Measuring Pavement Slipperiness with a Pendulum Decelerometer

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The procedure for using a pendulum-type (Tapley) decelerometer to measure the coefficient of friction is an empirical one in which the test car is braked for 1 sec and the maximum deceleration recorded by the device. The coefficient of friction determined in this way is reported to be close to the value obtained by measuring the stopping distance.

The value of the method is that it converts any car into a friction-measuring device merely by placing the self-contained decelerometer on the front floorboard of the car. Also it does not require that the test vehicle be fully stopped, hence it can be used in all but heavy traffic. Its low cost is also a great asset.

However, the relationship between the maximum deceleration during the first second and the average coefficient obtained by measuring the stopping distance is an empirical one. Therefore, before any faith can be placed on the method when used on American cars whose suspension systems and other factors differ, the degree of correlation must be established.

In 1960, stopping distance tests were run on 14 sites with 7 measurements per site. A movie camera recorded the action of a Tapley decelerometer and the deceleration data have been reduced from these films. The paper presents the data from this study and attempts to show the extent to which the empirical 1-sec braking procedure agrees with the stopping distance results.

• MANY METHODS have been used to measure pavement surface slipperiness. Some are complex, some are simple; some expensive, some inexpensive. A rational basis underlies some, some are empirical. None, however, are as simple to use or as inexpensive as the British "one-second" procedure using a pendulum decelerometer (Tapley).

The instrumentation for using the decelerometer consists of setting the device on the front floorboard of a standard commercial car (see Fig. 1). The procedure employed in Britain when using the instrument is to attain a speed of 30 mph, apply the brakes for 1 sec, then release them. The maximum deceleration that occurs during the 1-sec interval is recorded by a non-returning rachet device in the decelerometer. The British have found that a relationship exists between the coefficient of friction obtained by the 1-sec method and that obtained by theoretically correct procedures.

The coefficient of friction obtained with this procedure is only empirically related to the value obtained by bringing the vehicle to a complete stop and measuring the skidding distance. Because the relationship is empirical, it is necessary to compare the empirical 1-sec value with that obtained by the theoretically correct procedure under a variety of conditions.

The study reported here had as its purpose the comparison of the coefficient of friction obtained by the 1-sec decelerometer procedure with that obtained by measuring the stopping distance. To do this, twelve road surfaces were tested. The data were collected by means of a movie camera that recorded the action of a Tapley decelerometer and a stop watch during the stopping distance tests.

Giles (1), in a review of European methods, briefly discusses the use of the method and presents data that shows a good correlation between that procedure and the sideway force coefficient at 30 mph. The highway department of the State of Florida uses a somewhat similar procedure, but does not use a timing device. It was this information that prompted studies of the decelerometer method by the Virginia Council of Highway Investigation and Research.

In a previous study conducted by Allen and Dillard (2, 3), it was concluded that the Tapley decelerometer "can yield results of considerably greater accuracy than a number of much more complex devices already in use." This was not altogether an endorsement of the procedure for the other methods gave rather widely scattered results, but showed that the procedure held promise. Also, in that study only four sites were tested. It was concluded that additional study should be made of the decelerometer.

Also, the pendulum type decelerometer has been used for many years to measure the efficiency of brakes, but few data have been available with which to evaluate the equipment.

ACTION OF DECELEROMETER DURING SKIDDING

A typical deceleration curve for a skidding vehicle is shown in Figure 2. At the outset of a skid the coefficient of friction (c/f) rises sharply. The wheels are not fully locked during the early part of the skid-slippage between the brake shoe and the wheel is occurring. Slippage continues until the incipient peak is reached, the wheels then lock, and because the locked wheel coefficient is less than the incipient or "impending" skid coefficient, there is a slight drop in the coefficient. Once the wheels lock, the coefficient increases rapidly with a decrease in speed.

The pendulum decelerometer does not record the correct horizontal deceleration because of three factors which are potential sources of error:

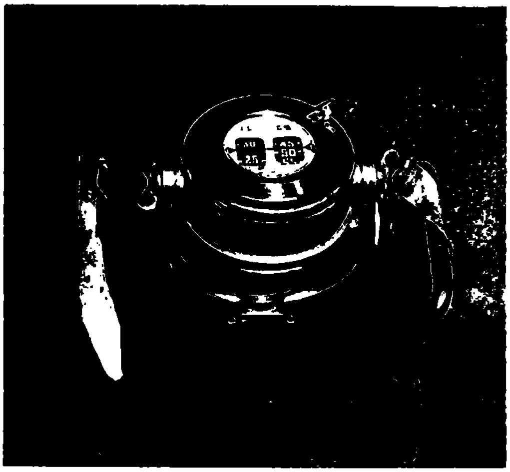

Figure 1. Tapley decelerometer positioned on front floorboard of car.

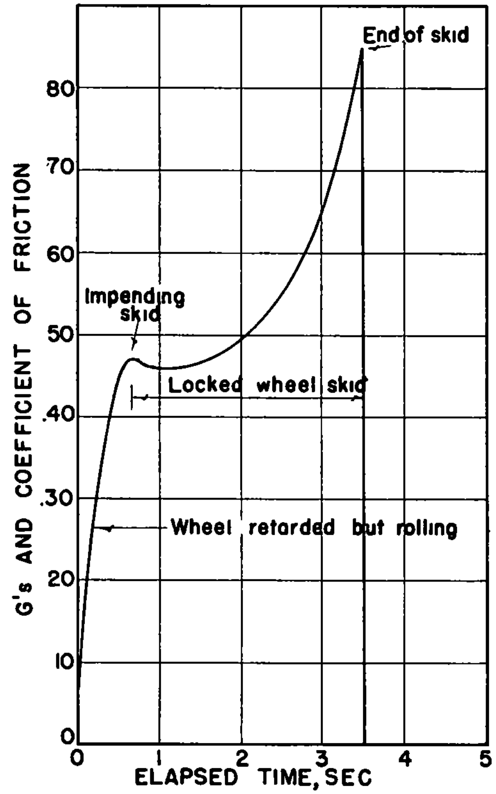

Figure 2. Typical change in c/f during a skid.

1. The "dive" of the test car as it skids. This means that the pendulum is not perpendicular to the car, hence the actual deceleration is less than the apparent by the amount of the angle of dive of the car.

2. The vertical accelerations that occur because the road is not smooth. Once the pendulum is out of a horizontal plane, the vertical accelerations develop a force on the

pendulum. These forces act both upward and downward.

3. The damping of the pendulum with a viscous liquid. Therefore, the deceleration at a given moment is not that recorded by the instrument but that actual deceleration occurring some time before.

Not all three sources of error are of significance.

The dive of the car does result in an appreciable error. Previous work by Dillard and Allen developed the relation for tilt for the 1958 Chevrolet used in the current study as

$$R_t \text{ (true deceleration)} = 0.94\ R_a \text{ (decelerometer reading)}$$

From information supplied by W. A. McConnell of the Ford Motor Company for the 1957 Ford used in the current study the relation is

$$R_t = 0.96\ R_a$$

The magnitude of the correction factor is, of course, dependent on the suspension system of a particular car. The error is lower for stiff suspension systems and higher for soft systems. Therefore, if the apparent deceleration were 0.60 g's, the true

TABLE 1

DESCRIPTION OF TEST SITES

Site	Car[a]	Approx. Age of Pavement (yr)	Aggregate	Binder	Type Mix	Texture	Virginia Designation
III	(C)	4	Sandstone	RC-3 asphalt	Surface treatment	Harsh	Surface treatment
IV	(F)	7	Gravel	AP-3 asphalt	Plant	Smooth	F-1
V	(C)	4	Gravel	Type I-a cement	PCC	Knobby	
VI	(F)	1	Gravel	Type II cement	PCC	Broomed	
VII	(F)	⅙	Granite	AP-3 asphalt	Plant	Smooth	F-1
VIII	(F)	5	Gravel	Type II cement	PCC	Broomed	Class "p" +25 ¢
IX	(F)	1	Granite	RC-2 asphalt	Surface treatment	Harsh	Surface treatment
X	(F)	3	Granite	AP-3 asphalt	Plant	Medium	I-3
XI	(F)	5	Limestone	AP-3 asphalt	Plant	Medium	I-3
XII	(F)	4	Limestone	AP-3 asphalt	Plant	Medium	I-3
XIII	(F)	2	Sand	AP-3 asphalt	Plant	Smooth	F-4
XIV	(F)	5	Limestone	AP-3 asphalt	Plant	Smooth	I-3

[a] C = 1958 Chevrolet; F = 1947 Ford.

deceleration would be 0.96 (0.6) = 0.58 g's. The coefficient of friction is numerically equivalent to the deceleration in g's.

The forces generated by vertical accelerations caused by the "bouncing" of the car as it proceeds through a skid are probably negligible from a practical standpoint. The relative smoothness of most road surfaces would not likely generate vertical accelerations of any magnitude at the speeds below 40 mph. In addition, the damping fluid in the decelerometer probably removes much of the short term vertical acceleration peaks.

According to Starks and Lister (4) the damping of the pendulum results in a lag of about 0.8 sec between the actual deceleration and the response of the instrument.

This lag had relatively little significance in the current study because of the procedure used for collecting the data, but may be of appreciable significance when the instrument is used for practical measurements. In the current study, in which the deceleration vs time relationship was obtained for the full skid, the curve is merely shifted by the extent of the lag. The practical implications of this are discussed later.

That some error exists between the true deceleration and the indicated deceleration must be granted. However, the study reported here is attempting to evaluate the relation between the indicated deceleration and the theoretically correct "average" deceleration obtained from measuring the stopping distance. Therefore, the error is of academic interest but not specifically related to analysis of the correlation.

PROCEDURE

The data were collected in early September 1960 as a part of a study in which the British portable tester was being correlated with a skid test car (5). Because the stopping distance results had to be obtained for that purpose, a movie camera was installed in the test vehicle to record the action of the decelerometer during the skid tests. The details of the testing procedure are described by Mahone (5) and only a brief description is offered here.

The test results from 12 sites are included in this study. The pavement textures and types were selected because they represented the widest divergence within the Commonwealth of Virginia. The description of the test sites is given in Table 1.

In conducting the test, a section of road was wetted with canvas soaker hoses. Stopping distance tests were made generally at 20, 30, and 40 mph, and during each test the action of the decelerometer and a stop watch was recorded by a movie camera. Two test vehicles were used—either a 1958 Chevrolet or a 1957 Ford. The data were obtained from the film and the decelaration (coefficient of friction) vs time curves plotted. From these curves the maximum coefficient occurring during the first second was obtained.

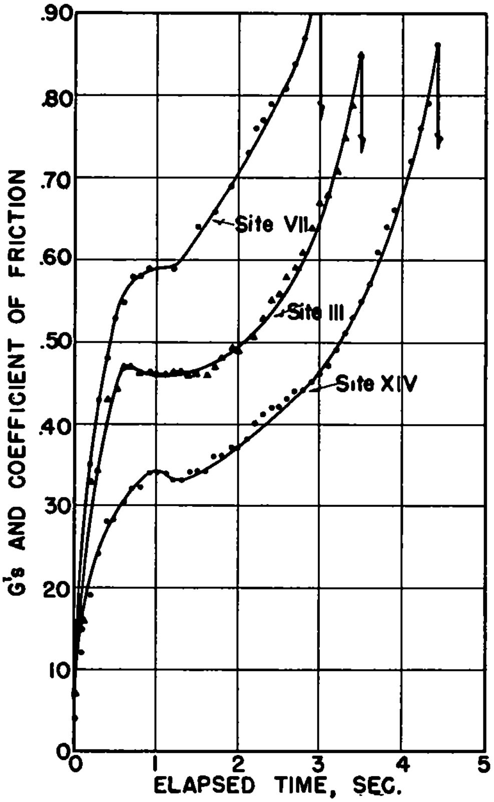

Figure 3. Trace of decelerometer readings on three sites at 40 mph. Incipient peak occurs at or before 1-sec elapsed time.

TEST RESULTS

Typical plots of the data for 40 mph are shown in Figure 3. The data show that the 1-sec interval occurs at approximately the same position along the curves;

i.e., near the incipient peak. Generally the incipient peak occurs before the 1-sec interval has elapsed. In the great majority of cases the maximum deceleration occurring during the 1-sec is the incipient peak coefficient. This was also true of the data collected in 1958 by Allen and Dillard.

The data for all speeds are summarized in Table 2. A plot of decelerometer

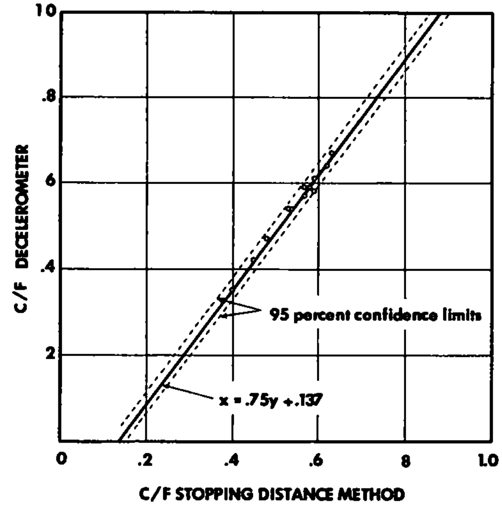

Figure 4. Correlation at 40 mph.

TABLE 2

SUMMARY c/f FROM DECELEROMETER AND STOPPING DISTANCE METHOD

Site	Speed (mph)	Coefficient of Friction	
		Skid Car	Decelerometer
III	30	0.48	0.52
	40	0.48	0.47
	50[a]	0.43	0.38
IV	20	0.63	0.88
	30	0.64	0.76
	40	0.62	0.64
V	30	0.56	0.62
	40	0.53	0.54
	50[a]	0.47	0.41
VI	20	0.61	0.84
	30	0.59	0.70
	40	0.59	0.61
VII	20	0.58	0.76
	30	0.59	0.67
	40	0.57	0.59
VIII	20	0.59	0.78
	30	0.58	0.67
	40	0.58	0.59
IX	20	0.54	0.65
	30	0.52	0.58
	40	0.54	0.54
X	20	0.63	0.86
	30	0.59	0.65
	40	0.59	0.58
XI	20	0.48	0.62
	30	0.47	0.51
	40	0.45	0.42
XII	20	0.57	0.76
	30	0.57	0.65
	40	0.57	0.57
XIII	20	0.64	0.86
	30	0.65	0.78
	40	0.63	0.67
XIV	20	0.39	0.52
	40	0.40	0.35

[a] Few tests were run at 50 mph.

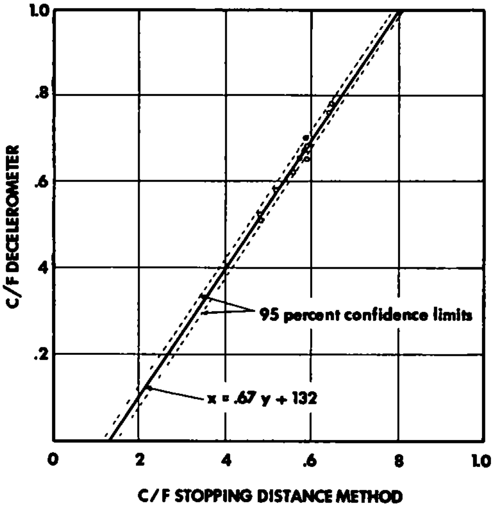

Figure 5. Correlation at 30 mph.

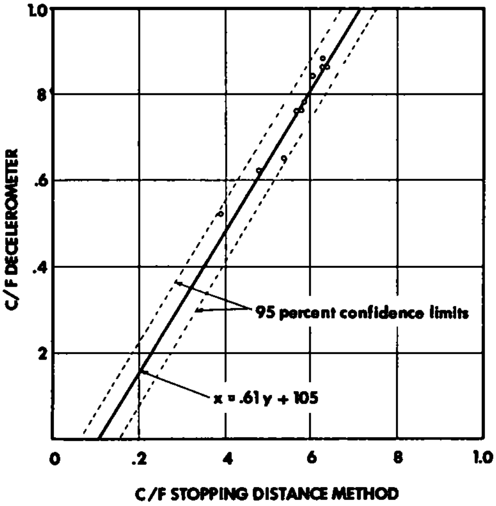

Figure 6. Correlation at 20 mph.

TABLE 3

ANALYSIS OF VARIANCE ON RESULTS OBTAINED AT 40 MPH[a]

Source of Difference	Degree of Freedom	Mean Square ($\times 10^{-4}$)	F
Between car and decelerometer	1	1.45	0.388
Within car and decelerometer	130	3.74	

[a] F factor for 95 percent level and for 1 and 130 degrees of freedom = 3.90; between car and decelerometer, F = 0.388. Because $0.388 < 3.90$, the conclusion is that no significant difference was found.

vs stopping distance results is shown in Figures 4, 5, and 6 for 40, 30, and 20 mph, respectively. Also shown is the band representing plus and minus two standard errors. These bands take into account the dispersion of the measurements about the regression line. The linear estimating equations are as below:

$$\text{At 20 mph, } X = 0.61\,Y + 0.105, \; SE = 0.02; \tag{1}$$

$$\text{At 30 mph, } X = 0.67\,Y + 0.132, \; SE = 0.007; \tag{2}$$

$$\text{At 40 mph, } X = 0.75\,Y + 0.137, \; SE = 0.0085; \tag{3}$$

in which

X = the coefficient of friction that the stopping distance method will yield;
Y = mean of six measurements obtained by 1-sec method, and
SE = standard error or estimate.

From these equations it is possible to estimate the stopping distance values from the 1-sec decelerometer results. That is, if the mean of six measurements made by the 1-sec decelerometer method at 40 mph is inserted in Eq. 3, the stopping distance value can be estimated within $\pm 2(0.0085) = \pm 0.016$ (see Appendix for calculations).

From the standpoint of the precision of the estimate, the correlation at 30 mph is superior. The standard error at 30 mph is least, followed by 50 mph, and the standard error at 20 mph is two to three times as large as at the other low speeds.

Table 2 shows that the absolute decelerometer coefficients at 40 mph are closer to the stopping distance results than are those from 20 and 30 mph. An analysis of variance was run to determine whether there was any statistical difference between the decelerometer and the stopping distance results. The results of this are given in Table 3. The conclusion reached is that no significant difference can be found between the coefficient obtained by the two methods. However, in a strict sense this does not necessarily mean that the results are interchangeable. Figure 6 shows that the line of best fit deviates from a 45° line. Therefore, there is some bias in the correlation. The regression line, in effect, removes the bias and provides a better method of comparing the results. However, from a practical standpoint the use of the decelerometer coefficients as direct estimates of the stopping distance results for 40 mph seems permissible.

ANALYSIS

It should be remembered that the decelerometer deviated from measuring the actual deceleration on three counts. However, there is reason to believe that these errors are not large and that the decelerometer does indicate quite closely the decelerations that occur during the braking of a passenger car.

If then the decelerometer results are relatively accurate, the question remains as to whether there is an experimental relationship between the "average" coefficient of friction obtained by measuring the stopping distance and the maximum deceleration during a specific time interval. There seems no basis for supposing a "necessary relationship" but that an experimental relationship does exist seems evident.

The maximum deceleration that was recorded during the first second of skid was generally the incipient peak. Therefore, it is this incipient peak that correlates well with the "average" stopping distance coefficient. In the study by Dillard and Allen conducted in conjunction with the First International Skid Prevention Conference, incipient coefficients were measured by the NASA trailer at constant speeds. These incipient coefficients also agreed quite well with the stopping distance coefficients. Except on one site, the results were very close and there was reason to suspect the results in that one case.

Therefore, there appears to be an experimental basis for suggesting that there is some similarity between the incipient coefficient and the average coefficient obtained from stopping distance results.

One further factor should be mentioned concerning the practical use of the equipment. The damping of the decelerometer, as mentioned previously, causes a lag in the response of the indicator. The use of a timing device must therefore take this into account. The test results of the current study show that the incipient coefficient correlates well with the average coefficient obtained from the stopping distance tests. Therefore, any timing device used should be adjusted to permit a release of the brakes as the incipient peak is reached. This, of course, may not be 1 sec from the time the brakes are applied.

It might also be mentioned that the incipient peak is discernible by directly observing the dial. The dial is unreadable during the "pre-incipient" portion of the skid but as the peak is reached and the leveling off begins the dial can be read. The research engineers of the Florida State Roads Commission use this technique for making measurements and are well satisfied with it.

SUMMARY AND CONCLUSIONS

The following conclusions are believed warranted by the data. The conclusions, of course, relate only to the vehicles that have suspension and braking systems similar to the 1958 Chevrolet and the 1957 Ford used in the tests.

1. The maximum deceleration that occurred during the first second of the skid was generally the "incipient peak."
2. The standard error of estimate was low (from a practical standpoint) for 30 and 40 mph, but appreciably large at 20 mph (95 percent confidence level). The theoretically correct stopping distance coefficient can be estimated from the decelerometer results within ±0.02 for 40 and 30 mph, and within ±0.04 for 20 mph.
3. There was no significant difference between the coefficients of friction obtained by the 1-sec method and the stopping distance method at 40 mph.
4. The relationship is an empirical one and must be restricted to the conditions of the correlation, but the data suggest that the use of a decelerometer to measure the incipient peak will provide a useful index of pavement slipperiness. The low cost of such instruments and relative little inconvenience to traffic makes the method a useful one.

REFERENCES

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4. Starks, H. J. H., and Lister, R. D., "The Characteristics and Performance of a Maximum Deceleration Meter for Testing Vehicle Brakes." Road Research Laboratory, London (1951).
5. Mahone, D. C., "A Correlation of the British Portable Tester and the Virginia Skid Test Car." Virginia Council of Highway Investigation and Research (1961).

Appendix

CALCULATIONS

Correlation Coefficient

$$r = \frac{\Sigma XY - \frac{\Sigma X \Sigma Y}{N}}{\sqrt{\left[\Sigma X^2 - \frac{(\Sigma X)^2}{N}\right]\left[\Sigma Y^2 - \frac{(\Sigma Y)^2}{N}\right]}}$$

in which

r = correlation coefficient;
X = mean c/f from stopping distance method for each site; and
Y = mean c/f from decelerometer method for each site.

Regression Line

$$X = \bar{X} + r \frac{\sigma_x}{\sigma_y} (Y - \bar{Y})$$

in which

$\bar{X}$ = grand mean c/f from stopping distance method for all sites;
$\bar{Y}$ = grand mean c/f from decelerometer for all sites;
σ_x = variance of stopping distance measurements; and
σ_y = variance of decelerometer.

Standard Error of Estimate

$$\text{Standard error} = \sigma_X \sqrt{1 - r^2}$$