Measurements of Pavement Friction By a Decelerometer

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● IN RECENT YEARS there has been an increased awareness of the problem of slippery pavements. Research has shown that the number of dangerously slick pavements is much higher than many engineers believed. Although most pavements develop sufficient friction with tires in dry weather, many become dangerously slick when wet. It has been shown that both concrete and asphalt pavements can, in some cases, become slippery in a short period of time when certain types of aggregate are subjected to heavy traffic volumes. Awareness of this problem led to the organization of the First International Skid Prevention Conference at the University of Virginia in 1958. The conference has been described (1), and present knowledge on the problem was summarized in a Proceedings of the Conference (2).

Accident rates have been shown to be related to slippery pavements, and methods have been developed for providing skid-resistant surfaces to both existing and new pavements. Pioneer work in several states and abroad has shown the feasibility of a systematic program of identifying slick pavements and applying adequate treatment to them. The need for such a program on a nationwide basis is recognized.

There is need for equipment, which should be as simple and inexpensive as possible, for measurement of the skid-resistance of pavements on a statewide basis. A decelerometer which has been used for this purpose in Great Britian appeared promising, and there was need to investigate its usefulness with American vehicles and conditions.

In connection with the Skid Prevention Conference, a correlation study was carried out in which several methods of measurement of road surface friction were compared by testing several pavement surfaces. The principal results of this study have already been reported (3, 1). A decelerometer was installed in one of the skid-test cars in the experiment, in order to compare its results to those of other methods of measurement. The purpose of this paper is to evaluate the results of this instrument in comparison with the more commonly used methods of measurement of pavement friction.

THE DECELEROMETER AS A DEVICE FOR MEASURING FRICTION

The British Road Research Laboratory evolved a test procedure for a commercially available portable decelerometer (4, 5, 6), which is simple, reliable, requires no maintenance, and can be purchased in the United States for under $200. This meter is of the damped pendulum type which has a scale reading directly in g's. If the wheels of the vehicle are locked, and air friction is neglected, the meter then reads the coefficient of friction directly. The meter, mounted on a heavy base, is set on the floor of the vehicle. The vehicle is brought to a speed of 30 mph on the site to be tested, and the brakes applied with sufficient force to lock the wheels. At the end of 1 sec, the brakes are released, and the decelerometer reading recorded. A ratchet device causes the meter to record the maximum deceleration reading obtained during the 1-sec interval. The British have obtained very good empirical correlations between friction measurements obtained in this manner and measurements obtained by other means.

If measurements by such a procedure are sufficiently valid, it would compare favorably with other methods of measurement, because of large advantages in simplicity, cost, convenience, and adaptability. The British procedure makes use of only one piece of additional equipment: a simple timing device to enable the driver to time the period of brake application accurately.

It would be possible for each county engineer to install such a device in a vehicle, and send it with a technician to any site suspected of being slippery. With measurement equipment available locally, advantage could be taken of rainy weather to cover areas systematically without the need for a tank truck to wet the pavement surface. Even state police officers could use such an instrument to reliably refer slippery sites to the highway department for further testing.

Also, because the instrument can be installed in any vehicle simply by setting it on the floor, it might be useful for studying the coefficients of friction obtained for various types of heavy vehicles both loaded and empty.

An interesting relationship derived by the Road Research Laboratory would make possible further uses. Granting certain assumptions, the distance a vehicle would skid of a complete stop from a speed V could be estimated from a brief measurement of the instantaneous deceleration at a speed $\frac{2}{3}$ V. (This relation will be discussed in detail later in this paper.) Use of such a brief skid would be much safer than a complete skid, and would make possible tests involving vehicles or sections of roadway such that a complete skid would be impractical.

However, a number of questions regarding the performance of such an instrument for pavement-friction measurements remain unanswered. Differences between British and American vehicles may be sufficient to invalidate the empirical correlation obtained in Great Britain, and further knowledge of its characteristics would be necessary before adapting it to other purposes. This study, therefore, endeavored to determine the applicability of the British procedure to the vehicle and pavements used in the Skid Prevention Conference correlation study, and to gain a better understanding of the behavior of this instrument in an American vehicle.

PROCEDURE

The procedure has been described in a previous paper (3). In brief, tests were made on four pavements with coefficients of friction ranging from poor (approximately 0.25) to excellent (approximately 0.65). A Tapley decelerometer of the type used by the British, and fully described by them (5), was mounted in a vehicle used to measure pavement friction by the stopping-distance method. It was mounted on the floor of the space normally occupied by the back seat. A movie camera recorded readings of the decelerometer, a speedometer, and a distance-meter for each of the 48 skids. This made it possible to compare the decelerometer directly with the stopping-distance method, inasmuch as observations for both were obtained simultaneously from the same vehicle.

RESULTS

Readings of the camera film were made, and results with standard tires are shown in Figure 1. (Results of the series of runs with regular tires were not included, because the pattern was essentially the same; the two sets of curves differed slightly in height.)

In Figure 2, an average curve for each site is shown. In addition, a corrected curve is shown which takes account of the tilt of the vehicle (and the pendulum decelerometer) caused by the elasticity of the car's suspension system. As explained in the previous paper, the correction for tilt was made assuming that tilt was a linear function of deceleration as measured by the decelerometer. Although this assumption probably does not hold exactly, it was felt that the deviation from the actual value of tilt would result in a negligible change in the corrected curve.

Examination of the decelerometer curves seems to show what might be expected for the deceleration of a fully braked vehicle—the deceleration increases sharply as the brakes are applied, reaching a maximum at the moment of impending skid, then quickly declining as the brakes lock. The curves then show the increase in coefficient with decreasing speeds which is characteristic of wet pavements. The curves for the excellent site, however, do not seem consistent with such an explanation, The low point at about

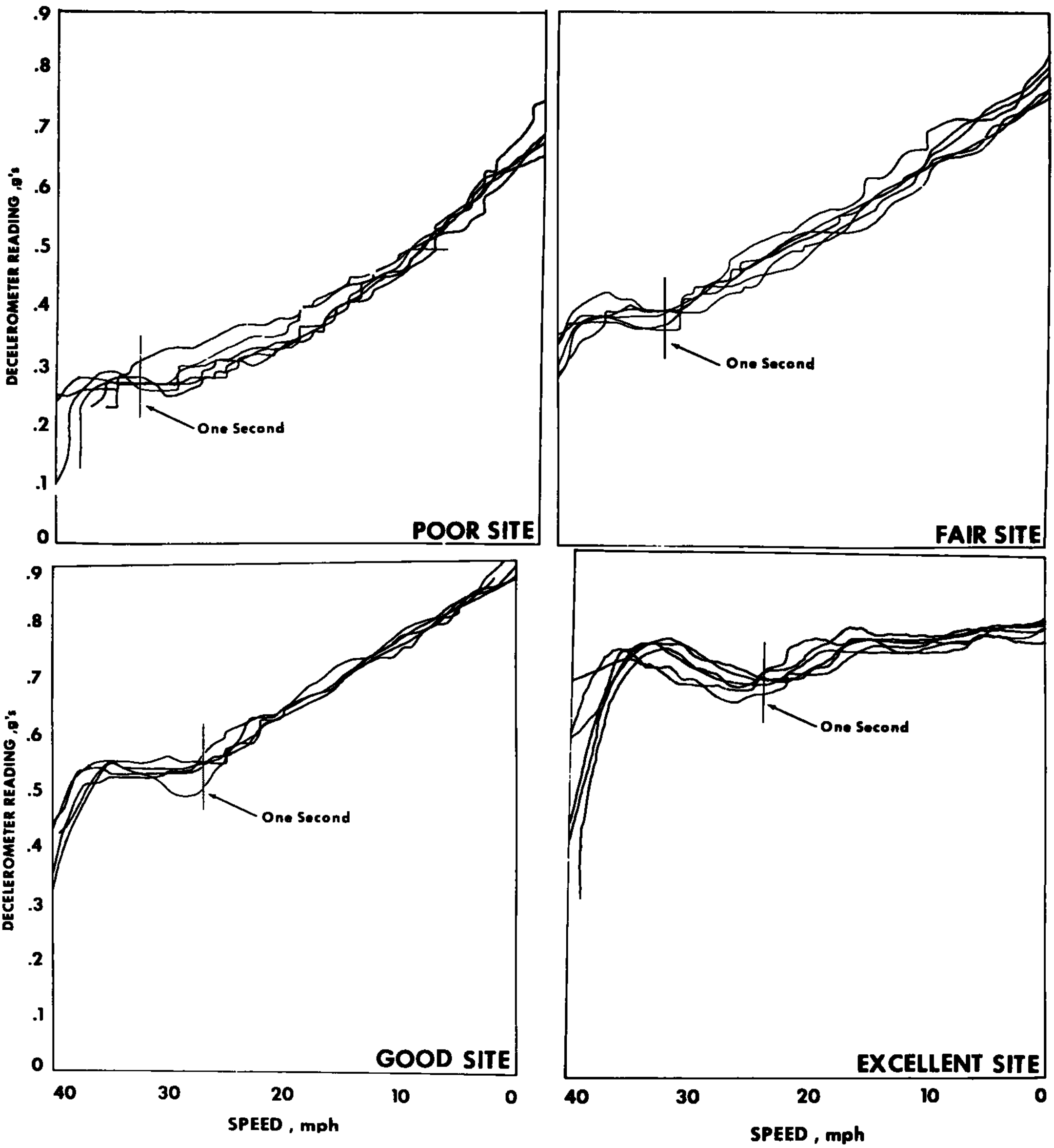

Figure 1. Instantaneous decelerometer readings during skids from 40 mph.

1 sec does not fit such a trend, and the curve as a whole suggests a damped oscillation. The question arises as to whether the fluctuations in decelerometer readings represent real fluctuations in deceleration, or merely fluctuations in the readings of the instrument.

The answer to such a question requires knowledge of the instrument. In their description of this decelerometer, Starks and Lister (5) point out that the pendulum is damped so that about 0.8 sec is required for a full reading to be obtained after a sudden deceleration of one g. Another factor, however, may also be affecting results. Lister (7) and Petring (8) have pointed out that vertical accelerations may also affect decelerometer readings once the pendulum is out of the vertical plane. The most desirable position for the instrument is at the center of tilt of the vehicle, so that tilt of

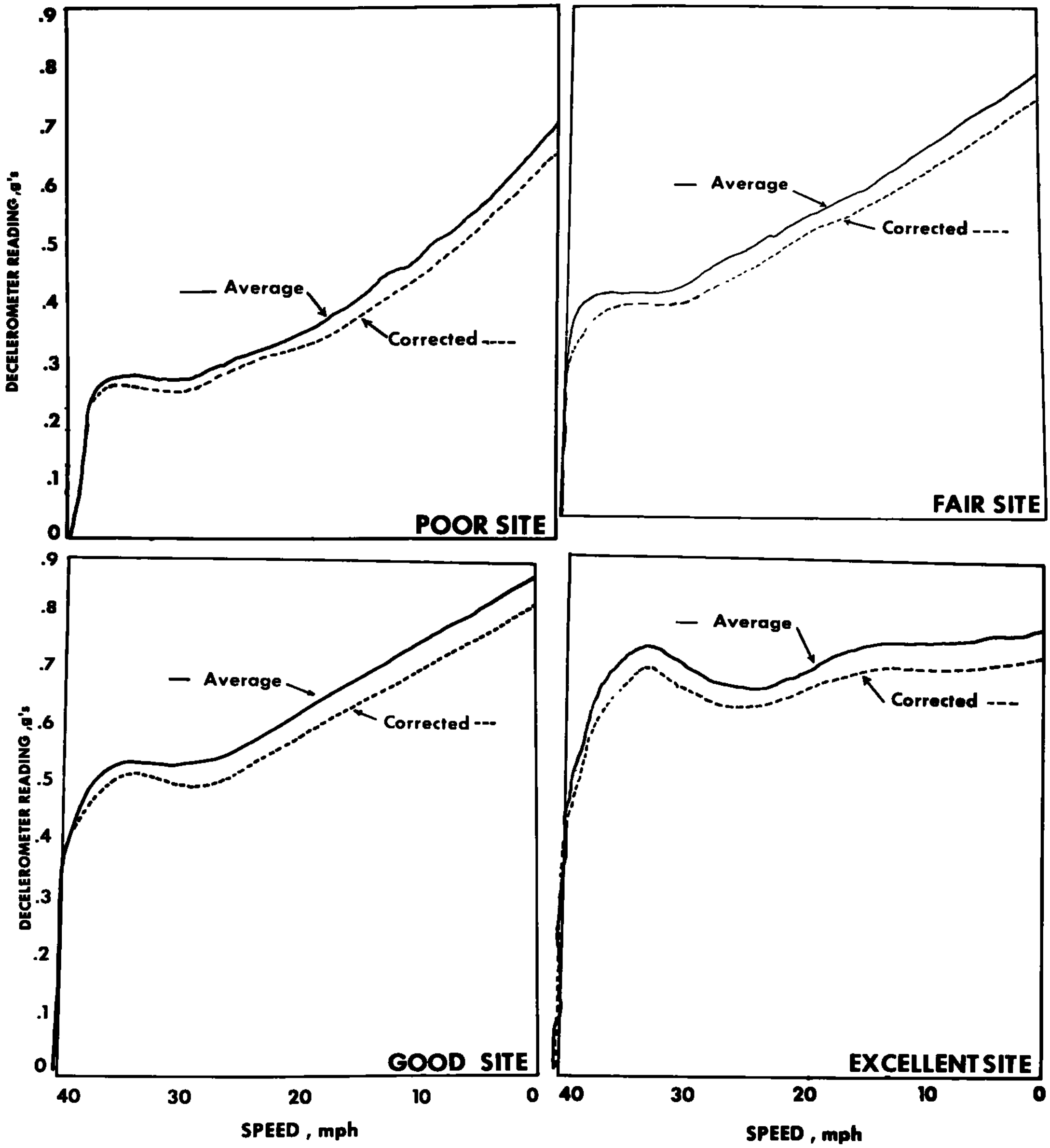

Figure 2. Average instantaneous decelerometer reading, with and without correction for tilt of vehicle.

the vehicle will not induce transient vertical forces. In this study the meter was behind the center of tilt, a sufficient distance that such vertical forces could have affected results significantly. Even with such a high damping factor, it is possible that irregularities in the curves, and even the peak at the first ½-sec of the skid, may be an artifact of the measuring instrument.

However, it is also possible that real irregularities in the deceleration of the vehicle occurred. The data on distance and speed, which were also recorded on film, were examined. However, distances could be read only to the nearest foot, and speeds only to the nearest mile per hour. Such accuracy was not sufficient for accurate evaluation of the transient accelerations in question. However, the data suggest that substantial fluctuations in deceleration did occur. Whether these might be caused by changes in weight distribution on front and rear tires as a result of the elastic action of the suspension system can be speculated upon.

The One-Second Maximum Method

The first comparison to be made was between the decelerometer results by the British method with results of other machines. The British method, by means of a ratchet in the decelerometer, retains the highest reading obtained during the first 1-sec period after the brakes are applied. The speed at which one second has elapsed is indicated for each site in Figure 1. It is noted that there is a tendency for the curves to dip, which is stronger for the higher friction pavements, and that the bottom of this dip occurs at about 1 sec. If the individual curves are examined, it can be observed that in most cases the decelerometer reading had reached a maximum and declined by the time 1 sec was reached. The maximum for each curve was recorded and the corrected values averaged. Figure 3 compares these averages with results of the trailers and the skidding cars. For the low-friction sites, results compare well with the results of the locked-wheel trailers. As expected, they fall below results obtained for the stopping distance vehicles. For the high-friction sites, the data suggest that the decelerometer 1-sec results are higher compared to the trailers. For the "excellent" site, decelerometer results were fully as high as the stopping-distance results. This is not surprising, however, inasmuch as there is for this site no strong trend for coefficients to be higher at lower speeds.

If the decelerometer 1-sec maximum method is evaluated in terms of its results, in the same manner that the other methods were evaluated, one could conclude that results seemed about as valid as results by the other methods. The previous paper (3) emphasized the large and consistent disagreements in the measurements obtained by the different machines. As long as the different methods of measurement show such a high degree of disagreement that it is not possible to determine what the "correct" value might be, it is difficult to evaluate the accuracy of any one method. Certainly the decelerometer does not appear noticeably less accurate than the other methods, and a case might be made that its accuracy is better than some.

However, it is possible to criticize these measurements on a theoretical basis. The tendency for results to be rather high for the high-friction site could also be due to the transient peak which occurred during the first second of the skid. Inasmuch as such a sharp peak was obtained in spite of the high damping factor, it seems clear that the height of the peak would be greatly affected by changes in damping factor. Even though the meter is reported to have its damping factor accurately compensated for temperature changes, reliance on such an instrument in the presence of such large transients would need to be preceded by considerable investigation. The British (9) have found their method satisfactory for most British vehicles, but have questioned whether it would be suitable for the "soft" suspension systems of American vehicles. Results of this study suggest that at least for the decelerometer so mounted in the vehicle used (1958 Chevrolet), which

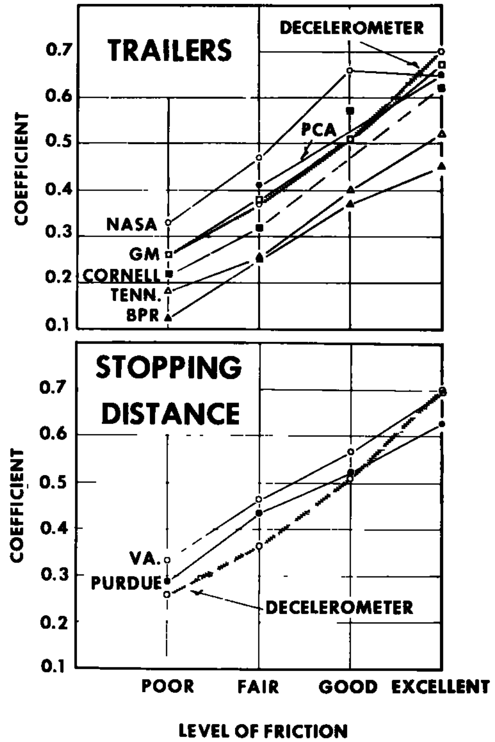

Figure 3. Decelerometer results by the one-second maximum method compared to trailer and stopping-distance measurements.

does not seem to have an atypical suspension system for American cars, transients are of such large magnitude as to cast doubt on the use of this method for precise measurements. Further research is needed to determine the effect of these transients on the accuracy of measurements.

The $^2/_3$ V Relation

R.J. Smeed of the Road Research Laboratory (4) has pointed out that under the assumption of a simple relationship between coefficient of friction and speed, the coefficient obtained by the stopping-distance method from an initial speed V can be predicted from measurement of the coefficient of friction at a speed $^2/_3$ V.

Comparisons were made between the decelerometer reading at $^2/_3$ V and the coefficient computed from the stopping-distance method, from the same car on the same skids. The results are given in Table 1. The discrepancies are considerable, and with the correction for tilt applied, all the decelerometer estimates are low. Examination of the curves shows that 26.7 mph nearly coincides with the dip in the curves already referred to. This is particularly true for the "good" site where the discrepancy is largest.

Explanation of the discrepancies is not difficutlt. The relation between the coefficient of friction μ and the instantaneous velocity v is expressed as a polynomial function

$$\frac{1}{\mu} = a_o + a_1 v + a_2 v^2 + - - - + a_n v^n$$

It is shown that if the coefficients of higher powers of the polynomial are small, the stopping distance of a vehicle can be closely approximated by the familiar formula

$s = \frac{V^2}{30\mu}$ where V is the initial speed and μ is the coefficient of friction measured at speed $^2/_3$ V.

Examination of Smeed's equations shows that the approximation is perfect if there is a linear relation between speed and the reciprocal of the coefficient of friction and becomes successively poorer as the relation differs from linearity. It can be shown that the error in the approximation is given by

$$\text{Error} = \frac{V^2}{30} \left\{ \frac{1}{9} a_2 V^2 + \frac{14}{135} a_3 V^3 + \frac{11}{81} a_4 V^4 + \ldots + \left[\frac{2}{n+2} - \left(\frac{2}{3}\right)^n\right] a_n V^n \right\}$$

Because each successive a-coefficient is multiplied by a higher power of the initial velocity V, the error rapidly becomes appreciable as the relation becomes more complex.

Evidence from previous research suggests that the basic relation between speed and the reciprocal of friction is sufficiently simple so that the approximation would be good. However, the present data included the transients in decelerometer readings already referred to. Because these transients produced a complex relationship, considerable error in the approximation would be expected. Only through reduction of these transients could the usefulness of the $^2/_3$ V relationship be utilized.

Variability of Decelerometer Readings

In the previous report, large differences in the variability of successive measurements at the same site were found for different machines. Comparable measures of variability were computed for the decelerometer readings. Table 2 shows these results compared to those of the other methods of measurement. Even for the most variable decelerometer index used, instantaneous decelerometer reading at $^2/_3$ V = 26.7 mph, the variability of successive measurement is about equal to that of the least variable trailers. In terms of variability, then, the decelerometer compares favorably with other methods of measurement.

TABLE 1

STOPPING DISTANCE COEFFICIENT AND DECELEROMETER READING AT A SPEED OF ⅔ V

Site	Stopping Dist. Coeff.	Decel. Rdg. at 26.7 mph Corrected	Decel. Rdg. at 26.7 mph Uncorrected
Poor	0.33	0.30	0.31
Fair	0.47	0.40	0.43
Good	0.57	0.51	0.57
Excellent	0.69	0.65	0.69

TABLE 2

VARIABILITY OF MEASUREMENTS—AVERAGE STANDARD DEVIATIONS OF REPEATED MEASUREMENTS

Trailers	
Bureau of Public Roads	0.040
Tennessee	0.037
Portland Cement Association	0.026
General Motors	0.020[1] - 0.027[2]
NASA	0.015[1] - 0.024[2]
Cars	
Purdue	0.013
Virginia	0.037
Decelerometer	
Average over whole skid	0.022
One-second-maximum	0.021
Instantaneous reading at ⅔ V	0.025

[1]Excluding one set of unusually variable readings.
[2]Including all readings.

Comparison of Stopping Distance and Trailer Measurements

It was planned to use decelerometer data to facilitate comparisons between coefficients by the stopping-distance method with those of the trailers. The deceleration of a skidding car at 40 mph should check with trailer measurements at the same site when measurements were made at 40 mph. By fitting a curve to decelerometer readings at each site by regression analysis, it was planned to make an estimate of the coefficient at 40 mph. However, the uncertainty associated with the transient changes in decelerometer readings made such a procedure unwise. Further research will be necessary for a precise comparison to be made between these two types of measurements.

FURTHER RESEARCH NEEDED

The need for further research on the use of such a decelerometer for measurement of pavement friction is intimately related to the need for research on other methods. Only when several machines consistently obtain nearly the same measurement of friction can the accuracy of any one method be evaluated. Further research on decelerometers should be correlated with research on other methods. The suitability of decelerometer measurements is also closely related to needed research on comparisons between the instantaneous deceleration of a skidding vehicle and measurements by locked-wheel trailers.

To answer the basic question raised by this study, it will be necessary to determine whether the transient changes in decelerometer readings were due to the instrument and the way it was used, or to real transient changes in deceleration of the vehicle. In order to obtain the actual deceleration, two types of instrumentation might be used: (1) a research-type decelerometer suitable for measuring such transients and not sensitive to vertical accelerations, or (2) devices capable of measuring distances to 0.1 ft and speeds to 0.1 mph. Devices for measurement of vehicle tilt would also be desirable.

If real irregularities in the deceleration of a skidding vehicle exist, they will pose serious problems for obtaining precise correlations between trailer measurements and stopping-distance measurements. If a peak in decleration occurs during the first ½ sec of the skid due to a slow locking of the wheels, consideration must be given to control of the rate of brake application, perhaps by apparatus such as that of the Purdue vehicle. If oscillations in deceleration are found to be a function of the "soft" suspension systems of American vehicles, consideration might be given to alteration of the suspension systems of vehicles to be used for testing.

SUMMARY AND CONCLUSIONS

A simple decelerometer offers an inexpensive, convenient, and adaptable means of measuring pavement friction. To evaluate the accuracy of such measurements, a Tapley decelerometer was included in a vehicle making locked-wheel stops. Results were compared to measurements of the same pavements obtained by the stopping-distance method and several towed trailers. Because the several machines obtained such large and consistent differences in measurements, it was not possible to make a precise evaluation of the accuracy of any one method. The decelerometer results appeared to be as valid as those obtained by the other more commonly used methods.

It seems clear that the decelerometer can yield results which have at least a "rough-and-ready" accuracy. In terms of reliability and consistency of results it compares favorably with other methods. In the opinion of the authors, this simple and inexpensive device, if used with a minimum of care, can yield results of considerably greater accuracy than a number of much more complex devices already in use.

However, transient changes in decelerometer readings, presumably a function of the suspension system of the American car used and/or the rate of brake application, cast some doubt on reliance on decelerometer readings for precise measurement. It is not clear whether the transient changes represent real changes in deceleration of the vehicle, or are an artifact of the instrument and the way it was used. If the transients are artifacts that can be overcome, such a decelerometer is a very promising method for measurement of pavement friction. If real transient changes in deceleration exist, there are important implications for relationships between friction measurements made by trailers and the skidding distances of vehicles. Further research is indicated on (1) the use of decelerometers, (2) the irregularities of the deceleration of skidding cars, and (3) the relations between friction measurements by the stopping-distance method and by towed trailers.

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