Operating Characteristics and User Satisfaction of Commercially Available NDT Equipment

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ABSTRACT

The results of a recent study conducted for FHWA are presented herein. The objective of the study was to develop a ready reference that describes available nondestructive testing (NDT) devices and methods for use in designing the thickness of asphalt concrete overlays for flexible pavements. The report was developed to serve as a guide to practicing highway engineers who are considering the purchase of new equipment or developing (or modifying) overlay design procedures for flexible pavements. A conscientious effort was made to determine and evaluate factors that agencies noted as important decision criteria in selecting NDT devices. The analysis was limited to equipment currently available from commercial sources. Equipment characteristics were provided by the manufacturers. To determine user feelings concerning the NDT equipment, a questionnaire was sent to selected agencies and available literature was reviewed. Summary tables of equipment characteristics and operating capabilities are provided. Selected overlay design procedures that use NDT input were described in the report; however, in this paper only basic equipment characteristics and user comments concerning the equipment are discussed.

In this paper the results of a recent study conducted for FHWA (1) are described. The objective of the study was to develop a ready reference that describes available nondestructive testing (NDT) devices and methods for use in designing the thickness of asphalt concrete overlays for flexible pavements. In the following sections basic equipment characteristics and user comments concerning the equipment are presented.

DESCRIPTION OF NDT EQUIPMENT

Four general classes of NDT equipment are routinely used to collect deflection data (1): static deflection equipment, automated beam deflection equipment, steady-state dynamic deflection equipment, and impulse deflection equipment. The basic characteristics and costs of each of the commonly used commercially available NDT devices are given in Table 1.

Static Deflection Equipment

Devices that measure the deflection response of a pavement to slowly applied loads are generally classed as static deflection equipment. The most commonly used equipment in this class are Benkelman beam devices. Other equipment that has been used includes plate bearing test equipment and curvature meter (2).

The Benkelman beam was originally a 12-ft (3.65-m) beam pivoted at the third point. This provides an 8-ft (2.44-m) probe with the extreme tip resting on the pavement and supported at the near third point by a pivot point. The rear end is a 4-ft (1.22-m) cantilever beam that moves upward when the pavement deflects downward. A dial indicator rests on the rear end and measures this movement.

This type of device requires a loaded truck to create the deflection to be measured. It has been used for many years, and much of the early work in deflection-based overlay design for flexible pavements was based on this device (3,4). The deflection measurements are made by using one of two more or less standard procedures: AASHTO T256-77, "Standard Recommended Practice for Pavement Deflection Measurements" (5); and the Asphalt Institute's rebound deflection testing procedure (6).

Generally, only the maximum deflection is measured with beams. The major technical problems associated with the beams include ensuring that the front supports are not in the deflection basin, and the difficulty or inability in determining the shape and size of the deflection basin.

Automated Beam Deflection Equipment

Commercially available equipment that automates the Benkelman beam process is the La Croix Deflectograph. It has been used widely in Europe and other parts of the world; however, it has not been used widely in the United States. The traveling deflectometer is a similar device that was built for the California Department of Transportation and has been in use by that agency for several years.

The La Croix Deflectograph consists of a two-axle, six-tire truck with deflection-measuring beams connected to a placement frame and necessary displacement measurement and recording equipment. The beam probes (one for each dual wheel set) are mounted on a common frame mounted below the truck and pivot. The frame with both beams is placed on the road surface in front of the oncoming dual wheels. As the wheel approaches the beam tip, the beam rotates about the pivot and the rotation is measured by inductive displacement transducers. This measurement continues until the wheels pass the beam tip. During this period the beam remains in the same location as the vehicle approaches it. The beams and frame are then lifted from the pavement surface, moved forward, and repositioned to begin a new cycle. The system can be set up to record the deflection basins as the vehicle approaches the beams.

TABLE 1 Characteristics of Commercially Available NDT Devices

Device Name	Principle of Operation	Load Actuator System	Minimum Load (lb)	Maximum Load (lb)	Static Weight on Plate (lb)	Type of Local Transmission
Benkelman beam (AASHTO)	Deflection beam	Loaded truck axle	NA	NA	NA	Truck wheels
Deflection beam (British)	Deflection beam	Loaded truck axle	NA	NA	NA	Truck wheels
La Croix Deflectograph	Mechanized deflection beam	Moving truck loaded with blocks or water	Empty truck weight	Loaded truck wheel weight (9,000)	NA	Truck wheels
Dynaflect	Steady-state vibratory	Counter rotating masses	1,000	1,000	2,100	Two 16-in.-diameter urethane-coated steel wheels
Road rater						
Model 400 B	Steady-state vibratory	Hydraulic rotating masses	500	2,800	2,400	Two 4 x 7-in. pads with 5.5-in. center gap[c]
Model 2000	Steady-state vibratory	Hydraulic rotating masses	1,000	5,500	3,800	Circular plate 18 in. diameter[e]
Model 2008	Steady-state vibratory	Hydraulic rotating masses	1,000	8,000	5,800	Circular plate 18 in. diameter
Falling weight deflectometer						
KUAB 50	Impact	Two dropping masses	1,500	12,000	?	Sectionalized circular plate 11.8 in. diameter[f]
KUAB 150	Impact	Two dropping masses	1,500	35,000	?	Sectionalized circular plate 11.8 in. diameter[f]
Dynatest model 8000 falling weight deflectometer	Impact	Dropping masses	1,500	24,000	?	Circular plate 11.8 in. diameter

Note: 1 in. = 25.4 mm, 1 lb = 4.45 N, 1 lb = 0.45 kg, NA = not applicable.

[a]Costs $71,000 without truck, but requires 1 to 3 man-months to install on purchasers' vehicle.

[b]One in each wheelpath.

[c]Circular plates are available.

The load on the rear axles can be varied from 12,000 to 26,000 lb (5 442 to 11 791 kg). The vehicle can move at 1.25 to 2.5 mph (2 to 4 km/h) while collecting data at 12- to 20-ft (3.5- to 6-m) intervals.

The technical problems of automated beam equipment are similar to any beam equipment. If the deflection basin is large, the point used for reference may be in the basin. In addition, it is difficult to determine deflection at a given point. It cannot be used to determine load transfer across a joint or crack. Also, the large amount of data collected by this equipment requires automated collection and analysis.

Steady-State Dynamic Deflection Equipment

Any device that produces a sinusoidal vibration in the pavement with a dynamic force generator is classed in this group. The most commonly used commercially available devices are the Dynaflect and various models of the road rater. These devices place a static load on the pavement surface. A steady-state sinusoidal vibration is then induced in the pavement with a dynamic force generator. The magnitude of the peak-to-peak dynamic force (high to low) must be less than twice the static force to ensure that the device does not bounce off the pavement surface. This means there must always be some amount of dead weight or static force applied. As the dynamic peak-to-peak loading is increased, this preload must also be increased. Some researchers are concerned that this preload changes the stress state of the existing pavement and may cause the pavement to exhibit an altered response to the load. Therefore an inertial reference is used, and the magnitude of the deflection change can be compared directly with the magnitude of the dynamic force.

Dynaflect

The Dynaflect was one of the first pieces of commercially available steady-state dynamic deflection devices. It is a trailer-mounted device that can be towed by a standard automobile.

A static weight of 2,000 to 2,100 lb (907 to 952 kg) is applied to the pavement through a pair of rigid steel wheels. The dynamic force generator uses a pair of unbalanced flywheels, which rotate in opposite directions at a speed of 8 cycles per second to produce a 1,000-lb (4.45-kN) peak-to-peak force. The deflection is measured by using five velocity transducers (geophones). The transducers are suspended from a placing bar normally placed in the center of the loaded area and at 1-ft (305-mm) intervals. The testing frequency and deflection measurements of all five transducers register on the standard digital control unit simultaneously. This unit also controls the equipment operation. An optional data terminal is available that controls the operation, prints the data on paper tape, and records the data on magnetic cassettes.

The normal sequence of operation is to move the device to the test point and hydraulically lower the loading wheels and transducers to the pavement surface by using the remote control unit. A test is run and the data are recorded. At this point the operator has the option of raising both the sensors and the loading wheel or only the sensors. If the next test point is nearby, the sensors can be raised, and the device can be moved to the next site at speeds up to 6 mph (9.7 km/h) on the loading wheels.

Technical limitations of the device include: peak-to-peak loading is limited to 1,000 lb (4.45 kN), load cannot be varied, frequency of loading cannot be changed, the deflection directly under the load cannot be measured, and it is difficult to determine the contact area.

Road Rater

The road rater is the second series of steady-state dynamic deflection equipment commercially available. There are three production models: 400 B, 2000, and 2008. They vary primarily in the magnitude of the

Method of Recording Data	Type of Carriage	Type of Prime Mover	Basic Cost ($)	Contact Area (in.^{2})	Vibratory Frequency and Range (Hz)	Deflection Measuring System	No. of Deflection Sensors	Normal Spacing of Sensors	Load Measuring System
Manual	NA	NA	1,000	NA	NA	Dial indicator	1	NA	None
Manual	NA	NA	1,500	NA	NA	Dial indicator	1	NA	None
Manual, printer, or automated	Truck	None	166,500[a]	NA	NA	Inductive displacement transducers	2[b]	NA	None
Manual, printer, or automated	Trailer	Tow vehicle	22,185	~32	8	Velocity transducers	5	Center and at 1-ft intervals	None
Manual, printer, or automated	Trailer[d]	Tow vehicle	30,580	56	5-70	Velocity transducers	4	Center and at 1-ft intervals	Load call
Manual, printer, or automated	Trailer	Tow vehicle	40,800	254	5-70	Velocity transducers	4	Center and at 1-ft intervals	Load cell
Manual, printer, or automated	Trailer	Tow vehicle	64,000	254	5-70	Velocity transducers	4	Center and at 1-ft intervals	Load cell
Manual, printer, or automated	Trailer	Tow vehicle	70,000	109	NA	Seismic deflection transducers	5	Center and 0.6 to 8.0 ft	Load cell
Manual, printer, or automated	Trailer	Tow vehicle	85,000	109	NA	Seismic deflection transducers	5	Center and 0.6 to 8.0 ft	Load cell
Manual, printer, or automated	Trailer	Tow vehicle	86,500	109	NA	Velocity transducers	7	Center and 0.6 to 7.4 ft	Load cell

[d] Earlier versions of the model 400 were mounted on vehicles.

[e] Plates of other diameters are available.

[f] Solid plates and plates of other dimensions are available.

load they apply. These models are all trailer mounted, although the 400 B can be mounted in the cargo bay of a van. The static weights are created by the weight of the force actuator system and hydraulic pressure against the trailer. The load is applied to the pavement surface through a steel loading plate. The standard loading plates are 4 x 7-in. (101.7 x 177.8-mm) steel pads with a 5.5-in. (140-mm) center gap for the model 400 B and an 18-in.-diameter (457.2-mm) circular plate for models 2000 and 2008; however, other sizes and shapes of loading plates are available for all models. The dynamic force generator uses a lead-filled steel mass that is accelerated up and down by a servo-controlled hydraulic actuator.

The deflection is measured by using four velocity transducers that are lowered onto the pavement at the same time the loading plate is lowered. One sensor is located in the center of the loaded area, and the remaining three sensors are attached to an arm trailing the plate, normally at 1-ft (0.3-m) intervals from the center.

Both the amplitude and frequency can be changed. This allows different dynamic peak-to-peak loadings of 500 to 3,000 lb (2.2 to 13.3 kN) for the model 400 B; 1,000 to 5,500 lb (4.4 to 28.9 kN) for the model 2000; and 1,000 to 8,000 lb (4.4 to 42.1 kN) for the model 2008. The force is measured with a strain-gauge-type force transducer in all models. The loading frequency can be varied continuously from 5 to 70 cycles per second at 0.1-cycle-per-second increments.

The signals from the transducers are all registered simultaneously with the force and frequency on liquid crystal meters of the standard control box. This unit also controls the complete operation of the device, including setting or changing the force and frequency. An optional automated system that uses a Hewlett Packard model 85 computer (HP-85) is available for the equipment, which will control the complete operation, print the results on paper tape, and record the data on a magnetic cassette.

The normal sequence of operation is to move the device to the test point and hydraulically lower the test plate and deflection sensors to the surface by using the remote control system next to the driver. A test is run at selected loads and frequencies, the loading plate and sensors are lifted from the surface, and the device is ready to move to the next test site.

Technical limitations of this equipment include the limited load levels for some models, the need for a heavy static preload for the heavier devices, and the nonuniform loading configurations.

Impulse Deflection Equipment

Equipment that delivers a transient force impulse to the pavement surface is included in this group. The equipment uses a weight that is lifted to a given height on a guide system and is then dropped. The falling weight strikes a plate, which transmits the force to the pavement. By varying the mass of the falling weight or the drop height or both, the impulse force can be varied.

In addition to the advantages listed for the dynamic deflection devices, loadings in the range of actual wheel loadings can be obtained. The impulse equipment has a relatively small preload compared with the actual loadings. The resulting deflection closely simulates deflections caused by a moving wheel load.

Some dynamic deflection equipment such as the FHWA thumper and road rater can be used to generate an impulse-type loading by placing a static load on the pavement and reacting against that load with half-sine wave deflection impulse. However, preload problems still persist for the road rater devices.

Dynatest Falling Weight Deflectometer

The most widely used falling weight deflectometer (FWD) in the United States is the Dynatest model

8000 Falling Weight Deflectometer System. It is trailer mounted and can be towed by a standard-sized automobile.

The impulse force is created by dropping weights from different heights. By varying the drop heights and drop weights, a force range of 1,500 to 24,000 lb (7 to 105 kN) can be developed. The weights are raised hydraulically and released by an electronic signal. The weights drop onto a rubber buffer system (different for each weight configuration) to provide a load pulse in approximately a half-sine wave form. The load is transmitted to the pavement through an 11.8-in.-diameter (300-mm) loading plate. The impulse load is measured by using a strain-gauge-type load transducer (load cell).

The deflection is measured by using up to seven velocity transducers with one in the center of the loading plate and the remainder mounted on a bar that is lowered automatically with the loading plate. The information from the transducers and load cell are fed into an HP-85 computer, which records the information on paper tape and a magnetic cassette. The HP-85 also controls the complete operation. The display, printed results, and stored results can be in either metric or standard units.

The normal sequence of operation is to move the device to the test point and hydraulically lower the loading plate and transducers to the pavement. A test sequence is then completed by using the desired number of drops at each height selected. The loading plate and sensors are then hydraulically lifted, and the device is ready to move to the next site.

KUAB Falling Weight Deflectometer

The KUAB is mounted in an enclosed trailer that can be towed by a standard-sized automobile. The impulse force is created by dropping a set of two weights from different heights. By varying the drop heights and weights, the impulse force can be varied from 2,698 to 35,000 lb (12 to 150 kN). The two-mass falling weight system is used to create a smoother rise of the force pulse on pavements with both stiff and soft subgrade support.

A rise time from no load to peak load is developed in approximately 28 microseconds, which approximates the load development time of a vehicle traveling at approximately 44 mph (70 km/h). The load is transmitted to the pavement through an 11.8-in.-diameter (300-mm) loading plate. On smooth pavements a solid plate is recommended. On uneven surfaces a segmented steel plate with hydraulic load distribution is used.

A load cell is used to measure the load generation of the equipment. The deflection is measured by using five absolute seismic displacement transducers (seismometers) that are lowered automatically with the loading plate. One sensor is placed through the middle of the loading plate; the remaining sensors can be placed from 7.9 to 100 in. (200 to 2500 mm) from the center of the plate. The signals from the seismic displacement transducers and load cell are fed into an HP-85 computer. The HP-85 also controls the complete operation of the device.

The normal sequence of operation is the same as for the Dynatest FWD. The trailer is completely encased, including the bottom, in a protective cover. The bottom cover is automatically opened for the test. The test system is supported by a three-leg guide system that is lowered to the road for the test sequence.

Phoenix Falling Weight Deflectometer

The Phoenix FWD is also trailer mounted. The mast and weight are mounted by a pivot so they can be transported in a horizontal position for long distances, but they can also be placed upright for testing and travel in the test area.

A single weight can be dropped from different heights to develop impact loads of 2,248 to 11,240 lb (10 to 50 kN). The load is transferred to the pavement through an 11.8-in.-diameter (300-mm) plate. The deflection is measured by using three deflection sensors. One is located in the center of the loading plate, and the others are located at 11.8 and 29.5 in. (300 and 749 mm) from the center.

These sensors are set automatically by the equipment as the plate is lowered. The force is calculated based on drop height. The deflection measurements are recorded on an HP-85 computer, which also controls the operation of the equipment.

The primary advantages of the impulse deflection equipment are that the created deflection basins closely match those created by a moving wheel load of similar magnitude, and that the magnitude of the force can be quickly and easily changed to evaluate the stress sensitivity of the pavement materials being tested.

USER COMMENTS ON EQUIPMENT

Several factors were reviewed to determine which factors should be considered when making a decision to purchase an NDT device. Information included availability, cost, characteristics, principle of operation, estimated maintenance cost, estimated cost of operation, estimated cost of data reduction, ease of use, and traffic control requirements. Information on data bank availability and data acquisition systems was also collected.

To get input from actual equipment users, a review was made of printed information and a questionnaire was sent to a select group of users. Nine state agencies were selected primarily on the basis of available information that indicated that the state had been active in the use or development (or both) of deflection-based overlay design procedures for flexible pavements. In addition, agencies were selected to cover all types of NDT equipment as much as possible. Agencies that use more than one type of equipment were also given precedence over those that use only one device. The states contacted were Arizona, California, Florida, Illinois, Kentucky, Minnesota, Pennsylvania, Texas, and Virginia.

The U.S. Army Corps of Engineers Waterways Experiment Station was contacted because of its work in evaluating several devices (7). Great Britain and South Africa were contacted because of their use of the La Croix Deflectograph.

Some of the equipment used by states replying to the questionnaire are older models that are no longer available from the manufacturer. Their performance may not represent the performance of the newer models that are currently available and described earlier. In particular, the road raters used by Kentucky and Pennsylvania, along with the FWD used by Arizona, are no longer production models. This will be so noted when appropriate.

The responses from each of the agencies contacted are given in Table 2.

DATA SUMMARY OF USER COMMENTS

Selected data for the deflection beams, Dynaflect, FWDs, road raters, and automated beam equipment are presented in tabular format in the basic report. The data from each user agency are presented along with the means and standard deviations for each selected item (the mean and standard deviation may have lim-

ited use with the small number of data points). All readers are cautioned against reading only the summarized totals. Much of the variation that appears is caused by the difference between users rather than equipment. For instance, one could infer from the tables that the average daily traffic control costs are higher for the Dynaflect than for the road rater. However, if the data in Table 2 are studied, it will be noted that every agency that used more than one automated device reported the same traffic control costs for both devices. As a result, it can be surmised that there is no significant difference in traffic control costs attributable to different automated NDT devices.

Time in Service

The time in service of the NDT equipment varied from less than 1 year to more than 20 years. Benkelman beams have been in service the longest. The Dynatest FWDs have been in service the least amount of time (no KUAB or Phoenix FWDs were reported in service in the United States). The mechanized beams, Dynaflects, and road raters vary in service time from 5 to 17 years. No La Croix Deflectographs are currently used in the United States.

The time in service, as well as the number of agencies owning a particular device, may be a function of how long the device has been available. No

TABLE 2 Summary of Agency Responses to Questionnaire

Agency	Type & Model of Equipment	Length of Time Used (years)	Number of Personnel in Operating Crew	Professional Qualifications of Crew		
				Engineer	Technician	Driver
Arizona (AZ-D)	Dynaflect	12	2		X	
(AZ-F)	Falling Weight Deflectometer	3	2		X	
California (CA-TD)	Travelling Deflctometer	16	2		X	X
(CA-D)	Dynaflect	17	1		X	
Florida (FL-F)	Falling Weight Deflectometer	1	2		X	
(FL-D)	Dynaflect	16	2		X	
Illinois (IL-D)	Road Rater 200-8X	6	2		X	
(IL-BB)	Benkelman Beam	20-	3		X	X
Kentucky (KY-R)	Road Rater 200	12	1-2	X	X	
Minnesota (MN-F)		1	1-2		X	
(MN-R)		5	1		X	
Pennsylvania (PA-R)	Road Rater 400	10-12	1		X	
Texas (TX-D)	Dynaflect 100-8A	18	2		X	
Virginia (VA-D)	Dynaflect	16	1		X	
VA-BB)	Benkelman Beam	20-	3		X	X
Great Britian (GB-DF)	Deflectogragh	16	2		X	X
(GB-BB)	Benkelman Beam	20-	3		X	X
South Africa (SA-DF)	Deflectograph	10	2		X	X
WES (WE-RR)	Road Rater 2008	5	1		X	
(WE-F)	Falling Weight Deflectometer	2	2		X	

R = ROAD RATER
D = DYNAFLECT
F = FALLING WEIGHT DEFLECTOMETER
TD = TRAVELLING DEFLECTOMETER
BB = BENKELMAN BEAM
DF = LaCROIX DEFLECTOGRAPH

Agency	Purpose of Collecting Data					Number of Test Points per Day	Number of Load Levels per Point	Number of Man-Hours per Test Day
	Overlay Design	Layer Mat'l Properties	Load Limits	Condition Evaluation	Pavement Management			
AZ-D	YES	YES	NO	YES	NO	75	1	16
AZ-F	NO	YES	NO	YES	NO	75	2	16
CA-TD	YES	NO	NO	YES	NO	1500-2000	1	16
CA-D	YES	NO	NO	YES	NO	420	1	8
FL-F	NO	NO	NO	YES	YES	100-200	1-3	16
FL-D	NO	NO	NO	NO	NO	200-400		20
IL-R	YES	YES	NO	YES	YES	150-200	1	12-16
IL-BB	YES	YES	NO	YES	YES	100	1	18-24
KY-R	YES	NO	NO	YES	YES	300-400	1	8-16
MN-F	YES	YES	NO	NO	NC	200-300	1-4	8-16
MN-R	YES	NO	YES	NO	NO	360	1	8
PA-R	YES	NO	YES	NO	NO	150-400	1	8
TX-D	YES	YES	YES	YES	YES	150-400	1	16
VA-D	YES	NO	YES	YES	YES	100	1	24
VA-BB	YES	NO	YES	YES	YES	50	1	24
GB-DF	NO	NO	NO	YES	YES	2500-4000	1	24-32
GB-BB	NO	NO	NO	YES	NO	100	1	16
SA-DF	YES	NO	NO	YES	YES	3000	1	8
WE-R	YES	YES	YES	NO	YES	200	2	16
WE-F	YES	YES	YES	NO	YES	200	2	

TABLE 2 continued

Agency	Automatic	Keyborad Entry	Manual Data Sheets	Equipment Produced Printout	Data Storage Medium: Magnetic Tape	Cassette/ Diskette	Data Sheets	Equipment Produced Printout	Cost to Prepare & Analyze One Day's Data	Supporting Data Needed: Layer Thicknesses	Layer Stiffnesses	Marshall Stability	Flow	Hveem Stability	Base Properties	Subbase Properties	Subgrade Properties
AZ-D			X		X				$25	YES					*	*	*
AZ-F			X		X				$25	YES					*	*	*
CA-TD			X				X		$200	YES							
CA-D			X				X		$200	YES							
FL-F	X			X	X			X	8-16 hrs.								
FL-D				X				X									
IL-R			X				X		$500-$600	YES	NO	NO	NO	NO	NO	NO	YES
IL-BB			X				X		$250-$300	YES	NO	NO	NO	NO	NO	NO	YES
KY-R	X		X			X	X		$300	YES	NO	NO	NO	NO	NO	NO	NO
MN-F	X			X	X	X				YES	YES	YES	YES	NO	NO	YES	YES
MN-R	X			X	X	X				YES	NO	NO	NO	NO	YES	YES	YES
PA-R			X		X				$100	NO	NO	NO	NO	NO	NO	NO	NO
TX-D	X		X			X	X		$50	YES	NO	NO	NO	NO	NO	NO	NO
VA-D			X				X		$75	YES	NO	NO	NO	NO	YES	YES	YES
VA-BB			X				X		$75	YES	NO	NO	NO	NO	YES	YES	YES
GB-DF			X	X					$145-$725	YES	NO	NO	NO	NO	NO	NO	YES
GB-BB									$15-$50	YES	NO	NO	NO	NO	NO	NO	YES
SA-DF				X			X	X	$200	NO	NO	NO	NO	NO	NO	NO	NO
WE-R				X				X	$500	YES	NO	NO	NO	NO	T	T	T
WE-F				X				X	$500	YES	NO	NO	NO	NO	T	T	T

Agency	Enviromental Corrections: Temperature	Moisture	Seasonal	Enviromental Testing Restrictions: Season	Temperature	Average Annual Maintenance Cost	Traffic Control Methods: Warning Signs	Barricades	Mobile Lane Closure	Mobile Barricades	Flashing Lights	Flagmen	Traffic Control Cost Per Test Day
AZ-D	NO	NO	NO	YES		$5000	YES	NO	YES	YES	YES	YES	$750
AZ-F	NO	NO	NO	YES		$5000	YES	NO	YES	YES	YES	YES	$750
CA-TD	NO	NO	NO	YES		$3000	YES	NO	YES	NO	YES	YES	$600
CA-D	NO	NO	NO	YES			YES	NO	YES	NO	YES	YES	$600
FL-F	YES	YES	YES				YES	YES	YES	NO	YES	NO	$140
FL-D	NO	NO	NO	YES	NO		YES	NO	NO	NO	NO	YES	$140
IL-R	YES	NO	YES	NO	NO		YES	YES	YES	NO	YES	YES	$200
IL-BB	YES	NO	YES	NO	YES	$1600	YES	YES	YES	NO	YES	YES	$250-300
KY-R	YES	YES	YES	NO	YES	$100	NO	NO	YES	NO	YES	YES	$100
MN-F							YES	NO	YES	NO	YES	NO	*
MN-R	YES	NO	YES	YES	YES		YES	NO	YES	NO	YES	NO	*
PA-R	YES	NO	YES	NO	NO	$5600		NO	NO	NO	YES	YES	$200
TX-D	NO	NO	NO	NO	YER	$850	YES	YES	--	--	YES	YES	$100-$500
VA-D	YES	NO	NO	NO	YES	$875	YES	YES	YES	YES	YES	YES	$250
VA-BB	YES	NO	NO	NO	YES		YES	YES	YES	YES	YES	YES	$250
GB-DF	YES			YES	YES	$2900-4350	YES	NO	YES	--	--	--	--
GB-BB	YES			YES	YES	$15-70	YES	NO	YES	--	--	--	--
SA-DF	NO	NO		N/A			**	NO	YES	NO	YES	NO	
WE-R	YES	NO	YES	N/A	YES	$1000	NO	NO	YES	YES	YES	NO	$200
WE-F	YES	NO	YES	N/A	YES	$1500	NO	NO	YES	YES	YES	NO	$200

* Exact cost unknown, however, no difference in traffic control for FWD and Road Rater.
** Escort Vehicles
Included in total cost

particular inference should be made from these two statistics as far as reliability or usefulness is concerned.

Crew Size

All agencies reporting on the Benkelman beam indicated that they used a three-person crew. All agencies reporting on the mechanized beams indicated a two-person crew. All other devices had a one- or two-person crew.

It appears that the crew of three for the Benkelman beam and crew of two for the deflectograph are valid requirements. The number of personnel required for the crew of the current generation of Dynaflect, FWDs, and road raters will depend on the data recording and control system and testing requirements. The Dynaflect and road rater standard equipment require recording the data from a digital readout by hand. These devices can be more efficiently operated with an additional person to record the data.

Both of these can be equipped with an optional data recording system, and an automated data recording system is standard equipment on FWDs. In this mode they can be operated efficiently by a single operator. However, if the equipment must be accurately sited over a specific point, a second person may still be needed, although the Dynatest FWD has been sited with remote video. This is not normally a requirement in routine testing of flexible pavements.

Some concern was mentioned in the literature to indicate that a crew of two was necessary with automated equipment. A second operator was used to relieve the first operator because of operator fatigue (8).

Professional Qualification of Crew

All agencies indicated that they normally used experienced engineering technicians as the operating crew. Some agencies indicated that they used an engineer on the crew when they conducted research studies or other nonroutine testing. Those reporting on the Benkelman beam and deflectograph and traveling deflectometer indicated they also used a truck driver. Operator training requirements varied substantially. The range was from 1 day to 3 months; however, the equipment operation training portion of this time was normally 1 to 3 days. The remainder of the time was devoted to training the operator in selecting the proper testing locations and conditions. The majority of the long training periods was devoted to on-the-job training.

Number of Test Points Per Day

The lowest number of points tested per day was reported for the Benkelman beam. The range was 50 to 100 points per day. The traveling deflectometer and La Croix Deflectograph had the largest number at 1,750 to 3,250 points per day. The La Croix manufacturer stated that 12,000 measurements a day for 12.4 to 18.6 miles (20 to 30 km) could be achieved.

The range for the other devices was from 75 to 420 points per day. It is interesting to note that the Dynaflect had both those values reported. It was expected that the Dynaflect would have the largest number of points per day because it can test at only one load level and one frequency. Arizona and Virginia reported the lowest number of test points per day (75 and 100, respectively) for the Dynaflect. The low production rate appears to be caused by their test procedure and travel time between test points. There is no relation between the number of persons in the operating crew and the number of test points per day. For the Dynaflect, 200 to 300 points a day would appear reasonable with some lost time for travel to the test site, calibration, setup, and tear-down. If the travel time to and between sites is short, then a total of 300 to 400 points a day is possible.

The road rater would appear to have a similar range of test points per day when only one load and one frequency are used at each test site. Although the model 400 appears to have a slightly higher number of points per day than others, it must be realized that these models are no longer available. With the models available, there should be no difference in test rates among the 400 B, 2000, and 2008 models.

The Dynatest FWD has a slightly lower number of test points per day reported. However, all reporting agencies indicated that they ran more than one load level at each site. Therefore, the number of tests would be at least double the number of points. Approximately 200 points a day should be reasonable for moderate travel time to and between sites with two drop heights.

It should be noted that agencies that use equipment with more load-level capabilities tend to use more test time per test point because they often run more than one load level at a test point. As with vibratory devices, which are normally run at a steady load level and frequency for a short period to reach a steady pavement response (9), some of the agencies that use the FWD reported using a "seating load" on flexible pavements before testing. Either of these operations takes a small amount of additional time, about 15 to 30 sec per site. More accurate data comparing NDT devices in a controlled situation are required to develop a more accurate assessment of this parameter. It appears that the agencies that use more than one load level are sacrificing speed to collect more information at each site.

Cost Per Test Point

The cost to collect one day's data, or cost per test point, was an item that was considered. However, the different manners in which state agencies handle costs such as overhead made it almost impossible to get meaningful cost data. It was decided to use manhours instead of cost data as often as possible.

Maintenance Costs

The average annual maintenance costs of the various pieces of equipment were evaluated. This information was not reported on 8 of the 18 replies. Obviously, the Benkelman beam should, and did, have the lowest maintenance cost. However, the cost does not include the maintenance cost of the loaded truck required for the testing. The deflectograph and the traveling deflectometer have the highest maintenance cost at more than $3,000, which reflects the cost of maintaining both the vehicle and a rather complicated electrical and mechanical system.

Average annual maintenance costs vary considerably for the other equipment. Most of the reporting agencies indicated that the maintenance costs reported were estimates. Some agencies, such as in Pennsylvania where the model 400 road rater is used, included vehicle maintenance, fuel, and depreciation costs with the NDT device because the road rater is mounted on the vehicle. Other agencies, such as

Texas, were careful to avoid reporting tow vehicle costs. The mean maintenance cost for each device was between $2,000 and $3,500 per year. However, because of the large variation and small sample, no finding of significant difference can be substantiated. Of the two agencies that reported on the maintenance costs of two devices, Arizona indicated no difference in the maintenance costs of the Dynaflect and the FWD, whereas the U.S. Army Waterways Experiment Station indicated that the maintenance cost for the model 2000 road rater was slightly less than for the FWD. It should be noted that both of these FWD devices are older models that are no longer in production, but the costs indicate that major differences are not apparent. From the information available, it cannot be stated that there is a significant difference in the average annual maintenance costs among the Dynaflect, road raters, or Dynatest FWD. More accurate long-term data are needed to address this point.

Traffic Control Costs

The traffic control costs do not reflect a significant cost difference based on equipment type. Of the agencies that reported on more than one piece of equipment, only Illinois indicated a difference. Because the Benkelman beam testing required more time in one location with a stopped truck, Illinois was required to use more controls for the beam than were used for the road rater. All other agencies reported the same costs for both devices. This would indicate that the differences in cost are caused by the local agency's policies rather than equipment type. Except for the Benkelman beam, data do not provide evidence to indicate that a significant difference in traffic control cost exists among the equipment types. A good description of one state's traffic control procedure for NDT testing is given elsewhere (10).

Data Recording Method

Five of the twelve reporting agencies indicated that their only data recording method was manual. Four agencies reported that they had automated data recording systems, and three more reported that they had machine-generated printouts. All of the commercially available devices, including the Benkelman beam, can be provided with an equipment-generated paper recording. The Dynaflect, road raters, deflectographs, and FWDs can be provided with automatic magnetic cassette data recording systems. Some of the equipment manufacturers also provide programs to sort data to help break pavements into uniform sections based on deflections.

Data Storage

The data collected from NDT devices are stored in computerized data bases by four of the agencies reporting. All other agencies store the data on the medium on which they collected it (i.e., data sheets, cassettes, and equipment-produced printouts).

Towing Vehicle

The cost of the towing vehicle should be practically the same for all trailer-mounted devices. The model 2000 and model 2008 road raters are the heaviest devices and may require a vehicle with a larger towing capability. The general recommendations from the various agencies and reports include a vehicle with a diesel engine and automatic transmission because of the length of time the vehicle engine idles during testing and the number of frequent starts and stops. The vehicle should be equipped with heavy-duty suspension and an appropriate tow package to pull the trailer-mounted devices. Air conditioning is recommended to reduce operator fatigue; Minnesota recorded temperatures of 120° F (49° C) with doors open in the unairconditioned cab of a tow vehicle (8). High-intensity warning lights are recommended for safety. A distance measurement indicator for the vehicle and a pavement temperature sensing device that can make quick accurate readings, such as an infrared thermometer, are also recommended.

The Dynaflect, Dynatest FWD, and KUAB FWD operate on the vehicle's electrical system; therefore heavy-duty, 100-amp charging systems are required for the tow vehicles used with them. Vehicles with bucket seats appear to work best for the systems that use the computer controlling and recording system. This allows a stand to be mounted between the two front seats on which the computer can be mounted. This mount should provide a stable support during testing and traveling. It should also allow the computers to be easily removed for more secure storage when the equipment is not in use.

PREVIOUS STUDIES

Several studies of various models of the NDT equipment had been conducted previously; these were reviewed for this study. Summaries of the most pertinent studies and comments are included in the FHWA report (1). Although some reports discussed use of NDT equipment for other than flexible pavements, only the information pertinent to flexible pavements is discussed here.

One of the most comprehensive studies was the one by the U.S. Army Corps of Engineers Waterways Experiment Station (WES) (7), conducted between April 1978 and July 1979. In that study the Benkelman beam, the Dynaflect, an early model of the Dynatest FWD, a model 400 road rater (vehicle mounted), a model 510 road rater, a model 2008 road rater, and a WES 16-kip vibrator were all evaluated.

Several characteristics were analyzed in the study. These included ease of operation, speed of operation, manpower requirements, initial costs, operating costs, transportability by cargo aircraft, accuracy and reproducibility of deflection measurements, accuracy and reproducibility of force and frequency measurements, accuracy and reproducibility of force, velocity and deflection signals, and depth of significant influence.

University of Tennessee

The most recent work available was completed by Moore and Highter (11) of the University of Tennessee. This report, published in February 1983, was prepared for the Tennessee Department of Transportation. The researchers basically considered the Dynaflect, road rater, and Dynatest FWD in their study. They sent questionnaires to all agencies that they knew owned one or more of these three devices. They visited four agencies for personal interviews.

The three devices were evaluated based on "economic considerations, operational characteristics, technical merits and other factors pertaining to the applicability of each device for pavement evaluations and for determining overlay design parameters for use in the State of Tennessee" (11). The evaluation considered all devices equally equipped with automatic control and data recording systems.

Moore was gracious enough to share the raw data from his questionnaires with the authors of this paper. Most of this information is discussed in the preceding section; however, some more detailed information on user satisfaction and reasons for purchasing equipment are presented in the basic report (1).

University of Illinois

Two reports (10,12) published as a part of IHR Project 508, Load Response Characteristics of Flexible Pavements, considered the Benkelman beam, an early model 2008 road rater, and a Dynatest FWD. The study compared the equipment primarily in terms of pavement response to load, with responses measured under moving wheel loads. Moving wheel-load-induced deflections were measured with accelerometers implanted in the pavement section. The electrical responses were double integrated to determine deflection. The vehicle speed was measured by using timed responses of photocells at known distances.

The data from these reports indicate that the surface response produced by the FWD more closely simulates a pavement response under a moving truck than does the road rater or Benkelman beam. The road rater tends to produce a stiffened response in the pavement system, which indicates a stronger pavement than actually is present under moving wheel loads because of the static preload and steady-state harmonic loading without rest. Benkelman beam deflections are "quasi-static" loads that tend to overpredict deflections compared with those of moving wheel loads.

CONCLUSIONS

The following conclusions were made based on the data presented in the report:

1. Static load, automated beam, steady-state dynamic, and impulse NDT devices are all commercially available to U.S. agencies.
2. Deflection beams, dynamic deflection devices, FWDs, and automated beam devices can be used to measure maximum deflection.
3. The Dynaflect, road raters, Dynatest FWD, and KUAB FWD are equipped to more quickly and efficiently measure deflection basin parameters than the static and automated beam devices.
4. All automated beam, dynamic, and FWD devices have been equipped with automated equipment to record measured parameters and control the test cycles to facilitate rapid measurements.
5. Automated beam, FWD, and road rater model 2008 devices can develop loads at or near normal design loads.
6. Load as well as deflection can be easily measured by road raters, Dynaflect FWDs, and KUAB FWDs.
7. Devices that can produce several load levels up to or near design loads can be used to determine the stress sensitivity of the pavement system.
8. Steady-state dynamic devices that use a relatively heavy static preload change the stress state in the pavement before the testing.
9. All available NDT devices lack the capability for simple lateral movement to assist in precise load placement.
10. There are significant advantages for using an NDT load that equals that of a heavily loaded truck wheel load (e.g., 9,000 lb). The response of the pavement to this heavy load can be accurately measured and directly used for structural evaluations and overlay design without questionable correlations or stress sensitivity assumptions.
11. Automated NDT devices that have more than one load level and have load levels at or near design loads are more expensive than devices with relatively light loads. However, they provide additional information about the pavement section.

RECOMMENDATIONS

1. The location of deflection sensors on equipment such as the Dynaflect, road raters, and FWDs should be standardized.
2. Consideration should be given to standardizing the size and shape of loading plates (at least for the equipment with load levels approaching design levels). For equipment with load levels significantly less than design loads, development of loading plate size and shape to develop a minimum surface contact pressure should be considered.
3. The tire size and inflation pressure for trucks used as the loading vehicle for Benkelman beam testing should be standardized.
4. Load as well as deflection should be measured by NDT equipment.

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Discussion

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The Swedish National Road Administration has used FWDs for the past 13 years, and since 1976 has used the KUAB 50 FWD. Measurements are currently made by the Bearing Capacity Group, VFY, Härnösand. Such measurements are made on a routine basis; some figures from this work should be of interest to the readers because they probably reflect what a new user can expect to produce, after some "running-in time," with efficient equipment and efficient planning.

During 1984 more than 50,000 test points were measured. The distance between the points was 50 m, and the average capacity during 1984 was 264 points per day. Note that transportation time, time to find and mark out the test sites, "social visits" to the local road administrations, and so forth are included in the measuring time. Because measurements were made in an area the same size and shape as California, transportation time was significant; in some cases it took more than one day to transport the equipment to the site and back. During the main season--the spring--when the number of sites was sufficient for

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more efficient transportation planning, the average capacity was 310 points per day. One peak force level (50 kN) was used in each point. Using three peak force levels in each point reduced the capacity by about 15 percent. The average crew size was 1 person.

In regard to the costs mentioned in the paper--cost to analyze one day's data, average annual maintenance cost, and average daily traffic control costs--in Sweden, they were substantially lower in all three cases. Although such a cost comparison would be interesting, detailed reports are not given here because it may not be possible to make a meaningful comparison of such costs between countries.

Authors' Closure

We appreciate the additional operating information provided by Ullberg. The operating rate for a single force level presented by Ullberg is similar to the rate for the Dynaflect, which is a single load level test.

The test rates described in the basic report represent the testing program employed by the using agency as well as equipment operating capabilities. Ullberg's information further emphasizes the problem of comparing performance among different using agencies. All other agencies reporting on the FWD indicated that they used more than one load level.

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