Use of Noncontact Probes in Road Profiling

GERMAN CLAROS and W. R. HUDSON

ABSTRACT

The objective of this paper is to provide succinct information about the use of noncontact transducer devices connected to the high-speed profilometer for the purpose of measuring the road profile. The standard Surface Dynamics (SD) profilometer has two tracking wheels to measure the height between the frame of the car and the pavement, and that distance is used to obtain the road profile. Furthermore, extremely rough sections tend to damage the potentiometer, which is connected to the tracking wheels. The trailing arm, to which the tracking wheels are connected, is held in contact with the road by a 300-lb force exerted through a torsion bar. The standard profilometer functions at 20 mph, because at this speed the torsion bar minimizes the bouncing of the wheels. Speeds greater than 20 mph produce bouncing in the wheels, thereby deforming the profile. The use of noncontact probes in the profilometer gives the capability of increasing the profilometer speed during the profiling process, and damage to the potentiometers is avoided when rough sections are profiled. Profile data obtained with two noncontact devices are compared with data obtained on the same road with the standard profilometer. A comparison between noncontact devices at two different speeds (35 and 50 mph) is also made. General regression equations for predicting root-mean-square vertical acceleration (RMSVA) and serviceability index (SI) are presented.

Pavement roughness is one of the primary concerns in the evaluation of pavement riding quality. The Center for Transportation Research and the Texas State Department of Highways and Public Transportation use the Surface Dynamics profilometer Model 690D to obtain the road profiles of a group of sections. The road profiles of these sections are used as a master calibration of the Maysmeters used by the department. The profilometer uses two tracking wheels to sense the pavement surface in order to obtain the road profile. The purpose of this research is to evaluate the use of noncontact probes to replace the tracking wheels in the Surface Dynamic profilometer. A laser device and an infrared light linear transducer are evaluated in this study (1).

DESCRIPTION OF DEVICES

A brief description of the devices and their functions is included here to provide a better understanding of the noncontact probes.

Laser Device

The laser device used in this experiment is produced by Selective Electronic Co. (SELCOM) (SELCOM Operator's Manual, Selective Electronic Co., unpublished). The device is called an optocator. The optocator system contains two basic elements, the gauging probe and the central processing unit.

The gauging probe (Figure 1) consists of

1. A light source,
2. A camera unit with lens and detector, and
3. Analog and digital processing electronics.

The central processing unit (CPU) (Figure 2) has four principal functions:

1. Supplying power,
2. Receiving data from the gauging probe,
3. Processing data from the gauging probe, and
4. Outputting data.

Recording of data starts when the light source illuminates a 3/8- by 1/8-in. area of the surface to be measured via a lens system creating direct and scattered reflected light. Part of the scattered light is projected to the position of a sensitive photo detector in the camera (Figure 3). The light spot on the unique photo detector generates two currents, x_1 and x_2. The relation between the two currents gives the center of the light image on the detector. The two currents are converted into precise position information by the probe-processing electronics.

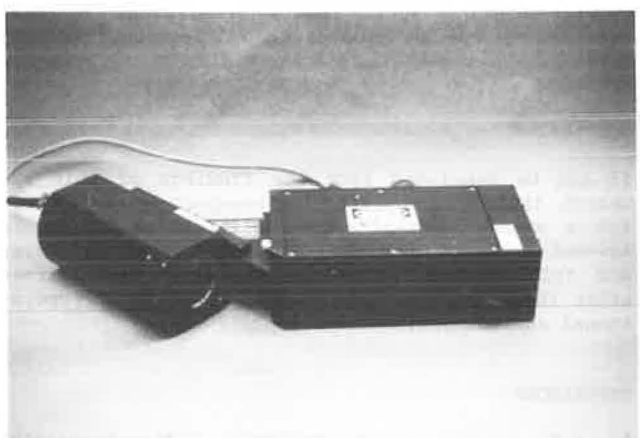

FIGURE 1 Laser Gaugin probe.

The light source is controlled to maintain a constant intensity on the detector surface. This permits wide variation in the measured surface reflec-

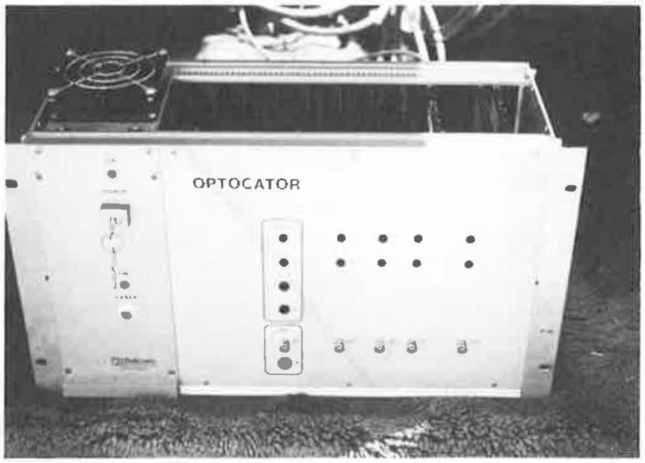

FIGURE 2 Laser central processing unit.

tivity-texture and color without affecting the measurement data. The light source is switched on and off 16,000 times per second, and therefore the system rejects any influence from ambient or background lighting. The output from the gauging probe is a digital or an analog signal.

<u>Infrared Light-Emitting Diode</u>

The infrared light-emitting diode (LED) was developed as a part of contract DOT-FH-11-8498 (System for Inventorying Road Surface Topography) between the FHWA and Southwest Research Institute.

The infrared LED concept for height measurement shown in Figure 4 is similar to that used with the laser. The infrared LED projects a beam downward normal to the pavement. Scattered energy from this illuminated spot is intercepted by the lens and focused on the dual element detector. As shown in Figure 4, the change in road height causes a change in the position of the image on the two electro-optical detector elements. The change in elevation is determined by comparing the electrical output from Detector 1 with that from Detector 2. In the initial position, the image of the spot is centered on the two detectors, and thus the electrical outputs are the same. If the image moves, falling more on one detector than on the other, the outputs are no longer equal and are proportionately different depending on the magnitude of the displacement. The difference in the electrical signals is proportional to the displacement and for small displacements it is nearly linear. For greater displacements the function is not linear but is proportional to the difference in the areas of the images on the two detectors.

A nonuniform reflectance surface will produce a

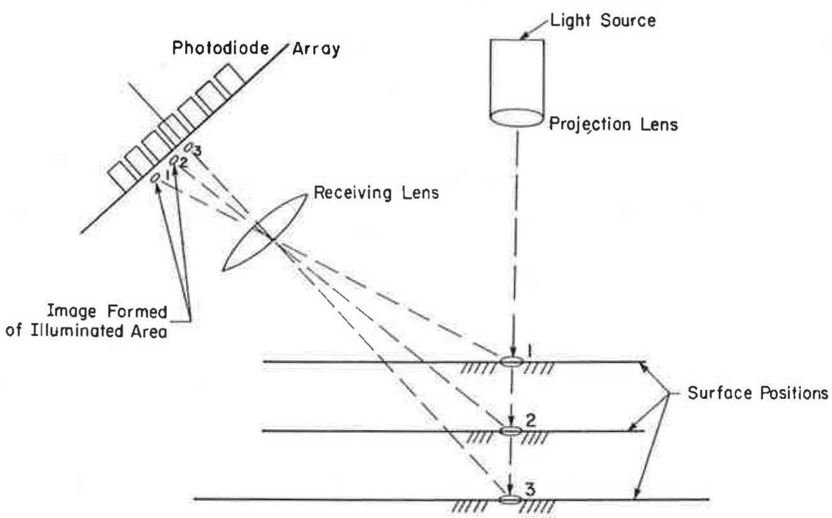

FIGURE 3 Basic noncontact lens displacement transducer design.

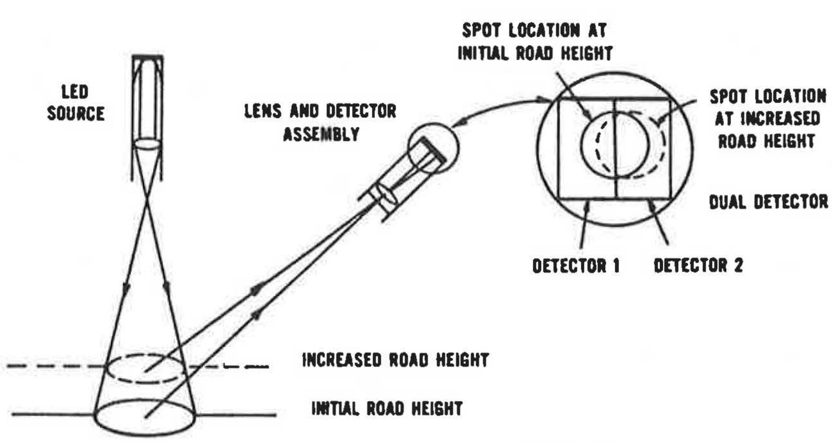

FIGURE 4 Optical height measuring technique, after SIRST *(2)*.

change in the average intensity of the portion of the spot image falling on each of the detectors. This problem is solved by using two photodetectors that are fed into a summing amplifier.

The infrared device is self-contained in a heavy aluminum housing (Figure 5). The infrared light is projected by a dual lens assembly that focuses it on a 4-in.-diameter spot on the pavement. The electronics required for amplifying and filtering the modulated output signal are included in this package.

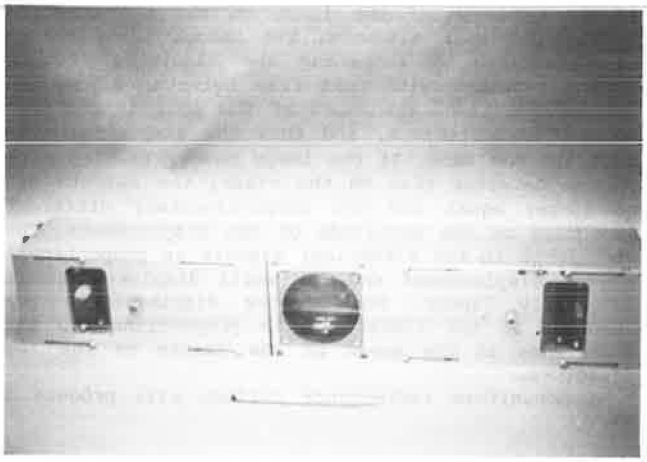

FIGURE 5 Front view of infrared device.

BENCH CALIBRATION OF DEVICES

A series of bench calibration tests was conducted on the sensors to determine the linearity, sensitivity, capability to indicate the average height from the surface, and height over the area of the illuminated spot. The sensitivity in terms of voltage output per unit change in height was measured for each device.

Laser Device

To obtain the relationship of voltage versus height to the target, the SELCOM device was mounted on a bench. A mobile target with the sensitivity required to measure a 0.10-in. vertical displacement was placed under the device. The analog output was obtained from the CPU and the analog signal was then measured by a voltimeter with a sensitivity of 0.001 volt.

The relationship of voltage versus height was obtained by moving the target 0.1 in. and recording the voltage reading. A linear regression analysis was performed with the data obtained. The corresponding regression equation is

$$Y = -0.0410 + 0.948\ x \qquad R^2 = 0.9994 \qquad (1)$$

where Y is voltage and x is distance between target and light source.

Forcing the regression through the origin gives

$$Y = 0.936\ x \qquad (2)$$

Figure 6 shows all the data points and the best fit line through the origin corresponding to Equation 2.

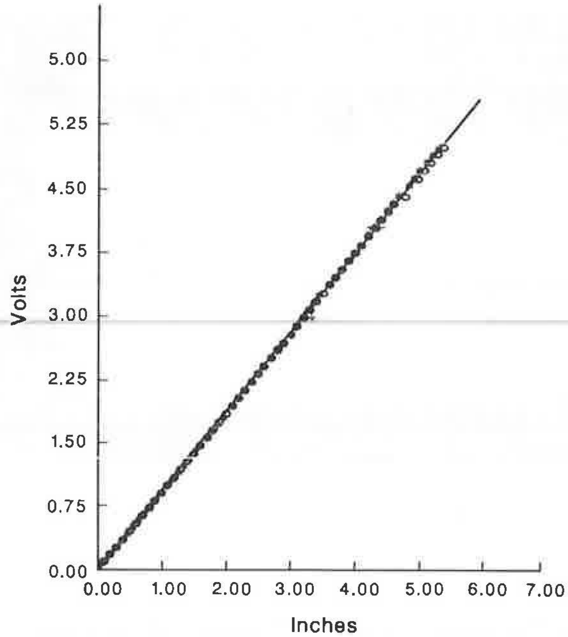

FIGURE 6 SELCOM linear regression.

Infrared Device

The infrared device was mounted on the bench in accordance with the recommendation of Southwest Research Institute (SRI). The initial distance between the light source and the target was set at 14 in. The working range of the device is ±2.5 in. with respect to that position.

The target was moved up and down in increments of 0.1 in. for which voltimeter readings were recorded. A linear regression analysis was performed on the data, and the corresponding equation is

$$Y = -0.368 - 3.01\ x \qquad R^2 = 0.994 \qquad (3)$$

where Y is voltage and x is distance between target and light source.

The regression line forced through the origin is

$$Y = -3.01\ x \qquad (4)$$

Figure 7 shows the final calibration for the infrared device.

GENERAL DESCRIPTION OF MOUNTING AND OPERATION OF PROFILOMETER

The Surface Dynamics profilometer device is described in detail elsewhere (3,4). The standard measuring system consists of (a) a set of two wheels, one in each wheelpath directly in line with the vehicle wheels; (b) two potentiometers, each connected at the bottom to a yoke extended from the trailing arm directly above the center of a road wheel to the vehicle body; (c) two accelerometers, each mounted inside the vehicle directly above the top of the potentiometers; and (d) a special digital computer with two independent circuits (one for each of the two profiles), which integrates the accelerometer signal twice and adds it to the potentiometer signal to produce a road profile for each wheelpath. All of these systems are shown in Figure 8.

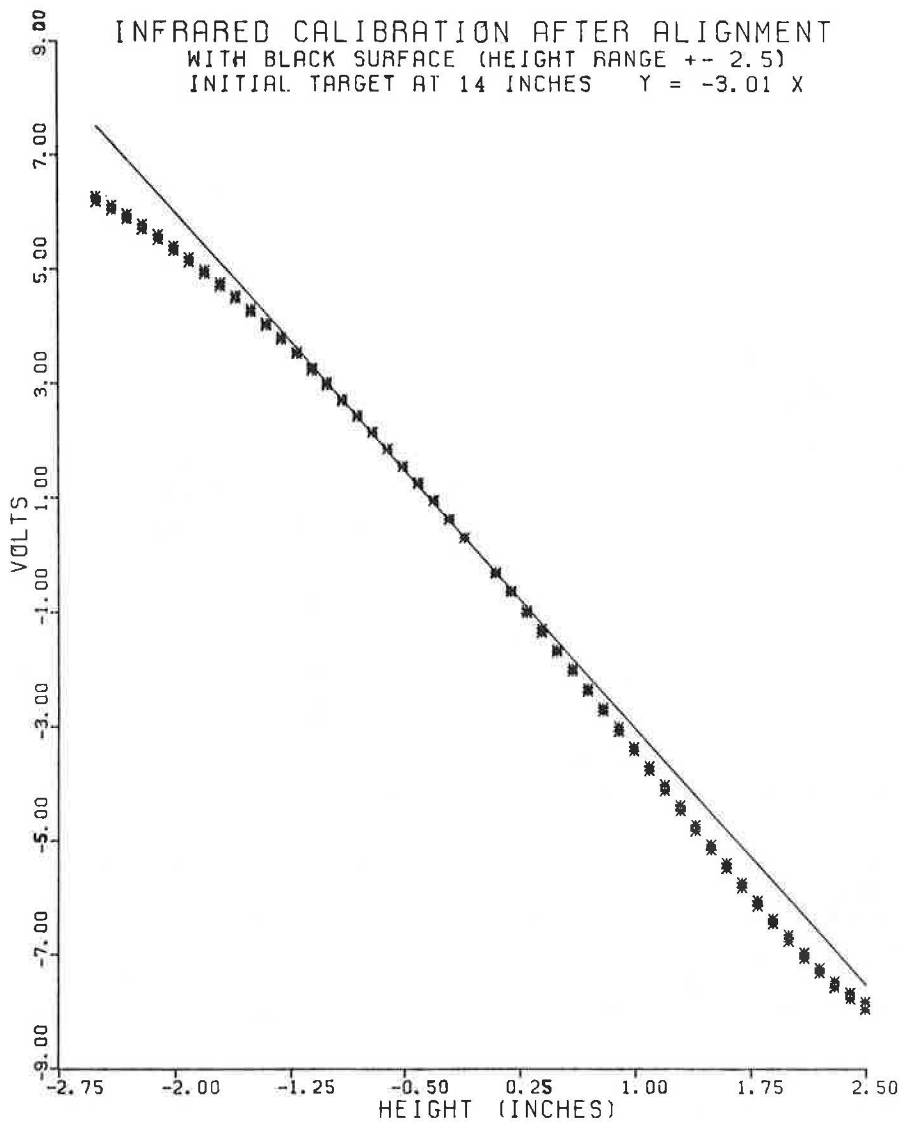

FIGURE 7 Infrared final calibration curve.

For the present research the tracking wheel and the potentiometer (Systems 1 and 2) were replaced by noncontact devices that perform the same function (i.e., measure the distance between the frame of the car and the pavement). The analog signal of these devices was transmitted to the computer in the profilometer to obtain the road profile using the procedure described previously.

The use of these noncontact devices has the following advantages:

1. The speed of the profilometer can be increased to 50 mph. The profilometer with the tracking wheel cannot go faster than 20 mph because the bouncing of the wheel deforms the profile. This increased capability is desirable on freeways with high traffic volumes where the average running speed is about 50 mph and where it is prohibitively expensive to close down a lane to conduct a profile measurement.
2. Sections with high levels of roughness tend to damage the potentiometers in the standard profilometer layout.

The SELCOM device can be mounted on the van. In the current research only one wheelpath was profiled (right wheelpath) because only one noncontact device was mounted at a time in the profilometer.

PRESENTATION OF RESULTS

To evaluate both noncontact probes, six flexible pavement sections, with three levels of serviceability index (SI), were chosen. The SI was measured with the old profilometer (January 1984). The sections are

Section No.	SI	Level
6	2.36	I (low)
2	2.48	
5	3.41	II (medium)
9	3.06	
7	4.75	III (high)
32	4.41	

The sections were profiled eight times each at two different speeds (35 and 50 mph). The order of

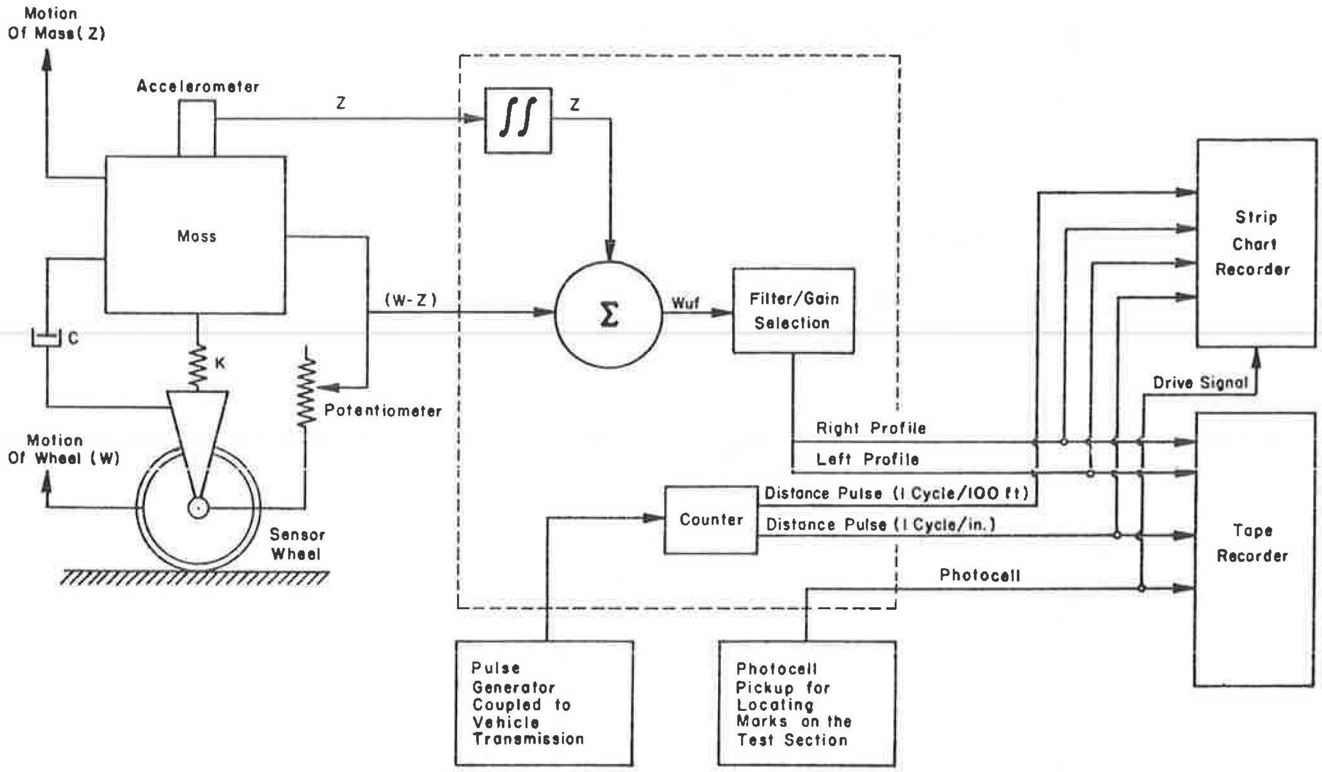

FIGURE 8 Detailed block diagram of measurement system, after Roberts et al. *(5)*.

the runs for each section was selected randomly and the number of runs was selected according to sample size theory for α and β equal to 5 percent (α probability of Type I error and β probability of Type II error). The root-mean-square vertical acceleration (RMSVA) for the 0.5-ft base length was used as an indicator of the variation in the RMSVA.

The profiling of the sections was performed with the SELCOM device (January-February 1984) and subsequently with the infrared device (February-March 1984). Every profile was analyzed using the RMSVA to evaluate the road profile. The RMSVA was calculated for nine base lengths. A description of this parameter is found elsewhere (4). The two noncontact probes were compared using the RMSVA. Their evaluations are presented in the following section.

RMSVA Coefficients of Variation (COV)

This parameter was used as an expression of the repeatability of the instrument when it was used on both the same wheelpath and the same section. These values were calculated for each base length.

A series of plots was developed for coefficient of variation versus base length for each combination of section, speed, and device.

From an inspection of these plots, it can be concluded that COV values are generally around 5 percent or less. It is important to emphasize that the wheelpaths were not marked for the profiling and the wandering of wheelpaths could explain part of this variation. The lanes were not marked in order to approximate real profiling conditions. Table 1 gives a summary of the differences for both speeds.

If the COV values for both speeds are compared, it can be concluded that the infrared device at 35 mph has lower values of COV than at 50 mph. On the other hand, the SELCOM device has lower values of COV at 50 mph than at 35 mph. Therefore the infrared device provides more repeatability at 35 mph, and the SELCOM does so at 50 mph.

TABLE 1 Comparison of COV for Both Devices

Speed (mph)	COV Infrared > COV SELCOM	COV Infrared = COV SELCOM	COV Infrared < COV SELCOM
35	Sections 2, 6, and 7	Sections 5 and 32	Section 9
50	Sections 6 and 7	Sections 2 and 5	Sections 9 and 32

Mean RMSVA

The values of the mean RMSVA were calculated for each section and for each base length. Plots of mean RMSVA versus base length for all the sections were drawn.

To estimate how different the RMSVAs are at 35 and 50 mph and whether the means of the two samples indicate that both samples were drawn from the same universe, a test to compare both samples was performed in which the null hypothesis was stated as follows:

$$Ho: \mu_{35\ mph} = \mu_{50\ mph}$$

The variances of the two populations were not assumed to be equal. A value of $\alpha \leq 5$ percent was considered to reject the null hypothesis. Table 2 gives a summary of all the values in which Ho was true (yes), where $\alpha \geq 5$ percent.

A comparison of mean RMSVAs for the SELCOM and the infrared device at both speeds is given in Table 3. From this table, it can be concluded that a mean RMSVA at 35 mph cannot be guaranteed to be equal to a mean RMSVA at 50 mph.

TABLE 2 Summary of Accepting or Rejecting Ho: $\mu_{35\ mph} = \mu_{50\ mph}$

Section	Device	Speed (mph)	Base Length (ft) 0.5	1.0	2.0	4.0	8.0	16.0	32.0	64.0	128.0	Old Profilometer (psi)
6	SELCOM	35/50	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	2.36
	Infrared		Yes	Yes	Yes	Yes	Yes	Yes	No	No	No	
2	SELCOM	35/50	No	No	Yes	Yes	Yes	Yes	Yes	Yes	No	2.48
	Infrared		Yes	Yes	Yes	Yes	Yes	Yes	No	No	Indeterminable	
5	SELCOM	35/50	No	No	No	No	No	Yes	Yes	Yes	Yes	3.41
	Infrared		No	No	No	Yes	Yes	No	No	No	Yes	
9	SELCOM	35/50	No	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	3.06
	Infrared		No	Yes	Yes	Yes	No	No	Yes	Yes	Yes	
7	SELCOM	35/50	No	No	No	No	No	No	Yes	Indeterminable	Indeterminable	4.75
	Infrared		Yes	No	No	Yes	No	No	Yes	Indeterminable	Yes	
32	SELCOM	35/50	No	No	No	No	No	Yes	Yes	Yes	Yes	4.41
	Infrared		Yes	No	Yes	Yes	No	Yes	Yes	Yes	Yes	

Note: Yes is accepting the null hypothesis Ho $\mu_{35} = \mu_{50}$; no is rejecting the null hypothesis.

TABLE 3 Comparison of Mean RMSVA at Both Speeds

Speed (mph)	Mean Infrared > Mean SELCOM	Mean Infrared = Mean SELCOM	Mean Infrared < Mean SELCOM
35	Sections 6 and 7	None	Sections 2, 5, 9, and 32
50	Sections 6 and 7	None	Sections 2, 5, 9, and 32

COMPARISON OF THE NONCONTACT DEVICES WITH THE PROFILOMETER STANDARD EQUIPMENT (track wheels)

A preliminary comparison is presented here of the noncontact devices (infrared and SELCOM) and the profilometer with the standard tracking wheels at 20 mph. This comparison is made for the infrared device at 35 mph and the SELCOM device at 50 mph. These speeds correspond to the lowest COV values obtained for each device. The comparison is based on both COV values and mean RMSVA.

Coefficient of Variation

Three sections were selected, each representing a level of serviceability index (SI). The comparison is carried out for each section.

Section 2

This section has an SI of 2.48 with a fine surface texture (Figure 9). The COV values are quite similar for the noncontact devices and for the profilometer with tracking wheels.

Section 5

This is a section with an SI of 3.41 (Figure 10) and with a coarse surface texture (chip seal). The COV values in this section are quite close to those on Section 2, and COV values increase only for the longer base lengths (64 and 128 ft). It can also be observed that the surface texture does not affect short base lengths as could be expected.

Section 7

This section has an SI of 4.75 with a fine surface texture (Figure 11). The COV values from the infrared device are higher than those from the other devices for the short base lengths (0.5 to 16 ft). The other devices (SELCOM and the standard profilometer) show low values of COV (around 4 percent); only the 128-ft base length for the SELCOM shows a large value of COV (20 percent). Further analysis of the three remaining sections (not reported here) provided additional data substantiating this conclusion.

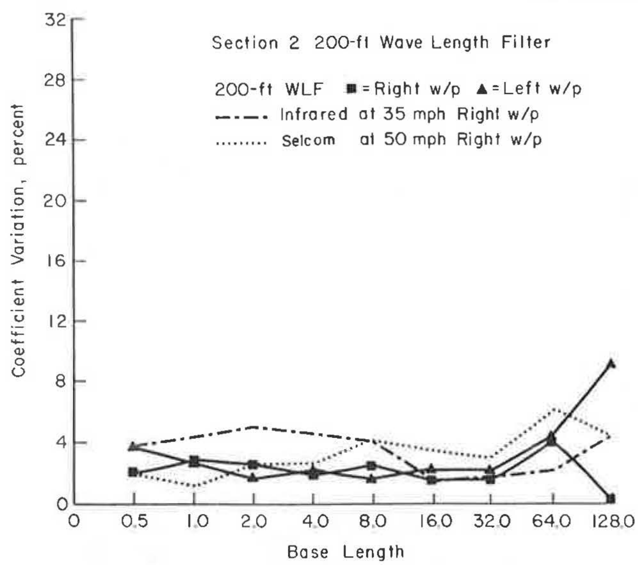

FIGURE 9 Section 2 COV percentage versus base length comparison.

From the standpoint of repeatability, as expressed by the coefficient of variation, it can be concluded that the infrared, the SELCOM, and the standard profilometer have approximately the same values. Therefore the repeatability is about the same for all of the devices.

Mean RMSVA

To perform a preliminary comparison of the mean RMSVA, Sections 2 and 5 were used. Figures 12 and 13 show the mean RMSVA versus base lengths for each one of the devices at the speeds selected. It can be

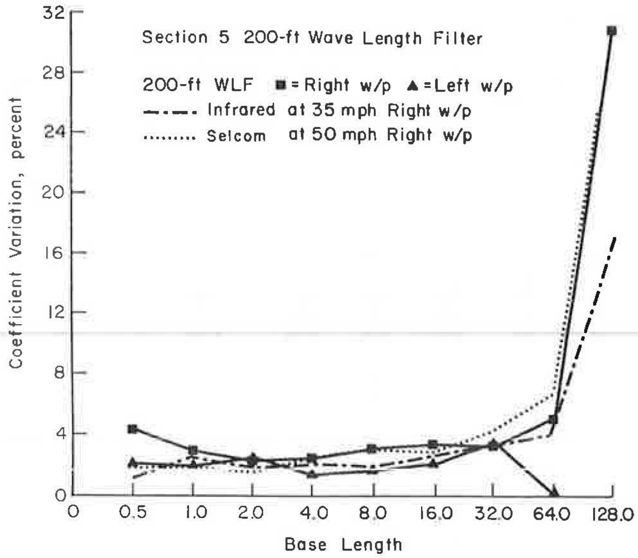

FIGURE 10 Section 5 COV percentage versus base length comparison.

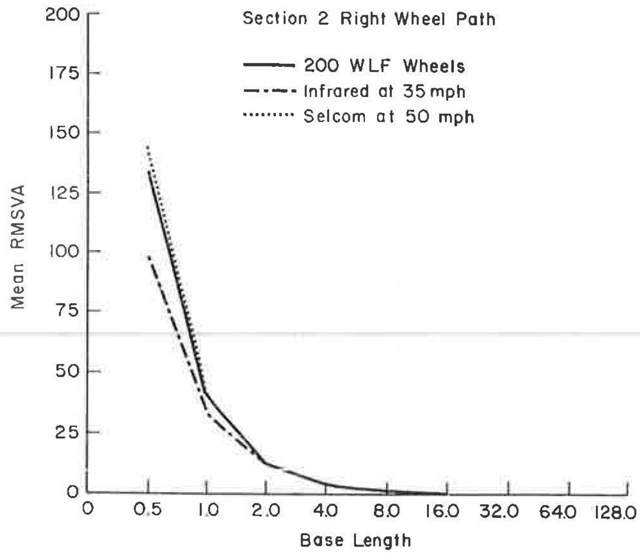

FIGURE 12 Section 2 mean RMSVA versus base length.

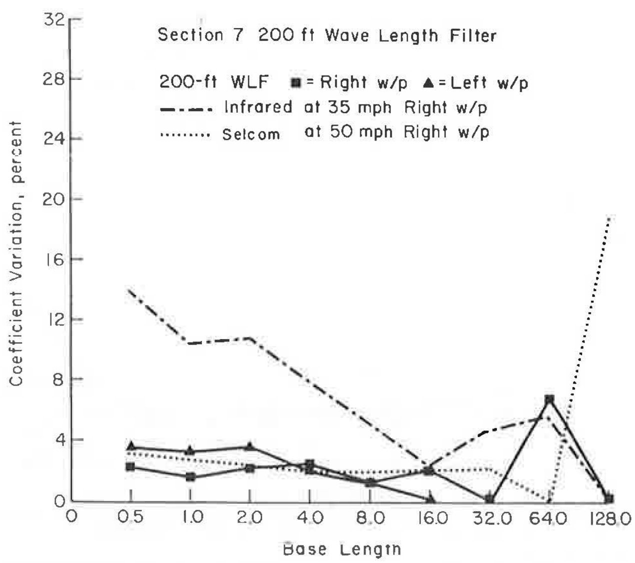

FIGURE 11 Section 7 COV percentage versus base length comparison.

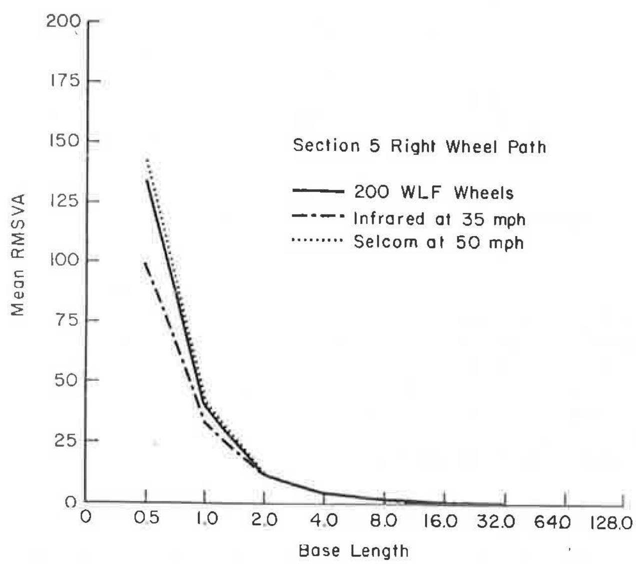

FIGURE 13 Section 5 mean RMSVA versus base length.

observed that the mean RMSVAs are different for each one of the devices in the short base length (0.5 to 2.0 ft), whereas for the long base length the values agree well.

Regression analyses were performed to predict the profilometer mean RMSVA with tracking wheels at 20 mph using the mean RMSVA of the noncontact devices. The regression equations have the following general form:

$$Y_i = C_o + C_1 X_i$$

where

Y_i = standard profilometer RMSVA for a base length i,
X_i = noncontact RMSVA for a base length i, and
C_o and C_1 = coefficients.

In Tables 4 and 5 are given the coefficients C_o and C_1 for 35 and 50 mph. The regression coefficient (R^2) is also given in Tables 4 and 5. It can be observed that the base lengths of 4.0, 8.0, 16.0 and 32.0 ft have the higher regression coefficients (R^2), indicating that it is possible to predict the RMSVA for the standard profilometer with great accuracy using the noncontact probes.

Present Serviceability Index

The present serviceability index obtained with the standard profilometer through a correlation with a rating panel can be predicted with the profilometer with noncontact probes. A multilinear regression analysis was performed for each device using all the data collected for the six sections.

The best regression equation for the infrared

TABLE 4 Regression Coefficient for SELCOM Device to Predict Standard Profilometer RMSVA

Speed (mph)	Base Length i (ft)	Intercept C_o	Coefficient C_1	Regression Coefficient (R^2) Adjusted for Degree of Freedom (%)
35	0.5	7.16	0.693	70.8
	1.0	1.73	0.764	62.5
	2.0	−0.156	0.923	66.3
	4.0	−0.142	1.062	77.9
	8.0	−0.129	1.11	94.8
	16.0	−0.055	1.12	99.2
	32.0	−0.0047	0.958	95.9
	64.0	0.0247	0.587	69.2
	128.0	0.0050	0.416	81.1
50	0.5	6.52	0.760	78.8
	1.0	−2.07	0.966	80.5
	2.0	−1.03	1.07	77.8
	4.0	−0.185	1.10	82.0
	8.0	−0.108	1.10	96.1
	16.0	−0.526	1.13	99.2
	32.0	−0.036	0.972	95.2
	64.0	−0.0214	0.623	72.6
	128.0	−0.0047	0.443	81.8

TABLE 5 Regression Coefficient for Infrared Device to Predict Standard Profilometer RMSVA

Speed (mph)	Base Length i (ft)	Intercept C_o	Coefficient C_1	Regression Coefficient (R^2) Adjusted for Degree of Freedom (%)
35	0.5	−22.5	1.28	39.2
	1.0	−2.85	1.07	47.7
	2.0	0.773	0.871	60.2
	4.0	0.331	0.831	82.9
	8.0	0.0878	0.816	90.8
	16.0	0.0467	0.831	96.6
	32.0	0.0189	0.827	98.8
	64.0	0.0115	0.663	92.0
	128.0	0.0022	0.479	91.5
50	0.5	−7.17	1.13	30.8
	1.0	−0.287	0.987	42.1
	2.0	0.849	0.840	53.2
	4.0	0.313	0.818	81.7
	8.0	0.0716	0.798	91.1
	16.0	0.0451	0.799	96.1
	32.0	0.0105	0.883	96.0
	64.0	0.0194	0.619	82.1
	128.0	0.0041	0.445	82.1

device at 50 mph, which does not include too many terms, is

$$SI = 5.5913 - 6.0268x_1 + 13.678x_2 - 7.9256x_3 \quad (5)$$

$R^2 = 0.983$

where

x_1 = RMSVA for an 8.0-ft base length,
x_2 = RMSVA for a 16.0-ft base length, and
x_3 = RMSVA for a 32.0-ft base length.

The regression equation for the SELCOM device at 50 mph is

$$SI = 6.911 - 7.7725x_1 + 4.0807x_2 + 81.654x_3 \quad (6)$$

$R^2 = 0.998$

where

x_1 = RMSVA for an 8.0-ft base length,
x_2 = RMSVA for a 16.0-ft base length, and
x_3 = product of (RMSVA) 4.0 and (RMSVA) 8.0.

SHORTCOMINGS

Infrared Device

The infrared device averages the height for all the points inside the 4-in.-diameter spot; therefore any wide crack or joint is included in the average. The relationship of output voltage versus height obtained in the bench calibration is an S-shaped curve. Fitting a linear relationship for voltage versus height gives approximately a ±0.10-in. error for the extreme points. The infrared spot size is fairly large, which reduces the accuracy of the height measurement. A recent conversation with representatives of Southwest Research Institute indicates that a reduction in the spot size could be made easily, with the additional advantages of an improvement in the resolution and the linearity of the apparatus. The new spot diameter could be reduced to 2.0 in.

SELCOM (laser) Device

The most serious disadvantage of this probe is signal dropout. The light beam is very small (3/8 by 1/8 in.). This condition makes it susceptible to the surface texture of the pavement. Coarse surface texture (chip seals) produces shielding effect on the scatter light causing a dropout in the signal, which generates missing data in the profile. During the noncontact probe evaluation, a digital filter was used inside the VERTAC program in order to eliminate these points on the profile. This probe has fewer dropouts as the speed is increased to 50 mph. A recent conversation with SELCOM representatives indicates that an increase in the light intensity and the angle of the camera viewer could minimize signal dropout.

CONCLUSIONS

On the basis of this study and comparison of the noncontact devices, it can be concluded that

1. The infrared and the SELCOM devices and the standard profilometer (with tracking wheels) have approximately the same coefficient of variation. Therefore repeatability is about the same for all the devices.
2. The mean RMSVA remains constant for the long base lengths (4.0, 8.0, 16.0, 32.0, 64.0, and 128.0 ft) for all three devices, whereas for the short base length (0.5, 1.0, and 2.0 ft) the mean RMSVA is different for each of the devices.
3. The standard profilometer RMSVA for 4.0-, 8.0-, 16.0-, and 32.0-ft base lengths can be predicted with greater accuracy with the noncontact probes, as the data in Tables 4 and 5 indicate.
4. The serviceability index can be predicted using regression Equations 5 and 6.
5. The wheel track can be replaced in the profiling operation by the noncontact devices (SELCOM and infrared), which have the same accuracy, in addition to the following advantages:
   - The speed of the profilometer can be increased to 50 mph. This capability is desirable on freeways with high traffic volumes where it is prohibitively expensive to close down a lane to conduct a profiling operation.
   - Sections with high levels of roughness tend to damage the potentiometers in the standard profilometer layout. This can be avoided by using the noncontact probes.
   - High-frequency vibrations are transmitted by

the trailing arm to the frame of the car in the standard profilometer. Such high-frequency vibrations produce some error in the double integration of the vertical acceleration. This problem can be avoided by using noncontact probes.

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Estimation of Pavement Loading from Limited Vehicle Volume Sampling

A. T. PAPAGIANAKIS and A. T. BERGAN

ABSTRACT

A method is described for the approximate evaluation of pavement loading (i.e., EAL repetitions) from limited vehicle volume sampling. EAL repetition and truck volume data obtained from a weigh-in-motion (WIM) scale are analyzed. A time series model is fitted to the number of daily EAL repetitions. Strong seasonal trends are proven for the bi-hourly traffic volumes of five-axle semitrailer trucks during a period of 1 week (84 bi-hourly time spans). As a result, the daily traffic volumes of five-axle semitrailer trucks can be approximately determined by sampling five-axle semitrailer truck volumes for several hours only. Total daily EAL repetitions can be calculated from the daily volumes of the five-axle semitrailer trucks by multiplying by appropriate factors. The method of calculation of accumulated EAL involves the evaluation of EAL repetitions for several consecutive days and, subsequently, use of a regressive time series model developed to calculate future EAL repetitions.

Most highway agencies in North America use traffic volume and vehicle weight data as an essential input for their pavement management systems. Vehicle traffic volumes are obtained by sampling the number of vehicle axles through a highway network; axle load data are evaluated by sampling heavy trucks using static weigh scales. Traditionally, pavement loading, indexed by equivalent axle loads (EALs), has been predicted on the basis of vehicle traffic volumes, percentage of heavy trucks, and "weighted" EAL factors representative of the truck population in a jurisdiction (1,pp.1-5; 2). This method of evalu-