Demonstration of a New, Multi-Function, Nondestructive Pavement Testing Device

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INTRODUCTION

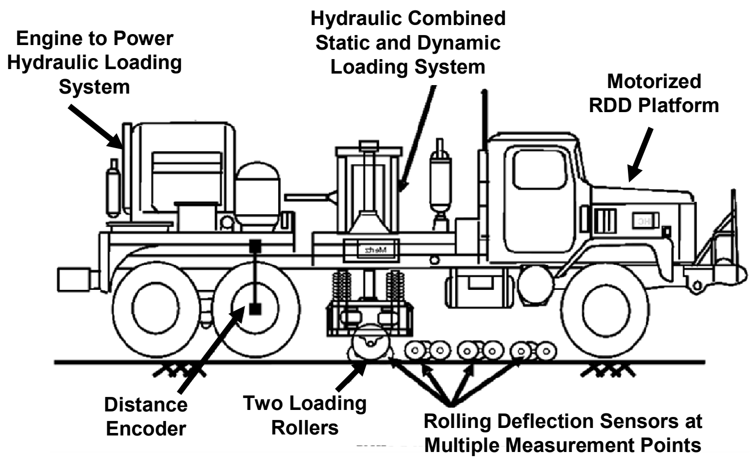
The Texas Department of Transportation (TxDOT) has been evaluating the structural condition of highway and airport pavements with multiple types of nondestructive testing (NDT) devices for more than four decades. Over the past fifteen years, new devices have been integrated into this pavement evaluation effort. One device is the rolling dynamic deflectometer (RDD). The RDD was originally developed through the TxDOT research program to determine continuous deflection profiles that are used in pavement structural assessments (Chen et al. [1]). TxDOT researchers have shown that RDD deflection profiles can be used more effectively when combined with other data such as pavement thickness and subsurface conditions (Scullion [2], and Nam et al. [3]). Therefore, TxDOT has supported development of a multi-function device which is equipped with RDD profiling and ground penetrating radar (GPR) functions. Additional functions that have been integrated into the new device are video cameras for pavement and right-of-way conditions, pavement temperature measurements and high-precision positioning. These multi-functions permit efficient comparisons of RDD deflection data with other NDT data logged by the different methods. The new device is called the Total Pavement Acceptance Device (TPAD). The TPAD has all functions combined on a single platform that can move along the pavement at 2 to 3 mph. All measurements are collected in a single pass and analysis software permits the data to be displayed in near-real time (less than 5 minutes after collection) so that the results can be used for preliminary evaluations of pavement conditions on-the-fly or can be used for more detailed analyses at a later time.

In this paper, a background on two of the nondestructive testing functions in the TPAD, the RDD and GPR systems, are briefly discussed. A description of the TPAD mobile platform and the RDD dynamic loading system are described. The developmental work for the speed-improved rolling sensors is also discussed. Finally, the TPAD is demonstrated by presenting RDD deflection profiles and GPR records collected at a testbed created at the TxDOT Flight Services Facility (FSF) are presented. The reliability of the data were also evaluated at the FSF testbed and found to be high as described herein.

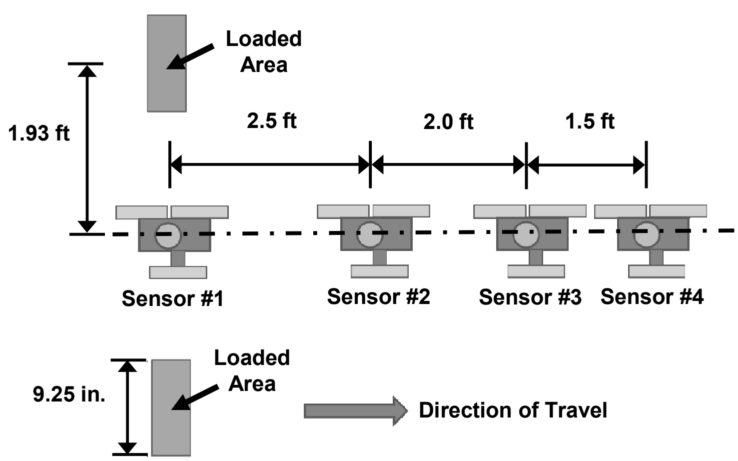
BACKGROUND ON RDD AND GPR TESTING FUNCTIONS IN THE TPAD

Rolling Dynamic Deflectometer (RDD)

The Rolling Dynamic Deflectometer (RDD) is a nondestructive testing device that involves measuring pavement deflections under controlled pavement loads while moving along the pavement. RDD deflection profiles have been used for about 15 years for structural-condition assessment of both highway and airport pavements. The RDD was developed by researchers at the University of Texas at Austin (UT) in the 1990's (Bay and Stokoe [4]). Dr. James Bay led the developmental work and Dr. Jefferey Lee and Dr. Boo-Hyun Nam advanced the rolling sensor design (Bay et al. [5], Lee and Stokoe [6], and Nam [7]). As shown in Figure 1a, the RDD is a truck-mounted device on which an electro-hydraulic loading system is used to deliver a static hold-down force combined with a dynamic sinusoidal force (typically 30 Hz) to the pavement through two loading rollers. An array of three to four rolling sensors that are positioned along the longitudinal centerline of the truck (see Figure 1b) is used to measure induced dynamic pavement deflections while the truck is moving along the pavement at a speed of about 1 mph. Sensor #1 is located mid-way between the two loading rollers and other sensors are spaced ahead of Sensor #1 in intervals ranging from 1.5 to 2.5 ft based on under-carriage constraint of the RDD truck.. A Distance Measurement Instrument (DMI) is attached on the rear wheel of the truck and is used to measure the distance traveled along the pavement. The deflection profile is produced with the recorded pavement deflections and distances. A typical deflection profile collected on a jointed concrete pavement (JCP) is shown in Figure 2. This deflection profile contains significant data that: (1) shows increased movements at all transverse joints and cracks, (2) allows joint types (construction vs. expansion vs. contraction) to be evaluated based on relative movements, (3) permits relative evaluation of load transfer at joints and cracks, and (4) permits evaluation of the extent and relative quality of mid-slab areas. RDD profiling has been used to: (1) delineate areas to be repaired, (2) help select possible rehabilitation treatments, (3) measure improvements due to the rehabilitations, and (4) evaluate changes with time, environmental conditions, and trafficking (Chen et al. [1]).



(a) Major Components of the RDD.



(b) Plan View of Loading Rollers and Rolling Deflection Sensors.

Figure 1. Schematic of the Original Rolling Dynamic Deflectometer (RDD) (Bay and Stokoe [4]).

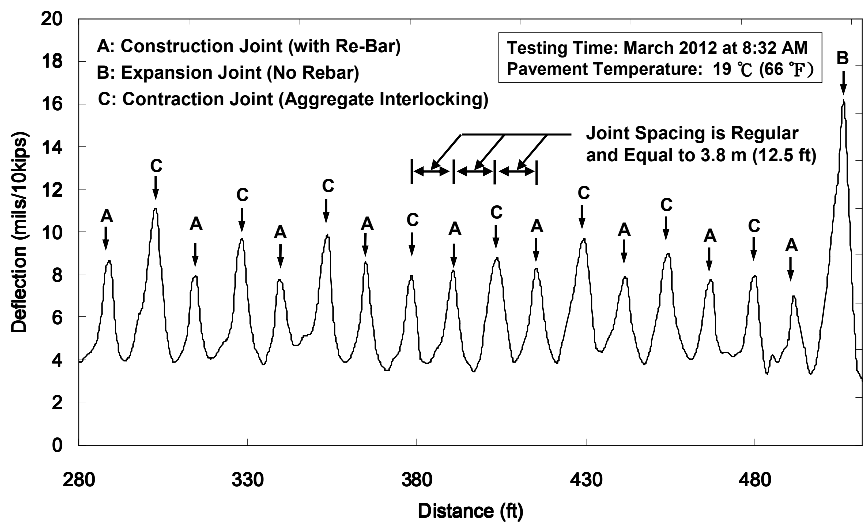


Figure 2. Typical RDD Deflection Profile Measured on a Jointed Concrete Pavement with Rolling Sensor #1.

Ground Penetrating Radar (GPR)

GPR uses radar pulses to image the subsurface. Electromagnetic waves (radio waves or microwaves) generated by a radar antenna penetrate into the subsurface and travel through the materials. These waves are reflected at interfaces with dissimilar dielectric properties. The reflected waves are collected by a receiving antenna. The arrival time and amplitude (strength of reflections) are related to the location and dielectric discontinuities (different dielectric constants) in the material (Maser and Scullion [8]). In general, the layers of the pavement system have different dielectric constants and electromagnetic waves are reflected at the layer boundaries. In addition, voids, moisture, and reinforcing steel in the subsurface can also be detected because they have different dielectric properties so the electromagnetic waves are reflected when the waves meet such conditions (material changes). The principle of GPR imaging is shown in Figure 3.

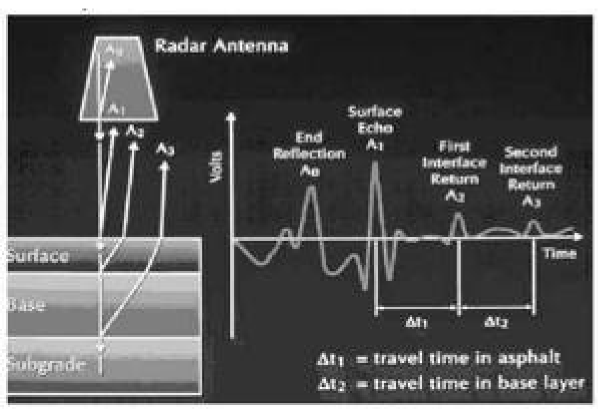


Figure 3. Typical GPR Waveform at One Point on the Pavement (from Bandara and Briggs [9]).

DESCRIPTION OF TPAD MOBILE PLATFORM AND PAVEMENT LOADING SYSTEM

The mobile platform of the TPAD is adapted from a small off-road vibrosies used in geophysical exploration that is built by Industrial Vehicles International (IVI) in Tulsa, OK (www.indvehicles.com). The TPAD platform is shown in Figure 4 and is hydraulically operated. The total weight of the mobile platform is about 18 kips and the dimensions are: 20 ft in length, 7.5 ft in width, and 7.8 ft in height. The TPAD has been modified to have a precise speed control system with a range of 0.5 to 10 mph. The loading system (see Figure 5) is capable of generating static forces of 3.4 to 14 kips and dynamic sinusoidal forces with a peak-to-peak amplitude of 2 to 24 kips over a frequency range of about 7 to 200 Hz. The static hold-down and dynamic sinusoidal forces are applied to the pavement through two loading rollers (see Figure 5). The loading rollers are 1.5 ft in diameter and 1.2 ft in width and made of 92 A durometer polyurethane which represents a hardness similar to a golf ball cover.

The vehicle cab has a size of 142 cubic feet and a heating/air-conditioning system to prevent temperature damage to the software and hardware system for data recording, TPAD operations and data analysis. This cab size is enough to accommodate the driver, operator of the data collection activities and all hardware systems. A 2,000-watt pure sine wave inverter is on-board to generate all electrical power required by the electrical systems. All movements of the mobile platform, RDD loading imparted to the pavement and raise/lowering capabilities of the rolling sensors (discussed below) are hydraulically powered.

SPEED-IMPROVED ROLLING SENSOR FOR TPAD RDD DEFLECTION MEASUREMENTS

One objective of the TPAD developmental work was to perform RDD deflection profiling of the pavement while continuously moving at speeds around 2 to 3 mph (or higher if readily attainable). To meet or exceed this target speed, the original RDD rolling sensors had to be improved. Based on earlier studies (Bay and Stokoe [4]), larger and wider wheels were

Figure 4. TPAD Mobile Platform (from Stokoe et al. [10]).

required. In addition, during prototype testing, it was found that a softer wheel tread is better in terms of reducing rolling noise and equal tread areas on both sides of the sensor cart improve cart tracking. The improvements made to the rolling sensors include: (1) incorporating better bearings to reduce rolling noise in the axles of the wheels and to provide better tracking of the cart, (2) using wider treads on the wheels to reduce rolling noise, (3) making the tread contact area on each side of the cart equal for better tracking, (4) reducing the modulus of the wheel treads to reduce the rolling noise (from a golf ball stiffness (50D durometer) to a pencil eraser stiffness (50A durometer)) and (5) changing the hold-down mechanism from an air-bag system on the top of the rolling sensor to a hanging-mass system to improve stability and reduce required under-vehicle clearance. The newly-designed sensor is currently called the speed-improved rolling sensor. The transducer used in the rolling sensor is a 2-Hz geophone, which has an output linear to the particle velocity at the pavement surface. A schematic of the speed-improved rolling sensor with the hanging-mass system of the hold-down mechanism is shown in Figure 6a. The location of the 2-Hz geophone is shown in Figure 6b and a photograph of the sensor is shown in Figure 6c.

Currently, three RDD rolling sensors are used in the TPAD to perform the deflection measurements. The three these sensors are positioned in an array along the longitudinal centerline of the TPAD as shown in Figure 7. The sensors are named according to their locations relative to the loading rollers; that is, the center sensor (CS) is located mid-way between the two loading rollers while the front sensor (FS) and the rear sensor (RS) are located forwards and backwards of the CS, each at a distance of about 2.1 ft. As indicated in Figure 6a, the diameter of the wheels on the cart of the CS is 9.5 in. while the wheel diameter on the carts of the FS and RS is 12.5 in. Larger diameter wheels are desirable because they reduce rolling noise. However, space limitations around the CS location limited the use of larger wheels for the CS. These three rolling sensors are attached to a towing frame. The towing frame enables the rolling sensors to be positioned as well as to be lowered (during the deflection measurement testing) and raised

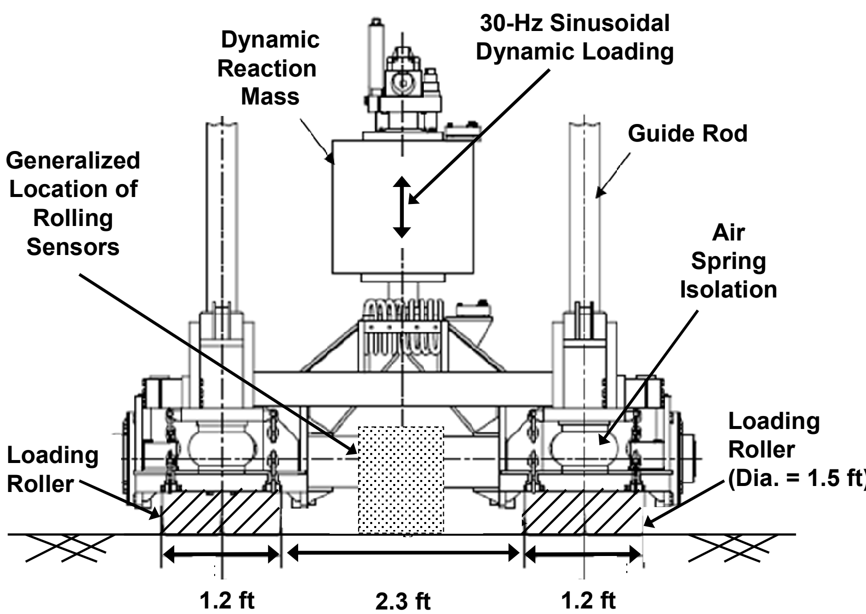
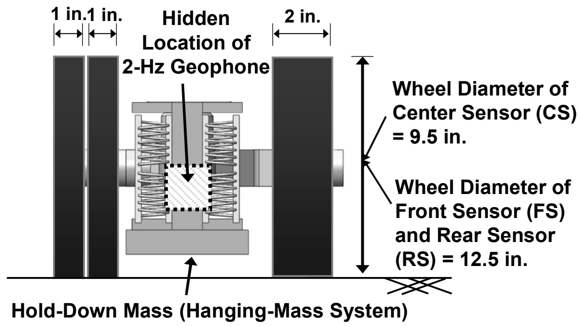
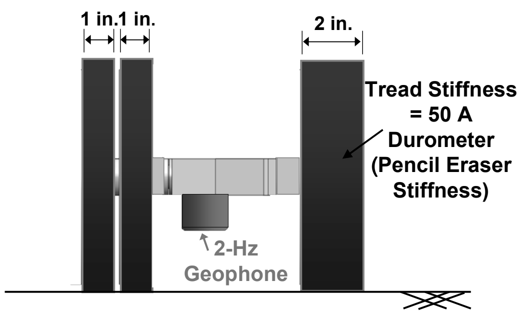


Figure 5. Cross-Sectional View of TPAD Loading System (from Stokoe et al. [10]).

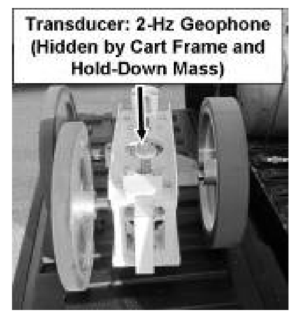
(during no testing) automatically with the loading system. The towing frame system is used to isolate the rolling sensors as much as possible from the TPAD mobile platform during pavement measurements to prevent transmission of vibrations from the TPAD to the rolling sensors.



(a) Schematic of Hanging-Mass System.



(b) Schematic Showing location of 2-Hz Geophone (with Hanging Mass System Removed).



(c) Photograph of Rolling Sensor.

Figure 6. Speed-Improved Rolling Sensor Used in RDD Measurements.

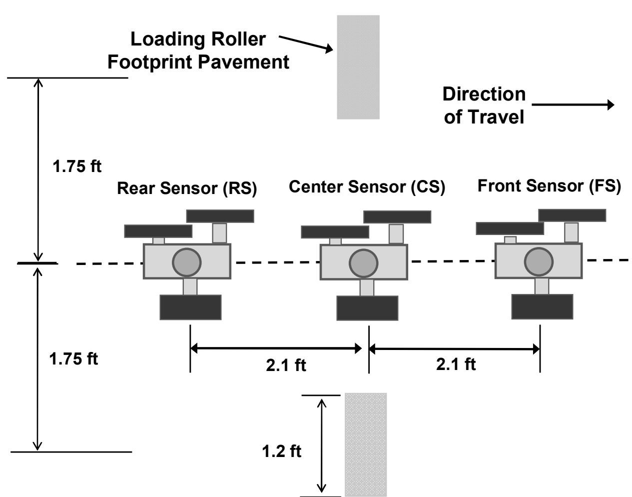


Figure 7. Revised Current Array of Three RDD Rolling Sensors in the TPAD (Stokoe et al [10]).

Calibration of three rolling sensors is performed at the pavement site using two 4.5-Hz geophones (reference transducers) that have been calibrated previously in the laboratory. The reference transducers are placed near both sides of each calibrated rolling sensor and are used to measure the motion on the pavement. In this process, the TPAD is stationary and the RDD loading system is used to apply static and dynamic forces to the pavement. The dynamic loading is applied over a range in excitation frequencies typically sweeping between 20 to 50 Hz. The average pavement deflections measured with the two reference transducers are compared with the deflection measured with the calibrated rolling sensor for each frequency. Calibration curves of the three rolling sensors are shown in Figure 8. As seen in the figure, the front and rear sensors showed similar curves while the center sensor showed a slightly different curve, likely because the center sensor has different sized wheels.

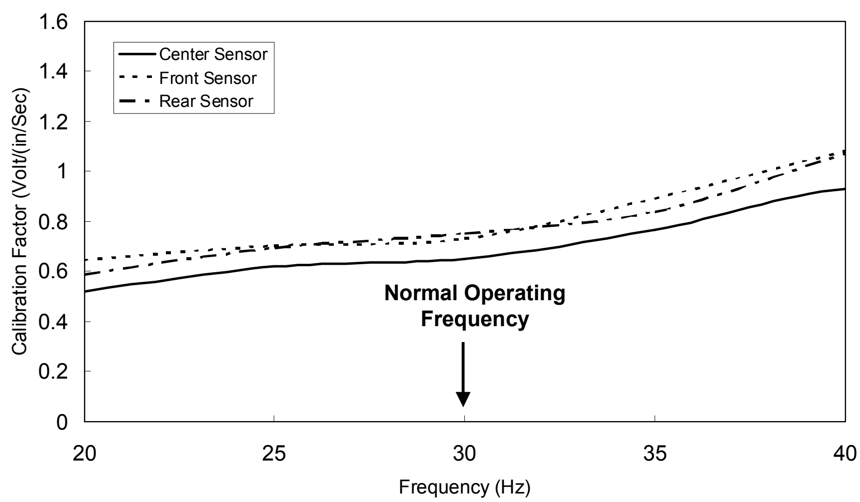


Figure 8. Calibration Curves of Three Rolling Sensors Evaluated at a Pavement Site before RDD Profiling Commenced.

TPAD TESTING AT TxDOT FLIGHT SERVICES FACILITY (FSF)

Testbed at TxDOT FSF

In the initial portion of this research, a testbed was developed at the TxDOT Flight Services Facility (FSF) at Austin Bergstrom International Airport (ABIA). The purpose of the testbed was to establish a pavement facility with known and well-documented conditions that could be used in future research projects dealing with rigid pavement testing. The pavement at the TxDOT FSF is a jointed concrete pavement (JCP). A 630-ft long testing path over which most testing has been performed is shown in Figure 9. This testing path was chosen because it traverses three different slab thicknesses and different joint types. As shown in Figure 9, the testing path consists of the following: (1) a 190-ft long section with 16-in. thick slabs and (2) a 440-ft long remaining section with 8- and 10-in. thick slabs. The plan dimensions of the 16-in. thick slabs are 25 by 25 ft while the plan dimensions of the 8- and 10-in. thick slabs are 12.5 ft by 12.5ft. According to the as-built drawings, the joints along the testing path include three types: (1) a construction expansion joint, (2) a construction joint with several rebar across the joint and (3) a contraction joint with aggregate interlocking.

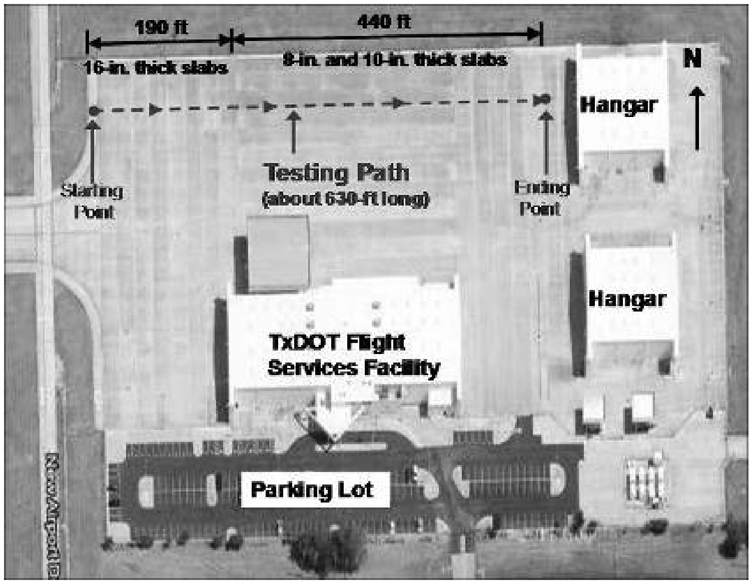


Figure 9. TxDOT Flight Services Facility at Austin Bergstrom International Airport with the TPAD Testing Path.

Continuous and Stationary RDD Deflection Measurements with Center Sensor (CS)

The TPAD at the starting point of the testing path is shown in Figure 10. Continuous (rolling) and stationary deflection measurements with the TPAD were performed. Testing speeds for the continuous profiling were 0.5, 1 and 2 mph. During the RDD continuous deflection measurements, the rolling sensors recorded the pavement deflections induced by the applied sinusoidal dynamic force at the RDD operating frequency of 30 Hz as well as the rolling noise over the frequency range from 25 to 35 Hz. The rolling noise was caused mainly by physical contact between the rolling sensors and pavement surface; that is, the main cause of the rolling noise is the pavement texture and discontinuities, with the largest component being the transverse joints (JCP), cracks and punchouts in the pavement. On the other hand, the stationary deflections are deflections measured at a point with the TPAD not moving. Therefore, no rolling noise is included in these measurements. Stationary deflection measurements represent the dynamic response of the pavement to the applied sinusoidal dynamic loading at a given location. The comparison between rolling and stationary deflections measured on 8-in. thick slabs (slabs 38 and 39), including three

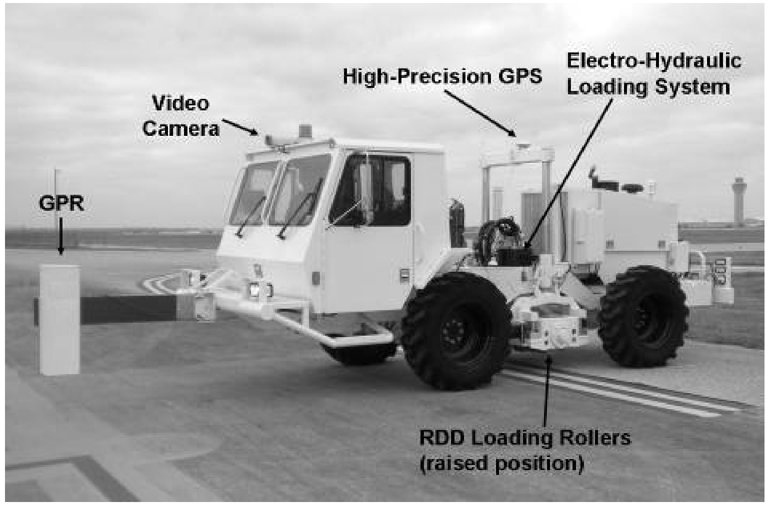


Figure 10. Photograph of the Total Pavement Acceptance Device (TPAD) at the Starting Point of the Testing Path at the TxDOT Flight Services Facility.

joints is shown in Figure 11. It is interesting to see that the stationary dynamic deflections are almost the same as the rolling dynamic deflections in the mid-slab areas. Differences in the medians are about 0.120 mils/10kips or about 3 % of the average mid-slab deflections. As expected, stationary deflection differences are higher around joint areas. These higher stationary deflections around joints occur because the continuous measurements presented in Figure 11 are averaged values determined over a distance of about 1.5 ft (centered around the joint).This averaging over a give horizontal is the typical way by which RDD data are presented.

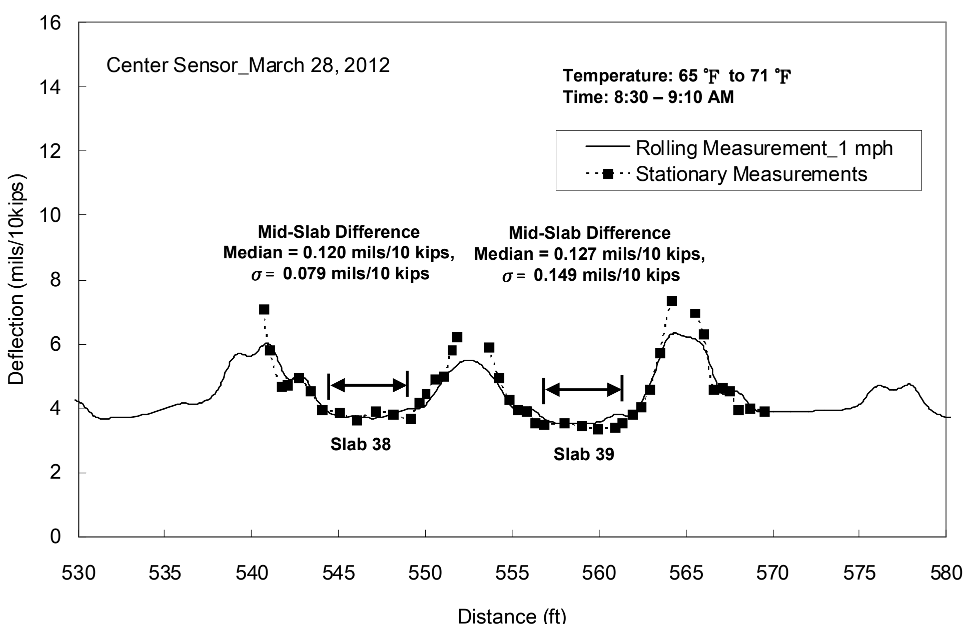


Figure 11. Comparison between Stationary and Continuous (Rolling) Dynamic Deflections.

Since, slower testing speeds generate lower rolling noise, the deflection profile collected at 0.5 mph is used as the reference profile. The deflection profiles collected at 0.5 and 2 mph are compared in Figure 12. Both deflection profiles show a clear repeating pattern of joint and mid-slab deflections; peaks at joint locations and lower deflections in mid-slab areas. The beginning 190-ft long section of pavement has 16-in. thick slabs and hence shows much lower mid-slab deflections and joint movements while the remaining 440-ft long section with 8- and 10-in, thick slabs shows higher mid-slab deflections and larger joint movements. In addition, the deflection profile at 2 mph (the currently used testing speed) shows nearly the same profile as the profile at 0.5 mph (reference testing speed with lowest rolling noise). As discussed earlier, rolling deflections on mid-slab areas are very close to the stationary deflections. In Figure 13, average deflections of mid-slab areas measured at speeds of 0.5 and 2 mph are compared. Average mid-slab deflections were calculated for both speeds and then averaged mid-slab deflections on each slab collected at 2.0 mph were divided by the averaged mid-slab deflections collected at 0.5 mph. As seen in Figure 13, mid-slab deflections at both measurement speeds exhibit similar values, with the ratio of the two average mid-deflections nearly equal to one.

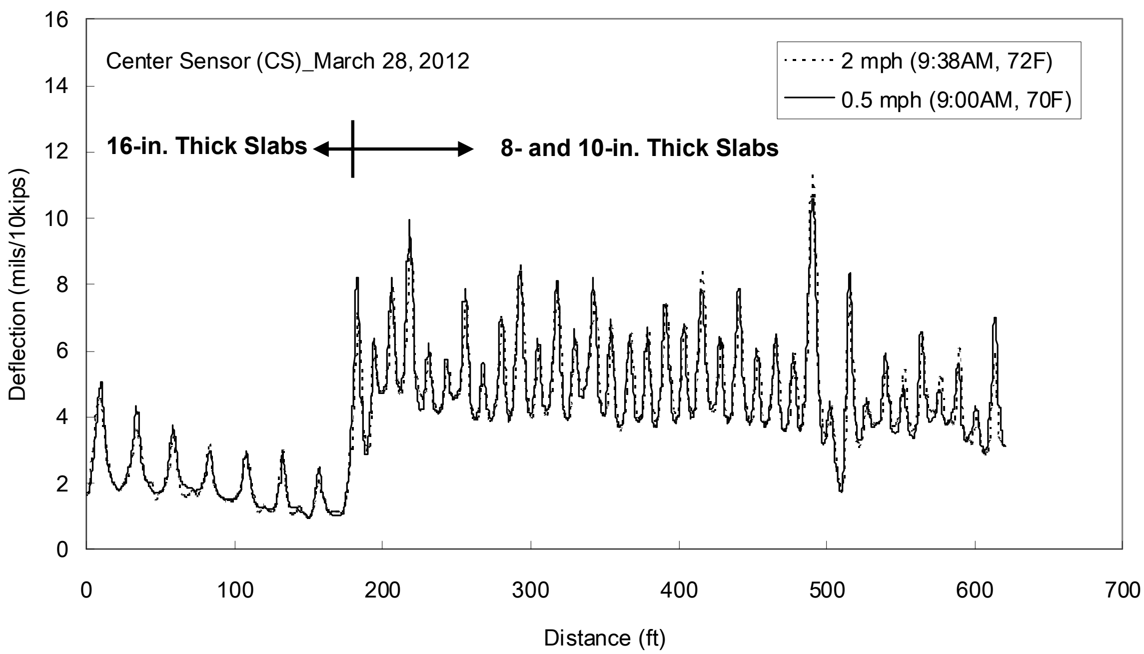


Figure 12. Continuous RDD Deflection Profiles at Testing Speeds of 0.5 and 2 mph.

Continuous GPR Profile

A continuous ground penetrating radar profile collected at the TxDOT FSF is shown in Figure 14. The x-axis is the 630-ft long testing path. The pavement characteristics identified in the figure are: (1) two transition zones in pavement thickness, (2) the steel re-bar in the 440-ft long section with 8- and 10-in. thick slabs, and (3) the bottom of the 8-in. thick slabs in the 440-ft long section which can be seen in the profile in color but not in black and white map. On the other hand, the bottom of 16-in. thick slab cannot be detected. It seems that the currently used air-coupled GPR antenna pulse (Wavebound 1 GHz horn antenna) could not penetrate deep enough to detect the reflection from the bottom of 16-in. thick slab.

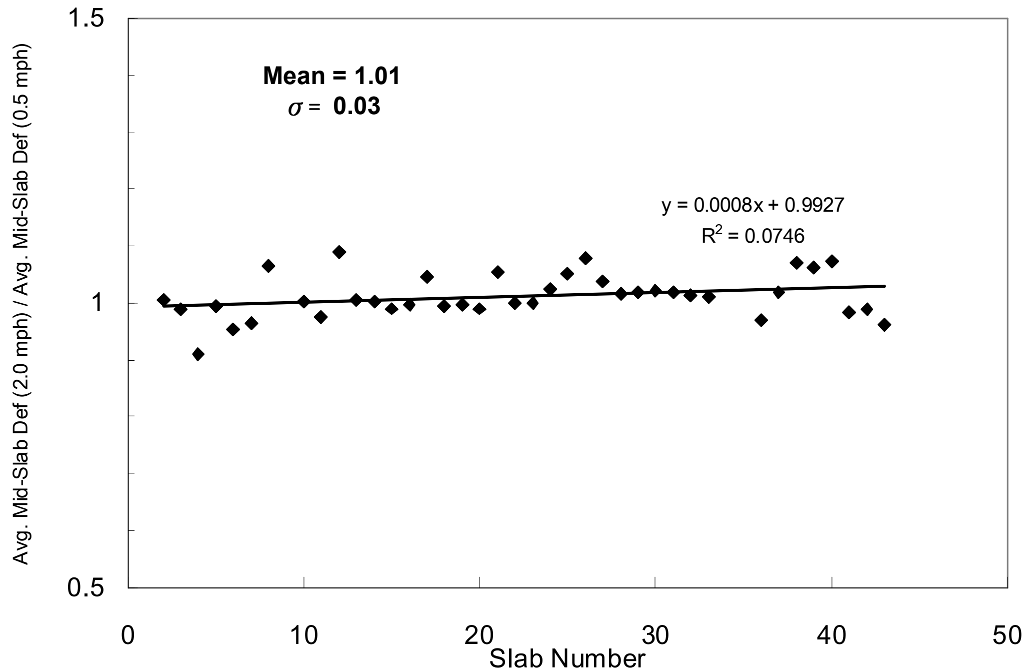


Figure 13. Profile along the Pavement of the Ratio of the Mid-Slab Deflections Determined at Testing Speeds of 0.5 and 2 mph.

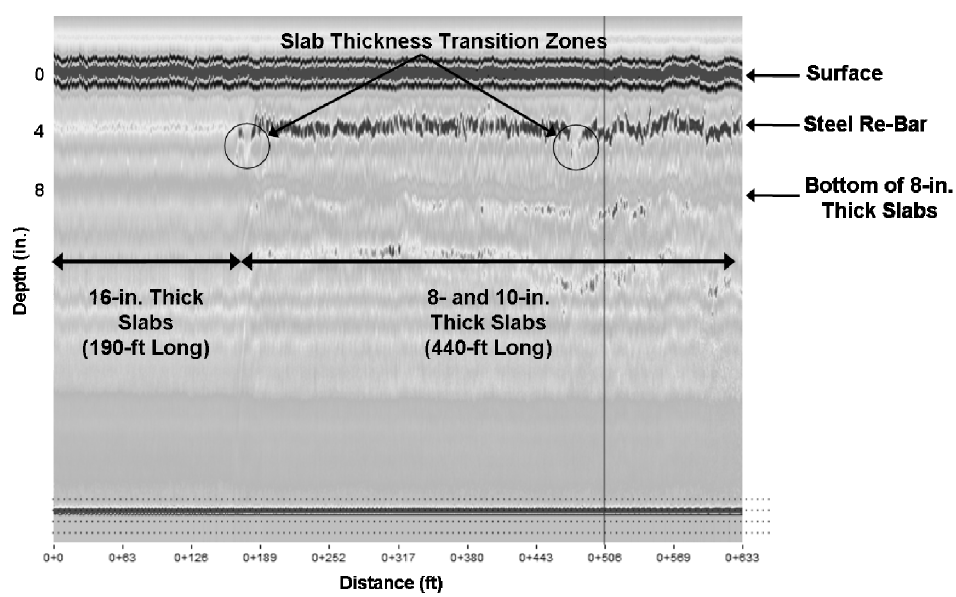


Figure 14. Continuous GPR Profile Collected along the Test Bed at the TxDOT Flight Services Facility (from Stokoe et al. [10]).

Identification of Joints with Poor Load Transfer Using the Front or Rear Rolling Sensors

When the TPAD approaches and passes over a transverse joint or crack, the array of loading rollers and rolling sensors transitions across the discontinuity as illustrated by positions A through E in Figures 15a through 15e, respectively, remembering that the loading rollers and the center rolling sensor (CS) are always at the same relative longitudinal position along the pavement. As noted in the figure, when the Front Sensor (FS) transitions across the discontinuity, it will move to the unloaded side until the CS and loading rollers cross the discontinuity. The characteristic pattern in the deflection profile resulting from this situation is illustrated in Figure 15f. Similarly, the characteristic patterns in the CS and Rear Sensor (RS) deflection profiles are illustrated in Figures 15g and 15h, respectively.

The deflection profile collected along the testbed at the TxDOT FSF with the FS at 2 mph is shown in Figure 16. The overall deflections collected with the FS showed a similar deflection pattern with the CS but with lower deflections than the CS because the FS is further from the loading rollers. Exceptions to this general relationship are at joint or crack locations with poor load transfer where the double-peak occurs. Two exceptions with double peaks at joint locations are shown in Figure 17 which is the expanded version of Region A in Figure 16. In Figure 17, the deflection patterns at joints and mid-slab areas are more clearly seen. The joint spacing corresponds to a slab length of 12.5 ft and two joints, Joints A and E, have double peaks. According to Falling Weight Deflectometer (FWD) testing, Load Transfer Efficiency (LTE) at Joint A is 21 % and at Joint E is 6 %, respectively. The other three joints in Figure 17, Joints B, C, and D, show only one peak. The LTE determined at Joint D is high, 98 % which is quite high but the joint is a construction joint with re-bars. It should be noted that the deflection pattern illustrated in Figure 15f for the FS exhibits a small, constant deflection across the poor-load-transfer joint. However, the actual pattern shown by Joints A and E in Figure 17 exhibits a narrow trough when crossing the poor-load-transfer joint. The reason for this difference is because of the averaging technique which is applied in the signal processing of the RDD data for filtering out the rolling noise. In this case, the averaging distance is 1 ft. Work is underway to reduce this averaging distance to less than 6 in.. Also, further combined RDD and FWD studies are planned.

CONCLUSIONS

A new pavement testing device, called the Total Pavement Acceptance Device (TPAD), has been developed with funding from TxDOT. The device is owned by TxDOT and presently operated under a joint implementation study with CTR at the University of Texas at Austin and TTI at Texas A&M University. The objective of TPAD testing is to nondestructively and nonintrusively investigate the structural adequacy of the complete pavement system. With the TPAD, multiple types of continuous measurements are obtained as it moves along the pavement at speeds around 2 to 3 mph, depending on pavement roughness. The multiple measurements include: (1) measuring continuous pavement deflections based on the Rolling Dynamic Deflectometer methodoloy, (2) generating ground penetrating radar profiles (pavement thickness and subsurface conditions), (3) logging global positioning (high precision testing locations), (4) measuring pavement surface temperature, (5) collecting digital video images of pavement and right-of-way conditions, and (6) logging precise distance measurements along the testing paths with a DMI.

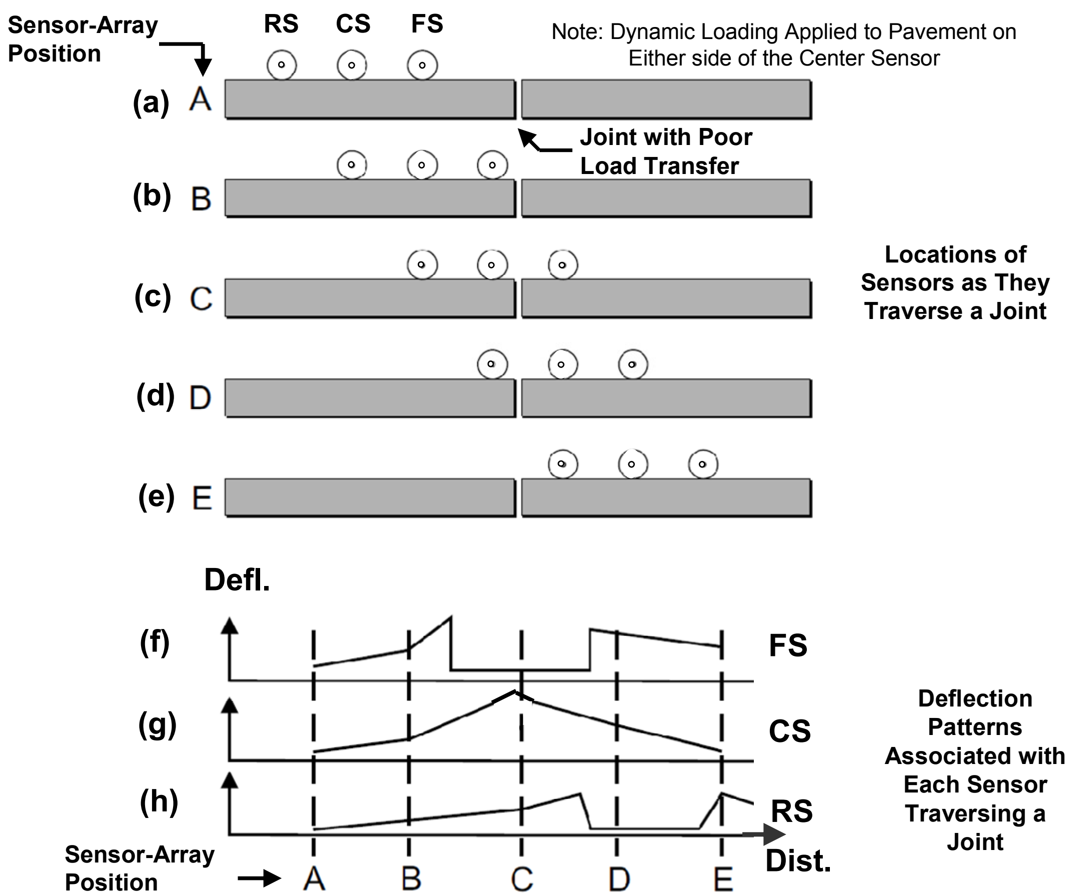


Figure 15. Schematic of Deflection Patterns of Each of the Three Rolling Sensors Crossing a Joint with Poor Load Transfer (from Stokoe et al [11]).

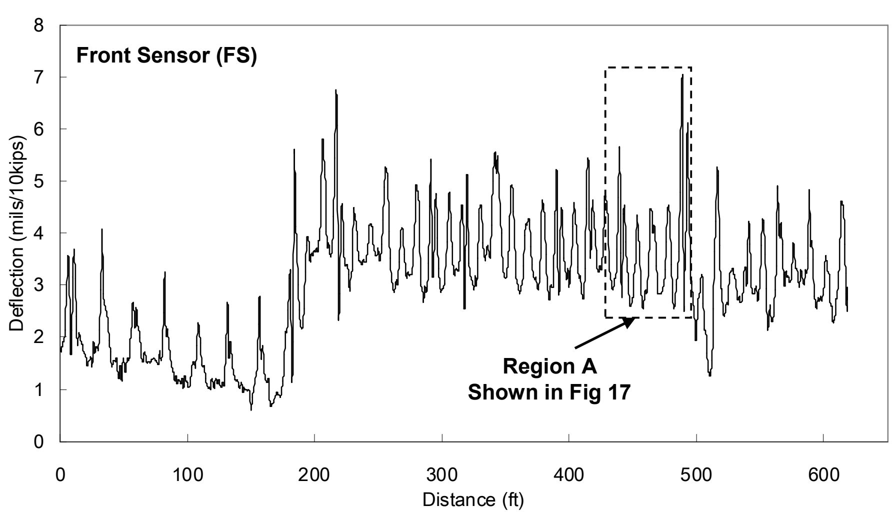


Figure 16. Deflection Profile Collected with the Front Sensor (FS) at a Testing Speed of 2 mph.

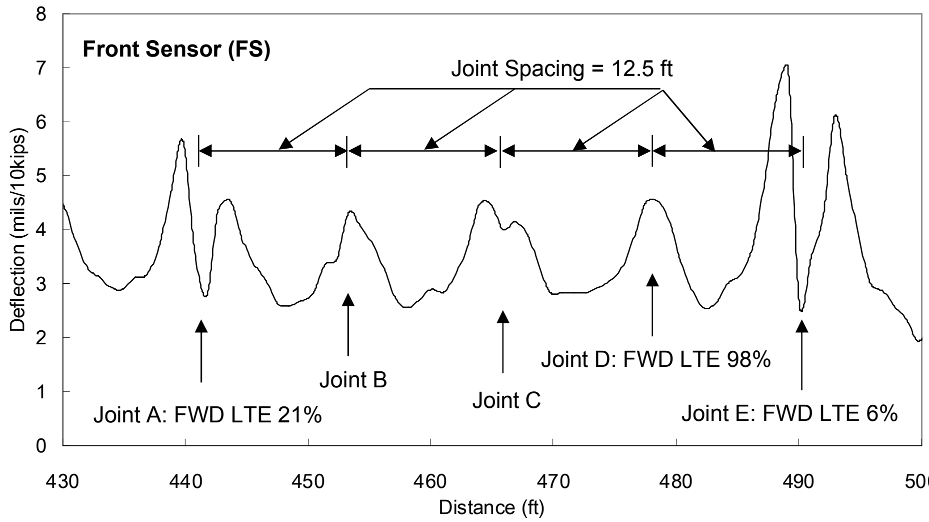


Figure 17. Expanded Deflection Profile from Figure 16a Showing Characteristic Double-Peak Patterns.

In this paper, a demonstration of TPAD testing on a testbed created at the TxDOT Flight Services Facility is presented. The RDD and GPR functions are discussed, with emphasis on the RDD measurements. The accuracy of the rolling deflection measurements were evaluated by comparing stationary and rolling dynamic deflections. Rolling deflections measured in mid-slab areas were within 3 % of the stationary values. On the other hand, rolling deflections underestimate deflections at the joint due to the longitudinal averaging performed during data processing. Work to improve (shorten the averaging distance) is underway. The use of the front sensor for identifying joints with the low load transfer is presented. The development of new device was successfully completed and the TPAD is presently transitioning from implementation projects to project-level activities.

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