is responsible for the facts and the accuracy of the data. The contents do not necessarily reflect the official views or policy of the U.S. Department of Transportation. The report does not constitute a standard, specification, or regulation.

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Prediction of Rigid-Pavement Performance From Cumulative Deflection History

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Data from the AASHO Road Test were used to investigate a functional relationship between the cumulative deflections sustained by a rigid pavement and a quantitative measure of the corresponding condition of the pavement. Cumulative deflections were estimated from periodic Benkelman beam deflections. Deflections had been measured at approximate 2-week intervals during the road test, and we assumed in the analysis that such deflections were representative of those that would have been measured had Benkelman beam deflections been measured continually. The present serviceability index (PSI) was used as a quantitative measure of pavement condition. Because of wide variation in response to loading of similarly constructed test sections and even between replicate test sections, no definitive relationship could be established that could predict PSI as a function of cumulative deflection. However, when data from test sections having the same slab thickness were averaged, a PSI-cumulative deflection relationship could be described by two straight lines intersecting at a threshold cumulative deflection. For cumulative deflections less than the threshold, an increase in cumulative deflection produced small changes in PSI; for cumulative deflection larger than the threshold, relatively small increases in cumulative deflection produced large changes in PSI. The level of the threshold cumulative deflection increased with increasing slab thickness.

Most methods of rigid pavement design for airfields and highways are based on considerations of load-induced stresses in elastic slabs. Repeated application of loads that induce stresses well below the modulus of rupture of a given material can cause the material to fail. This phenomenon, fatigue failure, is attributed to the fact that materials are not ideal homogeneous solids (1). Portland cement concrete (PCC) exhibits this behavior. Pavement distress due to fatigue may become more important in the future as aircraft and highway loads increase and exceed those contemplated by designers because the number of load repetitions that produce fatigue distress decreases as the load-induced stress increases.

Curves depicting the fatigue phenomenon usually have stress or strain on the ordinate versus cycles of load on a logarithmic abscissa. Such relationships are difficult for the pavement engineer to apply to in-service rigid pavements because measuring in situ stresses or strains is difficult and time consuming. Deflection measurements are made much more easily; the Air Force has a vehicle-mounted, optical-deflection measuring system under development that will be able to measure and compile deflections accurately with little or no interruption to traffic. Thus a correlation of deflections with a rigid-pavement performance index, which includes fatigue effects, would provide a valuable tool to the pavement engineer.

BACKGROUND INFORMATION

Fatigue of concrete has been investigated in terms of stress by several investigators (2, 3, 4). Nordby (4) reviewed research findings involving the fatigue of PCC and noted that most of the research performed on both plain concrete specimens and those with reinforcement similar to that of highway pavements was motivated by the fact that many failures of concrete pavements by cracking were due to repeated applications of stress. Fatigue research on plain concrete beams indicates (4) that plain concrete may not possess a fatigue limit within 10 million cycles of load, that inadequately aged and cured concrete is less resistant to fatigue than well-aged, well-cured concrete, and that as the induced stress is decreased the fatigue strength is increased substantially.

There is substantial agreement among fatigue investigators that, for reinforced concrete specimens (4), (a) most failures of reinforced beams were due to failure of the reinforcing steel that was accompanied by severe cracking in the concrete and stress concentrations associated with these cracks and (b) beams accumulated residual deflections over many cycles of load but recovered somewhat during rest periods, indicating, at

least for reinforced concrete beams, that the fatigue phenomenon is a function of the frequency of loading.

Lloyd, Lott, and Kesler (2) found that under repeated loading the strength of a specimen was reduced and the strength at failure was usually much less than the static flexural strength. PCC was found to behave similarly to other materials under cyclic loading in that the strength reduction was found to be proportional to the logarithm of the number of load cycles to failure. Because concrete does not have a fatigue limit (i.e., there is no stress level below which concrete can be stressed an indefinite number of times without fatigue failure), reference is frequently made to the fatigue strength of concrete. The fatigue strength is the strength expressed as a percentage of the static ultimate strength corresponding to a given number (frequently 10 million) of cycles of load (5).

Linger and Gillespie (6) reported a comprehensive evaluation of results of previous investigations of the fatigue characteristics of PCC and determined that the cumulated deformation was an indication of fatigue damage. Awad and Hilsdorf (7) found that damage to plain concrete caused by large repeated loads depends on the number of stress cycles and the total time the concrete has to sustain the stress. This finding seems to indicate that fatigue of a rigid pavement would depend on the speed of a vehicle and its wheelbase; both affect the frequency of loadings. Traffic spacing would also be a factor.

The experimental fatigue research on concrete beams reported in the literature was carried out on plain or reinforced specimens for which the support conditions remained constant throughout the test durations, which is in contrast to in-service conditions for rigid pavements. Special studies undertaken at the AASHO Road Test (8) revealed that, during periods of changing air temperatures, points on the surface of slabs were in continuous vertical motion, which would cause a continuous change in the geometry of slab support. At times, the slab would only be partially supported.

When Burmister (9) developed a theory of the structural behavior of rigid pavements, based on a layered solid elastic model, it was suggested that the design be based on a criterion of limited deformation under load. Although the tentative suggestion was that the maximum allowable deflection for a 203-mm (8-in) PCC slab be approximately 3.05 mm (0.012 in) to prevent fatigue failure (10), most design procedures used today are based on stress because a relationship between deflection and performance has not yet been developed for rigid pavements (11).

Ahlvin and others (12) recommended that consideration be given to the determination of maximum allowable deflections that can be tolerated in a rigid-pavement structure. They questioned whether designing for a given number of loadings by the largest load expected to use the pavement is realistic and suggested that "designs which incorporate strain and/or deflection histories should be investigated" to analyze random loading characteristics (mixed traffic with aperiodic loading frequency).

THEORY

Recently, a functional relationship has been shown to exist between the cumulative deflection that a flexible pavement experiences in its service life and the performance history of the pavement (13). The objective of this research effort was to determine if a similar relationship could be established for rigid pavements. Highter and Harr hypothesized that there is a functional relationship between the total energy imparted to a given rigid-pavement system as measured by cumulative deflections and the condition of that system.

Some methods of rigid-pavement design assume the existence of a reproducible stress-strain relationship. However, the field measurement of load-induced stress is very difficult and time consuming. The prediction of load-induced stresses is even more tenuous because the dynamic loads imposed on pavements by highway vehicles and especially aircraft are difficult to assess because they depend not only on characteristics of the vehicle but also on pavement roughness (14).

A need for an index that characterizes the dynamic response of a rigid pavement and can easily be measured becomes apparent. Cumulative deflections may provide such an index for flexible pavements (15). A theoretical basis for the supposition that cumulative deflections may also provide such an index for rigid pavements can be shown by the relationship between the load-induced deflection and strain energy of a plate (slab) supported on a Winkler foundation.

Rigid pavements are commonly modeled as plates supported by Winkler foundations. Timoshenko and Woinowsky-Krieger (16) analyzed a circular plate supported by a Winkler foundation. Assuming as an approximation that the deflections can be expressed as

$$w(r) = A + Br^2 \tag{1}$$

where A and B are constants, the total strain energy of the system for a load P applied at the center was found to be

$$U = 4B^2 D\pi a^2 (1 + \nu) + 1/2 \int_0^{2\pi}\int_0^{a} k(r)[w(r)]^2 \, r dr d\theta \tag{2}$$

where

$D = Eh^3/[12(1 - \nu^2)]$, flexural rigidity of the plate;
h = thickness of the plate;
a = radius of the plate;
ν = Poisson's ratio of the plate; and
k = modulus of subgrade reaction.

A and B are constants that are determined by imposing the condition that the total strain energy of the system is minimum when stable equilibrium is achieved. Since the maximum deflection occurs directly under the load ($r = 0$), Equation 1 indicates that A is the maximum deflection, w_{max}. Therefore, examination of Equation 2 indicates that the strain energy is a function of the plate and foundation parameters and the deflections. Equation 2 indicates that load-induced deflections are related to the strain energy of a deflected plate supported by a Winkler foundation. Within this context, the maximum deflected shape of a pavement provides a measure of the net energy introduced into a pavement by a load (vehicle or aircraft).

PROCEDURE AND ANALYSIS USED TO TEST WORKING HYPOTHESIS

To test the working hypothesis, rigid-pavement deflection measurements and corresponding assessments of the condition of the pavement over a sufficient period of time were required. The time interval over which these data were needed was such that the condition of the pavement changed markedly within the time interval. A sufficient time interval, then, depended on the design of the pavement, ambient conditions, and the nature and frequency of the traffic.

Data required to test the hypothesis were available in

Figure 1. Typical edge and corner deflection histories of AASHO Road Test section.

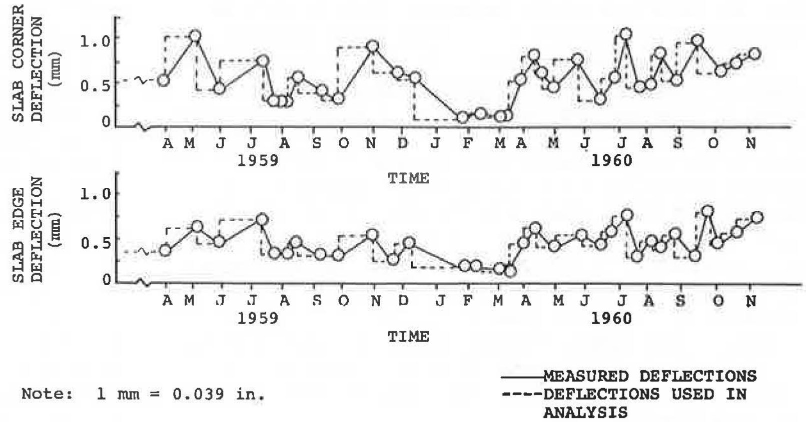


Figure 2. Serviceability versus cumulative corner deflection data for 203-mm slabs.

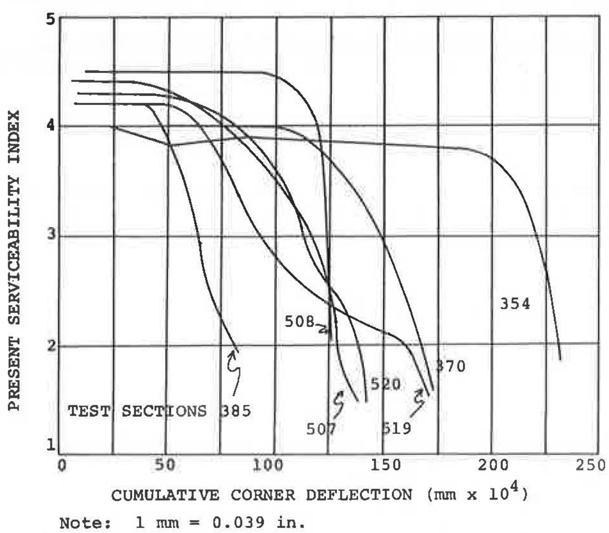
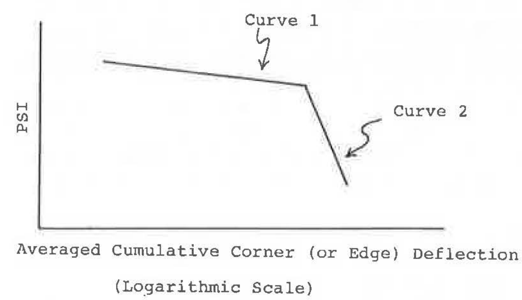


Figure 3. Curves of averaged data for three slab thicknesses.



the histories of some of the test sections trafficked in the AASHO Road Test. The present serviceability index (PSI) (17) of some test sections did not change appreciably during the road test, and data from those test sections, which were considered to be overdesigned for the purpose of this study, were not used.

When assembling AASHO Road Test data, we selected five variables as likely to be related to the PSI: cumulative deflection, axle load, reinforcing, subbase thickness, and slab thickness. However, in performance analysis carried out on road test data by others (1), subbase thickness and reinforcing were not found to be statistically significant and these variables were not considered further.

A function was sought that would predict PSI as a function of cumulative deflection, load, and pavement slab thickness:

$$\mathrm{PSI} = f_1 \text{ (cumulative deflection, load, slab thickness)} \quad (3)$$

If this function were known, predicting the serviceability level of a rigid pavement would be possible if deflection and traffic records were compiled.

A linear correlation analysis was carried out on the variables in Equation 3. The correlation matrix indicated a slight linear correlation between slab thickness and PSI and load and PSI. Further examination did not reveal a definite nonlinear relationship between slab thickness and PSI or load and PSI. Therefore, load and slab thickness were eliminated from Equation 3. Since both slab-corner deflections and slab-edge deflections were measured in the road test, regression analysis was performed on the following functions:

$$\mathrm{PSI} = f_2 \text{ (cumulative edge deflection)} \quad (4)$$

$$\mathrm{PSI} = f_3 \text{ (cumulative corner deflection)} \quad (5)$$

As expected, a strong linear correlation between edge and corner deflections was found to exist and Equations 4 and 5 were anticipated to have similar forms.

Throughout the duration of the AASHO Road Test, edge and corner Benkelman beam deflections were measured periodically. A typical deflection history for one test section is shown in Figure 1. Because deflection measurements were not taken continuously, estimating the deflections that occurred in the interval between contiguous deflection measurements was necessary. The deflection measurements (corner and edge) taken at the end of an interval were assumed to be representative of the deflections (corner and edge) throughout the interval. Deflections used in computing cumulative deflections are indicated by broken lines in Figure 1.

The wheel loads of the vehicles used in measuring Benkelman beam deflections were different from the wheel loads of the vehicles used for trafficking. To account for the change in load, we had to scale the Benkelman beam deflection data so that the deflections were representative of those caused by the vehicles used for trafficking. We assumed that the load-deflection relationship was linear. This assumption seems to be justified by previous findings (8, 18).

The traffic history of each test section was then applied to the scaled deflection measurements to obtain cumulative edge deflections and cumulative corner de-

Table 1. Results of linear regression analysis of averaged data for three slab thicknesses.

	Cumulative Edge Deflection						Cumulative Corner Deflection					
	Curve 1			Curve 2			Curve 1			Curve 2		
Slab Thickness (mm)	a_1	b_1	Range (mm)	a_1	b_1	Range (mm)	a_2	b_2	Range (mm)	a_2	b_2	Range (mm)
127	8.76	-0.85	<419 100	68.27	-11.44	>419 100	7.65	-0.63	<609 600	79.12	-13.04	>609 600
165	5.18	-0.14	<584 200	121.30	-20.27	>584 200	6.29	-0.35	<762 000	110.24	-18.05	>762 000
203	5.78	-0.30	<939 800	146.20	-23.81	>939 800	6.66	-0.45	<1 041 400	68.40	-10.74	>1 041 400

Notes: 1 mm = 0.039 in.
Curves are shown in Figure 3.

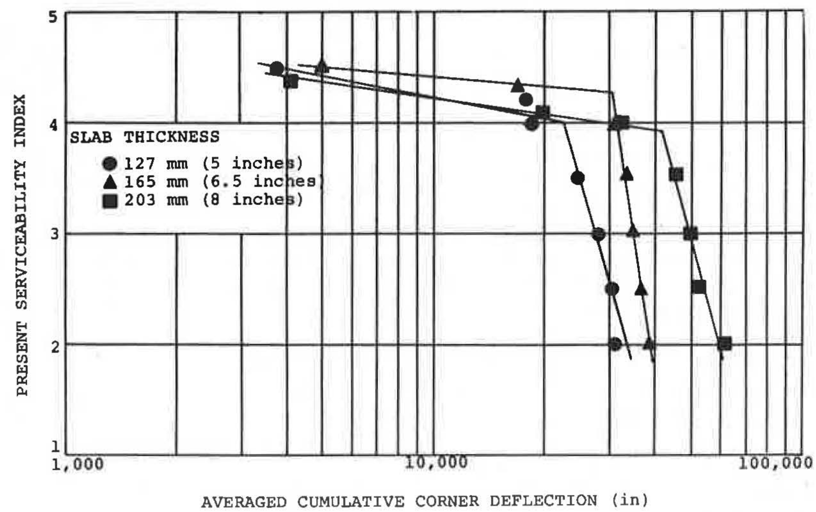


Figure 4. Serviceability versus averaged cumulative corner deflection for three slab thicknesses.

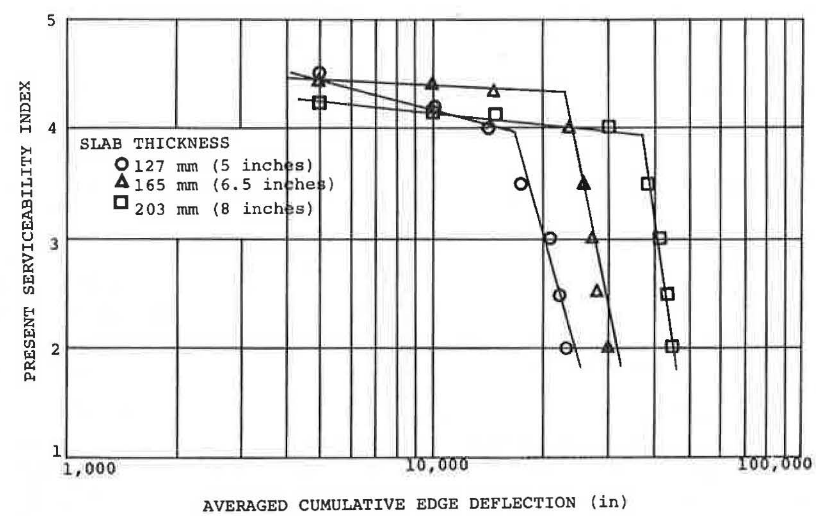


Figure 5. Serviceability versus averaged cumulative edge deflection for three slab thicknesses.

flections. The procedure whereby cumulative deflections were estimated for each test section can be expressed symbolically as

$$\text{Cumulative deflection} = \sum_{i=1}^{n} L/W_1\, D_i\, N_i \qquad (6)$$

where

L = load of trafficking vehicles,
W_1 = wheel load of vehicle used in Benkelman beam deflection measurement,
D_i = i th Benkelman beam deflection, and
N_i = number of trafficking loads applied between i th and (i - 1) Benkelman beam deflection measurement.

To investigate the nature of the functions in Equations 4 and 5, we plotted PSI versus cumulative corner and cumulative edge deflection data. PSI versus cumulative corner deflection curves for seven test sections are shown in Figure 2. Two observations are suggested from examination of Figure 2: The data extend over a wide range, and most of the curves are nearly horizontal for PSI values greater than 4 and then a break occurs after which a

relatively small change in cumulative corner deflection produces relatively large changes in the level of serviceability.

Before regression analysis was performed, an attempt was made to linearize the PSI and cumulative deflection data. The shape of the curves in Figure 2 suggested that linearization might be achieved by transgenerating the data by taking the natural logarithm of both the PSI and cumulative deflection. Regression analysis on the transgenerated data gave a multiple correlation coefficient (R^2) of about 0.5 for both cumulative edge and cumulative corner deflections. Thus, only about half the variation in the PSI level is explained by cumulative edge and cumulative corner deflections, but there exists at least a general relationship between PSI and cumulative deflections.

The regression analysis did not differentiate between the various slab thicknesses because of the lack of linear correlation between cumulative edge deflection and slab thickness and between cumulative corner deflection and slab thickness discussed previously. However, slab thickness can be taken into account if the data from test sections having the same slab thickness are isolated and then analyzed. To establish a more definitive functional relationship between cumulative edge deflection, cumulative corner deflection, and PSI, we averaged the data for each slab thickness. When these curves representing the averaged data were plotted to a semilogarithmic scale, each curve could be represented by two straight lines (Figure 3). One line represented the PSI and cumulative relationship for the initial part of the curve when there were small changes in PSI, and the second line approximated the curve where small changes in cumulative deflection resulted in large changes in the level of PSI. Simple linear regression analysis was carried out on the averaged data to obtain the parameters of the following regression equations:

$$\mathrm{PSI} = a_1 + b_1 \log_{10} (\text{cumulative edge deflection}) \tag{7}$$

and

$$\mathrm{PSI} = a_2 + b_2 \log_{10} (\text{cumulative corner deflection}) \tag{8}$$

The results of the analysis are given in Table 1 and are plotted in Figures 4 and 5, which indicate the following:

1. The relationships between PSI and cumulative corner and edge deflections are well defined for the averaged data;
2. The cumulative deflection corresponding to the intersection of the two straight lines composing each curve, referred to as the threshold cumulative deflection, increases as the pavement slab thickness increases;
3. The position and slope of the initial part of each curve are nearly the same for each slab thickness, and one can reasonably assume that the positions of the curves are related to the as-built condition of the pavement rather than slab thickness; and
4. Although the slopes of the second part of each curve appear to be about the same when plotted to a logarithmic scale, the cumulative deflection associated with reducing the PSI of the 203-mm (8-in) thick slab from 3 to 2 is nearly three times as great as that corresponding to a similar change in PSI for the 127-mm (5-in) slab.

SUMMARY AND CONCLUSIONS

The objective of this research was to test the validity of the following hypothesis: There is a functional relationship between the total energy imparted to a given rigid-pavement system as measured by cumulative deflections and the condition of that system.

Analysis of AASHO Road Test data indicates the hypothesis is valid for rigid pavements if the behavior of an average pavement of given thickness is considered. In addition, the following conclusions and observations can be stated.

1. The PSI and cumulative deflection relationship determined from averaged road test data indicates that early in the service life of a pavement increases in cumulative deflection result in small changes in PSI until a threshold cumulative deflection is reached. For cumulative deflections greater than the threshold value, the pavement serviceability decreases more rapidly as the cumulative deflection increases. This phenomenon was noted for both slab-edge and slab-corner cumulative deflections.
2. The threshold cumulative deflection at which a sharp break occurs in the PSI and cumulative deflection curve increases as the slab thickness increases. All other factors being equal then, the effects of increasing slab thickness are twofold: The deflection caused by a given load decreases as slab thickness increases, and the cumulative deflection corresponding to a given level of pavement serviceability increases as the slab thickness increases.

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Performance of the Mays Road Meter

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Serviceability index values obtained from the Mays meter and from the surface dynamics profilometer have been shown at times to differ by more than a point. A hypothesized explanation of these large discrepancies, based on the responses of the two machines to roughness with different ranges of wavelengths, is presented. Data from two sets of test sections are shown to be consistent with the hypotheses. The repeatability and day-to-day consistency of the Mays meter are also analyzed.

The Mays road meter (MRM) measures effect of the roughness of a road by summing the deflections of the rear axle of an automobile relative to the automobile body as the vehicle travels over the pavement. The mechanical details of the device, the measuring technique, and the calculation of a serviceability index (SI) from the MRM roughness measurement are discussed by Walker and Hudson (1).

The surface dynamics profilometer (SDP) is a more sophisticated device that can be used to obtain a measurement of road-surface elevation versus distance along the road in each wheel path. Obtaining an SI value for a road section as a function of the SDP measurements is also possible by using time-series analysis to compute characterizing measures of roughness and by using a regression model developed to relate roughness to serviceability.

Walker and Hudson discuss the calculation of SI values from measured profiles (2), and the measuring system is discussed by Walker, Roberts, and Hudson (3).

Periodically, an MRM must be recalibrated because of changes in the characteristics of the suspension system that affect the measurements (1). Significant changes in compression-rebound characteristics of shock absorbers or of stiffness of springs, for example, indicate the need for recalibration. The recalibration can be achieved by using SDP measurements because the performance of the SDP is very stable in time.

In addition to the shock absorber and spring characteristics, the following factors relating to the vehicle affect the MRM measurements: tire type and size, unsprung mass and sprung mass, including luggage and placement, mass of operating crew, and gasoline in tank. Sprung mass refers to the mass suspended by the springs. Because of hardware provisions within the SDP that are designed to remove the effects of the suspension system, the SDP measurements are affected drastically less by these factors than is the MRM (3).

An SDP measurement produces an approximate plot of the actual road profile (very long waves are removed by electronic filtering); however, the MRM produces only a single index that is believed to be related to the extent or severity of the roughness. Thus the two kinds of measurement are different in nature.

Because of the need for recalibration of MRMs and the much more detailed information provided by SDP measurements, the MRM will never completely replace the SDP and other similar systems. Because of its relatively low cost and simplicity of operation and maintenance, however, the MRM is more convenient for many purposes, particularly when only an overall indicator of roughness is needed and a large number of road sections are to be measured. Maintaining a fleet of MRMs to be used in different areas is feasible; however, owning a fleet of SDPs would involve a tremendous expense. Thus, there is considerable practical reason for interest in the adequacy of the MRM measurements.

Road meters similar to the Mays meter are used in many parts of the country. Although the results presented here apply only to the MRM, they are related in principle to the performance of other types of meters that are also based on the summation of rear-axle body deflections.

A set of roughness measurements were made on I-45 near Huntsville, Texas, to study the effects of swelling clay distress on the continuously reinforced concrete pavement (CRCP). Both the SDP and the MRM were operated on those sections, and large discrepancies between the SI values obtained from the two devices were observed.

DIFFERENCE BETWEEN SI VALUES FROM PROFILOMETER AND MAYS METER ON HUNTSVILLE SECTIONS

The CRCP test sections near Huntsville used in this study are sporadically affected by swelling clay and