Research Record

Pilot Study - Rolling Wheel Deflectometer, Falling Weight Deflectometer, and Ground Penetrating Radar on New Hampshire Roadways

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16. Abstract

The New Hampshire Department of Transportation Pavement Management Section's scope of work includes monitoring, evaluating, and sometimes forecasting the condition of New Hampshire's 4,560 miles of roadway network in order to provide guidance on rehabilitation or preservation treatments. Pavement Management monitors rutting, cracking, ride quality, and several other road and pavement parameters using a 2009 PathRunner XP Model LG-23 road and pavement condition data collection vehicle.

Supplemental methods to evaluate pavement structural capacity would enhance Pavement Management's ability to forecast pavement performance. This project evaluated non-destructive testing methods to evaluate pavement thickness and deflection information by means of ground penetrating radar (GPR) and rolling wheel deflectometer (RWD) testing respectively.

The GPR testing covered 115 miles and resulted with substantial variations in pavement thicknesses ranging from 4.0 to 12.0 inches. These predictions, when correlated with data from 35 ground cores, show an average accuracy of 6.5%. Although an initial purchase of a GPR system is costly, once in place, this testing is expected to cost $140 per lane mile compared to the cost of pavement core sampling at $10,000 per lane mile.

The RWD test routes totaled 650 lane miles. Average deflections ranged from 6.4 to 19.2 mils and representative deflections ranged from 9.2 to 22.4 mils. Falling weight deflectometer (FWD) deflections were similar RWD deflections with the best average and representative deflection correlations occurring at an FWD load plate pressure of 110 psi. RWD advantages over FWD include continuous pavement deflection profiles, no significant disruption of traffic, and $5,700 savings per lane mile.

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PILOT STUDY – ROLLING WHEEL DEFLECTOMETER, FALLING WEIGHT DEFLECTOMETER, AND GROUND PENETRATING RADAR ON NEW HAMPSHIRE ROADWAYS

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ACKNOWLEDGEMENTS

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EXECUTIVE SUMMARY

The New Hampshire Department of Transportation Pavement Management Section's scope of work includes monitoring, evaluating, and sometimes forecasting the condition of New Hampshire's 4,560 miles of roadway network in order to provide guidance on rehabilitation or preservation treatments. Pavement Management monitors rutting, cracking, ride quality, and several other road and pavement parameters using a 2009 PathRunner XP Model LG-23 road and pavement condition data collection vehicle.

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BACKGROUND

The NHDOT is responsible for maintaining a network of approximately 4,560 miles of interstates, highways, and local roadways throughout the state of New Hampshire. The vast majorities of these roadways were originally constructed and traditionally rehabilitated using flexible pavements. Rigid pavements exist in some sections of New Hampshire's roadways however most of them were rehabilitated or removed and replaced entirely with flexible pavements. Pavement preservation treatments are gaining acceptance in favor of traditional, more costly pavement overlay treatments.

The Pavement Management Section (PM) of the NHDOT Bureau of Materials & Research (M&R) was created in 2005 to provide project level pavement engineering support to the Bureau of Highway Design. Flexible pavement treatments are typically evaluated using AASHTO 1972 methods. The AASHTO 1972 methods rely in part on average annual daily traffic forecasts and estimates of equivalent single axle loads provided by the Bureau of Traffic. PM adopts a 20-year design life for most projects. The Geotechnical Section performs pavement core and base course sampling to support PM's design recommendations. Mechanistic-Empirical Pavement Design Guide methods have not been implemented because they are in early stages of local calibration.

Since its inception, PM's scope of work has expanded to include monitoring, evaluating, and sometimes forecasting the condition of New Hampshire's roadway network to provide guidance to the Commissioner's Office. PM monitors the condition of the network by collecting roadway information using a 2009 PathRunner XP Model LG-23 road and pavement condition data collection vehicle. PM collected road and pavement conditions from approximately 2,200 miles (51%) of the network between April and December 2010 as weather conditions permitted. PM monitors rutting, cracking, ride quality, and several other road and pavement parameters. PM also captures video images of the roadway, right-of-way, pavement surface, and roadside assets such as guardrail and signage. Among other things, proprietary software can identify cracks as small as 0.08 inches in the pavement surface using high-resolution imagery from the data collection vehicle. This information is used to evaluate existing roadway conditions; roadway condition changes are sometimes used for forecasting purposes.

Evaluating existing conditions and forecasting pavement distress from fatigue cracking information is expected to be useful on roadways where "top-down" cracking occurs. Top-down cracking typically occurs in pavement sections that are thicker than about 6 inches (e.g. interstates and highways). Top-down cracking begins at the pavement surface where stresses from tire/pavement interaction and asphalt binder weathering are greatest and propagates toward the bottom of the pavement section. Early detection of top-down cracking provides the opportunity to implement preventative maintenance treatments before pavement distress severity requires more comprehensive rehabilitation treatments.

"Bottom-up" cracking generally occurs where pavement thicknesses are thinner than about 6 inches (e.g. local roadways). Bottom-up cracking begins at the bottom of the pavement section, where stresses from traffic loading are greatest, and propagates toward the top of the pavement layer. By the time bottom-up cracking propagates to the surface, the pavement section could require total replacement. Interpretation of pavement deflection information could be useful in evaluating the structural capacity of pavement sections where cracking is not apparent.

Supplemental methods to evaluate pavement structural capacity would enhance PM's ability to forecast pavement performance. M&R's Research Section initiated this investigation to evaluate

non-destructive testing methods for efficiently obtaining pavement thickness and deflection information on the 4,560-mile network of interstates, highways, and roadways in New Hampshire.

OBJECTIVES

The objectives of this investigation were as follows:

1) Compare pavement thicknesses estimated from vehicle-mounted ground penetrating radar testing to pavement core samples collected at select highway locations.

2) Compare pavement deflection results from falling weight deflectometer and rolling wheel deflectometer testing of select highway sections.

GROUND PENETRATING RADAR (GPR) TESTING

Infrasense, Inc. of Arlington, Massachusetts performed GPR testing on May 8, 2007 under Special Statewide Geotechnical Consulting Agreement No. 5 with GEI Consultants, Inc. of Woburn, Massachusetts. Infrasense utilized a SIR-20 GPR system attached to a 1 GHz horn antenna mounted to the rear bumper of a Chevrolet sport/utility vehicle over the right wheelpath. A distance measuring instrument was attached to the vehicle's right rear wheel to actuate GPR scanning at a rate of once per foot of travel while traveling at normal highway driving speeds. The GPR technician manually entered milepost information en-route.

GPR testing was performed in the travel lane of I-93 NB between approximate mileposts 17.4 and 131.4. Pavement thickness measurements were averaged over 528 foot long (0.10 mile) sections and ranged from about 4 to 17 inches. At some locations, the GPR scans detected changes in the pavement section, which were interpreted to be individual pavement layer interfaces. On occasion, GPR scans also detected changes in the materials beneath the pavement, which were interpreted to be base course and natural subgrade material interfaces. The GPR test route is shown on Figure 1. Infrasense's summary report dated July 12, 2007 is provided in Appendix A.

Infrasense's cost estimates for GPR testing consisted of $1,300 for mobilization, $2,000 for equipment, field technicians, and data collection, $125 per lane mile for engineering and reporting. The total cost of the project was approximately $18,000.

PAVEMENT CORE SAMPLING

The Geotechnical Section collected pavement core samples at various locations throughout the state between April 12, 2005 and June 14, 2010. These samples were used to evaluate pavement treatment options for project work during that period. Roadway base course materials were sampled at some locations using an oversized split barrel sampler (3 inch ID). NHDOT Standard Specifications for Road and Bridge Construction, in effect during that period required, most base course materials to pass the 3 inch sieve. The oversized sampler was generally more successful collecting the required amount of material for laboratory testing. The fieldwork typically required traffic control. This was most often provided by NHDOT Bureau of Highway Maintenance district forces. M&R's Material Testing Section classified pavement core samples and determined grain size distributions of the base course samples. Core samples were collected from 340 interstate and highway locations throughout the state between April 12, 2005 and June 14, 2010 as shown on Figure 1.

Figure 1: GPR test route and pavement core sample locations

Sixty-six of these core samples were collected from various I-93 NB locations as outlined below:

I-95 NB Mileposts	Town(s)	Cores and Sampling Date	Section(s) resurfaced before GPR testing	Section(s) resurfaced after GPR testing
21.6 to 26.2	Manchester-Hooksett	6 (02/11/2009)	21.0 to 21.9 (1999) 21.9 to 25.3 (1998) 25.3 to 26.1 (1970's)	25.3 to 26.1 (2010)*
40.4 to 46.4	Concord-Boscawen	8 (04/12/2005)** 3 (05/28/2008)**	44.0 to 48.4 (2006)	41.0 to 44.0 (2009)
53.2 to 68.4	Northfield-Sanbornton	3 (05/28/2008) 2 (08/06/2008) 9 (02/04,11/2009)	54.3 to 56.7 (1991) 61.0 to 68.8 (1995)	48.4 to 54.3 (2008) 61.0 to 68.8 (2010)
95.4 to 101.1	Woodstock	5 (09/09/2008) 25 (04/12/2010)	95.3 to 101.1 (2004)	95.1 to 101.1 (2009)*
112.7 to 131.8	Bethlehem-Littleton	5 (06/26/2007)	112.7 to 123.9 (1991) 123.9 to 131.8 (2003)	None

*Roadway section under construction at the time this report was prepared.
**Pavement core samples collected before placement of current pavement treatment.

NHDOT's in-house cost for performing pavement core and base course sampling was estimated to be about $4,000 per day with an estimated production rate between 10 and 20 cores per day. Production rates could vary greatly depending upon test location proximity and favorable weather conditions.

FALLING WEIGHT DEFLECTOMETER (FWD) TESTING

The PM Section performed FWD testing between May 28 and June 24, 2008. The FWD apparatus consisted of a trailer-mounted Dynatest 8000 towed behind a modified Ford diesel-powered support van. The Pavement Management Research Laboratory at Worcester Polytechnic Institute in Worcester, Massachusetts provided the FWD apparatus to the Research Section for the fieldwork at minimal cost.

FWD testing simulated traffic loading by dropping a series of weights onto a load plate placed directly on the pavement surface. Weight and drop heights were varied resulting in load plate pressures from 55 to 146 pounds per square inch (psi). Pavement deflections were measured by an array of electro-mechanical extensometers attached to a metal beam suspended underneath the trailer just in front load plate. The load plate and extensometer beam could be retracted into the trailer chassis between test locations. Pavement deflections at five wheelpath and five center-of-lane locations spaced about 10 feet apart were measured at set intervals from the load plate in the direction of travel at each load plate pressure. FWD testing could not be performed while the apparatus was in motion; therefore, traffic control was required to perform the fieldwork. FWD test locations are shown on Figure 2.
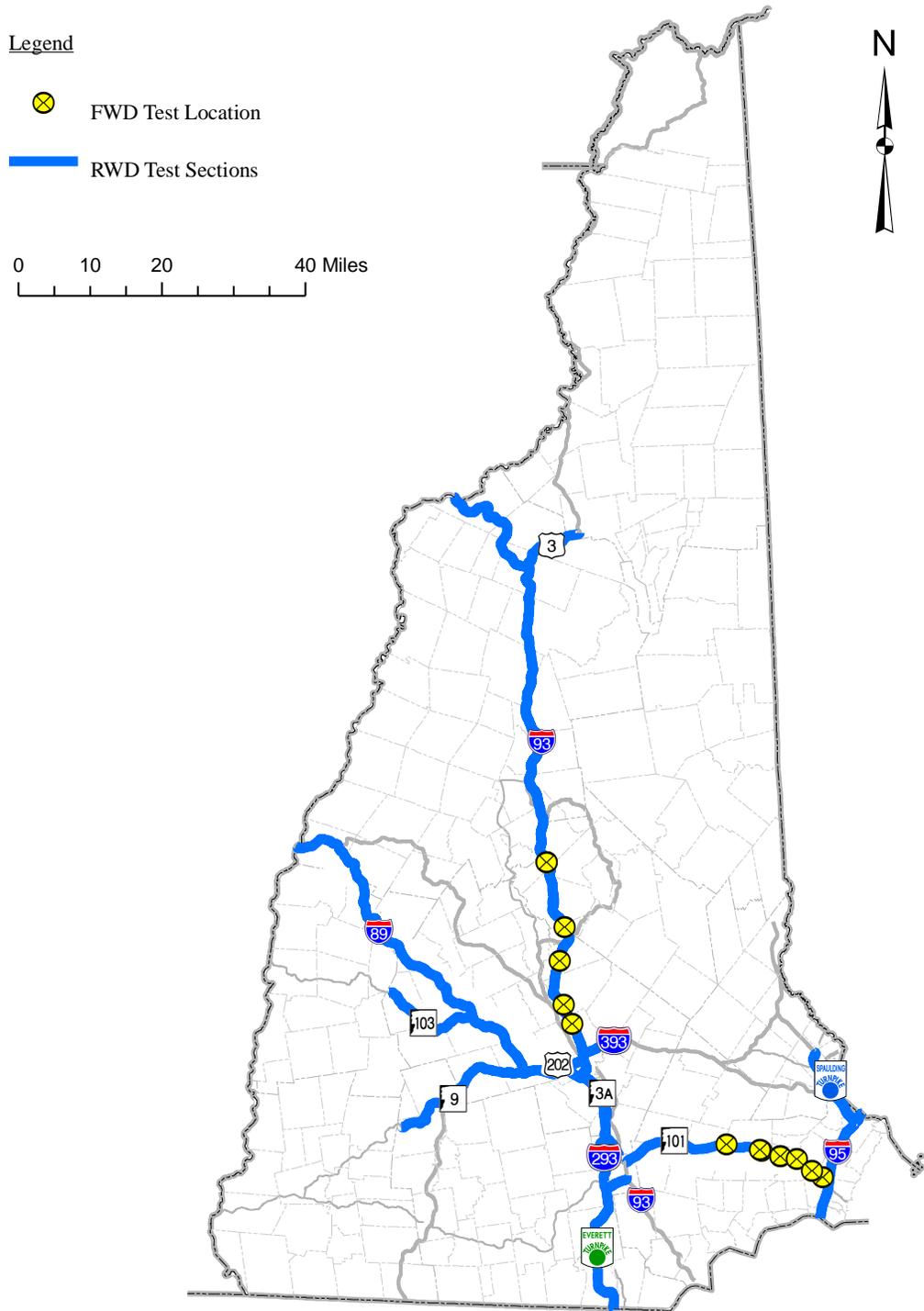
Figure 2: RWD test routes and FWD test locations

Pavement deflections were measured in thousandths of an inch (mil). One mil is 0.001 inches, approximately one-fourth the diameter of a human hair. Pavement deflections were averaged (δ_{aveFWD}) over 100 foot long (0.02 mile) sections and normalized to a standard temperature of 68°F for each load plate pressures. Representative deflections (δ_{repFWD}) for each of the test

locations were determined using a value equivalent to the average deflection plus two standard deviations (σ). Average deflections, standard deviations, and representative deflections for each test location are outlined below:

Highway	Travel Way	Passing Lane	Milepost(s)	Load plate pressures 85 to 146 psi		
				δ_{aveFWD} (mils)	σ (mils)	δ_{repFWD} (mils)
I-93 NB	Yes	Yes	40.5	9.3 - 14.2	0.6 - 0.7	10.4 - 15.6
			46.4	9.8 - 15.3	0.9 - 1.1	11.5 - 17.5
			53.3	8.5 - 13.4	0.4 - 0.7	9.3 - 14.7
			58.5	9.3 - 15.0	1.0 - 2.0	11.4 - 19.0
			68.4	9.7 - 12.0	0.7 - 1.0	11.1 - 17.1
I-93 SB	Yes	Yes	68.4	9.1 - 14.7	0.2 - 0.5	9.6 - 15.6
NH-101 EB	Yes	No	115.4	10.8 - 17.2	1.4 - 1.6	13.6 - 20.4
			120.4	18.2 - 25.7	3.6 - 3.7	25.5 - 32.9
			123.0	12.6 - 19.1	1.6 - 1.9	15.8 - 22.9
			130.2	10.0 - 15.5	0.4 - 0.5	11.0 - 16.3
NH-101 WB	Yes	No	120.2	11.2 - 17.3	1.0 - 1.2	13.1 - 19.7
			123.2	15.8 - 23.0	2.1	19.9 - 27.1
			125.6	11.1 - 16.5	1.3 - 1.4	13.7 - 19.4
			128.4	11.2 - 17.1	0.8 - 0.9	12.8 - 18.7

Average deflections ranged from about 8.5 to 25.7 mils and representative deflections ranged from about 9.3 to 32.9 mils. In general, average deflections increased about 5 mils between load plate pressures of 85 psi and 146 psi. Test locations with greater average deflections typically had broader ranges of standard deviations. Average deflections for load plate pressures of 85, 110, and 146 psi are shown on Figure 3.

Dynatest's cost estimates for FWD testing consisted of about $1,500 for mobilization (depending upon availability and proximity), $2,500 per day for equipment and field technicians, and $1,200 per day for data engineering and reporting cost. Dynatest FWD apparatus would also be required. Traffic control provided by NHDOT forces was estimated to cost $2,000 per day. Not including mobilization fees, the daily rate for Dynatest to perform FWD testing using NHDOT traffic control was approximately $5,700. Production rates were estimated to be between 3 and 5 test locations per day depending upon proximity and favorable weather conditions. Had Dynatest been contracted to perform this work, the estimated cost of the project would have been approximately $25,000.

**ROLLING WHEEL DEFLECTOMETER (RWD) TESTING**

Applied Research Associates, Inc. of Champagne, Illinois performed RWD testing between July 26 and 28, 2008 as a demonstration of their RWD capabilities. The RWD apparatus consisted of a custom built semi-trailer towed behind an International diesel-powered three-axle tractor. The semi-trailer was 53 feet long, which according to ARA was adequately long enough to separate the weight affects of the tractor from the semi-trailer. RWD testing measured pavement deflections from the 18-kip axle load of the semi-trailer while traveling at normal highway speeds. Tire inflation pressures for the semi-trailer were not provided; however, commercial tire manufacturer recommendations indicate semi-trailer tire pressures should range from 90 to 120 psi.

d ave FWD @ 85 psi

(a)

d ave FWD @ 110 psi

(b)

d ave FWD @ 146 psi
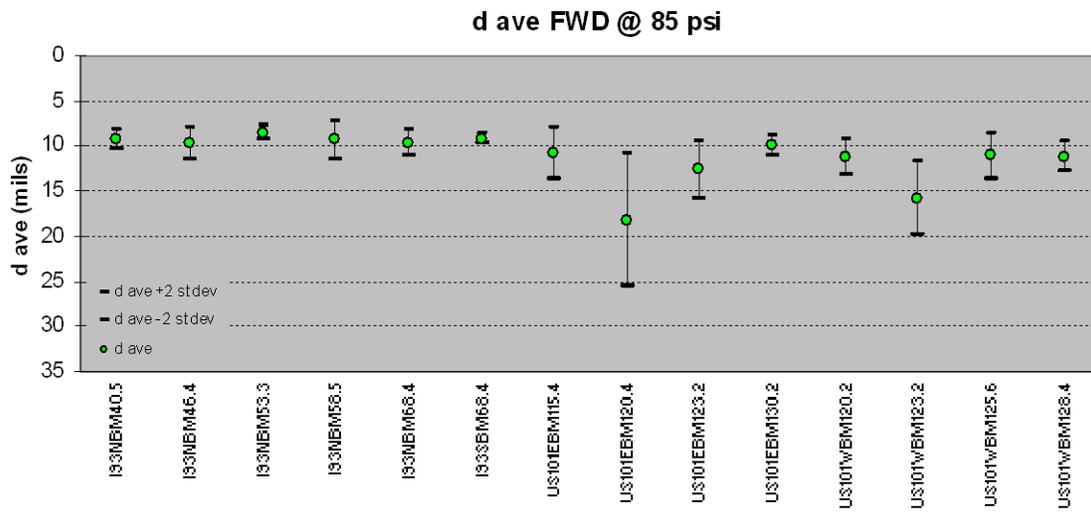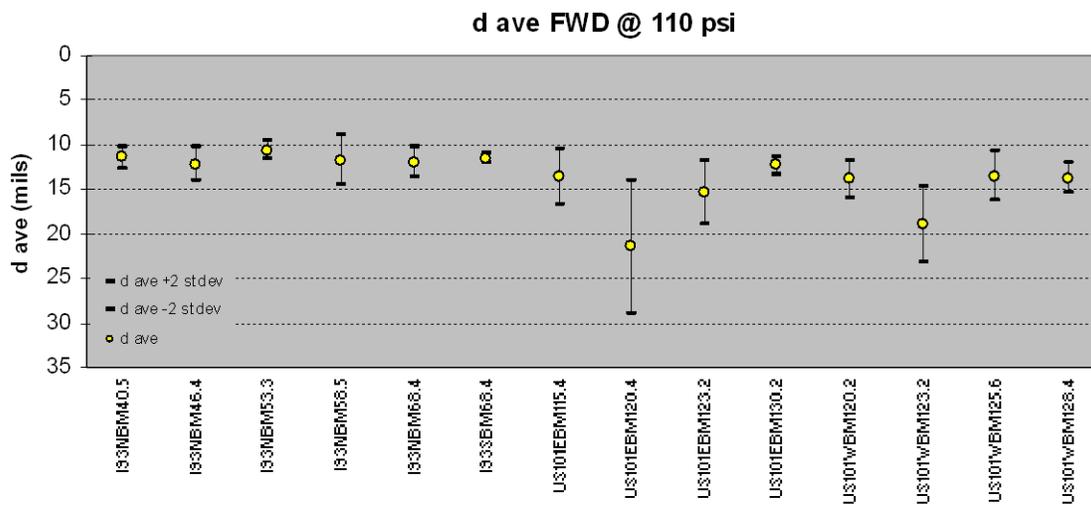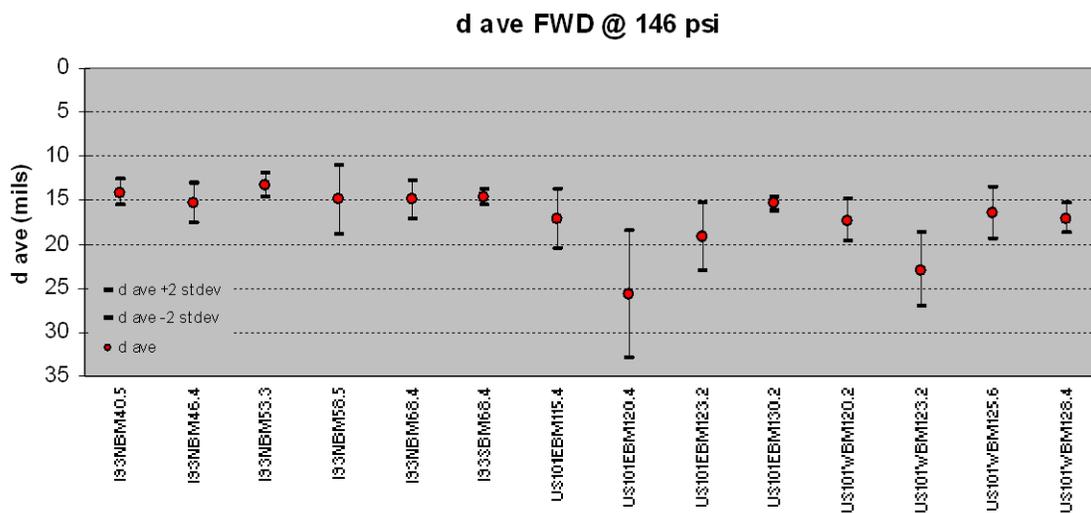
(c)

Figure 3: Average FWD pavement deflections at I-93 and NH-101 test locations

Pavement surface deflections were measured by an array of lasers attached to a metal beam mounted in a fixed position underneath the semi-trailer chassis just in front of the right set of tires. An additional laser was mounted between the right set of tires to measure pavement surface deflections at the axle. A distance measuring instrument was attached to the vehicle's right rear wheel to actuate RWD deflection measuring at a rate of once per 0.5 inch of travel while traveling at normal highway driving speeds. The RWD technician manually entered milepost information en-route. RWD test routes totaling 650 lane miles are shown on Figure 2. Applied Research Associates' summary report dated September 26, 2008 is provided in Appendix B.

Pavement deflections were measured in mils and were averaged (δ_{aveRWD}) over 528 foot long (0.10 mile) sections and normalized to a standard temperature of 68°F. Standard deviations for the individual 528 foot long segments were not provided, therefore the standard deviation of the average RWD deflection values within 0.50 miles before and after the FWD test locations were used to develop representative deflections (δ_{repRWD}) for those segments. Average deflections, standard deviations, and representative deflections for the RWD test segments are outlined below:

Highway	Travel Lane	Passing Lane	Milepost(s)	18-kip axle load tire pressures est. 90 to 120 psi		
				δ_{aveRWD} (mils)	σ (mils)	δ_{repRWD} (mils)
I-93 NB	Yes	No	40.1 to 41.1	12.8	1.9	16.6
			45.9 to 46.9	11.6	0.7	13.0
			52.8 to 53.8	12.7	0.9	14.5
			58.0 to 58.9	12.9	1.0	14.9
			67.9 to 68.9	11.9	1.0	13.9
I-93 SB	Yes	No	67.9 to 68.9	6.4	1.4	9.2
NH-101 EB	Yes	No	114.9 to 115.9	12.2	1.8	15.8
			119.9 to 120.9	n/a	n/a	n/a
			122.5 to 123.5	n/a	n/a	n/a
			129.7 to 129.9	10.9	0.2	11.3
NH-101 WB	Yes	No	119.7 to 120.7	12.8	2.7	18.2
			122.7 to 123.7	19.2	1.6	22.4
			125.1 to 125.8	11.5	1.3	14.1
			127.9 to 128.9	14.0	1.0	16.0

Average deflections ranged from 6.4 to 19.2 mils and representative deflections ranged from about 9.2 to 22.4 mils. Incremental average deflections for each 528 foot long section are shown on Figure 4 and Figure 5. These figures also include Applied Research Associates' overall representative deflection value for the roadway.

Applied Research Associates' cost estimates for FWD testing consisted of $2,000 for mobilization (depending upon availability and proximity), equipment, and field technicians, $160 per lane mile for data engineering and reporting. Production rates were estimated to be about 250 miles per day. Had Applied Research Associates' been contracted to perform this work, the estimated cost of the project would have been approximately $41,000.
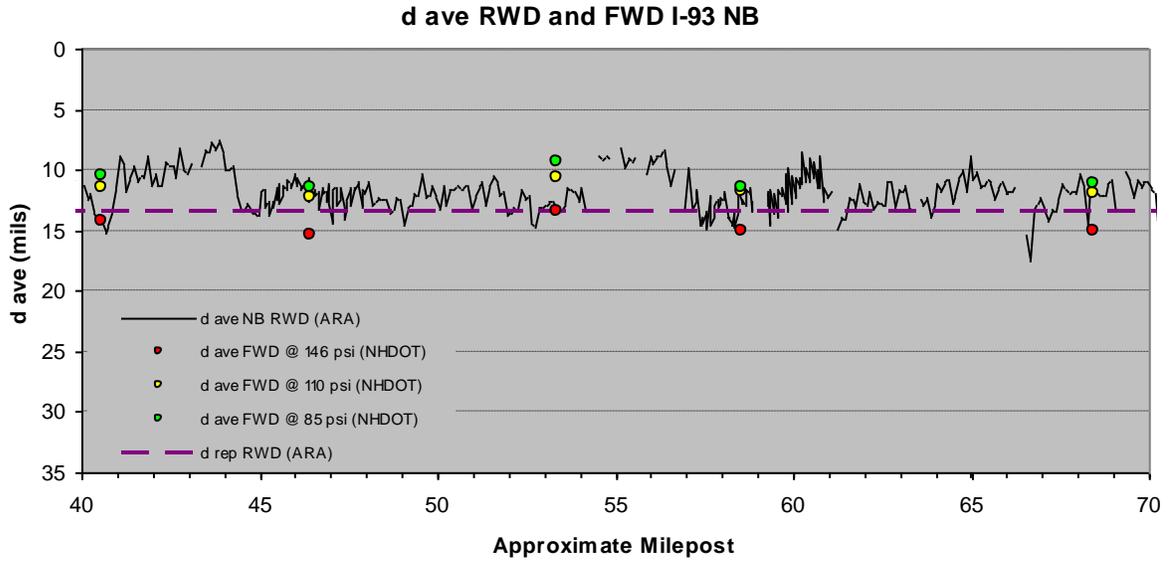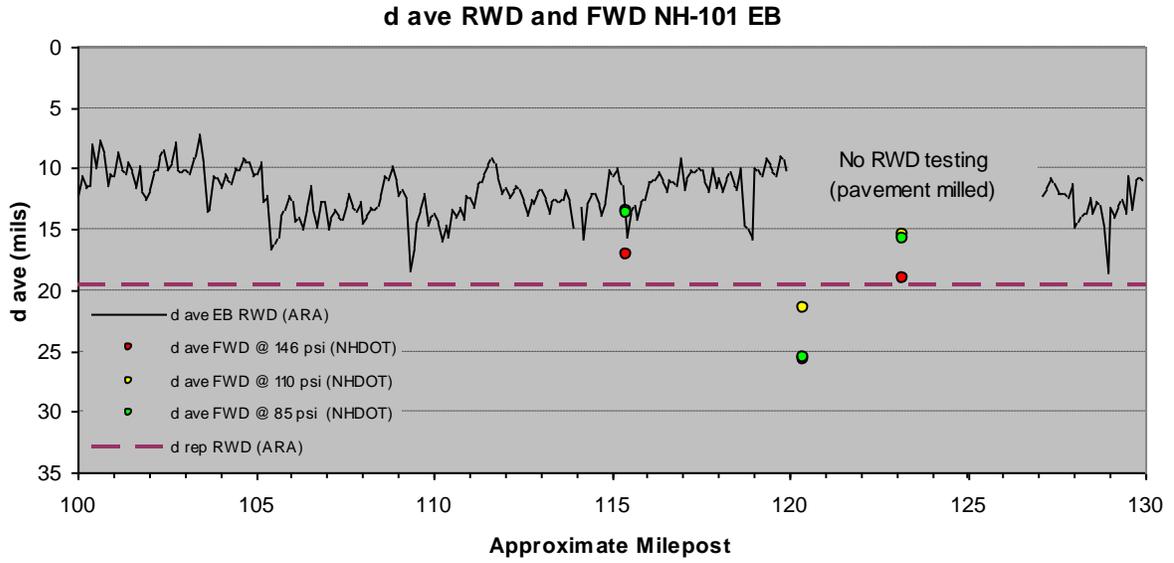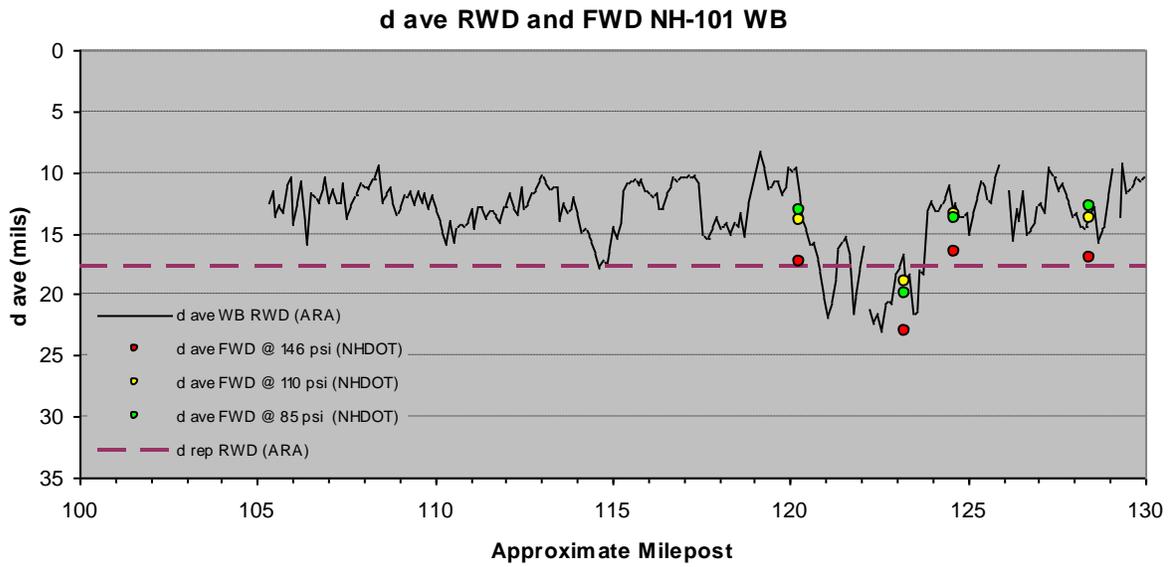
(a)
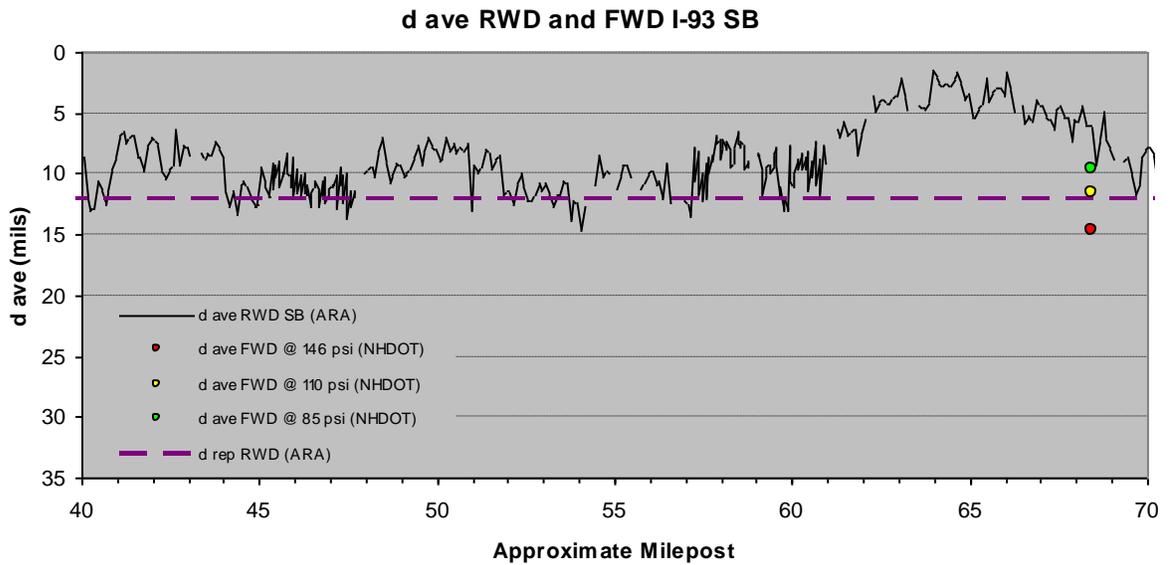
(b)

Figure 4: Average RWD and FWD pavement deflections on sections of I-93

d ave RWD and FWD NH-101 EB

(a)

d ave RWD and FWD NH-101 WB

(b)

Figure 5: Average RWD and FWD pavement deflections on section of NH-101

DISCUSSION

GPR Testing v. Pavement Core Sampling

GPR pavement thickness results are at 0.1 mile intervals and are an average of data analyzed at 0.1 foot intervals (528 thickness values located ±0.05 miles around each reported point). The I-93 NB core samples used for comparison were compiled from five years of tests. Pavement cores located in sections of pavement rehabilitation and outside of GPR surveyed travel lane were eliminated for relationship. The average difference between GPR results and 35 pavement cores was 6.5%.

Depending on the treatment of data, an accuracy of ±5-10% is expected. The density of the pavement cores, vehicle wandering during the GPR survey, and misidentification of the bottom of the asphalt concrete in GPR data can skew results for comparison. Figure 6 provides a plot of the GPR and pavement cores of the I-93 section comparison.
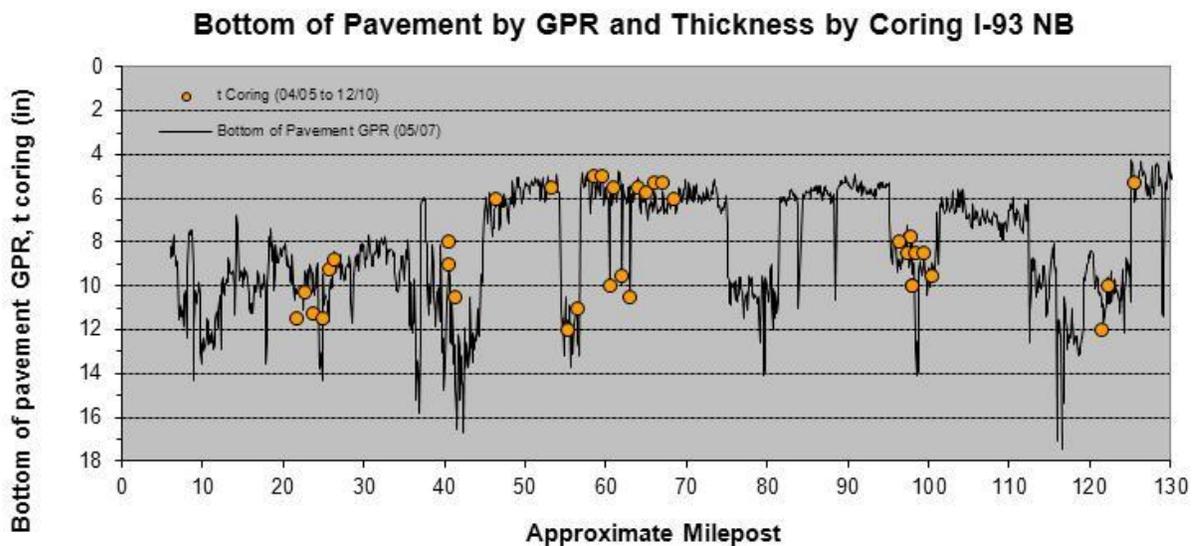
Figure 6: Average GPR pavement and core sample thicknesses in I-93 NB travel lane

GPR testing conducted on May 8, 2007 was not coordinated with pavement coring, which occurred between April 2005 and December 2010.

The following aspects of GPR testing and pavement core sampling revealed by this study include the following:

- Pavement core samples can be examined in the laboratory for pavement consistency and layer thickness, tested, and stored in the archives for further evaluation if required.

- Base course material samples collected during pavement coring can be examined in the laboratory for consistency and layer thickness, tested for soil index properties, and stored in the archives for further evaluation if required.

- NHDOT can perform pavement core and base course sampling using in-house forces and equipment. Pavement core and base course sampling at highway locations requires three drilling technicians and at least four maintenance workers to perform traffic control.

- GPR testing can provide a continuous pavement thickness profile whereas core sampling is limited to providing pavement thicknesses at discrete locations.

- GPR testing can be performed at normal driving speeds without significantly disrupting traffic conditions. GPR production rates at highway driving speeds are expected to be about 300 lane miles per day with results reported as the average pavement thickness for each 528 foot long section. Pavement core and base course sampling with traffic control at the same interval is expected to take approximately 2 lane miles per day.

- GPR testing is expected to be less expensive per lane mile than pavement core sampling. GPR testing performed by Infrasense is expected to cost about $140 per lane mile. Based on the core sampling production rate outlined above and a daily cost of $4,000 per day, the estimated unit cost for pavement core sampling is about $10,000 per lane mile.

- The purchase price of a GPR system for PM's PathRunner XP data collection vehicle that was comparable to the system used by Infresense for this study was estimated to be about $120,000.

FWD v. RWD Testing

FWD deflections were similar RWD deflections with the best average and representative deflection correlations occurring at an FWD load plate pressure of 110 psi (Figure 7). Noticeably greater amounts of deflection were measured on NH-101 EB and WB between mileposts 120 and 124. Based on the subjective rating system found in Applied Research Associates' summary report, structural capacity ratings from representative FWD deflections were similar to those based on representative RWD deflections as outlined below:

| Highway	Milepost(s)	δ_{repFWD} (mils) 110 psi	Structural Capacity Rating δ_{repFWD}	δ_{repRWD} (mils) est. 90-120 psi	Structural Capacity Rating δ_{repRWD}
I-93 NB	40.1 to 41.1	12.7	Good	16.6	Fair
	45.9 to 46.9	14.1	Good	13.0	Good
	52.8 to 53.8	11.6	Good	14.5	Good
	58.0 to 58.9	14.5	Good	14.9	Good
	67.9 to 68.9	13.7	Good	13.9	Good
I-93 SB	67.9 to 68.9	12.1	Good	9.2	Very Good
NH-101 EB	114.9 to 115.9	10.5	*Good*	15.8	*Fair*
	119.9 to 120.9	29.0	Very Poor	n/a	*n/a*
	122.5 to 123.5	19.0	Fair	n/a	n/a
	129.7 to 129.9	13.3	*Good*	11.3	*Good*
NH-101 WB	119.7 to 120.7	16.0	Fair	18.2	Fair
	122.7 to 123.7	23.0	*Poor*	22.4	*Poor*
	125.1 to 125.8	16.3	Fair	14.1	Good
	127.9 to 128.9	15.4	Fair	16.0	Fair

The following aspects of FWD and RWD testing revealed by this study include the following:

- RWD testing can provide a continuous pavement deflection profile whereas FWD testing provides pavement deflections at discrete locations. Continuous deflection profiles can be used to develop structural ratings for roadway sections and identify sections of pavement that could potentially be prone to early deterioration.

- RWD testing can be performed at normal driving speeds without significantly disrupting traffic conditions. FWD testing requires establishing a work zone around the test location by placing traffic control devices. Traffic control devices can consist of signs, cones, message boards, impact attenuators, and sometimes flaggers depending upon roadway and traffic conditions. The time to establish a 100 foot long work zone, perform FWD testing in two lanes, and demobilize from the test location was estimated to be about 60 to 90 minutes. This is about 0.04 lane miles per hour with a corresponding daily production rate of less than 0.5 lane miles per day. Improved FWD production rates could be achieved by minimizing the number of tests at each location. RWD testing rates were estimated to be 250 lane miles per day.

- The cost per lane mile for RWD testing is expected to be less than FWD testing. RWD testing performed by Applied Research Associates is expected to cost $60 per lane mile. Based on the FWD testing production rate outlined above and a daily cost of $5,700 per day, the estimated unit cost for FWD testing is about $11,400 per lane mile.

- NHDOT forces can perform FWD testing and traffic control however the NHDOT does not own FWD testing equipment. FWD testing requires two technicians and at least four people to perform traffic control for a total of six people. The purchase price of a Dyntatest 8000 FWD and dedicated support van was estimated to be about $180,000.
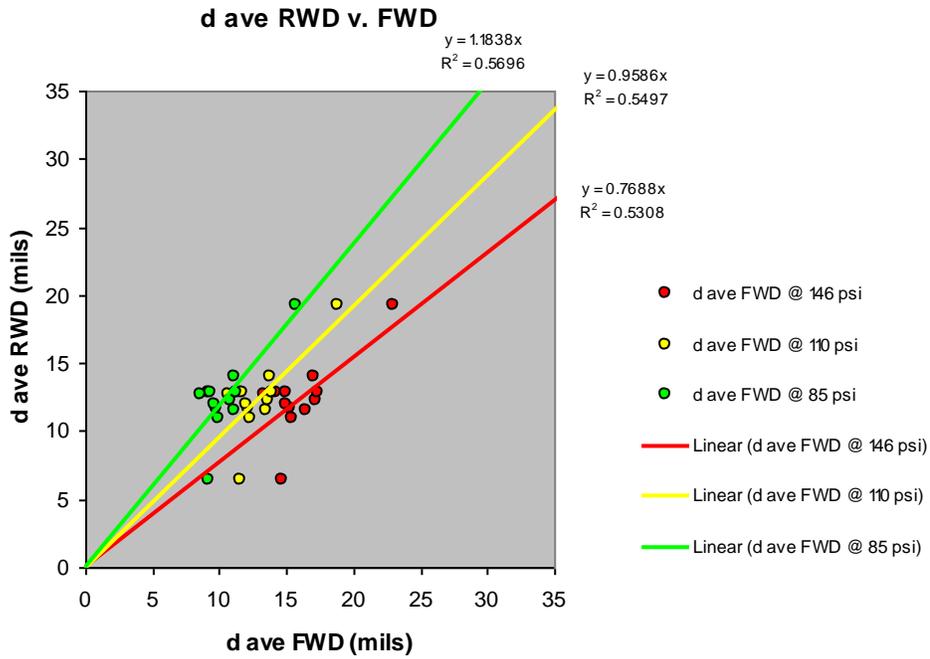
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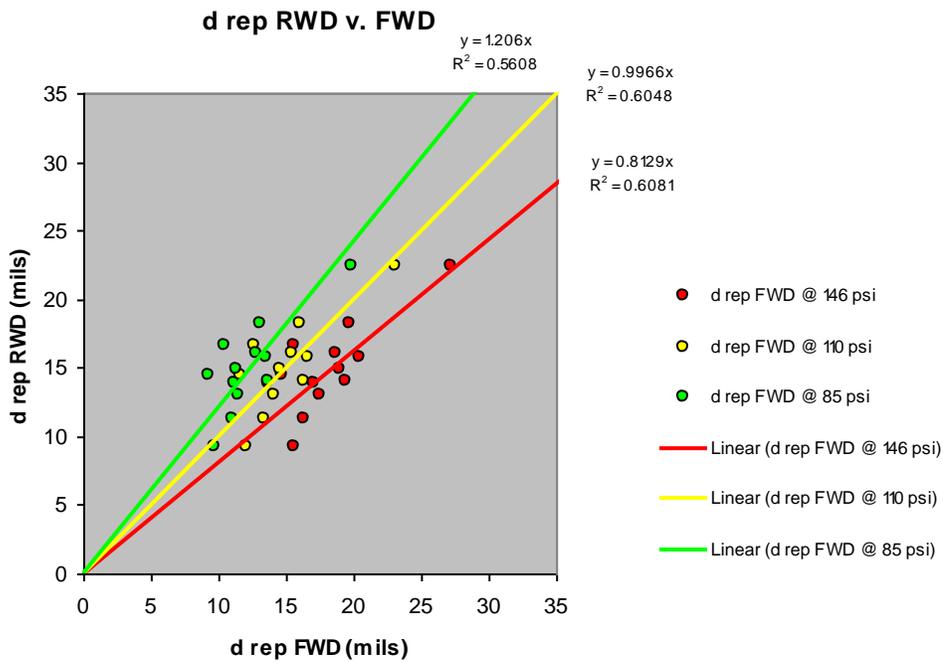
(b)

Figure 7: RWD v. FWD average and representative pavement deflections

RECOMMENDATIONS

The following recommendations are provided based on the work performed for this study:

- Continuous pavement thickness profiles from GPR testing and continuous pavement deflection profiles from RWD testing should be incorporated into the Pavement Management System to provide additional information for evaluating and forecasting pavement performance.

- GPR testing should be conducted on some of the highways and local roadways to determine if data quality and production rates are similar to those experienced on the interstate testing in this study. Local roadway test routes should have varying pavement thicknesses or pass through sites with high groundwater levels. A roadway constructed with a concrete pavement should also be tested.

- FWD testing should be performed on some of the highways and local roadways where RWD testing was conducted to determine if data quality and production rates are similar to those experienced on the interstate testing in this study.

- Additional rounds of RWD and GPR testing should be considered with respect to the NHDOT's 10-year plan, to provide some guidance to the amount of proposed paving work.

APPENDIX A

**Project Report - Ground Penetrating Radar (GPR) Pavement Layer
Thickness Evaluation of Interstate 93 in New Hampshire
Infrasense, Inc. (June 12, 2007)**

Ground Penetrating Radar (GPR) Pavement Layer Thickness Evaluation of Interstate 93 in New Hampshire

Project Report

submitted to the

GEI Consultants, Inc

400 Unicorn Park Drive
Woburn, MA 01801

by

INFRASENSE, Inc.

14 Kensington Road
Arlington, MA 02476

June 15, 2007

1.   Introduction

The overall objective of the project has been to evaluate the pavement layer thickness on Interstate 93 Northbound in New Hampshire between milepost 17.4 in the south and the milepost 131.4 at the Vermont border in the north. The total evaluated length is 114 lane miles. The evaluation has been carried out using Ground Penetrating Radar (GPR). The Ground penetrating radar layer thickness data will be used in conjunction with a demonstration of the Rolling Wheel Deflectometer, to be carried out later in 2007..

2.   Data Collection

The GPR survey was conducted on May 8, 2007, in the outside traveling lane The GPR equipment was a single 1 GHz horn antenna system manufactured by GSSI, Inc. of North Salem, NH and is shown in Figure 1. The antenna was positioned behind the right wheel of the survey vehicle, so that data would be collected in the right wheelpath. The vehicle was equipped with an electronic distance-measuring instrument (DMI) mounted to the rear wheel, providing continuous distance data as the GPR data was collected. The data collection and recording was controlled by the SIR-20 GPR system operated from within the survey vehicle. The data was collected at a rate of one scan per foot of travel.

Horn Antenna   DMI

Figure 1 – Field Setup of GPR Equipment

The GPR survey was carried out at normal interstate highway driving. A mark was manually placed in the data at one-mile intervals at the location of the observed mile markers.

3. Data Analysis

The data was analyzed according to the GPR analysis principles described in Attachment A.
For the pavement data, the marked milepost locations recorded during the GPR data collection
were correlated with the available milepost information, and the GPR distance scale was checked
against the mileposts distances. A sample of GPR data is shown in Figure 2.
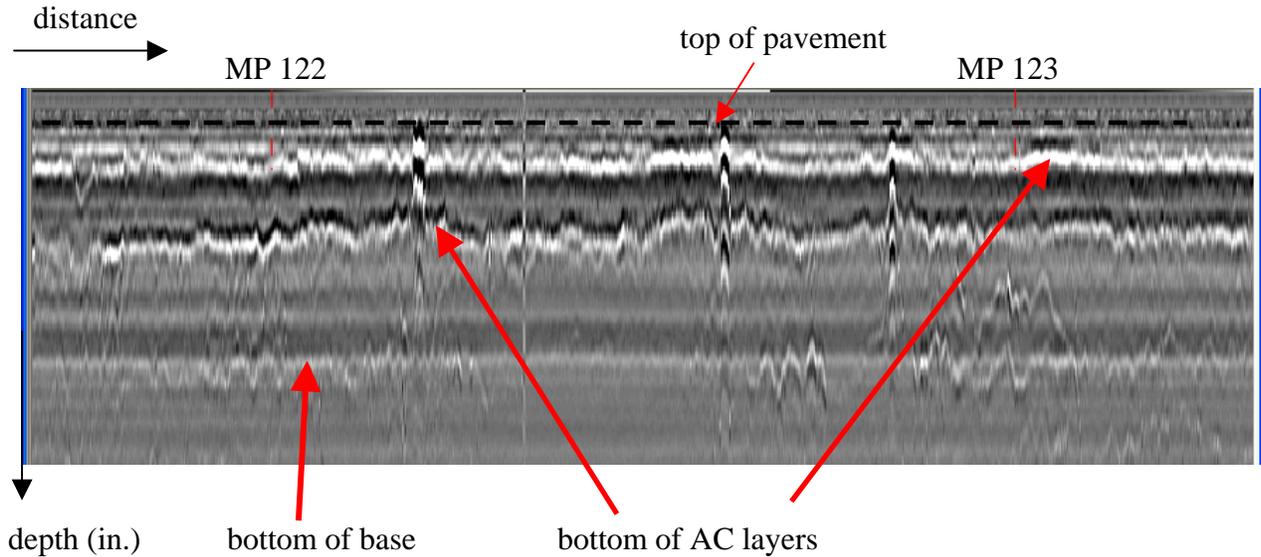
Figure 2 - Sample of GPR Data from Interstate 93

The thickness results are presented at 0.1 mile intervals based on data analyzed at one foot
intervals. The values presented at each 0.1 mile interval represent the average of 528 thickness
values located +/- 0.05 miles around each reported point. The data is presented as linear plots of
layer depth vs. milepost in Appendix B and in a spreadsheet transmitted with this report
These plots show the result of the GPR analysis, along with plan data and core data provided by
the NHDOT. For the GPR data, the blue plot line represent the bottom of AC layers, and the red
line plot line represents the bottom of the base layer. Note that there are some areas that show
multiple AC layers (upper and lower layer) as seen in Figure 2.. Depth of the base is provided
intermittently because it is detected intermittently.

The core data matches closely with the GPR thickness data at the core locations. There is good
agreement between the plan data in some areas, but not in all areas. The GPR data shows that
the asphalt is generally as thick or thicker that the plan quantities, except between MP 31 and 36
and between MP 119 and 121

ATTACHMENT A

Principles of GPR for Pavement Evaluation

Principles of GPR for Pavement Evaluation

Ground penetrating radar operates by transmitting short pulses of electromagnetic energy into the pavement using an antenna attached to a survey vehicle These pulses are reflected back to the antenna with an arrival time and amplitude that is related to the location and nature of dielectric discontinuities in the material (air/asphalt or asphalt/concrete, reinforcing steel, etc). The reflected energy is captured and may be displayed on an oscilloscope to form a series of pulses that are referred to as the radar waveform. The waveform contains a record of the properties and thicknesses of the layers within the pavement (Figure A.1).

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Horn Antenna

Asphalt

Base

Measurement Setup

Volts

Time

GPR Waveform

Distance

Depth

Sample Field

asphalt bottom reflection
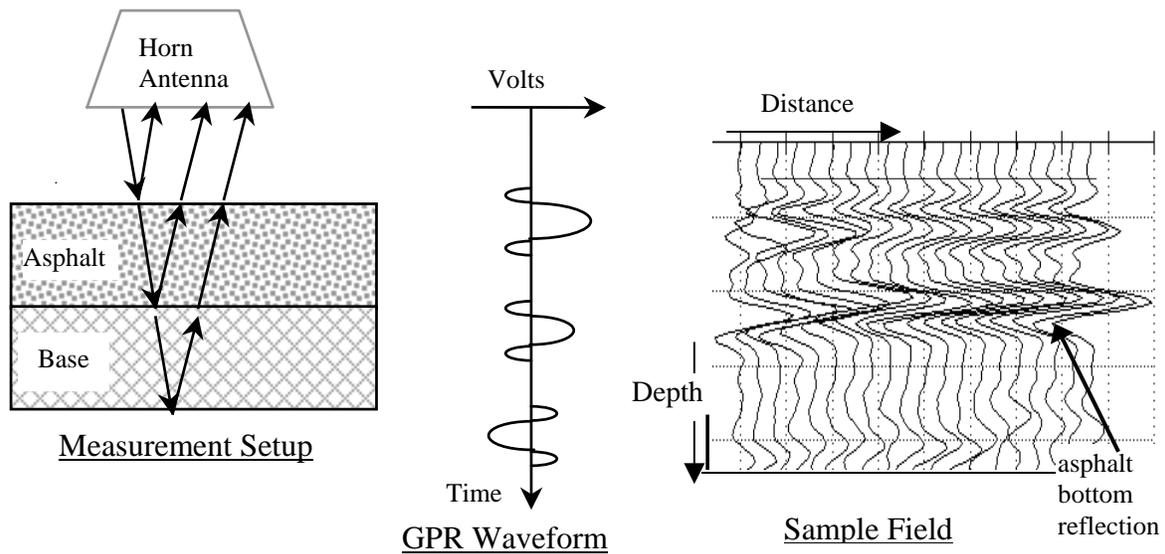
Figure A.1 – Structure of the GPR Signal for Pavements

The sequence of scans shown on the right of Figure A.1 is frequently coded in color or gray scale to produce the "B" scan representation, examples of which have been shown in Section3 of the report. The B scan provides the equivalent of a cross sectional view of the pavement, with the individual pavement layers showing up as colored horizontal bands.

Layer thickness is calculated from the arrival time of the reflection from the top and bottom of each layer as follows:

$$\text{Thickness (in.)} = (5.9\ t)/\sqrt{\varepsilon_a} \tag{1}$$

where time (t) is measured in nanoseconds and ε_a is the relative dielectric permittivity or "dielectric constant" of the pavement layer (Roddis, et. al., 1992).

Computation of the dielectric constant of the surface layer can be made by measuring the ratio of the radar reflection from the pavement surface to the radar amplitude incident on the pavement. The incident amplitude on the pavement is determined by measuring the reflection from a metal plate on the pavement surface, since the metal plate reflects 100% of the incident energy. Using this data, one obtains the asphalt dielectric constant, ε_a as follows:

$$\varepsilon_a = [(A_{pl} + A)/(A_{pl} - A)]^2 \tag{2}$$

where A = amplitude of reflection from asphalt, and A_{pl} = amplitude of reflection from metal plate (= negative of incident amplitude) (Roddis, et. al., 1992). Table A.1 shows typical dielectric constants and associated GPR velocities for pavement materials. Note that the range of dielectric constant for asphalt is large, due to the variations in density and aggregate composition.

Table A.1 – GPR Velocities and Dielectric Constants for Pavement Materials

Velocity			Dielectric constant	Notes
Metric		English		
m/ns	cm/ns	in/ns		
0.100	10.0	3.94	9.00	typical for pcc
0.105	10.5	4.13	8.16	
0.110	11.0	4.33	7.44	
0.115	11.5	4.53	6.81	
0.120	12.0	4.72	6.25	
0.125	12.5	4.92	5.76	
0.130	13.0	5.12	5.33	
0.135	13.5	5.31	4.94	typical for ac
0.140	14.0	5.51	4.59	
0.145	14.5	5.71	4.28	
0.150	15.0	5.90	4.00	
0.155	15.5	6.10	3.75	

A similar calculation can be made for the dielectric constant of the base material. Changes in base moisture content have a strong effect on the base dielectric constant, and thus the base dielectric constant can be used as an indicator of high moisture content.

The calculations described above are automated in Infrasense's PAVLAYER© data analysis software program for computing pavement layer thickness and changes in pavement layer properties. The analytical techniques described above serve as the basis for data analysis carried out during this project, as described in Section 3 of the report.

References

Roddis, W.M., Kim, Maser, K.R., and Gisi, A.J., (1992), "Radar Pavement Thickness Evaluations For Varying Base Conditions," *Transportation Research Record No. 1355,* TRB National Research Council, pp. 90-98, 1992.

ATTACHMENT B

Plots of Layer Thickness
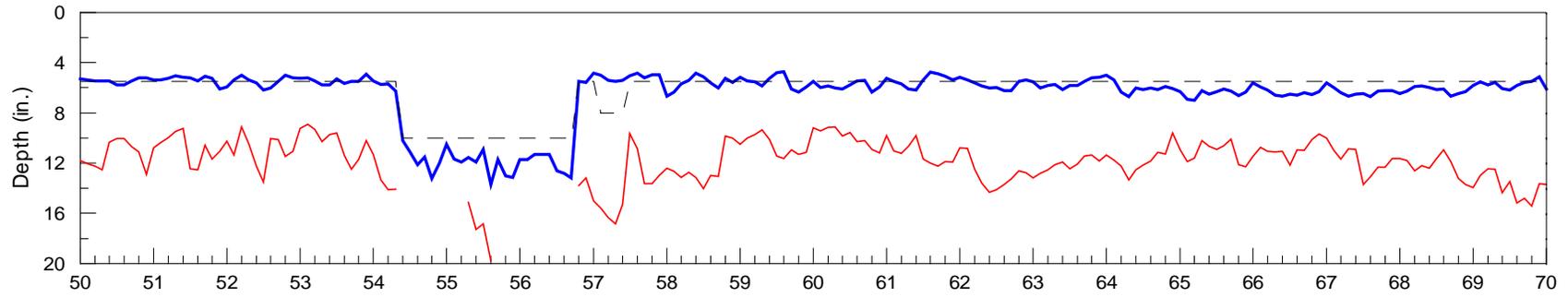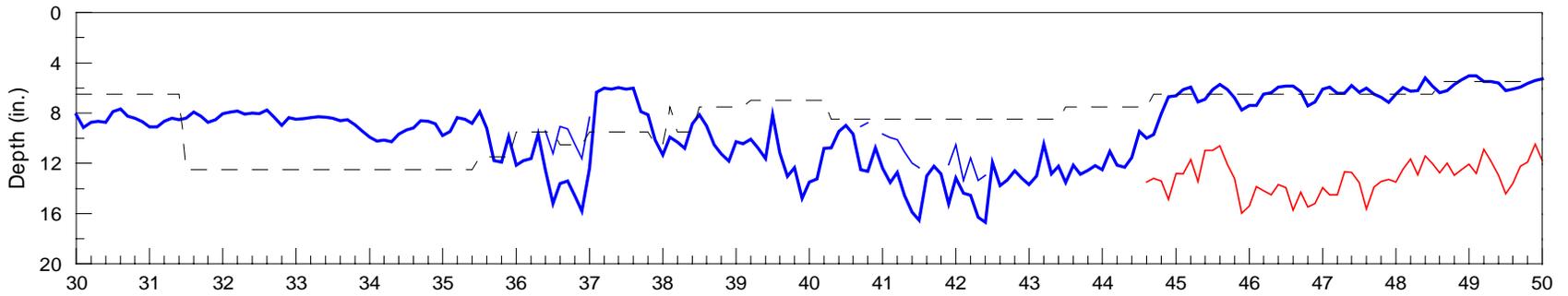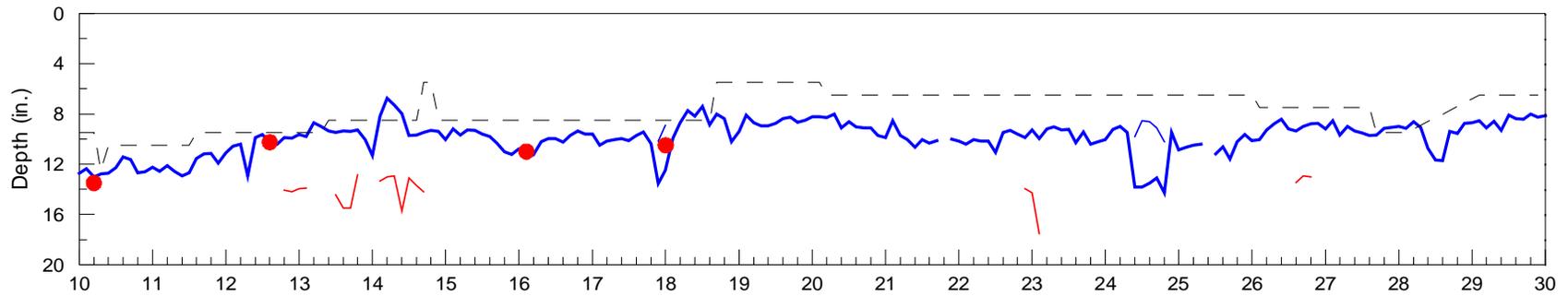
Legend

Upper AC
Total AC
Base
Plan thickness
Cores

GPR Pavement Thickness Evaluation
Interstate 93

Prepared by: LAM   Date: 05/23/07
Checked by: KRM   Date: 05/25/07

INFRASENSE, Inc.

Arlington, MA 02476

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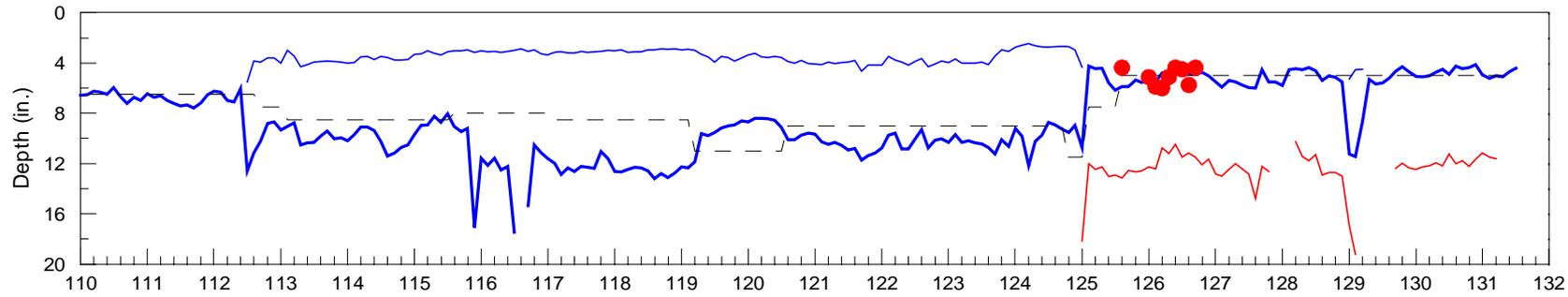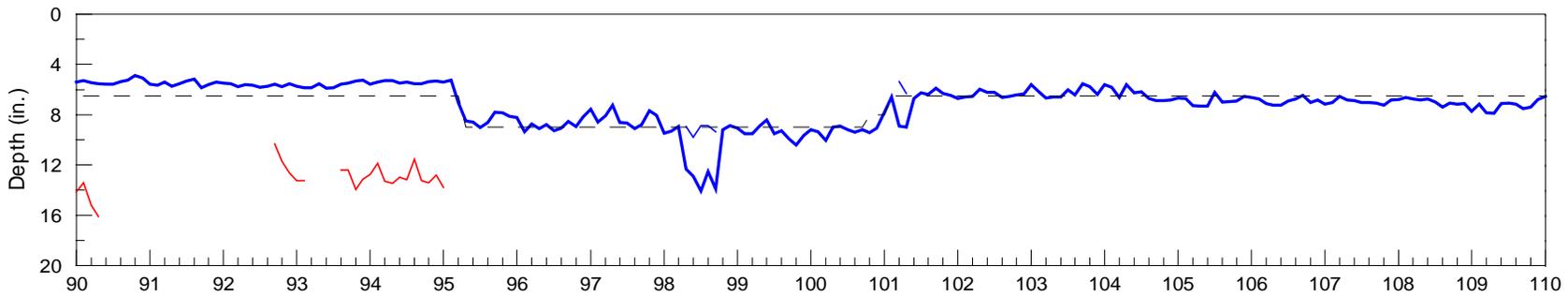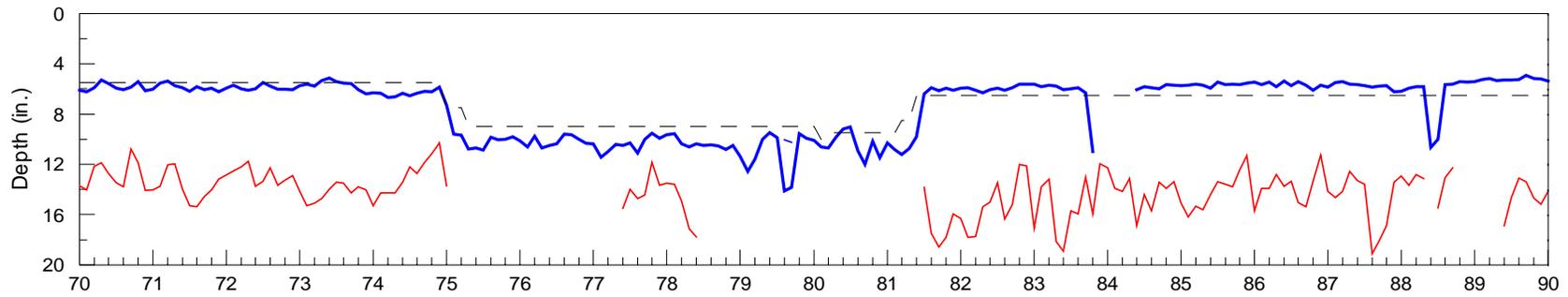
Legend

Upper AC
Total AC
Base
Plan thickness
Cores

GPR Pavement Thickness Evaluation
Interstate 93

Prepared by: LAM   Date: 05/23/07
Checked by: KRM   Date: 05/25/07

INFRASENSE, Inc.

Arlington, MA 02476

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APPENDIX B

**Rolling Wheel Deflectometer (RWD) Demonstration for the
New Hampshire Department of Transportation (NHDOT)
Applied Research Associates, Inc. (September 26, 2008)**

September 26, 2008

Mr. Eric Thibodeau
New Hampshire Department of Transportation
Bureau of Materials and Research
5 Hazen Dr.
Concord, NH 03302-0483
(603) 271-1750 telephone
Ethibodeau@dot.state.nh.us

Subject: **Rolling Wheel Deflectometer (RWD) Results for the New Hampshire Department of Transportation (NHDOT).** ARA Project No. 16860.

Dear Mr. Thibodeau:

Applied Research Associates (ARA), Inc. appreciates the opportunity to submit the results of RWD testing performed on selected New Hampshire highways. This report summarizes the RWD device, testing program, and results.

It has been a pleasure for ARA to provide these services to you, and we look forward to your feedback regarding this innovative device. If you have any questions or comments, please feel free to contact us.

Sincerely,

Douglas A. Steele, P.E.   William R Vavrik, Ph.D., P.E.
Senior Engineer   Midwest Division Manager

Attachment

Cc: Mr. Thomas Van, FHWA

FINAL REPORT

Rolling Wheel Deflectometer (RWD) Demonstration for the New Hampshire Department of Transportation (NHDOT)

Prepared for:

New Hampshire Department of Transportation
5 Hazen Dr.
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Tel. (603) 271-1750

Prepared by:

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September 26, 2008

TABLE OF CONTENTS

EXECUTIVE SUMMARY

The Rolling Wheel Deflectometer (RWD) is an innovative device to efficiently measure continuous pavement deflections at normal highway speeds. This previously-not-available data presents many potential benefits to pavement managers and highway agencies, mainly by measuring pavement structural response for use in network-level pavement evaluation and management. This report summarizes a pilot study performed for the New Hampshire Department of Transportation (NHDOT).

Testing Program

- Applied Research Associates (ARA), Inc. performed RWD testing on 13 roadways in both directions (25 sections total), consisting of Interstates, U.S., and state routes. The test sites included two-lane (one lane in each traffic direction) and multi-lane roads, all of flexible pavement design.

- For each road, the RWD measured a continuous deflection profile in the outer wheel path of the outermost (travel) lane. The RWD operated at prevailing highway truck speeds, typically ranging from 45 to 65 mph. ARA tested 648 lane-miles over a 3-day testing period from July 26-28, 2008 on test roads selected by NHDOT.

- ARA post-processed raw laser and distance (DMI) data to calculate deflection. A quality control process removed any non-representative RWD data due to truck and pavement factors, such as excessive truck bouncing at bridge joints. Overall, a negligible amount of data (less than 1 percent) was removed.

- RWD deflections averaged over 0.1-mi intervals were plotted for each highway to provide a deflection profile that showed the magnitude and variability of the pavements' structural responses, as well as changes in pavement stiffness. A statistical summary was developed to show the mean deflections and representative deflections (i.e., mean plus 2 standard deviations, or 98th percentile deflection) for each road. In some cases, repeat testing of pavement sections was performed, as well as testing of both lanes (travel and passing lane) at the same location.

- Pavement structure data (i.e., AC thickness) were provided by NHDOT for use in normalization of deflection data to temperature.

Findings

- The pool of roads tested produced mean deflections ranging from 7 to 15 mils, with the lower deflections generally occurring on the thicker, higher volume pavements, and higher deflections on the thinner or deteriorated roads, as expected. In general, the RWD deflections are reasonable for the pavement types and conditions tested.

- Falling weight deflectometer (FWD) data collected on I-93 northbound between mile markers 31.4 and 33.6 produced deflections ranging from 8 to 10 mils, which once normalized to a standard temperature, compared well with the RWD deflections at the same location.

- In addition to calculating mean deflection for each road, ARA determined the Representative Deflection for each section, defined as the mean plus 2 standard deviations (i.e., 98th percentile). This value is more appropriate than just mean deflection as it takes into account structural variability within a section. This is important as weaker areas (i.e., areas of higher deflection) show structural distress first. Representative deflections ranged from 10 to 20 mils. Deflections in this range typically correspond to pavements with fair to good structural capacity.

- ARA assigned structural ratings to each road based on their Representative Deflections. This resulted in the following distribution of ratings for the 25 road sections: 12 percent = very good, 52 percent = good, and 36 percent = fair. The rating criteria selected by ARA are conceptual only, and can be modified by NHDOT accordingly.

Other Benefits

- The RWD is capable of good productivity, testing 648 lane-miles over a 3-day test period. Productivity is governed primarily by the length and geographic distribution of test sites. In general, NHDOT's selection of contiguous test sections allowed for good productivity.

- The RWD is a safe method for collecting highway structural data, as it does not require lane closures or interruptions to the highway users. The RWD blends with surrounding traffic, operating at prevailing highway speeds for tractor-trailer combinations, typically 45 to 65 mph.

- In addition to deflections, the RWD also collected continuous digital images of each road. With additional effort, the RWD could be enhanced to collect inertial longitudinal profiles for use in calculating the International Roughness Index (IRI). The combination of pavement deflection, condition rating, and IRI would make the RWD a powerful single device for the collection of multiple PMS data types.

ACKNOWLEDGEMENTS

INTRODUCTION

The Rolling Wheel Deflectometer (RWD) is an innovative device for the efficient, high-speed determination of highway pavement structural response. The current prototype was developed jointly by the Federal Highway Administration (FHWA) Office of Asset Management and Applied Research Associates (ARA), Inc. It uses four triangulation lasers mounted beneath the bed of a semi-trailer to measure a continuous pavement deflection profile when loaded by the trailer's 18-kip single axle load. The system has undergone extensive field testing, having performed pilot studies for numerous state highway agencies, including Texas, Indiana, Virginia, California, Kansas, and Connecticut DOTs. Field testing has verified the RWD's capability to measure pavement deflections at highway speeds. The RWD is currently available to perform commercial testing services for highway agencies.

In July 2007, ARA performed a field demonstration for the New Hampshire Department of Transportation (NHDOT). This report summarizes the testing program and results.

Figure 1. Interstate 93 near Franconia.

RWD DESCRIPTION

Equipment

The RWD is comprised of a set of four triangulation lasers attached to an aluminum beam mounted beneath a custom designed 53-ft trailer. The trailer is sufficiently long to isolate the deflection basin produced by the RWD trailer's 18-kip, dual tire, single-axle from deflections produced by the RWD tractor. Figure 2 shows an overview of the RWD truck, trailer, and laser mounting beam. In addition, the natural frequency of the trailer's suspension of 1.45 to 1.8 Hz is low enough that it does not couple with the high-frequency vibration of the 25.5-ft aluminum beam used to support the lasers. The beam uses a curved extension to pass under and between the dual tires, placing the rearmost laser approximately 6 inches rear of the axle centerline and 7 inches above the roadway surface, as shown in figure 2. The wheels have been spaced a safe distance from the laser and beam using custom lugs and a spacer.

Figure 2. Overview of the RWD and a close-up of laser D between the dual tires.

Measurement Methodology

The RWD utilizes a "spatially coincident" methodology for measuring pavement deflection. Three lasers placed forward of the loaded axle are used to define the unloaded pavement surface profile and a fourth laser (D) placed between the dual tires measures the deflected pavement surface. Deflection is calculated by comparing the undeflected pavement surface with the deflected pavement profile at the same location. This method was originally developed by the Transportation and Road Research Laboratory (TRRL) and furthered by Dr. Milton Harr at Purdue University.

At 55 mph, the RWD's 2-kHz lasers take readings approximately every 0.5 in, resulting in extremely large data sets. To make the data set manageable and to reduce the random error of individual readings, data are averaged over an interval suitable for pavement management purposes, typically 0.1-mi (528-ft). At normal highway speeds, a 0.1-mi average contains approximately 12,000 individual laser readings.

TESTING PROGRAM

ARA performed testing on July 26-28, 2008 on roads selected by NHDOT. The roads consisted of Interstate, U.S., and state routes throughout the state. All pavements were of flexible design and pavement thickness data were provided by NHDOT. The RWD performed testing in the outer wheel path of the outermost (travel) lane in both traffic directions, using NHDOT's mile marker system for reference, where available. In the case of roads without posted mile markers, the RWD referenced test data using its onboard distance measuring instrument (DMI). A total of 648 lane-miles were tested over a 3-day period. Figure 3 shows the test road locations. Table 1 summarizes the test roads and AC pavement thicknesses, as provided by NHDOT.

The RWD was operated by two people—a driver and an operator. During data collection the operator entered event markers corresponding to bridges, changes in pavement surface type, and zones of significant acceleration/deceleration. Event markers are used during data processing for removal of outlier data resulting from localized anomalies. In addition to deflection data, the RWD also records continuous digital images and GPS coordinates for each road. In general, the RWD tested at prevailing highway truck speeds (i.e., 45 to 65 mph), whenever conditions permitted.

Figure 3. New Hampshire test roads.

3

Table 1. Summary of the New Hampshire test roads.

Road	Direction	From/To Mile Marker (or DMI)	From/To Landmark	AC thickness, in
I-89	NB & SB	0 to 60	I-93 to Vermont State Line	6.5 to 11
I-93	NB & SB	23 to 130	I-293 to Vermont State Line	5 to 15
I-95	NB & SB	0 to 15	Massachusetts State Line to Maine State Line	5 to 12
I-293S	SB	12 to 1	I-93 to I-93/NH 101	5 to 8
I-393	EB & WB	0 to 3	I-93 to Exit 3	8.5
US 3	NB & SB	0 to 11[a]	I-93 to US 302	4 to 5.5
US 4	NB & SB	0 to 12	I-95 to Exit 9	4 to 11
US 202	EB & WB	0 to 12[a]	I-89 to NH 9	5 to 7
NH 3A	NB & SB	0 to 7[a]	I-89 to Hackett Hill Rd.	6.5 to 7.5
NH 9	EB & WB	0 to 13[a]	US 202 to Rest Area	3.5 to 5.5
NH 101	EB & WB	100 to 130	I-93 to I-95	5.5. to 18
NH 103	WB/NB & EB/SB	0 to 16[a]	I-89 to Traffic Circle	3.5 to 6
FEET/453	NB & SB	0 to 20	Massachusetts State Line to I-293	5 to 11

[a] Mile markers not posted. Section referenced using the RWD's DMI and the start of the section as mile 0.

DATA PROCESSING AND FILTERING

Data were processed in the office using proprietary RWD software. The software processes the raw RWD files to calculate and display the following parameters per sample unit (0.1-mi):

- ➢ Mean RWD deflection and deflection deviation within a sample unit
- ➢ Truck speed and speed deviation within a sample unit
- ➢ Pavement surface temperature.
- ➢ Linear referencing based on the Distance Measuring Instrument (DMI), GPS, and physical mile markers.
- ➢ Event markers, such as bridges, intersections, or other references.

A typical RWD raw data file of 40-mi length (approximately 1 Gb in size) is reduced to an HTML output file of minimal size, making the data set manageable. Final processing and preparation for reporting are performed in spreadsheets with the use of customized macros.

The following sections present the quality control process followed to ensure valid RWD results. This process is used to eliminate outlier data due to either truck or pavement factors (e.g., excessive truck bouncing due to bridge joints) from the data set. Typically, only a very small percentage of the data is removed (e.g., less than 1 percent).

Truck Speed and Speed Variation

Figure 4 shows the average truck speed for US 3 northbound from I-93 to US 302. This road presented typical speed variations due to vertical and horizontal curves, as well as the acceleration and deceleration zones at the start/stop of the test run. Variations in this range are not great enough to have a significant effect on the resultant deflection.

Significant accelerating and decelerating of the RWD may cause excessive bouncing of the trailer, resulting in invalid laser readings at isolated locations. When this happens, the RWD deflections are reviewed to determine whether they have been influenced by the truck's bouncing. In this particular case, the truck speed deviations resulted in the elimination of a very small amount of effected data (i.e., less than 1 percent).

Pavement Surface Temperature

The RWD collects pavement surface temperatures using an infrared thermometer. These temperatures, in conjunction with air temperature and AC layer thickness, are used to adjust the field deflections to a standard temperature of 68 ºF. The BELS3 method is used to predict the AC mid-depth temperature and the AASHTO 1993 method is used to correct the RWD maximum deflection, based on the predicted AC temperature.
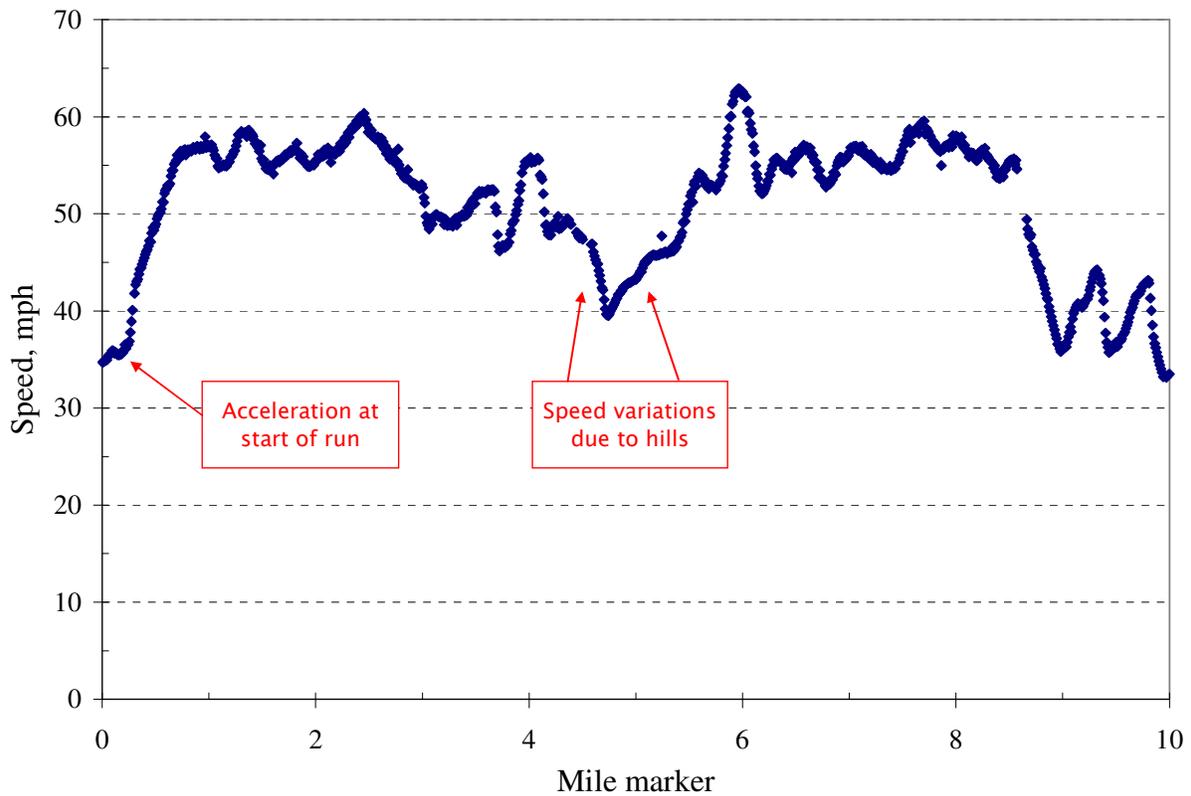
Figure 4. Average truck speed—US 3, I-93 to US 302 - northbound.

Bridges and Intersections

Finally, deflections were reviewed with respect to pertinent events that were recorded in the data file through the use of markers. These events include bridges, changes in pavement type, areas of significant braking or acceleration, and other discrete events that may have affected isolated deflection readings. In cases where localized deflections were determined to coincide to the noted events, they were removed from the data set.

RWD DEFLECTION RESULTS

This chapter presents sample RWD deflection profiles for several New Hampshire highways, followed by a statistical summary of all the roads tested. Detailed profiles for all roads are displayed in appendix A. Figures in this chapter show average RWD deflections calculated at 0.1-mi intervals and normalized to a standard temperature of 68 ºF. In some cases a 1-mi moving average is shown is shown as well.

Multiple Pavement Sections on I-89

Figure 6 presents the RWD results and digital images taken on I-89 northbound. In general, this a medium to thick AC pavement built for heavy, interstate traffic. According to NHDOT records, the AC thickness ranges from 6.5 to 11 in. I-89 consists of multiple pavement sections ranging from fair to new condition, and several sections have had maintenance performed on them. Overall, deflections ranged from 6 to 15 mils with an average of approximately 11 mils. Deflections at the north end were slightly higher than those at the south, possibly indicating a change in subgrade support along the length of the project. Deflections between the northbound and southbound lanes were generally similar; however there were areas such as around mile marker 53 where one lane was noticeably higher and more variable than the other. The representative deflections (i.e., mean plus 2 standard deviations) on this road indicate pavements with good structural capacity at the north end, and very good structural capacity at the south end.

Localized Weak Section on NH 103

Figure 7 shows the RWD deflections and the variable conditions of State Route 103. Mile zero was referenced to the traffic circle near the state park at the west project end. According to NHDOT's records, this is a thin pavement section with AC thicknesses ranging from 3.5 to 6 in. The pavement condition reflected this, as there were several areas with significant cracking. The RWD deflections show a localized weak area around miles 2 to 3, and again between miles 11 and 14. The RWD's video confirmed extensive pavement distress in these areas. Overall, deflections on this road typically ranged from 11 to 18 mils, with deflections greater than 20 mils in the localized weak areas.

Repeat Runs on NH 3A

Due to the RWD being stored at the NHDOT Bow Maintenance Shed, multiple RWD runs were performed on the section of State Route 3A from the Bow Shed to Hackett Hill Road, southbound. Figure 8 displays the data. Multiple runs showed good consistency in RWD deflections, once the deflections had been normalized to a standard temperature to account for different thermal conditions between test runs. Overall, deflections ranged from 8 to 18 mils with the lower, more uniform deflections between mile 0 and 1.5 (mile 0=Hackett Hill Road), and higher deflections from mile 1.5 to the shed. Video confirmed much pavement distress in the higher deflection areas, including fatigue cracking in the vehicle wheel paths. The representative deflection of approximately 17 mils for this route indicates a pavement with fair structural capacity.
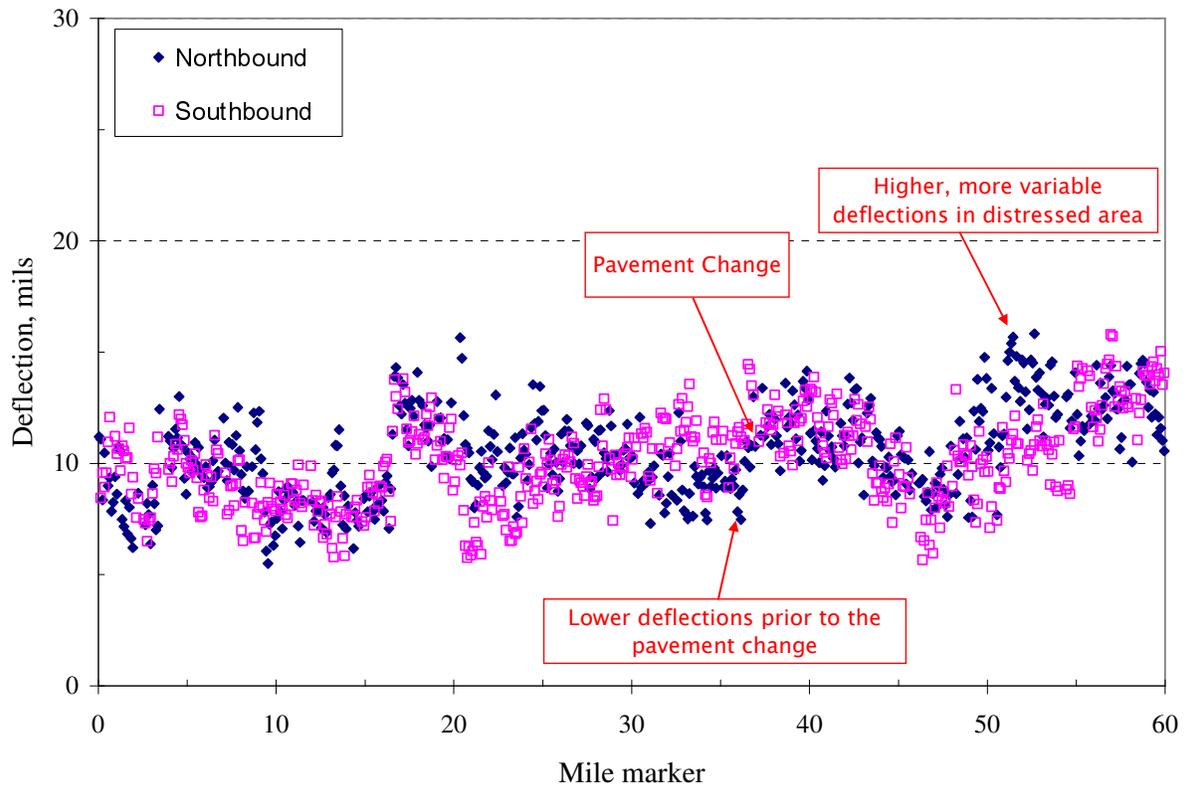
Figure 6. I-89 northbound—(from left to right) A pavement change corresponding to a change in deflections at mile marker 36.4. Lower deflections prior to the pavement change at mile marker 34.6. A distressed area with higher, more variable deflection at mile marker 51.
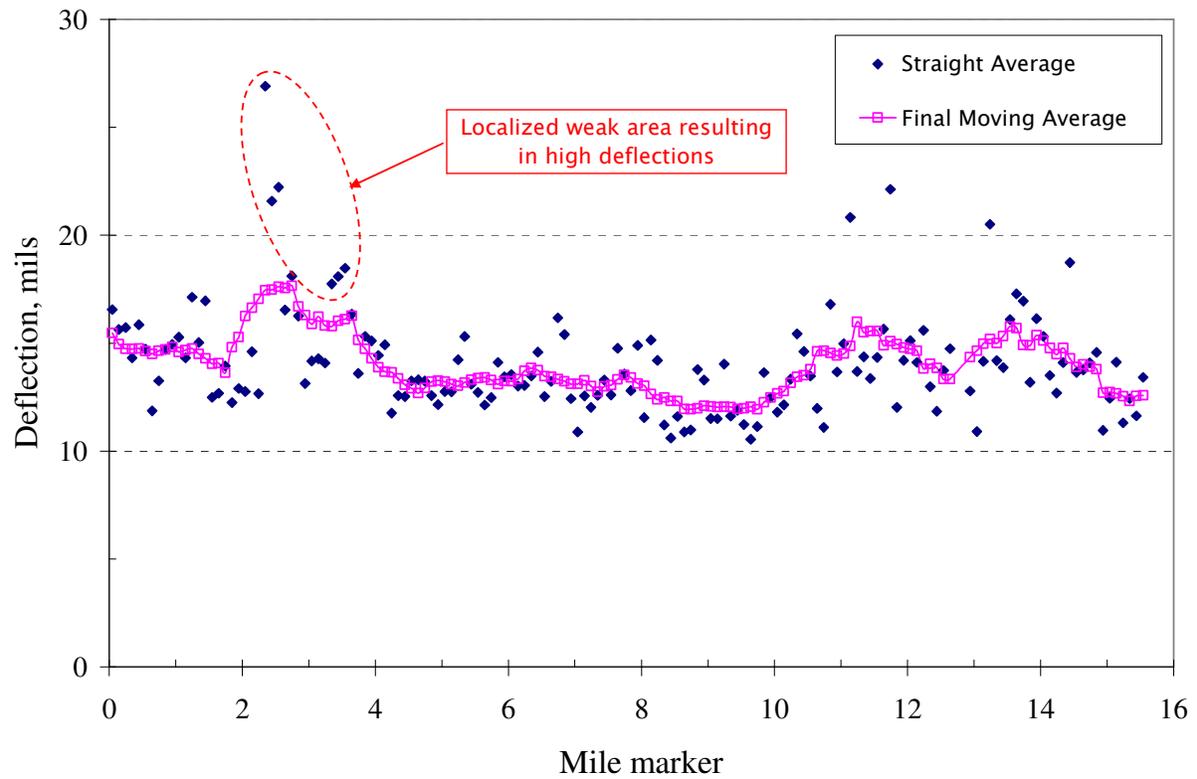
Figure 7. State Route 103 eastbound—A localized weak area resulted in high deflections about 3 miles east of the traffic circle/park.
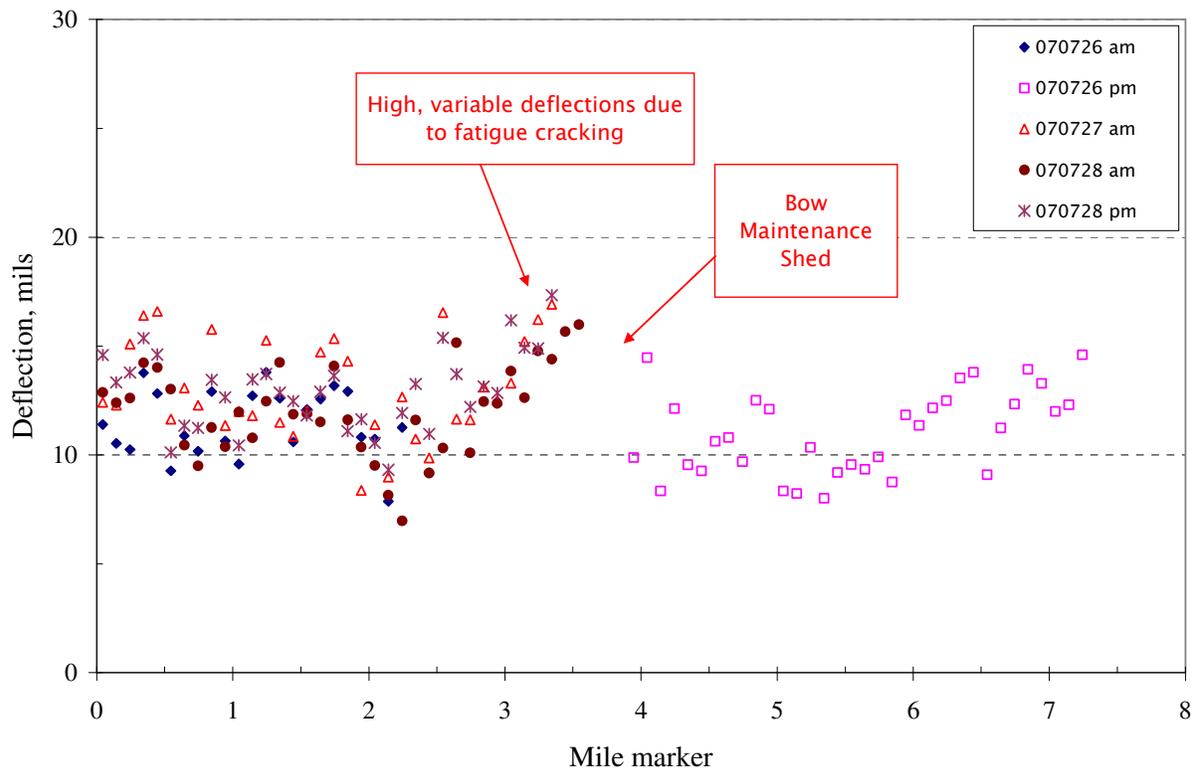
Figure 8. NH 3A southbound—Fatigue cracking in the outer wheel path resulted in high, variable deflections just south of the Bow Maintenance Shed.

Statistical Summary

Figure 9 presents a statistical summary for all 25 road sections tested. For each section, the mean deflection and a range representing +/- 2 standard deviations is displayed. Therefore, the higher the mean value, the weaker the pavement structure. Likewise, the wider the vertical band, the higher the deflection variability within the section. In general, it is desirable to have pavements with low deflections and good uniformity (i.e., low standard deviations). The data show that mean deflections ranged from 7 to 15 mils, with the lower deflections generally occurring on the thicker pavements and the higher deflections occurring on the thinner or deteriorated pavements.
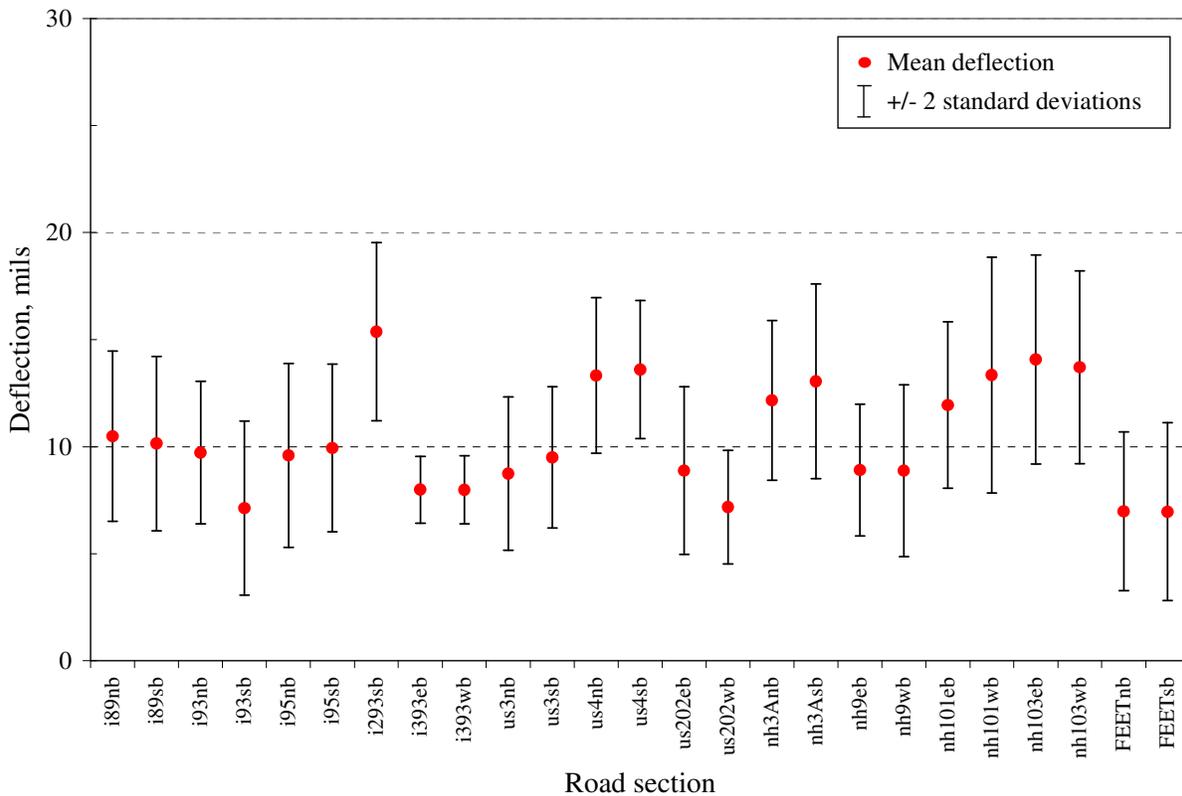
Figure 9. Statistical summary of the mean deflection and variability of each road.

From a pavement performance point of view, the upper limit of pavement deflections is actually more indicative of expected performance than mean values, as the weaker pavement areas are expected to show structural distress first. Therefore, by defining the section's representative deflection as its mean plus 2 standard deviations (i.e., the 98th percentile), section variability is also taken into account. Figure 10 displays the 25 pavement sections ordered by their representative deflection, lowest to highest. The values range from 10 to 20 mils. Subjective ratings describing the structural capacity of each deflection level (e.g., excellent to very poor) have been assigned to each deflection increment of 5 mils.
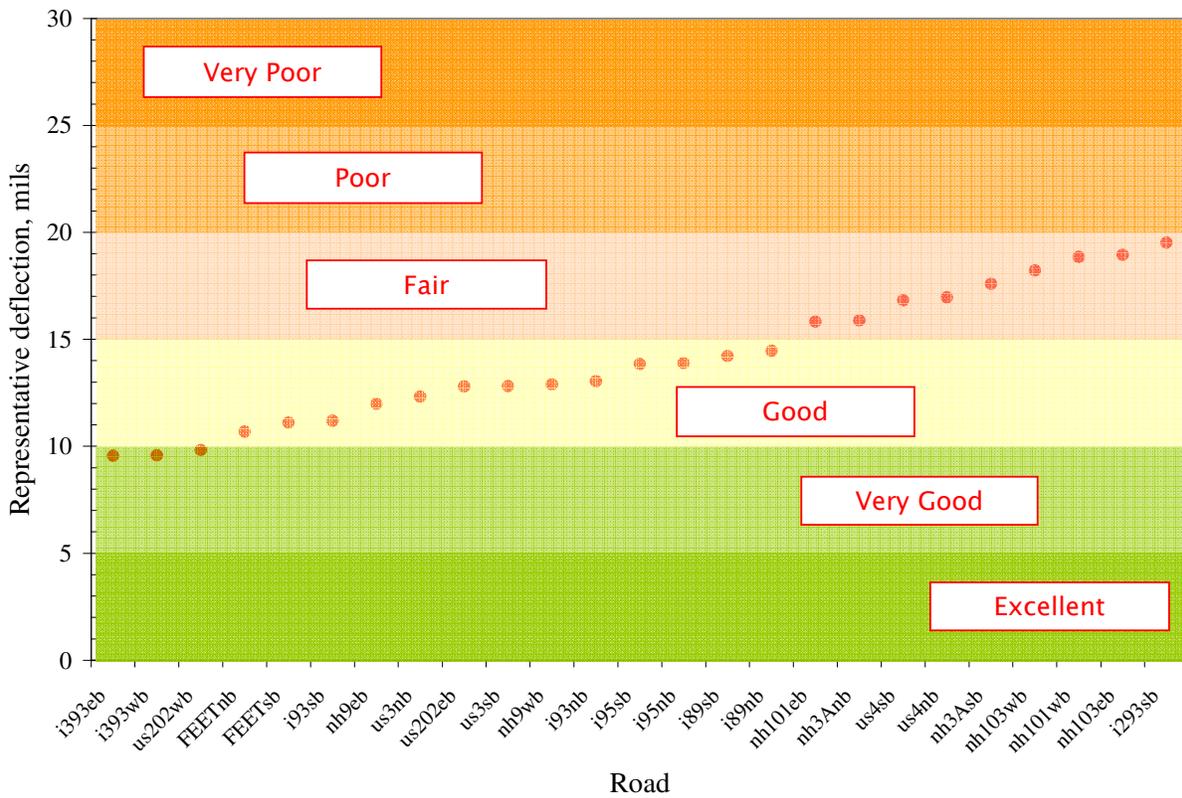
Figure 10. The structural capacity of each section can be characterized by its representative deflection (i.e., mean deflection plus 2 standard deviations).

POTENTIAL USES OF RWD DATA

The RWD provides an efficient means of collecting continuous pavement deflections over a large number of roads, thereby providing pavement structural capacity data not previously available for network-level evaluation and management. As this data has become available, the methods and techniques to use this information in pavement management are also being developed. Several manners of incorporating RWD data into pavement management practices include:

- **Treatment matrices**: This was recently performed on an RWD-based pavement management implementation for Champaign County, IL. RWD data were used in conjunction with visual condition ratings to determine when pavement maintenance and rehabilitation should be performed and appropriate strategies for individual pavement sections (for example, maintenance, surface treatments, overlays, or reconstruction).

- **Pavement preservation:** There is interest from state agencies in using the RWD to identify which roads are suitable candidates for pavement preservation (i.e., maintenance and surface treatments), as opposed to those that require structural improvement. Obviously, if a road lacks structural adequacy, then pavement preservation is not an effective expenditure of funds. The RWD could be used to establish threshold deflection values for when pavement preservation is appropriate, given a specific traffic level.

- **RWD-based structural ratings:** Structural ratings can be applied to different deflection levels to describe a road's structural capacity. For example, deflections from 0 to 10 mils, 10 to 20 mils, and 20 to 30 mils represent pavements with High, Medium, and Low structural capacities, respectively. These ratings could be customized for each agency and other factors, such as traffic level.

The data collected as part of this study, along with NHDOT's pavement management experience, present an excellent opportunity to develop these methodologies.

APPENDIX A

RWD Deflection Profiles

I-89.
Northbound travel and passing lanes.

I-89.
Southbound travel and passing lanes.

A.1

I-89.
Northbound and southbound travel lanes.

I-93.
Northbound travel and passing lanes.

A.2
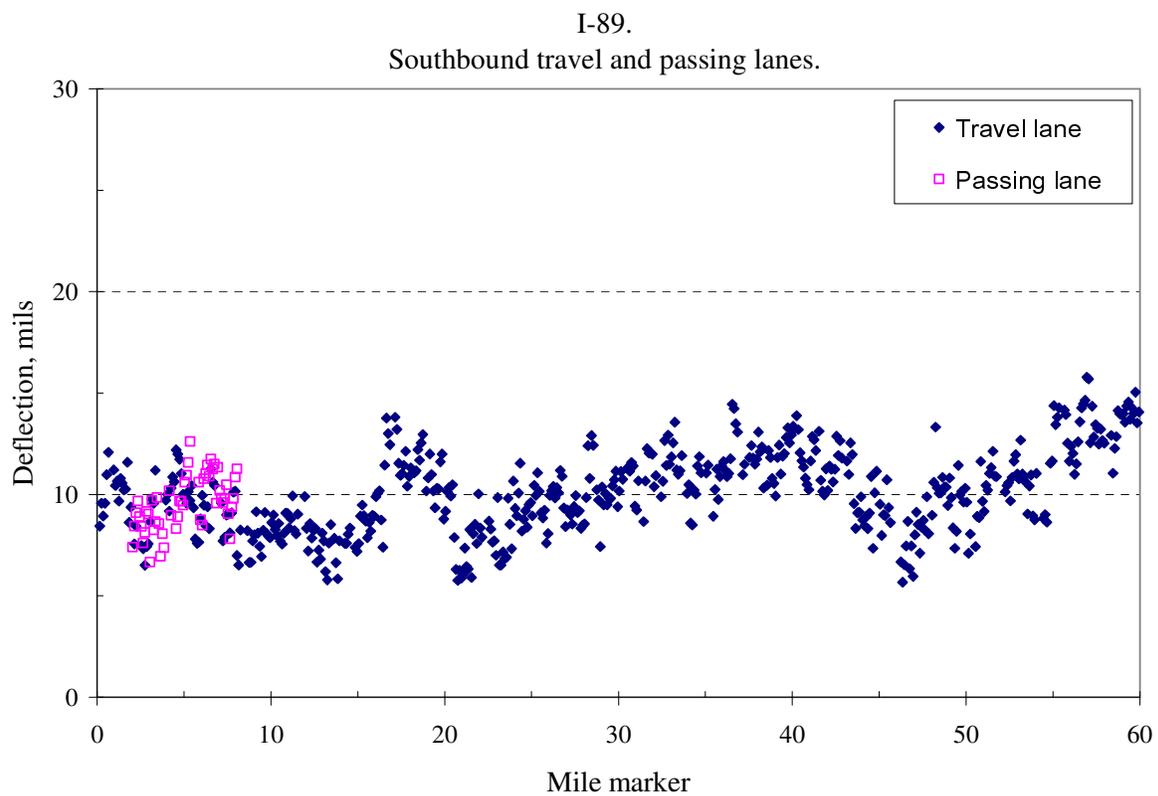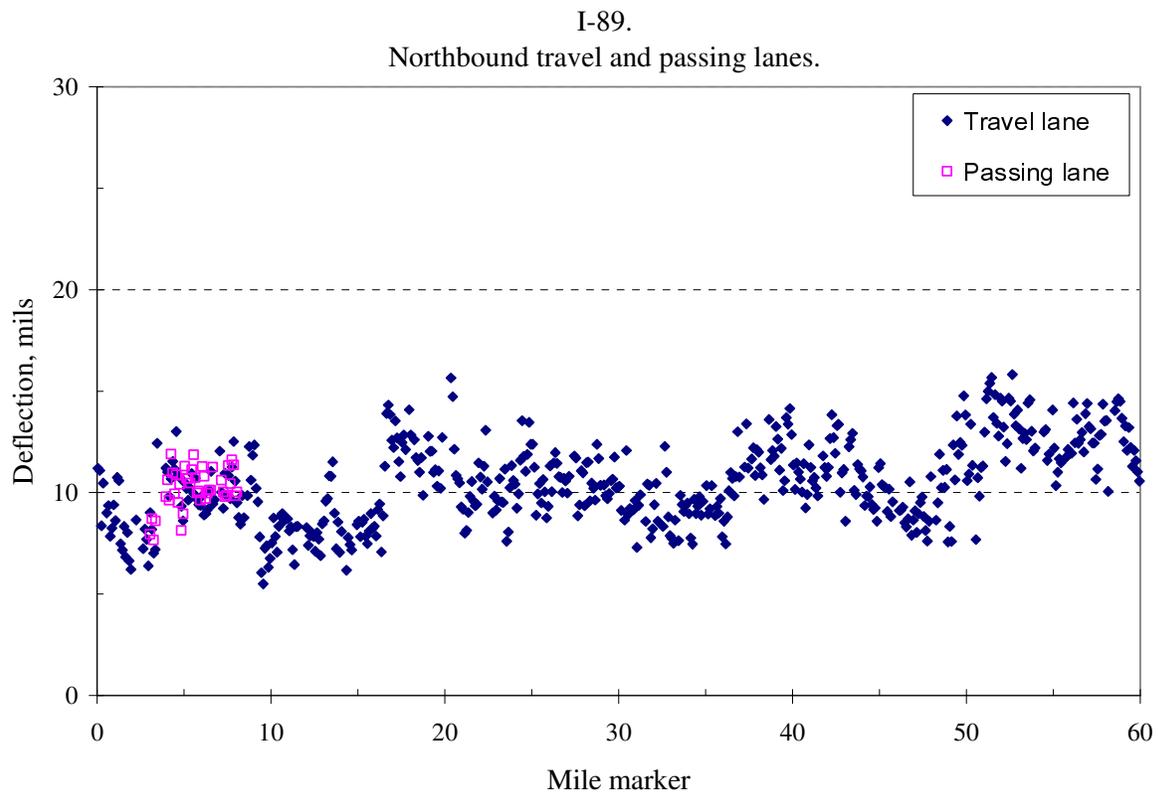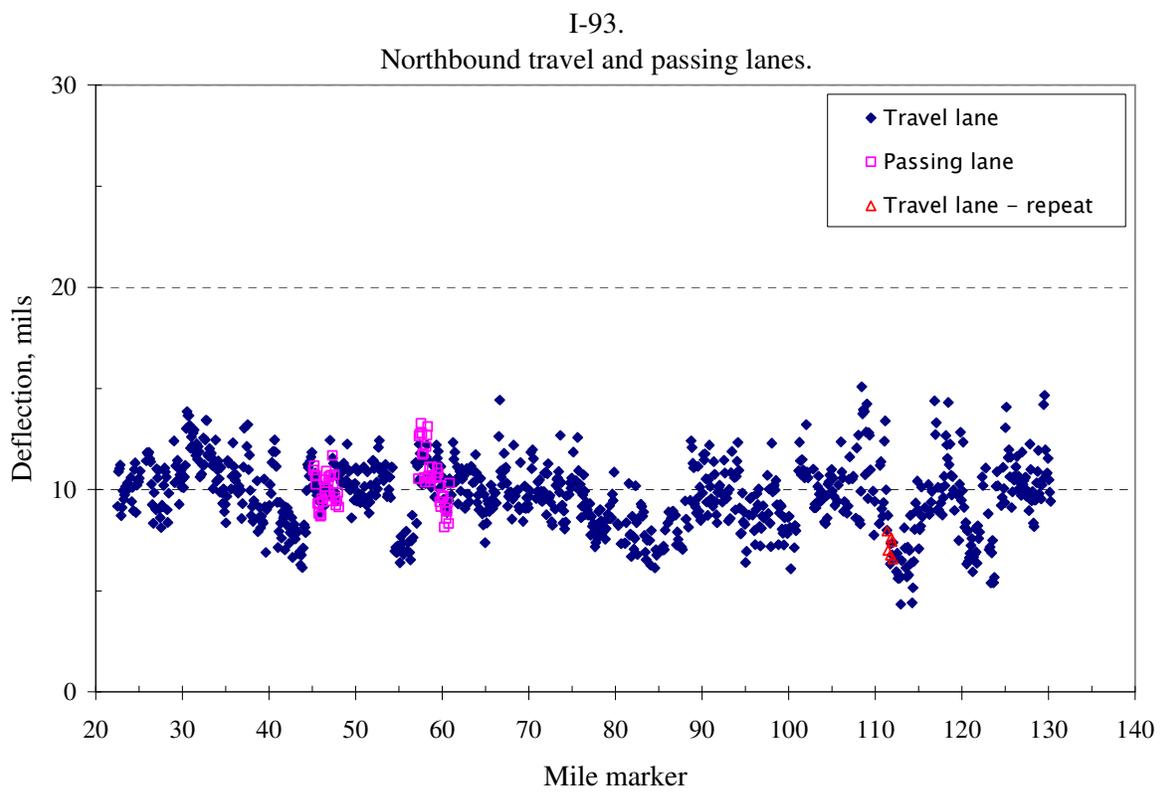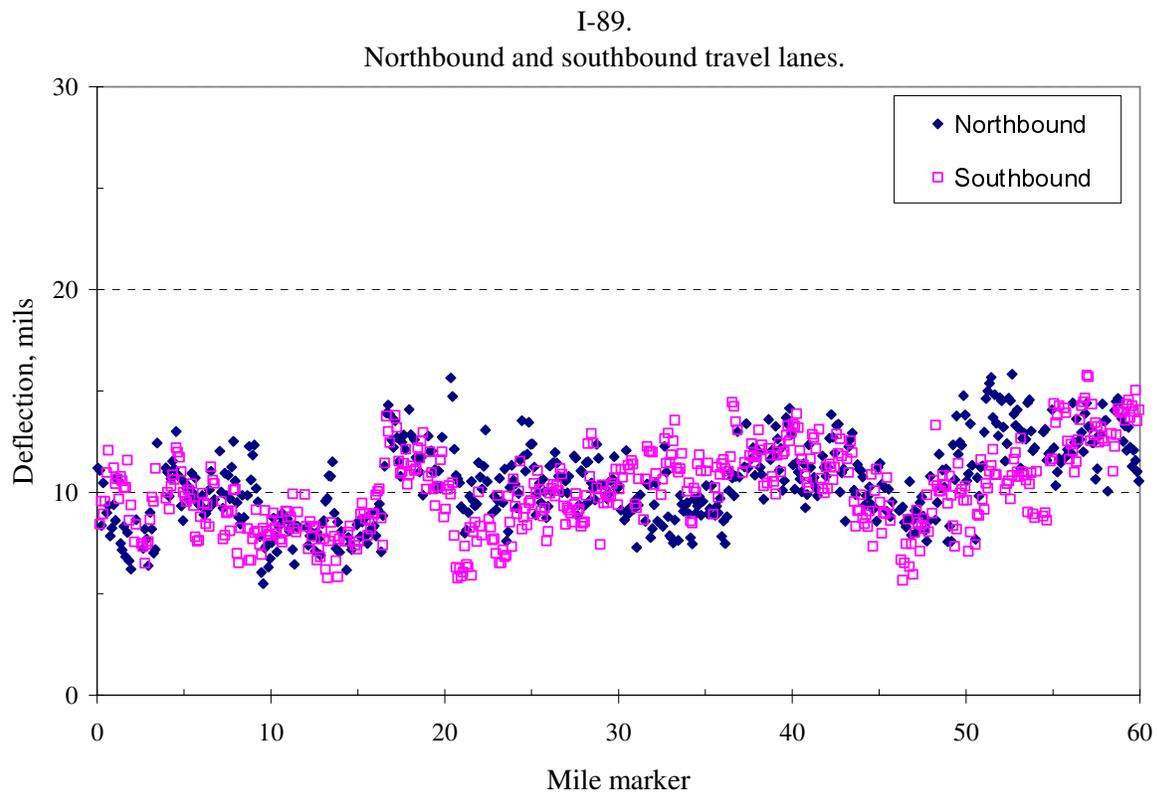
I-93.
Southbound travel and passing lanes.
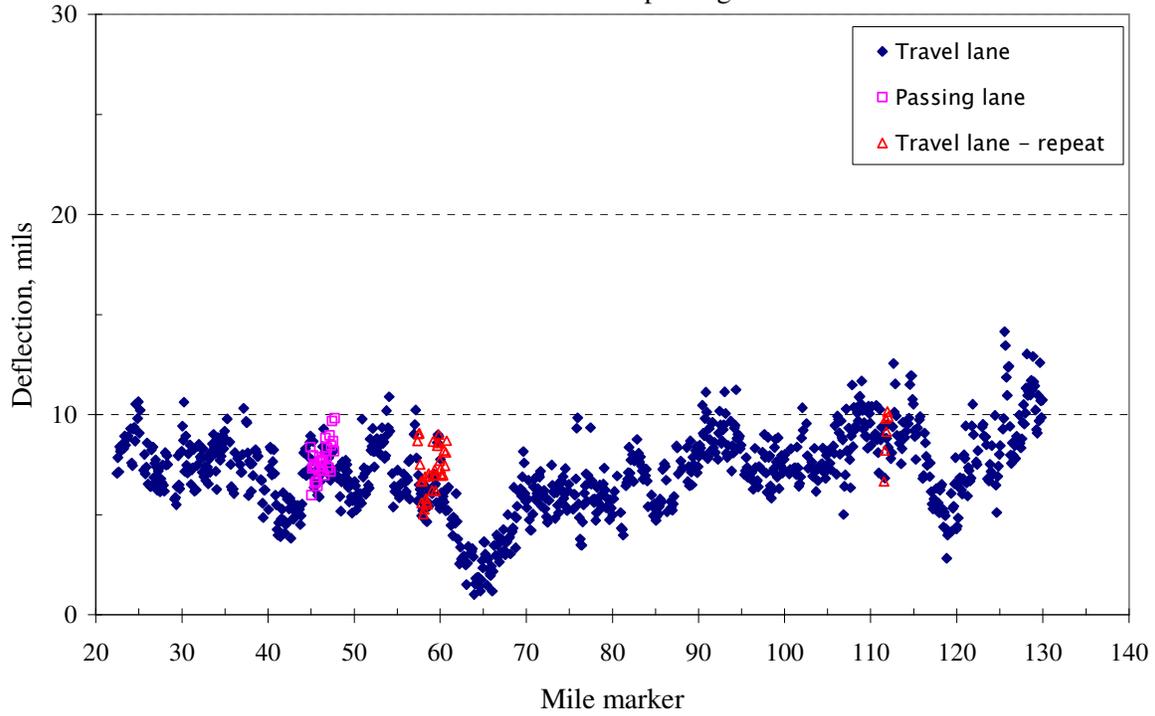
I-93.
Northbound and southbound travel lanes.

A.3
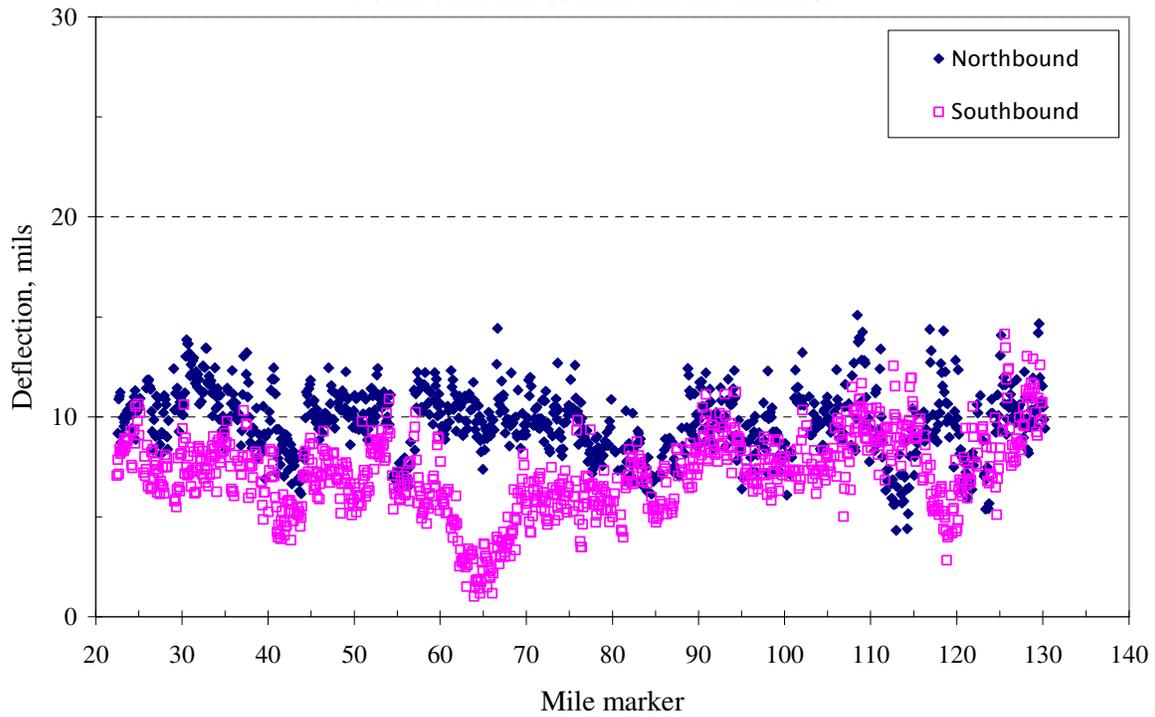
I-95.
Northbound travel lane.
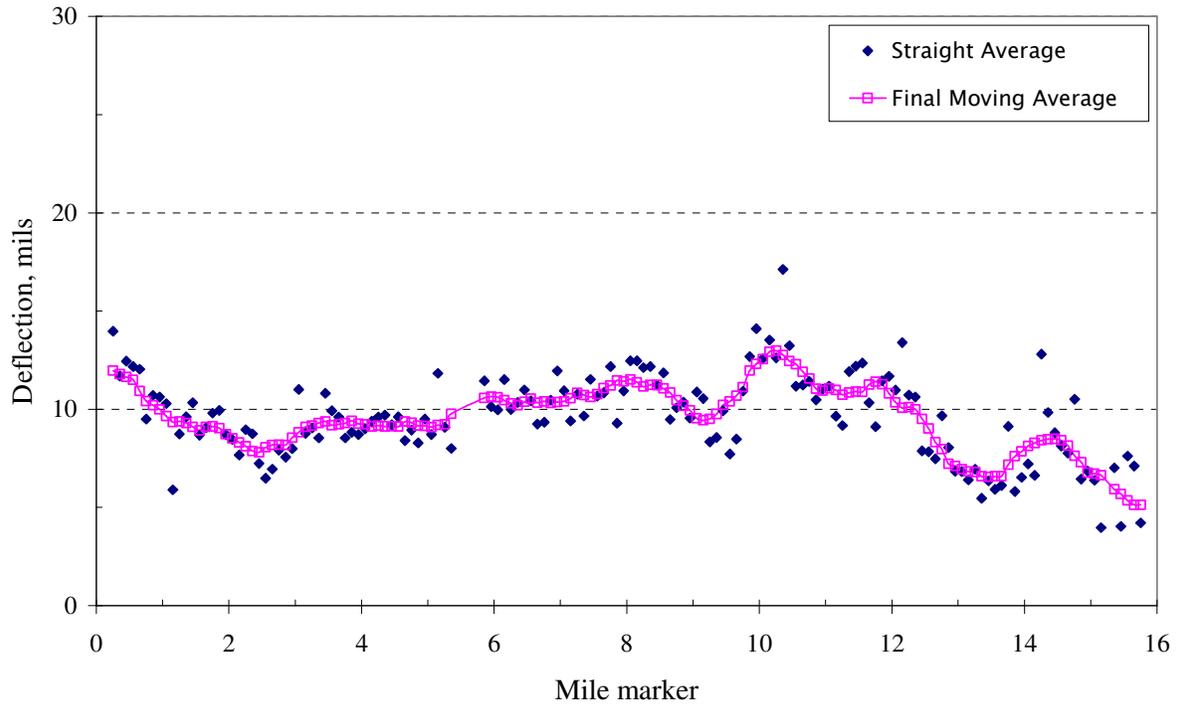
I-95.
Southbound travel lane.

A.4
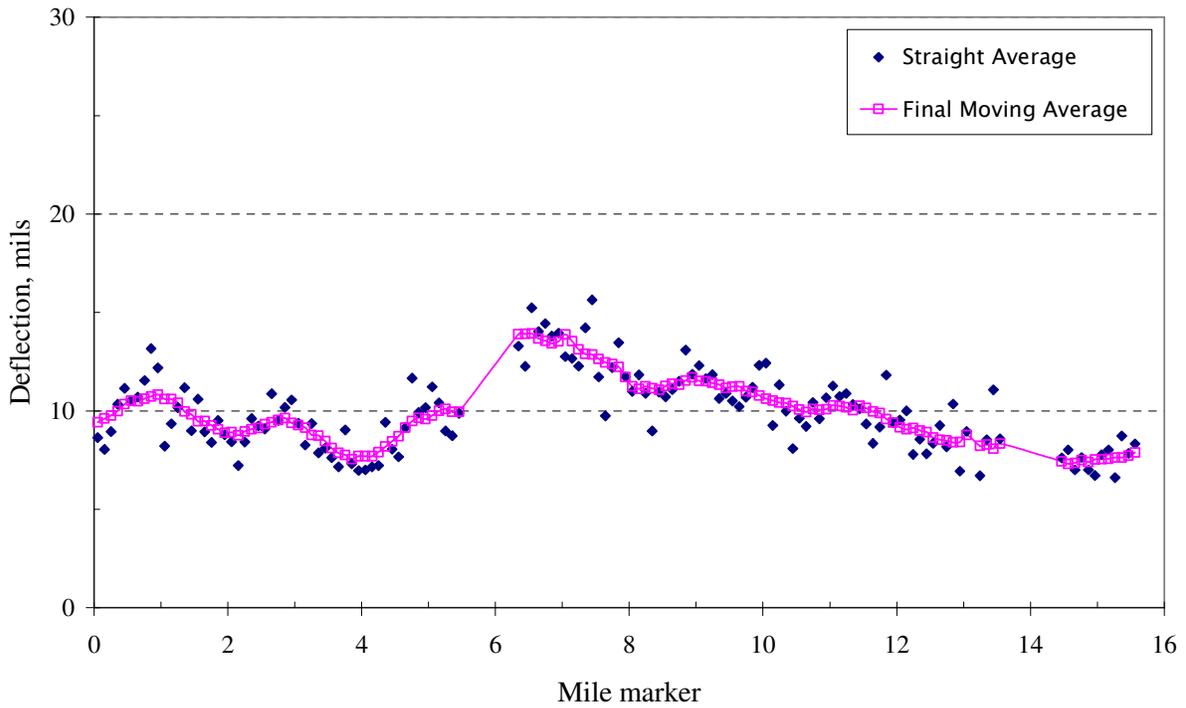
I-95.
Northbound and southbound travel lanes.
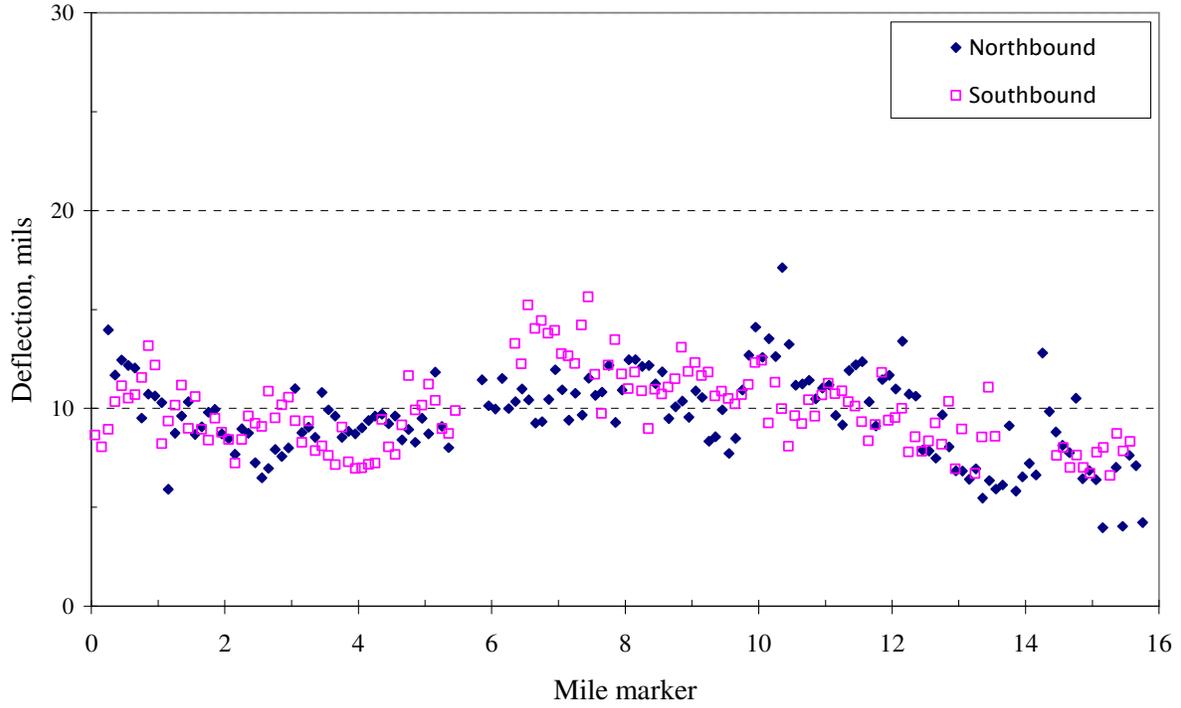
I-293.
Southbound travel lane.

A.5
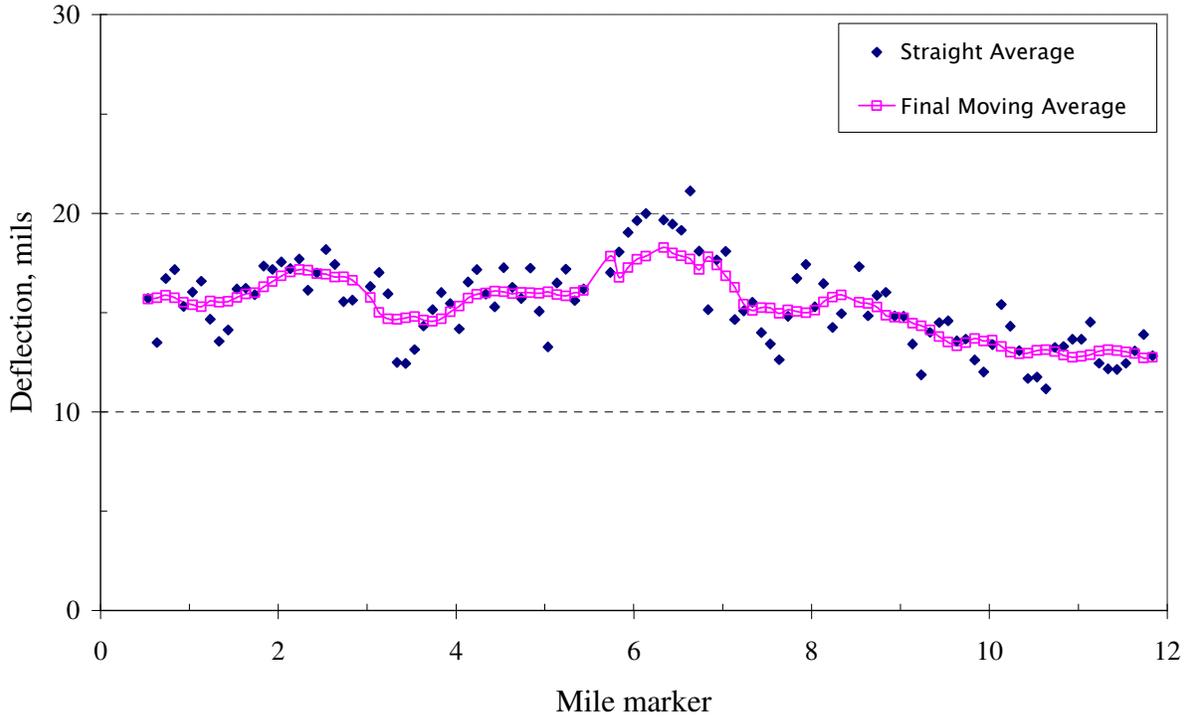
I-393.
Eastbound travel lane.
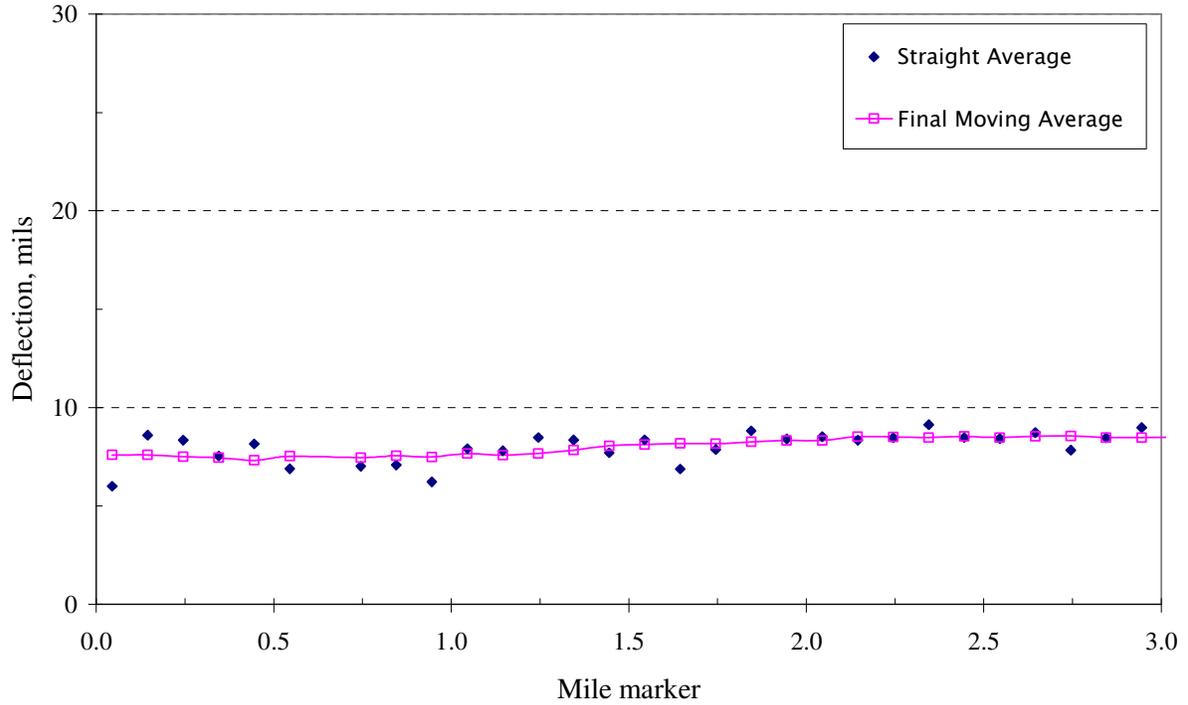
I-393.
Westbound travel lane.

A.6
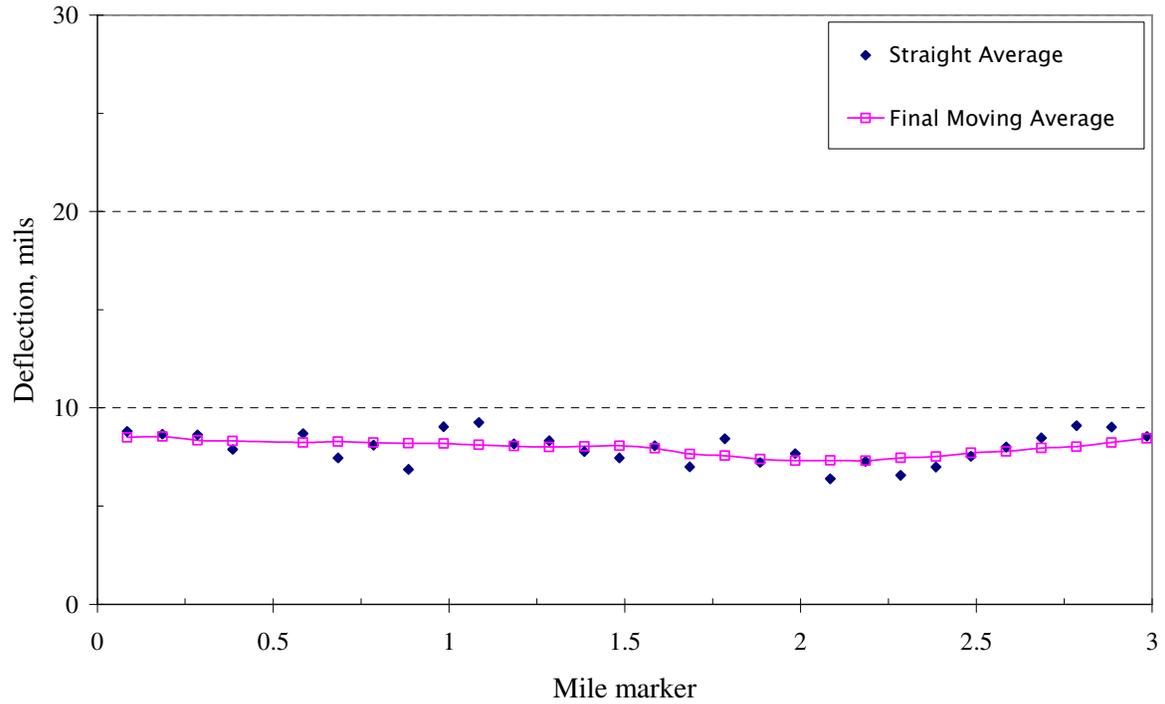
I-393.
Eastbound and westbound travel lanes.

US 3.
I-93 to US 302 - northbound.

A.7
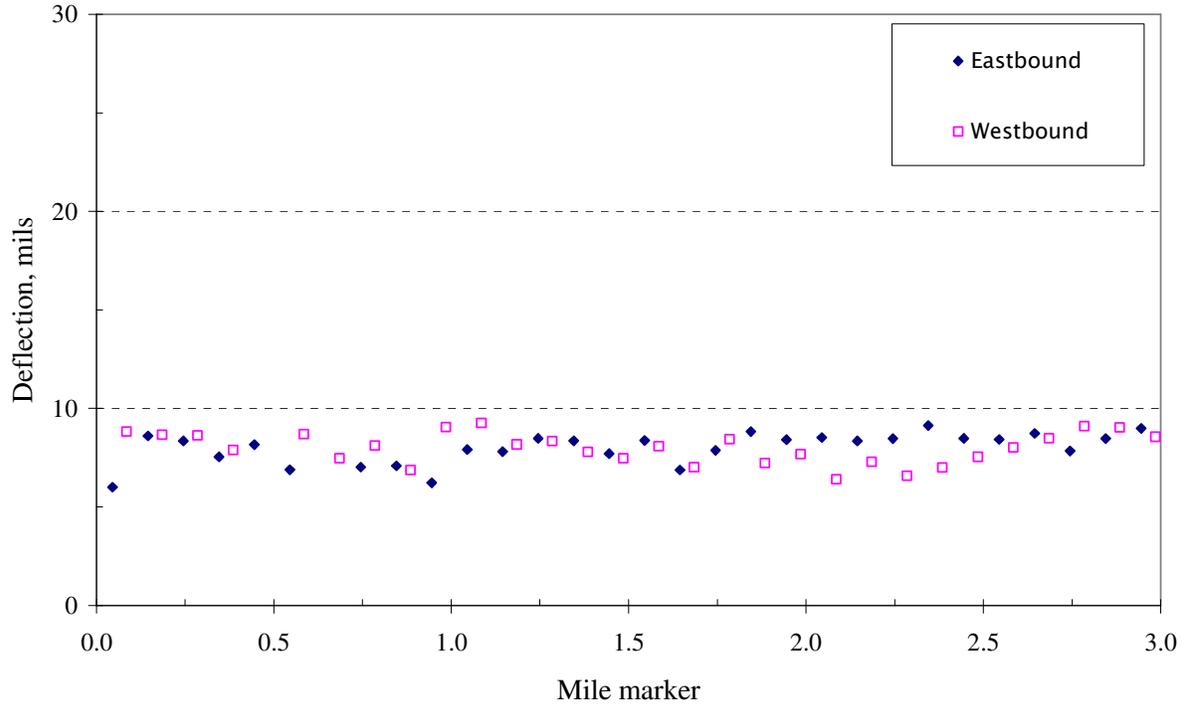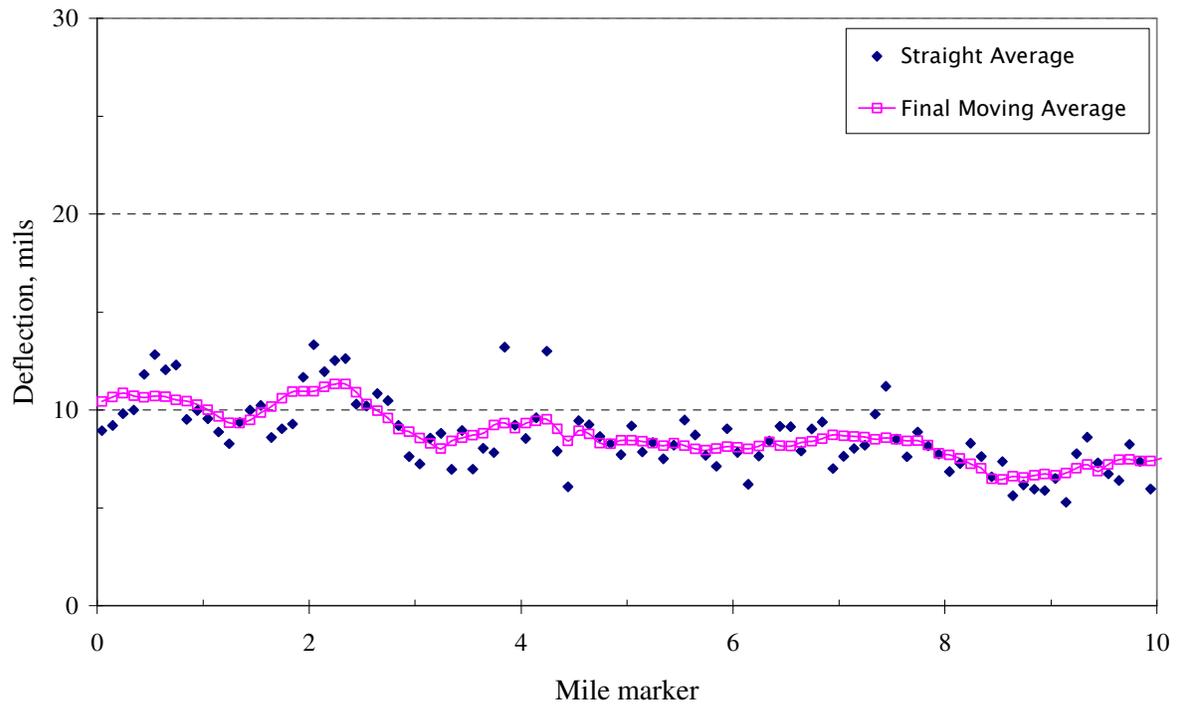
US 3.
US 302 to I-93 - southbound.
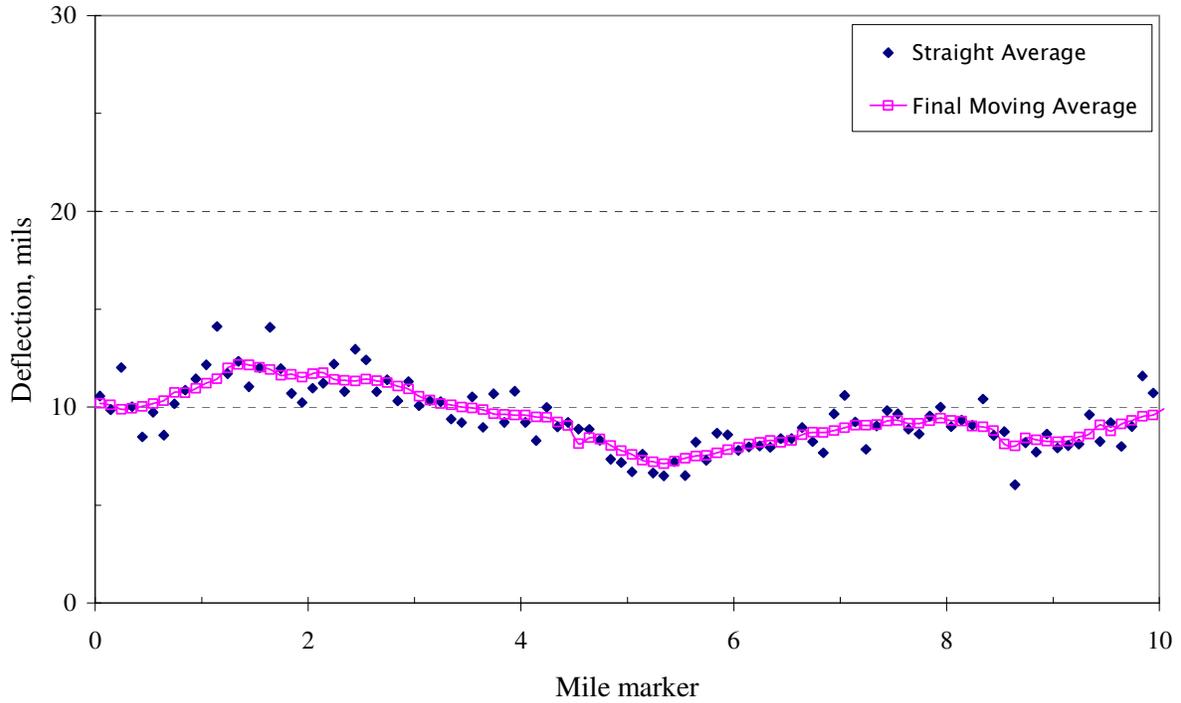
US 3.
I-93 to US 302 - northbound and southbound lanes.
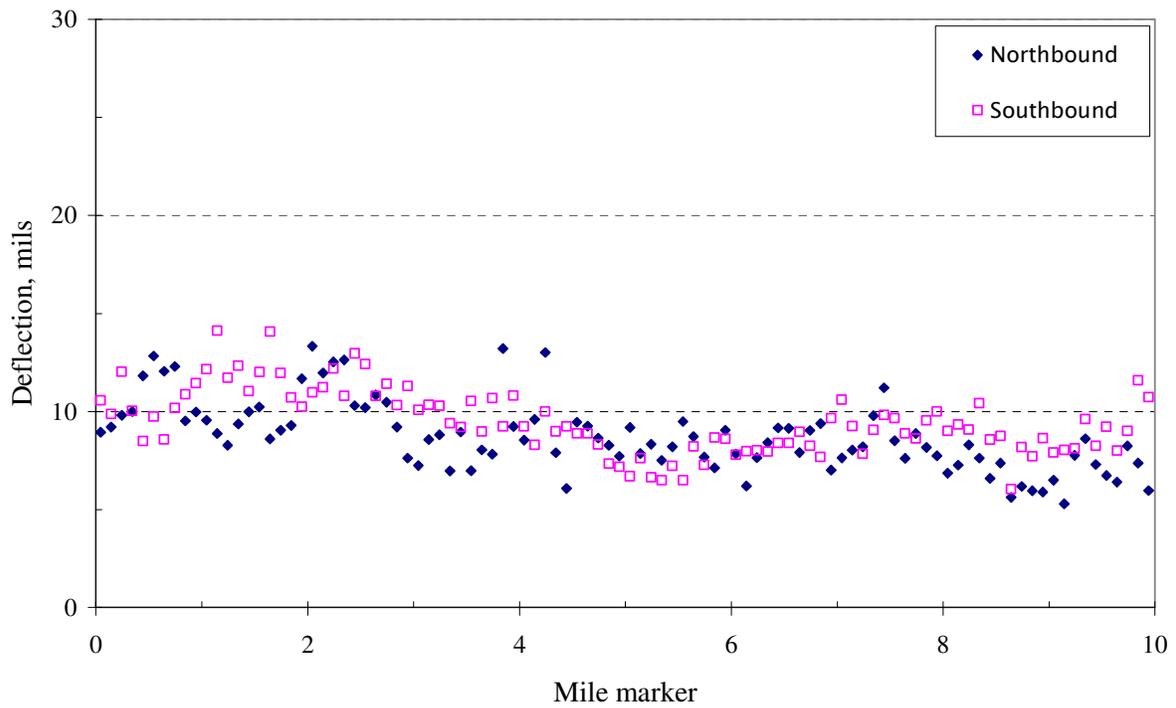
US 4.
I-95 to Exit 9 - northbound.
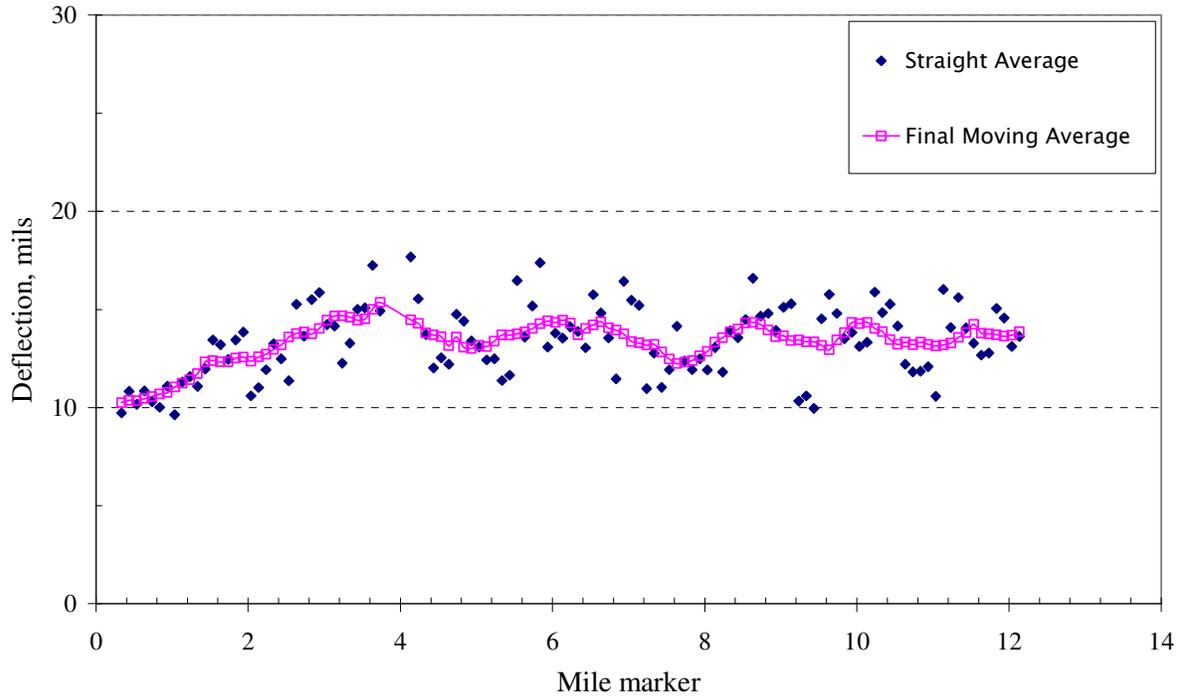
US 4.
Exit 9 to I-95 - southbound.

A.9
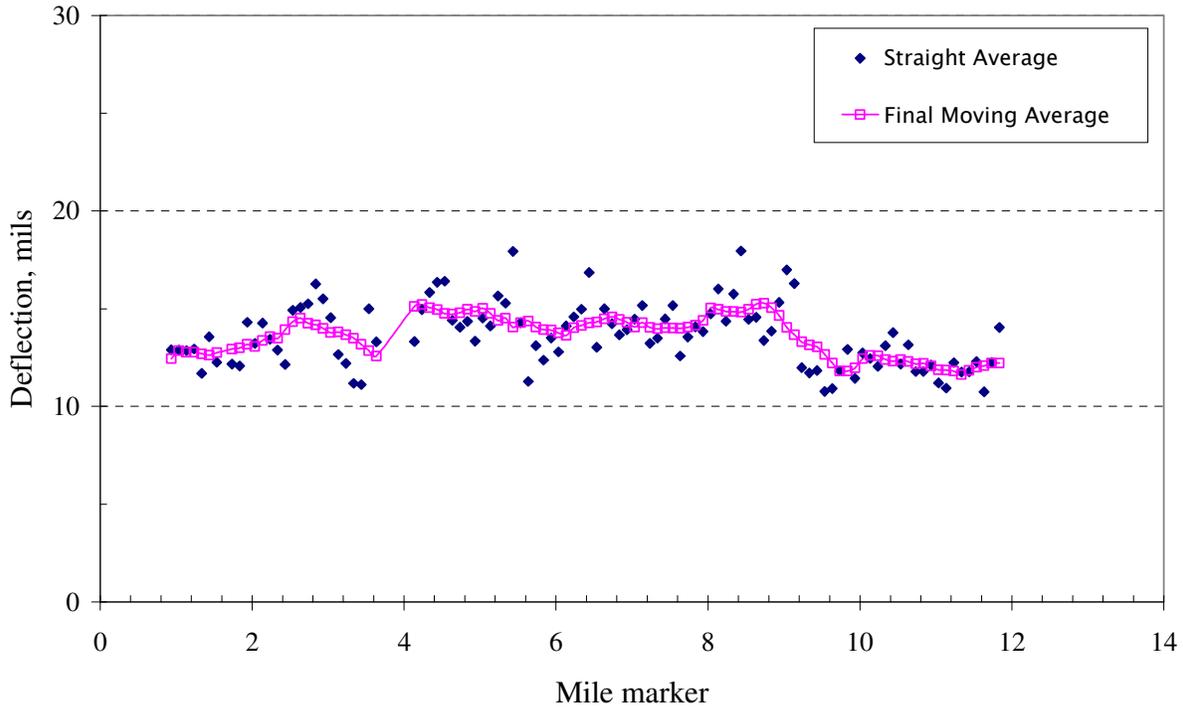
SR 3A.
Hackett Hill Rd. to Bow Shed - northbound.
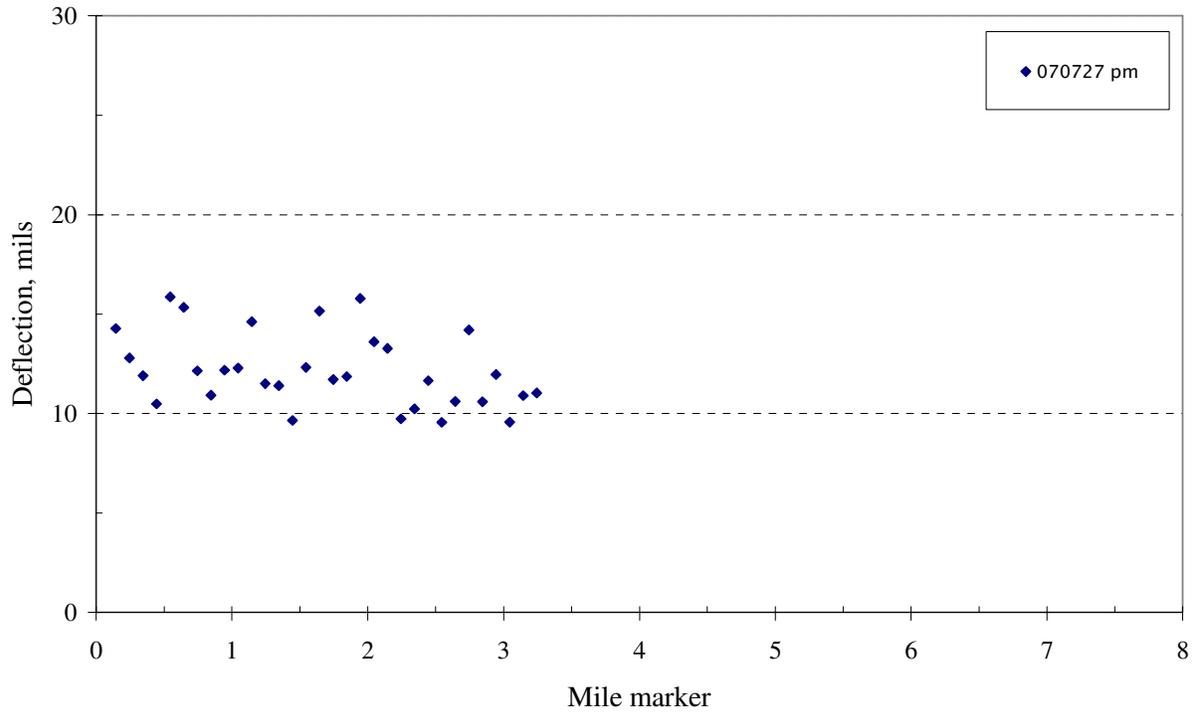
SR 3A.
I-89 to Hackett Hill Rd. - southbound.

A.10
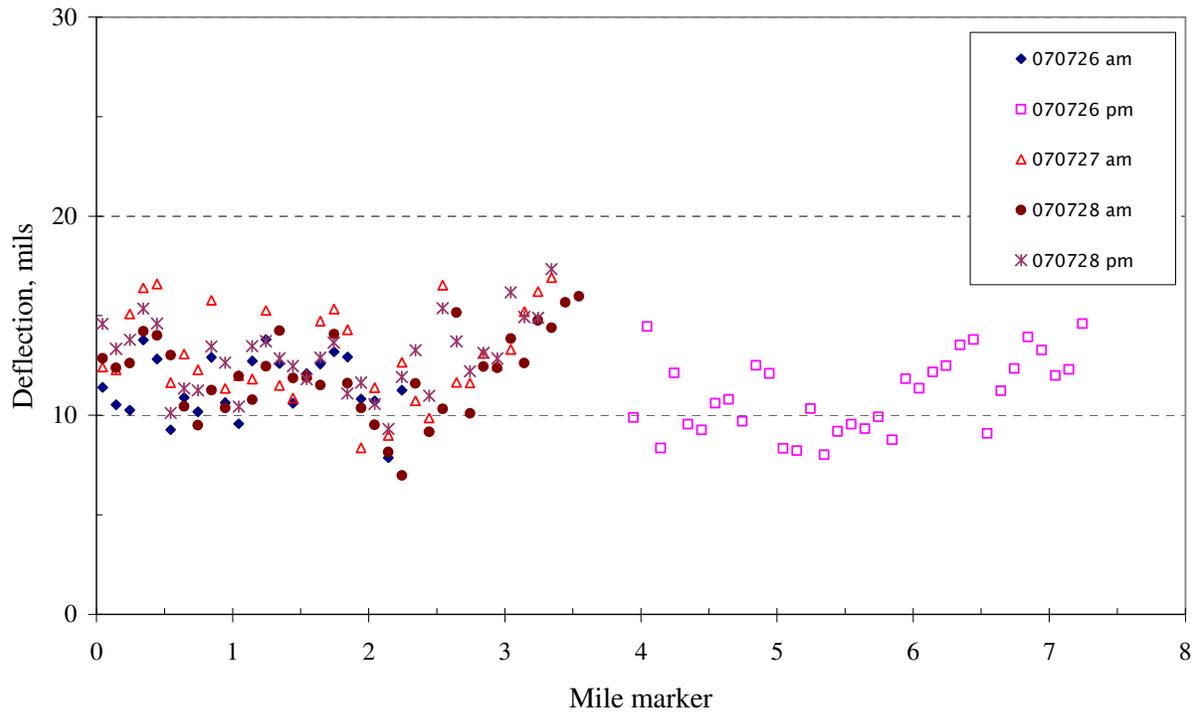
NH 9.
Rest Area to US 202 - eastbound.
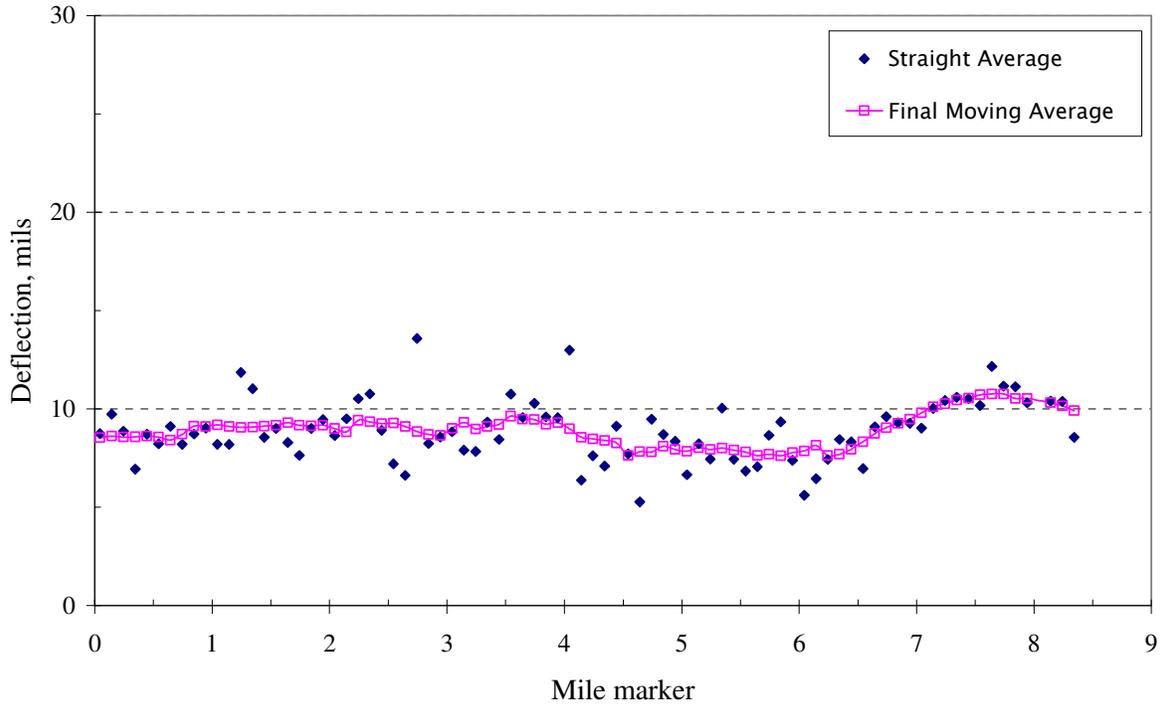
NH 9.
Rest Area to US 202 - westbound.

A.11
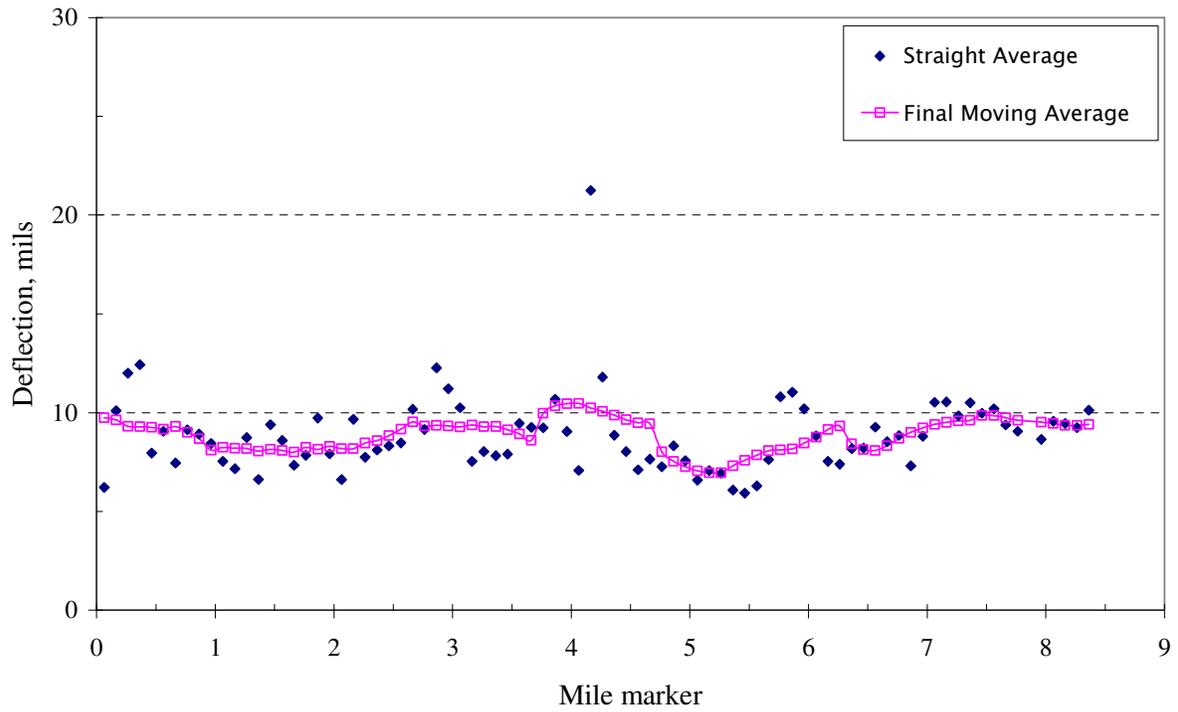
NH 9.
Rest Area to US 202 - eastbound and westbound lanes.
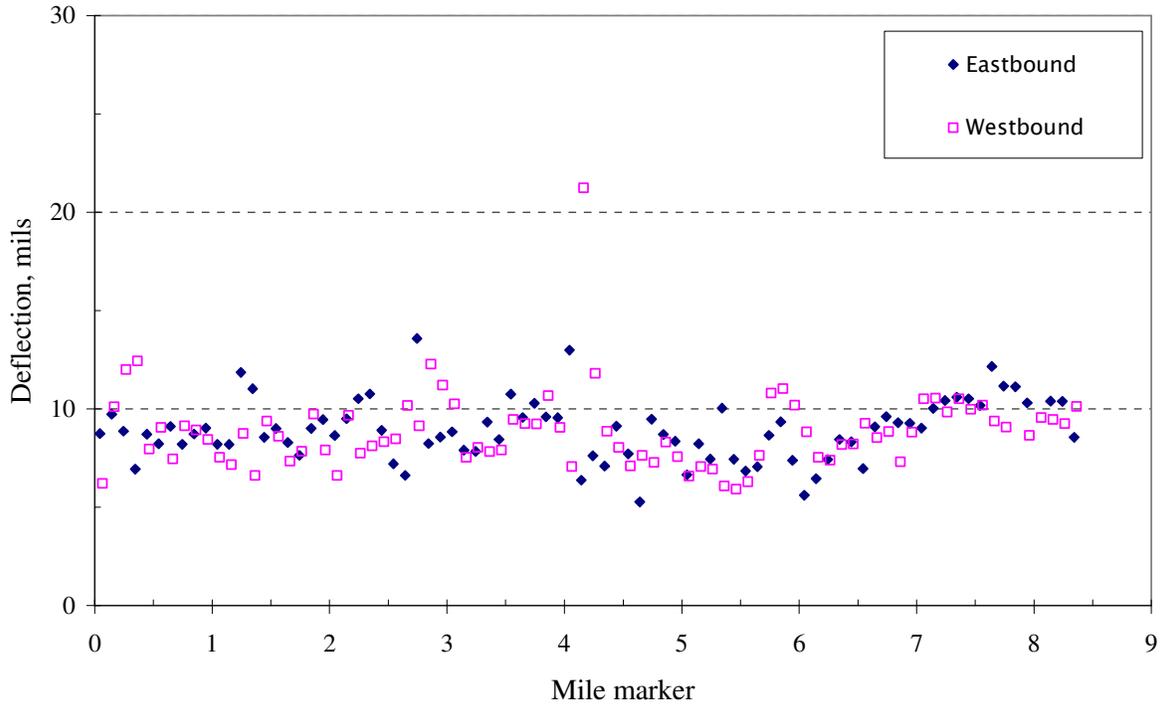
NH 101.
Eastbound travel and passing lanes.
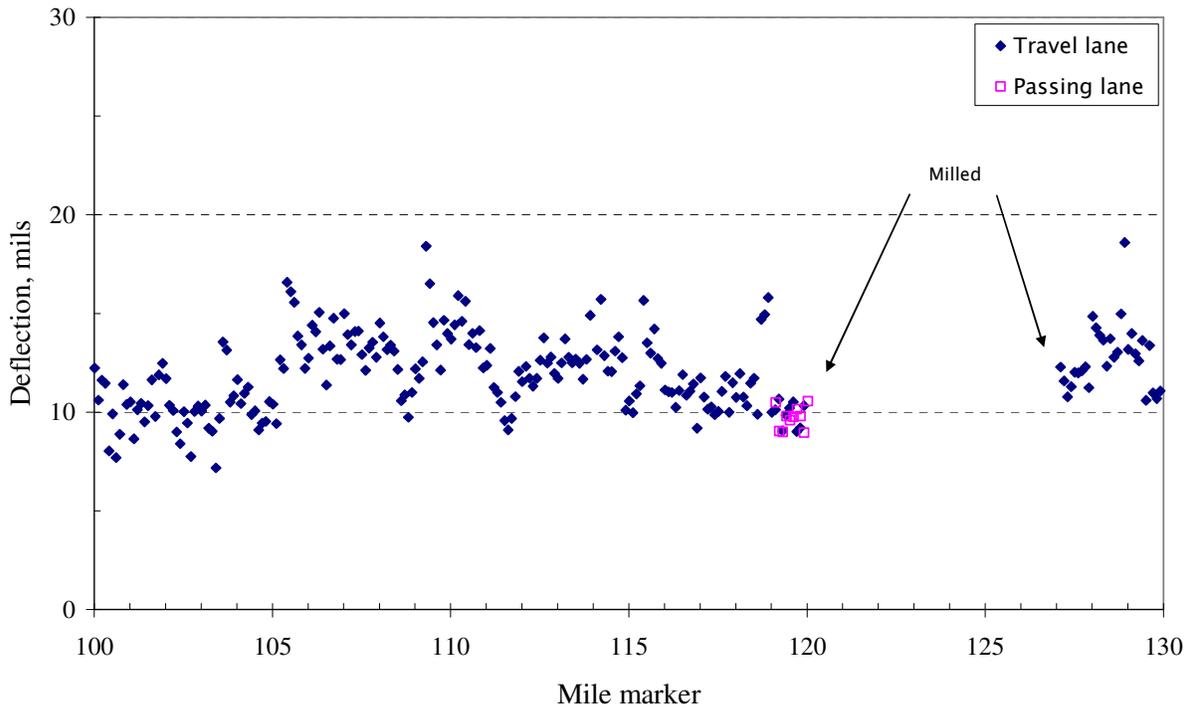
NH 101.
Westbound travel and passing lanes.
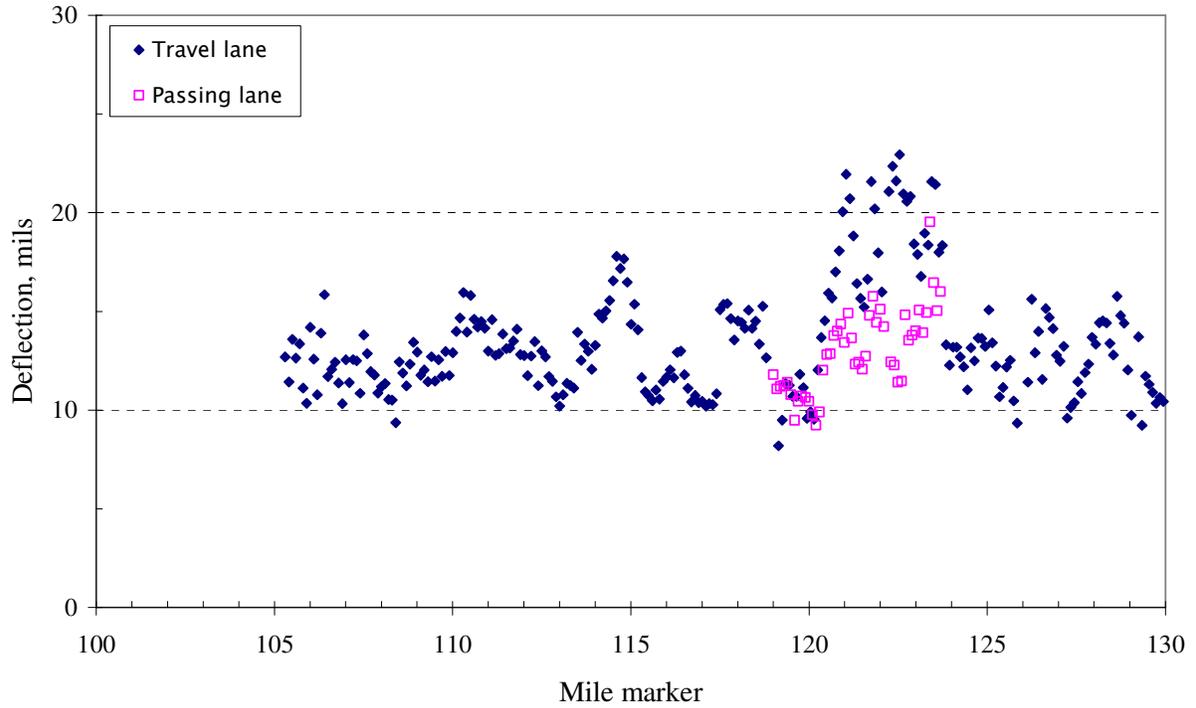
NH 101.
Eastbound and westbound travel lanes.
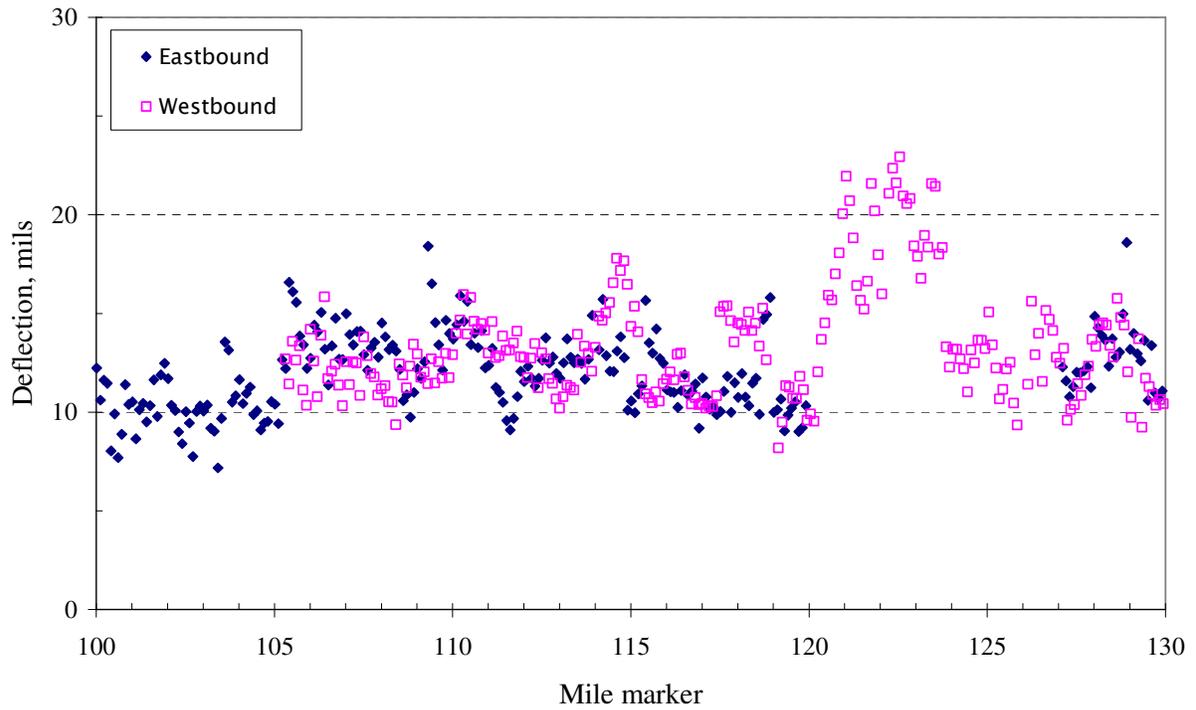
NH 103.
Traffic Circle/Park to I-89 - eastbound.
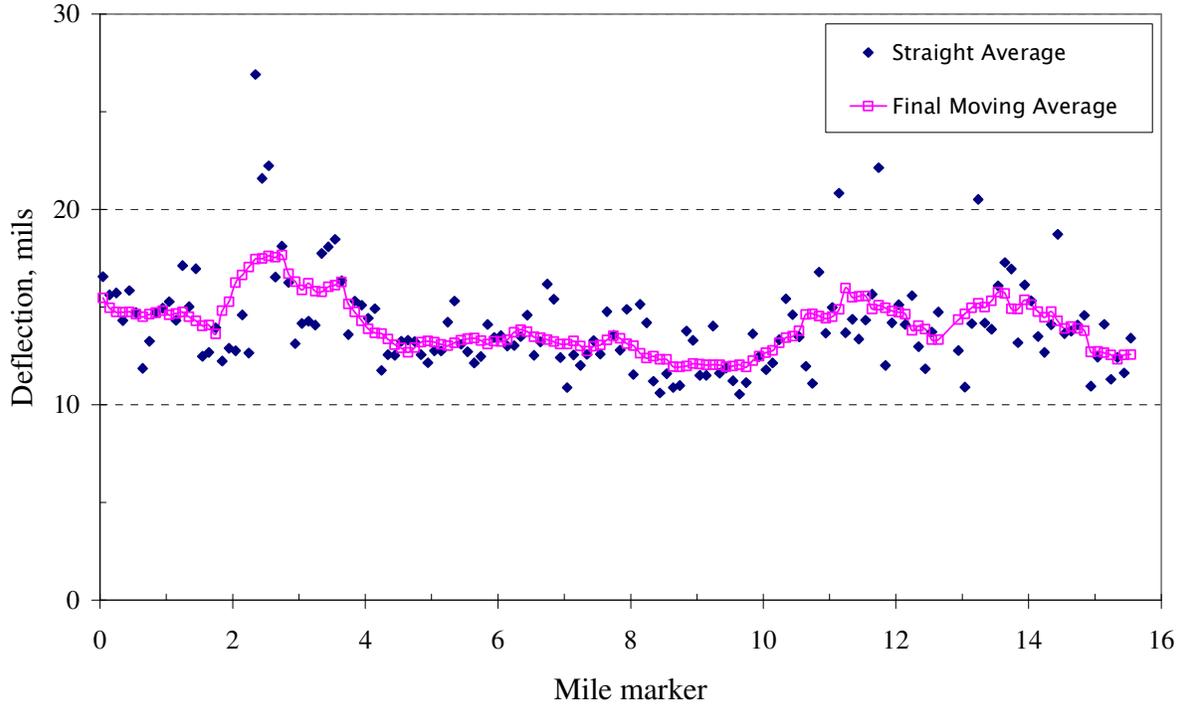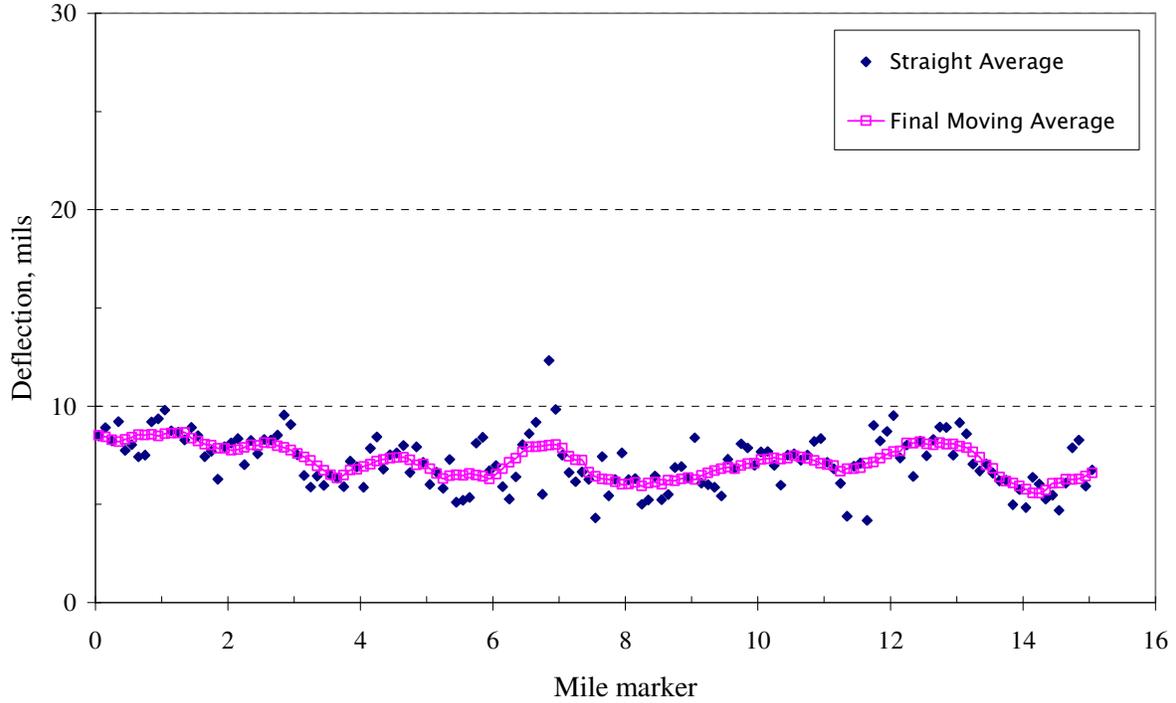

NH 103.
I-89 to Traffic Circle/Park - westbound.

A.14
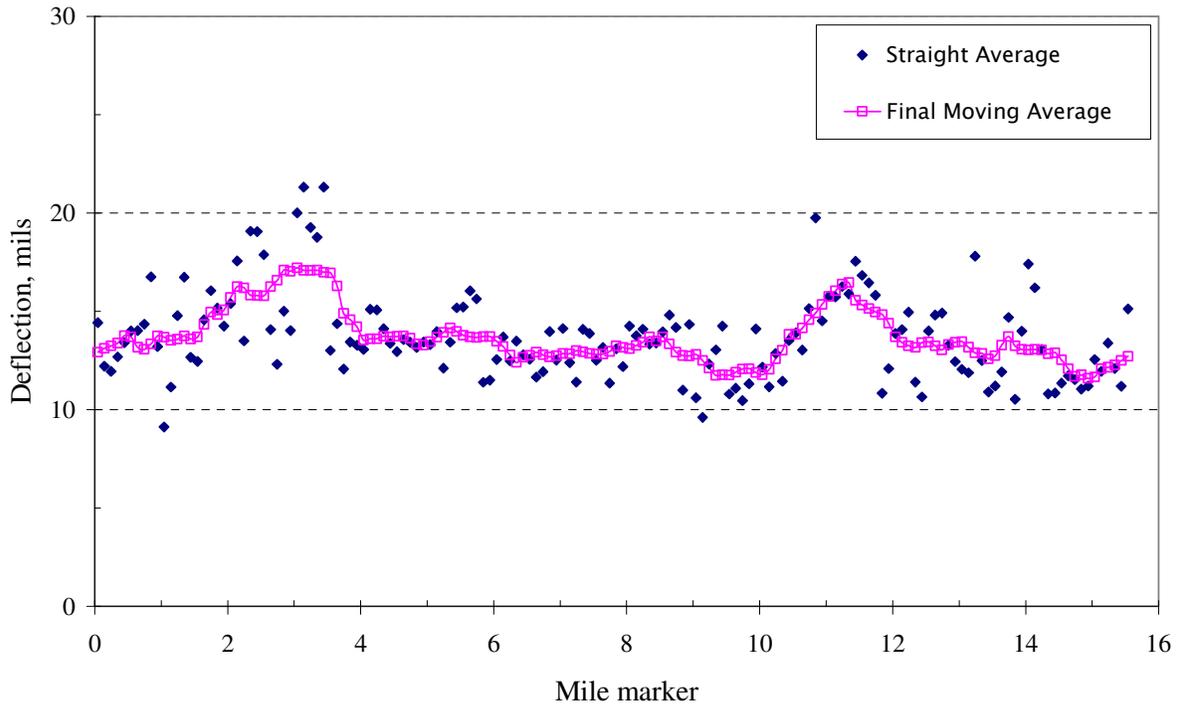
NH 103.
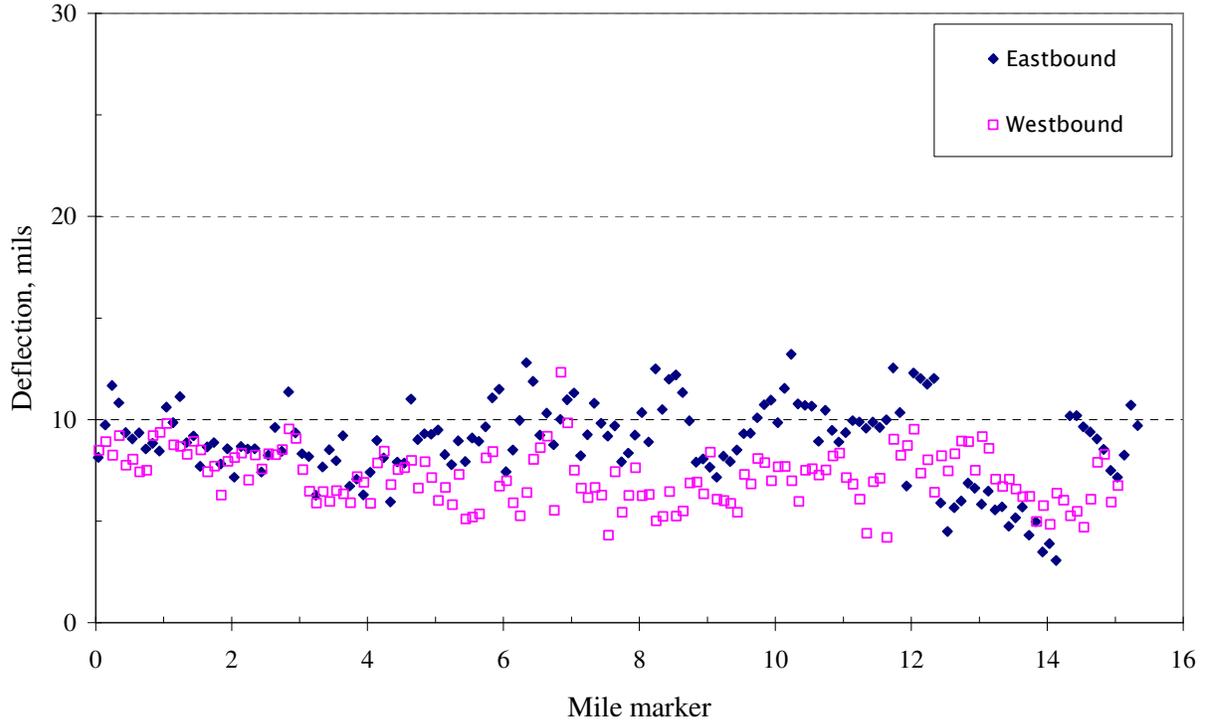### Traffic Circle/Park to I-89 - eastbound and westbound lanes.
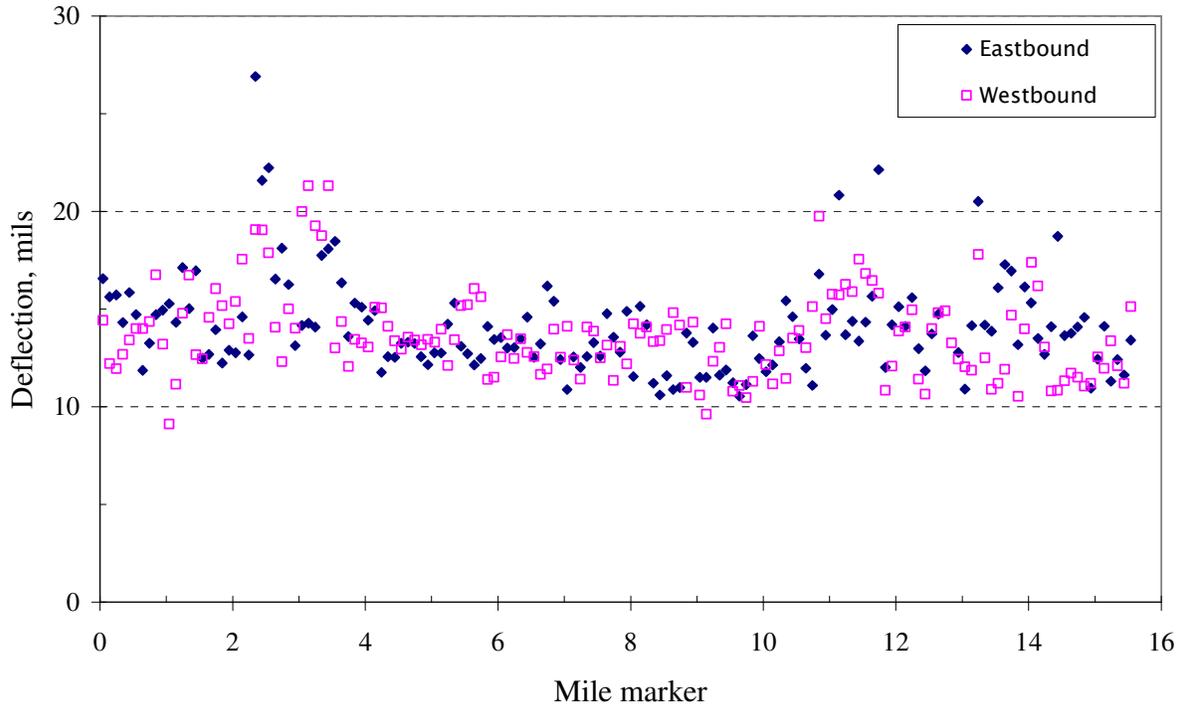
US 202.
NH 9 to I-89 - eastbound.
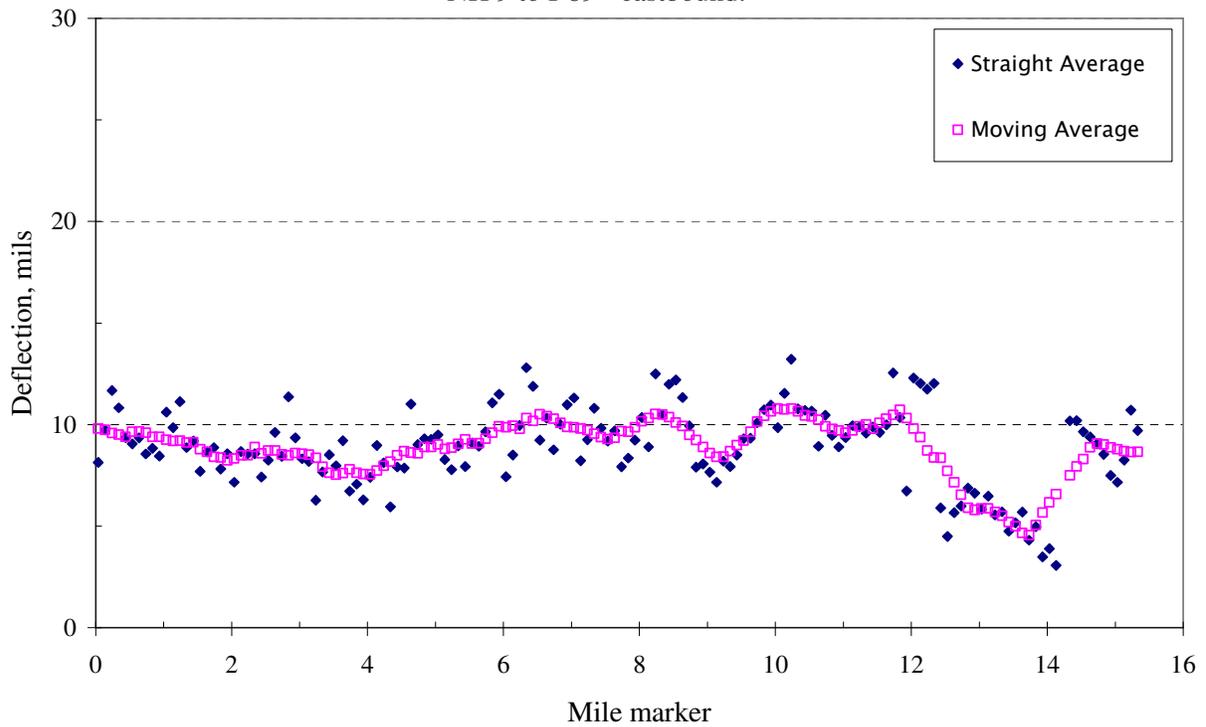
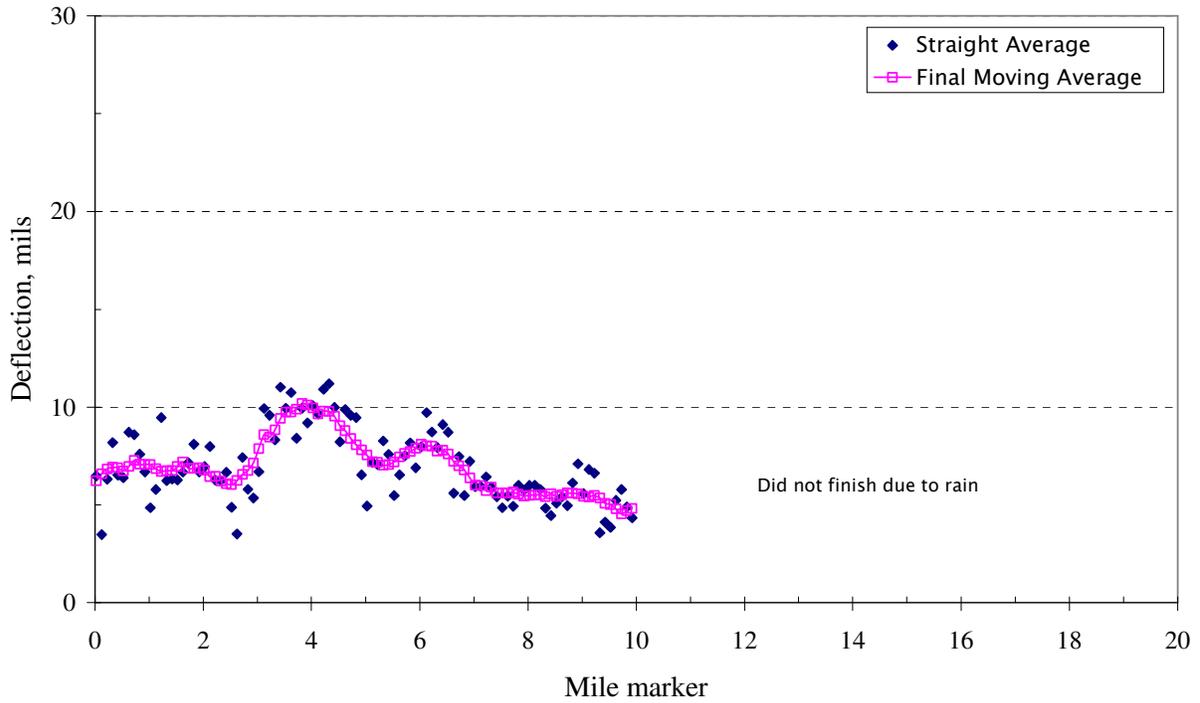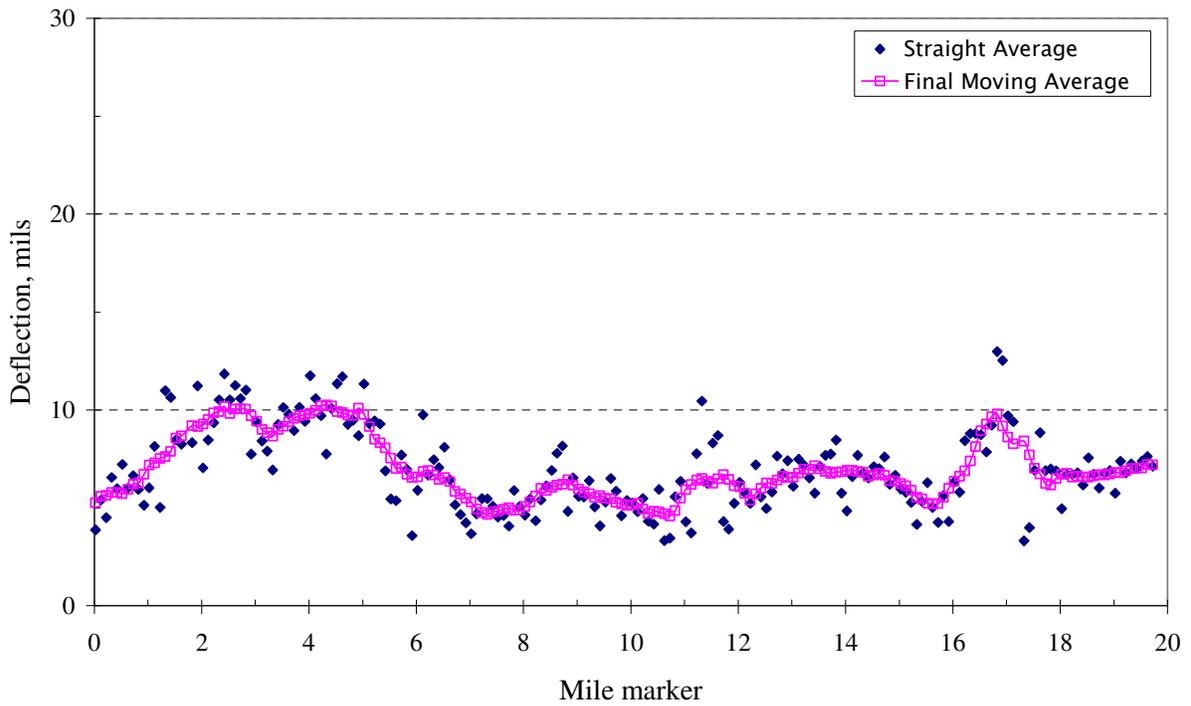US 202.
I-89 to NH 9 - westbound.

US 202.
NH 9 to I-89 - eastbound and westbound lanes.

Feet/453.
Northbound travel lane.

Did not finish due to rain

Feet/453.
Southbound travel lane.

A.17

Feet/453.
Northbound and southbound travel lanes.