

*Virginia Transportation Research Council*

# *research report*

Investigation  
of the Rolling Wheel Deflectometer  
as a Network-Level Pavement Structural  
Evaluation Tool

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**FINAL REPORT**

**INVESTIGATION OF THE ROLLING WHEEL DEFLECTOMETER  
AS A NETWORK-LEVEL PAVEMENT STRUCTURAL EVALUATION TOOL**

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## ABSTRACT

The Virginia Department of Transportation (VDOT) currently uses the results of automated surface distress surveys to assist in developing pavement maintenance strategies for its interstate and primary roadways. Totalling nearly 27,000 lane-miles, these roadways consist of flexible, rigid, and composite (flexible over rigid) pavements. These video-based surface distress data consist of quantities of distress that are visible in the pavement surface. Obtaining structural data from falling weight deflectometer (FWD) testing has only recently been implemented at the network level.

A growing area of interest in pavements research is developing new and faster technologies that are well suited for nondestructively assessing the pavement structure without causing delays to the traveling public. One recently developed system, the rolling wheel deflectometer (RWD), measures the response from one-half of an 18-kip single-axle load traveling at normal highway speeds. This technology can measure deflections for approximately 200 to 300 lane-miles per day, which is approximately 10 times the production of traditionally used FWD testing. The primary advantages of using RWD are twofold: the testing can be conducted at highway speeds for increased safety, and the loading by the RWD is thought to replicate better the actual dynamic effects on pavements caused by heavy vehicle loading. A potential application might be to use the RWD to pre-screen the pavement network to identify areas where more detailed investigations are needed (e.g., by traditional FWD testing).

This report provides the results of RWD testing on three Virginia routes and a comparison of the deflection results obtained with RWD and FWD testing on sections of I-64 and I-81. The RWD provided deflection measurements over long distances at or near highway speeds with minimal interruption to the highway users, and the RWD and FWD deflection results were not well correlated. Further, the standard deviation of the RWD deflection results fluctuated with changes in surface mixture type. For these reasons, the study recommends that VDOT not pursue additional RWD testing on roadways that are expected to have low deflection values and are likely to be uniform in structural cross-section (i.e., conditions that might be expected on interstate facilities).

## **FINAL REPORT**

### **INVESTIGATION OF THE ROLLING WHEEL DEFLECTOMETER AS A NETWORK-LEVEL PAVEMENT STRUCTURAL EVALUATION TOOL**

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## **INTRODUCTION**

The Virginia Department of Transportation (VDOT) currently uses the results of automated surface distress surveys to assist in developing pavement maintenance strategies for interstate and primary roadways. Totalling nearly 27,000 lane-miles, these roadways consist of flexible, rigid, and composite (flexible over rigid) pavements. These video-based surface distress data consist of quantities of distress that are visible in the pavement surface. Obtaining structural data from falling weight deflectometer (FWD) testing has only recently been implemented at the network level.

The FWD applies a pulse load (using known weights that are dropped from specific heights onto a load plate) and measures the response (deflections) to those loads at nine surface locations, starting at the center of the loading plate and extending radially 72 in from the load plate center. The deflection basin at each test location is indicative of the stiffness of the underlying pavement structure. A production rate of approximately 2.5 lane-miles per day is typical, assuming testing at a 75-ft interval. This testing scheme is best suited for project-level testing. A recently developed network-level FWD test protocol has the ability to achieve a production rate of approximately 20 to 25 lane-miles per day, assuming an 0.2-mi interval (Diefenderfer, 2008; Galal et al., 2007).

A growing area of interest in pavements research is developing new and faster technologies that are well suited for nondestructive assessment of the pavement structure without causing delays to the traveling public. One recently developed system is the rolling wheel deflectometer (RWD), which is being developed by Applied Research Associates, Inc. (ARA), with support from the Federal Highway Administration.

The RWD system is mounted within a custom-designed 53-ft semi-trailer. The measured deflection is the response from one-half of an 18-kip single-axle load traveling at normal traffic speeds. At the time this testing was conducted, an aluminum reference bar, suspended beneath the trailer, contained four laser sensors to measure the distance to the pavement surface (Figure 1). Three lasers are used to measure the distance to the unloaded pavement surface (i.e., forward of and outside the deflection basin), and a fourth laser, located between the dual tires and just behind the rear axle (Figure 1), measures the distance to the deflected pavement surface. The deflection is calculated by comparing the laser scans profile as the RWD moves forward. Additional details of the RWD deflection measurement process are presented elsewhere (Steele, 2005; Steele and Hall, 2005; Steele and Vavrik, 2006). Recent upgrades to the RWD have



**Figure 1. Overview of RWD**

included improved laser sensors that are located within a temperature-controlled housing (M. Elseifi, personal communication). The result of these improvements on comparison testing with FWD is unknown at this time.

In contrast with the FWD, the RWD technology can test approximately 200 to 300 lane-miles per day, a production rate that is approximately 10 times greater than the current FWD network testing sequence (Diefenderfer, 2008; Galal et al., 2007). A potential benefit of the RWD is that the load, loading mechanism, and loading rate of the RWD are thought to match more closely the actual dynamic effects on pavements caused by vehicle loading. In addition, the RWD testing is conducted at or near highway speeds with limited or no traffic control requirements and minimal interruption to the highway users. However, the RWD does not allow for some of the structural capacity analysis offered by the FWD. It is anticipated that the RWD could be used to pre-screen the pavement network to identify areas that might require additional and more detailed study by traditional techniques such as the FWD.

Tests conducted for the Indiana Department of Transportation (DOT) (Steele, 2005) and for the Texas DOT (Steele and Hall, 2005) suggested that the RWD can supply useful data. These tests, which also included extensive comparative work with more conventional deflection equipment, provided valuable insight into the system's sensitivity to certain operating conditions (thermal influences) and various pavement surface characteristics. What remains to be determined is how best (1) to deploy a network-level structural assessment tool in the context of Virginia's pavement management system, and (2) to compare the RWD output with traditional deflection measurements.

## **PURPOSE AND SCOPE**

The purpose of this study was to demonstrate and validate the RWD as a device to measure pavement deflections on three test sections when the RWD is traveling at highway

speeds. Companion FWD testing was performed on the two interstate test sections and a statistical analysis was used to compare the results from these two devices.

The scope of the project encompassed portions of I-81, I-64, and a loop consisting of three primary routes in Virginia.

## METHODOLOGY

Three tasks were conducted to achieve the study objectives:

1. *RWD testing was performed at three sites:*

- *Site 1:* I-64 (between Exit 107 and Exit 136)
- *Site 2:* I-81 (between Exit 283 and Exit 251)
- *Site 3:* U.S. 522 / U.S. 211 / U.S. 29 Loop (between Culpeper, Sperryville, and Warrenton).

The eastbound and westbound directions for Site 1 and the northbound and southbound directions for Site 2 were tested with three repetitions each. The testing in Site 3 was conducted in a clockwise direction and was repeated twice.

2. *FWD testing was performed at the two interstate sites, Sites 1 and 2, as a comparison.*

3. *The RWD and FWD data were analyzed using three steps.* In the first step, the RWD data were plotted to identify any visually observable trends. In the second step, the RWD data were analyzed statistically. In the third step, the RWD and FWD results were compared. A *t*-test was used to analyze the RWD data collected on repeated runs at the same site to determine if the populations of deflection data were from the same distribution. In addition, a linear regression analysis was performed to determine the correlation between the RWD and FWD results for each site. The correlation analysis was performed to determine if the two devices similarly identified high- and low-deflecting pavements.

## RWD Testing

RWD testing was performed by ARA between October 17 and 22, 2005, at test sites identified by the Virginia Transportation Research Council (VTRC). The sites were selected to address the following variables:

- repeatability of the RWD deflection on the same test site
- effect of pavement types (composite vs. flexible) on the collected RWD deflection values



- effect of temperature on repeatability and measured deflection values
- impact of surface texture on the measured RWD deflection profile.

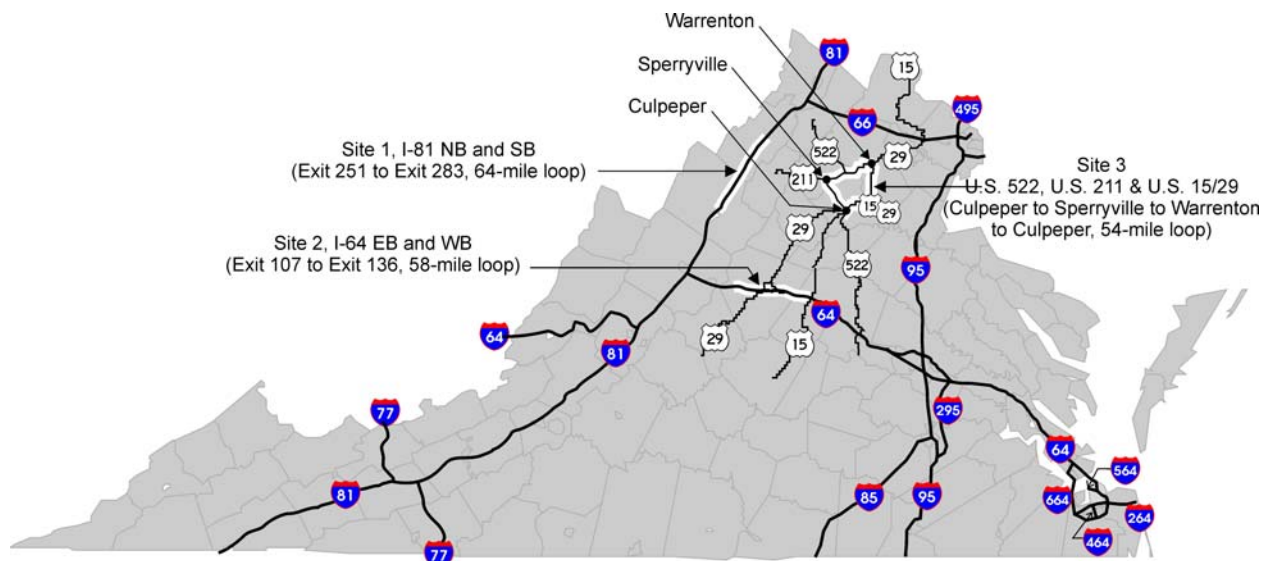
The RWD testing was conducted on the following sites:

*Site 1: I-64.* The travel lane between Exit 107 (Crozet) and Exit 136 (Zion Crossroads) was tested in both directions; testing was repeated three times with an approximate total distance of 175 mi. The pavement is composed of hot-mix asphalt (HMA) placed over an existing continuously reinforced concrete pavement (CRCP).

*Site 2: I-81.* The travel lane between Exit 283 (Woodstock) and Exit 251 (Harrisonburg) was tested in both directions; testing was repeated 3 times with an approximate total distance of 192 mi. The pavement is composed of HMA placed over an untreated aggregate base.

*Site 3: U.S. 522 / U.S. 211 / U.S. 29 Loop.* The travel lane between Culpeper and Sperryville (U.S. 522), Sperryville and Warrenton (U.S. 211), and Warrenton and Culpeper (U.S. 29) was tested in a clockwise direction; testing was repeated twice with an approximate total distance of 108 mi. The pavement is composed of a mixture of HMA over untreated aggregate base and HMA placed over cement-treated aggregate base.

The total mileage across the three test sites was approximately 475 mi. Testing occurred in the travel lane where more than one lane in each direction was present. Figure 2 presents an overview of the three sites.



**Figure 2. Overview of RWD Test Sections and Companion FWD Test Sections in Virginia**

## **RWD Data Collection and Analysis**

RWD testing was performed continuously on each test site, and the data were subdivided into 0.1-mi sections. The deflection under the wheel assembly is the primary response value measured by the RWD, and the average value from each 0.1-mi section is discussed in more detail herein. The standard deviation of the deflection readings, temperature, and speed of the RWD are also provided.

Raw RWD deflection data were processed, and the deflection output was averaged over 0.1-mi intervals. The data were also temperature corrected to a reference temperature of 68° F. The data processing and temperature correction were completed by ARA. The 0.1-mi interval was considered appropriate for network-level evaluation and is compatible with VDOT's current pavement management system. Similarly, the data obtained by the FWD were collected at the same testing interval.

## **FWD Testing**

FWD deflection measurements on Sites 1 and 2 were taken between April and May 2006 by VDOT personnel. As FWD testing is an evaluation tool used by many DOTs (Diefenderfer, 2008; Hossain et al., 2000; Nouredin et al., 2003; Zaghoul et al., 1998; Zhang et al., 2003), the researcher considered it to be an acceptable standard by which the RWD could be compared. However, it is important to recognize that the general operating procedures of the two devices are very different, as discussed in the "Introduction" section. The FWD comparison was performed to determine if there was any correlation in measurements obtained with the two devices (RWD versus FWD) such that areas of high or low deflection would be consistently identified using the data from both devices.

## **FWD Data Collection and Analysis**

FWD data were collected and analyzed based on the methodology of the American Association of State Highway & Transportation Officials (1993); however, only the deflection under the load plate at the 9,000 lb load level is presented in this report as it is most comparable to the output of the RWD. FWD data were collected at 0.1-mi intervals and were referenced using VDOT's linear referencing system (i.e., county- and state-relative mile markers).

The data obtained with the FWD from Sites 1 and 2 were analyzed by dividing the pavement into structurally homogeneous sections. Additional details on this process are presented elsewhere (Diefenderfer, 2008). Although data from the FWD were analyzed with respect to each homogenous section, data from the RWD were processed continuously across the different pavement sections. To account for any differences in temperature between the RWD and FWD testing, temperature corrections employing the *BELLS3* equation was performed on the FWD data collected on Site 2 (I-81) to normalize the temperature to a standard temperature of 68° F. Temperature correction was not performed on the data from Site 1 (I-64) as the pavement was analyzed as a composite structure. In addition, FWD data were normalized to a 9,000 lbf load. RWD data were supplied as being temperature corrected. It is also important to

note that no pavement maintenance was performed on the test sites between the dates of RWD and FWD testing.

## RESULTS AND DISCUSSION

### RWD Testing

In the following sections, the RWD deflection profiles for three sites are presented and discussed. These sites include two interstate locations and one location on a series of primary routes tested as a loop. The two interstate sections are composed of a thicker flexible pavement (composed of dense-graded and stone matrix asphalt [SMA] mixtures on the pavement surface) over an aggregate base and a flexible pavement overlay (composed of dense-graded or SMA mixtures on the pavement surface) placed on CRCP. The primary routes are composed of a thinner flexible pavement placed over a treated and untreated aggregate base. The average RWD deflection from each 0.1-mi section is shown graphically. In addition, the standard deviation of the deflection readings, temperature, and speed of the RWD are provided in tabular form.

#### Site 1: I-64

Site 1 extends from Crozet to Zion Crossroads between mile markers 107 and 136, as indicated in Figure 2. Figures 3 and 4 present the RWD results for the eastbound and westbound directions of I-64, respectively. The pavement thickness varied between approximately 4 to 6 in of HMA over 8 in of CRCP. Based on visual observation, the majority of the deflections ranged from approximately 2 to 8 mils (1 mil = 0.001 in).

Table 1 presents the measured parameters of three RWD passes on eastbound and westbound I-64 as provided by ARA. The *standard deviation of all average deflections*

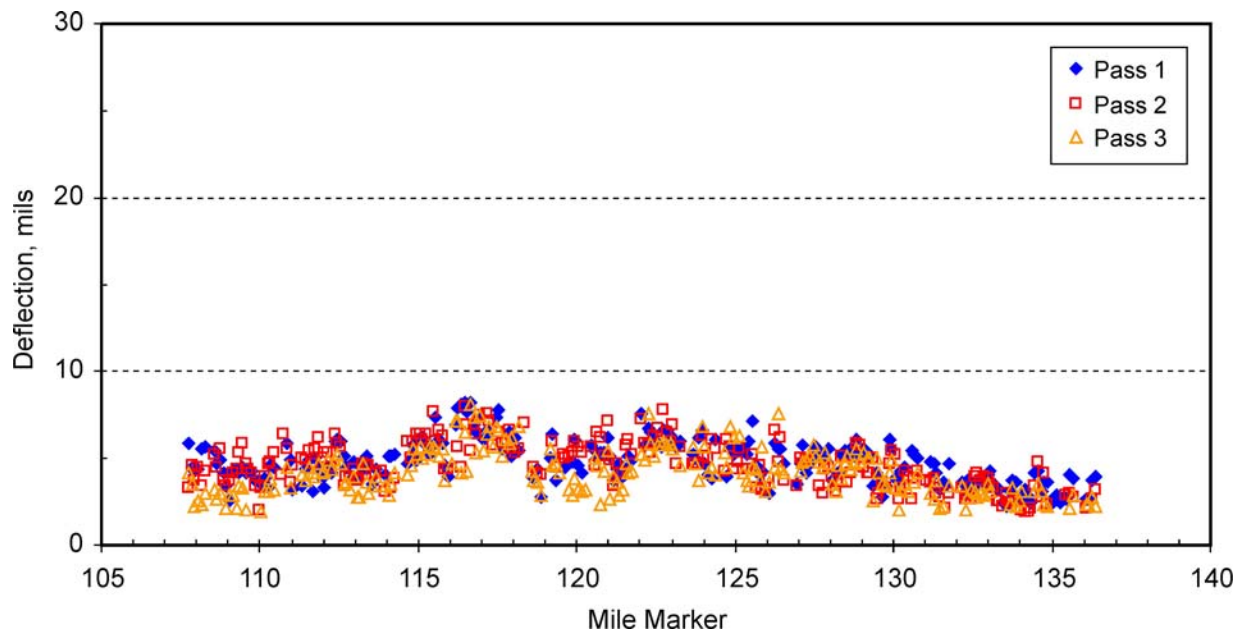


Figure 3. Eastbound I-64 RWD Deflection, Passes 1, 2, and 3

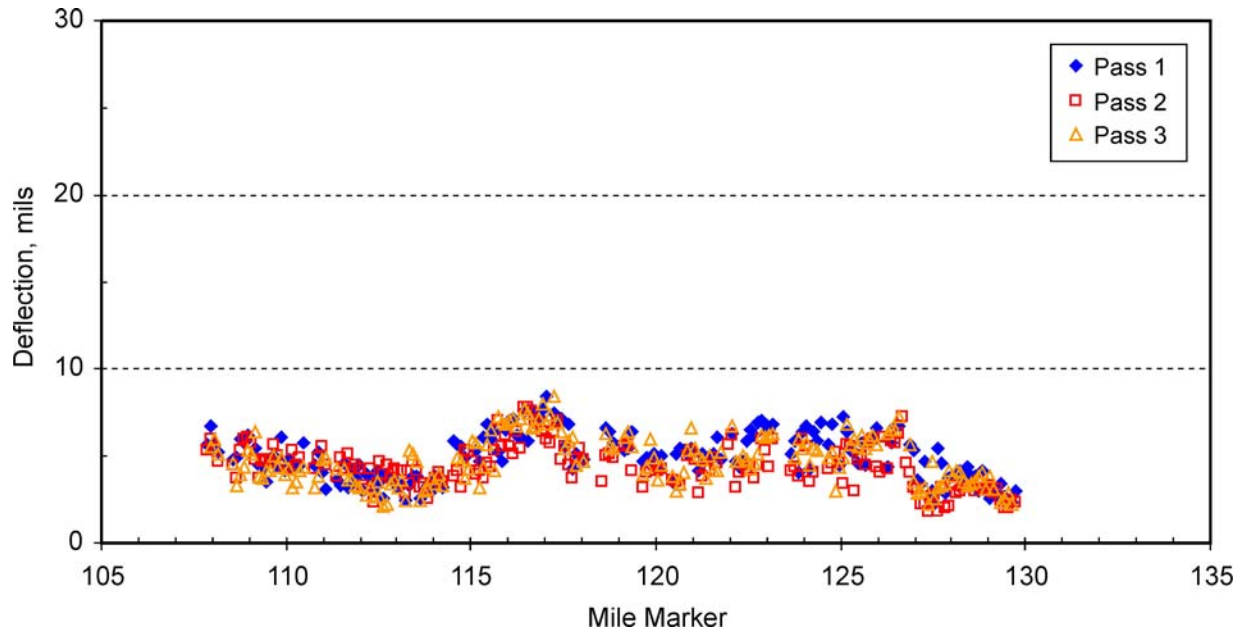


Figure 4. Westbound I-64 RWD Deflection, Passes 1, 2, and 3

Table 1. RWD Deflection Results: Eastbound and Westbound I-64

Direction/ Pass No.	Average No. of Observations per 0.1 Mile	Average Deflection (mils)	Standard Deviation of All Average Deflections (mils)	Average Standard Deviation of 0.1-Mile Deflections (mils)	Average Speed (mph)	Average Pavement Surface Temperature (°F)
<b>Eastbound</b>						
Pass 1	12,160	4.76	1.26	44.28	59.2	78.2
Pass 2	12,708	4.62	1.33	45.13	56.5	86.0
Pass 3	12,573	4.21	1.31	45.40	57.3	92.2
<b>Westbound</b>						
Pass 1	12,227	4.95	1.35	53.62	58.8	77.3
Pass 2	13,073	4.43	1.23	54.89	55.0	88.4
Pass 3	12,782	4.73	1.39	55.55	56.3	97.3

The average deflection values are temperature corrected. *Standard deviation of all average deflections* indicates the variability of the average deflection values *between* the 0.1-mi sections tested (if the 0.1-mi deflections were considered a batch, this would be a measure of the between batch variability). *Average standard deviation of 0.1-mi deflections* represents the average variability *within* each individual 0.1-mi section (a measure of the within batch variability).

indicates the variability of the average deflection values *between* the 0.1-mi sections tested (if the 0.1-mi deflections were considered a batch, this would be a measure of the between batch variability). The *average standard deviation of 0.1-mi deflections* represents the average variability *within* each individual 0.1-mi section (a measure of the within batch variability). The increase in pavement surface temperature from the first pass to the third pass was a result of typical pavement heating during the day. The average deflection values are temperature corrected.

Previous RWD testing indicated that heating of the trailer brake assembly, through repeated braking during testing of short sections, influenced the measured deflection results (Steele and Hall, 2005). This trend was not seen in the data, as shown in Table 1.

### Site 2: I-81

Site 2 extends from Harrisonburg to Woodstock between mile markers 251 and 283, as shown in Figure 2. Figures 5 and 6 show the RWD results for the northbound and southbound directions of I-81, respectively. The pavement within Site 2 is a relatively thick flexible pavement with the HMA thickness ranging from approximately 10 to 12 in over an approximately 6-in-thick aggregate base. Based on visual observation, the majority of the deflections ranged from approximately 4 to 16 mils in the northbound direction and from approximately 1 to 9 mils in the southbound direction.

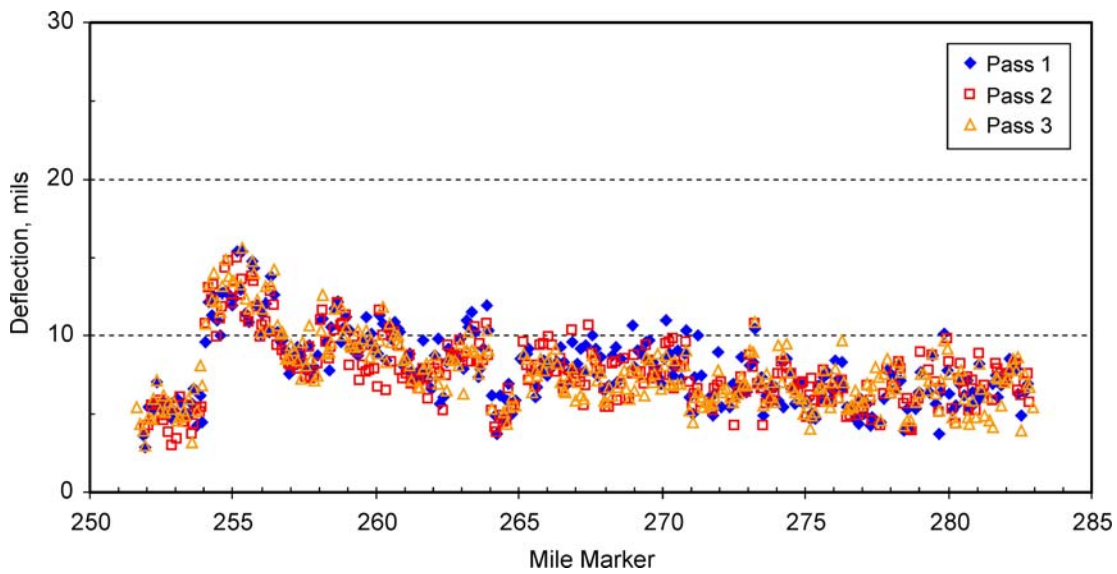


Figure 5. Northbound I-81 RWD Deflection, Passes 1, 2, and 3

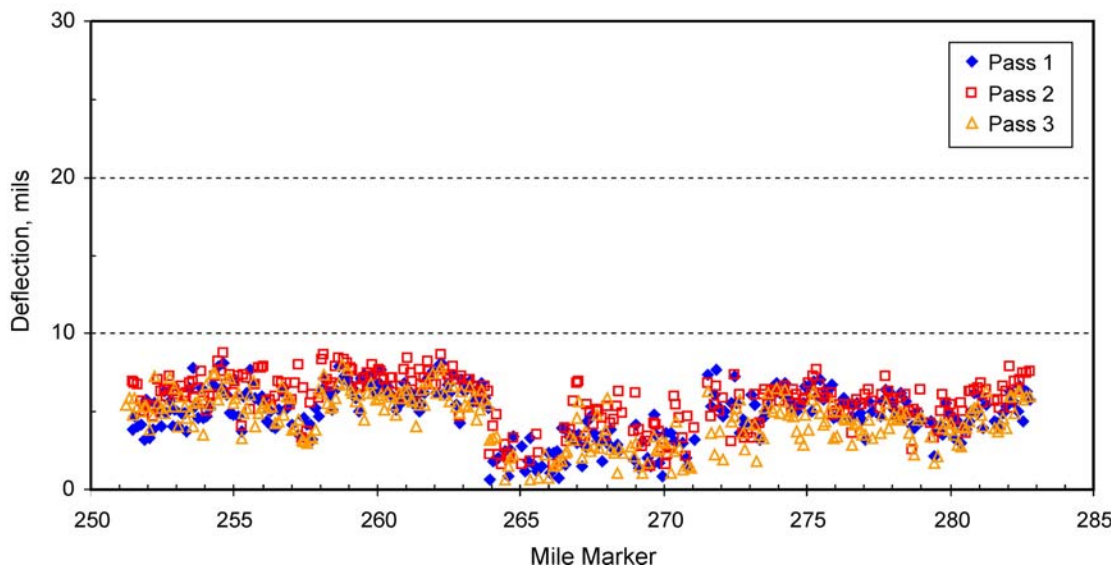


Figure 6. Southbound I-81 RWD Deflection, Passes 1, 2, and 3

Table 2 presents the RWD measured parameters from three passes and the overall average results from the three RWD passes on northbound and southbound I-81 as provided by ARA. Table 2 also shows an increase in pavement surface temperature as a result of typical heating during the course of the day.

**Table 2. RWD Deflection Results: Northbound and Southbound I-81**

Direction/ Pass No.	Average No. of Observations per 0.1 Mile	Average Deflection (mils)	Standard Deviation of All Average Deflections (mils)	Average Standard Deviation of 0.1-Mile Deflections (mils)	Average Speed (mph)	Average Pavement Surface Temperature (°F)
<b>Northbound</b>						
Pass 1	12,140	7.93	2.27	51.03	59.0	75.0
Pass 2	11,813	7.68	2.20	51.51	60.6	87.8
Pass 3	11,680	7.71	2.29	50.75	61.2	98.0
<b>Southbound</b>						
Pass 1	11,755	4.92	1.66	58.86	60.9	79.7
Pass 2	12,034	5.73	1.59	57.59	59.5	93.4
Pass 3	11,726	4.58	1.59	57.50	61.1	100.4

The average deflection values are temperature corrected. *Standard deviation of all average deflections* indicates the variability of the average deflection values *between* the 0.1-mi sections tested (if the 0.1-mi deflections were considered a batch, this would be a measure of the between batch variability). *Average standard deviation of 0.1-mi deflections* represents the average variability *within* each individual 0.1-mi section (a measure of the within batch variability).

### Site 3: U.S. 522 / U.S. 211 / U.S. 29 Loop

Site 3 comprises a series of connected routes that form a circular loop. This loop consists of northbound U.S. 522, from Culpeper to Sperryville; eastbound U.S. 211, from Sperryville to Warrenton; and southbound U.S. 15/29, from Warrenton to Culpeper. This loop was tested twice with the RWD. The pavement within Site 3 was expected to show the highest deflection and deflection variability as a result of being composed of high- and intermediate-volume primary routes. In general, the pavement conditions along the section were more variable than for the two interstate sections.

#### *U.S. 522: Culpeper to Sperryville*

Figure 7 shows the RWD results for the northbound lane of U.S. 522 from Culpeper to Sperryville (approximately 18 mi). Although the pavement is reported to be only slightly thinner than that of the other roads on this loop, the deflections were considerably higher with more variability than the other two segments on the loop. Based on visual observation, the majority of the deflections ranged from 8 to 25 mils.

The RWD measured properties of the two passes are presented in Table 3 as provided by ARA. As the testing occurred during the late afternoon / evening hours, the pavement surface temperature decreased with each pass.

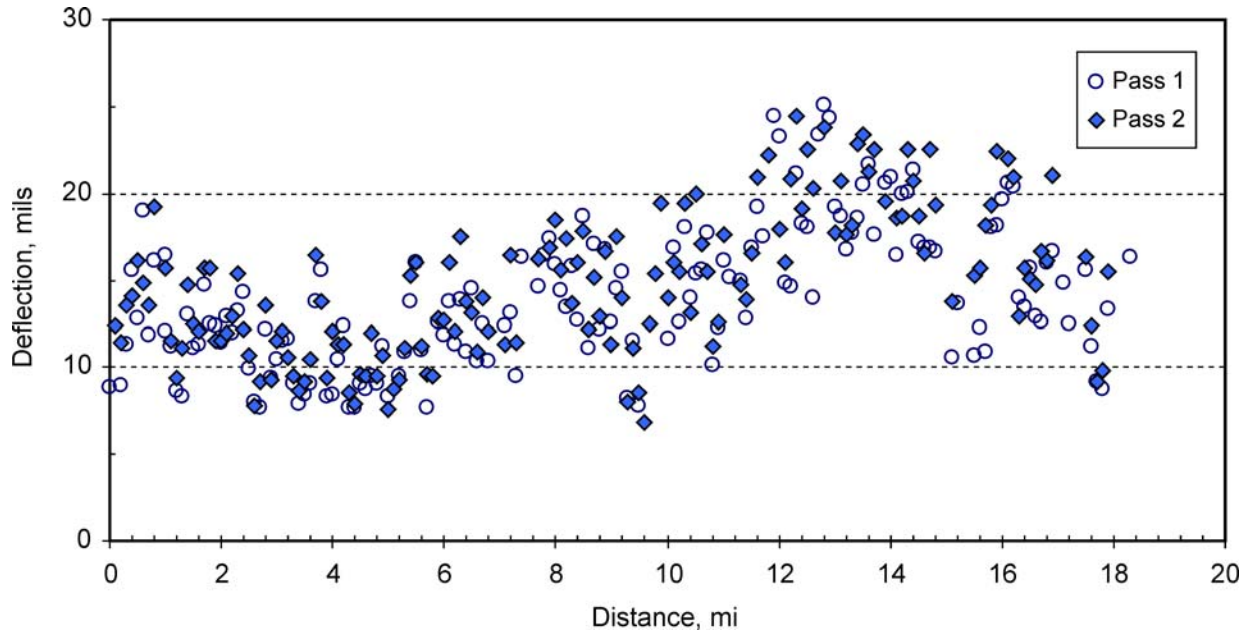


Figure 7. Northbound U.S. 522, Culpeper to Sperryville

Table 3. RWD Deflection Results: Northbound U.S. 522, Culpeper to Sperryville

Pass No.	Average No. of Observations per 0.1 Mile	Average Deflection (mils)	Standard Deviation of All Average Deflections (mils)	Average Standard Deviation of 0.1-Mile Deflections (mils)	Average Speed (mph)	Average Pavement Surface Temperature (°F)
Pass 1	14,606	13.99	4.00	45.80	49.2	98.4
Pass 2	13,347	14.70	4.12	43.19	54.0	86.4

The average deflection values are temperature corrected. *Standard deviation of all average deflections* indicates the variability of the average deflection values *between* the 0.1-mi sections tested (if the 0.1-mi deflections were considered a batch, this would be a measure of the between batch variability). *Average standard deviation of 0.1-mi deflections* represents the average variability *within* each individual 0.1-mi section (a measure of the within batch variability).

*U.S. 211: Sperryville to Warrenton*

Figure 8 shows the RWD results for eastbound U.S. 211 from Sperryville to Warrenton, a segment of about 26 mi. Based on visual observation, the majority of the deflections ranged from approximately 4 to 20 mils.

The RWD measured properties of the two passes are presented in Table 4. As the testing occurred during the late afternoon / evening hours, the pavement surface temperature decreased with each pass.

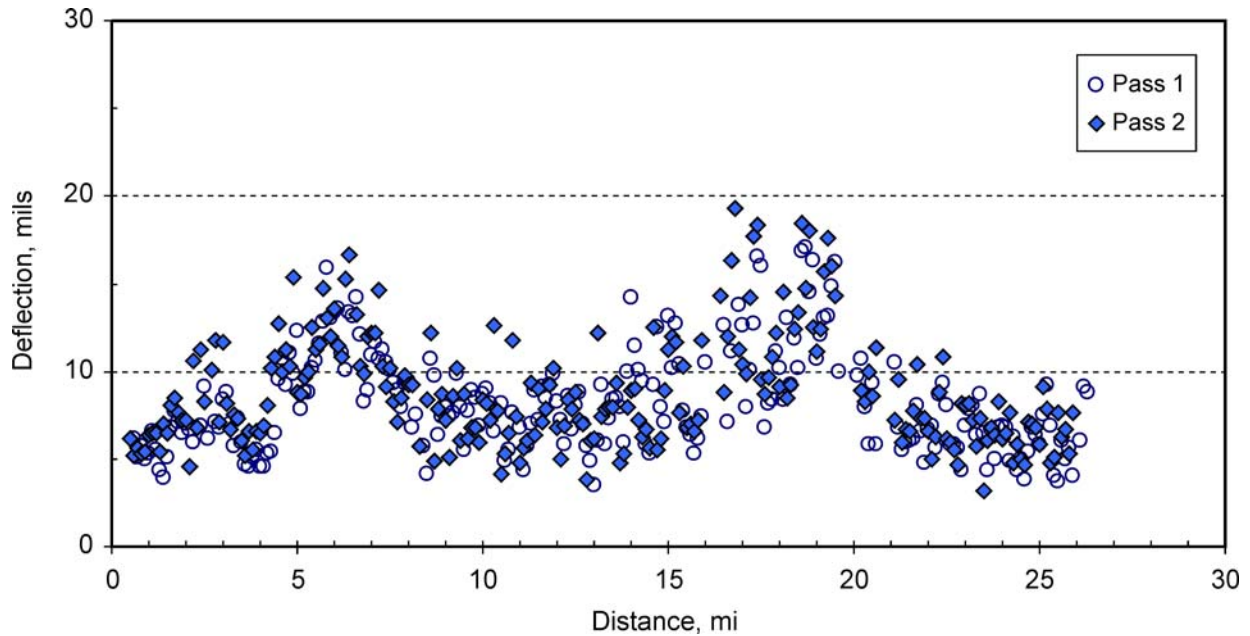


Figure 8. Eastbound U.S. 211, Sperryville to Warrenton

Table 4. RWD Deflection Results: Eastbound U.S. 211, Sperryville to Warrenton

Pass No.	Average No. of Observations per 0.1 Mile	Average Deflection (mils)	Standard Deviation of All Average Deflections (mils)	Average Standard Deviation of 0.1-Mile Deflections (mils)	Average Speed (mph)	Average Pavement Surface Temperature (°F)
Pass 1	12,606	8.27	2.89	42.21	57.3	93.9
Pass 2	12,200	8.78	3.13	42.13	59.2	80.5

The average deflection values are temperature corrected. *Standard deviation of all average deflections* indicates the variability of the average deflection values *between* the 0.1-mi sections tested (if the 0.1-mi deflections were considered a batch, this would be a measure of the between batch variability). *Average standard deviation of 0.1-mi deflections* represents the average variability *within* each individual 0.1-mi section (a measure of the within batch variability).

*U.S. 15/29: Warrenton to Culpeper*

RWD deflections for the U.S.15/29 segment (approximately 23 mi) are presented in Figure 9. Based on visual observation, deflections ranged from approximately 2 to 20 mils.

The RWD measured properties of the two passes are presented in Table 5. As the testing occurred during the late afternoon / evening hours, the pavement surface temperature decreased with each pass.



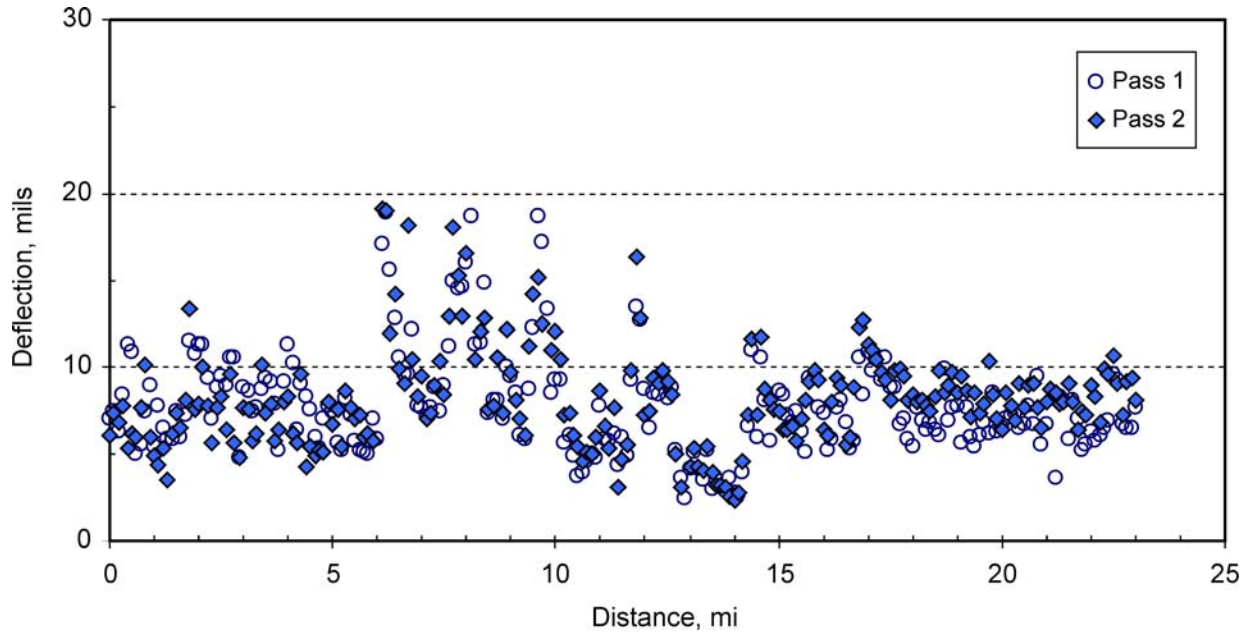


Figure 9. Southbound U.S. 15/29, Warrenton to Culpeper

Table 5. RWD Deflection Results: Southbound U.S. 15/29, Warrenton to Culpeper

Pass No.	Average No. of Observations per 0.1 Mile	Average Deflection (mils)	Standard Deviation of All Average Deflections (mils)	Average Standard Deviation of 0.1-Mile Deflections (mils)	Average Speed (mph)	Average Pavement Surface Temperature (°F)
Pass 1	13,263	7.83	2.91	42.63	56.1	89.8
Pass 2	13,357	8.15	2.86	41.84	54.8	78.2

The average deflection values are temperature corrected. *Standard deviation of all average deflections* indicates the variability of the average deflection values *between* the 0.1-mi sections tested (if the 0.1-mi deflections were considered a batch, this would be a measure of the between batch variability). *Average standard deviation of 0.1-mi deflections* represents the average variability *within* each individual 0.1-mi section (a measure of the within batch variability).

### FWD Testing

FWD deflection testing was performed on two of the three pavement sites tested by the RWD: Site 1 (I-64) and Site 2 (I-81). The FWD and RWD tests were not performed at the same time. The RWD results from both sites and the FWD results from Site 2 (I-81) were temperature corrected. The FWD results from Site 1 (I-64) were not temperature corrected as this section was analyzed as a composite structure. In addition, the FWD results were normalized to 9,000 lbf to correspond better with the loading applied by the RWD. Although the FWD applied load, measured deflection at nine sensors, and other data were collected, only the temperature-corrected (Site 2 only) and normalized deflections at the load plate ( $D_0$ ) are provided here.

#### Site 1: I-64

Site 1 extends from Crozet to Zion Crossroads between mile markers 108 and 136 as shown in Figure 2. Figures 10 and 11 show the FWD normalized deflection  $D_0$  for the eastbound

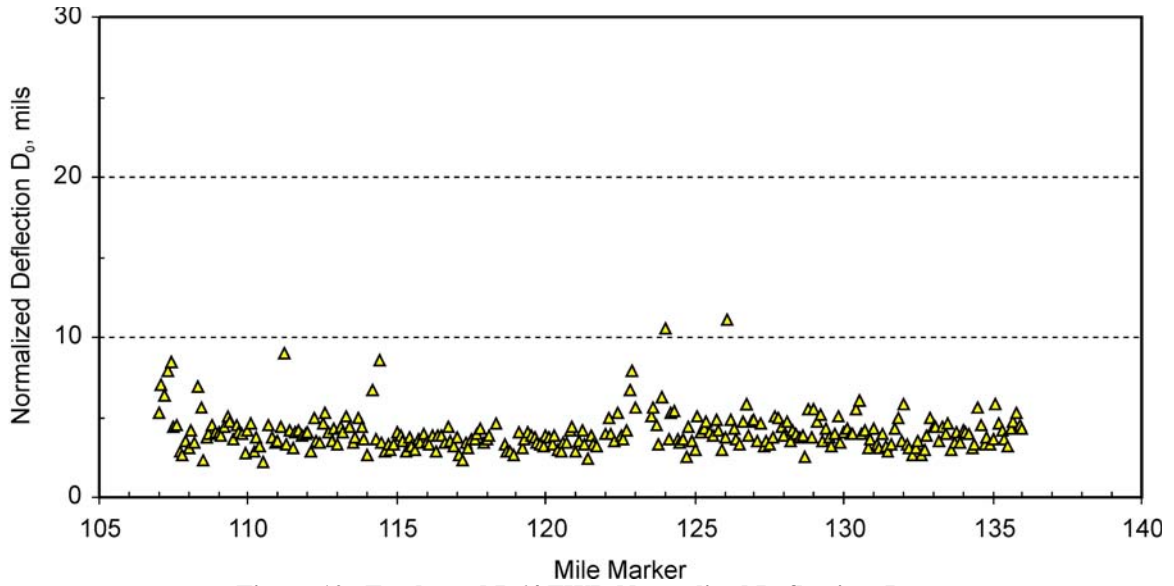


Figure 10. Eastbound I-64 FWD Normalized Deflection,  $D_0$

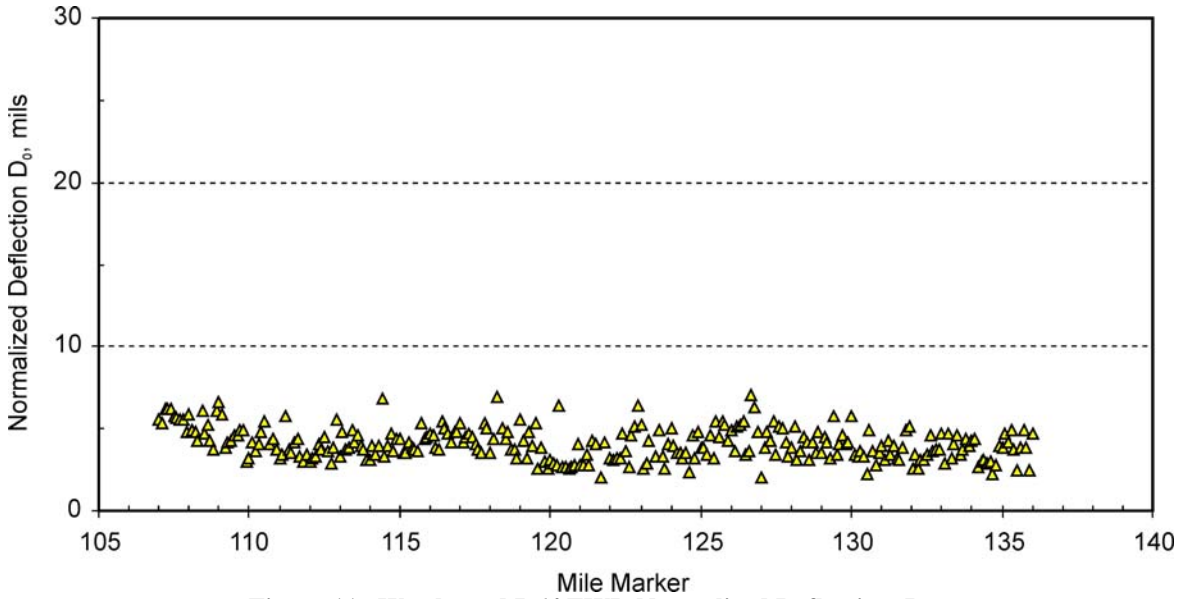


Figure 11. Westbound I-64 FWD Normalized Deflection,  $D_0$

and westbound directions, respectively. Based on visual observation, the majority of the deflections in the eastbound and westbound directions ranged from approximately 2 to 8 mils with periodic spikes (in the eastbound direction) approaching 12 mils. Table 6 summarizes the FWD deflection data for eastbound and westbound I-64.

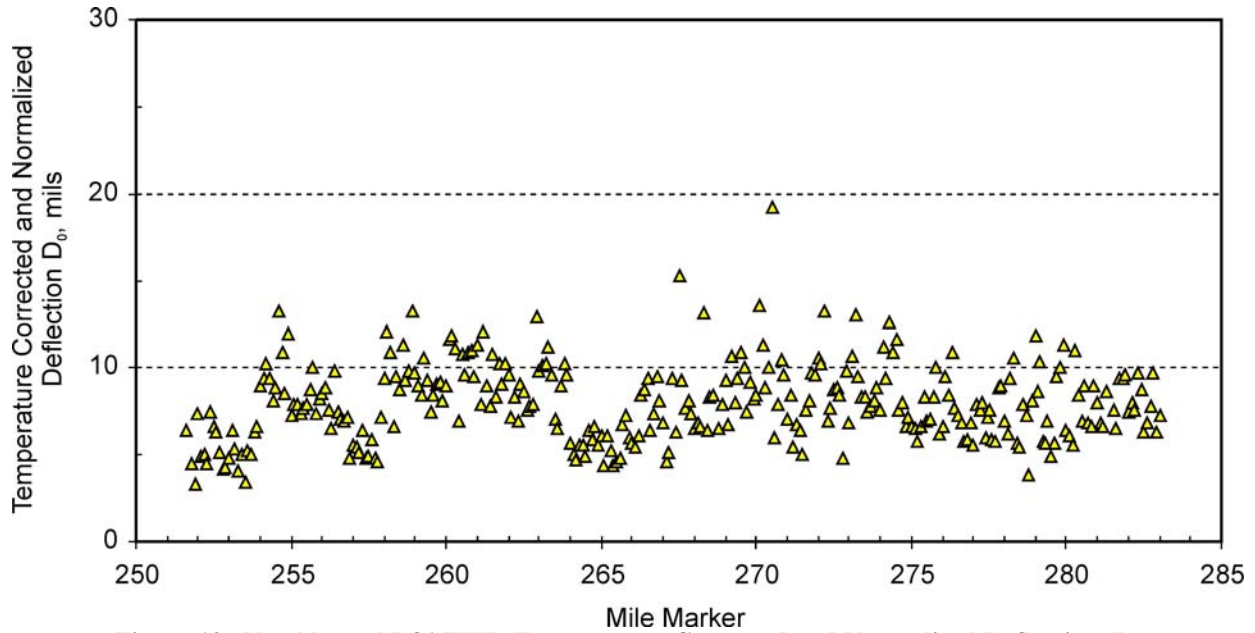
Table 6. FWD Deflection Results: Eastbound and Westbound I-64

Direction	No. of Observations	Average Deflection, $D_0$ (mils)	Deflection Standard Deviation (mils)
Eastbound	279	4.06	1.18
Westbound	286	4.09	0.98

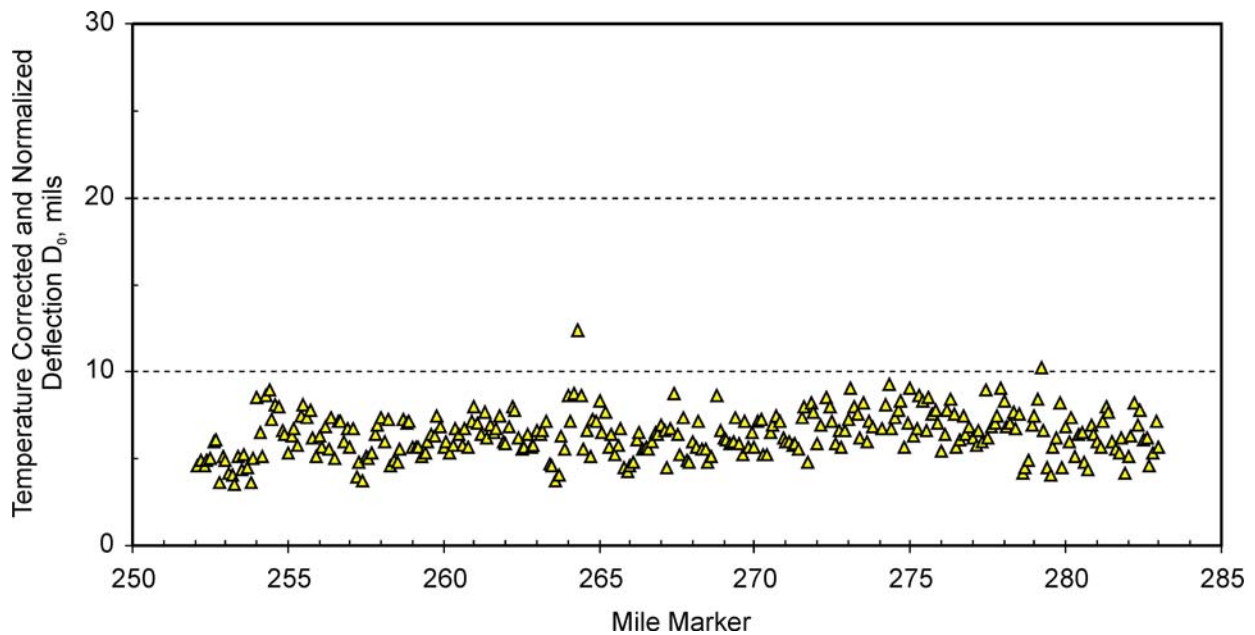
The deflection values are normalized to 9,000 lbf.

**Site 2: I-81**

Site 2 extends from Harrisonburg to Woodstock between mile markers 252 and 283, as shown in Figure 2. Figures 12 and 13 show the FWD temperature-corrected and normalized deflection  $D_0$  for the northbound and southbound directions, respectively. Based on visual observation, the majority of the deflections ranged from approximately 3 to 13 mils in the northbound direction and from 3 to 9 mils in the southbound direction. Table 7 summarizes the FWD deflection data for northbound and southbound I-81.



**Figure 12. Northbound I-81 FWD Temperature-Corrected and Normalized Deflection,  $D_0$**



**Figure 13. Southbound I-81 FWD Temperature-Corrected and Normalized Deflection,  $D_0$**

**Table 7. FWD Deflection Results: Northbound and Southbound I-81**

Direction	No. of Observations	Average Deflection, $D_0$ (mils)	Deflection Standard Deviation (mils)
Northbound	314	7.96	2.21
Southbound	307	6.40	1.28

The deflection values are temperature corrected and normalized to 9,000 lbf.

### Repeatability Analysis of RWD Results

Since the RWD testing was performed with multiple runs on each site (three replicates for Sites 1 and 2 and two replicates for Site 3), a statistical  $t$ -test was used to analyze the RWD data collected on repeated runs at the same site to determine if the populations of deflection data were likely from the same distribution (i.e., determine the repeatability of measuring the same pavement). Table 8 shows the results of the analysis. Testing was performed using non-paired data and assuming equal variances (following an  $F$ -test that confirmed this assumption). As a significance level of 0.05 was assumed in all cases, a  $p$ -value less than 0.05 indicates the means are not likely from the same distribution. From Table 8 it is seen that the results of 8 of the 15 tests were statistically similar. Table 8 also shows that the results were statistically similar for all three routes on the primary loop (Site 3), an area having a relatively higher deflection and greater variability.

**Table 8. Results of Statistical Testing of RWD Deflection Data**

Site No.	Direction	Comparison	$p$ -Value (two-tailed)	Result (Means likely from same distribution?)
1 (I-64)	Eastbound	Run 1 vs. Run 2	0.25	Yes
		Run 1 vs. Run 3	$6.21 \times 10^{-6}$	No
		Run 2 vs. Run 3	$9.52 \times 10^{-4}$	No
	Westbound	Run 1 vs. Run 2	$5.78 \times 10^{-5}$	No
		Run 1 vs. Run 3	0.12	Yes
		Run 2 vs. Run 3	0.03	No
2 (I-81)	Northbound	Run 1 vs. Run 2	0.17	Yes
		Run 1 vs. Run 3	0.23	Yes
		Run 2 vs. Run 3	0.87	Yes
	Southbound	Run 1 vs. Run 2	$6.18 \times 10^{-9}$	No
		Run 1 vs. Run 3	0.01	No
		Run 2 vs. Run 3	$1.07 \times 10^{-16}$	No
3 (U.S. 522)		Run 1 vs. Run 2	0.12	Yes
3 (U.S. 211)		Run 1 vs. Run 2	0.06	Yes
3 (U.S. 15/29)		Run 1 vs. Run 2	0.24	Yes

### Regression Analysis of RWD and FWD Results

As FWD testing is a commonly used tool to assess the structural capacity of pavements by measuring the deflection from an applied load, comparisons between the FWD and RWD results were performed. The RWD testing was performed continuously on each test site. The data were subdivided into 0.1-mi sections, and the data for each 0.1 mi were averaged (Tables 1

through 5 show the average number of observations per 0.1-mi section, ranging from approximately 11,700 to approximately 14,600). The FWD testing was performed by collecting one observation every 0.1 mi along the same test site. Therefore, each RWD data point represents a continuous deflection profile averaged every 0.1 mi and each FWD data point is a discrete measurement. Testing with both the FWD and RWD was performed on Sites 1 (I-64) and 2 (I-81).

### Regression Analysis: 0.1-Mile Interval

A regression analysis was performed to compare the results of the RWD and FWD testing. For this analysis, the output from the two devices at each test site was treated as paired data; any missing 0.1-mi observation from one device was removed from the corresponding observation obtained by the other device. Following this procedure, a linear regression was performed in an effort to define any relationship between the two devices. The FWD was considered as the reference device; thus, FWD data were considered the independent variable and RWD data the dependent variable. The respective devices used a distance measuring instrument to track their location from a common starting location. However, the researcher acknowledges that it is possible that any potential errors in position measurement could accumulate throughout each test run. Table 9 shows the results of the regression analysis including the slope and intercept values for a linear trend line (of the form  $y = mx + b$ ) and the adjusted coefficient of determination (adjusted  $R^2$ ).

As seen in Table 9, the data from the two devices were not well correlated at each test site. The Appendix shows additional figures including plots of the FWD-RWD paired data and the residuals with respect to mile marker. Although further investigation into the relationship between the residuals and mile marker may prove useful, this was not undertaken during this study. However, it did lead the researcher to perform an analysis by homogeneous surface interval.

**Table 9. Results of Regression Analysis Comparing RWD and FWD Deflection Data: 0.1-Mile Interval**

Site No.	Direction	Linear Regression Model Coefficients		Adjusted Coefficient of Determination ( $R^2$ )
		Slope (m)	intercept (b)	
1 (I-64)	Eastbound	0.0421	4.5945	0.0012
	Westbound	0.1763	4.2278	0.0122
2 (I-81)	Northbound	0.3619	5.4303	0.1287
	Southbound	0.2700	3.2241	0.0358

### Regression Analysis: Homogeneous Surface Interval

A second regression analysis was performed to compare the results of the RWD and FWD testing by averaging the deflection data from each device for each homogeneous surface (i.e., averaged by like surface mixture types). A similar comparison was performed by Gedafa et al. (2008) with the thought that a broader analysis would be more suitable for network-level testing. Table 10 shows the mile markers for the different mixture types at Sites 1 and 2.

**Table 10. Locations of Homogeneous Surface Mixture Types**

Site No.	Direction	Homogeneous Surface Mixture Segment	From Mile Marker	To Mile Marker
1 (I-64)	Eastbound	1	107.485	115.99
		2	115.99	118.471
		3	118.471	119.035
		4	119.035	126.705
		5	126.705	131.104
		6	131.104	135.93
		7	135.93	136.344
	Westbound	1	107.289	114.429
		2	114.429	119.05
		3	119.05	126.68
4		126.68	129.949	
5		129.949	136.366	
2 (I-81)	Northbound	1	249.63	254.1
		2	254.1	257.97
		3	257.97	263.4
		4	263.4	264.97
		5	264.97	266.12
		6	266.12	274.559
		7	274.559	275.909
		8	275.909	282.862
	Southbound	1	250.24	253.96
		2	253.96	258.04
		3	258.04	263.95
		4	263.95	273.51
		5	273.51	283.88

The linear regression analysis was repeated in an effort to define any relationship between the two devices when the data were averaged over a longer interval. Again, the FWD data were considered the independent variable, and the RWD data the dependent variable. Table 11 shows the results of the regression analysis including the slope and intercept values for a linear trend line (of the form  $y = mx + b$ ) and the adjusted coefficient of determination ( $R^2$ ). As seen in Table 11, the data from the two devices were not well correlated even when the data from each test site were averaged over a larger interval.

**Table 11. Results of Regression Analysis Comparing RWD and FWD Deflection Data: Homogeneous Surface Interval**

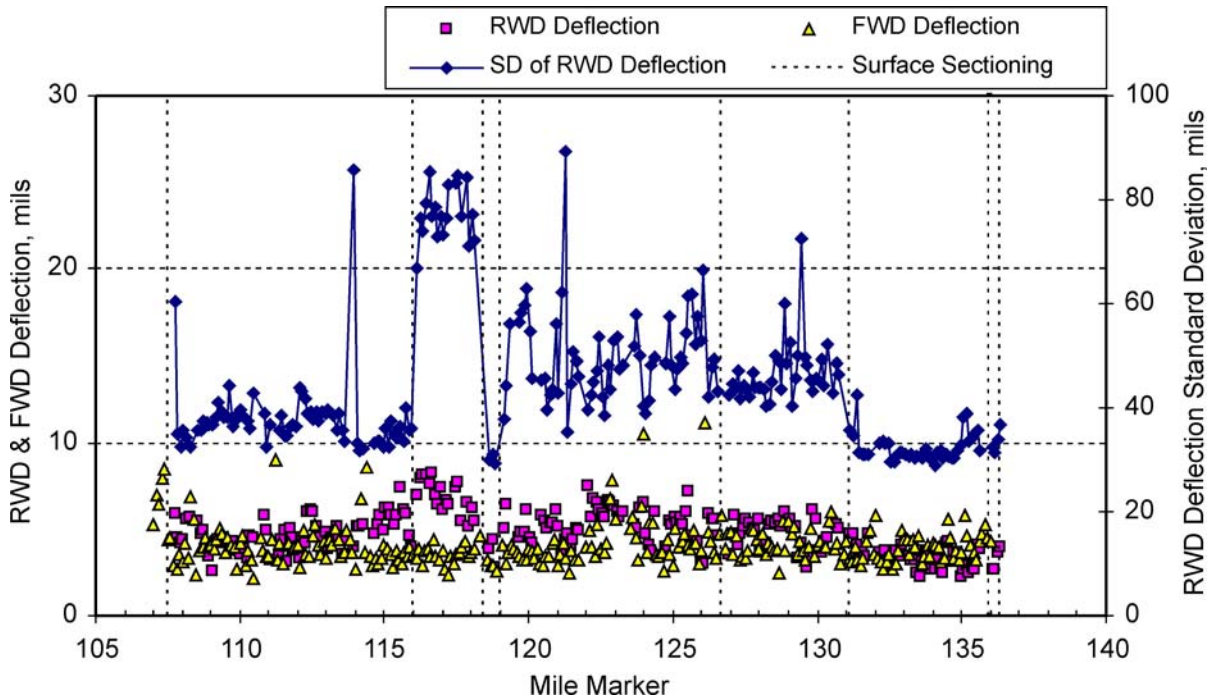
Site No.	Direction	Linear Regression Model Coefficients		Adjusted Coefficient of Determination ( $R^2$ )
		Slope (m)	Intercept (b)	
1 (I-64)	Eastbound	0.4551	3.0587	0.0324
	Westbound	-0.5587	7.2389	0.0131
2 (I-81)	Northbound	0.6025	3.2316	0.2199
	Southbound	-0.0704	5.4496	0.0025

### Comparison of RWD and FWD Results (With Respect to Mile Marker)

Following the regression analysis, the deflection output from the two devices was compared with respect to mile marker in an effort to determine if any other visually observable trends were evident. Figures 14 and 15 show the RWD (Pass 1) deflection and standard deviation of each 0.1-mi section, the FWD deflections, and the boundaries of different surface mixtures (from Table 10) at Site 1 (I-64) in the eastbound and westbound directions, respectively. The standard deviation of the RWD deflection varied with surface mixture type (changes in surface mixture type are shown as vertical dashed lines) at the locations tested.

Figures 16 and 17 show the RWD (Pass 1) deflection and standard deviation of each 0.1-mi section, the FWD deflections, and the boundaries of different surface mixtures (from Table 10) at Site 2 (I-81) in the northbound and southbound directions, respectively. The standard deviation of the RWD deflection varies with surface mixture type (changes in surface mixture type are shown as vertical dashed lines) at the locations tested.

Figures 14 through 17 show that the pavement surface mixture type appears to have an influence on the standard deviation of the RWD deflection. It is the researcher's opinion that this is likely through influence of the surface texture. This is especially evident in Figure 17: approximately between mile markers 264 and 271, the RWD reports a lower deflection as compared to the surrounding pavement and the FWD does not. In this same location, the standard deviation of the RWD deflection is much higher than that for the surrounding



**Figure 14. Eastbound I-64: RWD Pass 1 Deflection and Standard Deviation; FWD Deflection,  $D_0$ , and Surface Mixture Type Sectioning.** The standard deviation of the RWD deflection varied with surface mixture type (changes in surface mixture type are shown as vertical dashed lines) at the locations tested.

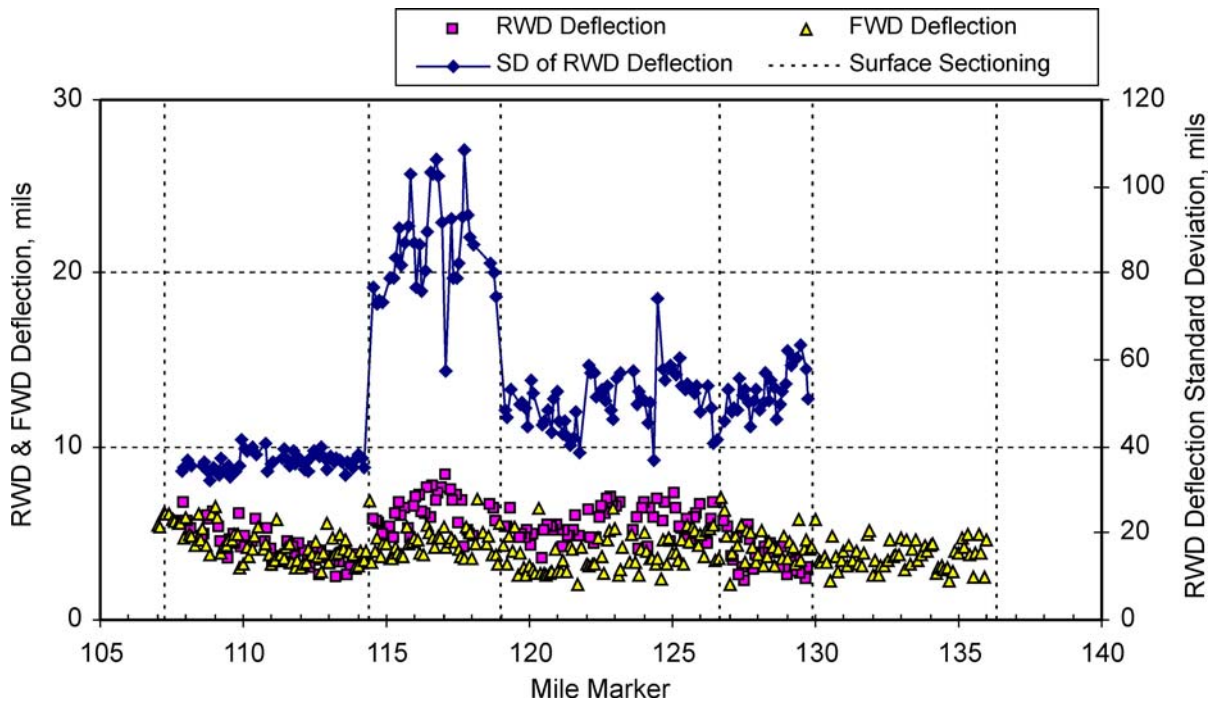


Figure 15. Westbound I-64: RWD Pass 1 Deflection and Standard Deviation; FWD Deflection,  $D_0$ , and Surface Mixture Type Sectioning. The standard deviation of the RWD deflection varied with surface mixture type (changes in surface mixture type are shown as vertical dashed lines) at the locations tested.

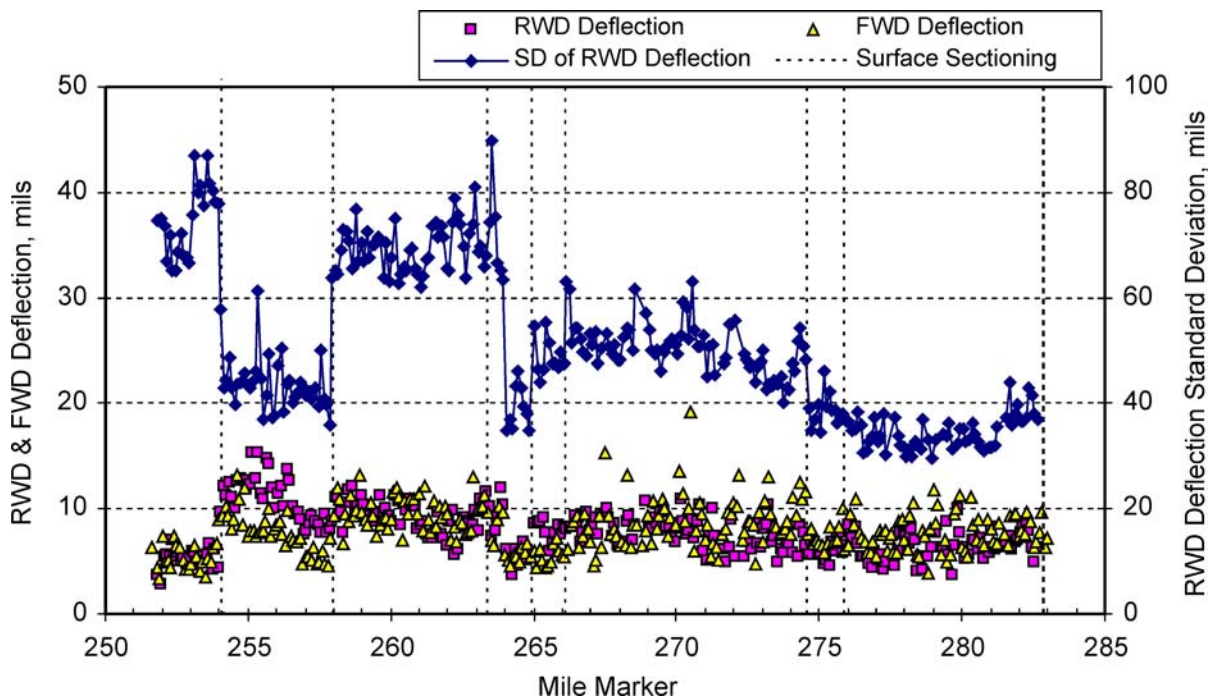


Figure 16. Northbound I-81: RWD Pass 1 Deflection and Standard Deviation; FWD Deflection,  $D_0$ , and Surface Mixture Type Sectioning. The standard deviation of the RWD deflection varies with surface mixture type (changes in surface mixture type are shown as vertical dashed lines) at the locations tested.



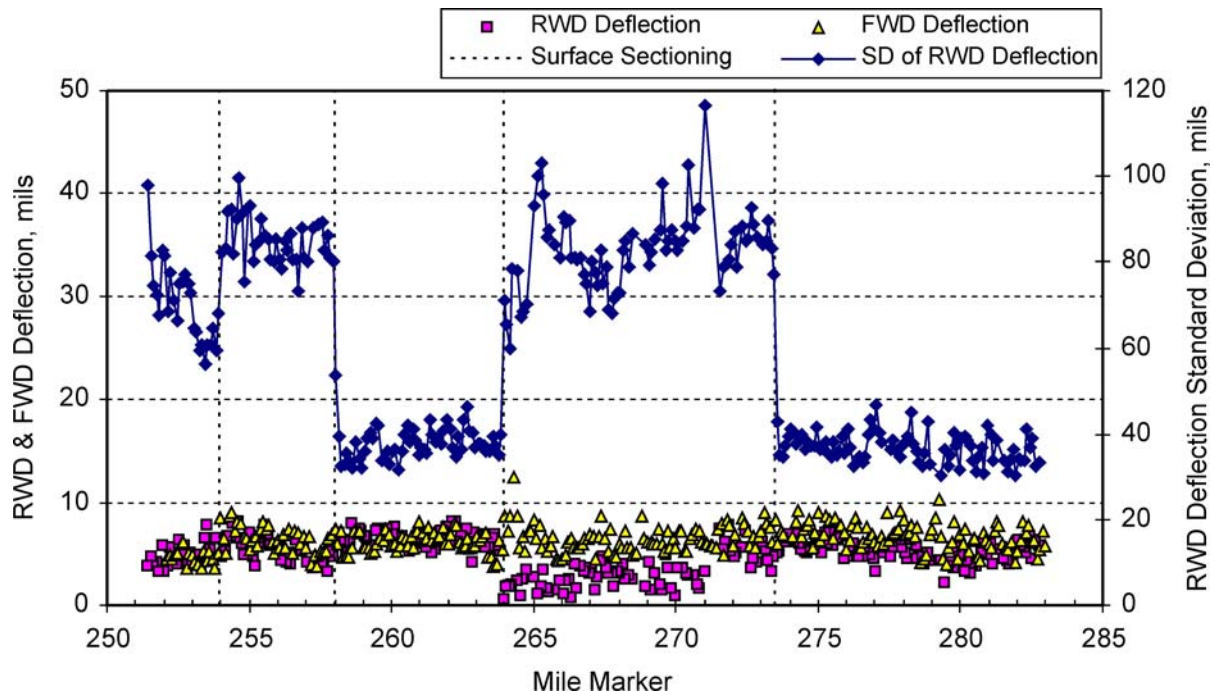


Figure 17. Southbound I-81: RWD Pass 1 Deflection and Standard Deviation; FWD Deflection,  $D_0$ , and Surface Mixture Type Sectioning. The standard deviation of the RWD deflection varies with surface mixture type (changes in surface mixture type are shown as vertical dashed lines) at the locations tested.

pavement. The surface mixture tested ranged from Marshall-era and SuperPave-era dense-graded mixtures to gap-graded SMA mixtures. However, the researcher could not discern any consistent trend with regard to standard deviation and mixture type. Intuitively, a higher standard deviation could tend to indicate a coarse surface texture and lower values could indicate a smooth surface texture. Therefore, it is suggested that the RWD-measured deflections are actually composed of two components: *deflection and surface texture*.

## SUMMARY OF FINDINGS

- The RWD was able to test long pavement distances at or near highway speeds with minimal interruption to the highway users.
- The RWD deflection results were repeated two or three times on each site. In 8 of 15 instances, the repeated measurements were statistically similar.
- The range of RWD and FWD deflection values was similar.
- The RWD and FWD deflection results were not well correlated, with adjusted  $R^2$  values ranging from 0.0012 to 0.1287 when a 0.1-mi interval was considered.
- The RWD and FWD deflection results were not well correlated, with adjusted  $R^2$  values ranging from 0.0025 to 0.2199 when the data by similar surface mixture type were averaged.

- Comparison between RWD and FWD deflection results with respect to mile marker shows that the standard deviation of RWD deflections at each 0.1-mi section fluctuates at changes in surface mixture type.

### **STUDY LIMITATIONS**

- Potential influences from seasonal variability on RWD and FWD deflection readings (given they were conducted approximately 5 months apart) were not considered.
- Potential texture effects on RWD deflection readings were briefly discussed but not considered further.
- The potential physical differences in load pulse applied to the pavement by the two devices were not considered.
- The regression analysis was performed by comparing a single data point collected every 0.1 mi from the FWD to an average of approximately 12,000 data points per 0.1 mi from the RWD.

### **CONCLUSIONS**

- The RWD deflection results were statistically different when repeated on certain sites. Thus, RWD deflection measurements are not always repeatable for some pavement structural sections.
- As the RWD and FWD results were not well correlated on the sites tested, the RWD is not a suitable tool with which to pre-screen the pavement network prior to traditional FWD deflection testing. This conclusion is based on companion FWD testing on interstate pavements.
- The RWD deflection results were influenced by surface mixture type in that the standard deviation of 0.1-mi deflections varied with changes in the surface mixture type.

### **RECOMMENDATIONS**

1. *VDOT's Maintenance Division and Materials Divisions should continue to use FWD deflection testing to characterize structurally the pavement network.* The results of this research study indicate that the version of the RWD studied is not a suitable tool with which to pre-screen the pavement network given the type of pavements (interstate facilities) tested during this study. However, a recent study by Gedafa et al. (2008) on non-interstate pavements showed a better correlation between FWD and RWD results than was found in this study.

2. *The Virginia Transportation Research Council should test pavements having a wider range of deflection values than were incorporated in this study during any future studies of pavement deflection equipment.* A recently completed FWD network survey of Virginia's interstate system (Diefenderfer, 2008) could be used to identify areas of interstate pavement having both high- and low-deflecting areas. These results were not considered in this study as they were not yet available at the inception of this study.
3. *The Virginia Transportation Research Council should consider the duration of the load pulse on the resulting deflection measurements during any future study of pavement deflection equipment.* This potential phenomenon was not considered in this study, and it is unclear at this time what the effects, if any, would be on the pavements considered in this study.
4. *The Virginia Transportation Research Council should continue following RWD studies performed by other state DOTs.* At the time this report was completed, the Louisiana Transportation Research Council was conducting a similar evaluation with an RWD equipped with an upgraded laser system (M. Elseifi, personal communication).

## **BENEFITS AND IMPLEMENTATION PROSPECTS**

This study does not recommend implementing deflection testing using the RWD on low-deflecting pavements similar to those tested in this study by both the RWD and FWD. It is hoped that future devices will offer a means of rapidly testing the structural capacity on a continuous basis with minimal interference to the traveling public. However, other recently completed work (Gedafa et al., 2008) shows more promise for RWD deflection testing on non-interstate pavements. In addition, future equipment upgrades to the RWD may improve correlations with traditionally used deflection testing equipment.

## **ACKNOWLEDGMENTS**

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## **REFERENCES**

American Association of State Highway and Transportation Officials. (1993). *Guide for Design of Pavement Structures*. Washington, DC.

- Diefenderfer, B.K. (2008). *Network-Level Pavement Evaluation of Virginia's Interstate System Using the Falling Weight Deflectometer*. VTRC 08-R18. Virginia Transportation Research Council, Charlottesville.
- Galal, K.A., Diefenderfer, B.K., and Alam, J. (2007). *Determination by the Falling Weight Deflectometer of the In-Situ Subgrade Resilient Modulus and Effective Structural Number for I-77 in Virginia*. VTRC 07-R1. Virginia Transportation Research Council, Charlottesville.
- Gedafa, D.S., Hossain, M., Miller, R., and Steele, D.A. (2008). Network Level Pavement Structural Evaluation Using Rolling Wheel Deflectometer. Paper presented at the 87th Annual Meeting of the Transportation Research Board, Washington, DC.
- Hossain, M., Chowdhury, T., Chitrapu, S., and Gisi, A.J. (2000). Network-Level Pavement Deflection Testing and Structural Evaluation. *Journal of Testing and Evaluation*, Vol. 28, pp. 199-206.
- Noureldin, S., Zhu, K., Li, S., and Harris, D. (2003). Network Pavement Evaluation with Falling-Weight Deflectometer and Ground-Penetrating Radar. In *Transportation Research Record: Journal of the Transportation Research Board*, No. 1860. Transportation Research Board of the National Academies, Washington, DC, pp. 90-99.
- Steele, D.A. (2005). *Final Report for Rolling Wheel Deflectometer (RWD) Demonstration for the Indiana Department of Transportation*. ARA Project No. 16860/1. Applied Research Associates, Champaign, IL.
- Steele, D.A., and Hall, J.W. (2005). *Final Report for Rolling Wheel Deflectometer (RWD) Demonstration and Comparison to Other Devices in Texas*. ARA Project No. 15874. Applied Research Associates, Champaign, IL.
- Steele, D.A., and Vavrik, W.R. (2006). *Rolling Wheel Deflectometer (RWD) Results for the Virginia Department of Transportation*. ARA Project No. 16860/4. Applied Research Associates, Champaign, IL.
- Zaghloul, S.M., He, Z., Vitillo, N., and Kerr, J.B. (1998). Project Scoping Using Falling Weight Deflectometer Testing: New Jersey Experience. In *Transportation Research Record: Journal of the Transportation Research Board*, No. 1643. Transportation Research Board of the National Academies, Washington, DC, pp. 34-43.
- Zhang, Z., Claros, G., Manual, L., and Damnjanovic, I. (2003). Evaluation of the Pavement Structural Condition at Network Level Using Falling Weight Deflectometer (FWD) Data. Paper presented at the 82nd Annual Meeting of the Transportation Research Board, Washington, DC.



## APPENDIX

### REGRESSION ANALYSIS OF RWD AND FWD DEFLECTION OUTPUT

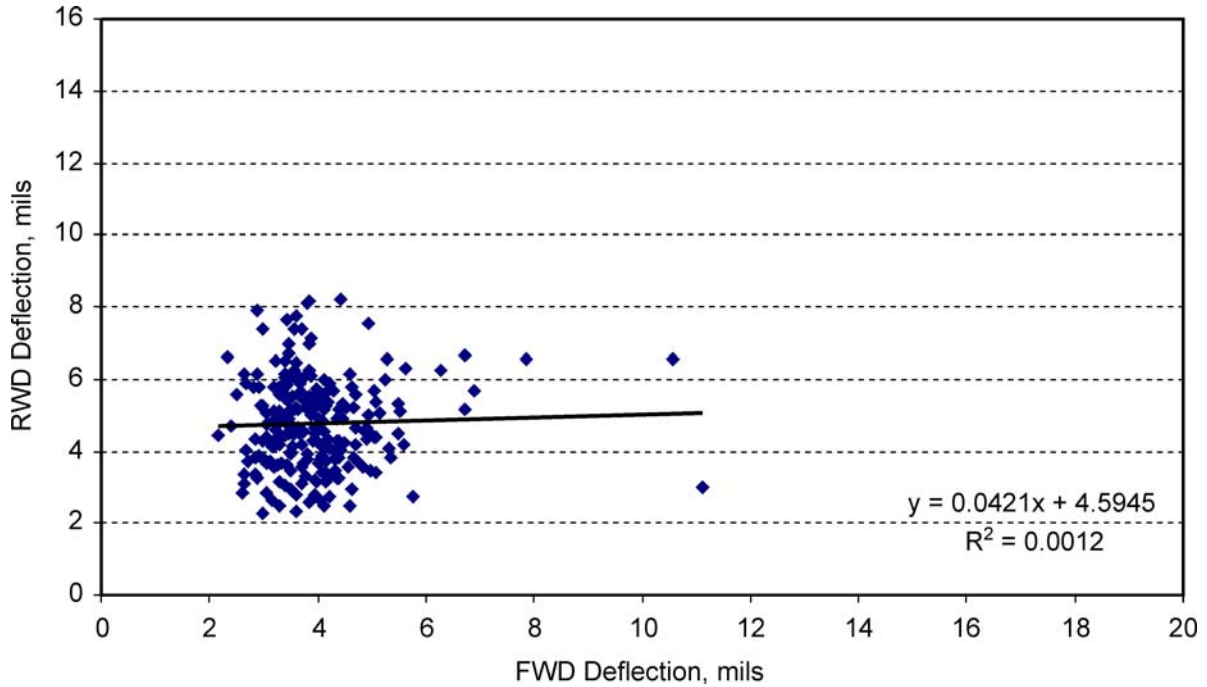


Figure A1. Eastbound I-64 regression analysis comparing FWD versus RWD deflection output.

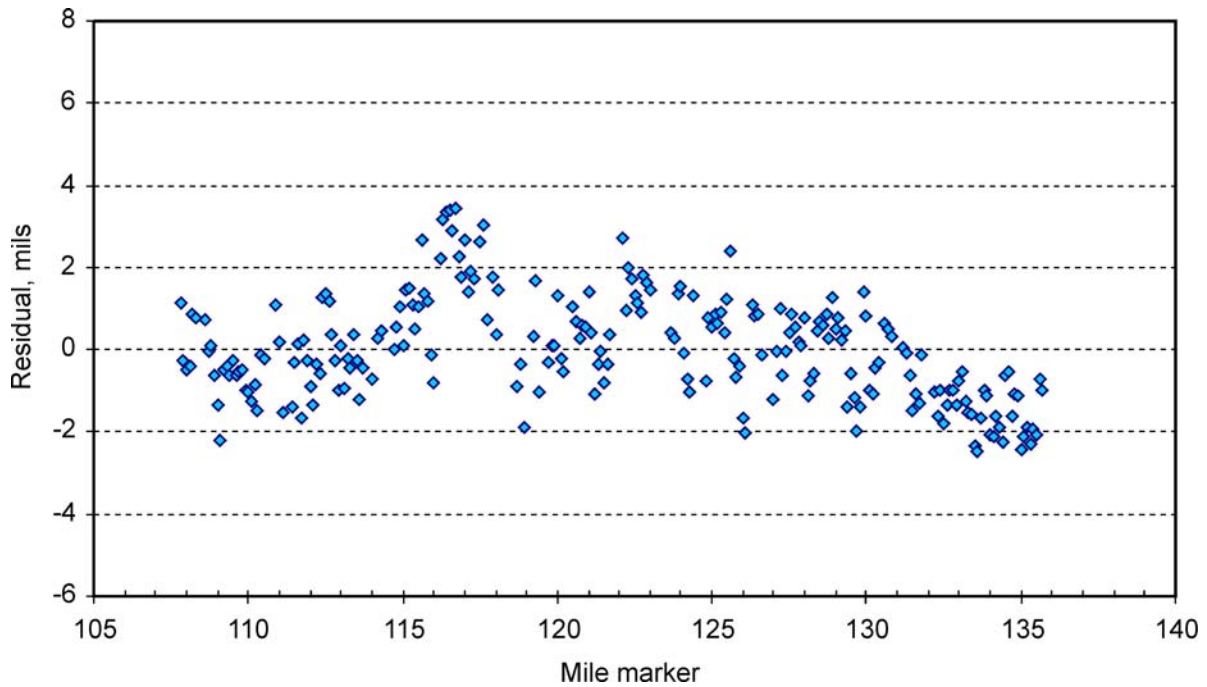


Figure A2. Eastbound I-64 residuals (with respect to mile marker) from regression analysis comparing FWD versus RWD deflection output.

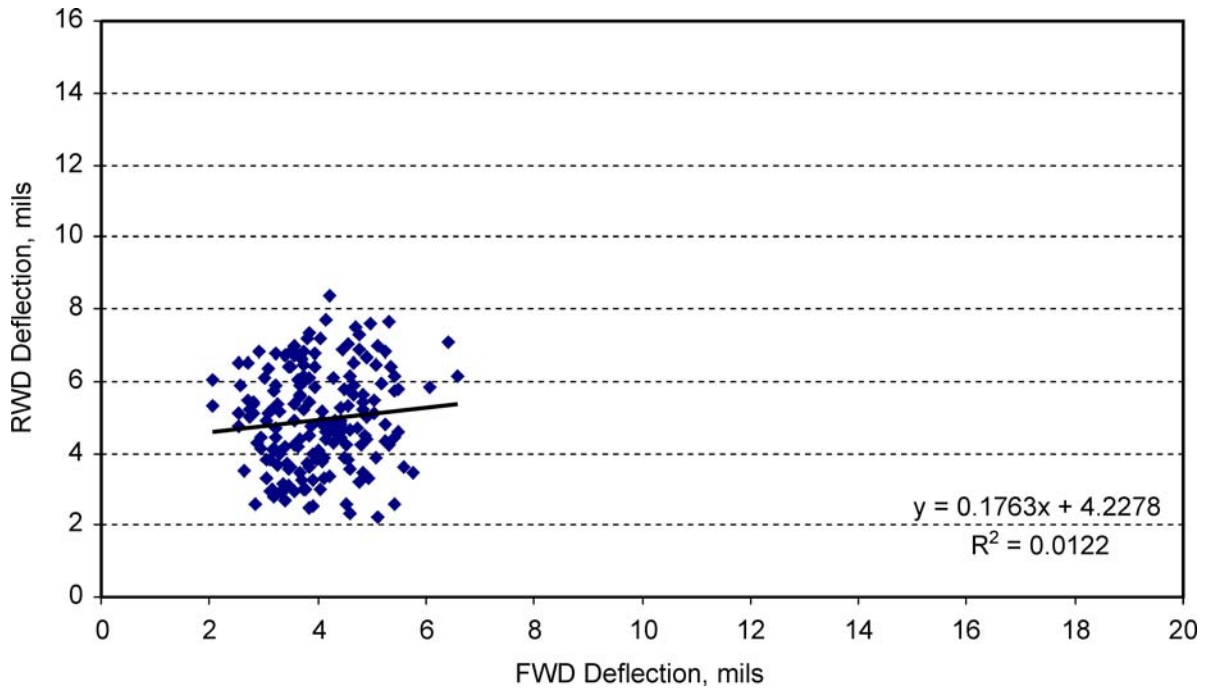


Figure A3. Westbound I-64 regression analysis comparing FWD versus RWD deflection output.

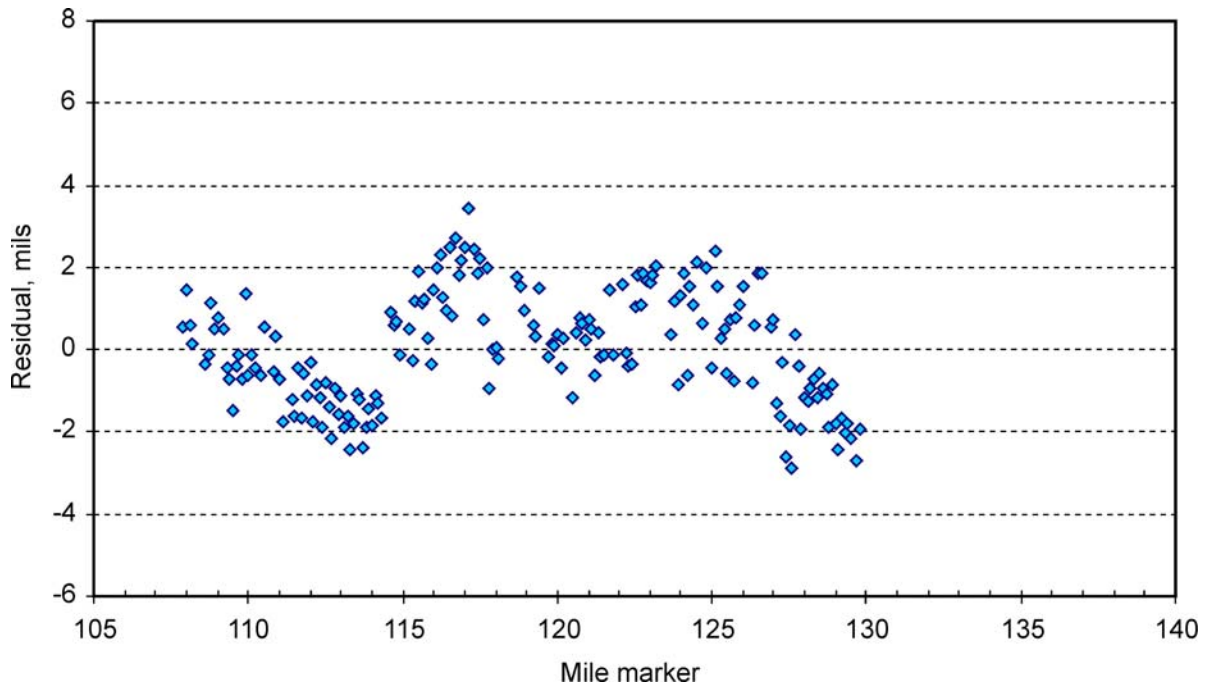


Figure A4. Westbound I-64 residuals (with respect to mile marker) from regression analysis comparing FWD versus RWD deflection output.

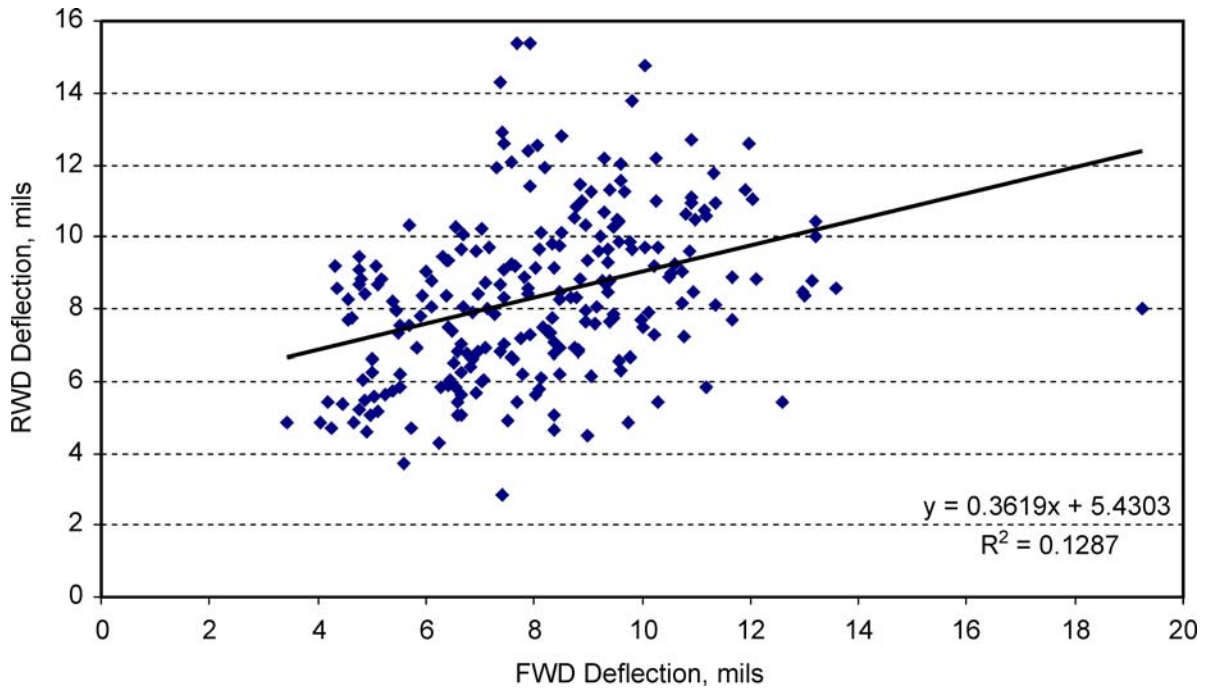


Figure A5. Northbound I-81 regression analysis comparing FWD versus RWD deflection output.

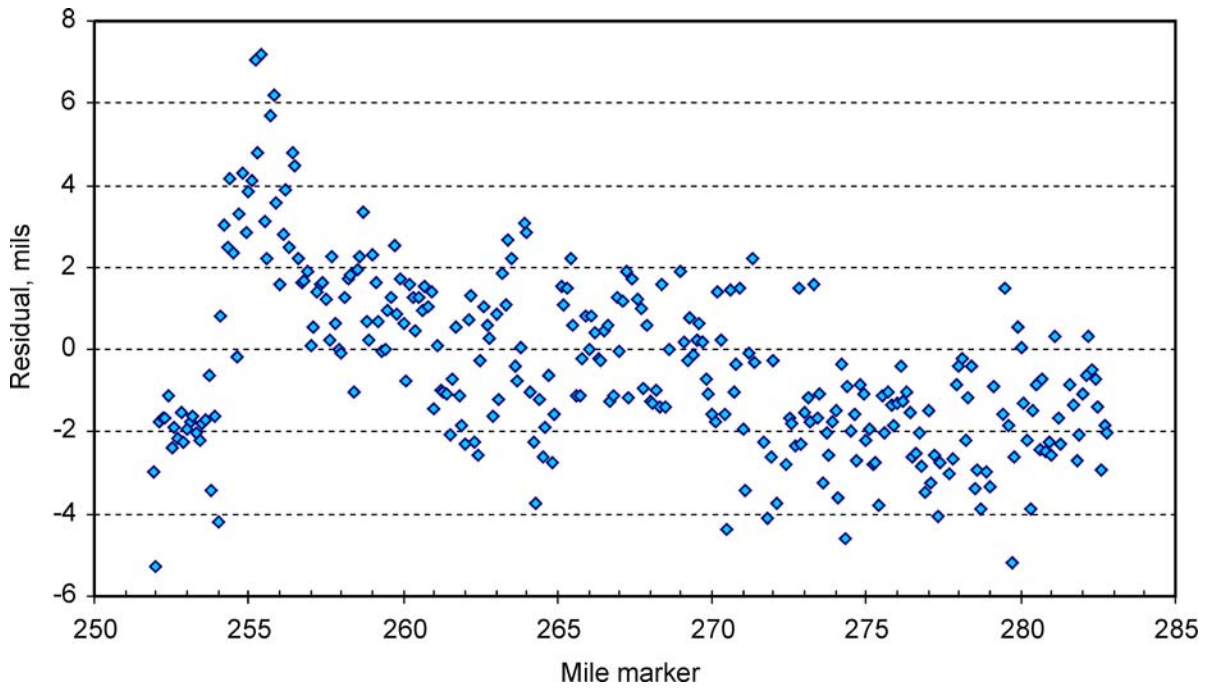


Figure A6. Northbound I-81 residuals (with respect to mile marker) from regression analysis comparing FWD versus RWD deflection output.



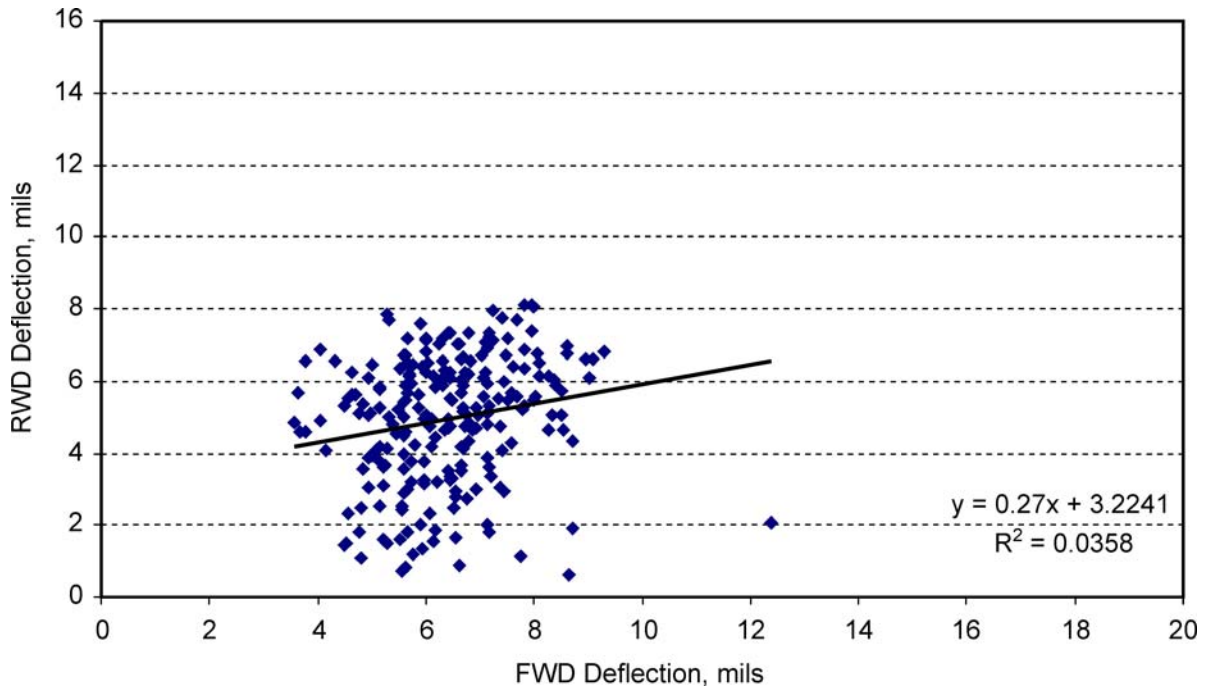


Figure A7. Southbound I-81 regression analysis comparing FWD versus RWD deflection output.

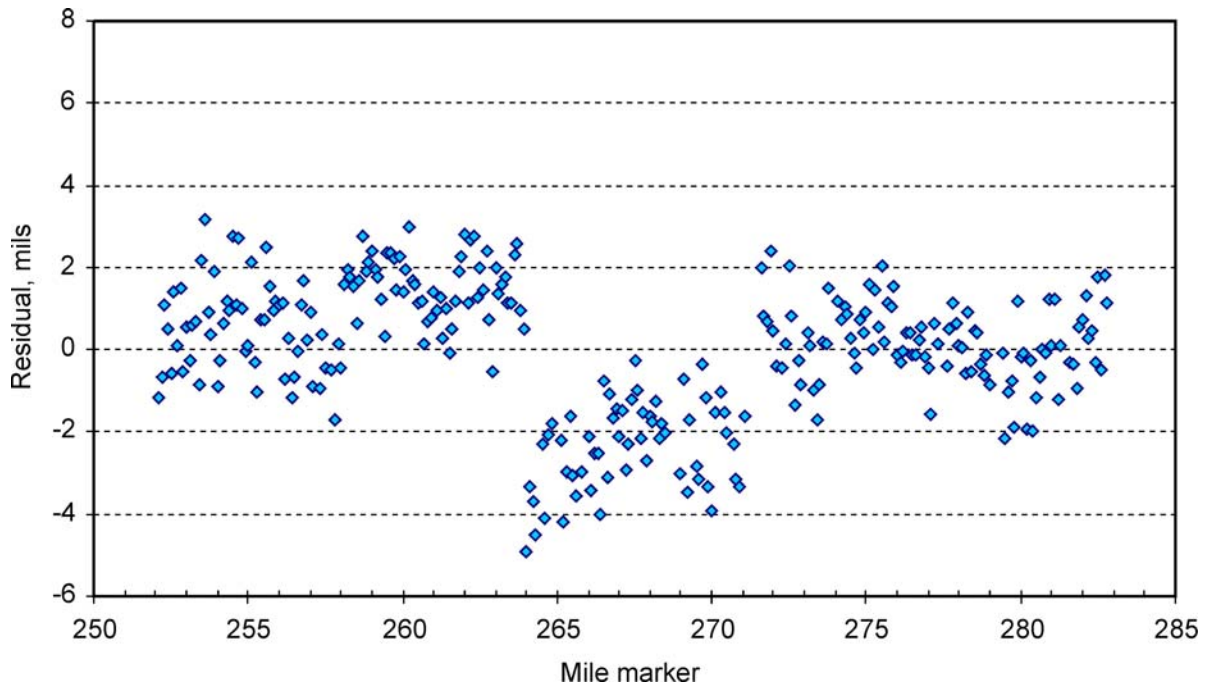


Figure A8. Southbound I-81 residuals (with respect to mile marker) from regression analysis comparing FWD versus RWD deflection output.