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Abridgment

Overview of Road Meter Operation in Measuring Pavement Roughness, with Suggested Improvements

M. SAYERS AND T.D. GILLESPIE

Road meter systems that measure vehicle response to pavement roughness have limited accuracy, but more importantly, cannot be calibrated validly for use on all types of roads without access to a General Motors Research Laboratory-type profilometer. Even with good practice on the part of the users that eliminates the obvious effects of varied tire pressure, cargo weight, faulty components, and the like, limitations inherent to the road meter system remain. These limitations are due to the unique dynamic properties of each vehicle, the nonlinearities inherent to the vehicles and road meter instruments, and nonuniformities of the tire and wheel assemblies. This paper explores various improvements to road meters that will reduce the required calibration effort. The major source of nonlinearities in the vehicle-road meter systems are due to the road meter instruments and can be eliminated by the use of an equivalent electronic meter based on a linear transducer. With linear meters, it becomes possible to measure and correct for vehicle motions caused by tire and wheel nonuniformities. This can be done in the laboratory on a smooth drum roller or by special processing of on-road measurements keyed to wheel rotation as detected by an inductive pickup. However, even then, reference road-type surfaces are still required for calibration to scale the vehicle dynamic response. Only by the addition of accelerometers is it possible to compensate for vehicle dynamic response by simpler means of calibration. With this level of instrumentation, the road profile can be roughly determined and the road meter system has become a crude profilometer.

Road meter systems have become increasingly popular for quantifying pavement serviceability due to their relatively low cost and simple operation. These systems consist of a conventional automobile or special trailer, together with a road meter [such as

Figure 1. Typical installation of road meter in vehicle.

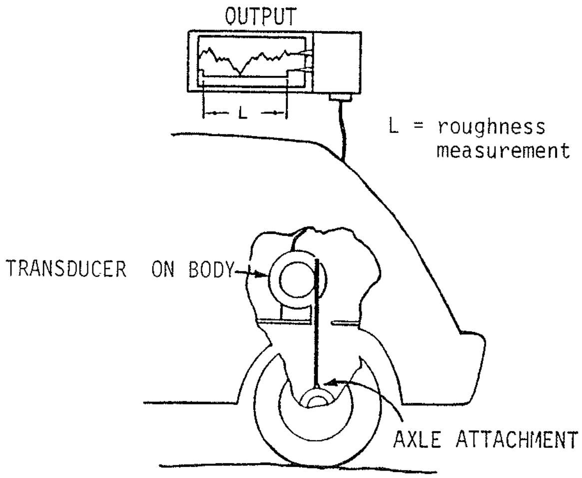
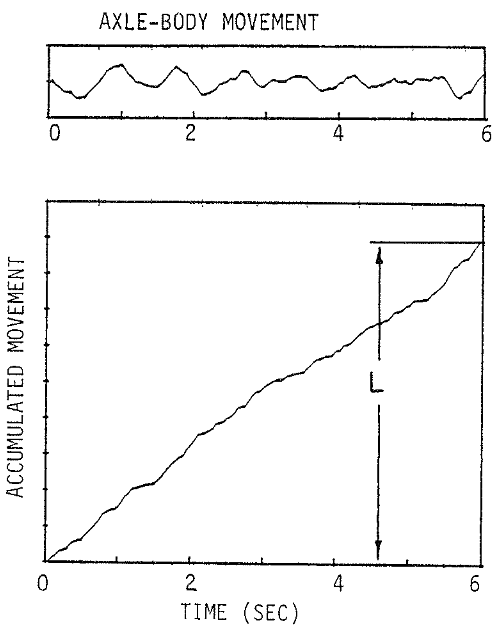


Figure 2. Relation between the road meter measurement and the axle-body movement of vehicle.



a Mays meter or Portland Cement Association (PCA)-Wisconsin meter] that measures motion of a solid axle relative to the vehicle body. Figure 1 shows the essential layout of a typical road meter system. Traversing a road, these motions detected by the road meter constitute the response of the vehicle to road roughness; thus, road meter systems are often called by the more technical name of response-type road-roughness-measuring systems. Ideally, the road meter instrument accumulates the movement of the axle relative to the body, as shown in Figure 2. The total accumulated movement, normalized by the length of the pavement (or more properly, by the time duration of the measurement), is then used as the roughness numeric.

This approach to measurement of road roughness is prone to many sources of variability, such that frequent calibration is needed to maintain acceptable accuracy. Due to shortcomings in the available calibration methods, the National Cooperative Highway Research Program (NCHRP) has sponsored a research project (1) to examine the problems in the calibration and use of road meter systems. The findings of that research indicate that valid calibration methods for existing systems are necessarily and unavoidably time consuming. This paper draws on these findings as a start in addressing the question: Can road-meter-type systems be improved to provide better accuracy and require less calibration effort? The alternate approach for measuring road roughness is with a General Motors Research Laboratory (GMR)-type profilometer, which offers greater precision and flexibility, together with much more modest calibration requirements. But the high initial cost of the profilometer puts it beyond the reach of most highway agencies. In this paper, the GMR profilometer represents a standard of performance that the suggested improvements in road meter design seek to reach.

PROBLEMS IN CALIBRATING ROAD METER SYSTEMS

Any calibration method for road meter systems must meet the simple criterion that two systems, properly but separately calibrated, be able to produce nearly identical roughness measurements for any section of road. If this is the case, the calibration is valid.

The first problem in calibrating road meter systems has been the lack of a well-defined roughness numeric that could be used as a reference for the calibrated roughness scale. The present serviceability rating (PSR), developed by the American Association of State Highway Officials (AASHO) (2), requires a panel of judges to subjectively rate the pavement section. PSR is thus an imprecise and inconvenient calibration reference. As a part of NCHRP project 1-18 (1), a reference roughness statistic was developed for the purpose of calibrating road meter systems. By its exact nature, it requires a profilometer to determine its value for existing road sections. But, even with the capability of assigning objective reference roughness values to surfaces, calibration of road meter systems is complicated by four categories of characteristics inherent in passenger cars, trailers, and road meters. These characteristics, outlined below, cannot be eliminated from existing systems by even the most diligent efforts in terms of maintenance and proper use of the equipment and so must be dealt with by the calibration process.

Vehicles That Have Unique Dynamic Properties

The overall dynamic properties of a vehicle are determined by the weight, compliance, and damping properties of its individual components. The properties differ from vehicle to vehicle and over the life of a vehicle. The properties of one vehicle can also change with environmental conditions; for example, damping provided by shock absorbers nearly always increases at colder temperatures. Since every vehicle has unique response properties, no two vehicles can be used to measure exactly the same quality of roughness. Tailoring of the dynamic properties of vehicles to match the reference is beyond the scope of available technology. Vehicle sensitivity to unique features in a roughness spectrum can be reduced by installing very stiff shock absorbers, and this practice is recommended as means for improvement (1).

But, overall, one must recognize that differences exist among vehicles and adjust roughness measurements obtained from a particular road meter system with empirical regression equations obtained in a calibration. Because pavements each have a unique roughness spectrum, a road meter system can overrespond to one road section (relative to a reference

Figure 3. Effect of hysteresis in road meter on the measured roughness statistic.

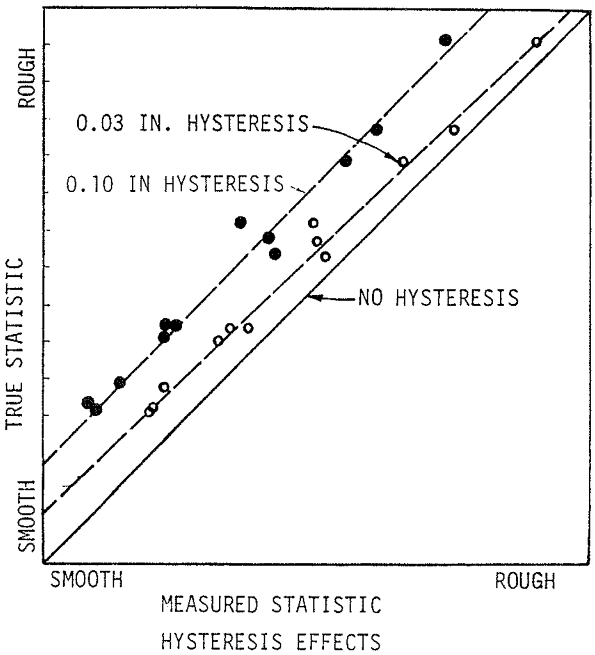
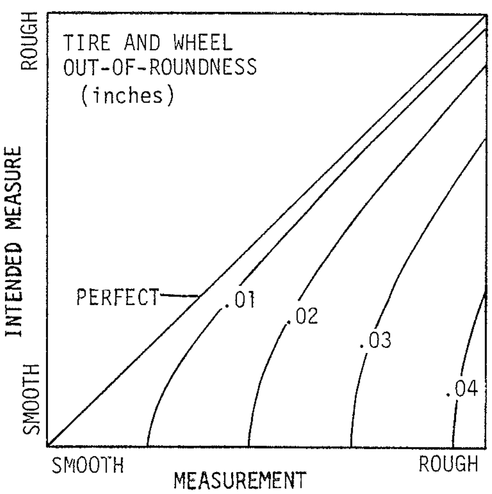


Figure 4. Effects of tire and wheel nonuniformity on the actual road meter measurement.



vehicle) and underrespond to another. This produces a random error and, to prevent bias in the regression equation, a number of pavements must be used to provide the data base for the regression.

Vehicles Are Not Linear

Vehicles contain many components that have friction or free play between them and are damped mainly by shock absorbers that are tuned by the manufacturer to provide a good ride over all operating conditions by giving them complicated nonlinear properties. Thus, if the roughness spectra of two surfaces differ by a factor of two, the corresponding vehicle motions will generally change by a different factor. Another characteristic of nonlinear systems is that the response at one frequency is dependent on the excitation at other frequencies. Thus, calibration must involve broad-spectrum roughness typical of real roads. Also, the best regression equation may not be a straight line that passes through zero, so the calibration must include at least two different levels of road roughness.

Road Meters Are Not Linear

Although road meters are intended to transduce and accumulate axle-body motion, as shown in Figure 2, they do so by employing a number of discrete switches that are only capable of detecting position within a certain interval. As a result, they quantize the axle-body position and create random error and compromise meter repeatability when the road is so smooth that the size of the axle-body motion is close to the quantization interval.

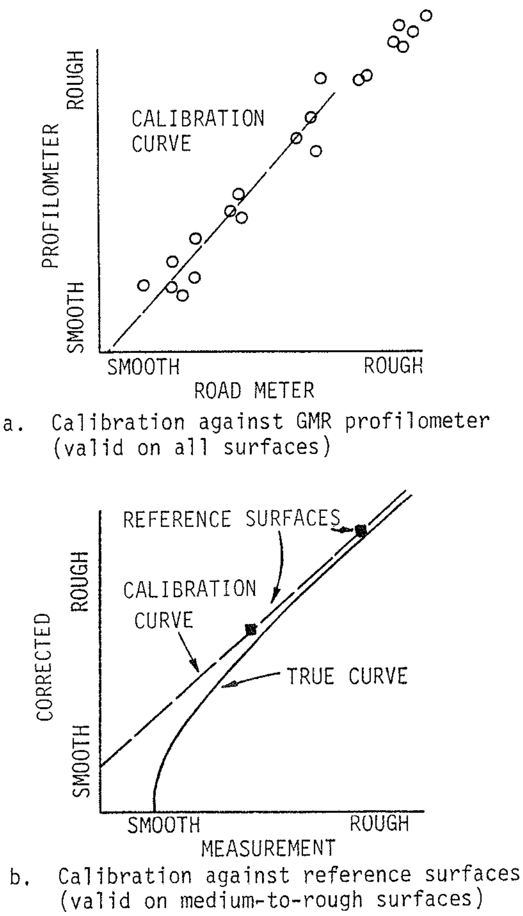
A more serious problem with modern road meters is that there are gaps between the switches, so that when the axle-body position moves from one switch to another, the response is not immediate. If the motion should reverse in this gap, a count is lost. This effect (called hysteresis) results in a roughness measurement that is lower than the true value. Until this time, hysteresis has not been recognized as important to performance and hence is variable among and within models of commercial road meters. Figure 3 demonstrates the effects of hysteresis by comparison of measurements taken simultaneously with two road meters installed in a single passenger car. Note that regression equations between the true roughness values (obtained with a linear transducer) and the measured values do not pass through zero and that the loss due to hysteresis is fairly constant for all roughness levels. In addition to this constant effect, random error also increases with the hysteresis in the road meter. In practice, the hysteresis nonlinearity in many commercial meters is so large that the vehicle nonlinearities are trivial by comparison.

Tires and Wheels Are Not Round

A road meter system not only responds to pavement roughness but also to other disturbances, most notably those caused by nonuniformities in the rotating tire and wheel assemblies. Whether the nonuniformity is caused by imbalance, runout (dimensional out-of-roundness), variation in radial stiffness, or all three, it is manifest as a periodic forcing at the rotation frequency of the wheel (approximately 10 Hz at 50 mph). Although the forcing does change with speed, at one particular speed it always has the same amplitude. Hence, its effect on the roughness measurement is more noticeable on smooth roads. Figure 4 shows this effect for different levels of wheel runout amplitude. Tire and wheel nonuniformities can be reduced, but a perfectly uniform assembly is impossible to obtain and roughness measurements on smooth roads will always be biased, as shown in the figure.

In practice, the rightand left-hand wheels will always have slightly different circumferences; as a result, the phasing between them will slowly change. When the nonuniformities from each side are in phase, the axle receives maximum excitation. And when they are completely out of phase, they cancel and provoke a minimum response. The distance needed for the phasing to cycle from in-phase to out-of-phase to in-phase again can be more than a mile. Accordingly, measurements on smooth roads may be subject to a slowly changing error that is consistent only over long distances. Measurements for sections shorter than one mile should be obtained by averaging the results of several runs together to reduce the random error from this source.

Figure 5. Examples of road meter calibrations.



Calibration of Existing Road Meter Systems

This outline of the quirks and complicated behavior of existing road meter systems should make clear that a valid calibration is no small task. Each of the four categories discussed above must be addressed by the calibration process if on-road measurements from different systems are to be converted to a common roughness scale. Two approaches are possible and are illustrated in Figure 5.

First, regression equations can be calculated by running the road meter system over a number of roads, together with a GMR-type profilometer equipped to provide the reference roughness measures. Vehicle dynamics, nonlinearities, and tire and wheel nonuniformities will all be included and taken into account by the regression relationship that acts as the calibration curve (see Figure 5a). Since tire and wheel nonuniformities provoke a speed-dependent response, different regressions should be made for each measurement speed used in normal practice. And since vehicle properties change with time, temperature, and other variables, calibrations must be conducted frequently. Due to the uniqueness of any one road section, 10 or more sections should be included for each regression to avoid biasing the calibration. This method has been demonstrated to be effective; however, it is time-consuming and requires access to a profilometer, which is both rare and expensive.

A second approach, which eliminates the need for a profilometer, is to perform the calibration with surfaces that have known roughness properties. This can be done with hydraulic shakers, by responding to tape-recorded reference profile signals, or by fabricating artificial surfaces that have roughness properties typical of real roads. (However, a surface that has a roughness spectrum unusual for real roads cannot provide a calibration that is valid for on-road measurements.) Artificial surfaces were designed as part of the NCHRP project 1-18 to be traversed at 15 mph and to provide excitation typical of rough, bituminous roads that are traversed at 50 mph. The roughness value associated with the surface is defined by its profile; hence, the precision of the calibration is limited by the precision of the surface profile. By reducing the calibration speed, the task of minimizing background roughness from the underlying surface and from fabrication imprecision is reduced. The surfaces were designed to be average to the extent that they had no peculiarities that were significant enough to bias the calibration.

The main problem with a reduced-speed type of surface or a hydraulic shaker is that forcing due to the tire and wheel nonuniformities is not replicated because the wheels are not rotating at the proper rate. As Figure 5b illustrates, the resulting calibration is reasonably accurate for moderate and rough pavements (assuming tire and wheel nonuniformities are small due to good maintenance practice), but not for smooth pavements. If the magnitude of the tire and wheel nonuniformities were known, the calibration curve could be modified analytically, as shown in Figures 4 and 5b; however, it is impossible to establish this magnitude with existing meters.

POSSIBLE IMPROVEMENTS IN ROAD METER DESIGN

After a review of the operation and calibration of road meter systems as they now exist, hardware changes that could improve accuracy or ease the task of calibration can now be considered. Table 1 lists, for a number of instrumentation types, the minimum calibration that would be required to correct for each of the four categories of road meter and vehicle performance characteristics that act together to require such a lengthy calibration process.

Note that, for the basic Mays meteror PCA meter-based system, the tire and wheel nonuniformity problem puts the tightest constraints on possible calibration methods, as only a regression with a profilometer is valid. But, if the user of such a system is not interested in rating smooth pavements, the effects of tire and wheel nonuniformities are not as important, and then the major constraints are imposed by the nonlinearities in the system.

Linear Transducer

Given that the main nonlinearities in a road meter system are contributed by the meter, the obvious first step in hardware improvement is their elimination. The most simple device that would accomplish this is based on a velocity transducer mounted exactly like a road meter transducer between the axle and body of the vehicle, as shown in Figure 6. The output voltage, after it has been rectified and integrated electronically, is proportional to the accumulated axle-body displacement that existing road meters try to measure. This type of road meter eliminates hysteresis and quantization effects on roughness measurements, requires fewer parts than existing meters, and, if mass produced, could be much less expensive. Building such a meter from scratch today costs about $200 in parts, including power supply, transducer, electronics, and display.

Perhaps a more significant advantage of a linear transducer over a conventional road meter is that

Table 1. Minimum calibration efforts required to correct for performance variables.

Type of Instrumentation	Performance Variables: Individual Vehicle Dynamics	Vehicle Nonlinearities	Meter Nonlinearities	Tire and Wheel Nonuniformities
Mays meter, PCA meter[a]	Artificial surface[b]	Two artificial surfaces[b]	Two artificial surfaces[b]	Regression equations from real roads and profilometer
Linear transducer	Artificial surface[b]	Two artificial surfaces[b]	None	Smooth drum rollers
Linear transducer, inductive rotation pickup	Artificial surface[b]	Two artificial surfaces[b]	None.	Single road test, spectrum analyzer or computer
Two accelerometers	One special surface[c]	One special surface[c]	None	Smooth drum rollers
Two accelerometers, inductive rotation pickup	One special surface[c]	One special surface[c]	None	Single road test, spectrum analyzer or computer
Accelerometer, noncontacting probe	None	None	None	None

[a]Existing.
[b]Surface must replicate roughness spectrum of average road. It cannot have any peculiarities, typical of individual sections of road, that would bias the calibration.
[c]Surface can have any profile, as long as it is known.

Figure 6. Linear road meter system.

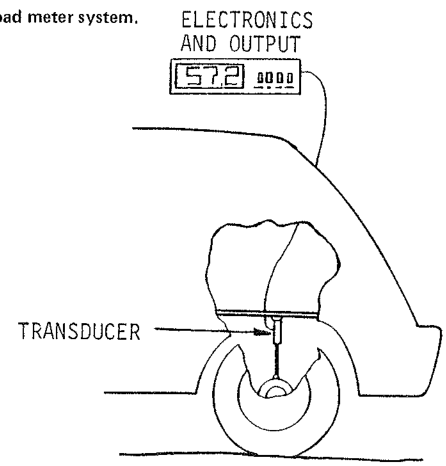
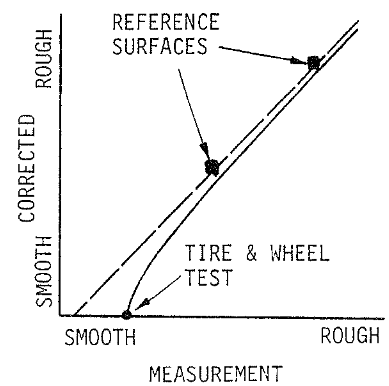


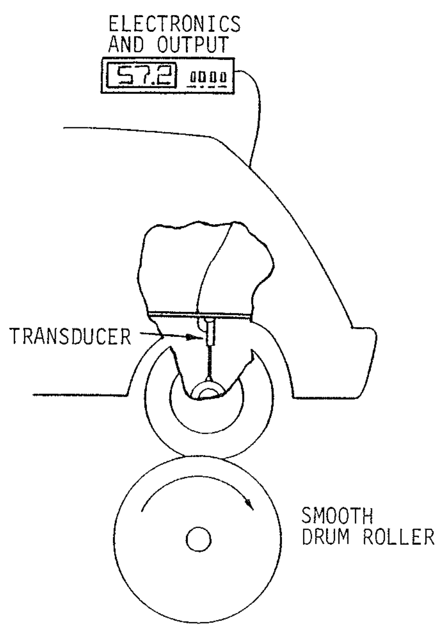
Figure 7. Calibration of linear road meter system.



tire and wheel nonuniformities can be quantified and used to adjust a calibration curve found with two reference surfaces. All that is needed is the apparent roughness due only to the wheels on a perfectly smooth road, as indicated in Figure 7. The most direct method is to place the rear wheels of the vehicle on a smooth drum roller, run the vehicle at speed, and observe the measured roughness, as shown in Figure 8. (This approach will not work with existing road meters because they will not respond to small amplitude, high-frequency vibrations unless they are simultaneously subjected to larger amplitude vibrations caused by pavement roughness.)

A second method for determining the role of tire and wheel nonuniformities involves mounting an inductive sensor on a wheel to produce an electric pulse with each revolution. This set-up is illustrated in Figure 9. The record of pulses, together with the linear transducer signal, can be used to quantify the effect of the tire and wheel nonuniformities, even if the vehicle speed and the tire phasing change slowly throughout the test. The two records are used to compute the coherence function between the axle-body motion and the average rotation rate of the wheels. The coherence function tells how much of the output is correlated with the wheel rotation and allows the operator to place a precise number on the apparent roughness provoked by the tire and wheel nonuniformity. Note that the inductive sensor and spectrum analyzer are only required for calibration and not for full-time use. Hence, an agency that has a fleet of road meter systems could obtain a single sensor-spectrum analyzer package that would be circulated among the different vehicles.

Figure 8. Use of smooth drum roller and linear transducer measured to establish the roughness induced by tire and wheel nonuniformities.



Conceptually, this approach of discerning the apparent roughness induced by tire and wheel nonuniformities is superior to the drum roller approach, due to the nonlinearity of the vehicle suspension. The amount of amplification in the vehicle can be

Figure 9. Use of rotation sensor, linear transducer, and spectrum analyzer to determine the measured roughness induced by tire and wheel nonuniformities while traversing normal pavement.

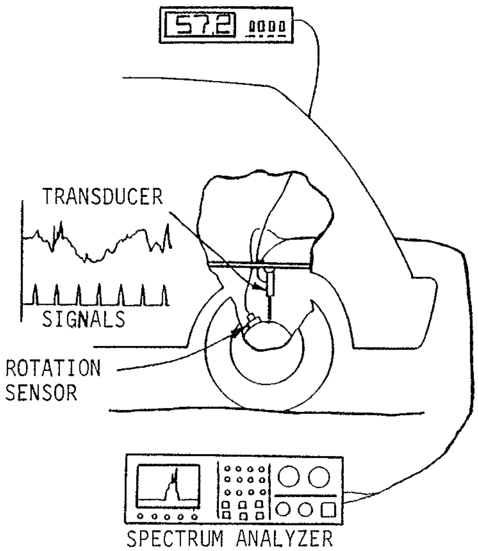
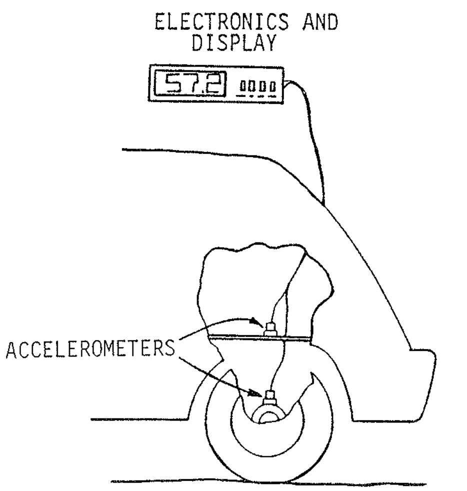


Figure 10. Example of crude profilometer with quarter-car simulation, based on two linear transducers.



different on a drum roller than on the road.

Two Accelerometers

Even at this point the unique vehicle dynamic properties are still present to influence the measurement obtained, which mandates calibration on known road-type surfaces. These effects can be eliminated by the addition of an accelerometer with the linear transducer, or alternately, simply two accelerometers, as shown in Figure 10.

The vertical acceleration of the body, immediately above the rear axle, can be written as

$$\ddot{z}_s + (1/M_s)\ (\text{suspension force}) + (1/M_s)\ (\text{other forces}) = 0 \qquad (1)$$

where $\ddot{z}_s$ is the acceleration and M_s is the sprung mass. The suspension force consists of all forces from springs, sway bars, shock absorbers, and friction. Virtually all of the nonlinearities are contained in the suspension force, and in addition, most of the time-varying components that cannot be maintained (mainly damping characteristics) are also included. The other forces term includes effects due to the front-axle excitation and to wind. The vertical acceleration of the rear axle, neglecting tire and wheel nonuniformities, is

$$\ddot{z}_u - (1/M_u)\ (\text{suspension force}) + (K_T/M_u)\ (z_u - z) = 0 \qquad (2)$$

where

z_u = vertical axle position,
z = average (of the two wheel locations) pavement elevation,
$\ddot{z}_u$ = axle acceleration,
M_u = unsprung mass, and
K_T = tire spring rate (sum of both wheels).

If we neglect the other forces term, Equation 1 can be solved for the suspension force term and combined with Equation 2 to yield

$$z = z_u + (M_u/K_T)\ (\ddot{z}_u) + (M_s/K_T)\ (\ddot{z}_s) \qquad (3)$$

Since z_u can be found by doubly integrating $\ddot{z}_u$, Equation 3 shows that two accelerometer signals ($\ddot{z}_s$ and $\ddot{z}_u$) and two coefficients (M_u/K_T and M_s/K_T) can ideally remove all vehicle dynamics and leave the profile. The profile would then be input to the reference quarter-car simulation with well-known response properties (that will not change with time) to obtain the conventional roughness measurement. Note that this scheme also eliminates the nonlinearities in the suspension so that the final measurement is linearly related to roughness.

The basic limitations on the accuracy of the profilometer are imposed by (a) the presence of other forces in Equation 1, (b) the accuracy with which the two coefficients M_u/K_T and M_s/K_T can be determined, and (c) the time stability of the two coefficients. Since this type of system has not been built and tested, the importance of these three factors can only be estimated. Tests on a road simulator with four hydraulic shakers, together with computer studies, have indicated that the other forces are indeed small (1).

Determination of the two coefficients is, in fact, the calibration of this system. The two coefficients can be found by running the vehicle over any known profile (which need not have the roughness spectrum of a typical road) at several speeds. Sinusoidal bumps or eccentric drum rollers, run at two speeds, would provide the most straightforward determination of the coefficient values, but there are no theoretical problems with using more convenient shapes, such as a plywood sheet laid on a smooth surface.

Variations in the coefficients with time can be minimized by maintaining a steady load condition (M_s), which requires that the level of gasoline be kept within fairly close limits and a constant hot air pressure be maintained in the tires (K_T). If necessary, a separate empirical curve could be used to relate the M_s/K_T coefficient with gasoline level and cargo weight. K_T might change as the tires wear and age; if so, the coefficients would have to be reestablished periodically.

Since the response properties that vary with temperature, humidity, and so on are eliminated (along with the individual dynamic properties), calibration of this system, of the same kind needed with the others, is not needed. As Figure 11 shows, the relation between the corrected and uncorrected measurements is due solely to tire and wheel nonuniformities. As before, their effect can be compen-

Figure 11. Calibration of crude profilometer.

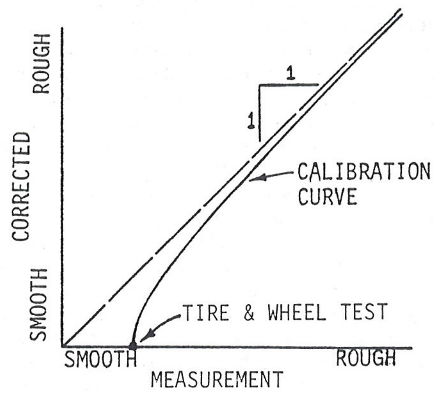
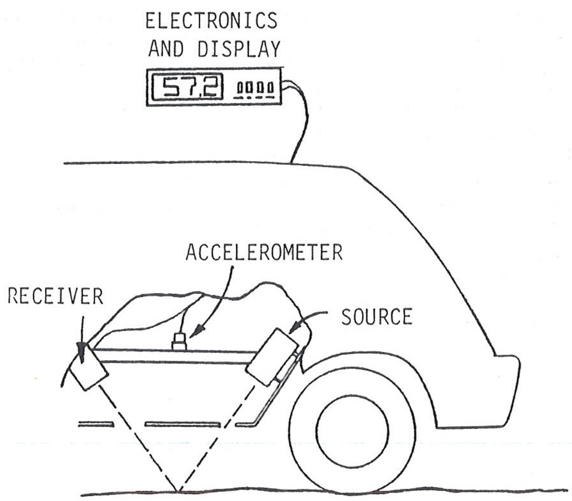


Figure 12. Noncontacting profilometer with quarter-car simulation.



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-