April 6, 2005

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**Subject:** **Rolling Wheel Deflectometer (RWD) Results for the Eastern Federal Lands Highway Division (EFLHD) on the Natchez Trace Parkway.** ARA Project No. 106450

Dear Mr. Amenta:

Applied Research Associates (ARA), Inc., appreciates the opportunity to submit to the Eastern Federal Lands Highway Division (EFLHD) the results of RWD testing performed on the Natchez Trace Parkway. This report summarizes the RWD device, testing program, and results.

It has been a pleasure working with EFLHD on this project. If you have any questions or need additional information, please do not hesitate to contact us.

Sincerely,

Douglas A. Steele, P.E.
Senior Engineer

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

Attachment

cc. Mr. Thomas Van, FHWA
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# Rolling Wheel Deflectometer (RWD) Testing on the Natchez Trace Parkway
**April 6, 2005**

## INTRODUCTION

The 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 displacement lasers mounted underneath the bed of a semi-trailer to measure a continuous deflection profile of the pavement when loaded by the trailer's single axle, dual tires. The system has undergone several field tests, including a comprehensive study in Texas in 2003. The field testing has identified several needed areas of improvement and development of the RWD has continued to make refinements in its calibration, data collection, and data processing activities.

In November, 2004, ARA conducted RWD testing on the entire length of the Natchez Trace Parkway in a study funded jointly by the Eastern Federal Lands Highway Division (EFLHD) and the FHWA Office of Asset Management. This report provides a description of the RWD methodology, the testing program performed on the Natchez Trace, and the RWD results. Figure 1 shows a typical view of the roadway.

Figure 1. Overview of the Natchez Trace Parkway.

# RWD DESCRIPTION

## Equipment

Figure 2 shows an overview of the RWD truck, trailer, and beam. The 53-ft trailer was custom designed and built specifically for the RWD. Its length minimizes pitching of the reference beam, thereby minimizing the laser range needed to accommodate bouncing of the trailer during normal operation. In addition, its natural frequency 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. 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. The wheels have been spaced a safe distance from the laser and beam using custom lugs and a spacer. The beam and extensions are covered with foam rubber material for thermal insulation. Figure 3 shows the laser and spacer between the tires.

Figure 2. Overview of the RWD.

Figure 3. Laser placed between the dual tires.

**Measurement Methodology**

The RWD utilizes a "spatially coincident" methodology for measuring pavement deflection. Three lasers are used to measure the unloaded pavement surface (i.e., forward of and outside the deflection basin), and a fourth laser, located between the dual tires and just behind the rear axle, measures the deflected pavement surface. Deflection is calculated by comparing spatially coincident scans as the RWD moves forward. In other words, the profile of the undeflected pavement surface is subtracted from the profile of the deflected pavement surface measured at the same exact locations. This method was originally developed by the Transportation and Road Research Laboratory (TRRL) and furthered by Dr. Milton Harr at Purdue University. It was later employed on the Dynatest/Quest prototype RWD.

It is important to remember that at 55 mph and a 10 kHz sampling rate a reading is being taken approximately every 0.1 in. The random error associated with the individual deflection readings can be very high, due to factors including equipment limitations and pavement factors. For example, due to pavement texture, one laser may read the top of an aggregate while the next laser to pass over that point may read the valley between two adjacent aggregates. This type of error is random, resulting in an approximately equal distribution of overestimated deflections, as underestimated deflections. If a sufficiently large number of readings are averaged, the random error is reduced to the point that the overall mean is not significantly affected by the random noise. For this project, ARA processed the data at 0.1-mi (528-ft) intervals.

## TESTING PROGRAM

Testing was performed between November 15 and 19, 2004, beginning at the north project end (i.e., mile marker 440). Data was collected in approximate 30- to 40-mi segments to maintain manageable raw data file sizes, and to allow periodic checking of RWD results in the field. Table 1 summarizes the data collection runs. In total, 26 test passes were made.

Table 1. Test log.

| Run no. | Date | Direction | Start time | End time | Start mile marker | End mile marker | Comments |
|---|---|---|---|---|---|---|---|
| 1 | 11/15/2004 | Southbound | 8:33 | 9:28 | 440 | 410 | Start S. of Nashville |
| 2 | | | 9:37 | 10:13 | 409 | 381 | |
| 3 | | | 10:29 | 11:07 | 379 | 351 | |
| 4 | | | 11:51 | 12:35 | 350 | 318 | |
| 5 | | | 12:44 | 13:07 | 317 | 298 | Detour 298-293 |
| 6 | | | 1:14 | 13:46 | 293 | 268 | End at Tupelo |
| 7 | 11/16/2004 | | 11:29 | 12:20 | 269 | 230 | |
| 8 | | | 12:26 | 13:09 | 228 | 194 | |
| 9 | | | 13:43 | 14:33 | 191 | 146 | |
| 10 | | | 14:47 | 15:37 | 144 | 102 | End N. of Jackson |
| 11 | 11/17/2004 | | 8:36 | 9:24 | 86 | 45 | Start S. of Jackson |
| 12 | | | 9:42 | 10:27 | 44 | 10 | End N. of Natchez |
| 13 | | Northbound | 10:45 | 11:32 | 10 | 50 | Start N. of Natchez |
| 14 | | | 11:45 | 12:28 | 51 | 86 | End S. of Jackson |
| 15 | 11/18/2004 | | 1:45 | 2:14 | 102 | 127 | Short day due to rain |
| 16 | 11/19/2004 | | 9:13 | 9:31 | 104 | 116 | Wet pavement |
| 17 | | | 9:41 | 10:03 | 117 | 135 | Wet pavement |
| 18 | | | 10:06 | 10:21 | 137 | 148 | Wet pavement |
| 19 | | | 10:51 | 11:03 | 150 | 151 | Wet pavement |
| 20 | | | 11:57 | 12:34 | 160 | 192 | |
| 21 | | | 12:54 | 1:45 | 194 | 238 | |
| 22 | | | 1:46 | 2:13 | 240 | 263 | |
| 23 | | | 2:42 | 3:16 | 265 | 293 | Detour 293-298 |
| 24 | | | 3:22 | 4:13 | 298 | 339 | |
| 25 | | | 4:14 | 5:15 | 341 | 392 | |
| 26 | | | 5:16 | 6:17 | 393 | 441 | End S. of Nashville |

Prior to mobilization to the Natchez Trace, the RWD lasers and distance measuring instrument (DMI) were calibrated at the ARA facility in Champaign, IL. At the beginning of each day's testing, the RWD lasers were turned on at least 30 minutes prior to testing and the RWD was driven at highway speeds for at least 20 minutes before collecting data. This is done to ensure that the lasers are warmed-up and stable, and that the RWD trailer (specifically the aluminum mounting beam and laser bodies) have reached thermal equilibrium.

During testing, the RWD was accelerated to a target speed of 55 mph, which varied approximately 5 to 10 mph, depending on the road's geometry (both horizontal and vertical curves). Overall, the RWD was able to maintain a good constant speed, with few interruptions due to slow-moving vehicles, turning vehicles, or other obstructions in the roadway.

The RWD was operated by a 3-person team, which included a driver, an operator, and an additional person who operated an automated digital camera system and record notes on the pavement surface types and condition. The digital images were used during data processing to provide a video documentary of field conditions. During testing the RWD operator entered event markers in the raw data file that corresponded to physical mile markers, the beginning and ending of bridges, changes in pavement surface type, and zones of significant acceleration/deceleration of the RWD. These event markers were used during data processing to reference the RWD data and for filtering of outlier data due to localized events, such as bridges and significant speed changes. In addition, GPS coordinates are collected for geo-referencing of RWD data.

# RESULTS

Final data processing was performed in the office using the RWD's proprietary software. The software processes the raw RWD files to calculate the following parameters per sample unit (in this case 0.1-mi intervals):

- Mean RWD deflection per sample unit, mils
- Deflection variation within a sample unit, mils
- Mean pavement surface temperature, ºF
- Temperature variation, ºF
- Mean truck speed, mph
- Speed variation
- Linear referencing based on the DMI, GPS, and physical mile markers

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 RWD results and a discussion of items of interest. The detailed results are included electronically in appendix A.

## Overall Trends

### *RWD Deflections*

The overall RWD deflection profile for the entire 440-mi Natchez Trace, both directions, is presented in figure 4. The data represents approximately 8,000 mean deflections calculated at 0.1-mi intervals. Each mean value represents approximately 60,000 individual deflection readings. The data in figure 4 is unfiltered, meaning outlier values due to localized events such as bridges, has not been eliminated. A filtered version of the results is presented later. In addition, the data has not been normalized to a single temperature to remove the effects of asphalt temperature susceptibility. The RWD collected temperature data that can be used for this purpose; however, the required pavement layer information data, such as asphalt thickness and base type, was not available at the time of this analysis to perform a temperature correction. Finally, the data has been reconciled to the physical mile markers in the field.

Figure 4. RWD deflection profile.
Unfiltered data. No temperature correction.

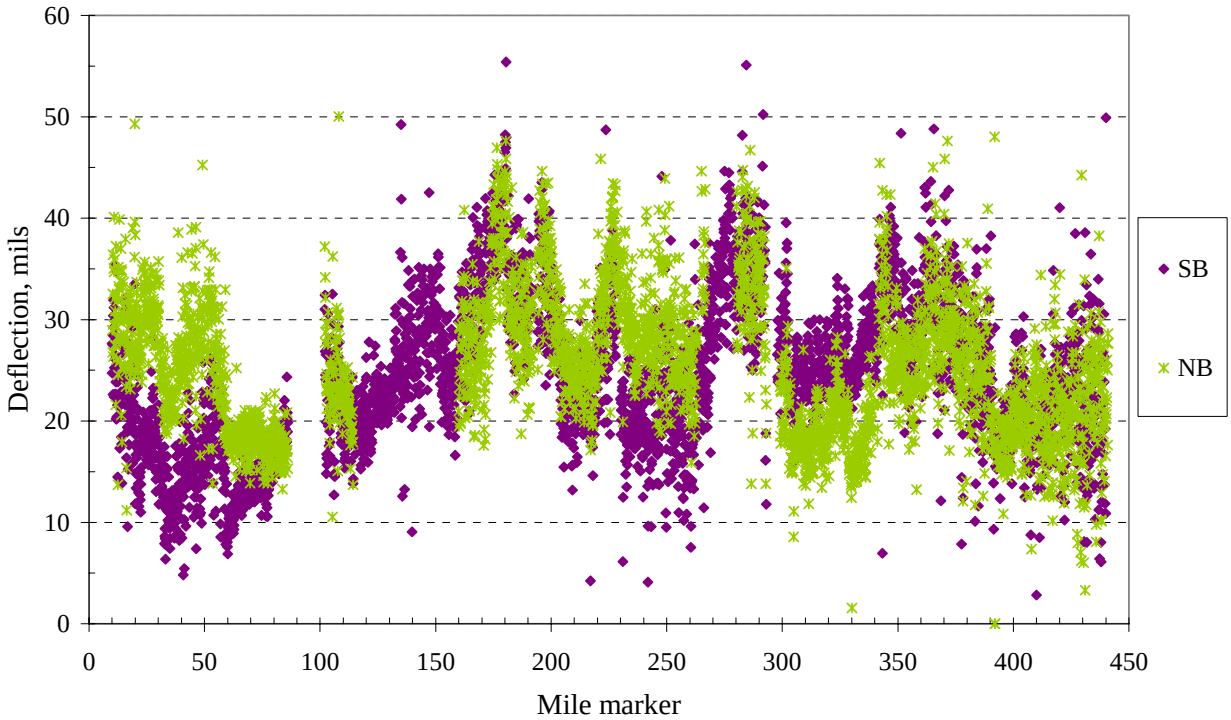



Figure 4 shows that the deflections are highly variable over the roadway, with the vast majority of values ranging from 7 to 48 mils. The mean value for the entire roadway is approximately 25 mils. Values in this range are typical for thin- and medium-thick flexible pavements constructed over variable subgrades. It can be seen that the overall lowest deflections occurred at the south project end between mileposts 60 and 82. On the other hand, in the central and northern portions of the project from mileposts 160 to 195, 270 to 295, and 340 to 395, the deflections are the overall highest for the roadway. Higher deflections indicate a comparatively weaker pavement structure, due to a combination of either thinner or weaker pavement materials, or a weaker subgrade.

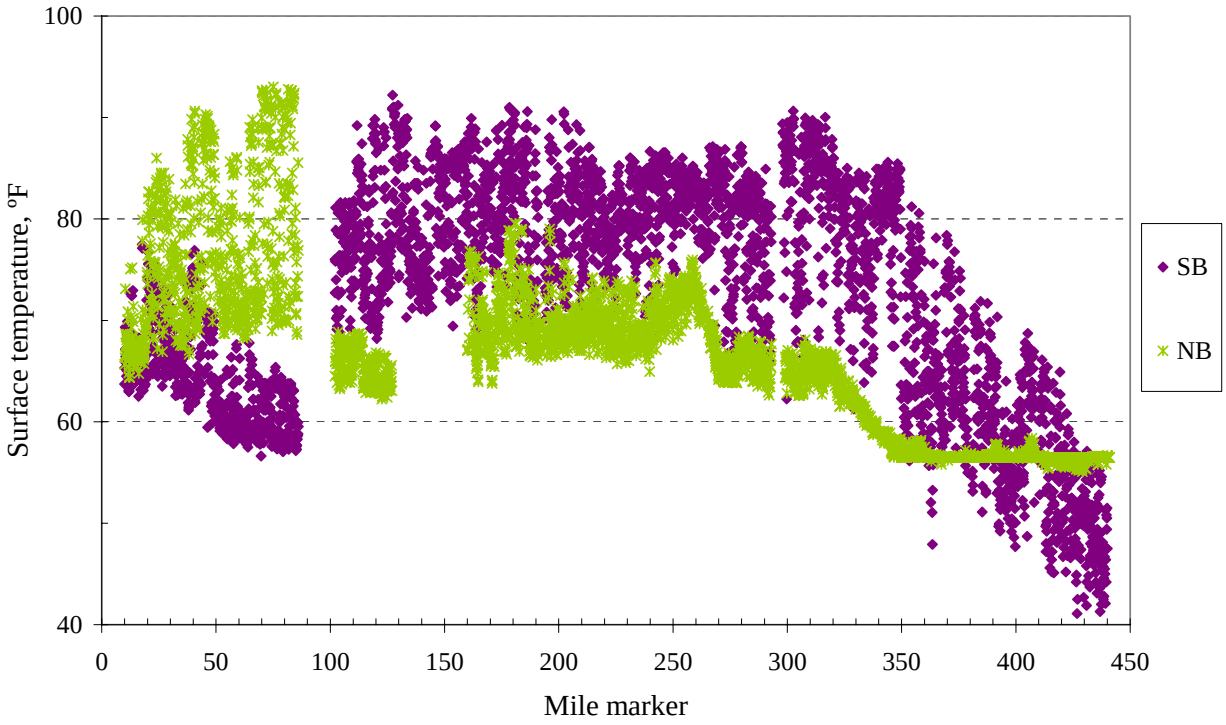
In many sections, the deflections between northbound and southbound lanes shown nearly identical trends and magnitudes, such as between mileposts 100 and 110, 160 and 230, and between mileposts 340 and 440. On the other hand, many sections show similar trends between lanes; however, the magnitude of the deflections in one lane is shifted, relative to the other lane. Some of this shift in magnitude can be explained by the temperature data and its effect on asphalt stiffness.

*Temperature Effects on Flexible Pavements*

Figure 5 presents the pavement surface temperature data collected by the RWD's onboard infrared thermometer. The values in figure 5 are mean values for each 0.1-mi interval. It is evident that temperatures conditions were highly variable during testing, ranging from approximately 40 to 93 ºF. In the southbound direction, temperatures were cool in the morning and stabilized during the day. Average temperatures were highly variable due to variable cloud cover and shading along the roadway. In the northbound direction between mileposts 100 and 320 testing was done during overcast conditions, and temperatures were much more uniform over the project length. Finally, the portion between northbound

mileposts 320 and 440 was tested following sundown and it can be seen that temperatures were extremely uniform at night.

Figure 5. Pavement surface temperature during testing.
November 15-19, 2004.




A comparison of figures 4 and 5 shows that in many cases the deflection difference between northbound and southbound lanes can be explained by the differences in temperature at the time of testing. For example, between mileposts 10 and 90 the northbound lane produced higher deflections, consistent with the higher temperatures present during the time of the northbound testing. Likewise, between mileposts 300 and 340 the temperatures in the northbound lane were lower than the southbound, consistent with its lower temperatures.

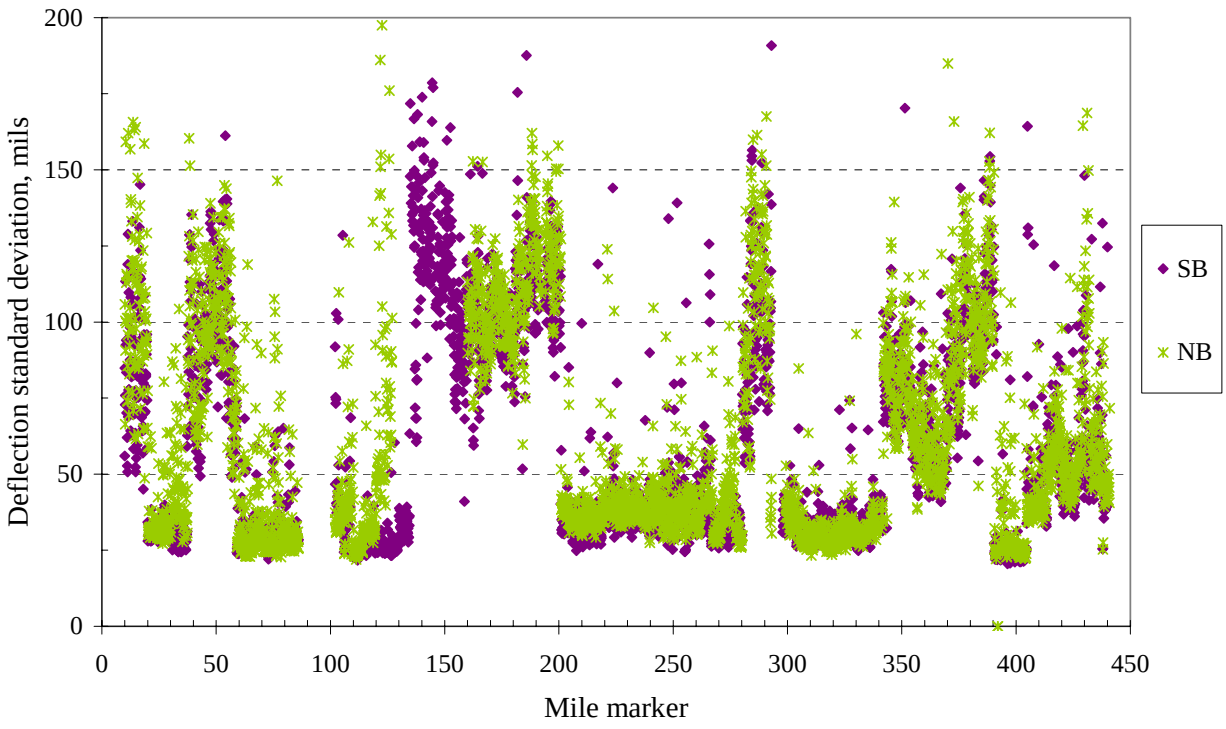
Deflections between adjacent lanes did not always follow a temperature-related trend, such as the cases where both lanes gave similar results, in spite of a difference in temperatures. Although detailed pavement layer thickness information was not available for this analysis, a review of field notes and video showed that most of the areas that were insensitive to temperature changes correspond to chip seal pavements, while the areas where deflection differences occurred correspond to hot-mix asphalt (HMA) pavements. This would indicate that the chip seal pavement deflections are less sensitive to temperature changes as compared to HMA pavements, as would be expected.

*Indirect Measure of Surface Texture*

As stated, mean values for each sample unit are the average of approximately 60,000 individual readings. At a speed of 55 mph, this corresponds to a laser reading approximately every 0.1 in (2.5 mm). As a byproduct of averaging, the RWD also calculates the variability within a sample unit in terms of the mean deflection's standard deviation. As opposed to variability *between* sample units (which is driven by deflection variation along the roadway length), variability *within* a sample unit is primarily a function of pavement texture. On a roadway such as the Natchez Trace, the pavement textures varies significantly along its length due to the interchanging of HMA (smooth) and chip seal (rough) surfaces. Figure 6 displays the deflection variability within a 0.1-mi sample unit, which provides an indirect measure of pavement surface texture. A comparison with field notes shows that the groups of values that fall below a standard deviation of 50 mils corresponds to HMA pavement surfaces, while the higher, more variable values ranging from 50 to 200 mils coincides with chip seal surfaces.

It should be noted that the higher in-sample deviations associated with the chip seal pavements do not significantly affect the RWD's ability to predict the mean deflection for the sample unit, as the tremendous number of individual readings used to calculate the mean effectively cancel out this random error.

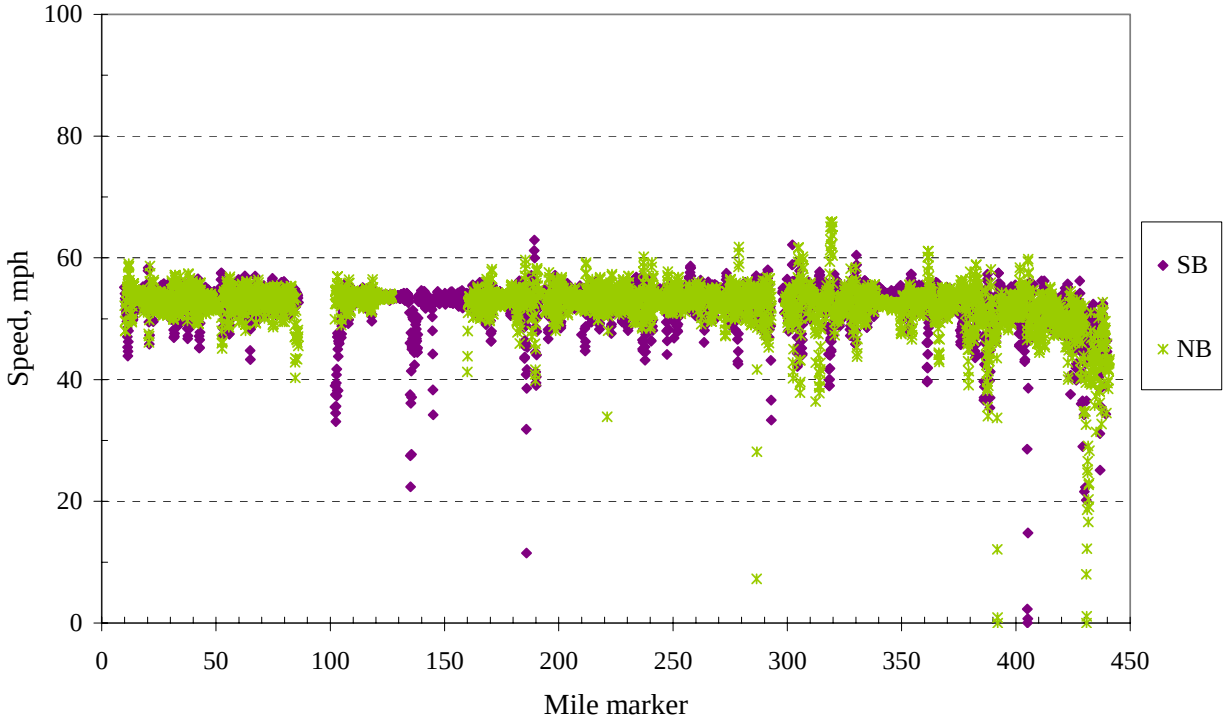
Figure 6. Deflection deviation within 0.1-mi intervals.
(Indirect measure of surface texture).



Truck Speed Variation

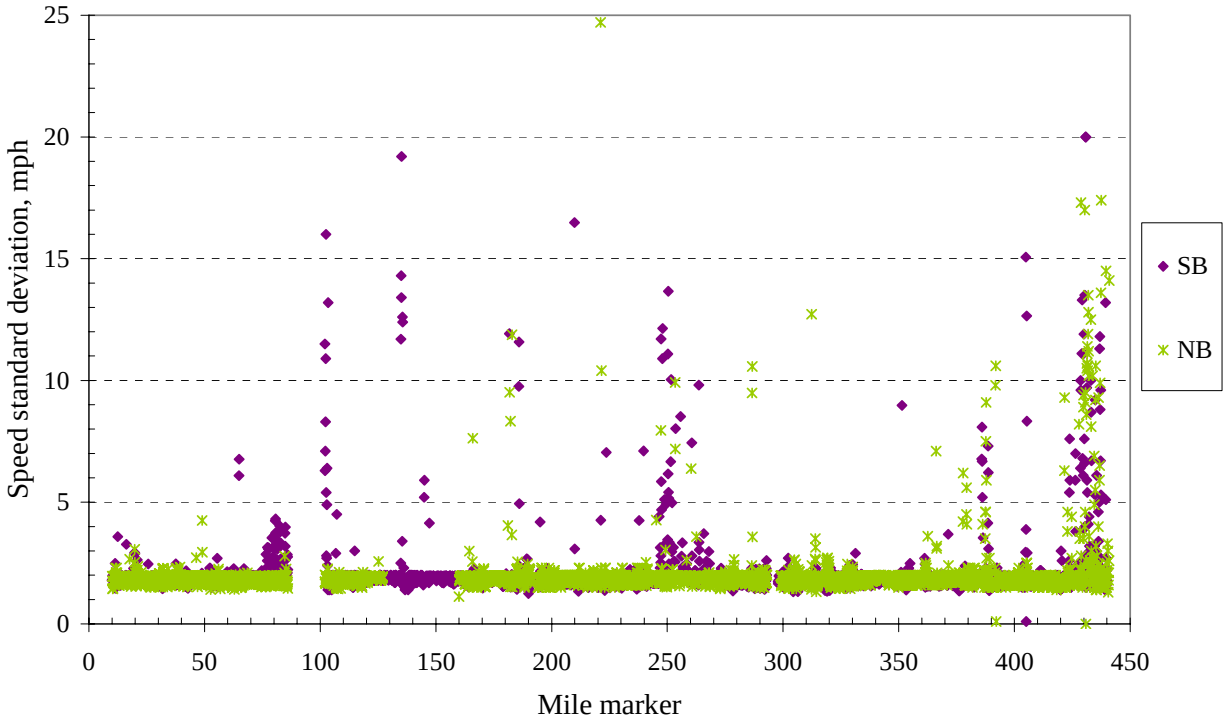
A typical question regarding RWD deflections is the variability of measured response with changing truck speeds. While it's true that the visco-elastic nature of asphalt materials makes deflections speed dependent, our experience has shown that these variations only become significant at very low vehicle speeds, for example at less than 15 mph. For variations of +/- 5 to 10 mph at a target speed of 55 mph, normal speed variations (for example, due to horizontal and vertical curves) do not significantly affect the deflection results. Figure 7 displays the mean truck speed per sample unit, which shows that the overwhelming majority of the roadway was tested at speeds ranging from 45 to 60 mph, with an average of approximately 55 mph. A few sample units had average speeds less than 30 mph, and these values were reviewed individually to determine whether their values should be filtered out of the final results.

Figure 7. Truck speed during testing.
Both directions.




In addition, truck speed could vary within a sample unit, if there was the need for significant braking or accelerating, such as the cases of slow moving vehicles, turning vehicles, or other localized obstructions. The effect of braking/accelerating can affect RWD deflections, if it causes the RWD trailer to bounce enough to make the lasers go out of their valid measurement range. Figure 8 shows the truck speed variation within each sample unit. Typically, the standard deviation of the truck speed was about 2 mph. There were many outliers over the project, with a large portion of these occurring between mileposts 420 and 440, the most complicated segment in terms of road geometry. Sample units with high speed variability were reviewed individually to determine whether the speed fluctuations significantly affected deflections.

Figure 8. Speed variation within 0.1-mi intervals.
Both directions.

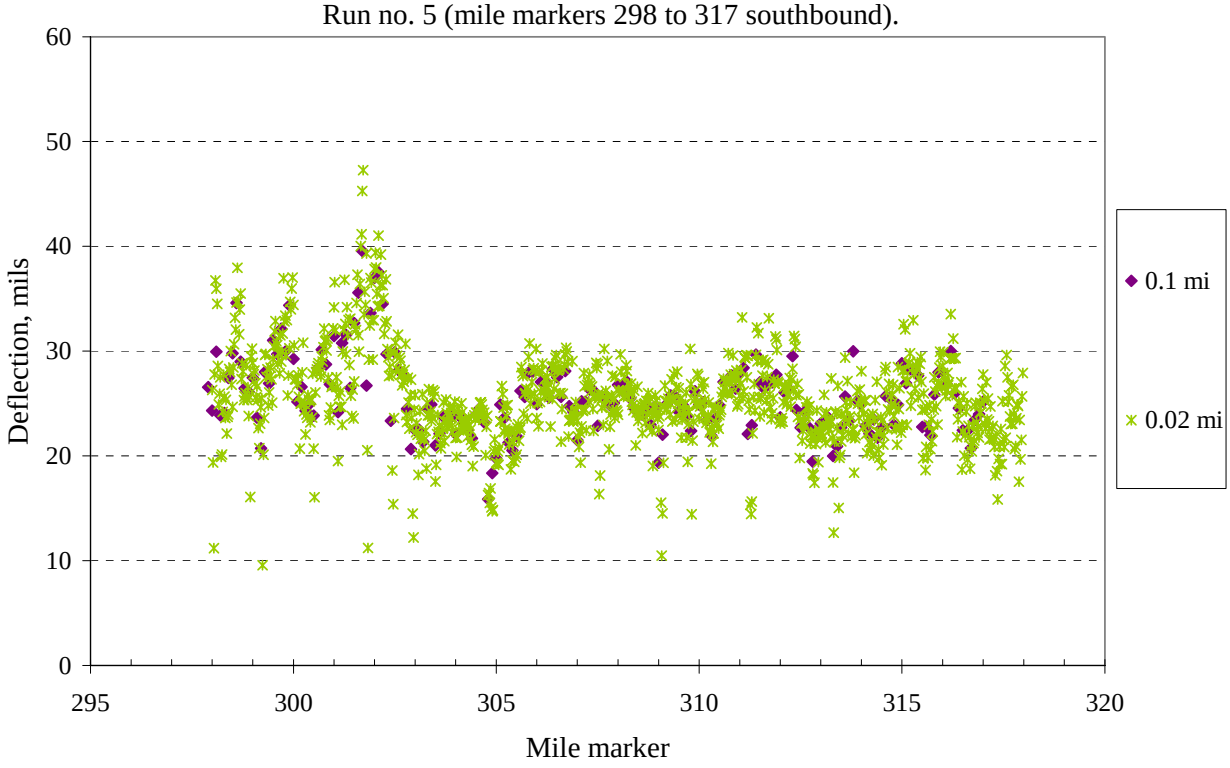



*Variation of Sample Unit Length*

EFLHD has requested that deflection results be reported at 0.02-mi intervals, to correspond with their existing pavement management database. Attempts were made to report values at this interval; however, the RWD post-processing software requires further modification to handle the more intensive calculations. Although the software modifications could not be completed prior to issuing this report, a sample of the effect of a shorter averaging interval is shown in figure 9 for test run no. 5.

It shows that decreasing the sample unit length does not significantly affect the overall trend (or the mean deflection for the overall section), but it does increase variability over the section length. This is as expected, as shorter sample units provide fewer data points (in this case by a factor of 5) for averaging out random error due to surface texture, truck bounce, laser random error, and so on. A review of the results in figure 12 shows that at 0.02-mi intervals there are many outliers that deviate +/- 5 to 10 mils from the majority of values. While it is possible that these reflect locally stronger areas of pavement, it is much more likely that the results show the effect of random error. Based on this limited sample, and the reasonableness of the variation shown in the 0.1-mi data, we caution against using a sampling interval that is too small to sufficiently reduce random error.

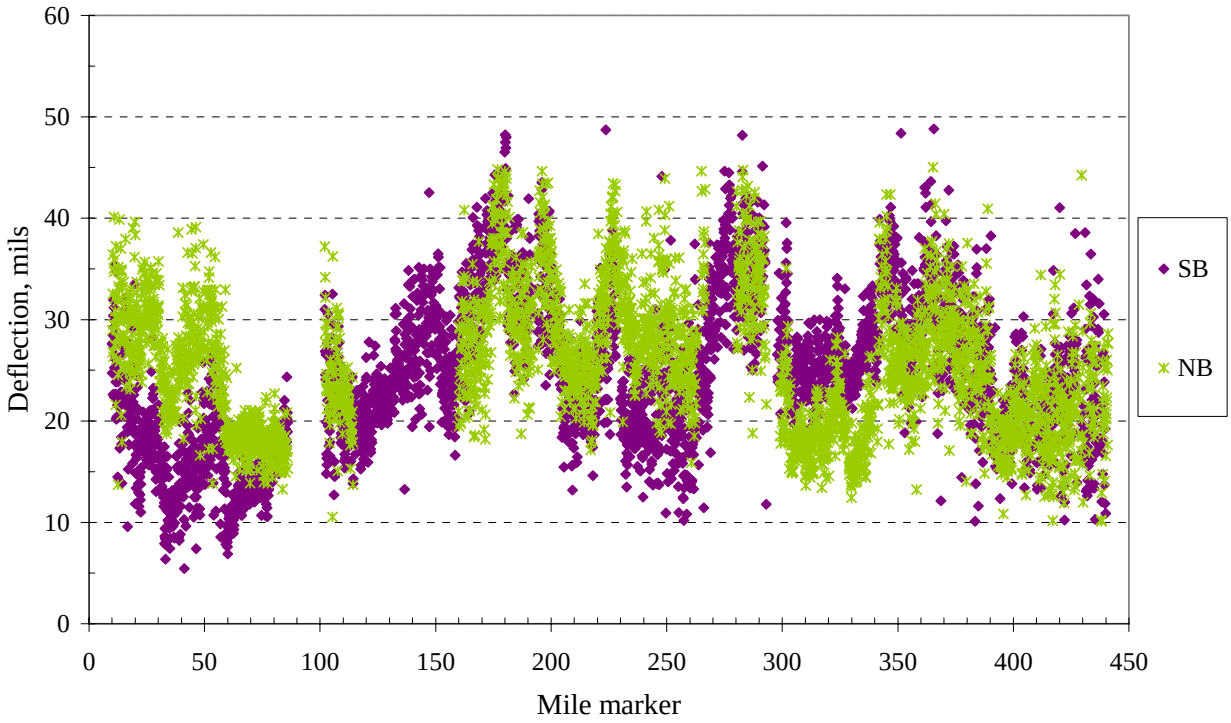
Figure 9. Effect of sample unit length on RWD deflections.
Run no. 5 (mile markers 298 to 317 southbound).




*Filtered Deflection Profile*

As discussed above, the deflection values were reviewed in detail to evaluate the validity and reasonableness of results. Outliers were analyzed in conjunction with comments entered during field testing to determine their cause, and values were filtered if they appeared to be significantly biased by factors such as vehicle speed changes (i.e., due to braking/accelerating), localized roughness (i.e., bridge joints), or other factors, such as a wet pavement surface. The filtered pavement profile is presented in figure 10.

Figure 10. RWD deflection profile.
Filtered data.




*Detailed Deflection Profiles*

The filtered deflection results have been graphed in detail in two manners—by lane and by data run. This is to allow detailed analysis of the results, if desired. These graphs are included electronically in appendix A and samples of each are provided below. Figures 11 and 12 show the data separated by test run number for mileposts 350 to 440 for the southbound and northbound lanes, respectively. Figure 13 presents the same data combined on a single graph, with data in each direction presented as a single series.

Figure 11. Example of detailed data separated by test run.
Mile Marker 350 to 440 southbound.

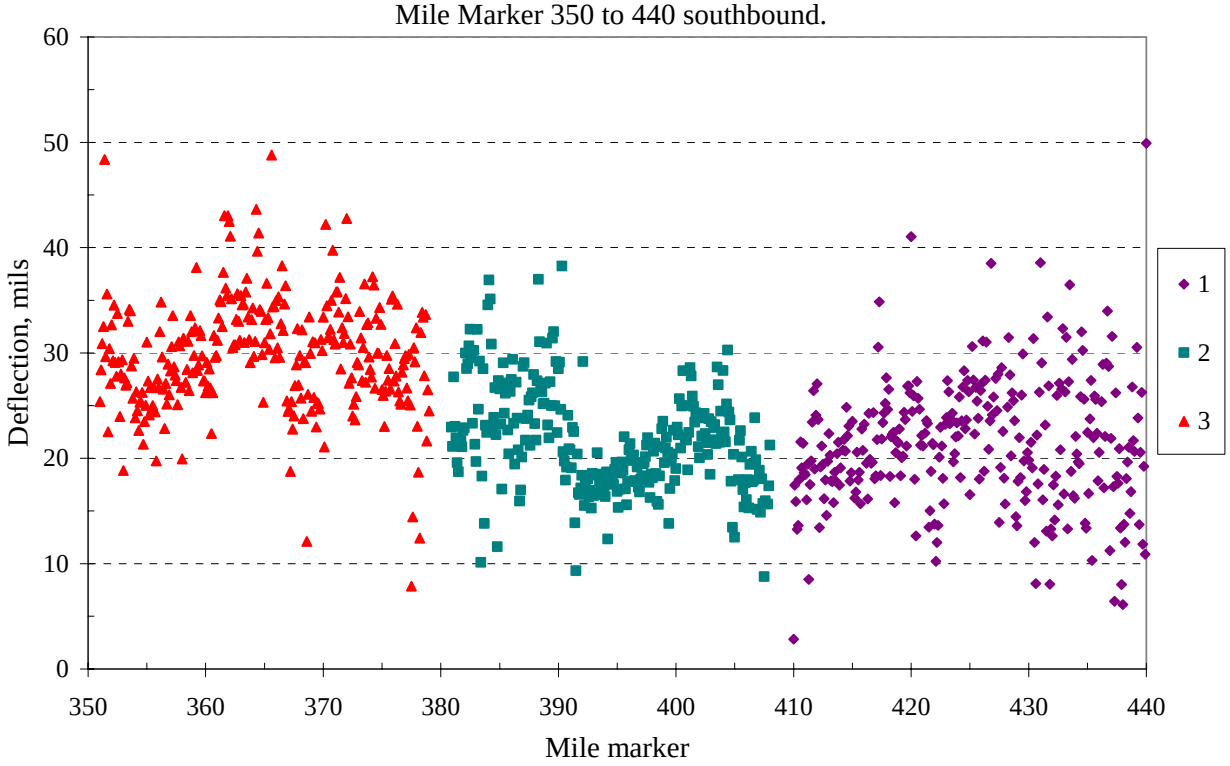



Figure 12. Example of detailed data separated by test run.
Mile Marker 350 to 440, northbound.

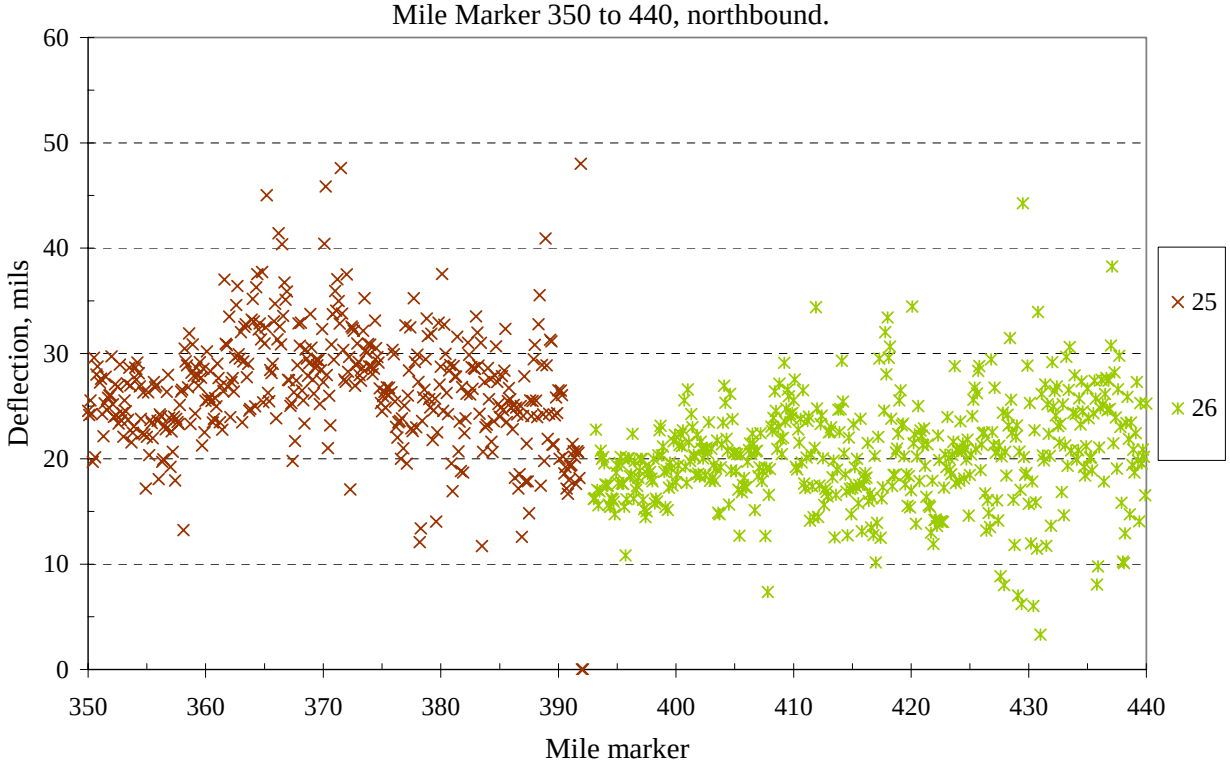
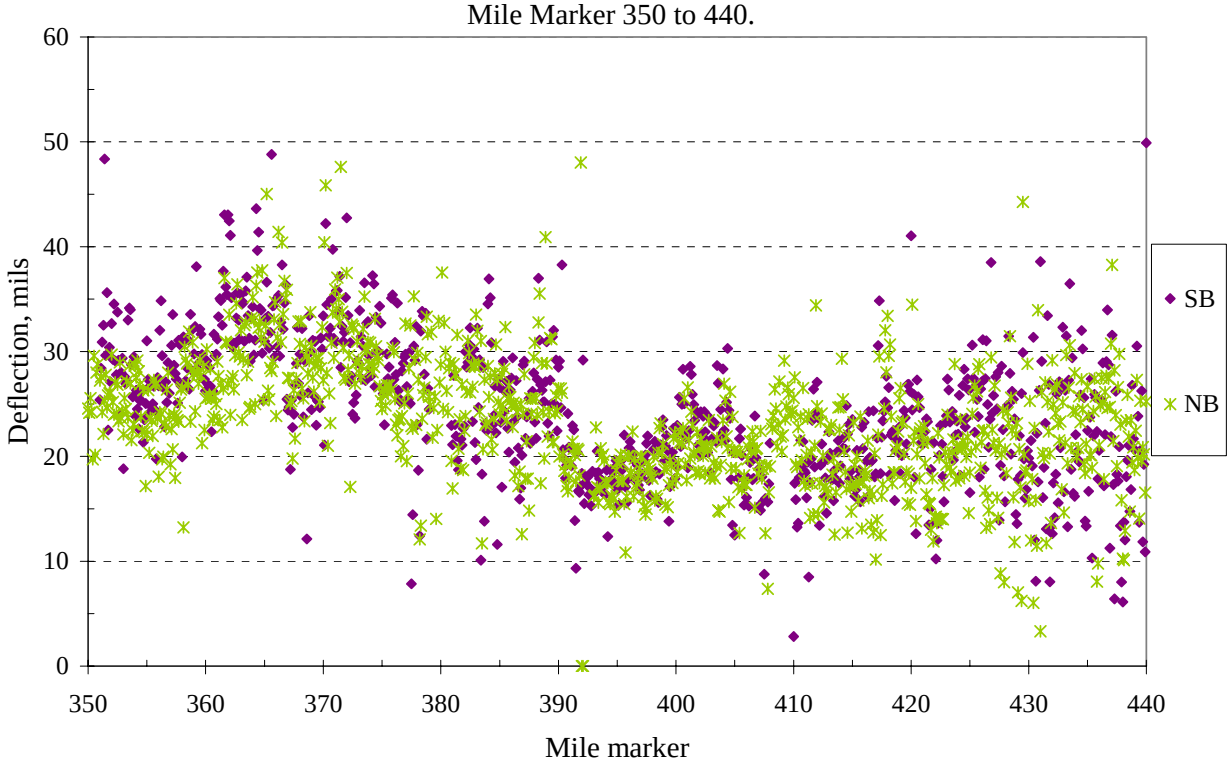


Figure 13. Example of detailed data separated by lane.
Mile Marker 350 to 440.




## CONCLUSIONS

RWD survey was performed on the entire 440-mi Natchez Trace Parkway, both directions. Deflections were measured approximately every 0.1-in and average over 0.1-mi intervals to reduce random error due to surface texture, truck dynamics, and laser random error. In addition to mean RWD deflection per sample unit, several other parameters where recorded and output, including—in-sample deflection variability, pavement surface temperature, truck speed, linear referencing, and GPS referencing. In addition the RWD field team recorded general pavement condition information and digital images along the entire project. All of the above information was used during data analysis to determine both the validity and reasonableness of the RWD deflections. Detailed pavement layer information (including asphalt thickness and base type) were not available during this analysis.

**Findings on the Natchez Trace Parkway**

RWD testing provided the following findings:

- Deflections over the roadway were highly variable, with the majority ranging from 7 to 48 mils and a mean of approximately 25 mils. Deflections in this range are typical for thin- and medium-thick flexible pavements.

- The lowest deflections were measured at the south project end between mileposts 60 and 82. The highest deflections (which are the areas of weakest pavement structure) were detected from mileposts 160 to 195, 270 to 295, and 340 to 395.

- Due to the nature of the pavement structures (i.e., thin HMA and chip seal pavements), the deflection trends, magnitudes, and variation are being driven primarily by variations in the subgrade support, including soil modulus and depth to bedrock (where near the surface). Secondary factors include surface and base thickness and stiffness.

- Approximately 50 percent of the study showed similar deflections between the northbound and southbound lanes at the same mile markers. The majority of these locations consist of chip seal pavements, whose deflections are relatively insensitive to temperature variations. Areas where deflections varied between lanes showed similar deflection trends, but a shift in magnitude. The majority of these sections are HMA pavement, which are temperature sensitive. The deflection trends in these sections are consistent with the trends in pavement temperatures measured by the RWD.

- The RWD deflections presented in this report have not been corrected to a standard temperature, as detailed layer thickness information needed for this procedure was not available at the time of this analysis. This correction can be made if we are provided the HMA thickness and base type.

**Future RWD Development**

The RWD is a prototype device that is currently in the process of going from the research stage to becoming a commercial device. In this respect, ongoing development is taking place to improve the RWD's ability to measure accurate, repeatable deflections at highway speeds, and to improve the efficiency of data processing and reporting. Specific improvements that are currently under development include:

- The RWD computer hardware is being upgraded and the its software re-written to make more efficient use of computer resources. This will provide the ability to more efficiently compute deflections over shorter sample unit lengths, such as 0.02-mi intervals.

- The post-processing software is being modified to allow calculation of average values at fixed intervals (e.g., 0.02-mi intervals) without reconciliation to the physical mile markers recorded in the field. The current software automatically reconciles stationing between mile markers.

- Filtering of RWD results will be automated to more efficiently remove erroneous data (due to bridges, etc.,) and generate graphs. This will aid in field quality checking of results and allow faster delivery of final results.

In addition, ARA is pursuing research to support pavement managers in the use of RWD data in network-level evaluation and pavement management. Themes that we intend to develop, include:

- Development of a Structural Index, based on the RWD results in conjunction with other pavement information, such as layer thicknesses.

- Decision-making trees, based on RWD deflections, pavement condition, and roughness indices.

- Dynamic segmentation of RWD profiles to identify structurally uniform sections.

- Establishing acceptable RWD deflection levels (or Structural Index values) for different road classifications and/or traffic levels. For example, in the case of the Natchez Trace, determine a

target deflection threshold value based on the specific project conditions (e.g., subgrade, climate, materials, and traffic). Therefore, based on the measured deflection magnitudes and variability, it can be determined which pavement sections provide sufficient structural capacity for their anticipated use and traffic, and which sections require structural improvement.

The Natchez Trace Parkway provides an excellent opportunity to develop these tools, which can be used to the benefit of EFLHD on this and other federal roadways.