February 27, 2008

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

Dear Mr. Derewianka:

Applied Research Associates (ARA), Inc. appreciates the opportunity to submit the results of RWD testing performed on selected Connecticut 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.
Senior Engineer

William R Vavrik, Ph.D., P.E.
Midwest Division Manager

Attachment

Cc: Mr. Edgardo Block, ConnDOT
Cc: Mr. Thomas Van, FHWA

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FINAL REPORT

Rolling Wheel Deflectometer (RWD) Demonstration for the Connecticut Department of Transportation (ConnDOT)

Prepared for:

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February 25, 2007

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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 Connecticut Department of Transportation (ConnDOT).

Testing Program

- Applied Research Associates (ARA), Inc. performed RWD testing on 26 roadways, consisting of Interstates, U.S., and state routes. The test sites included two-lane (one lane in each traffic direction) and multi-lane roads, primarily of flexible pavement design. Several composite pavements (AC/PCC) were included in the study.

- For each road, the RWD measured a continuous deflection profile in the outer wheel path. The RWD operated at prevailing highway truck speeds, typically ranging from 40 to 65 mph. ARA tested 212 lane-miles over an 8-hour testing period on September 22, 2007. ARA tested roads in central and eastern Connecticut, as selected by ConnDOT.

- 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.

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

Findings

- The diverse pavement set produced mean deflections ranging from 5 to 13 mils, with the lower deflections generally occurring on the thicker pavements, while higher deflections were produced on thinner or deteriorated roads, as expected. Although an independent measure of deflections was not available for data validation (e.g., falling weight deflectometer data), in general, the RWD deflections are reasonable for the pavement types and conditions tested.

- 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 8 to 18 mils. Deflections in this range typically correspond to pavements with very good to fair structural capacity.

- ARA assigned structural ratings to each road based on their Representative Deflections. This resulted in the following distribution of ratings for the 26 roads: 15.4 percent = very good, 61.5 percent = good, and 23.1 percent = fair. The rating criteria selected by ARA are conceptual only, and can be modified by ConnDOT accordingly.

Other Benefits

- The RWD is capable of good productivity, testing 212 lane-miles in an 8-hour test period. Productivity is governed primarily by the length and geographic distribution of test sites. In general, ConnDOT'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 performed at 50 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

ARA would like to express our appreciation to the FHWA Office of Asset Management for their sponsorship and support of the RWD program. Specifically, we would like to recognize Mr. Thomas Van and Mr. Stephen Gaj for their continued leadership and support. In addition, we are appreciative to Mr. Michael Arasteh (FHWA Baltimore Resource Center) and Mr. Max Grogg (FHWA Iowa Division) for their input and support of the RWD program.

ARA is thankful to ConnDOT for their assistance in coordinating this pilot study. Specifically, we would like to recognize Mr. Michael Derewianka and Mr. Edgardo Block of the Pavement Management Section for their assistance.

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, including pilot studies for numerous state highway agencies, including Texas, Indiana, Virginia, California, and Kansas DOTs. Field testing has verified the RWD's capability to measure pavement deflections at highway speeds. Currently, ARA is enhancing and improving the device to make it available for commercial data collection services.

In September 2007, ARA performed a field demonstration for the Connecticut Department of Transportation (ConnDOT). This report details the testing program and RWD results.

Figure 1. Route 97 in Connecticut.

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 September 22, 2007 on roads selected by ConnDOT. The roads consisted of Interstate, U.S., and state routes in central and eastern Connecticut. The majority of pavements were of flexible design, with the exception of several composite (AC/PCC) sections that were tested. Testing was performed in the outer wheel path of the lane tested, referenced using ConnDOT's mile marker system, where posted. In the case that mile markers were not observed during data collection, the RWD referenced test data using its onboard distance measuring instrument (DMI) and using the section start as the reference point. A total of 212 lane-miles were tested over an 8-hour period. Table 1 summarizes the test roads and AC pavement thicknesses, as provided by ConnDOT. Figure 3 shows the test road locations.

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., 40 to 65 mph), whenever conditions permitted.

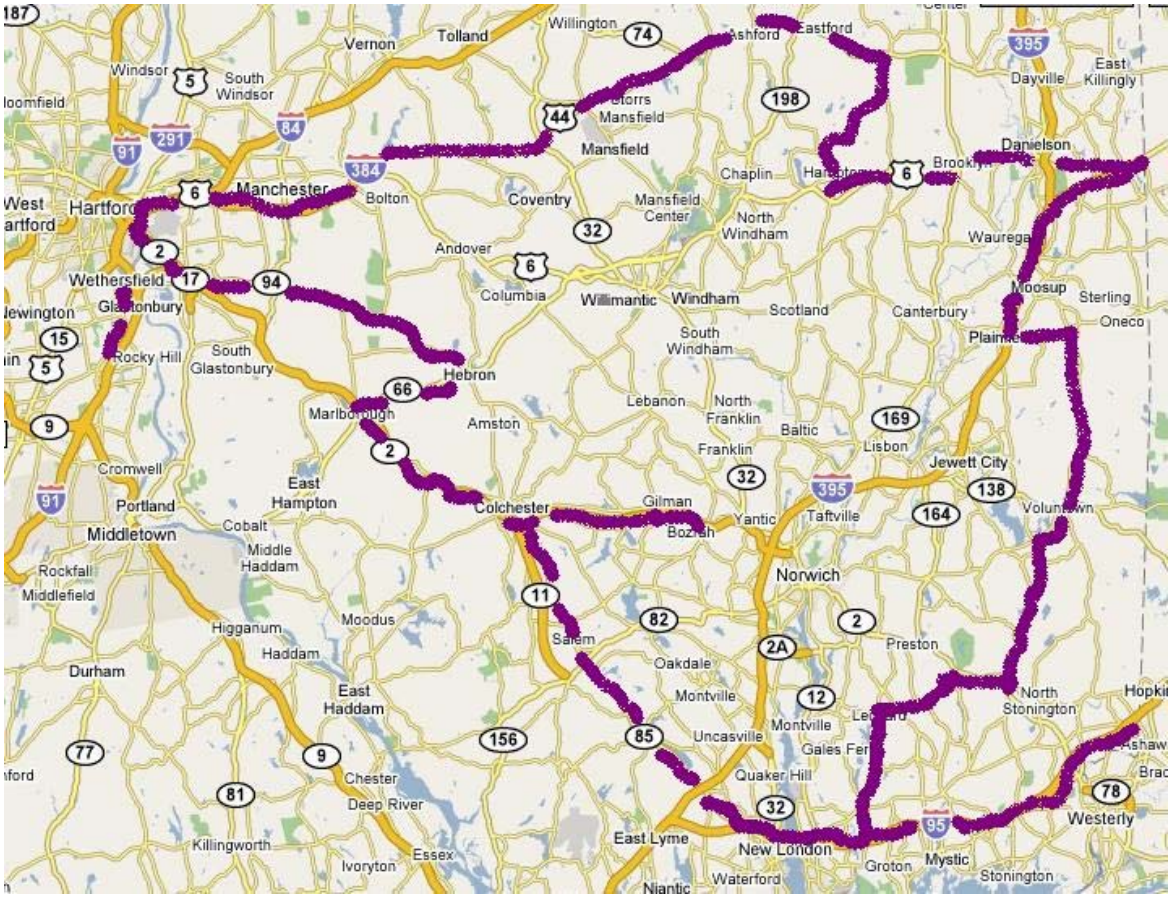


Figure 3. Connecticut test roads.

Table 1. Summary of the Connecticut test roads.

Road	Direction	Begin MM	End MM	Length, mi	From	To	AC thickness, in	Pavement Structure Comments
Rt. 3	N	6.59[a]	14.48	7.1	West St.	Rt. 2	6 to 8	
Rt. 2	E	4.60	5.31	1.0	Rt. 3	Rt. 94	Composite	
Rt. 94	E	0.00[a]	9.33	9.3	Rt. 2	Rt. 85	8 to 9	
Rt. 85	S	30.27[a]	25.52	4.7	Rt. 94	Rt. 66	8 to 9	
Rt. 66	W	25.90[a]	20.54	5.4	Rt. 85	SR 2	6 to 9	
Rt. 2	E	15.22	23.73	13.0	Rt. 66	Exit 23	7.5	Rubblized
Rt. 2	W	11.50	12.02	9.0	Exit 23	Rt. 85	4 to 5	
Rt. 85	S	19.11[a]	0.93	18.0	Rt. 16	I-95	8 to 9	
I-95	N	91.94	111.57	18.0	Rt. 85	Exit 93	10	Small composite sections
I-95	S	111.57	97.83	11.0	Exit 93	Rt. 117	10	Small composite sections
Rt. 117	N	1.24[a]	7.12	5.9	I-95	Rt. 214	5 to 7	
Rt. 214	E	2.92[a]	7.30	4.2	Rt. 117	Rt. 2	4 to 5	
Rt. 2	E	47.99[a]	51.11	2.4	Rt. 214	Rt. 201	7 to 9	
Rt. 201	N	4.13[a]	12.08	7.2	Rt. 2	Rt. 165	5 to 6	
Rt. 165	E	10.15[a]	12.12	2.0	Rt. 201	Rt. 49	4 to 5	
Rt. 49	N	13.05[a]	21.74	8.7	Rt. 65	Rt. 14A	3	Reclaimed
Rt. 14A	W	7.02[a]	3.66	3.4	Rt. 49	I-395	4 to 5	
I-395	N	30.00	35.50	5.0	Rt. 14A	I-695	9	
I-695	E	0.00[a]	4.49	5.2	I-395	State Line	11	Cold in place recycled
Rt. 6	W	116.33[a]	101.30	16.8	State Line	Rt. 97	10 to 13	
Rt. 97	N	16.80[a]	29.14	7.9	Rt. 6	Rt. 44	8 to 9	
Rt. 44	W	96.27[a]	67.96	25.5	Rt. 97	I-384	7 to 9	
I-384	W	8.53[a]	0.00	7.8	Rt. 44	I-84	Composite	Small flexible section
I-84	W	66.46	63.18	4.3	I-384	Rt. 2	Composite	
Rt. 2	E	0.47	4.02	2.0	I-84	Rt. 3	Composite	
Rt. 3	S	14.48[a]	6.59	7.0	Rt. 2	West St.	6 to 8	

[a] Mile markers not observed in the field. 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 easily viewable and manageable.

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 I-95 northbound from Route 85 to the Rhode Island state line. This road presented typical speed variations due to climbing hills and negotiating 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.

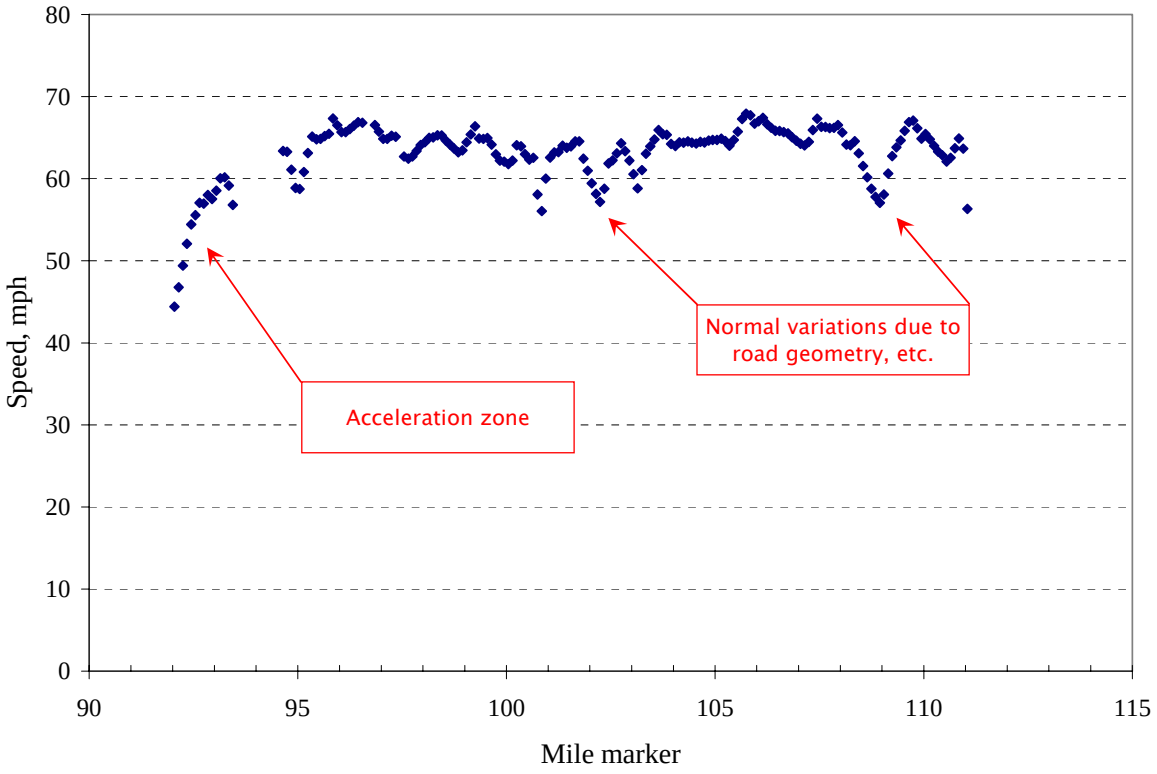


Figure 4. Average truck speed—I-95, Route 85 to state line - northbound.

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 Connecticut 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. The representative RWD deflection (i.e., mean plus 2 standard deviations) is shown as well. This corresponds to the 98th percentile (meaning 98 percent of the data is lower than this value) and it is considered more representative of expected pavement structural capacity than the mean RWD deflection itself, as it takes into account pavement variability. In other words, the weaker pavement areas (i.e., areas of high deflection) are expected to show structural deterioration first.

AC in Good Condition on I-384—Low and Uniform Deflections

Figure 6 presents the RWD results and a digital image taken on I-384 from Route 44 to I-84. In general, this pavement is in very good condition and appears to have a fairly new AC surface. According to ConnDOT's data, the roadway is composite (AC/PCC) with one small section of 12-in AC pavement. Overall, deflections ranged from 2 to 8 mils with an average of approximately 5 mils. The representative deflection (i.e., mean plus 2 standard deviations) of this section was 8 mils. Deflections in this range indicate a pavement of good structural capacity, due mainly due to the underlying PCC slab.

Change in Pavement Structure and Condition on Route 201—Low and Medium Deflections

Figure 7 shows the RWD deflections and the variable conditions of Route 201 from Route 2 to Route 165. According to ConnDOT's data, the AC thicknesses on Route 201 ranged from 5 to 6 in. The RWD deflections show a distinct change in pavement structure at mile 4. From mile 0 to 4 the deflections are low and relatively uniform, corresponding to a pavement in good condition with good structural capacity. However, from mile 4 to 7 the deflections increase drastically and are highly variable. This indicates a pavement with lower structural capacity and more variability, likely due to cracking, as observed by the RWD's digital images. Representative deflections for the stronger and weaker sections of Route 201 are 11 and 22 mils, respectively.

Multiple Pavement Structures on Route 2—Very Low, Low, and Medium Deflections

The RWD deflection profile and representative images for Route 2 from Route 66 to Exit 23 are presented in figure 8. Deflections are high (but uniform) from mile 15 to 20, corresponding to the recently rubblized pavement in this area. Rubblizing of an underlying PCC slab can produce higher deflections, as the pavement is converted from a rigid to a flexible pavement, depending on the thickness of the overlying AC surface. Deflections in this section ranged from 9 to 15 mils, with a representative deflection of approximately 14 mils.

From mile 20 to 31.5 the pavement is reported to consist of 7.5 in of AC over a stabilized base, resulting in a low representative deflection of approximately 6 mils. However, photos indicate there may be small sections of composite pavement around miles 23 to 26, and the RWD supports this as well, producing pockets of very low deflections in this area. Higher deflections were measured from mile 31.5 to 33.5, corresponding to a flexible pavement with significant cracking. The representative deflection in this section is approximately 11 mils. Deflections measured in the eastbound and westbound lanes over the same mile markers were very similar, as shown in figure 8.

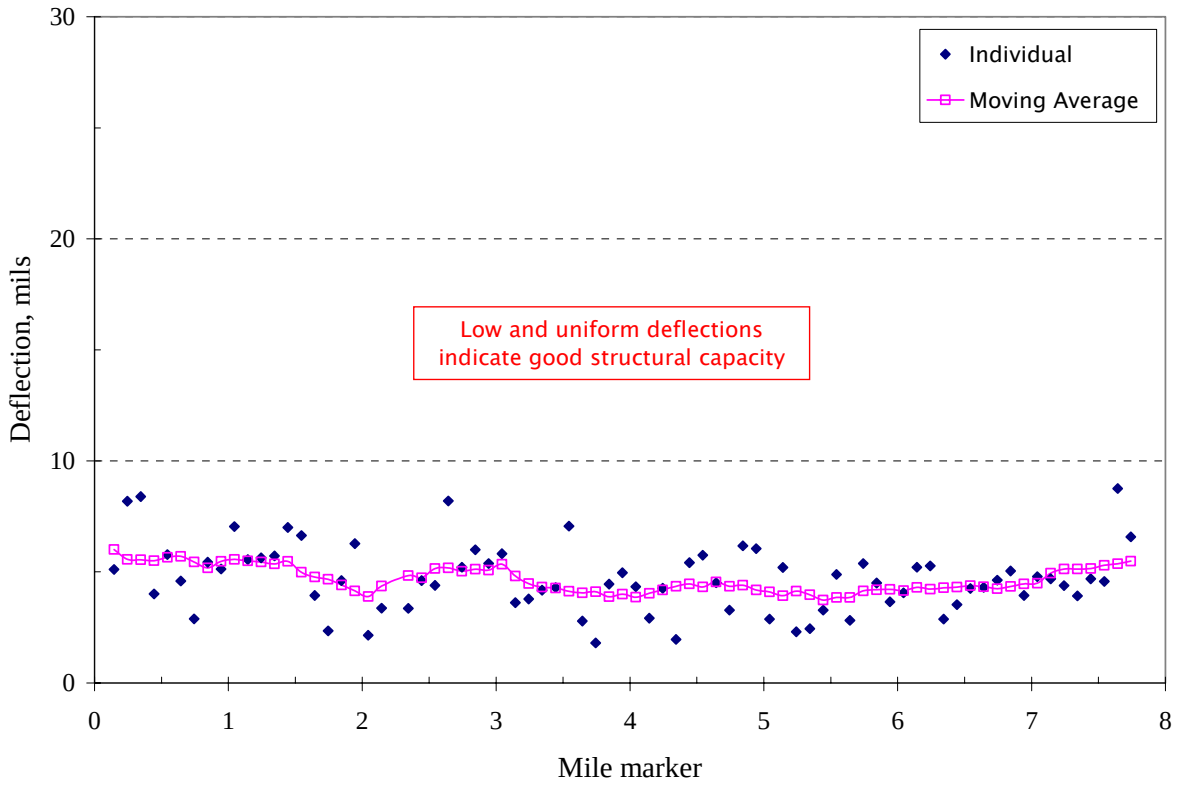


Figure 6. I-384—Route 44 to I-84, westbound. Low and uniform deflections indicate good uniformity and structural capacity for this composite pavement.

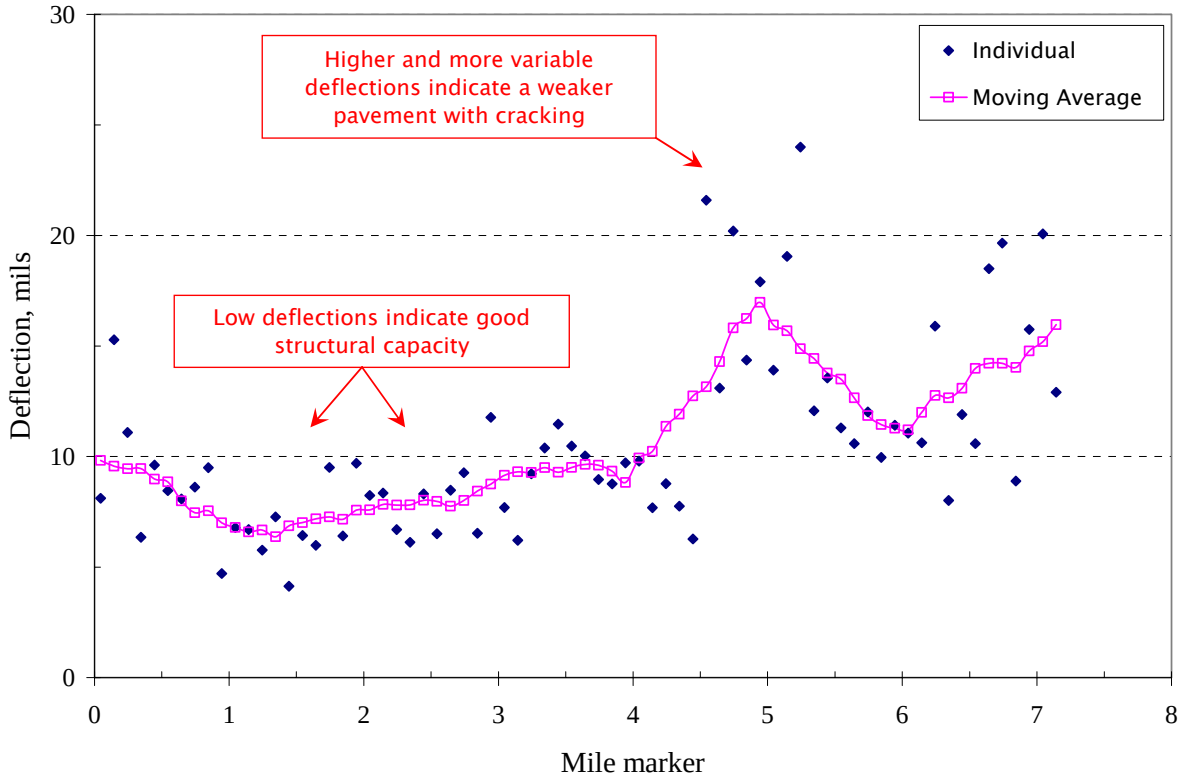
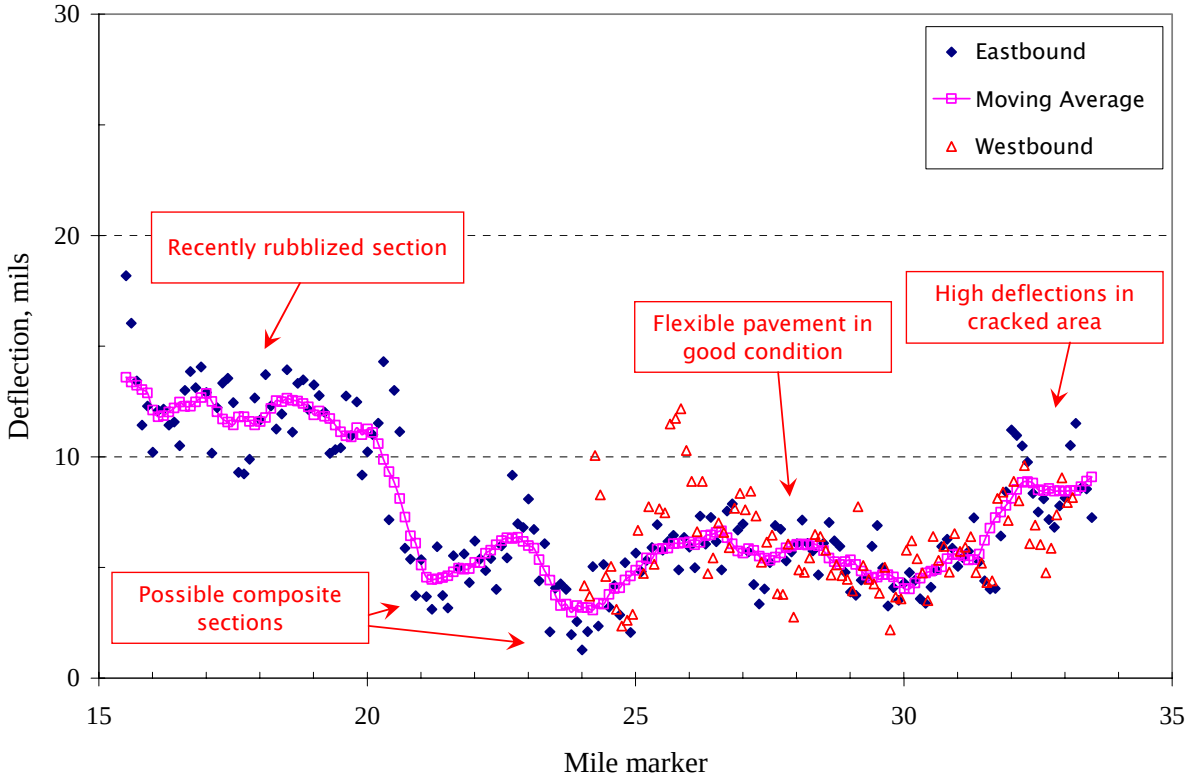


Figure 7. Route 201—Route 2 to Route 165, northbound. The RWD shows a change in pavement structural response at mile marker 4.5. From mile 0 to 4.5 (left photo) the deflections are low and the pavement is in good condition. From mile 4.5 to 7 (right photo) the deflections are high and there is significant cracking.



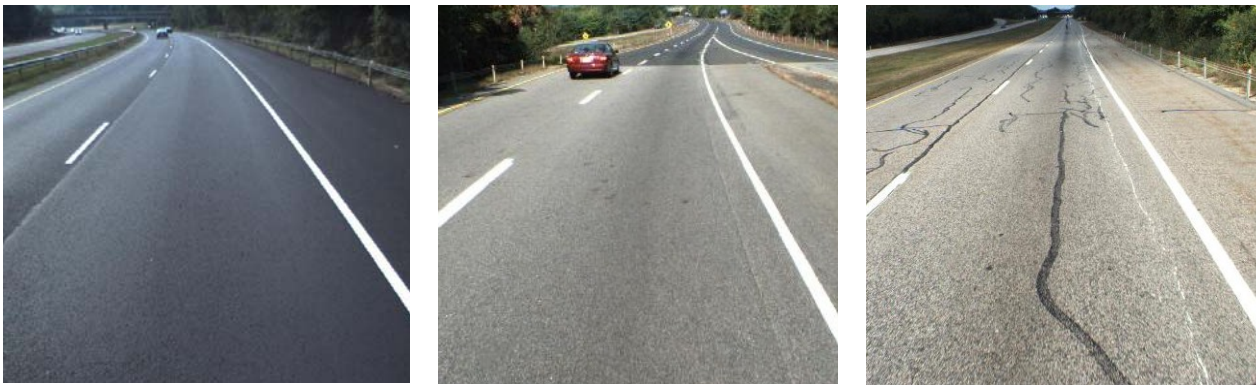


Figure 8. Route 2—Route 66 to Exit 23, eastbound and westbound. The RWD shows multiple pavement sections. From mile 15 to 20 (left photo) the underlying PCC pavement has been recently rubblized and overlaid with AC. From mile 20 to 31.5 (center) there is a flexible pavement in good condition, and from mile 31.5 to 33.5 (right photo) deflections increase and the pavement shows significant cracking.

Statistical Summary

Figure 9 presents a statistical summary for all 26 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 5 to 13 mils, with the lower deflections generally occurring on the thicker pavements and the higher, more variable deflections occurring on the thinner or deteriorated pavements, as expected.

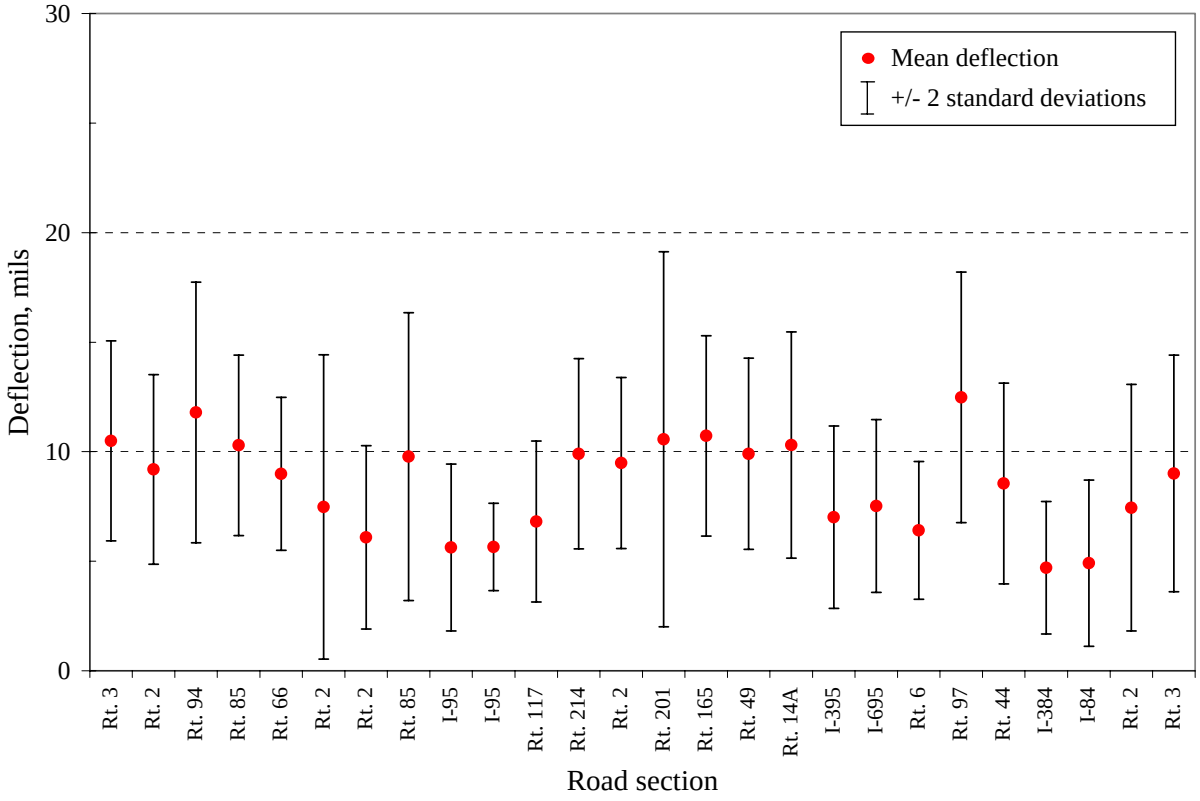


Figure 9. Diverse pavement conditions produced a wide range of deflections and variability.

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 26 pavement sections ordered by their representative deflection, lowest to highest. The values range from 8 to 18 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.

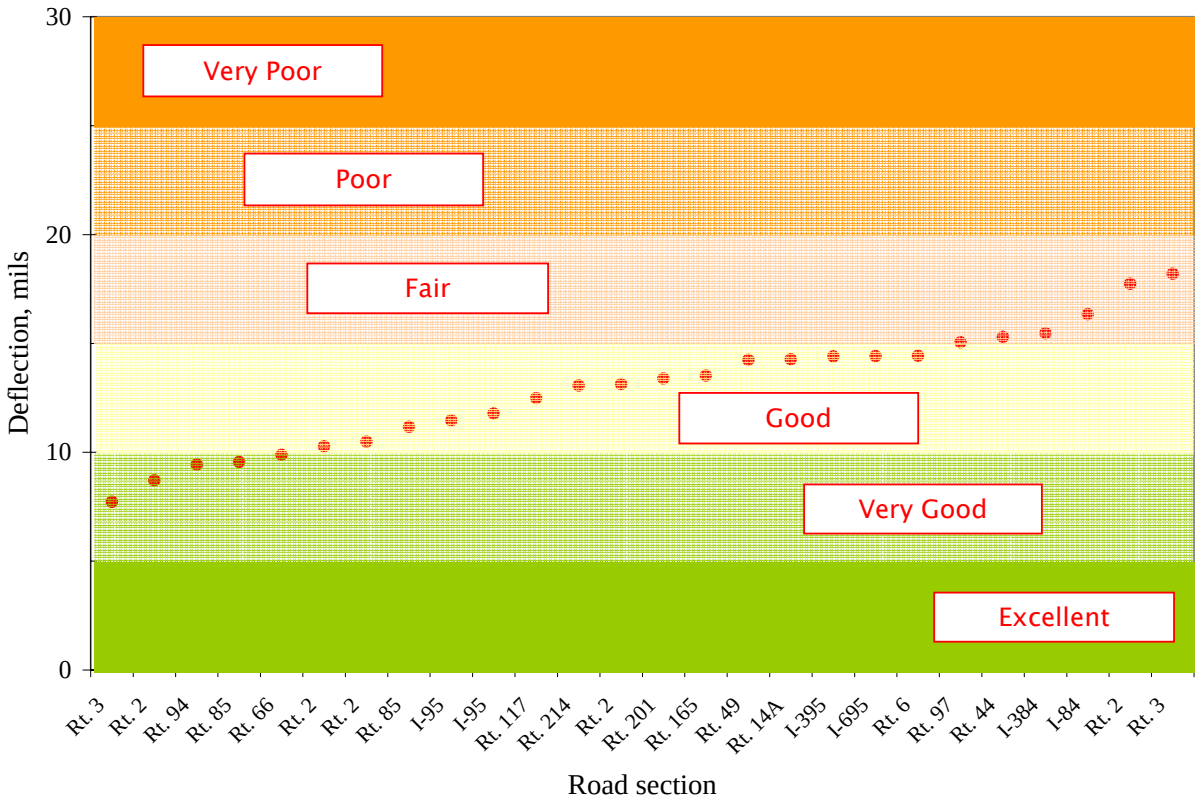


Figure 10. The structural capacity of each section can be characterized by its representative deflection (i.e., mean deflection plus 2 standard deviations).

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.

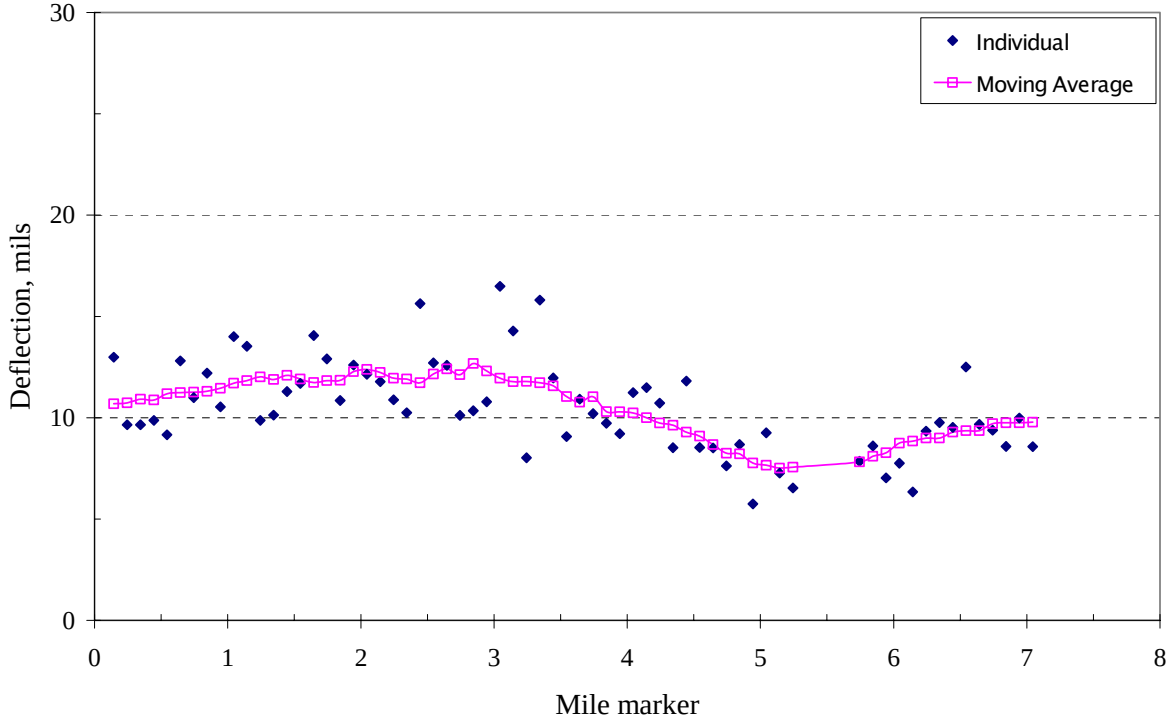
- **RWD-based structural ratings:** Structural ratings can be applied to different deflection levels to describe a road's structural capacity. For example, deflections from 0 to 10 mils, 10 to 20 mils, and 20 to 30 mils represent pavements with High, Medium, and Low structural capacities, respectively. 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 ConnDOT's pavement management experience, present an excellent opportunity to develop these methodologies.

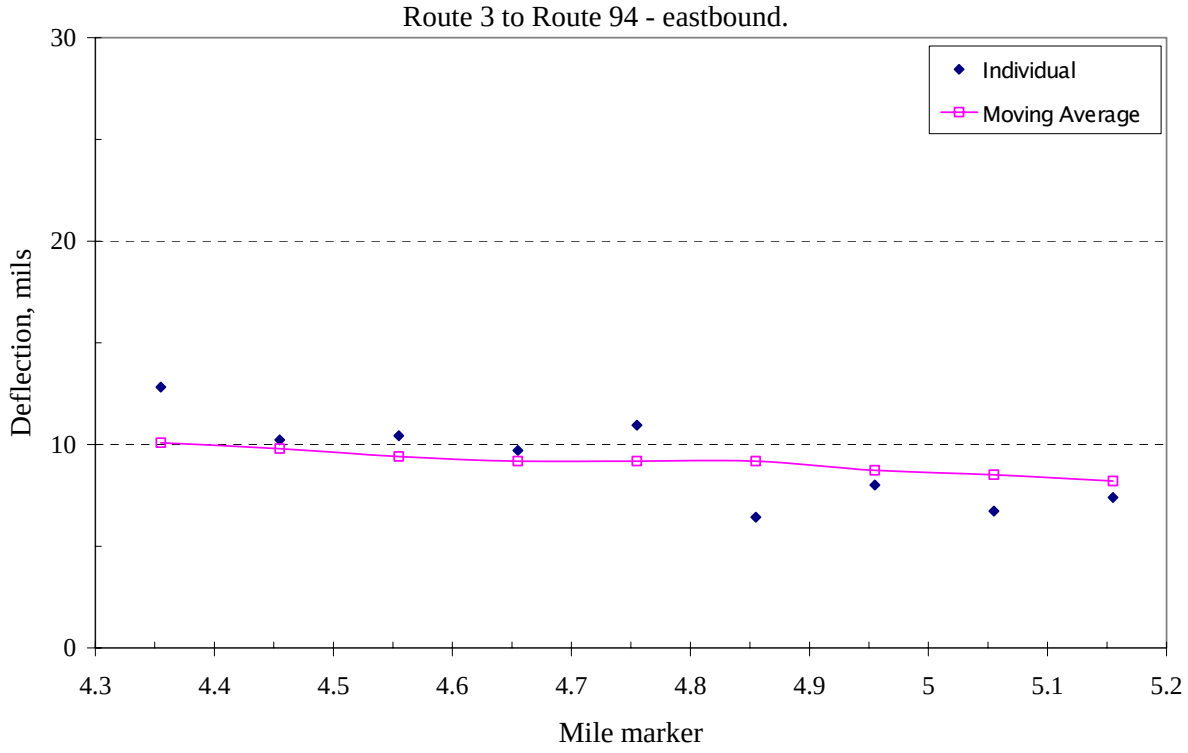
APPENDIX A

RWD Deflection Profiles

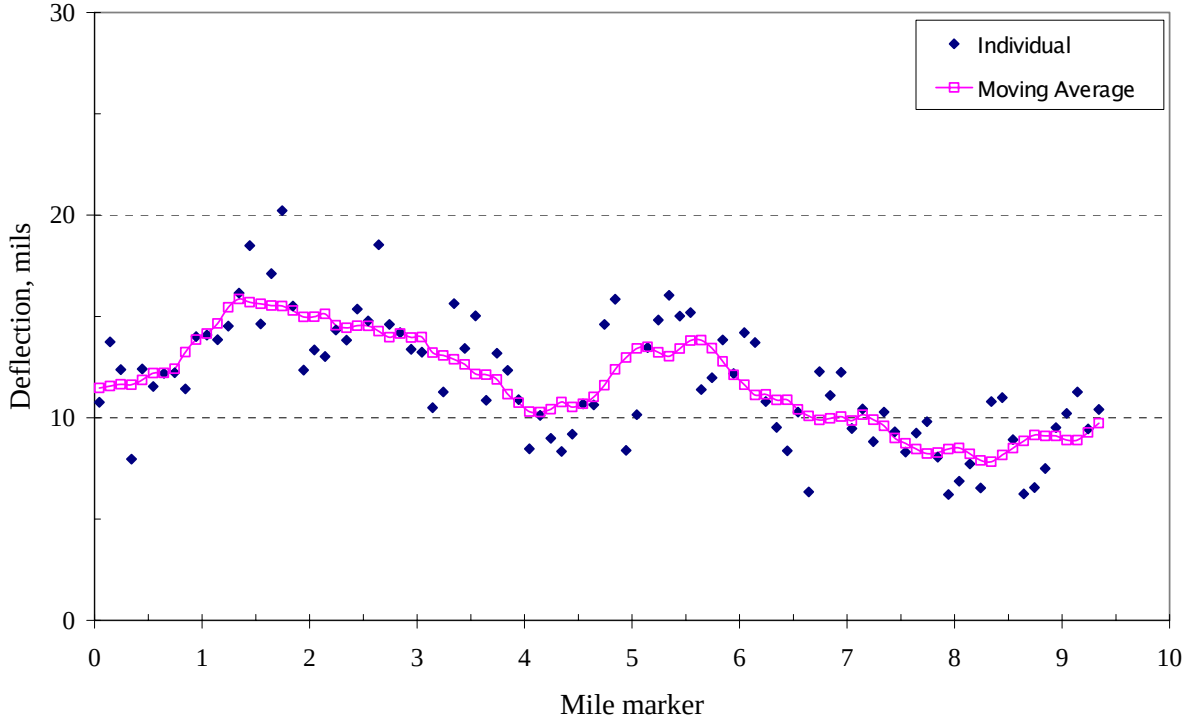
Route 3.
West Street to Route 2 - northbound.



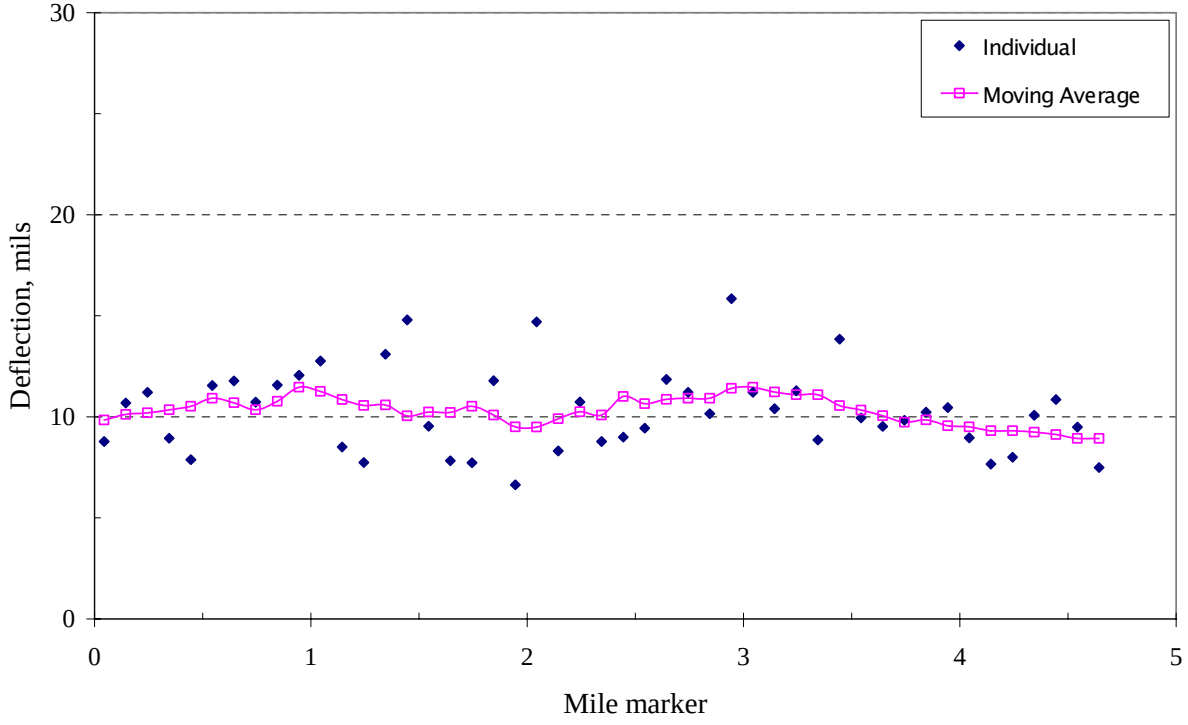
Route 2.
Route 3 to Route 94 - eastbound.



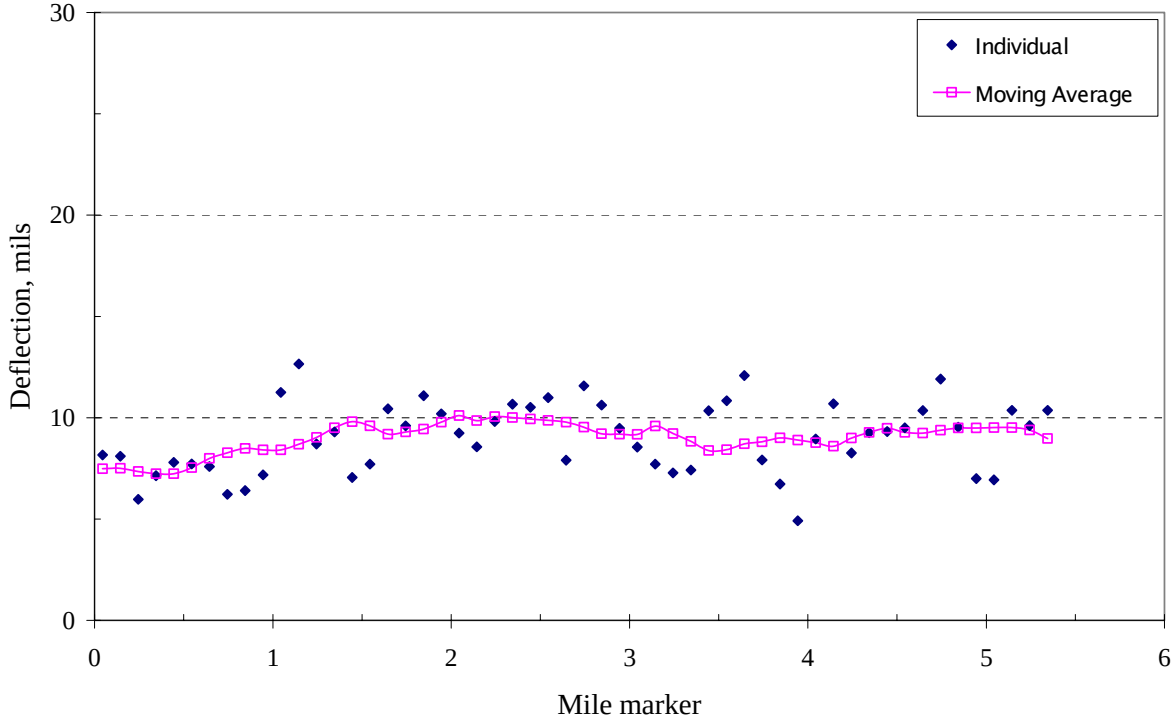
Route 94.
Route 2 to Route 85 - eastbound.



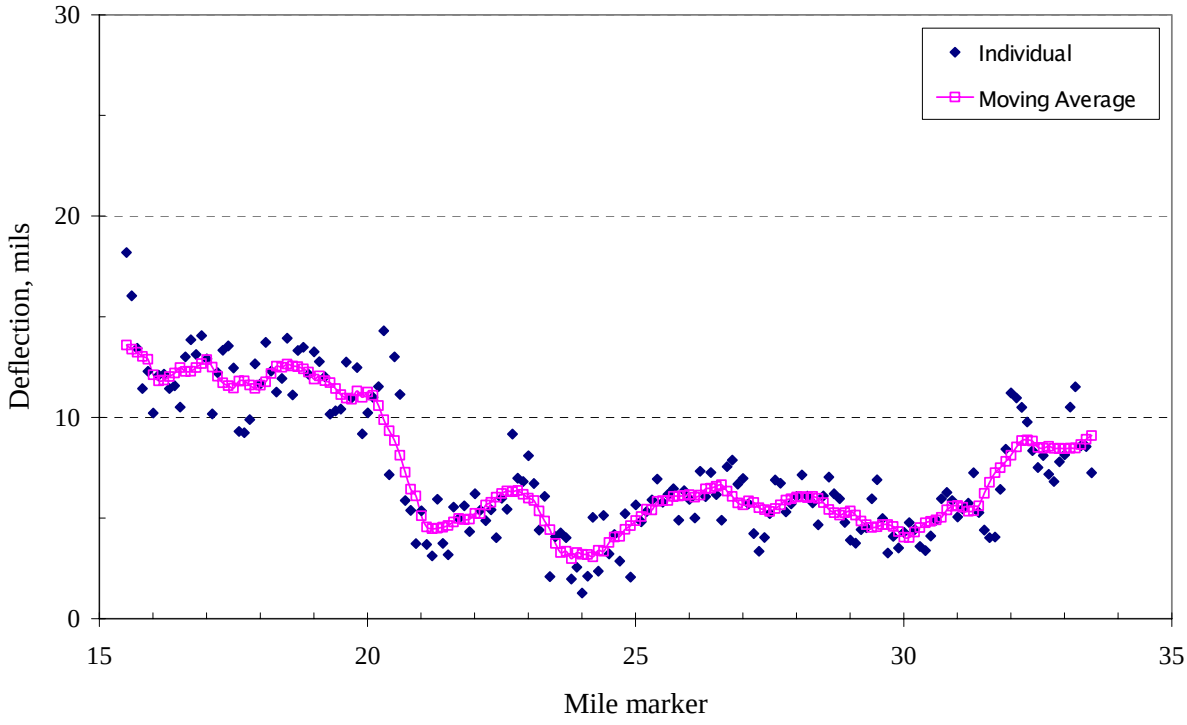
Route 85.
Route 94 to Route 66 - southbound.



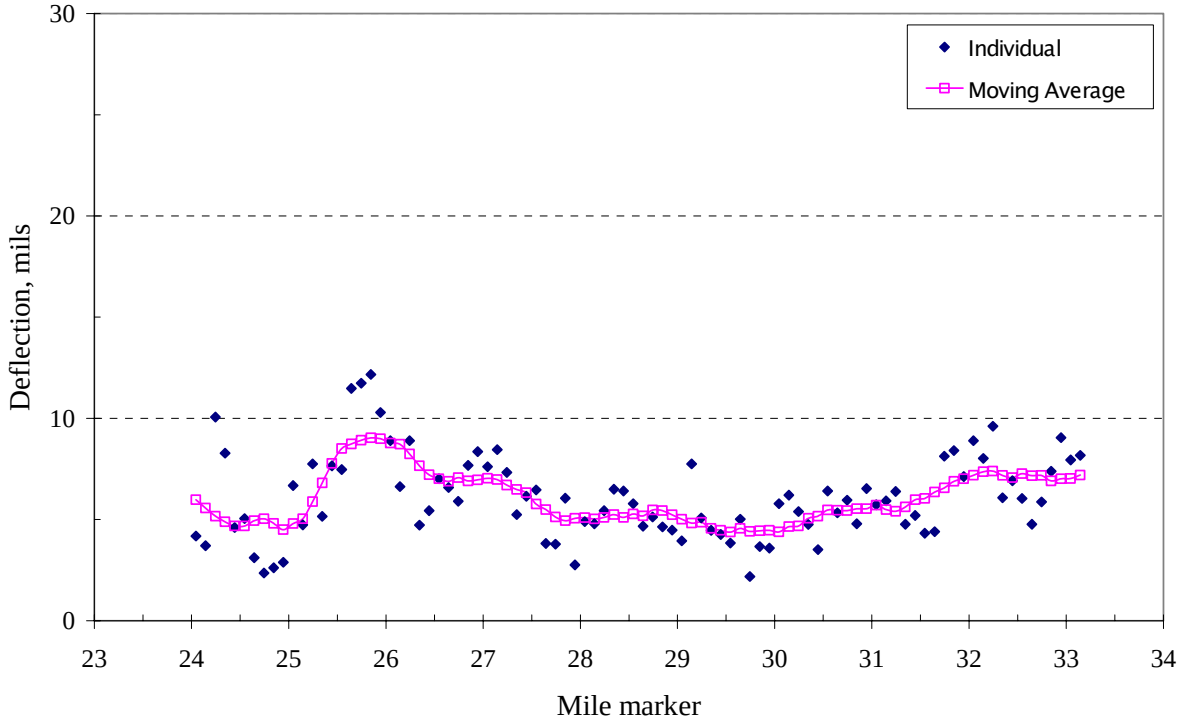
Route 66.
Route 85 to SR 2 - westbound.



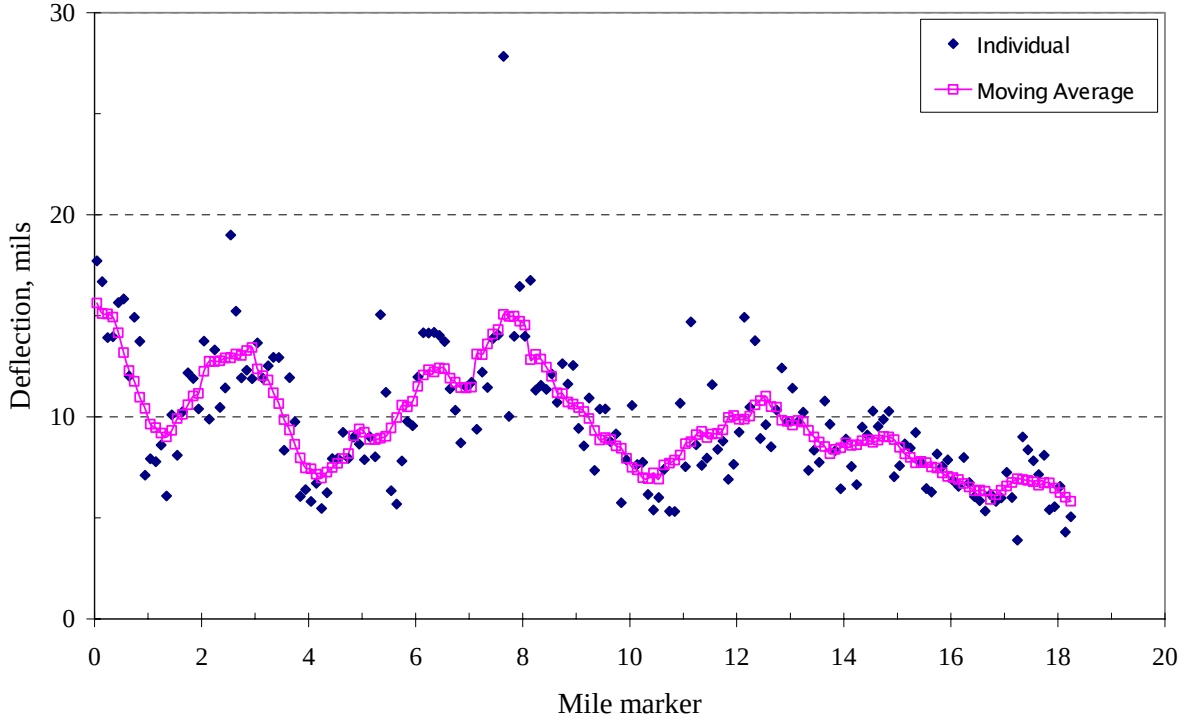
Route 2.
Route 66 to Exit 23 - eastbound.



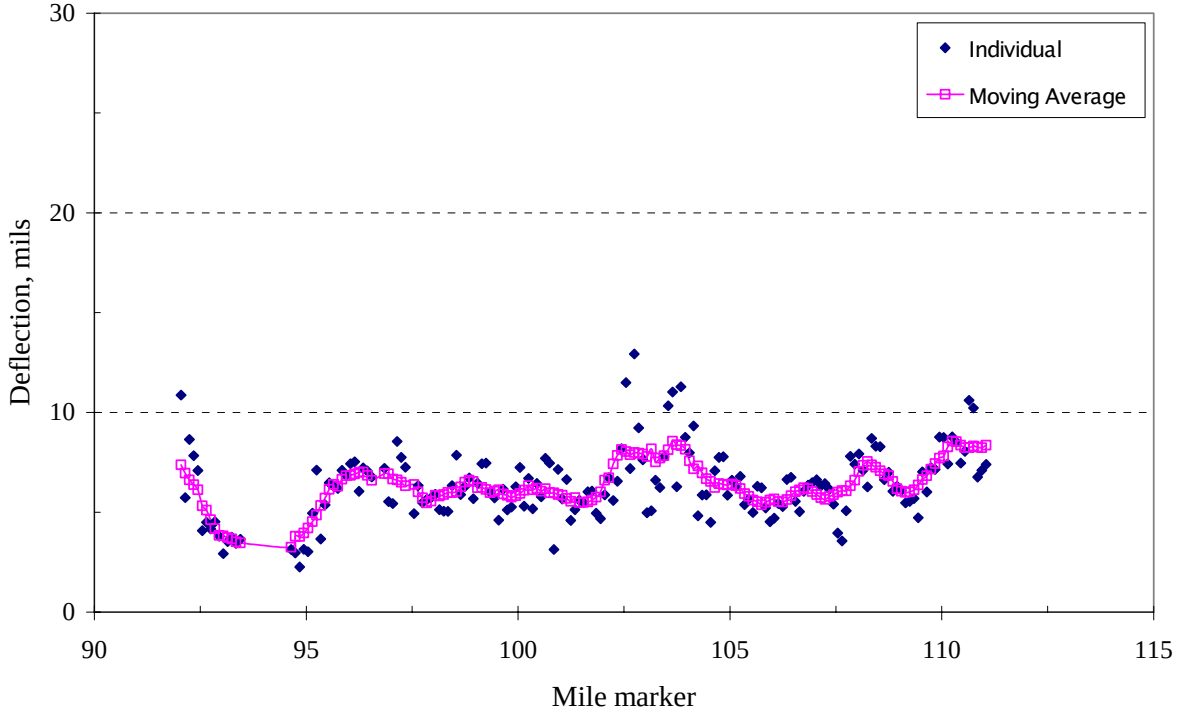
Route 2.
Exit 23 to Exit 18 - westbound.



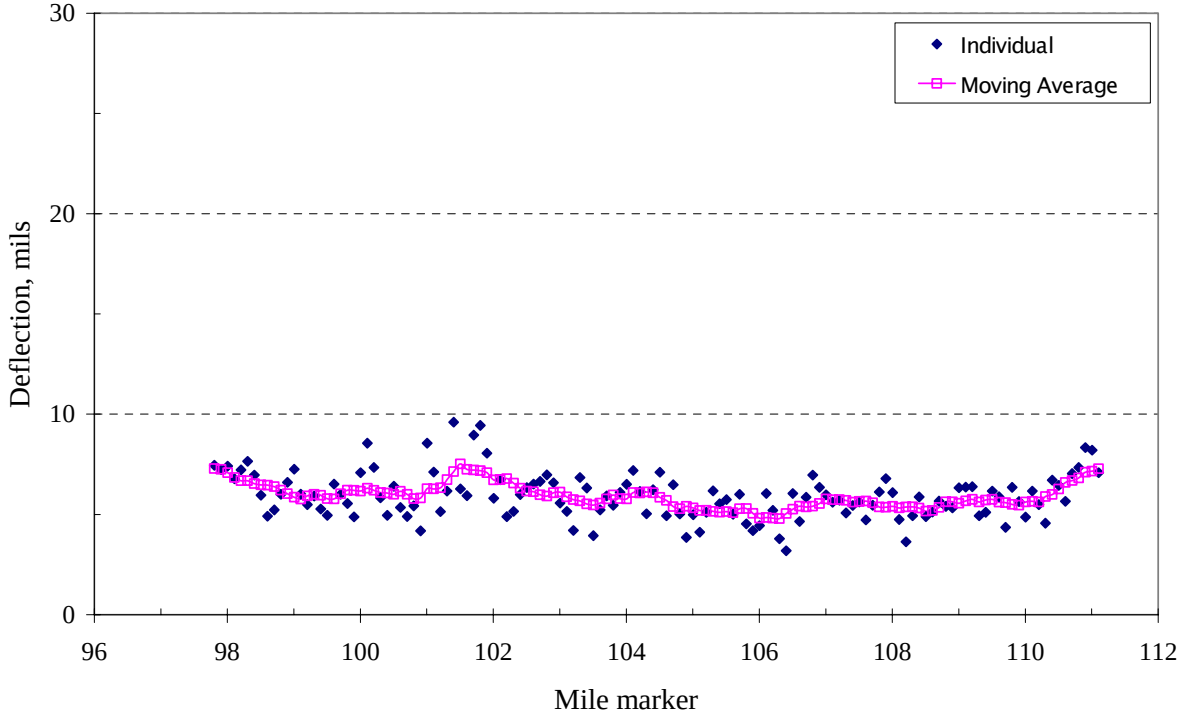
Route 85.
Route 16 to I-95 - southbound.



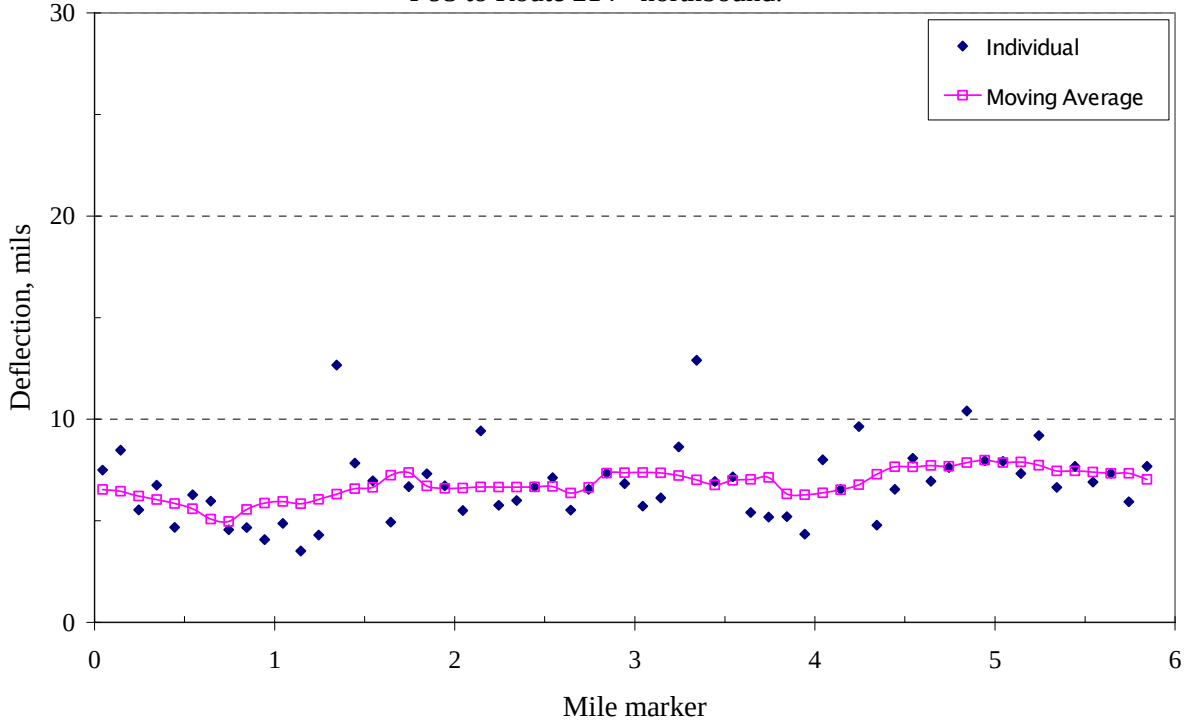
I-95.
Route 85 to Exit 93 (State line) - northbound.



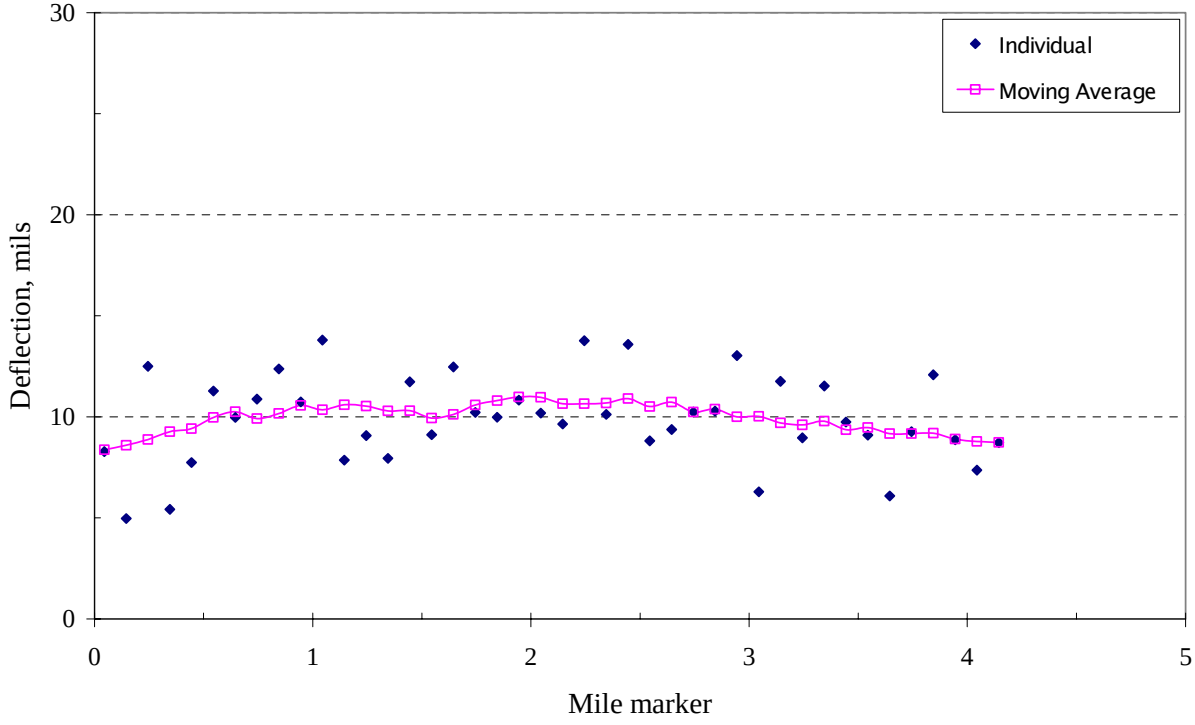
I-95.
Exit 93 (State line) to Route 117 - southbound.



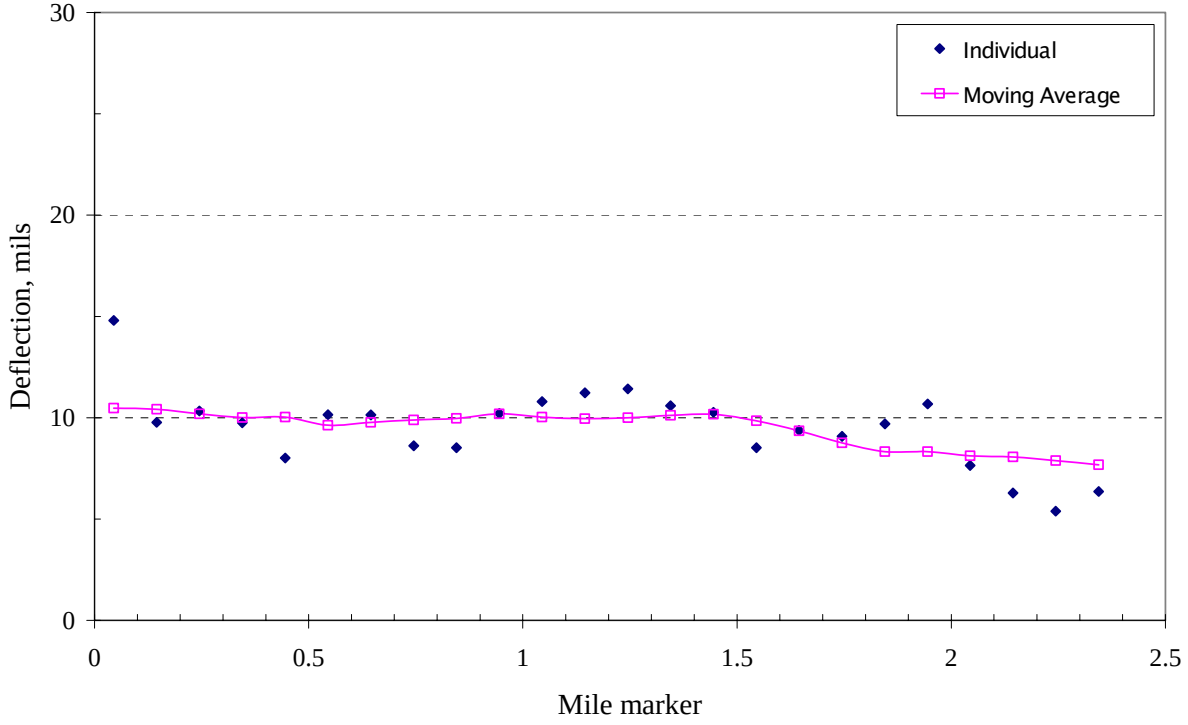
Route 117.
I-95 to Route 214 - northbound.



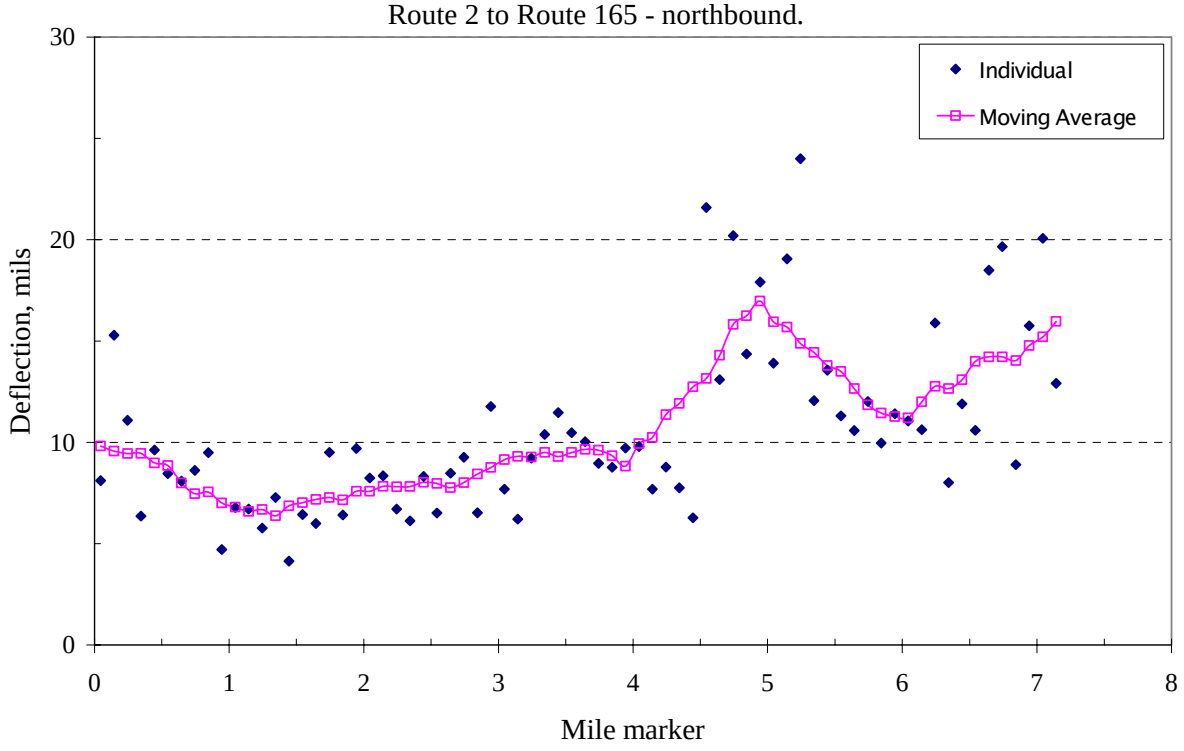
Route 214.
Route 117 to Route 2 - eastbound.



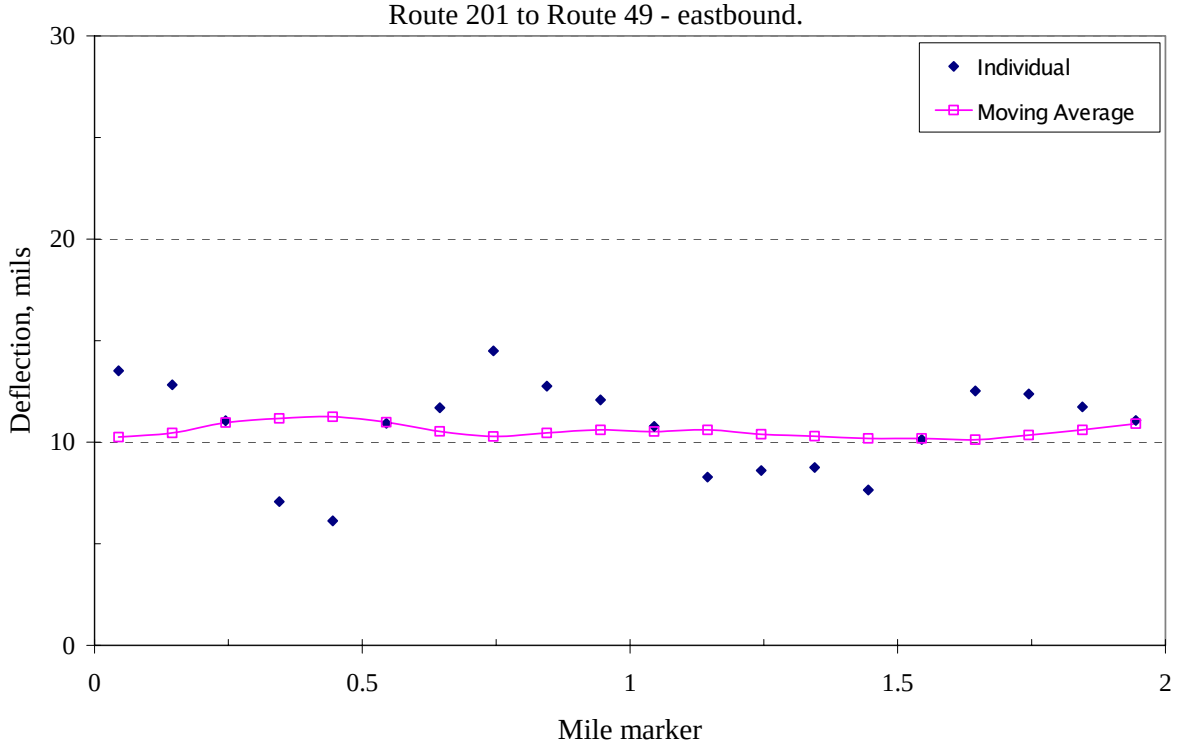
Route 2.
Route 214 to Route 201 - eastbound.



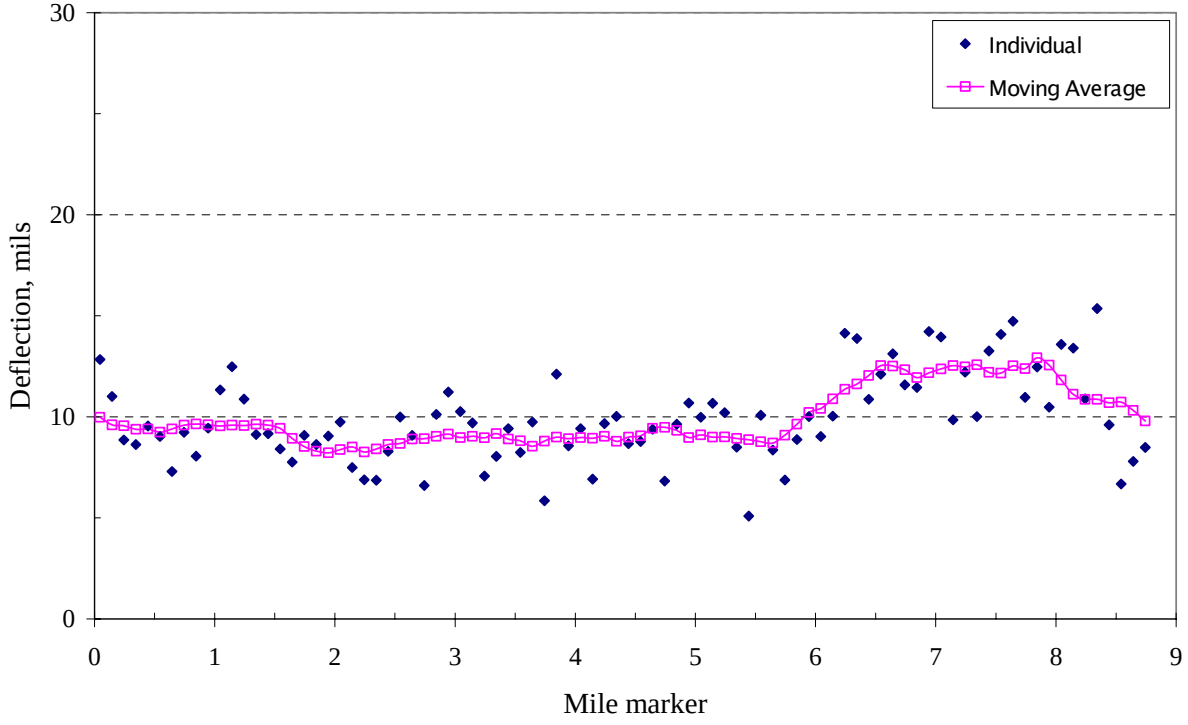
Route 201.
Route 2 to Route 165 - northbound.



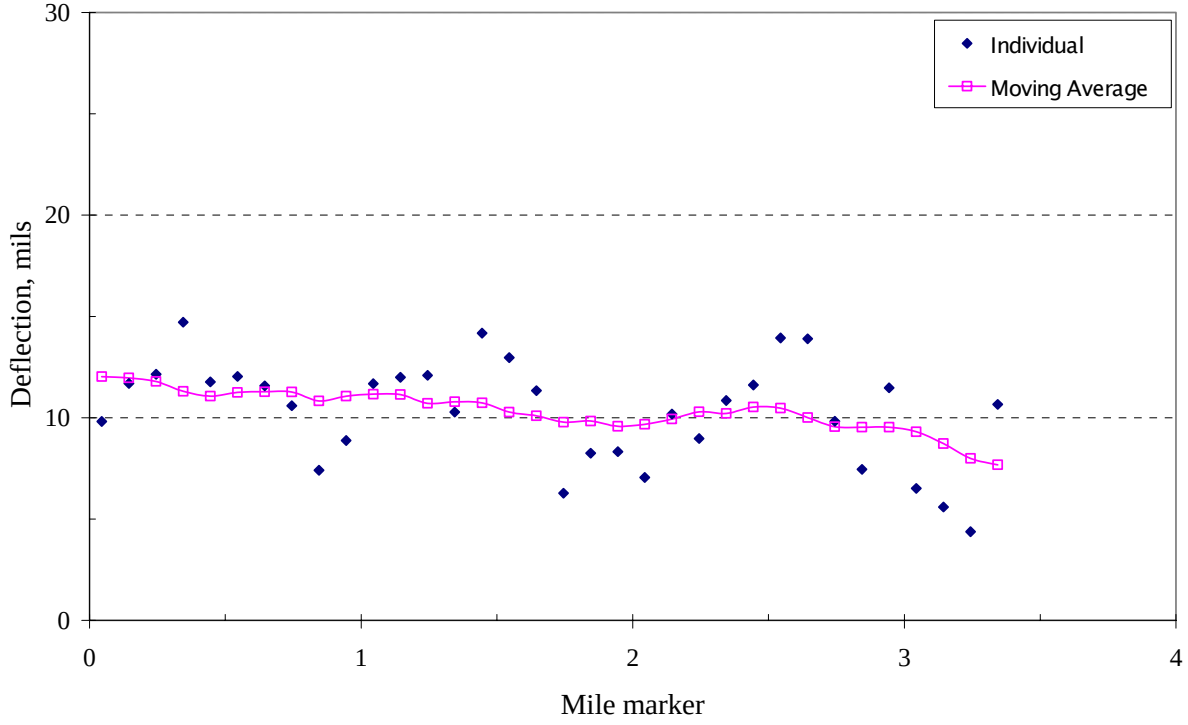
Route 165.
Route 201 to Route 49 - eastbound.



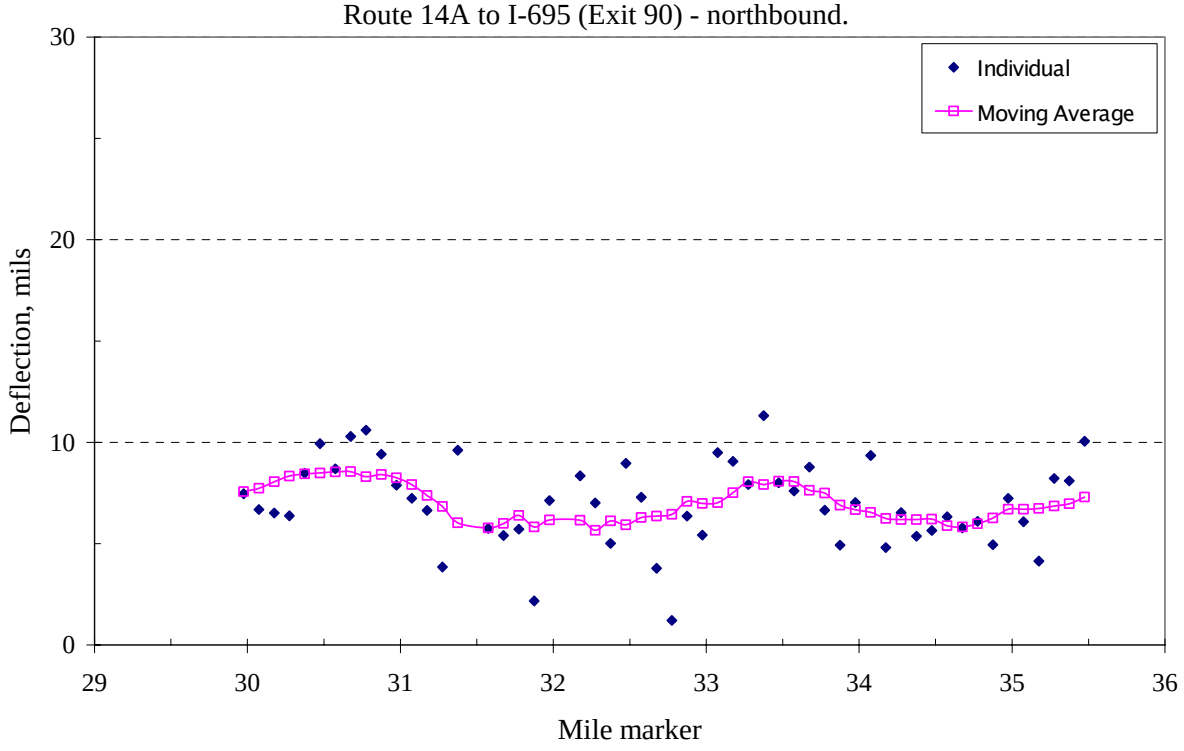
Route 49.
Route 65 to Route 14A - northbound.



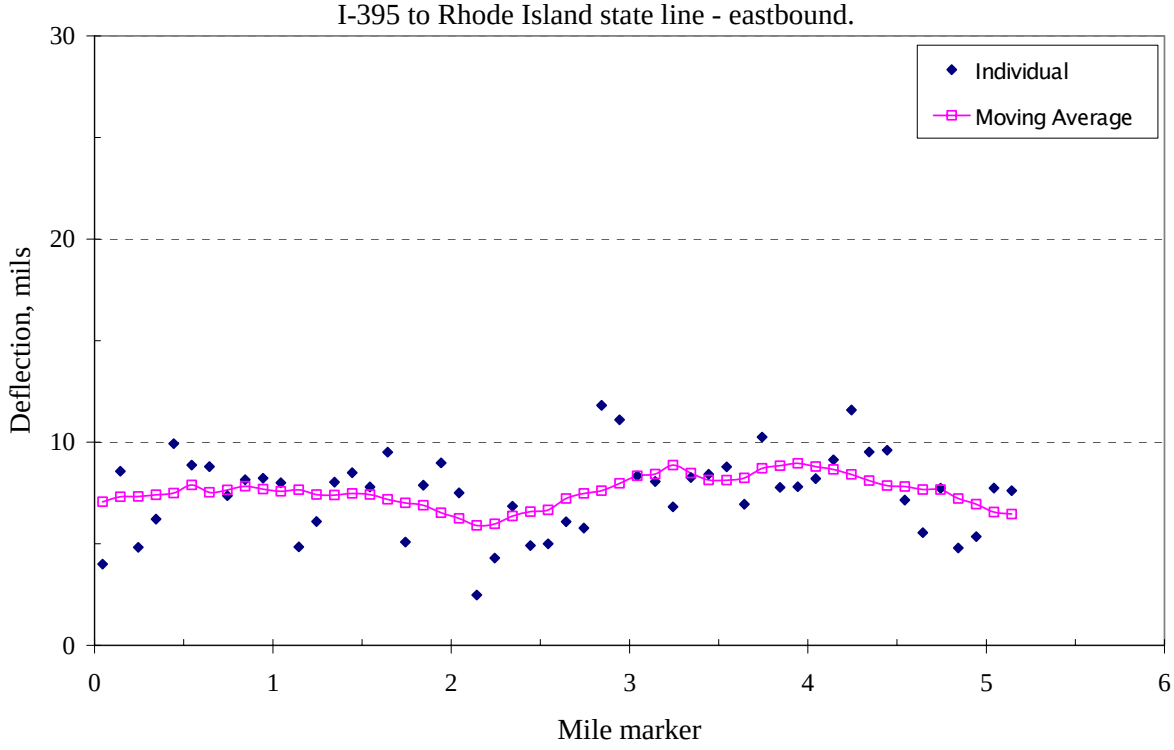
Route 14A.
Route 49 to I-395 - westbound.



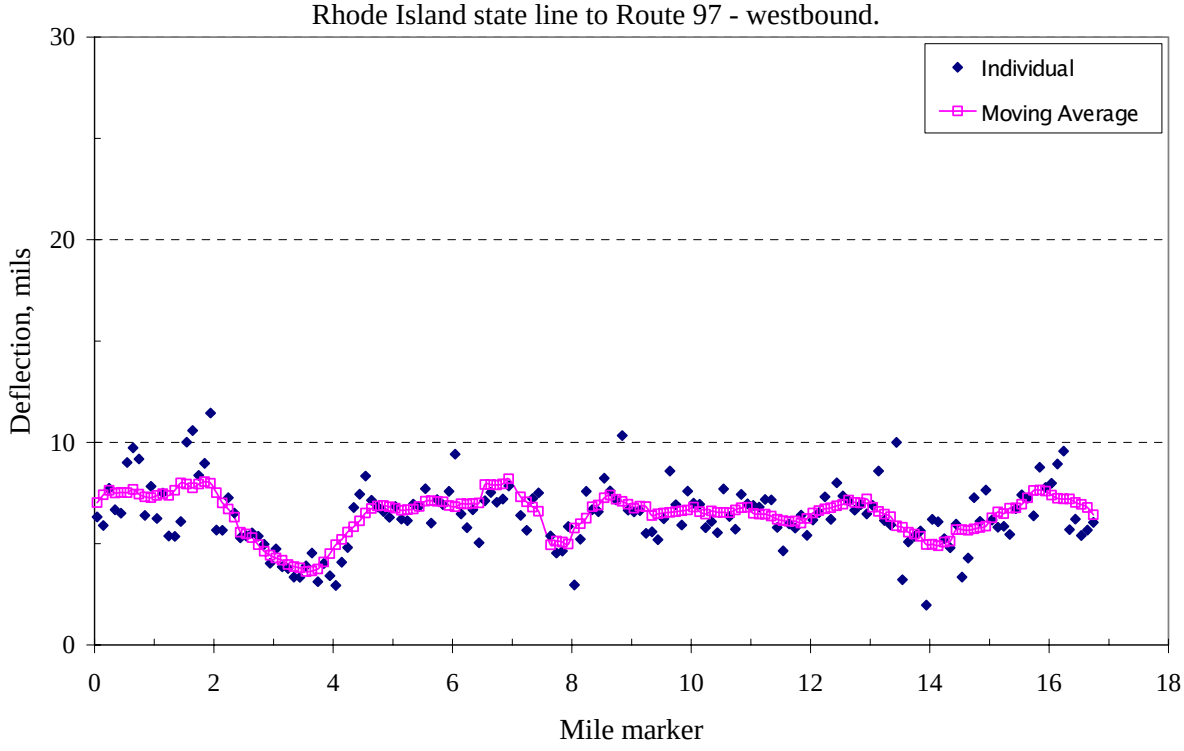
I-395.
Route 14A to I-695 (Exit 90) - northbound.



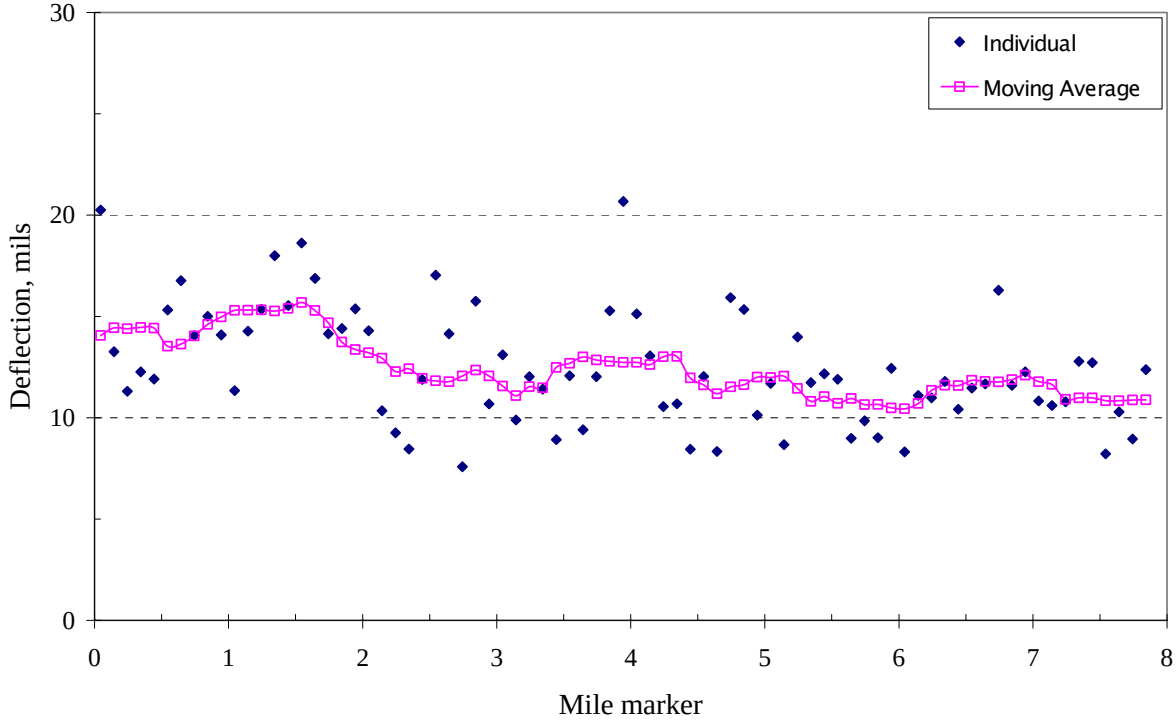
I-695.
I-395 to Rhode Island state line - eastbound.



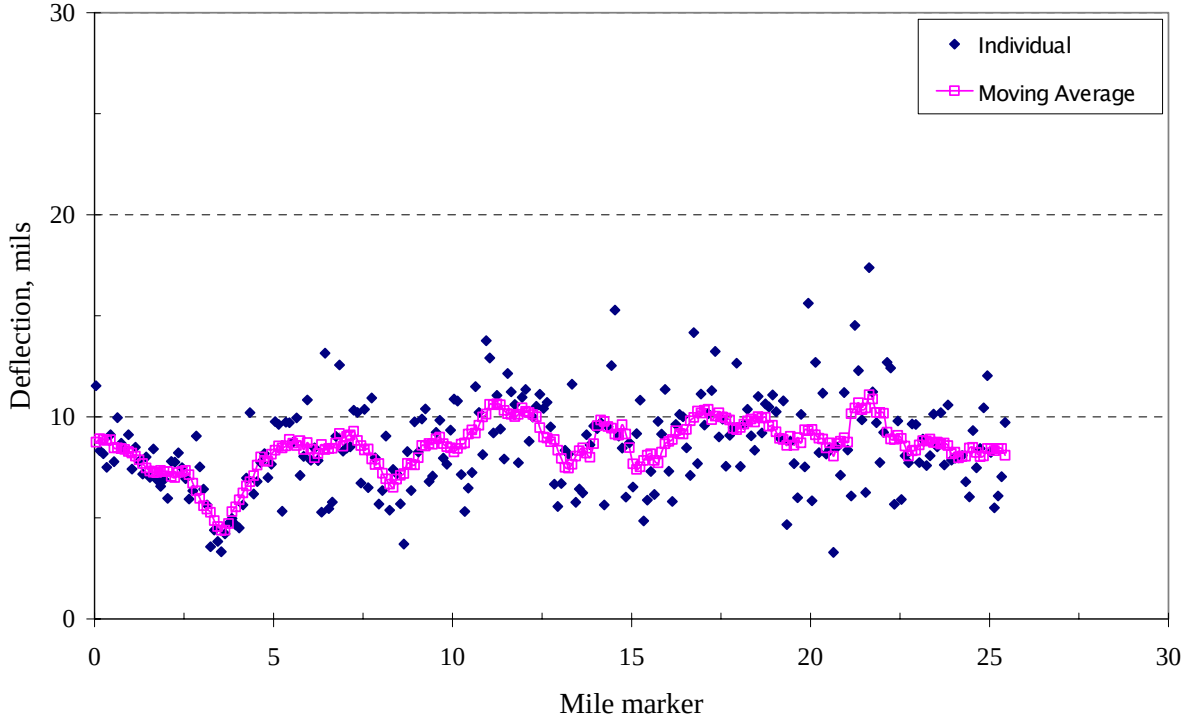
Route 6.
Rhode Island state line to Route 97 - westbound.



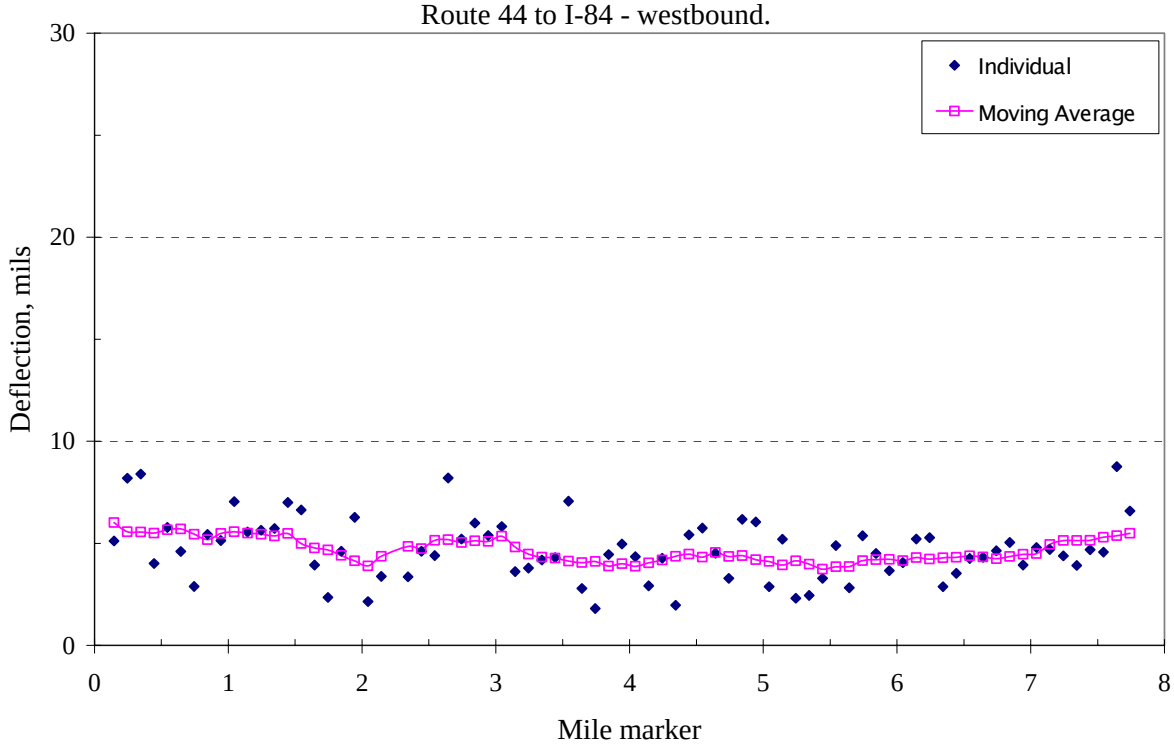
Route 97.
Route 6 to Route 44 - northbound.



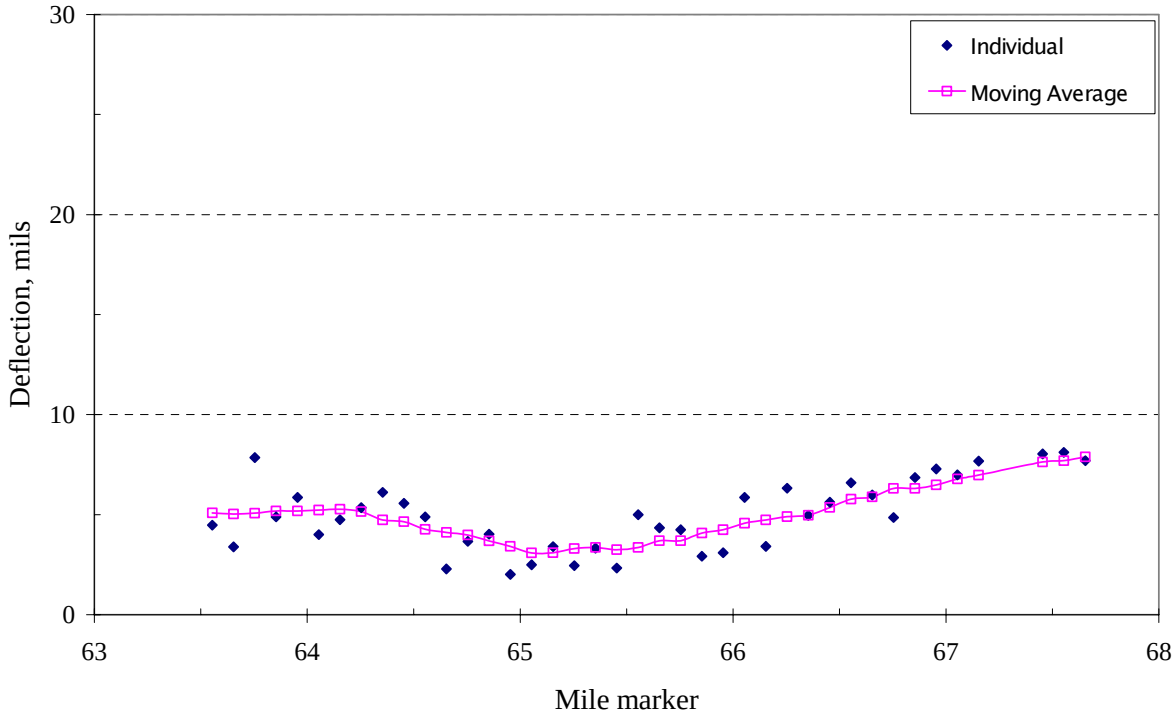
Route 44.
Route 97 to I-384 - westbound.



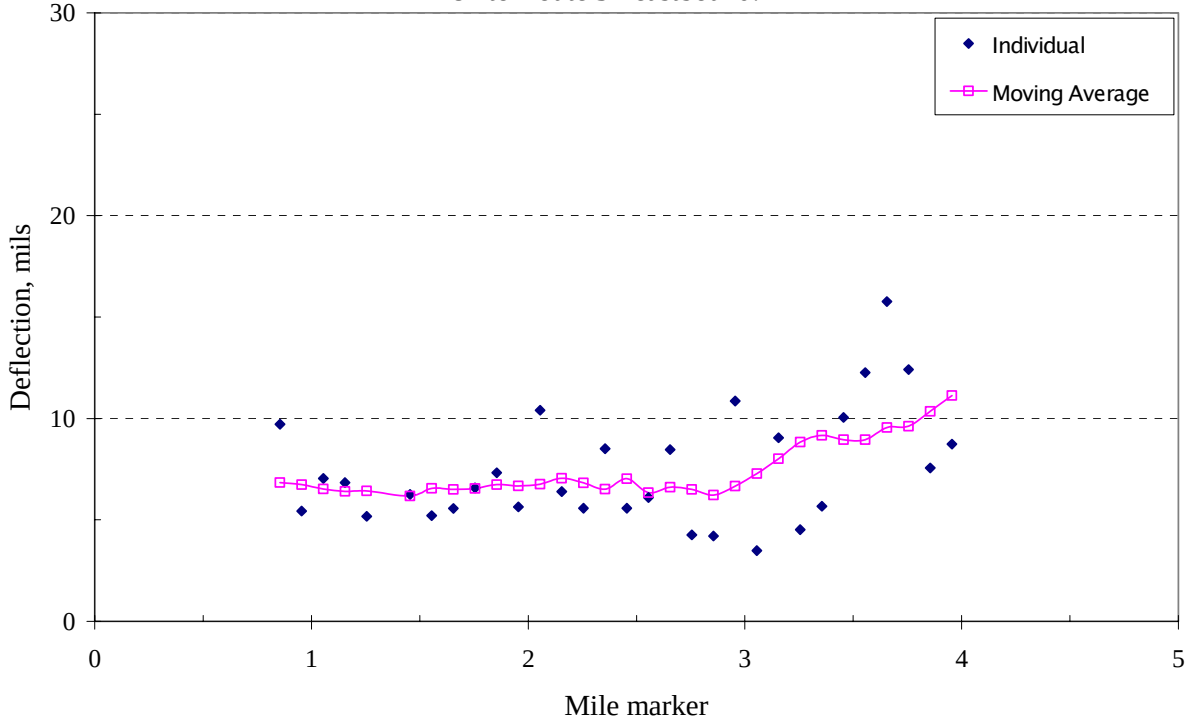
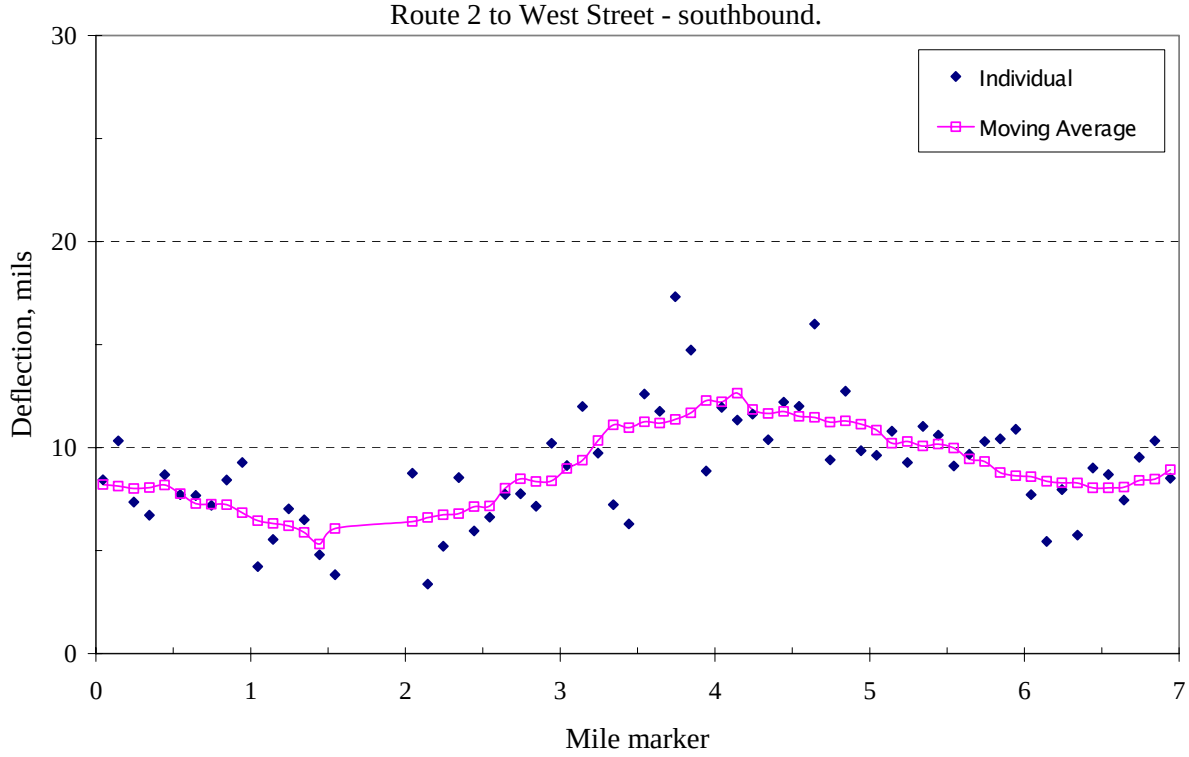
I-384.
Route 44 to I-84 - westbound.



I-84.
I-384 to Route 2 - westbound.



Route 2.
I-84 to Route 3 - eastbound.



Route 3.
Route 2 to West Street - southbound.