted in inches per mile units. The need for presenting calibration curves in terms of ARV instead of the inches per mile statistic is, of course, another argument for its use.

REFERENCE ARV MEASUREMENT

The most fundamental problem in calibrating roadmeter systems has been the lack of a well-defined absolute reference measure against which to calibrate. ARV (as well as inches per mile) is a measure of vehicle response at the selected test speed, so no single objective measurement of pavement roughness can be expected to relate to roadmeter statistics at arbitrary test speeds. Further, since

Figure 6. Linear regressions of Mays and PCA meter measurements of ARV against true ARV when mounted in one vehicle.

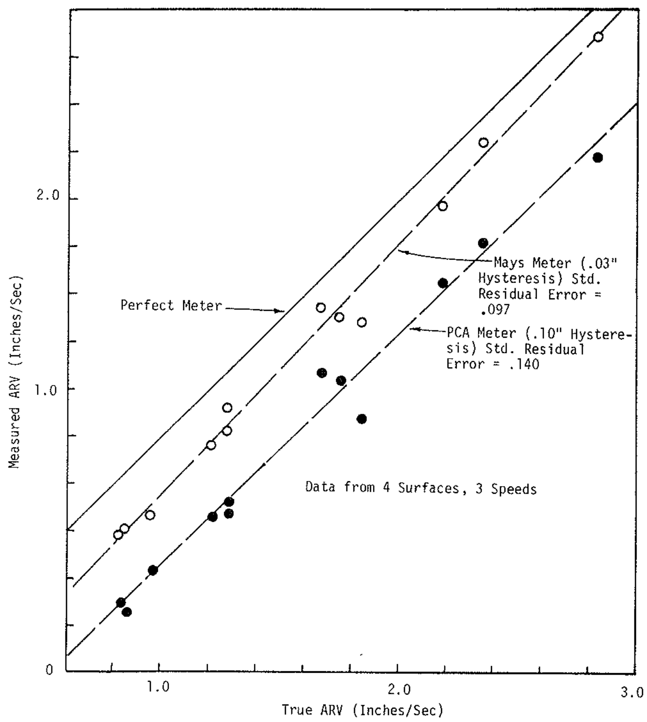


Figure 7. Linear regressions for Mays and PCA meter measurements of inches per mile against true inches per mile.

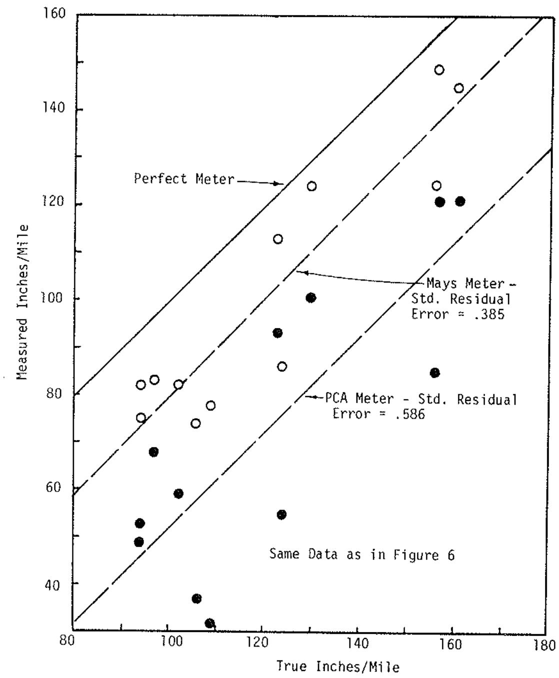


Figure 8. Reference pavement roughness measuring system.

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

$$M_s\ddot{Z}_s + M_u\ddot{Z}_u + K_tZ_u = K_tZ$$

$K_s/M_s = 62.3\ 1/\text{sec}^2$

$K_t/M_s = 653\ 1/\text{sec}^2$

$M_u/M_s = .150$

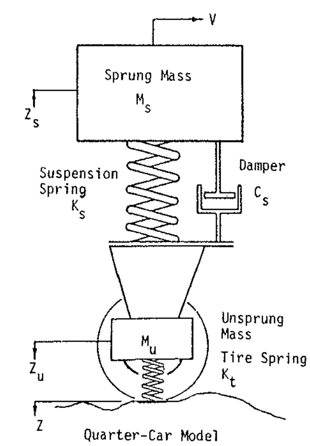
$C_s/M_s = 6.00\ 1/\text{sec}$

$$\text{RARV} = \frac{1}{T}\int_0^T |\dot{Z}_s-\dot{Z}_u|\,dt$$

T = Measurement time (sec)
= 3600 · L/V

L = Road length (miles)

V = Speed (mph)



individual vehicles and roads have unique properties, perfect agreement between any two systems, even after calibration, is impossible. But clearly, the reference measure should agree closely with the measures made with roadmeter systems. In essence, a reference pavement roughness measure should:

1. Provide a measure that correlates highly with PSR for all speed and pavement conditions,
2. Provide a measure that correlates well with existing roadmeter systems for all conditions, and
3. Be clearly defined to the extent that measurements taken anywhere, at any time, have the same scale.

By and large, these objectives are met by use of the ARV concept to describe pavement roughness as measured by roadmeters and by defining a reference against which to calibrate. A reference system is presented in Figure 8 that is defined by the differential equations and parameter values shown in the figure. These equations can be manipulated analytically to provide a linear response function or copied into a digital computer simulation. Alternatively, a physical system can be built that treats the equations as the performance objectives. The most practical physical system is an electronic circuit that, when given a voltage proportional to pavement profile at the correct speed, provides an output voltage proportional to the axle-body motion. Of course, the consequence is the need for an instrument for profiling actual road sections, a natural result of defining a roughness measure so precisely. In fact, the precision of a reference ARV (RARV) measurement is limited only by the precision of the profilometer. With existing General Motors Research Laboratory (GMR)-type profilometers, this results in errors of less than one percent.

The adequacy of the RARV statistic defined in Figure 8 has been established by experimental correlation with a number of roadmeter measurement systems (1). A roadmeter measuring system can be calibrated to the RARV roughness scale by using regression equations to relate the true RARV value to the ARV measurement over a selection of roads. The resulting numeric is then designated the calibrated ARV (CARV), which ideally agrees closely with the RARV value. However, a random error is still present, which reflects the uniqueness of each roadmeter system. Although temptation is to report results in the format familiar to most roadmeter users (such as in/72 s = inch/mile at 50 mph), in fact there is no universal inch per mile standard that will yield the same meaning to all users. But on the reference scale, the existing data show that, on a fair road (RARV = 1.0 in/s), the roadmeter systems have a precision of about 10 percent, but on smoother pavements, the relative error is much greater and can be on the order of 50-100 percent. On the other hand, roadmeter systems demonstrate better accuracy on rougher roads (5 percent and better) (1).

REPORTING ARV MEASUREMENTS

In all, three classes of ARV statistics have been presented. The first, ARV as obtained with a roadmeter, will include effects of meter hysteresis and individual vehicle response properties as well as the pavement properties and measurement speeds. Raw ARV measurements from different systems do not quantify roughness on a common scale, and any comparisons between ARV measures from different systems are not valid. The second class is RARV, a well-defined property of pavement profile at a given (simulated) measuring speed. It requires a profilometer, together with the vehicle simulation shown in Figure 8. Its precision is limited only by the precision of the profilometer; errors less than one percent (0.01 in/s) are easy to maintain with current profilometers (1). The third class is the CARV measurement that is obtained by using the regression relation between raw ARV values from a given roadmeter system and the true RARV values. CARV is the best estimate of RARV that can be made with a particular roadmeter system.

CARV measures taken by different systems can be compared directly because they are based on the same RARV scale. Measures taken at different speeds are also comparable if they are taken at typical traffic speeds. Because the ARV measure is dependent on speed, roughness measurement practice with roadmeters will be improved by subscripting measurements with the test speed (e.g., $CARV_{35}$ = 1.6 in/s).

The validity of the RARV statistic for all types of pavement has not yet been completely established in the field, although the limited data gathered during a correlation program show no bias for different pavement types (1). Because the RARV statistic is influenced by the same roughness features that cause typical ride and suspension motions, unlike the CHLOE profilometer and BPR roughometer, there is no obvious reason to suppose that the RARV is biased by pavement type. Hence, it is suggested as a single objective measure of pavement serviceability for all conditions until a better measure can be developed through further research to relate subjective ratings to specific road roughness qualities.

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Road Roughness: Its Evaluation and Effect on Riding Comfort and Pavement Life

A.A.A. MOLENAAR AND G.T. SWEERE

This paper describes the evaluation of road roughness and its influence on driving comfort and pavement deterioration. Distinction is made between an inventory and a diagnostic survey. The equipment used for both surveys is described. They are a ridemeter for the inventory survey and a high-speed profilometer for the diagnostic survey. Since the ride index, which is given by the ridemeter, is dependent on the measuring vehicle, relations are established between the ride index and fundamental indicators of road roughness as determined with the high-speed profilometer. Based on measurements with the high-speed profilometer, the impact of road roughness on the structural deterioration of the pavement and on the riding comfort is calculated. Also, the impact of road roughness on the safety of the road user is described. By using the results of these calculations and the relation that exists between ride index and fundamental indicators of road roughness, acceptance levels for the ride index were established. These acceptance levels can be used as a guide in the evaluation of the results of the inventory survey.

In order to know whether pavement is still in a good condition, the highway engineer should frequently perform condition surveys. Those condition surveys should consist of monitoring the strength characteristics (e.g., deflection, cracking, and rutting), skid resistance, and roughness of pavements (1). Since road roughness affects, to a large extent, the dynamic loading of the pavement caused by the tire, it also affects the development of the structural deterioration of the pavement and the safety of the road user. So road roughness should be taken into account in evaluating the strength of the pavement and the safety of the road user (Figure 1). Because evaluation of a whole road network will result in a mass of data, the survey should be done in two phases:

1. An inventory survey and
2. A diagnostic survey.

The inventory survey can be done by means of measurements that are easy and cheap to use and can be executed at high speed. To this group of measurements one can count the Mays meter, the Portland