

Comprehensive Evaluation of Five Sensors Used To Measure Pavement Deflection

VIVEK TANDON AND SOHEIL NAZARIAN

The results of a comprehensive evaluation of five sensors used in pavement instrumentation are discussed. These five sensors are velocity transducer (geophone), accelerometer, linear variable differential transformer, laser optocator, and proximeter probe. The sensors were selected because of their commercial availability and their potential effectiveness in deflection measurement. The main two parameters studied were the accuracy and precision of each sensor. These parameters were studied in a laboratory environment to minimize the effects of uncertainties that may affect the results. Various impact shapes and duration were investigated. The magnitude of deflection was also varied over a wide range. In addition, factors such as cost and field-worthiness were also considered. It was found that for pavement evaluation, geophones appear to be the optimum sensors. Geophones, if used properly, will provide adequate accuracy and precision at minimal cost.

The use of mechanistic pavement design methodologies is increasingly emphasized. To successfully implement these methodologies, the response of pavement to applied loads should be accurately determined. Among the major response parameters to be considered are the deflections, deformations, and strains within the pavement system.

The state-of-practice in determining these parameters is the employment of deflection-based nondestructive testing (NDT) devices. Unfortunately, because of inherent theoretical and experimental problems with the NDT methods, the levels of accuracy and precision with which displacements and strains within the pavement are measured are not known.

To determine these uncertainties, pavements are typically instrumented. Three of the most popular sensors are linear variable differential transformers (LVDTs), velocity transducers (geophones), and accelerometers. Two other promising sensors are the laser devices and the noncontact proximeter probes. The limitations and advantages of these sensors as applied to pavement instrumentation are not well known.

The results of a comprehensive study conducted to determine the suitability and accuracy of these sensors are discussed here. The working principles and specifications of each sensor are discussed. The setup used for evaluating the precision and accuracy of different sensors and the evaluation process involved in determining the most suitable sensor are described. Finally, based on this evaluation process, the most appropriate sensor is selected.

DESCRIPTION OF SENSORS

The nature, specifications, and accuracy of each sensor are extensively reported elsewhere by Tandon and Nazarian (1). A brief description of each sensor is presented next.

Accelerometers

Accelerometers are important vibration measurement sensors that are available in wide ranges of sizes and response characteristics. As shown in Figure 1a, accelerometers use a sensing mechanism to measure the acceleration that acts upon a mass. Under a dynamic motion, the mass is accelerated at a certain rate as a result of force exerted on the spring. Because the spring deflection is proportional to the force applied to the mass and the force is proportional to the acceleration of the mass, the spring deflection is a measure of acceleration.

There are several advantages to the use of accelerometers. Piezoelectric accelerometers generate large output-voltage signals, are compact, and possess high natural frequencies. These properties make an accelerometer a good tool for accurate shock and vibration measurements.

There are also disadvantages associated with accelerometers, however. Piezoelectric accelerometers are not reliable at low frequencies. The lowest frequency that can be accurately measured with an accelerometer depends on the value of discharge time constant (1).

Linear Variable Differential Transformers

LVDTs use the principle of change in magnetic coupling (or reluctance) to determine deflection. Basically, an LVDT consists of a case and a core (Figure 1b). The case of an LVDT contains three coils: one primary and two secondary. The basic function of secondary coils is to produce opposing voltages. When the core is in a neutral or zero position the voltages induced in the secondary windings are equal and the net output is zero. The output voltage will be nonzero when the core is moved. The output voltage will be positive or negative depending on the relative position of the case and the core rod.

As the core rod penetrates farther into the core, magnetic coupling between the primary and one of the secondary coils increases; meanwhile the coupling between the primary and the other secondary coil decreases. Therefore, the net voltage increases as the core is moved away from the neutral position.

The advantages of the LVDT are several. There is no physical contact between the case and the core; thus there is no

V. Tandon, Pennsylvania State University, Department of Civil Engineering, University Park, Pa. 16802. S. Nazarian, University of Texas at El Paso, Department of Civil Engineering, El Paso, Tex. 79968-0516.

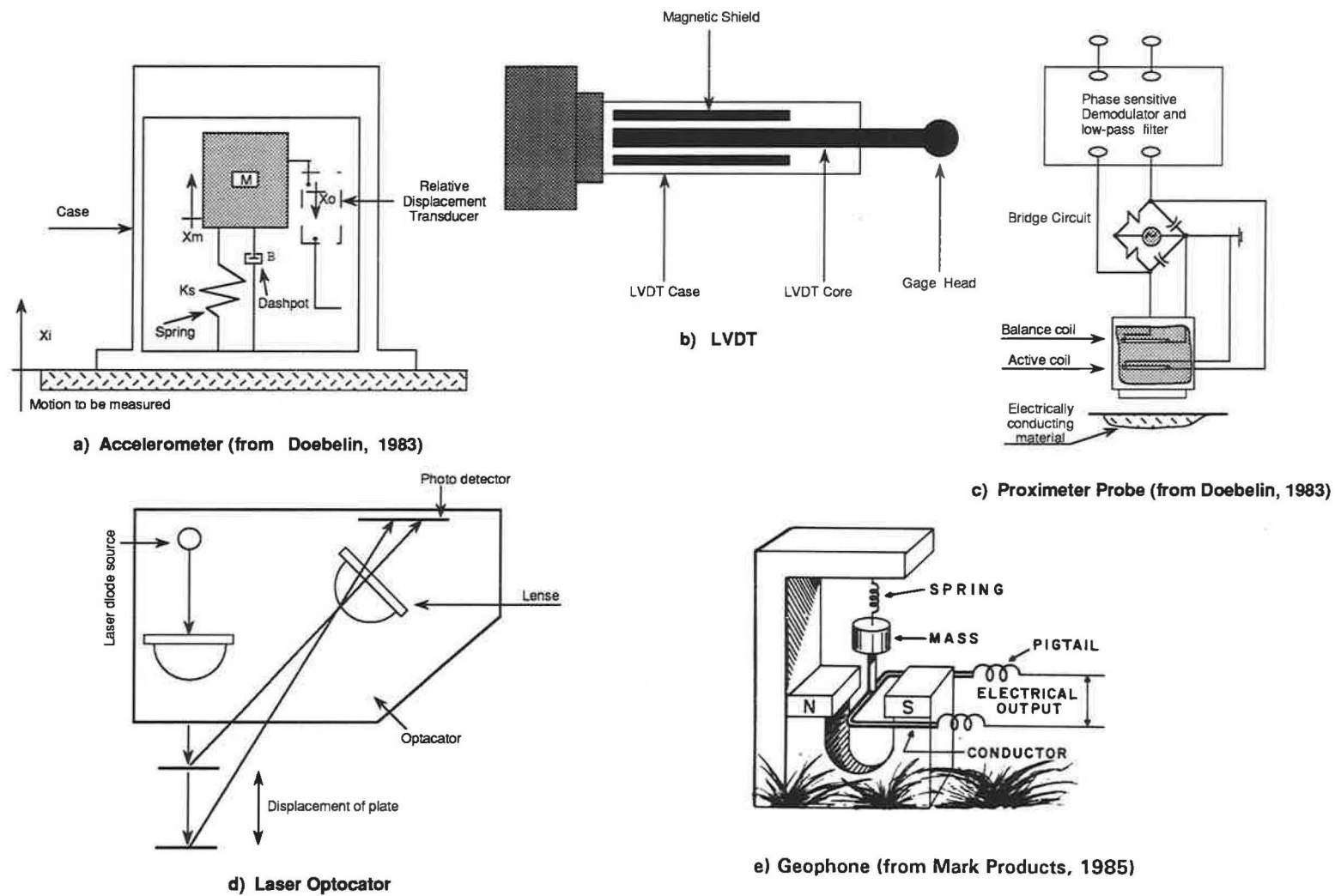


FIGURE 1 Schematic of sensors used.

friction or wear. As a result of the introduction of DC-DC circuitry, LVDTs have become highly sensitive and extremely rugged at the expense of reduced reliability.

There are also several disadvantages associated with the LVDT setup. Dynamic response of an LVDT is limited. Therefore, motions with high frequency contents cannot be detected by an LVDT. There are small radial and longitudinal magnetic forces in the core if it is not centered radially and at the null position, which results in less reliability of measured deflection. The use of LVDTs in the field is difficult and expensive. The output of the LVDT is linear only in a certain range, near the neutral position of the core. Therefore, the LVDT should be mounted such that the core is positioned near the neutral position.

Proximeter Probes

Proximeter probes are noncontact inductive displacement transducers. Generally, the transducer system consists of a proximeter, a probe, and an extension cable (Figure 1c).

The proximeter performs two functions within the transducer system. The first is to generate a high-frequency signal and transmit the signal to the probe tip. The second is to receive the signal from the probe tip and process it to produce a DC output proportional to the displacement of the material being observed.

Major advantages of proximeters are as follows. Proximeter output can be read easily with any type of DC voltmeter. Application of high frequency radio signals yields a higher signal-to-noise ratio because more energy is transferred in less time, which immunizes the system from noise. The probe can be connected to the proximeter with a long cable; therefore the probe can be conveniently located near the (conductive) target material.

There are, however, some drawbacks associated with proximeters. The calibration of a proximeter varies based on the target material used. The input voltage must also be constant and equal to the input voltage supply used when calibrating the proximeter. Proximeters can measure deflections accurately only if the probe is in the close vicinity of the target (within 2 mm). As such, the chances of damaging the probe as a result of a sudden increase in the deflection of the target material is high. It is not always easy to maintain a 2 mm gap between the target and probe under field conditions. It is also difficult to mount a proximeter perpendicular to the target in the field. For accurate measurement, the probe should be exactly perpendicular to the target; otherwise the deflection obtained may not be reliable.

Laser Optocator

The laser optocator is a noncontact displacement transducer. As shown in Figure 1d, it consists of a light source (either ultraviolet or infrared) and a photodetector (or light-sensitive transistor) to receive the reflected signal. A beam of light from the light source is aimed at the surface. The beam of light is reflected back and is focused on the photodetector through a lens. The photodetector sends a signal to the signal

processors according to the position of the focused beam on the photodetector.

The laser used in this study is an accurate deflection measuring tool. However, it is not a practical instrument, especially for field use. To avoid scatter of infrared laser rays, the observed target should be smooth, which is not characteristic of pavements. In addition, good resolution at very low deflections (about 1 mil) could not be obtained in this experiment.

Velocity Transducers (Geophones)

Geophones are coil-magnet systems, as shown in Figure 1e. A mass is attached to a spring, and a coil is connected to the mass. The coil is located such that it crosses the magnetic field. An impact causes the magnet to move, but the mass remains more or less stationary, causing a relative motion between the coil and magnet. This relative motion generates voltage in the coil that is proportional to the relative velocity between the coil and magnet.

Geophones are small in size, light in weight, and inexpensive compared to other transducers. The output of a geophone can be connected to any recording device without using an amplifier. Geophones are rugged and can withstand both high and low temperatures.

LABORATORY SETUP

In the setup for determining the accuracy and precision of deflections of all sensors, a thick concrete block was selected and leveled perfectly. Such a structure results in minimal differential movement among different components in the system. An exciter was kept between the two walls of the block. A circular aluminum plate, 8 in. in diameter, was screwed securely to the exciter. The geophones were rigidly fastened to the plate using a specially designed casing. An accelerometer was fastened to the top of the casing of each geophone. To place the LVDT and proximeter, a square aluminum plate was fastened to two beams connected rigidly to two steel plates (Figure 2a). The two steel plates were securely connected to the concrete. Two holes were bored in this aluminum plate for mounting the LVDT and proximeter. The LVDT was fixed to the top plate so that the gage head of the LVDT was touching the bottom plate attached to the shaker. Because the proximeter had been calibrated using 4140 steel as a target material, a small circular piece of 4140 was screwed in the lower plate, providing proper target material for the probe. The proximeter was also attached to the top plate in a similar manner as used for the LVDT, using an adjustable connector.

The second half portion of the bottom plate was reserved for the laser optocator. The laser required sufficient unobstructed area for sending and receiving laser beams. The laser was fixed to the top steel plate with the help of another vertical plate, as shown in Figure 2b.

The accuracy and precision of sensors were determined for four different waveforms (sine, half-sine, square, and triangular). Sine waves were generated using the HP 3562A analyzer; the other waveforms were generated using model 75

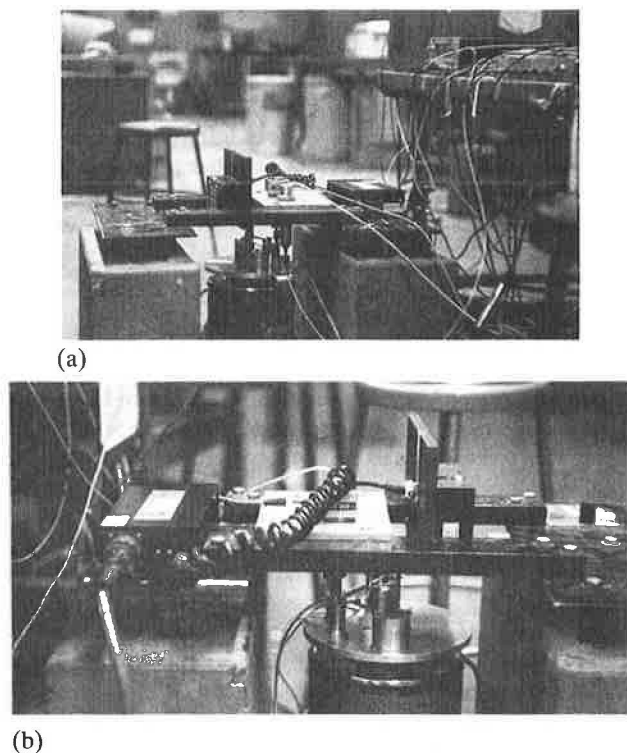


FIGURE 2 Experimental setup: (a) layout and (b) close-up.

Wavetek arbitrary waveform generator. The procedure used to obtain deflections is different for each device and each waveform. For an in-depth understanding of procedures used to determine deflections from each sensor, the reader may refer to other work by the authors (1).

EVALUATION OF SENSORS

To evaluate fully the five candidate sensors, several parameters were considered. The parameters studied were amplitude of vibration, type of excitation, and frequency content of vibration. Tests were carried out in the laboratory environment so that these variables could be easily controlled.

The amplitude of vibration was varied from 1 to 25 mils. Such a broad range of amplitude was studied to ensure proper response of the sensors to small and large amplitudes. Small amplitudes of vibration allowed examination of the effects of background noise (signal-to-noise ratio) for each sensor. Tests at large vibration amplitudes were carried out to determine the range of usefulness of each sensor.

Different types of excitation were investigated to determine the versatility of each sensor for use with different types of NDT devices. The steady-state vibration and impulse (transient) motions were examined. Three types of impulses—half-sine, triangular, and square—were used. The steady-state vibration is used by several NDT devices such as the dynaflect and road rater. Falling weight deflectometers (FWDs) impart impulse, or transient, loads to pavements.

The effect of frequency content on the behavior of each sensor was also studied. For the steady-state tests, the frequency of vibration was varied between 5 and 100 Hz. The

lower frequency signifies the lower limit of operation of the shaker's amplifier. The amplifier cannot adequately amplify steady-state signals below 5 Hz. The upper frequency limit (100 Hz) is practically the highest frequency of interest in the deflection-based tests. For the impulse tests, the duration of impulse was varied from 12.5 to 175 msec, to cover the frequency ranges of interest in NDT methods.

Steady-State Tests

Two series of tests were carried out using the steady-state vibration setup. The laser device was not used in the first series because it is expensive to rent the device. It was added to the testing sequence of the second series. Because of time limitations, the extent of deflection data collected with the laser device is relatively limited.

All combinations of frequency and amplitude evaluated in the steady-state tests are presented in Table 1. Typically, at each frequency measurements in the range of amplitudes of 1 to 25 mils were carried out. The amplitude of vibration was limited to about 20 to 25 mils. At a frequency of 100 Hz, displacements larger than 5 mils could not be generated because of the shaker's characteristics.

An example of data collected at each frequency and each amplitude is shown in Table 2. Two geophones (Geo 1 and Geo 2), two accelerometers (Acc 1 and Acc 2), an LVDT, and a proximeter (Prox) were used in all tests.

The recording device used in this experiment was a two-channel spectral analyzer. Therefore, only two devices could be compared at one time. To remove any bias in the data as a result of sequence of testing, deflections were compared in random order. This sequence is depicted in the second and third columns of Table 2. Each sensor was compared twice with the other five sensors. The actual deflections from each pair of sensors are reflected in the fourth and fifth columns of Table 2. The difference between the deflections of the two sensors was calculated and is presented in the sixth column.

The proximeter was selected as the reference sensor to facilitate the evaluation process. The proximeter sensors can

TABLE 1 Summary of Steady-State Tests

Frequency (Hz)	Approximate Deflection (mils)				
5	1	5	10	18	25
10	1	5	10	18	25
15	5	8	10	15	18*
20	5	10	14	18*	22
30	5	15	18*	22	--
40	1	5	10	18*	22
50	1	5	10	18	25
75	1	5	10	18	--
100	1	5	--	--	--

Shaded Cells correspond to tests performed with and without laser device

*Only tested when laser was present

TABLE 2 Testing Sequence Used in Steady-State Deflection Measurements at Each Frequency and Amplitude (Without Laser Device)

Frequency Used : 05 Hz			Source Level: 0.020 Volts		
File No.	Device Used		Deflection (mil)		Difference (percent) ⁺
	Channel 1	Channel 2	Channel 1	Channel 2	
1	Acc 1	Geo 1	1.48	1.51	-1.75
3	Prox	Acc 2	1.53	1.53	-0.13
5	LVDT	Acc 2	1.49	1.51	-1.34
7	Geo 2	Geo 1	1.50	1.50	-0.07
9	Prox	Geo 2	1.53	1.49	2.71
11	LVDT	Acc 1	1.50	1.47	2.33
13	Prox	LVDT	1.53	1.49	2.61
15	LVDT	Acc 1	1.51	1.48	1.99
17	Acc 1	Geo 2	1.50	1.49	0.40
19	Prox	Geo 1	1.53	1.51	1.50
21	Acc 1	Geo 1	1.49	1.51	-1.34
23	LVDT	Prox	1.50	1.53	-2.00
25	Geo 2	Acc 1	1.52	1.51	0.66
27	Prox	Acc 1	1.54	1.49	3.12
29	Acc 1	Acc 2	1.48	1.52	-2.70
31	Acc 2	Prox	1.54	1.53	0.46
33	Prox	Geo 2	1.54	1.50	2.34
35	Acc 2	Geo 2	1.52	1.51	0.66
37	Acc 1	Prox	1.50	1.54	-2.40
39	LVDT	Geo 1	1.51	1.52	-0.93
41	Acc 2	Geo 1	1.56	1.53	1.99
43	LVDT	Acc 2	1.51	1.54	-1.99
45	Geo 2	Geo 1	1.53	1.52	0.33
47	Acc 2	Geo 2	1.54	1.51	2.21
49	Acc 1	Acc 2	1.50	1.53	-1.73
51	Acc 2	Geo 1	1.54	1.52	1.30
53	Prox	Geo 1	1.55	1.52	1.94
55	LVDT	Geo 2	1.52	1.51	0.59
57	LVDT	Geo 1	1.51	1.52	-0.93
59	Geo 2	LVDT	1.53	1.51	1.31

⁺Difference = {Channel 1 - Channel 2}*100/Channel 1

accurately measure small deflections in the laboratory environment because of their noncontact nature. An example of comparison of deflections obtained from the proximeter and other sensors is shown in Table 3 for the data presented in Table 2.

In the next step, the average, standard deviation, and variance of deflections were calculated for each sensor. As reflected in Table 2, each device was used 10 times for comparison purposes. As an example, the statistical information obtained from data in Table 2 is presented in Table 4. It can be seen that the average varies between 1.49 mils and 1.53 mils, about 0.04 mils difference, and the overall variance is less than 0.02 percent.

TABLE 3 Accuracy Determined from Data in Table 2

File No.	Device Used		Deflection (mil)		Difference (percent) ⁺
	Channel 1	Channel 2	Channel 1	Channel 2	
3	Prox	Acc 2	1.53	1.53	-0.13
9	Prox	Geo 2	1.53	1.49	2.71
13	Prox	LVDT	1.53	1.49	2.61
19	Prox	Geo 1	1.53	1.51	1.50
23	LVDT	Prox	1.50	1.53	1.96
27	Prox	Acc 1	1.54	1.49	3.12
31	Acc 2	Prox	1.54	1.53	-0.46
33	Prox	Geo 2	1.54	1.50	2.34
37	Acc 1	Prox	1.50	1.54	2.34
53	Prox	Geo 1	1.55	1.52	1.94

⁺Difference = {(Prox. defl.)-(Other Device defl.)}*100/(Prox. defl.)

A laser device was added to the second series of tests. The laser device was rented for 2 weeks. Therefore, the number of tests had to be modified and reduced. The compilation of all steady-state tests carried out in the presence of the laser device is presented in Table 1.

An example of data collected at one frequency and one amplitude in the presence of the laser device is presented in Table 5. In these tests, each device was compared with the laser once. As such, six deflections were obtained from the laser device for each setup. The statistical information on these six measurements was calculated for evaluation purposes. This information is presented in Table 5. As before, the two devices that were compared are shown in the second and third columns; measured deflections with the corresponding sensors are shown in the fourth and fifth columns; and finally, the differences in deflections are reflected in the sixth column.

TABLE 4 Precision Determined from Data in Table 2

Test No.	Device Used	Average Deflection (mil)	Standard Deviation (mil)	Variance (percent)
1	Accelerometer 1	1.49	0.01	0.02
2	Accelerometer 2	1.53	0.01	0.02
3	Geophone 1	1.52	0.01	0.01
4	Geophone 2	1.51	0.01	0.02
5	Proximeter	1.53	0.01	0.00
6	LVDT	1.51	0.01	0.01

TABLE 5 Testing Sequence Used in Steady-State Deflection Measurements at Each Frequency and Amplitude (With Laser Device)

Frequency Used : 10 Hz			Source Level: 0.045 Volts		
Test No.	Device Used		Deflection (mil)		Difference (percent)*
	Channel 1*	Channel 2	Channel 1	Channel 2	
1	Laser	Geo 1	5.19	5.13	1.16
2	Laser	Prox.	5.20	5.12	1.54
3	Laser	Acc 2	5.19	5.23	-0.77
4	Laser	LVDT	5.19	5.12	1.35
5	Laser	Geo 2	5.19	5.13	1.16
6	Laser	Acc 1	5.20	5.08	2.23

* Average = 5.19 mil
 Standard Deviation = 0.00 mil
 Variance = 0.00 percent

*Difference = {Channel 1 - Channel 2}*100/Channel 1

Impulse Tests

Each sensor was subjected to three different types of impulse for evaluation purposes. These impulse types were half-sine, square, and triangular. The pulse width was varied from 12.5 msec to 175 msec to cover a wide range of frequencies. Typically, the pulse width for loads applied with the FWD varies between 25 msec and 75 msec. Therefore, this experiment should cover all ranges of interest in pavement evaluation. Normally, as the pulse width increases the dominant frequency content of the pulse decreases. As an example, a pulse width of 25 msec corresponds to frequencies in the range of 0 to about 25 Hz. However a pulse of 175 msec corresponds to frequency range of 0 to 2 Hz.

Nominal deflections used were 5, 15, and 25 mils. As for the steady-state tests, the lower limit (5 mils) was used to evaluate the effects of undesirable, external, electrical, and environmental noise, whereas the upper limit was used to evaluate the working range of each sensor.

Tests with the impulse motion were carried out in two phases: without the laser device and with the laser device. A matrix of all tests carried out with the half-sine impulse in the absence of the laser device is shown in Table 6. The half-sine impulse

TABLE 6 Summary of Impulse Tests

Pulse Width (msec)	Deflection (mils)			Type of Impulse*
12.5	5	15	25	1
25	5	15	25	1,2,3
50	5	15	25	1,2,3
75	5	15	25	1,2,3
100	5	15	25	1,2,3
112.5	5	15	25	1
125	5	15	25	1,2
150	5	15	25	1
175	5	15	25	1,2

Shaded areas correspond to tests performed with and without laser device.

*Type of Impulse: 1 = Half-Sine, 2 = Square, 3 = Triangular

tests are quite comprehensive because this is the shape of the pulse typically used in NDT devices.

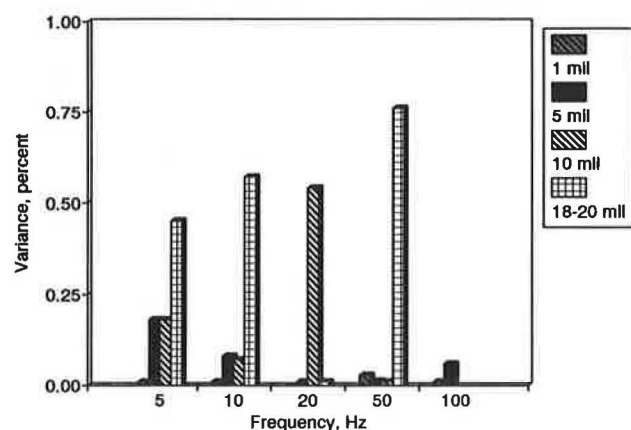
In the absence of laser device, the sequence of tests carried out at any given impulse width and amplitude was identical to that of the steady-state tests. Once again, the proximeter was used as the reference source to demonstrate the differences in the measured deflections. In the last step, the statistical information on measurements made by each device was determined. The mean, standard deviation, and variance for each device were obtained for the steady-state tests.

PRECISION AND ACCURACY OF SENSORS

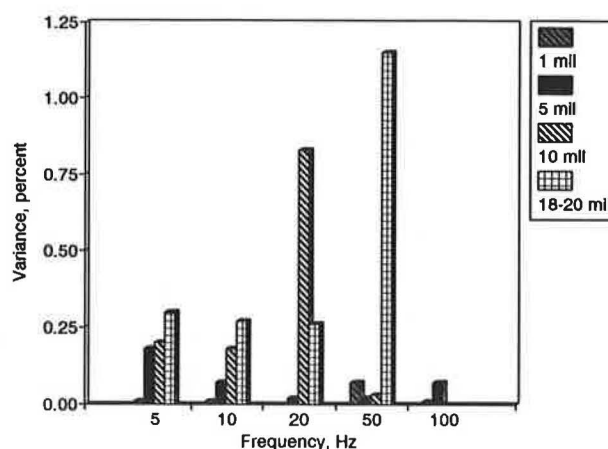
In this section the accuracy and precision of the sensors as measured in an ideal laboratory setting are compared. It is understood that the level of precision and accuracy realized in the field may be significantly greater (worse) than those reported herein. The values reported herein can be considered as minimum acceptable levels. Based on the experience of the authors, the accuracy and precision of the geophones and accelerometers in the normal field condition can be 50 percent greater (worse) than those reported herein. For the other devices the normal levels of accuracy and precision can be two to three times greater (worse) than those reported herein. It is intuitive that the accuracy and precision expected in the field depends directly on the level of care and sophistication in the installation of the equipment.

Steady-State Motion

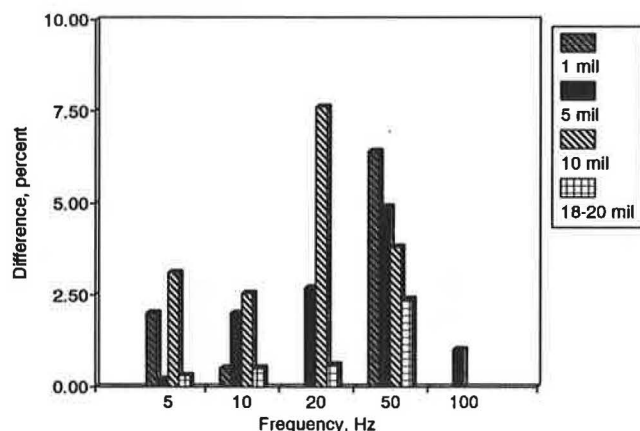
As mentioned in the previous section, for each frequency and each amplitude, deflections were measured 10 times. The precision of each sensor in terms of variance of the 10 repetitions (only 6 repetitions were performed when the laser device was used) at any given frequency and nominal deflection was determined. The variances determined in this manner are illustrated as a function of frequency in Figure 3 for the geophone and Figure 4 for the LVDT. As seen in Figure 3, the variance for deflections from the geophone is less than 0.75 percent. As a result, the variation in deflections from geophones is well within background noise. The LVDT device also performs well under the steady-state loads (Figure 4).



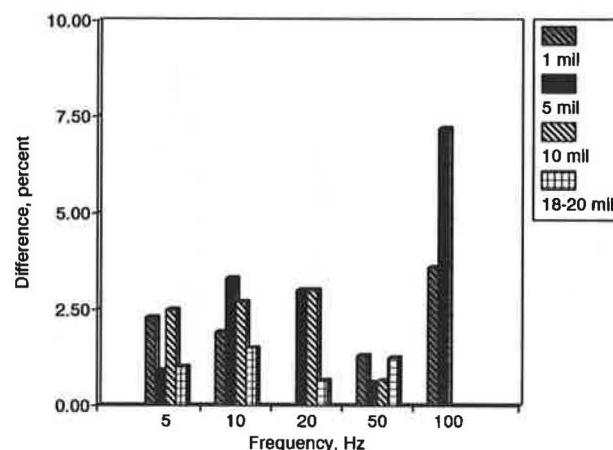
a) Variance



a) Variance



b) Difference from Proximeter Deflections

FIGURE 3 Evaluation of accuracy and precision of geophone under steady-state loading.

b) Difference from Proximeter Deflections

FIGURE 4 Evaluation of accuracy and precision of LVDT under steady-state loading.

The variances are usually less than 0.5 percent, except two cases in which the variances were about 1 percent.

The results for the other three devices are not included here. These results are comprehensively reported elsewhere by the authors (1). The variances at all deflection levels for accelerometers are less than 1 percent, which translates to a maximum standard deviation of 0.2 mils. This deviation is well within the level of background noise. The laser device exhibits little variance. In most cases the variance is almost zero. The precision of the proximeter is quite good on the order of 0.5 percent. At high amplitudes of vibration, the variance is about 0.75 percent, which is still quite small.

The accuracy of each device was determined by comparing deflections measured with each device against those measured with the proximeter. The maximum difference between deflections measured by the accelerometers and the proximeter is about 5 percent. The accuracy of geophones is generally within 4 percent (Figure 3). The LVDT has similar accuracy when compared with the proximeter (Figure 4). The laser

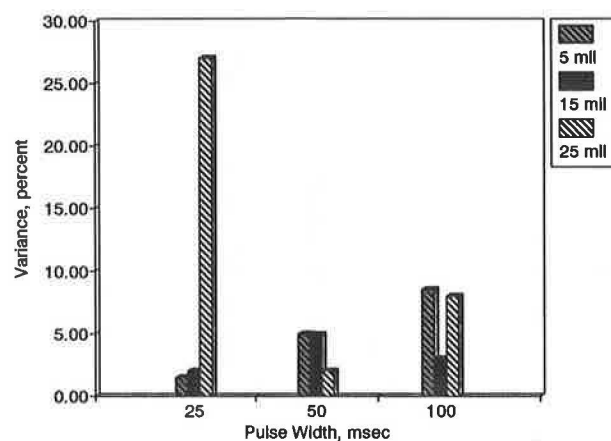
device compared favorably with the proximeter. In all cases, deflections from the two devices do not differ more than 1.5 percent.

Impulse Motion

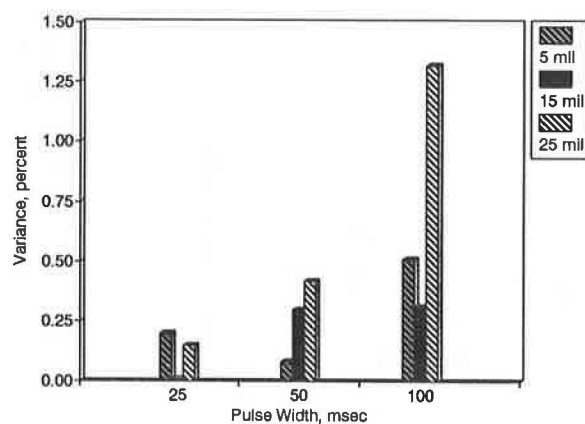
Precision and accuracy of the five sensors were also evaluated under half-sine, square, and triangular impulses. Shown in Figures 5 through 9 are the evaluation of the precision and accuracy of the five sensors under half-sine impulse. The accelerometer exhibited a large variation in deflections. Variances greater than 5 percent were not uncommon.

Contrary to the accelerometer, the variances measured with the geophone are less than 2 percent in all cases. Such a small variation can easily be attributed to background noise. In most cases the variance is below 0.5 percent.

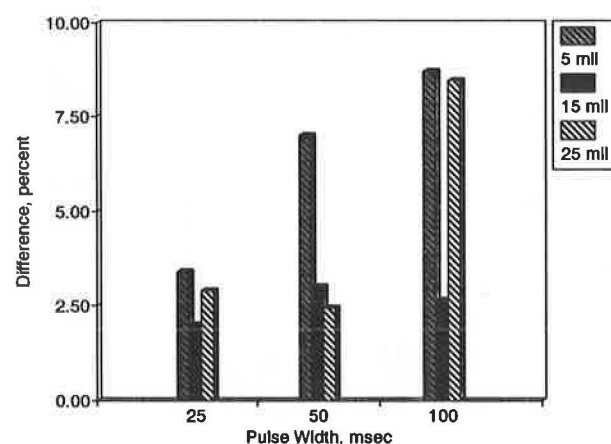
The LVDT also is quite precise. The maximum variance is about 1.25 percent and is typically less than 0.5 percent. The



a) Variance

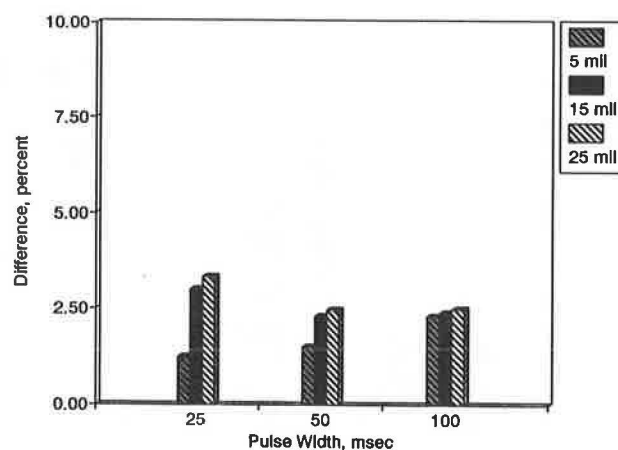


a) Variance



b) Difference from Proximeter Deflections

FIGURE 5 Evaluation of accuracy and precision of accelerometer under half-sine pulse loading.



b) Difference from Proximeter Deflections

FIGURE 6 Evaluation of accuracy and precision of geophone under half-sine pulse loading.

laser device is not as repeatable as it was under the steady-state conditions. However, in all conditions (but one) the repeatability of data is within 1.5 percent. For all the experiments carried out with proximeter device the maximum variance is only about 0.60 percent.

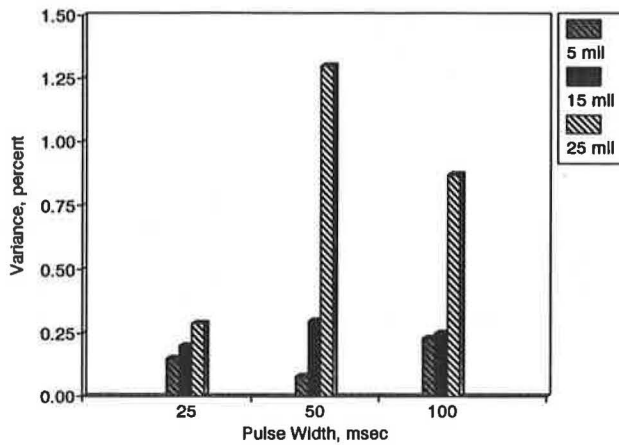
The accuracy of the accelerometer is unacceptably low for an impulse width of 100 msec. For large pulse widths, vibrations are not accurately measured with an accelerometer. The accuracy of the accelerometer at shorter pulse widths is within 3 percent. The accuracy of the geophones and the LVDT is quite good; deflections measured with both sensors are within 2.5 percent of deflections measured with a proximeter in almost all cases. Therefore, one may confidently use a geophone or an LVDT for accurate measurement of deflections under impulse loading.

The accuracy of the laser device as compared with a proximeter normally varies between 0.5 and 4 percent. Therefore, it seems that a geophone or an LVDT may produce more consistent and accurate results.

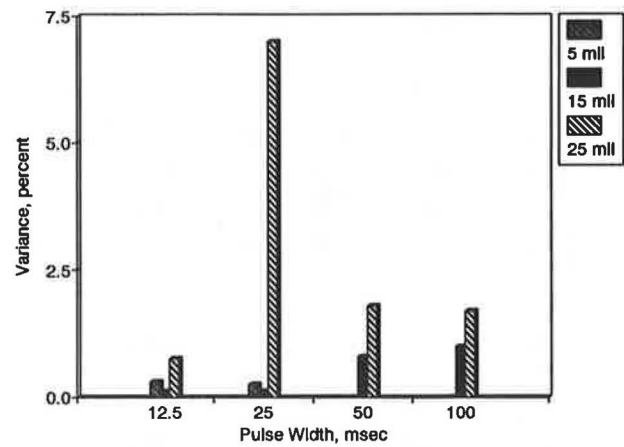
OVERALL EVALUATION AND CONCLUSIONS

The advantages and disadvantages of all sensors as well as their direct and indirect costs are presented in Table 7. In general, accelerometers are well-calibrated sensors because their calibration curves can be traced to the National Bureau of Standards. However, piezoelectric accelerometers are not capable of accurately measuring motions of large duration (1). Accelerometers used in this study function in the frequency range of 10 Hz to 10 kHz. A significant portion of the energy imparted to a pavement by an impulsive NDT device is below 10 Hz limit; the dynaflect device vibrates at a frequency of 8 Hz. The original cost of the accelerometers is high and the connecting microdot coaxial cables used for connecting the accelerometers to the amplifiers are not very field-worthy. The cost of the coaxial cable itself is almost the same as the cost of a geophone.

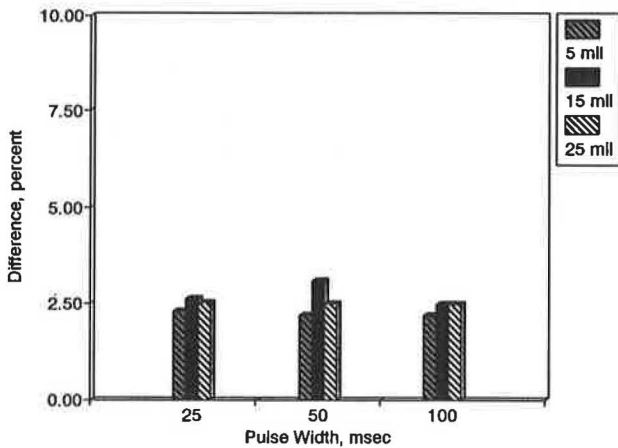
A proximeter probe is a good tool for measuring deflection in the laboratory. However, the mounting of a proximeter is



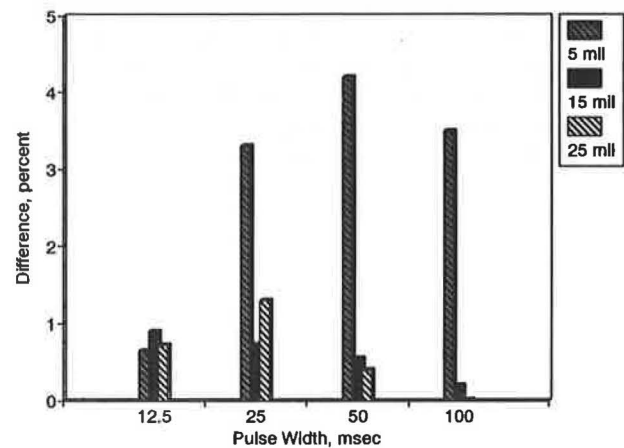
a) Variance



a) Variance



b) Difference from Proximeter Deflections

FIGURE 7 Evaluation of accuracy and precision of LVDT under half-sine pulse loading.

b) Difference from Proximeter Deflections

FIGURE 8 Evaluation of accuracy and precision of laser under half-sine pulse loading.

a problem in the field. In other words, the gap between the proximeter probe and target material should be well controlled throughout the experiment. Also, the input power supply should be of high quality to maintain a constant voltage. The gap between the proximeter and probe is small (about 2 mm); therefore, the chances of damaging the probe in the field are high. The proximeter probe should be mounted perfectly horizontal, which may be difficult in the field.

The LVDT is a good sensing device because of its infinitesimal resolution. However, it has mounting problems similar to those of the proximeter. It is possible to design and construct a mounting system. However, the cost may be prohibitive.

The laser device is an accurate and precise sensor. However, its target must be an extremely smooth surface (which a pavement is not). In the laboratory, a properly machined plate was used. Even under this condition, the data obtained from the laser for 1 mil deflection had a very poor resolution. Once again, the mounting problems must be addressed. In addition, the cost of a laser is high compared with the costs of the other devices.

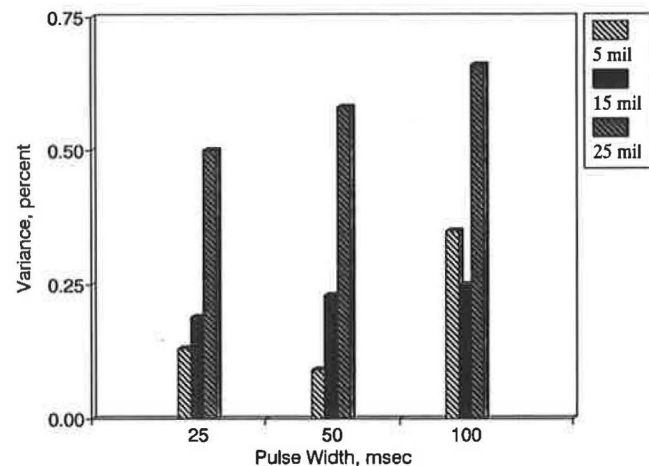
**FIGURE 9** Variability in deflection measured with proximeter as a function of half-sine impulse.

TABLE 7 Comparison of Different Characteristics of Sensors Evaluated

Sensor	Accelerometer	LVDT	Geophone	Proxi-meter	Laser
Cost	\$350	\$350	\$40	\$400	> \$10,000
Supporting Device(s)	Power Amplifier (\$300)	Power Supply (\$400)	--	Power Supply (\$400)	--
Precision, Steady-State	Moderate	Good	Good	V. Good	Excellent
Precision, Impulse	Poor	Good	Good	V. Good	Good
Accuracy, Steady-State	Moderate	Good	Good	Excellent	Excellent
Accuracy Impulse	Poor	Good	Good	Good	Good
Field Worthiness	Good	Moderate	V. Good	Moderate	Poor
Mounting	Very Easy	Difficult	Very Easy	Difficult	Difficult

In contrast with the other sensors, geophones do not have mounting problems, but the data reduction process is rather complicated. The geophone is rugged enough for field testing and costs less than any other sensor. The geophone does not need any special type of mounting fixture: it can be attached to the pavement anywhere with modeling clay. No post- or

pre-amplification or signal conditioning is needed for data collection. This results in large savings.

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