Development of a High-Speed Rolling Wheel Deflectometer
By

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Summary

Applied Research Associates, Inc. (ARA) is developing a high-speed Rolling Wheel Deflectometer (RWD) under SBIR/FHWA-sponsored research. The current RWD consists of a dual-wheel, single-axle semi-trailer equipped with four spot lasers mounted on an aluminum beam beneath the trailer. Three lasers are used to measure the unloaded pavement surface, and the fourth laser, placed near the center of the dual tires, measures within the deflection basin under an 18-kip single axle load.

The RWD has been assembled, and preliminary field runs have been made on thin and thick AC pavement sections. The RWD results have been compared to Falling Weight Deflectometer (FWD) and accelerometer-determined deflections on the same pavement sections and have produced encouraging results, although with some limitations. Several needed improvement were identified.

Future plans for the RWD include system upgrade, further field testing over a wider variety of pavement types and conditions, demonstrations, including comparisons to instrumented test pavements, and eventually the manufacture of a production-level device.

Acknowledgments

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Research Objective

The research objective is to develop an RWD that meets the pavement structural assessment needs of pavement managers. The primary challenge is to develop a high-speed means of measuring pavement deflections under a moving truck wheel load.

As directed by the project sponsor, the RWD should be capable of performing the following functions:

- Measure deflections produced by an actual moving truck load
- Collect data at a minimum of 50 mph
- Make continuous deflection measurements
- Produce results appropriate for network-level pavement management applications

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The Challenge

The main challenge of this research is detecting pavement deflections (measured in thousandths of an inch) that are superimposed on pavement surfaces with roughness and texture that are many orders of magnitude greater than the pavement deflection itself. In addition, for safety and productivity reasons, it is desirable to collect data at normal highway speeds. Therefore, the dynamic truck movements further complicate deflection sensing.

Differences between RWD- and FWD-Produced Deflections and Devices

The FWD has become the standard for evaluating the structural response of pavements, primarily for project-level analyses. The FWD delivers an impact to the pavement surface and very accurately measures the resulting pavement deflections, when in the static position. On the other hand, the RWD deflection basin is produced by the transient movement of a loaded axle. The current prototype is intended to measure only a single deflection (slightly forward of the wheel load), and not an entire deflection basin. The data are not of the degree of accuracy of the FWD standard; however, the objective is to obtain sufficient accuracy and repeatability that, combined with the RWD's productivity and continuous measurement, the data are appropriate for network-level applications.

Some of the differences between RWD- and FWD-produced deflections and devices are listed below:

- Impact vs. transient load. Due to inertial and viscoelastic effects of paving materials, the same RWD and FWD loads may produce deflection basins that differ in magnitude and basin shape. The FWD applies a vertical load pulse at nearly constant frequency with depth, whereas the RWD applies both a vertical and horizontal load component with frequency decreasing with depth.

- The RWD transmits load to the pavement surface by means of dual rubber tires spaced a few inches apart. The footprints of the dual tires are roughly elliptical. The FWD uses a single, circular plate to transmit load to the pavement. This affects the basin shape, primarily near the load points, but does not have a significant effect further away from the load.

- FWDs typically store only the peak deflection for each individual sensor, even though deflections at the outer sensors have not reached their maximum values at the same instant as the center deflection, due to the propagation of the deflection pulse. The peak deflections are superimposed to form a single deflection basin that never existed in time. The RWD sees the actual deflection basin that exists in time as the device travels along the pavement.

- Location of maximum deflection and symmetry. The FWD maximum deflection occurs beneath the load plate, and the basin is approximately symmetrical. The

RWD maximum deflection typically occurs a few inches behind the moving wheel, and the trailing deflection basin is wider than the forward basin, as the pavement does not rebound as quickly as it deflects downward.

- Typical FWD testing programs call for dropping a fixed weight from one or more multiple preset drop heights. When a given mass is dropped from a fixed height at multiple locations along the road, the only variable that affects the measured load is the stiffness of the pavement itself. In the case of the RWD, the load on the pavement surface varies along the length of the road, as the trailer bounces due to pavement roughness. Therefore, the actually load applied to the pavement by the RWD varies more than the relatively constant FWD load, resulting in greater deflection variability for a given section.

RWD Measurement Methodology

Spatially Coincident Profiles

The methodology used for determining moving wheel deflections is based on shifting (i.e., fitting) of fixed-laser profiles of spatially coincident points representing undeflected and deflected pavement states. This methodology was first developed by TRRL [1] and furthered at Purdue University under the direction of Prof. Milton Harr in the late 1970's [2]. This technique was later employed on the prototype RWD developed by Dynatest/Quest. Figure 1 shows an illustration of the concept.

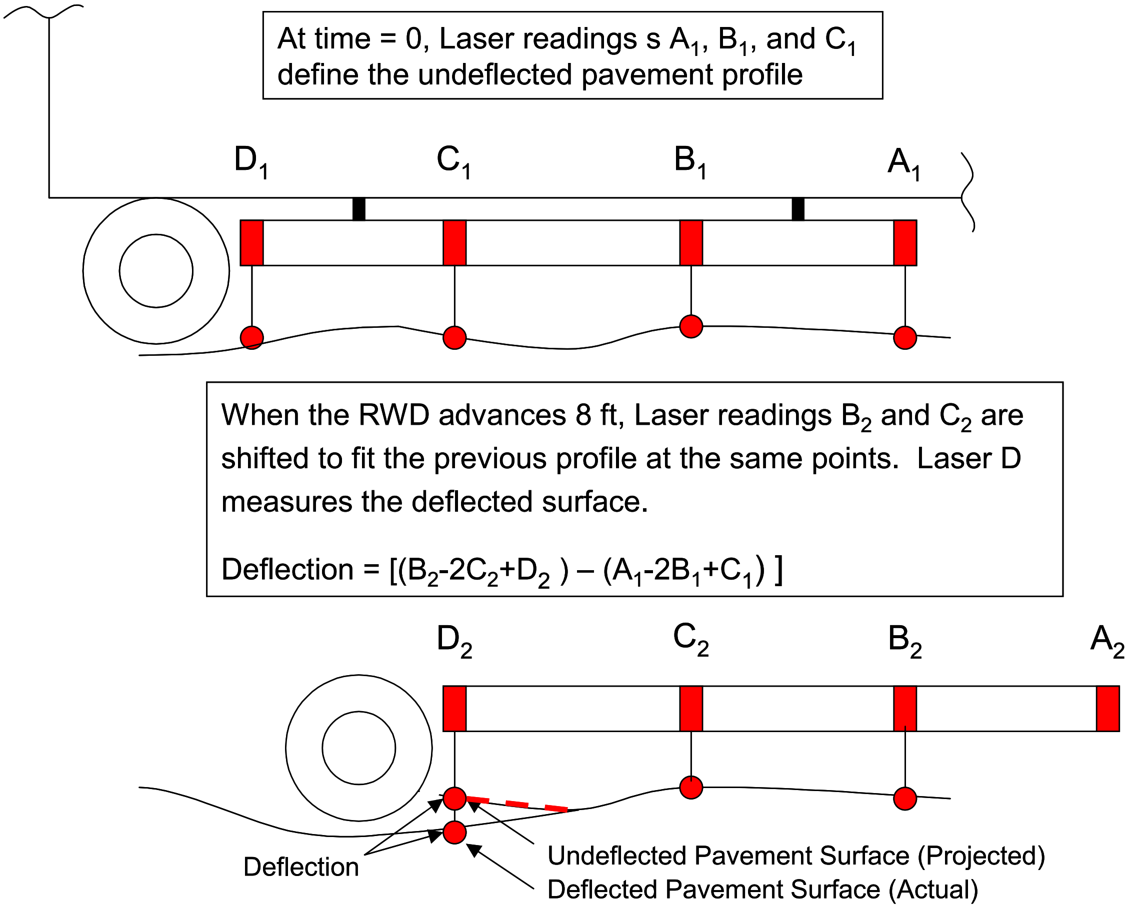
The spatially coincident method utilizes the three lead sensors, A, B, and C, to define the undeflected pavement profile at time=0. When the RWD advances 8 ft, sensors B, C, and D measure the profile previously defined by lasers A, B, and C. Due to dynamic truck effects (e.g., bounce and pitch), readings B_2 and C_2 will be different than the previous corresponding readings, A_1 and B_1. Assuming the beam is rigid with negligible bending, the profile defined by readings B_2 and C_2 is shifted in slope and magnitude to fit the previous readings at the same locations, A_1 and B_1. This allows for a comparison of the pavement surface at the same location between its undeflected and deflected states (i.e., D_2 and C_1. Deflection is calculated from the following equation:

$$\text{Deflection} = [\ (B_2-2C_2+D_2) - (A_1-2B_1+C_1)\ ]$$

Where:

A_1, B_1, and C_1 = Laser readings A, B, and C at time=0
B_2, C_2, and D_2 = Laser readings B, C, and D after 8 ft of travel

The above is configured for measuring deflection at a single point in the basin, under sensor D. The system can also be modified to measure deflection at additional points in front of sensor D. For each additional point, two more sensors would be required, one in front of sensor D, and the other at the same distance in front of sensor C. Deflection at the additional point(s) is given by a modified version of the above equation.


At time = 0, Laser readings s A_1, B_1, and C_1 define the undeflected pavement profile

When the RWD advances 8 ft, Laser readings B_2 and C_2 are shifted to fit the previous profile at the same points. Laser D measures the deflected surface.

Deflection = $[(B_2-2C_2+D_2) – (A_1-2B_1+C_1)]$

Figure 1. Spatially coincident profiles are fitted to determine the difference between the pavement profile in undeflected and deflected states.

Treatment of Random Errors

The theory of propagation of errors addresses the question, “to what degree do uncertainties in each of several directly measured quantities affect the final result?” The project team considered the propagation of random errors in determining both the number of lasers and laser spacings. We determined that the lowest propagation of random error resulted when four lasers were used, spaced at equal 8-ft intervals. Nevertheless, many factors contribute to potentially large random errors in the measurement system. These include roadway factors (e.g., texture and roughness), laser accuracy and precision, and RWD factors, such as the bounce and pitch of the RWD trailer.

Peekna [3] has shown that, as deflection readings are averaged over a given roadway length, the error of the average reading decreases by a factor of $1.29/\sqrt{n}$. Therefore, if enough readings are used to calculate the mean deflection, the associated error is decreased to an acceptable limit for network-level purposes. At an RWD survey speed of 55 mph and a laser sampling rate of 2 kHz, a sample is being taken approximately every 0.5 in. Based on this data collection rate, Peekna estimates that, with road surface roughness and texture comparable to the test sections, a 50-ft length of roadway provides a sufficient number of readings to lower the random error in the mean deflection to within an acceptable level.

Treatment of Systematic Errors

Taking into account the propagation of systematic, correlated errors proved very useful in forming guidelines for laser-sensor calibration, certain design features, and driver behavior, such as minimizing sudden steering corrections.

Design

ARA has designed and manufactured a semi-trailer to which the lasers and beam are mounted. Figure 2 shows a photograph of the RWD, and its pertinent design features are described in the following paragraphs.

Figure 2. Overview of the RWD.

Trailer

The single-axle, dual-tire trailer is 53 ft long and can vary the single axle load from 18,000 to 24,000 lb (through the use of water tanks permanently installed over the rear axle). It was manufactured with a heavy-duty suspension that minimizes lateral wander and has a low natural frequency (1.45 to 1.8 Hz), such that trailer bouncing frequency is very low relative to the aluminum beam vibration. A long trailer was selected to minimize pitching (i.e., differential bouncing from front to rear of trailer) and to allow for a long beam length, where the forward lasers are sufficiently far away from the rear tractor axle.

Mounting Beam and Wheels

The cross section of the aluminum support beam is 2 in x 8.5 in. The distance between lasers A and D is 24 ft. Its dimensions were selected to provide sufficient rigidity such that high frequency beam vibrations do not couple with the low frequency bounce of the RWD trailer. It is supported at appropriate intermediate points to minimize beam bending due to vertical acceleration and wrapped in insulation to maintain a uniform internal temperature.

ARA installed custom-built steel rims and aluminum spacers to provide approximately 1 in clearance on each side of the rear laser and the dual tires. The laser spot on the rear laser is 10.9 in forward of the center line of the rear axle. Figure 3 shows the aluminum beam with the rear laser extended between the dual tires.

Figure 3. Aluminum beam with rear laser extended between the dual tires. (Note that the photo was taken prior to wrapping of the beam with thermal insulation.)

Lasers

The RWD uses four 16-kHz LMI-Selcom spot lasers with a maximum analog output rate of 2,000 samples per second. This corresponds to a sample every 0.48 in at 55 mph. The LMI-Selcom lasers have a 1.5-mm spot size with a 70-mm measurement range and a 300-mm standoff distance. Their resolution is approximately 18 microns (1 micron = 0.001 mm) with an accuracy of 0.2 percent or better of the measurement range.

Data Acquisition System, Operating Software, and Data Analysis Software

Laser signals are acquired by a data acquisition board installed in Pentium III desktop computer located in the RWD trailer. ARA has developed software that powers the lasers, generates output files, and stores the files on the computer hard drive. The laser readings are referenced longitudinally by monitoring the ABS tone counter that is part of the rear axle braking system. In addition to the lasers and distance meter, the RWD continuously measures the pavement surface temperature with a Raytek infrared thermometer. Finally, the data acquisition system is capable of handling the output from accelerometers mounted to the aluminum beam. The accelerometers are used for monitoring beam movements and diagnostic purposes during the prototype development.

ARA has developed data processing software for analyzing the laser data using the spatially coincident methodology. Currently, the data are post-processed within a matter of minutes on the same computer used for data collection.

Laser Calibration

The LMI-Selcom lasers are each supplied with their factory calibration factors. Nevertheless, ARA developed a water calibration procedure to be used on the lasers when they are mounted on the beam. We developed this procedure for two purposes—to determine the relative difference in elevation of the lasers with respect to a level surface, and to determine the relative scale factor of each laser to high accuracy. The water calibration device consists of four interconnected water containers, one placed under each laser with the trailer in the static condition. A polypropylene float with an adhesive target is placed in each container. Because the water containers are interconnected, a level measurement surface is established by the four floats.

The spatially coincident methodology in effect assumes that all lasers are along a straight line; however, this cannot be achieved mechanically to the degree of accuracy required for this system. Therefore, the water calibration compares all of the laser readings with the beam parallel to the water level to determine the exact difference in elevation of each laser, as mounted to the beam. Furthermore, by raising and lowering the water level in the device, each laser experiences the same change in elevation between the water surface and the laser. The recorded changes in elevation are compared between the four sensors, and their scale factors are adjusted accordingly. These adjustment factors are applied first to the raw calibration data used to determine the relative differences in laser heights. Both the difference in relative elevation and adjusted scale factors are applied to the raw laser readings obtained during field testing to determine the final laser readings used for deflection calculation.

Proof of Concept Testing

Field Test Sections

ARA conducted field testing of the RWD the week of July 21, 2002, to determine the capability of the prototype device to measure repeatable, accurate pavement deflections. The proof of concept testing took place in Champaign, IL, on thin and thick pavement sections located on Staley Road. The thin pavement section consists of 6 in of asphalt concrete (AC) over a 10-in granular base. The thick pavement section is an 11-in full-depth AC pavement placed on 12 in of lime-treated subgrade. The native subgrade soil for both sections is a silty clay. We tested 500-ft sections in both lanes of the thin and thick pavement sections. In general, both pavements were in fair condition with small amounts of transverse and longitudinal cracking, low-severity rutting, and weathered surfaces. The pavements have an International Roughness Index (IRI) of approximately 1.5 m/km.

RWD Results

The RWD made multiple passes over the 500-ft test sections on July 24-26. In each test section passes were made at target speeds of 30 and 55 mph. The RWD collected data at the rate of 2,000 samples per second, and a mean deflection was calculated for the entire 500-ft section based on thousands of individual readings. Overall, six passes were made on each of the thin and thick sections.

To expand the RWD data set, additional runs were made without in situ instrumentation on August 6-7, 2002. Figures 4 and 5 present both the July and August RWD data. It is important to remember that the data points in the figures represent the mean RWD deflection for the 500-ft test section based on the average of thousands of laser readings.

Figure 5 shows the mean deflections for the thin section varied from approximately 11 to 17 mils, depending on the day and time of testing. It is important to note that the deflections have not been normalized to a single temperature and, therefore, reflect the actual temperature conditions present at the time of testing. Ambient temperatures during this period varied from approximately 85 to 100 °F.

The thick pavement mean deflections in figure 4 ranged from approximately 8 to 14 mils, again depending on the day and time of testing.

Figure 4. RWD deflections @ 18 kips.
Thick AC pavement - multiple dates.

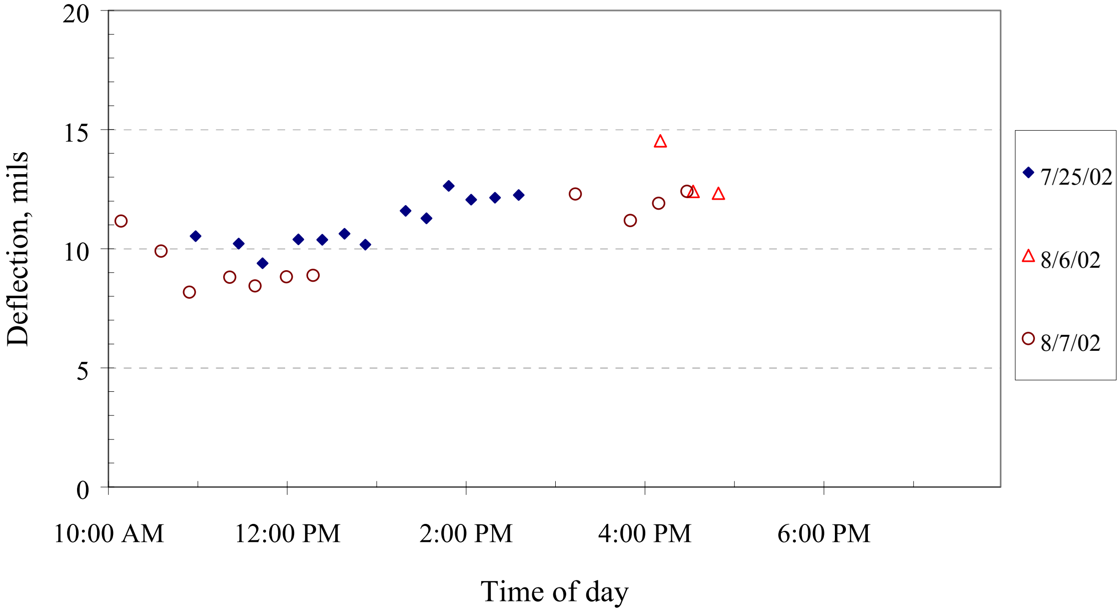
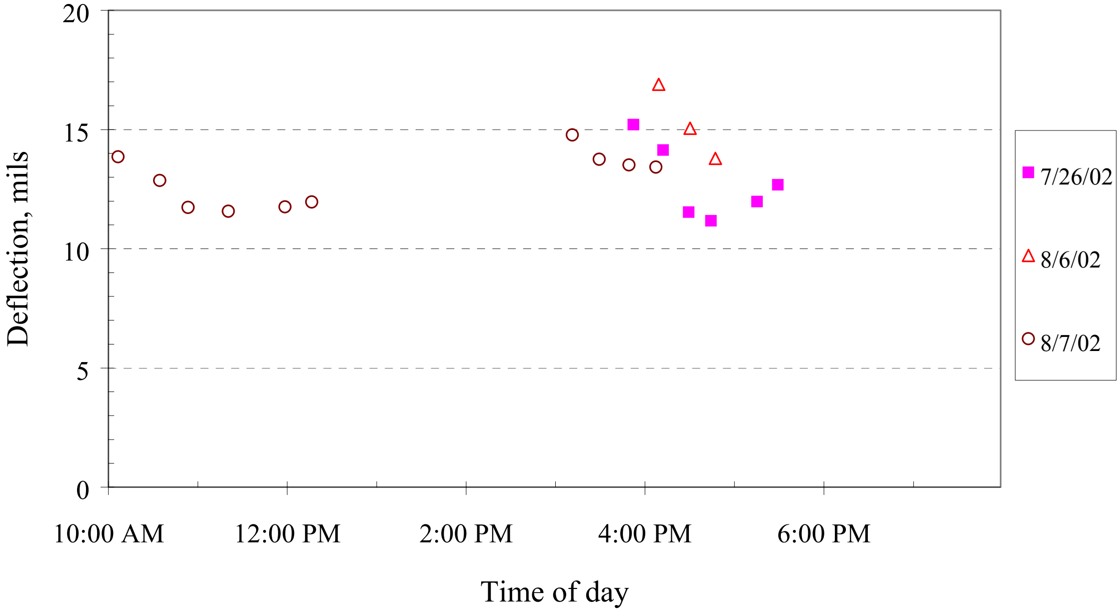


Figure 5. RWD deflections @ 18 kips.
Thin AC pavement - multiple dates.



Comparison to Accelerometer Reference Deflections

During the July RWD testing, the pavement was instrumented with an accelerometer placed in a metal sensor holder that was grouted into the AC layer, such that the lid of the container was flush with the pavement surface. The accelerometer data were double integrated to provide reference deflections for comparison with the RWD results. The accelerometer was installed at three statistically representative locations in each of the thin and thick sections, based on previous screening with an FWD. Construction Technologies Laboratories (CTL), Inc., performed the accelerometer data collection and processing, and the results are shown in figures 6 and 7 for the thick and thin sections, respectively.

Figure 6. Comparison of RWD and accelerometer deflections.
Thick AC pavement - July 24-26, 2002.

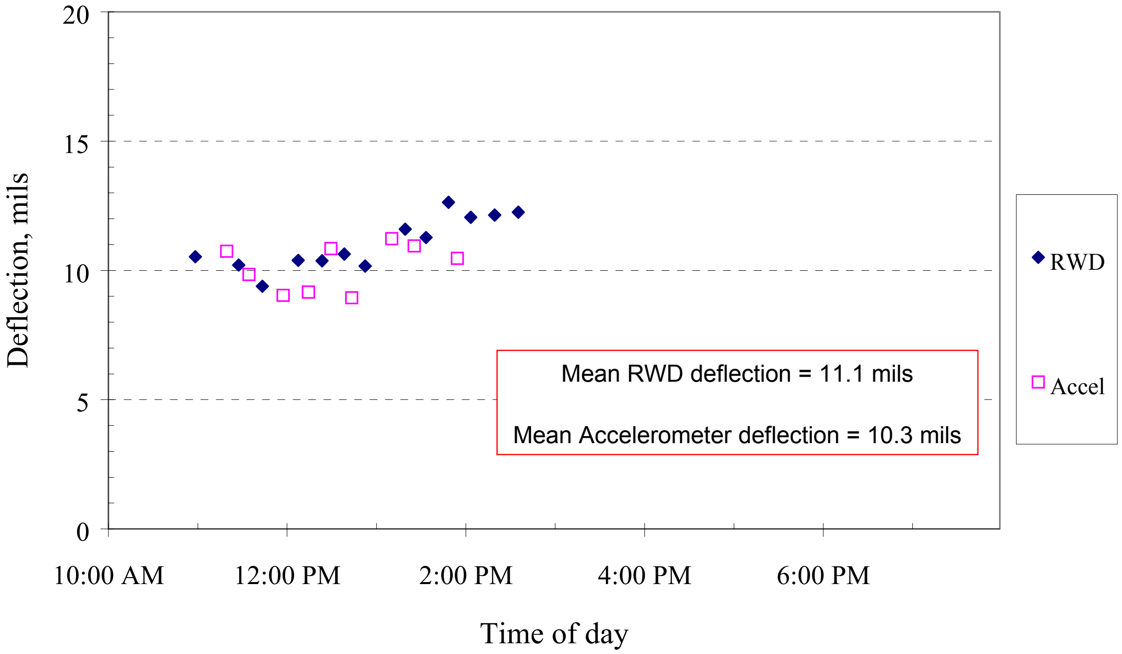
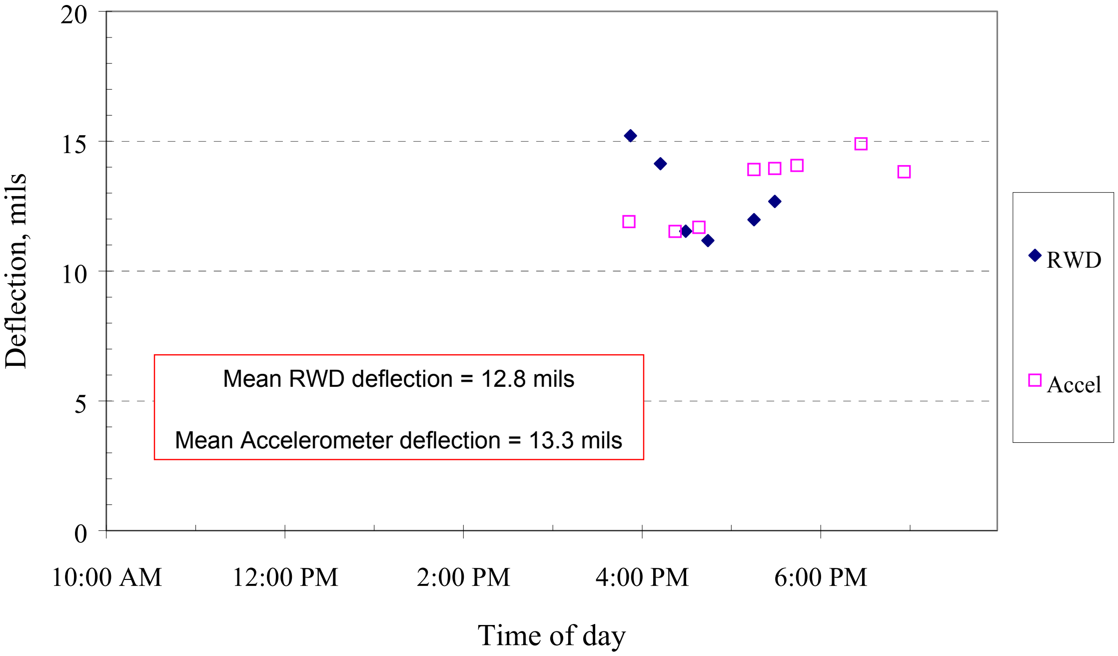


Figure 7. Comparison of RWD and accelerometer deflections.
Thin AC pavement - July 24-26, 2002.



The data show a good comparison between the RWD and accelerometer-determined deflections for both the thick and thin pavement sections. In the case of the thick pavement, the mean deflections of all test runs were 11.1 and 10.3 mils for the RWD and reference sensor, respectively. For the thin pavement, the RWD and reference deflections averaged 12.8 and 13.3 mils, respectively.

It is important to bear in mind that, in the current RWD configuration, the laser placed between the dual tires is actually 10.9 in forward of the axle centerline. In addition, for moving wheel loads, the peak deflection actually occurs a few inches behind the load center. Other references indicate that this lag distance can range from 5 to 8 in, depending upon the pavement structure. Therefore, the deflection measured by the RWD is approximately 16 to 18 in forward of the peak deflection. For this analysis it was assumed that the peak RWD deflection occurs 6 in behind the axle center line, making the location of the RWD laser 16.9 in forward of the location of peak deflection (i.e., 6+10.9 in = 16.9 in). Therefore, we determined the deflection at the corresponding location (i.e., 16.9 in) in the accelerometer-determined deflection basin for comparison to the RWD results.

Comparison to FWD Deflections

ARA had performed FWD testing on Staley Road on July 12, 2002, to evaluate section uniformity and to select instrumentation locations. Temperature conditions at the time of FWD testing were similar, but not identical, to those present 2 weeks later during the

RWD trials. Figures 8 and 9 present the FWD deflections at the 18-in sensor normalized to 9,000 lbf for the thick and thin sections, respectively.

Figure 8. FWD deflection profile @9,000 lbf and 18-in sensor.
Thick AC pavement - July 12, 2002.

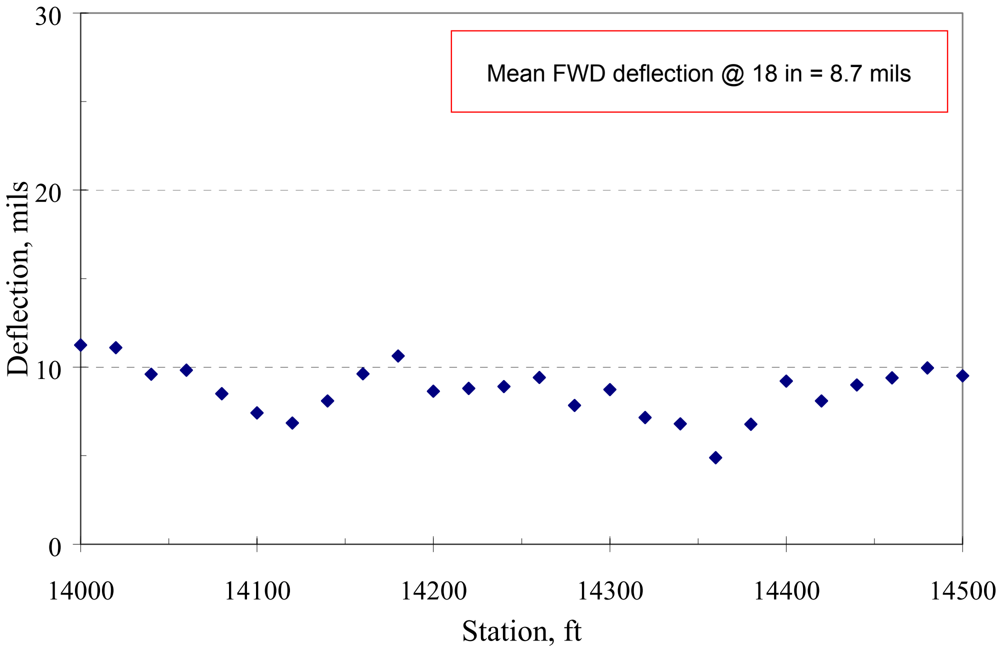


Figure 9. FWD deflection profile @9,000 lbf and 18-in sensor.
Thin AC pavement - July 12, 2002.

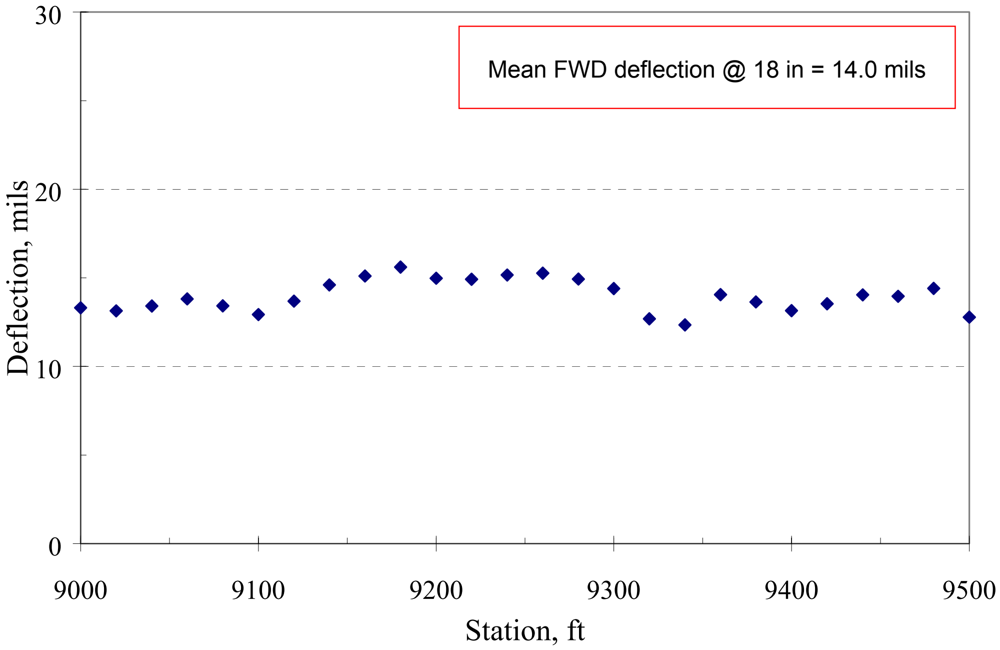


Table 1 shows a comparison of the mean deflections for the RWD, accelerometer, and FWD (at an offset of 18 in).

Table 1. Summary of RWD, accelerometer, and FWD results.

Device	RWD	Accelerometer	FWD
Date tested	July 25-26, 2002	July 25-26, 2002	July 12, 2002
Thick pavement mean deflection, mils	11.1	10.3	8.7
Thin pavement mean deflection, mils	12.8	13.3	14.0

Conclusions and Future RWD Development

The main objective of this research was to prove that the concept of using spot lasers mounted on a rigid beam can effectively measure the deflections produced by a semi-trailer load moving at normal highway speeds. The current device is a prototype that is intended to determine a representative deflection for a given pavement section for use by pavement managers. It is not designed to provide the level of accuracy or basin definition required for project-level analysis and, therefore, is not intended to be a replacement for FWDs.

We field tested the device on thin and thick AC pavement sections and compared with deflections from pavement instruments, as well as FWD deflections. Based on the field tests, we have learned the following:

- Multiple RWD passes made on several days for the same section produced results that were reasonable in magnitude and showed fair repeatability. The RWD was able to detect changes in pavement stiffness due to temperature changes between different days and at different times on the same day.

- The RWD results compared well with deflections obtained from an accelerometer embedded in the AC layer at the time of testing. The RWD results compared less well with FWD deflections; however, this may be due to differences in pavement temperatures between the FWD and RWD test dates, as well as the inherently different deflection basins produced by impact and moving wheel loads.

- The RWD prototype is physically limited from being able to measure deflections directly at the axle centerline, between the dual tires. In its current form, the laser used to calculate deflection is located 10.9 in forward of the axle centerline. Combined with the delay in the peak deflection with respect to the axle centerline (approximately 6 in behind the axle), the RWD effectively measures 16 to 18 in forward of the actual peak deflection. This results in smaller deflections and provides less contrast between pavements of varying stiffness. Approaches planned for the next stage in the development may wholly or partially overcome this limitation.

- RWD results are sensitive to factors that do not affect FWD-measured deflections, such as driver habits (uniform speed and minimizing sudden steering corrections), pavement texture, and roughness.

- Future plans include upgrading the system to measure or infer the deflection directly under the axle with reasonable accuracy. We also anticipate further field testing over a wider variety of pavement types and conditions, demonstrations for agencies, including comparisons with instrumented pavements, and the manufacture of a production-level device capable of testing pavement networks.

References

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