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OPERATIONAL EFFECTS OF WIDE EDGE LINES APPLIED TO HORIZONTAL CURVES ON TWO-LANE RURAL HIGHWAYS

Final Report

PennDOT/MAUTC Partnership, Work Order No. 4
Research Agreement No. 510401

November 2, 2006

By Eric T. Donnell, Mason D. Gemar, and Ivette Cruzado

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Department of Transportation

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16. Abstract
The Pennsylvania Department of Transportation and other state transportation agencies are required to provide edge line delineation on two-lane arterials when traffic volumes exceed 6,000 vehicles per day and the pavement width is at least 20 feet. Other combinations of pavement width and traffic volume may also warrant edge line delineation. The standard edge line width is 4 inches; however, an edge line width of 8 inches can provide greater emphasis for motorists. There is a need to evaluate the effectiveness of providing wider edge lines on horizontal curves to determine if they provide improved delineation for motorists on two-lane highways.

The objective of this project was to evaluate the operational effects of using wider edge lines on horizontal curves along two-lane rural highways. A before-after observational study with comparison sites was used to evaluate the change in several performance measures, including mean speed, speed variance, encroachment frequency, mean lateral vehicle position in the travel lane, lateral vehicle position variance, and speed and lateral vehicle position differential between the tangent and midpoint of a horizontal curve. Day and night time periods were considered as were approach tangent and horizontal curve locations. The effects of vehicles traveling in the opposing travel lane were also considered in the evaluation. The results indicate that wide edge lines, applied to horizontal curves on two-lane rural highways in Pennsylvania, do not consistently change the encroachment proportion along curves, nor do they consistently change driver behavior patterns at all treatment locations as measured by speed and lateral vehicle position. The location of speed deceleration, based on a subjective assessment of speed profile plots, provides evidence that drivers recognize curves at night from a greater distance with wide edge lines when compared to similar curves with standard, 4-inch-wide edge lines.

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1. INTRODUCTION

Longitudinal pavement markings are used to delineate the horizontal limits of a travel lane, convey regulations or warnings, provide guidance to road users, and supplement other traffic control devices. The Manual of Uniform Traffic Control Devices (MUTCD) (*1*) contains information about pavement marking application standardization, including color, width, and pattern. These standards are principally based on the number of travel lanes, lane width, and average daily traffic (ADT). For example, the Pennsylvania Department of Transportation (PennDOT) and other state transportation agencies are required to provide edge line delineation on two-lane arterials when traffic volumes exceed 6,000 vehicles per day and the pavement width is at least 20 feet (*1*). Other combinations of pavement width and traffic volumes may also warrant edge line delineation. The standard edge line width is 4 inches; however, an edge line width of 8 inches can provide greater emphasis for motorists.

The MUTCD does not contain warrants based on the safety or operational effects of pavement marking presence; however, it does indicate that edge line markings should not be used where "an engineering study or engineering judgment indicates that providing them is likely to decrease safety." It is believed that pavement markings provide the necessary guidance to motorists to adequately traverse a roadway section, especially at night in unlighted areas. In addition, the presence and type of pavement markings and their retroreflectivity level are often said to influence roadway safety and mobility. While it is possible that traffic volume warrants alone are adequate to standardize pavement marking treatments, safety as measured by crashes and surrogate measures may better guide traffic engineers in appropriate application of this important traffic control device.

The objective of this project was to evaluate the operational effects of using wider edge lines on horizontal curves along two-lane rural highways in Pennsylvania. During a recent study by the Federal Highway Administration (FWHA) in Delta, Pennsylvania, experimental participants subjectively indicated that wider edge lines on horizontal curves provided improved guidance, especially during nighttime driving conditions (*2*). The present study is based on quantifiable driver performance measures, including mean speed and speed variance on both the approach tangent and mid-point of horizontal curves, mean lateral vehicle position in the travel lanes on the approach tangent and mid-point of a horizontal curve, and the proportion of vehicle encroachments onto the shoulder or opposing travel direction at each study location. Because the wide edge lines were applied to horizontal curves during the study period, several years of safety data were not available to perform a crash-based evaluation of their effectiveness. However, quantification of driver behavior, as measured using various operational measures, may be useful in determining safety consequences of wide edge lines on horizontal curves.

To accomplish the research objectives, several tasks were undertaken. A critical literature review described the safety and operational evaluations that have been performed for a variety of pavement markings. The literature review also examined the various methods used to collect and analyze driver behavior data. A synthesis of the literature review is contained in the second section of this report. Study sites were then selected in consultation with the PennDOT Bureau of Highway Safety and Traffic Engineering. Four treatment sites were identified along with four similar comparison sites. A data collection and analysis plan was then developed to outline the wide edge line evaluation protocol. The study sites and data collection methodology are described in the third section of this report. Once the performance measure data were collected at each study site, the data were compiled, screened, and analyzed to determine the effects of wide edge lines on driver behavior. The fourth section of the report describes the analysis methodology while the fifth section describes the analysis results. Finally, conclusions from the research are discussed in the last section of the report.

2. LITERATURE REVIEW

This section critically synthesizes available research aimed at documenting the correlation between safety and mobility and edge line pavement marking presence, width, and retroreflectivity level. It also contains a review of data collection and analysis methods used in past research to evaluate driver performance. This chapter is organized into the following sections: safety effects of pavement marking presence; safety effects of raised pavement markers on horizontal curves; surrogate measures of safety; driver behavior and performance measures; explicit wide edge line evaluations; and data collection and analysis methods used in past research.

2.1 SAFETY AND PAVEMENT MARKING PRESENCE

Unfortunately, little research has been conducted on the safety effects of explicitly providing edge line pavement markings on roadways. What research does exist seems to indicate that centerline and edge line pavement markings, when applied on two-lane, low-volume roadways, may decrease certain crash types. Potters Industries (*3*) reported that two-lane roadways with yellow centerline markings experienced 40 percent fewer total crashes compared to the same roadways without any centerline pavement markings. Furthermore, roadway sections with an edge line and a single center white pavement marking were evaluated after conversion to a double yellow and skip line, and a 15 percent reduction in total crash frequency was reported. However, on this same type of roadway Al-Masaeid and Sinha (*4*) found a 3.4 percent increase in the total number of accidents after improving pavement markings (the finding was not statistically significant). The analysis was then refined to consider only those sites that had a higher-than-average crash frequency in the before condition, and a statistically significant reduction of 13.5 percent in the total crash frequency was found.

Miller (*5*) performed a benefit-cost analysis of centerline and edge line pavement marking applications using material, crash, and traffic congestion data. Based on existing literature, it was concluded that adding centerlines and edge lines to roadways reduces crashes by 36 percent and adding edge lines to roads with centerlines reduces crashes by 8 percent. The average benefit-cost ratio computed in the analysis was 60, or $1 spent on longitudinal pavement markings yields $60 in increased safety and reduced congestion benefits.

Tsyganov et al. (*6*) conducted a study in Texas to analyze the effectiveness of edge lines at reducing crashes. The parameters used in the crash analysis included lane and shoulder width, horizontal curvature, and traffic volume. The results indicated that edge line treatments on rural two-lane roadways may reduce accident frequency with the highest safety impact on curved segments of narrow roadways. Also, edge line presence shows some positive safety impact during darkness that may be related to better driver perception of path and speed.

2.2 SAFETY EFFECTS OF RAISED PAVEMENT MARKERS ON HORIZONTAL CURVES

Several research studies have been conducted to evaluate the safety effects of raised pavement markers (RPMs) on two- and four-lane highways. RPMs are commonly mounted on or in the roadway surface and act as a guide to position motorists in the travel lane or as a supplement or substitute for pavement markings (*1*). While RPMs are not recommended as a supplement for right edge line markings on two-lane rural highways, they are commonly used as a supplement for centerline markings. This section describes past research related to the safety effects of RPMs on horizontal curves of two-lane rural highways. Although the RPMs are used as a centerline safety treatment, their effects should be documented in case they are considered in combination with wide edge lines on horizontal curves.

Before-after methods have mainly been used to evaluate RPM safety effectiveness. The results have been mixed, with some locations exhibiting increased crash frequency while others displayed a decreased crash frequency. Khan (*7*), for example, studied the safety effects of raised pavement markers on rural highways in Ohio. The total, daylight, and nighttime crash frequencies decreased 9.2, 11.2, and 5.3 percent, respectively, after installing RPMs. Chi-square tests indicated that the reported crash reductions were statistically significant at horizontal curves, through approaches, interchange gore areas, and intersections with a left-turn lane, but not statistically significant at narrow bridge and stop-controlled approaches.

In the mid-1970s, the Georgia Department of Transportation installed RPMs on centerlines of nearly all horizontal curves above six degrees of curvature (*8*). The Department reported that nighttime crashes were reduced by 33 percent when compared to daytime crashes at locations that were modified in 1976, reduced by 32 percent at locations modified in 1977, but increased by 53 percent at locations modified in 1978. When aggregating all nighttime crashes, an overall reduction in crash frequency of 22 percent was reported.

The safety effects of permanent raised pavement markings (PRPMs) were recently evaluated using the empirical Bayes' before-after study methodology (*9*). Data from six states (Illinois, Missouri, New Jersey, New York, Pennsylvania, and Wisconsin) were used in the analysis with mixed results. Non-intersection locations along two-lane roadways and four-lane freeways were considered. Accident modification factors (AMFs) were developed to guide decisions on the application of PRPMs on two-lane roadways and four-lane freeways. An AMF is the ratio between the expected crash frequency per unit of time after PRPM implementation to the estimated crash frequency per unit of time had PRPMs not been installed. If an AMF exceeds 1.0, a crash increase is expected after installation of the treatment. Table 1 shows the AMFs developed for two- and four-lane roadways based on ADT volumes and degree of horizontal curvature.

Table 1. Accident Modification Factors for Two-Lane Highways and Four-Lane Freeways (*9*)

Two-lane Roadways			Four-lane Freeways	
ADT	AMF: Degree of Curve ≤ 3.5	AMF: Degree of Curve > 3.5	ADT	AMF
0-5,000	1.16	1.43	≤20,000	1.13
5,001-15,000	0.99	1.26	20,001-60,000	0.94
15,001-20,000	0.76	1.03	>60,000	0.67

There is a significant research base related to the safety effectiveness of raised pavement markers on horizontal curves. However, until recently much of this work was based on simple before-after analyses that typically contain regression-to-the-mean bias, where roadways with high crash frequencies were treated with RPMs in anticipation of improving road safety. The empirical Bayes before-after evaluation (*9*), designed to reduce these biases, concurred with the earlier research in the conclusion that RPMs may increase crash frequency at some locations and decrease crash frequency at others. This contradictory finding suggests that further research must be completed to determine the true safety effectiveness of RPMs.

2.3 SURROGATE MEASURES OF SAFETY

As crashes are rare and complex events, surrogate measures of safety are often used to evaluate the effectiveness of a given roadway treatment. A study by Thompson (*10*) was performed to determine crash surrogate measures that can be used to identify hazardous locations and evaluate potential treatments. It was concluded that the outside-lane crash rate, specifically for horizontal curves, can be estimated from measurements of vehicle speed differential between the approach and midpoint of the curve. Although an extensive correlation has not been made between surrogate measures and crash occurrence, these measures can be used to review operational behavior. To be an effective proxy for safety, an operational characteristic must be measurable and must have a known relationship to safety (*11*). Several authors (*12; 13)* have reported that the variance of lateral vehicle position is correlated with accident frequency. Garber and Ehrhart (*14*) indicate that crash rates increase as the standard deviation of speed increases at all flow rates on two-lane nonfreeways in Virginia. In assessing longitudinal pavement marking effectiveness, these surrogate measures include vehicle operating speeds, encroachment frequency, and vehicle lateral position in travel lanes. This section describes research into the effect that various pavement marking material types have on each of these three safety surrogates.

2.3.1 Vehicle Speed

Khan (*7*) evaluated vehicle operating speeds before and after RPM installation at several locations in Ohio. The mean and 85^{th}-percentile operating speeds generally increased (by 1 to 3 mph) at night after installation of the RPMs on a rural two-lane curved highway segment. Similar results were reported at two narrow bridge approaches. There were generally not significant changes in average or 85^{th}-percentile operating speeds on two uncontrolled through-intersection approaches, while on a four-lane undivided highway with a 45-mph posted speed limit, there was generally a 1- to 2-mph reduction in mean and 85^{th}-percentile operating speeds.

Mullowney (*15*) evaluated the mean and variance of vehicle operating speeds after installation of RPMs at two horizontal curve locations in New Jersey. Results of the research suggest that motorists tend to operate more consistently, as evidenced by a flatter speed profile, after installation of RPMs.

A before-after with control group experiment was conducted (*16*) using speed data from two-lane rural highways in Georgia to evaluate the effectiveness of RPMs. When compared to the control group, average nighttime vehicle travel speeds approaching a horizontal curve increased by approximately 1 mph after installation of RPMs. Similar findings were reported at locations within the horizontal curve and at both speed data collection points 6 months after RPM installation.

Krammes and Tyer (*17*) evaluated speeds at the midpoint of horizontal curves and speed change from the beginning to the midpoint of five horizontal curve locations on two-lane rural highways in Texas. A before-after operational analysis was performed to assess the effects of installing new RPMs at each site. The findings indicate that mean vehicle operating speeds are consistently 1 to 3 mph higher after installing new RPMs.

Average vehicle operating speeds were compared both before and after RPM installation at two horizontal curve locations in Tennessee (*18*). The "before" analysis condition consisted of only the center- and edge line markings. In the "after" condition RPMs were installed with 20- and 40-ft spacing. There was no statistically significant change in mean vehicle operating speeds at either site after installation of RPMs. Within data collection zones, the mean speed generally changed by less than 1 mph from the before to after condition.

van Driel et al. (*19*) performed a meta-analysis of vehicle operating speeds based on edge line presence. The range of reported before-after results was -3 mph (reduction in mean speed) to +8.1 mph. An overall increase in mean speed after installing edge lines on roadways that previously only had a centerline was less than 0.5 mph.

2.3.2 Encroachment

Many of the vehicle speed studies cited previously (*7; 15; 17; 18; 19*) also evaluated vehicle position or encroachment frequency. Generally, encroachment frequency decreased after installation of RPMs on various roadway types. The following summarizes the results of several encroachment-based studies:

- Mean lateral position shifted away from the center of horizontal curves (0.2- to 0.8-ft) during nighttime driving conditions after installation of RPMs in Ohio (*7*). Vehicle placement variability decreased at all horizontal curve measurement spots, resulting in a small decrease in the number of vehicle centerline encroachments. Significant decreases (9 and 39 percent) in the encroachment percentage were reported at a narrow bridge approach during both daytime and nighttime conditions, respectively. Small decreases in the encroachment frequency were reported at through-intersection approaches after installation of RPMs.

- Vehicle centerline encroachments were reduced by 4 to 12 percent after installation of RPMs at two, two-lane highway and one four-lane curved undivided highway locations in New Jersey (*15*).

- The proportion of centerline encroachments on curved rural highway sections decreased by 15 to 46 percent at five study sites after installing RPMs in a Texas study (*17*).

- Mean encroachment distance decreased by approximately 4 inches at two study sites after installation of RPMs with 40-ft spacing. When compared to the 40-ft interval, an additional 1-inch decrease with 20-ft spacing at both sites was reported (*18*).

2.3.3 Lateral Vehicle Position

Zador et al. (*16*) evaluated lateral vehicle position after installation of RPMs at 12 horizontal curve locations in Georgia. On average, lateral vehicle position shifted 0.4 to 0.7 ft away from the centerline at points prior to and within a horizontal curve, respectively, immediately and 6 months after installation of RPMs.

Krammes and Tyer (*17*) evaluated vehicle lateral placement at the midpoint of horizontal curves on rural two-lane highways. After installing new RPMs, the mean lateral placement of vehicles shifted 0.9 to 1.7 ft away from the roadway centerline when compared to the before condition at five study locations. The before condition consisted of weathered centerline markings and post-mounted delineators. The standard deviation of lateral vehicle placement decreased after installation of the RPMs.

A meta-analysis of lateral vehicle position was also performed by van Driel et al. (*19*). Based on research conducted in the United States, the change in mean lateral position after installing edge lines on roadways that previously only had a centerline was approximately 0.5 inch toward the centerline. The range of reported before-after results in the United States was a -10.5-inch shift (toward the centerline) to a +14-inch shift away from the centerline.

2.4 DRIVER BEHAVIOR AND PERFORMANCE

Pavement markings, particularly longitudinal treatments, have definite impacts to both driver behavior and performance. The impacts of pavement markings on driver behavior can be quantified by measurements of driver perception or vehicle operations such as speed and lateral placement. Consequently, driver performance can be determined by evaluating the changes in operational behavior due to treatments and assessing the quality of the results. Driver behavior and performance are related to the ability of the driver to detect and process information from the roadway. Several topics have been identified to have a relationship to this ability, including edge line treatments, horizontal curve delineation, and the visibility of pavement markings.

2.4.1 Edge Line Treatments

Research in the Netherlands analyzed the effects of road edge lines on driver behavior measured in terms of driver performance, physiological parameters, and self-reports (*20*). The purpose of the study was to determine if road edge lines could influence driver behavior in a way that would lend itself to reducing the number of vehicles leaving the traveled way and potential crashes along unmarked rural roads. It was determined that road departures are frequently the result of lane tracking errors, limited visibility, and driver fatigue. Past research had shown that perception of the road edge and peripheral vision could be improved by edge lines and that measuring this effect could be achieved by evaluating driver behavior.

The analysis included two control and two treatment roads with low traffic densities. The data were collected using video cameras and monitoring equipment installed on the vehicle. The results showed that speeds were higher on roads with edge lines and that vehicle position was oriented more toward the center of the roadway, especially during nighttime conditions. Regardless of the lateral position, no adverse effects were noted with respect to oncoming traffic. In addition, while speeds may have been higher on the roads with edge lines, the recorded data as well as the subjective user comments supported a decrease in driver effort in terms of maintaining vehicle speed and lateral position for the roads with edge lines.

It was also noted that road markings tend to heighten driver awareness, which may translate into improved performance. Zwahlen and Schnell (*21*) reported that drivers tend to focus on the right edge line to detect the end of pavement markings and that headlights are often aimed at angles slightly down and to the right, further emphasizing the importance of adequate edge line delineation for roadway navigation. In his study, Miller (*22*) determined that using edge lines on two-lane rural highways is cost effective if an annual average of one non-intersection crash occurs every 15.5 mi of roadway.

A study in Louisiana (*23*) focused on the potential positive and negative effects on driver behavior due to edge line application. The variables included in the analysis were highway geometry (pavement width, pavement condition, road alignment [tangent vs. curve]) and traffic conditions (traffic volume, operating speed, and percentage of heavy vehicles). The study also considered roadside conditions, edge-drop, and oncoming vehicles for impacts on driver behavior.

The conclusions indicated that edge lines influence drivers to maintain a more centralized position, particularly during nighttime conditions, representing the possibility of reducing ROR and head-on crashes. It was also shown that drivers tend to position themselves farther from the road edge regardless of the roadway alignment. However, the impact of edge lines on curve segments was inconclusive due to the limited number of study sections. Lastly, it was determined that edge lines have little or no effect on average operating speed.

2.4.2 Horizontal Curve Delineation

The FHWA states that pavement markings and delineation devices are important for path guidance on horizontal curves, especially during twilight and night conditions (*24*). They provide information for the driver about the vehicle's lateral position and the boundaries of the traveled way. The study by Krammes (*17*) investigated delineation treatments and their effect on driver behavior negotiating curves on two-lane rural highways. Background information for the report suggested that the delineation of the roadway is especially important for curves because the crash rate on curves is three times that of tangent sections, including a rate four times greater for single vehicle run-off-the-road (ROR) crashes. A crash analysis performed by Hall (*25*) highlighted this point. The majority of the ROR crashes investigated in his study of approximately 530 miles of two-lane rural highway were identified as having occurred on curve segments.

Zador et al. (*16*) further reported that ROR crashes tend to involve drivers missing the curve and occur on the outside of the roadway. This problem may be attributed to the fact that driver paths along curves do not often follow the center of the lane, a driver behavior known as "curve lengthening" or following a path that flattens the curve until a point when a sharp turn is required by the driver. This problem is more noticeable for left curves where drivers have more trouble perceiving roadway information. The report cited research suggesting that a decrease in the variability of vehicle speed and lateral position, attributed to benefits in safety, is a result of improved curve delineation.

It has also been noted by Zwahlen and Schnell that the average curve begin-detection distance for a left curve is shorter than that for a right curve (*21*). Visibility distances were about 10-15 percent longer for horizontal right curves than tangent sections, which subsequently had

15-20 percent longer visibility distances than left curves. In addition, it was shown that for sharp left curves, visibility distances are about half that of a level, tangent section (*26*).

2.4.3 Visibility of Pavement Markings

Adequate visibility of pavement markings is important for drivers to properly identify the boundaries of lanes and to accurately navigate the roadway. Zwahlen and Schnell have conducted multiple studies extensively investigating the visibility of pavement markings based on material color, retroreflectivity, line pattern and width (*21; 27; 28; 29; 30*). Most of their studies were conducted using the following restraints: a closed course, nighttime conditions, dry weather, low speeds (5-10 mph), and a sample of young drivers with ideal visual capacity. In one report (*21*), nighttime detection distances for left and right curves along with pavement markings of varying width and color were evaluated under low-beam illumination. Detection distance is defined as the distance from which the driver identifies a target, such as a pavement marking, to the object itself (longer detection distances being the ideal result). The results revealed only minor effects of line width or color on marking visibility, but did show significant differences in detection distance based on line pattern.

In another study by Zwahlen and Schnell (*28*), the effect of material color and retroreflectivity on driver performance was evaluated by measuring nighttime detection distances. Based on the set-up of the test course, it was determined that the beginning of highly retroreflective materials could be detected from the starting position; therefore, only detection distances for the end of the pavement marking strips, or end-detection distances, were used in the evaluation. It was determined for young drivers that highly-retroreflective, white material provided the longest end-detection distance, with highly-retroreflective yellow and medium-retroreflective white material performing nearly as well. The study resulted in average detection distances of 35 m (115 ft) and 62 m (203 ft) for low- and high-retroreflectivity material, respectively. The medium-retroreflectivity material resulted in an average end-detection distance of 59 m (194 ft) with a standard deviation of 27 m (88 ft). Therefore, it was suggested that increasing the retroreflectivity of pavement markings will result in a significant increase in detection distance.

Several other studies by Zwahlen and Schnell (*27; 29; 30*) were used to establish a relationship between driver preview distances and pavement marking retroreflectivity levels. Preview distance is measured as a function of the time it takes for the driver to acquire and process visual information from the roadway and the time it takes to traverse the distance between the vehicle and an object. The necessary preview time for pavement markings is defined as 3.65 seconds. It was found that retroreflectivity levels had a significant effect on the end-detection distances of pavement markings for both old and young drivers, although levels below 200 mcd/m^2/lx were not analyzed in these studies. It was also found that older drivers are more explicitly dependent on marking retroreflectivity.

In response to the mandate imposed by the FHWA to establish minimum retroreflectivity levels of pavement markings, results were obtained from computer-based modeling to determine adequate retroreflectivity based on preview distances using a 95th percentile driver age of 62 (*27; 31*). The results of the study showed that increasing vehicle speeds results in a large increase in the minimum required retroreflectivity in order to maintain a preview time of 3.65 seconds. It was also shown that using raised pavement markings can reduce preview times and greatly improve visibility when adequately maintained.

Another study (*29*) was used to determine the end-detection distance of a tape centerline without edge lines as a function of line width and configuration. The study also compared detection distances between centerline-only and fully marked treatments (centerlines and edge lines) with different line widths (2, 4, or 8 inches), retroreflectivity (medium or high), and centerline configurations (double solid versus single dashed). The results of the study showed that line pattern, line width, and retroreflectivity were statistically significant for end-detection distances, indicating that a positive correlation exists between a larger surface area of retroreflectivity and increases in the end detection distance.

In one of the studies that focused on the visibility of pavement markings as a function of retroreflectivity (*30*), additional conclusions were made regarding driver age and illumination. It was found that, for young drivers, higher illumination levels can partially compensate for a lower pavement marking retroreflectivity; however, the effect of illumination level for older subjects was very minimal, demonstrating their reliance on marking retroreflectivity. The average end detection distances ranged from 124.8 m for the older drivers under low-beam illumination/medium retroreflectivity to 237.3 m for the young group under high-beam/high retroreflectivity. In all, the end detection distances were at least 50 percent greater for the younger drivers regardless of retroreflectivity or illumination level.

In a report summarizing previous findings, Zwahlen and Senthilnathan (*26*) concluded that in order to increase visibility distances for left curves under low-beam illumination, higher in-service levels of pavement marking retroreflectivity or brighter and/or wider pavement markings should be implemented, especially as spot treatments.

2.5 SAFETY AND OPERATIONAL EFFECTS OF WIDE EDGE LINES

Wide longitudinal lines have been defined in the MUTCD standards as "at least twice the width of a normal line" and a normal line is defined as "4 to 6 inches wide" (*1*). Therefore, wide edge lines have been characterized as having a width of 8 inches. It has been hypothesized that the benefits from using lane markings can be enhanced by utilizing wider than the minimum standard line width. Furthermore, a number of researchers have reviewed the potential safety benefits of their installation, specifically on two-lane rural highways as a continuous or spot treatment. Their studies have involved evaluating crash data, driver behavior, and surrogate measures of safety with respect to the use of wide edge lines.

2.5.1 Crash Data

Crashes related to edge lines have been commonly defined as run-off-road (ROR) crashes on dry or wet pavement due to the relationship between the delineation of the road edge and lane keeping (crashes during snow and ice conditions being discarded, since these conditions significantly reduce the visibility of edge lines). ROR crashes have been known to represent a rather significant portion of crashes occurring on rural highways, including those of high severity. Therefore, improving lane marking visibility by utilizing wider edge lines has been viewed as a potential cost-effective means of addressing this problem. However, crash studies related to wide edge lines have often yielded statistically insignificant or inconclusive results.

Cottrell (*32; 33*) evaluated wide edge line safety using a before-and-after analysis with a comparison group for three two-lane rural (60.7 miles) roadways in Virginia. Data were collected at three roadway sections, each with a treatment location painted with 8-inch edge lines for the after period and a comparison location re-striped with 4-inch edge lines. Special emphasis was placed on reviewing ROR crashes due to their relationship with edge lines, and since wider edge lines were thought to influence driver position toward the centerline, opposite-direction crashes were also analyzed. The crashes were measured in terms of crash frequency and were divided into the following categories: ROR crashes, ROR crashes involving DUI, ROR crashes on curves, ROR crashes during darkness, and opposite-direction crashes.

The results suggested that overall reductions in the number of ROR crashes occurred at the treatment sites when compared to the control sites, but the results were not statistically significant. No conclusive connection was made between the type of ROR crash and wide edge lines. Changes in crash frequency for the opposite-direction crashes were inconsistent and also statistically insignificant. The overall conclusion of the report was that there was no evidence from the data to support any difference between 4-inch and 8-inch edge lines in terms of crash frequency in general or for any of the specific categories analyzed.

ROR crashes were also the focus of the report by Hall (*25*), which identified that an approach to reducing ROR crashes is improving the roadway to reduce the number of vehicle encroachments. The study focused on two-lane rural roadways in New Mexico with unusually high ROR crash rates. A portion of the identified miles were painted with 8-inch edge lines and the rest, painted with 4-inch edge lines, were used for comparison. A before-and-after analysis was conducted on the roadways to determine if the wide edge line treatments caused a statistically significant reduction in the number of crashes.

The overall ROR crash rate, in terms of crashes per million vehicle miles traveled, dropped approximately 10 percent for the treatment sites and 16 percent for the comparison sites. It was therefore concluded that the resultant decrease was due to a regression to the mean and not the type of edge line treatment. Additionally, the analysis of ROR crash rates was further divided into daytime versus nighttime crashes, crashes occurring on straight versus curve segments, and opposite-direction crashes. While it was concluded from the results that wide edge lines produced no significant reduction in the number of crashes, regardless of the criteria, the percentage of nighttime crashes dropped 9 percent for the treatment sites as opposed to only 3 percent at the comparison sites. The overall conclusion of the report was that the results did not support the use of 8-inch edge lines to reduce crash frequencies, although the time periods used for the analysis were relatively short. The recommendation was to discontinue the use of wide edge lines in New Mexico and as of 2002 the state had not changed its policy (*34*).

Another before-and-after comparison analysis was conducted by Hughes et al. (*35; 36*) using data obtained from seven states (Alabama, Maine, Massachusetts, New Mexico, Ohio, South Dakota, and Texas) including over 2,000 miles of roadway. The study, completed in 1989, was limited to two-lane rural roadways with ADT ranges of 2,000 to 5,000 and 5,000 to 10,000 vehicles per day. The objectives of the study were to determine if 8-inch edge lines reduce the occurrence and severity of ROR crashes compared to 4-inch edge lines, and if wide edge lines are cost effective.

The study was conducted using 4-inch edge lines for all of the segments in the before period and a re-striping for the after period with either a 4-inch control or an 8-inch treatment edge line. A crash analysis and a cost-effectiveness analysis were performed as part of the study. For the crash analysis, both the control and treatment groups were studied for differences in crash frequency and rate for total, fatal and injury, and edge line-related ROR crashes. The results of the analysis for ROR crashes, along with the statistical conclusions, can be found in Table 2.

Table 2. Results of Wide Edge Line Safety Evaluation (*36*).

Average Daily Traffic	State	Apparent Change in Edge Line-Related Accident Rate	Statistical Conclusion	Test Section Mileage	Probability of a Type I Error	Probability of a Type II Error
2,000 - 5,000 vpd	Alabama	-6%	Significant Decrease	575	0.1	0.20
	Texas	3%	No Significant Change	244	0.1	>.50
	New Mexico	30%	No Significant Change	91	0.1	>.50
	Ohio	2%	No Significant Change	401	0.1	>.50
	South Dakota	-50%	Significant Decrease	50	0.1	>.50
	Maine	-10%	No Significant Change	192	0.1	0.50
5,000 - 10,000 vpd	Texas	72%	Significant Increase	44	0.1	0.15
	Ohio	-5%	No Significant Change	190	0.1	>.50
	Maine	10%	Significant Increase	30	0.1	0.50

The cost-effectiveness analysis was conducted using costs in three categories: supplier costs, non-crash user costs (user delay/operating costs during re-striping), and crash costs. It was determined that both the 4-inch and 8-inch edge lines have approximately the same service life and that 8-inch edge lines cost, on average, \$200 to \$250 more per mile on two-lane rural roads. Therefore, for 8-inch edge lines to be cost effective, they must produce a 1 percent reduction in the average crash frequency of edge line-related crashes per year. This conclusion is similar to other research stating that 8-inch edge lines are a cost-effective replacement for 4-inch edge lines if they can be attributed to a reduction in crashes of only 0.7 percent when the ADT exceeds 1,000 vehicles per day (*24*).

The overall analysis of the results indicated that none of the changes in ROR crashes was statistically significant at the 10 percent level. It was concluded that wide edge lines did not produce a significant change in crash frequency on two-lane rural highways with traffic volumes between 5,000 and 10,000 vehicles per day. Wider edge lines were only recommended on two-lane rural highways with ADT volumes in the range of 2,000 to 5,000 vehicles per day, in areas that experience frequent rainfall, and on roads with pavement widths of at least 24 ft (with unpaved shoulders).

In 1986, it was reported in *Better Roads* magazine that the implementation of 8-inch edge lines reduced single-vehicle crashes in New Jersey (*37*). Wide edge lines were installed on all of the county roads in Morris County, New Jersey. In a comparison between 1980, when 4-inch edge lines were used, and 1983, after the 8-inch edge lines were in place, the number of single-vehicle crashes declined 10 percent at the 95th percentile level of significance. This was compared to a 2 percent decrease for other county roads in New Jersey. The results also showed that the number of multi-vehicle, head-on collisions did not significantly change during the study period, indicating that there appeared to be no increased risk for this type of crash with wide edge lines.

While these and other results of crash analyses are encouraging, they are largely statistically insignificant or derived from a small, isolated sample of data. However, other studies have been performed to analyze the effects of wide edge lines on driver behavior and surrogate measures of safety to determine if they could yield more informative results.

2.5.2 Driver Behavior and Surrogate Measures of Safety

Although cost-effective evaluations are good for identifying potential safety treatments, they are difficult to perform for the use of wide edge lines due to the inconsistent results from crash analyses and service-life information. In addition, crash studies require a large amount of data over a relatively long period of time in order to establish statistically significant results. Therefore, numerous studies have been intended to identify the effects of wide edge lines on driver behavior and surrogate measures of safety.

Zwahlen and Schnell (*27*) completed several tests to determine if the nighttime detection distance for either continuous pavement markings or horizontal curves was dependent on line width. The results indicated that there was not a significant difference among detection distances for the beginning or end of a pavement marking for line widths between 4 and 8 inches. The results also showed that there is no significant difference in the average detection distance of a right curve with pavement marking widths of 4 inches versus 8 inches. However, there was a significant difference for a left curve, suggesting that the 8-inch-wide line has a longer detection distance.

In another study by Zwahlen and Schnell (*28*), it was determined that for high-retroreflectivity material, 8-inch double-solid, yellow centerlines provide the longest end-detection distance; however, for medium-retroreflectivity material, the differences were much smaller. It was therefore concluded that widening pavement markings is potentially only beneficial for highly retroreflective materials. It was also reported that the visibility of pavement markings for elderly drivers was affected more by their dimensions than their brightness, suggesting that potential benefits exist from using wider markings, especially for older drivers (*30*).

In a follow-up report to findings of Zwahlen and Schnell, among others, Gates et al. (*38*) promoted a discussion of the effects that pavement markings have on visibility-based parameters. It was noted that previous research had shown positive results for the long-range detection of wider-than-standard pavement markings and additional, subjective opinion revealed that increases in line width result in increases in the visibility of lines. It was also suggested that wider edge lines strengthen the visual signal in the driver's periphery, a benefit that might be more important for measuring the effectiveness of pavement markings than detection distances. This was supported by the fact that drivers have reported wide edge lines as being both more noticeable in the periphery and identifiable from greater distances, thus allowing for improved driver comfort and short-range driver performance.

Improved driver comfort has been positively attributed to wider edge lines through additional driver feedback. Drivers tend to "feel safer," "feel less tired," and "don't have to pay as much attention to the markings" when wide edge lines are used. This is especially important when the visual workload is increased, such as during nighttime conditions. Drivers can benefit from more visible road markings by allowing them to focus on other, more complex driving tasks. Therefore, it was suggested that wide edge lines perform better than standard-width edge lines and lead to improved highway safety; however, no determination has been made as to their additional effects on driver reaction and response.

A study by the Texas Transportation Institute investigated the use of wider longitudinal markings by agencies in the United States and around the world through survey and literature reviews (*34*). The report was conducted in 2001 and at the time 29 of 50 states used wider-than-standard markings for centerlines, edge lines, and/or lane lines and their use was on the rise.

However, most state agencies had not performed their own studies for measuring the effects of using wider markings, including more than half of those using them. It was shown that many rely on the experience of other agencies or engineering judgment for the decision to use them. The report also cited improved visibility as the most prevalent reason that state agencies use wider than 4-inch pavement markings. Figures and tables outlining the use of wider pavement markings by state, reasons for their use, basis for implementation, and observed benefits can be found in Appendix A.

International surveys found that many foreign agencies use wider than 4-inch markings and have for many years. Those agencies stated that wider markings benefit target detectability, result in longer preview distances, and have surrogate benefits including a more centralized position of vehicles without increases in speed. The main cited drawback of the use of wider markings is the increase in cost of materials, but no agencies indicated that they would discontinue using wider markings in favor of the 4-inch width. The most common reason cited for not using wider markings is the lack of conclusive evidence that wider markings reduce crashes.

Based on the literature, it was stated that wider edge lines are most likely to have benefits for horizontal curves, roadways with narrow shoulders, and construction work zones, as well as locations with low luminance contrast of markings and where older drivers are prevalent. While the literature favored the use of wider markings for spot locations, this type of treatment was the least extensive form of use found in the agency survey. Instead, the most common type of use identified was for all routes of a certain roadway classification. It was also suggested that since conclusive, cost-quantifiable data are likely not available and would be extremely difficult to measure, other proven measures of effectiveness are appropriate to justify the use of wide edge lines.

A research report by Bowman and Brinkman (*39*) focused on the impacts of low-cost crash countermeasures, including wide edge lines, on surrogate measures of safety. The report included a before-after analysis of 18 narrow-bridge approaches (9 bridges) along two-lane undivided highways with one-way volumes ranging from 800 to 2,625 vehicles per day. Bridges that could be classified as narrow were used for their susceptibility of being inadequate with respect to contemporary design standards. Since data on the number and nature of crashes on or near bridges are sparse, the study focused on the surrogate measures of driver speed and lateral placement.

In all, five measures of effectiveness (MOEs) were used in the study and included: mean speed over all tapeswitch deployments, maximum speed variation across deployments, mean speed and right-hand lateral position at each deployment, and deviations in right-hand lateral placement between deployments. Reductions in speed through the bridge approach, decreases in variation of speed and lateral placement, and movement away from the edge of traveled way were all assumed to be positive indicators that the countermeasures were effective. However, the analysis of the data yielded no significant differences in driver behavior when comparing the before-and-after time periods for the use of countermeasures. This was based on the conclusion that the sample set was adequate for providing statistically significant results.

In addition to the crash analysis by Cottrell, a study of the effects of wide edge lines on operational behavior was also performed using a before-after analysis (*40*). It was stated that uniform driving promotes better safety; therefore, the preferred edge line would be represented by results with lower speed variance. Cottrell also noted that safer driving behavior is associated with lower mean speeds. The results of the study showed that 4-inch edge lines were preferred based on speed variance; however, the 8-inch edge lines had lower mean speeds for both daytime and nighttime conditions. In both cases the results were not statistically significant.

The report also identified lateral placement as having a strong correlation to crash experience, noting that higher variance in lateral position results in a higher risk of crash occurrence. Also, according to Virginia policy, the predominantly recommended position of the vehicle is the center of the lane. Therefore, the preferred edge line resulted in a mean lateral placement closest to the center of the lane. The results of the study with respect to lateral placement variance indicated that the 4-inch edge line was preferred, but there was no significant difference between the widths. For mean lateral placement, the 8-inch edge line performed the best for both daytime and nighttime conditions and was statistically significant.

The results showed no significant difference between the edge line widths in terms of encroachments, but the preferred width was 4 inches for cars at night and 8 inches for trucks during both daytime and nighttime conditions. There were also significantly greater numbers of encroachments for trucks at night with the 4-inch edge lines. The measurement of mean lateral placement was the only other value of driver performance that resulted in a statistically significant difference between 4-inch and 8-inch edge lines. The results of the study, along with the statistical analysis, are shown in Table 3.

Table 3. Summary of Virginia Wide Edge Line Study (*40*)

Measure of Performance	Preferred Lane Width						Overall Preferred	0.05 Level of Significance
	Day			Night				
	4 in.	8 in.	No Difference	4 in.	8 in.	No Difference		
Lateral Placement Variance	4 (33.3)	1 (8.3)	7 (58.4)	3 (25.0)	0 (0.0)	9 (75.0)	4 in.	N
Lateral Placement Mean	1 (8.3)	11 (91.7)	0 (0.0)	0 (0.0)	7 (58.4)	5 (41.6)	8 in.	Y
Encroachment -								
Automobiles	6 (50.0)	6 (50.0)	0 (0.0)	4 (33.3)	1 (8.3)	7 (58.4)	4 in.	N
Trucks	2 (16.7)	4 (33.3)	6 (50.0)	0 (0.0)	2 (16.7)	10 (83.3)	8 in.	Day-N, Night-Y
Speed Variance	4 (33.3)	3 (25.0)	4 (41.7)	3 (25.0)	0 (0.0)	9 (75.0)	4 in.	N
Mean Speed	0 (0.0)	4 (33.3)	8 (66.7)	0 (0.0)	1 (8.3)	11 (91.7)	8 in.	N

Note: Percentages are shown in parenthesis (based on 12 total sites).

As part of the study performed by Hughes et al. (*35*), a performance analysis was conducted to measure the frequency of vehicle encroachment of the centerline, edge line, or both. Driver performance was evaluated for four sections of roadway along horizontal curves in Massachusetts. All four sites were painted with 4-inch edge lines during the before period. One section was painted with 4-inch edge lines for the after period while the remaining three sections were painted with 8-inch edge lines. According to the results, the relative odds that a lane departure would occur were lower in the after period for the 8-inch edge lines than the 4-inch edge lines.

In addition to testing driver performance in a free-flow setting, a couple of studies have been set up to evaluate wide edge lines as an alcohol countermeasure. One such study was conducted by Gawron and Ranney (*41*) to test driver performance on curves with different geometries, edge line widths (4 inch or 8 inch), and types of curve warning signs. Subjects conducted three separate 2-hour drives that included negotiating 150 curves in a driving simulator. The drivers were required to perform the three tests with Blood Alcohol Content (BAC) levels of 0.0, 0.7, and 0.12 percent, respectively. Review of previous research suggested that most speed reduction was made at curve approaches and that curve cutting is a very common driver tendency during curve negotiation. Therefore, the performance factors used in this study were curve-entry speed, lateral position on the approach and through-curve negotiation, heading, and lateral acceleration.

The general results of the study showed that decreases in curve radius result in decreases in curve-entry speed and increases in curve-cutting strategies. More specific results indicated strong and consistent effects of alcohol on driving performance, including increases in lane position errors and vehicle control variability. Alcohol effects were evident primarily on measures of tracking behavior and overall scenario performance. It was found that the presence of edge lines improved tracking as well as overall performance and that wide edge lines were associated with additional, although non-significant benefits. It was also determined that the effects of spot treatments were unclear and relatively weak.

Another study focused on the impacts of varying edge line widths on the behavior of both unimpaired and alcohol-impaired drivers (*42; 43*). The analysis was conducted at night on two-lane rural highways with different edge line widths in New Jersey. The test involved subjects twice driving a closed section of roadway with a control run at 0.00 BAC and a test run at one of three levels of alcohol dosage, 0.00, 0.05, or 0.08 BAC. Photographs were taken every 100 ft to accurately monitor the vehicle position throughout the course. The effects of the edge lines on vehicle position were insubstantial for the tangent sections and therefore the results focused on curve segments.

It was determined that while wider-than-standard edge lines did influence driver position toward the centerline, no increase in the number of centerline encroachments was observed. It was also concluded that the impact of 6-inch edge lines on driver behavior was somewhat reversed by 8-inch edge lines as drivers tended to shift away from the centerline and closer to the center of the lane with a wider edge line (see Figure 1 for more detail). The researchers noted that drivers seem to become more aware of the left boundary as they start to shift closer to the centerline, the expected trend for an 8-inch edge line.

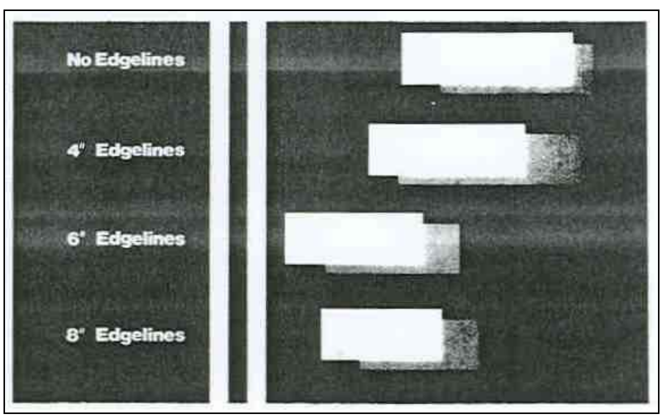

Figure 1. Driver to Driver Groupings Based on Lane Positioning.
[White - Dosed Group; Gray - Placebo Group] (*42*).

It was also noted that the variance of vehicle positioning was lowest for the section with 8-inch edge lines, indicating that drivers tend to better maintain the vehicle in a more centralized position (see Figure 2 for more detail).

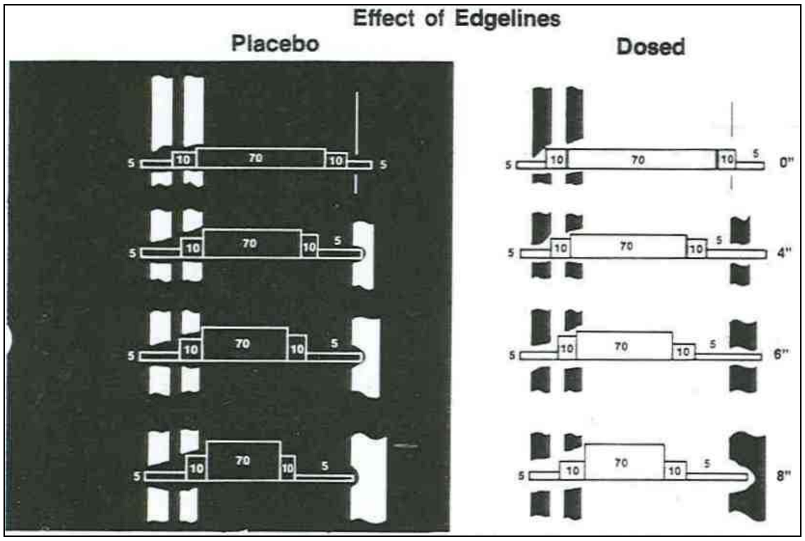

Figure 2. Driver Path Range: Effect of Edge Lines (*42*).

The two overall conclusions drawn from the results were that unimpaired drivers benefited from the presence of edge lines of any width and that alcohol-impaired drivers exhibited better driving behavior in the presence of wide edge lines than either standard or no edge lines. The effects of alcohol and different edge line widths are summarized in Table 4.

Table 4. Effects of Wide Edge Lines on Driver Performance (*42*).

Driver Performance	Alcohol Effect	Effect of 4 in. Edge line	Effect of Wide Edge line
Position Range	Increase	Decrease	Decrease Further
Variability	Increase	Decrease	Decrease Further
Average Position	Shift Toward Edge line	Shift Toward Centerline	Further Shift Toward Centerline
Grouping Dispersion	Mixed	Mixed	Tighter Grouping
Location	Move Right	Move Left	Move Further Left
FHWA Data	Reduces Good Driving	Maintains Good Driving	Maintains "More" Good Driving
Overall	Adverse	Beneficial	More Beneficial

It was discussed that a driver's capacity to collect guidance information and respond accordingly is linked to the ability of the driver to visually communicate with the roadway. It has been proven that alcohol diminishes this ability and is involved in up to 50 percent of fatal crashes. The results of the study determined that wide edge lines incrementally enhance the benefits observed from standard edge lines and may compensate for some of the visual capacity lost from alcohol impairment. It was also concluded that wide edge lines have the potential for similar effects on other types of driver impairment such as fatigue, drugs, and reduced visual ability due to old age.

Using wide edge lines to offset the visual deficiencies of older drivers has been emphasized by a number of researchers (*34*). Driver visual functions are important for receiving and processing roadway information and can deteriorate with age (*24*). One of these functions is contrast sensitivity, as defined by the ability to detect a difference between target and background luminance such as that from pavement markings and the roadway surface. It has been suggested from previous research that older drivers require as much as a 300 percent increase in stripe brightness when compared to younger drivers. While wider-than-standard stripes have not been directly related to differences in contrast, they have been linked to potential benefits with respect to driver behavior and surrogate measures of safety, with incremental improvements for older drivers.

A study was conducted (*44)* to determine if the visual deficiencies of older drivers could be countered with pavement markings. It was hypothesized that the additional effort by older drivers for both long preview distances and instant-to-instant vehicle control may be met by improvements in brightness and size of delineation and marking elements, particularly for nighttime driving situations. It was identified that older drivers have been shown to be overrepresented in left-curve and head-on crashes.

The preliminary assessment of pavement marking treatments was performed using a driving simulator. A number of treatments were evaluated including 4-inch and 8-inch edge lines at two brightness levels. The tests were conducted using low-beam headlights. The results of the simulator study showed that the wide edge lines performed better at the lower brightness level, but the 4-inch edge line at the higher brightness level performed the best. However, none of the results for these treatments were shown to be different statistically. Therefore, none of these particular treatments was chosen for future field evaluation.

A subjective assessment of the treatments indicated that the wide edge lines performed better than their counterparts, which brought up questions about the difference between the two types of evaluation and the validity of subjective ratings. It was determined that the subjective ratings from older drivers were so different from the objective results, they were not a good indicator of the performance of pavement markings.

A meta-analysis of the effects of altered road markings on the speed and lateral position of vehicles was conducted in 2003 by Davidse et al. (*45*). The analysis included 41 publications and 201 study results. Referenced research indicated that road markings were the most important road characteristic attributed to driver recognition of road type and the proper speed necessary to maintain safe operation. It was also shown that studies evaluating speed often included lateral position in their investigation; therefore, these two attributes of driver behavior were the focus of the analysis.

It was determined that reductions in average vehicle speed and lateral positioning closer to the center of the road are related to safer driver performance and a lower risk of crashes. The referenced research also attributed wider edge lines with vehicle positions farther from the edge of the road. Since many of the studies included in the meta-analysis had inconsistent or statistically insignificant results, the purpose was to determine if any overall conclusions could be made from the studies as a whole.

In addition to including a multitude of studies, the meta-analysis integrated a large number of variables into the study. Some of the variables included were road type; speed limit; width of lane, shoulder, and edge line; ADT; and time of day. Relevant results of the study as measured by effect due to alteration are shown in Table 5 (cl = centerline, el = edge line).

Table 5. Results from the Meta-Analysis (*45*).

Measure of Effectiveness	Type of Alteration	Number of Observations	Range of Results		Mean	Standard Deviation
			Min	Max		
Mean Speed (km/h)	cl + el => cl + 'other type of el'	86	-9.3	6.5	-0.7	3.0
	Overall Total	320	-10.6	10.6	-0.1	3.3
Variance in Speed (km/h)	Overall Total	231	-2.9	3.9	0.1	1.3
Mean Lateral Position (cm)*	cl + el => cl + 'other type of el'	80	-117	80	-3.0	30.0
	Overall Total	369	-124	80	-0.5	23.8
Variance in Lateral Position (cm)	Overall Total	234	-31	36	-0.2	9.0

*For results of mean lateral position, negative values represent movement toward the center of the roadway and positive values represent movement away or toward the road edge.

Alterations to existing road markings result in a small, positive effect on road safety in terms of a decrease in mean speed and a shift in lateral position toward the center of the roadway. Large standard deviations with highly variable ranges in overall results would be expected from such a vast range of alterations that included those likely to have opposite effects on speed and lateral position. The results of the analysis concurred with earlier studies showing that adding both centerlines and edge lines results in an increase in mean driver speed and, therefore, undesirable effects on safety. However, when an edge line is added to a road with a centerline already in place, the result was just the opposite. It was also noted that the country of study had a potential impact on the results, as most rural roadways in Europe do not have paved shoulders; therefore, the effects of road markings on lateral position may have been influenced by the original tendencies of drivers.

2.6 METHODS TO COLLECT AND ANALYZE OPERATIONAL DATA

A number of studies have been conducted using data collection equipment to gather raw operations data in the field. A combination of road sensors and data recorders was often used to collect vehicle volume, speed, and lateral position data at individual sites. To supplement this information or to collect additional measurements, video cameras have also been utilized. The type and arrangement of equipment, the location and conditions of the test site, and the study type and statistical analysis are all important for the accurate collection and analysis of data. In order to efficiently evaluate data related to driver behavior, it is important to use effective and reliable equipment.

2.6.1 Type and Arrangement of Equipment

To test the accuracy and potential impacts on driver behavior of various speed-measuring devices, a study was conducted by Poe et al. (*46*) in 1996. Six speed devices were evaluated for accuracy against a control speed measured by a vehicle-mounted Lateral Acceleration Sensor System (LASS). The speed devices used in the study were a Nu-Metic Hi-Star magnetic sensor, a human observer, radar, pneumatic tubes, tapeswitches, and lidar (laser speed gun). One hundred speed measurements were conducted for each device to ensure the statistical significance of the data set. The second part of the experiment was conducted to determine the effects that each data collection device had on driver behavior. These effects were measured by observing the use of vehicle brake lights as drivers approached the devices. It was assumed that drivers who did not use their brake lights may have been influenced by the data collection device; however, there was no way of quantifying this response. Vehicles located in platoons or subjected to unusual events were discarded from the data set.

While the radar and lidar performed well in both tests, they require a significant workforce for collecting and recording data that include a large sample of vehicles over an extended period of time. It was also noted that while similar in setup and operation, pneumatic tubes are more bulky than tapeswitches and create an audio feedback that may influence driver behavior. They were also less accurate at measuring speed than the tapeswitches or the magnetic sensor. The results of the test indicated that for speeds over 15 mph, the tapeswitches were more accurate than the magnetic sensor. However, the magnetic sensor performed better than its larger and more visible counterpart in terms of observed impacts on driver behavior and ease of installation. The conclusion of the study was that the Hi-Star magnetic sensor was the best overall alternative for collecting accurate speed data for further analyses.

In addition to the performance evaluation of data collection equipment, it is important to note the type and set-up of equipment used on other projects involving field measurements. For the study by Cottrell (*40*), data collection devices were used to measure vehicle speed, lateral placement, and centerline encroachments. Lateral placement and speed data were collected using a Leupold and Stevens traffic data recorder. Speed was measured using two parallel sensor cables spaced 6 feet apart, perpendicularly to the edge line. The lateral displacement was measured using two additional sensor cables, one perpendicular and one typically 45^{o} to the edge line, again 6 feet apart at the edge of the pavement. The speed and lateral displacement cables were separated into two channels connected to the recording device. The data were recorded on a magnetic cassette tape and printed out for later analysis.

Centerline encroachment was measured by dividing the width of the travel lane into ten 10-inch sections or zones labeled numerically from the edge line. Using these zones, encroachments could be identified separately for cars and trucks based on average vehicle dimensions. A similar system was implemented by Gawron and Ranney (*41*), who recorded lateral position through curve negotiation by continuously determining the percentage of time the left side of the test vehicle was located in one of 12 numbered intervals. Each interval was measured in 1-ft increments perpendicularly to the direction of travel. Curve entry speed was also recorded at the end of the curve transition and the lateral position along the approach was evaluated at 100-ft intervals measured from this point back to the location of the curve warning sign.

Another study conducted in the 1980s by Dudek (*47*) focused on the effects of different centerline stripe spacings on measurements of vehicle speed, lateral distance from the centerline, and lane encroachments. The data were collected for both tangent and curve sections using a series of Z-type tapeswitch configurations that were wired to computers in vehicles parked off of the roadway. The tapeswitch layout for the curve sections included one configuration at a base station located upstream of the curve and three configurations installed at ¼, ½, and ¾ distance points from the beginning of the curve.

Preliminary testing for the study by Zador et al. (*16*) revealed that drivers do not begin to adjust their position until they are within 100 ft of the beginning of the curve, and most of the change in placement occurs within the first 200 ft of the curve. Therefore, the placement of two sets of data collection equipment was installed, one each at 100 ft before and 100 ft after the beginning of the curve. The equipment used for the study consisted of a traffic data recorder (TDR) and an arrangement of four tapeswitches. Three of the tapeswitches were installed perpendicularly to the direction of travel, with the first used to record volume counts and a parallel pair used to measure speed. The last tapeswitch was placed at a 45^o angle to measure lateral placement. This type of set up is similar to the one utilized by Bowman and Brinkman (*39*).

To measure driver behavior, Bowman and Brinkman (*39*) deployed four sets of tapeswitches along a single-approach lane, each attached to a recorder to collect time stamps. Tapeswitches were also used to collect data for the study by Krammes (*17*).

In a report by Mahoney et al. (*48*) in 2003, the impacts of centerline rumble strips on lateral vehicle displacement and speed were evaluated. Tapeswitches were used to collect data on the speed and lateral displacement of vehicles within a single lane of travel. To measure speed, two parallel tapeswitches were laid perpendicularly to the edge line with 60 ft of spacing between the sensors. It was determined that the spacing had to be short enough to sustain the assumption of constant velocity and long enough to minimize the measurement error associated with each sensor. Two additional tapeswitches were installed at 45^o angles to the edge line to record time stamps for both the left and right front tires as vehicles passed over them. Although the position of the vehicle was not recorded directly using this method, it was calculated from the data using a mathematical formula based on the geometry of the tapeswitch layout.

Since only one data logger was used for all four tapeswitches and the tapeswitches only measured approximately 10 ft, the layout had to be sufficiently organized such that each time stamp could be recorded independently and accurately. In addition, a video recorder, located inconspicuously, was used to screen the recorded data to exclude larger vehicles and those vehicles traveling in a platoon so that more accurate free-flow speeds could be obtained. Through a screening process, vehicles following with headways of 4 seconds or less were eliminated from the data set.

In 2005, a study was completed by Miles et al. (*49*) to test the effects of transverse, centerline, and edge line rumble strips on driver performance. In order to collect these data, devices were set up covertly to minimize impacts to driver behavior. Peek ADR 2000 traffic counters were used in combination with pairs of pneumatic road tubes spaced 16 ft apart, perpendicularly to the direction of travel. The data collected by the counters for each vehicle included date, time of day, number of vehicles per hour, vehicle classification, and vehicle speed. An attempt was also made to track each vehicle's progression through the site. In order to collect free-flow speeds, passenger vehicles following with less than 15-second headways were eliminated.

To analyze the effects of centerline rumble strips on driver behavior, several MOEs related to passing maneuvers were evaluated, including centerline encroachments. These data were collected using a test vehicle equipped with multiple cameras to record passing vehicle behavior. In addition to the MOEs analyzed for passing maneuvers, data were also collected for the lateral position of vehicles. These data were collected using a camera trailer during daytime conditions for approximately 3 hours of observation. To estimate the exact position of vehicles within the lane, a number of tape markers were placed parallel to the centerline at 6-inch intervals for reference in the video. Vehicle lateral position was then plotted in terms of distance from the outside edge of the centerline.

As part of the report, data were also collected related to the installation of edge line rumble strips including traffic volumes and speed, frequency of shoulder encroachments, vehicle classification, and lateral position of vehicles on the shoulder during encroachment maneuvers. Peek traffic counters and pneumatic road tubes were used to collect lateral position, volume, and speed data. Two parallel tubes placed perpendicularly to the direction of travel to measure vehicle speed along with one tube set at a 45° angle on the shoulder, collected lateral position data of encroaching vehicles. Video camera equipment was also used to verify lateral position in the travel lane and to classify reasons for shoulder encroachments during daylight hours.

In 2004, a study was conducted by De la Riva (*50*) to provide information on the operational and safety effects of road emergency flares. The analysis involved the deployment of treatments in a realistic setting and measurement of the behavior of passing vehicles with roadway sensors. Spot speeds in both passing lanes and the lateral placement of vehicles in the outside lane (of a 4-lane divided highway) were recorded to collect the vehicle operations data. The data collection also included estimates of sub-variables related to vehicle lateral separation from the edge line, including the resulting lane distribution and number of lane-straddling events.

The speed data were collected using parallel pairs of pneumatic tubes, installed 90° to the edge lines in both lanes of the roadway. The tubes were placed with a spacing of 25 ft for the inside lane and 80 ft for the outside lane. Another pair of parallel pneumatic tubes was placed at a 45° angle to collect the lateral placement of vehicles in the outside lane (closest to the incident) stretching 8 ft from the edge line to record the passenger-side tires. The sub-variable of lateral placement, lane straddling, was said to occur if the driver's-side wheels crossed the center of the roadway. Any vehicle traveling with a passenger tire beyond the range of the tube (8 ft) was determined to automatically encroach into the passing lane, as the remaining 4 ft of lane is smaller than the track width for compact cars. Therefore, if a vehicle was detected by the speed sensors in the outside lane, but not by the diagonal sensors, then the vehicle was recorded as straddling the centerline.

Two automatic traffic recorders (ATRs) were used to record time stamps each instance a vehicle passed over the sensors. It was noted through previous testing of the equipment that the pneumatic tubes used in the test were very accurate for determining vehicle lateral displacement (± ⅓ ft). An installation procedure was also developed, tested, and practiced to further minimize errors due to the incorrect placement of sensors and to speed up the installation process. The sensors were used in a high-speed environment, 65 mph speed limit, making them less perceptible to drivers.

2.6.2 Location and Conditions of the Test Site

As previously mentioned, it is important to note the conditions at the testing sites used in the reviewed studies, as they are often influential to driver behavior. The majority of the reviewed studies involved sections of two-lane rural highways. However, the test locations along a particular route and the environmental conditions often varied between collection periods. As with many of the other studies, Cottrell (*40*) performed tests during both daytime and nighttime conditions at locations with ADT volumes in the range of 2,000 to 4,000 vehicles per day. In the study by Dudek (*47*), data were collected during hours of darkness only with dry pavement conditions. Tests conducted within both studies utilized both tangent and curve sections of roadway. While the analysis by Thompson (*10*) similarly used two-lane undivided highways, it also involved a field study of isolated curve locations, specifically with approach speeds between 35 and 55 mph. Several other studies exclusively examined curve locations, stressing their importance with regard to ROR crashes and the use of pavement markings.

Unlike the aforementioned studies, the data collected and analyzed by Mahoney et al. (*48*) involved only tangent locations to minimize the effect of horizontal curvature on speed. The data were collected during daylight hours so that a video recorder could be used to screen the recorded data with its clock display synchronized with the data logger. In a similar fashion, the De la Riva (*50*) study involved collecting data on a tangent section; however, the road type was a four-lane divided highway. Data were again collected only during nighttime hours under dry pavement conditions.

In the in-depth analysis conducted by Miles et al. (*49*) for the transverse rumble strip evaluation, five horizontal curve sites were selected along two-lane rural highways. The sites were identified as hazardous based on higher than state crash rates. The data collection process included determining an adequate sample size, developing data collection procedures, and screening and formatting the data. The number of speed observations required was determined using an equation to estimate sample size. Speeds were collected at three locations for each of the five curve sites, including one far enough away that the curve was not visible to the driver, one adjacent to the curve warning sign, and one at the beginning of the curve. In addition, the data were collected during both daytime and nighttime conditions based on sunrise and sunset times. For the edge line rumble strip evaluation, data were also collected during both daytime and nighttime conditions.

2.7 SUMMARY

While the MUTCD contains warrants regarding the application of pavement markings to delineate travel lanes, these criteria are based principally on traffic volumes. It is well understood that pavement markings provide the necessary guidance to motorists, especially at nighttime, to adequately traverse a roadway section. Research to estimate the safety effects of wider edge line pavement markings has resulted in contradictory conclusions. Because safety study findings have been varied, there is a need to further investigate their safety effects using a large sample size in order to detect a statistically significant change in crash frequency. In the meantime, safety surrogate measures could be used instead of detailed crash analyses. Previous studies evaluating these measures have suggested that wide edge lines can yield positive results, especially during twilight or nighttime conditions, with incremental benefits for older or impaired drivers.

Previous studies requiring the collection and analysis of data have used numerous combinations of the type and setup of equipment and location and conditions of the test site. The study type most frequently identified in the literature review was a before-and-after analysis with a comparison group and involved a number of statistical tests depending on the type of data and results. Data collection with respect to wide edge line treatments has commonly involved the use of sensors placed in combination to collect vehicle speed, lateral position, and encroachments during dry weather for both daytime and nighttime conditions. For horizontal curve collection, equipment has frequently been set up along the curve approach and at a location at or before the midpoint of the curve.

3. SITE SELECTION AND DATA COLLECTION

This section of the report describes the study sites as well as the data collection methodology. Included are the type of data collected, the locations and times they were collected, a description of the data collection equipment and procedures, the basic relationships used to convert the time stamps given by piezoelectric sensors to vehicle speed and lateral position, and possible sources of measurement error.

3.1 Data Collection Locations

Data were collected to determine the mean and variance of lateral vehicle position and vehicle operating speed. Vehicles were also observed to identify lane-line encroachment frequency while speed profile plots were developed to identify where possible braking occurred on the approach to or within horizontal curves. The data collection took place at eight separate curve locations, all two-lane rural roads, and in two distinct periods, each separated by approximately 4 to 8 weeks. Before any data were collected, the lane lines were re-striped at all eight locations in accordance with standard PennDOT pavement marking application procedures. This ensured that the pavement marking visibility throughout the experimental period was high. Following this application, "before" period data were collected at each of four treatment and four comparison sites. The edge lines at the treatments sites (i.e., horizontal curves) were then striped with 8-inch-wide edge line markings. The remaining four locations were used as comparison sites to identify any effects other than the treatments on the performance measures. Subsequently, data were collected at each of the eight sites for the "after" period. The eight locations, along with their experimental designation (i.e., treatment site or comparison site), are listed in Table 6.

Table 6. Data Collection Sites.

Curve No.	Site Designation	SR	Segment	County	Treatment
1	Treatment	14	210	Lycoming	8-inch Edgeline
2	Comparison	14	190	Lycoming	4-inch Edgeline
3	Treatment	87	140	Lycoming	8-inch Edgline
4	Comparison	87	150	Lycoming	4-inch Edgeline
5	Treatment	118	230	Lycoming	8-inch Edgeline
6	Comparison	225	280	Northumberland	4-inch Edgeline
7	Treatment	225	120	Northumberland	8-inch Edgline
8	Comparison	118	210	Lycoming	4-inch Edgline

Each treatment site (1, 3, 5, and 7) has a corresponding comparison site (2, 4, 6, and 8). Comparison sites should be used whenever the general effectiveness of the treatments under study is not known or is inconsistent. For this observational study, each comparison site has similar characteristics to the corresponding treatment site. These characteristics include posted speed limit, lane width, and ADT. Therefore, generic comparisons of the before-after data can be made and the effects that the treatments have on the performance measures can be separated from the effects caused by other factors (i.e., percentage of heavy vehicles, traffic growth, public awareness, and population characteristics). In each case, a comparison site was located on the same roadway as a treatment site. The comparison site was located upstream of the designated treatment site. As such, motorists first encountered the comparison site before traveling through the treatment site. The wide edge line treatment was applied to both sides of the roadway. The geometric characteristics for each treatment and comparison site are shown in Table 7.

Table 7. Geometric Features for Each Treatment and Comparison Site.

ID	Site Designation	SR	Segment	Lane Width (ft)	Shoulder Width (ft)	Curve Radius (ft)	Curve Direction	Approach Tangent Grade (%)	Average Daily Traffic (veh/day)
1	Treatment	14	210	11	5.5	1579	R	-1.80	3196
2	Comparison	14	190	11	4	2000	R	0.60	3196
3	Treatment	87	140	10.5	4	1429	L	0.70	5700
4	Comparison	87	150	11	4	1072	L	-0.40	5700
5	Treatment	118	230	11	4	1667	L	-0.20	3423
6	Comparison	225	280	10.5	6.5	858	L	0.30	3009
7	Treatment	225	120	11	9.5	2500	R	2.30	3009
8	Comparison	118	210	10.5	5.5	1072	R	3.20	3423

Photographs of each data collection site are shown in Appendix B. Additionally, a sample of the wide edge line treatment is shown in a photograph contained in Appendix B.

3.2 Collection Periods and Durations

Data were collected on weekdays only. The weather was clear, with normal visibility and no precipitation (i.e., rain, snow, or fog). The roadway condition was also dry, without the presence of standing water from an earlier rain or melting snow. At each site, the data collection session took place during both daytime and nighttime conditions, typically for a total of 24 hours. The session was long enough so that enough data were collected to satisfy the sample size requirements after the data were screened.

3.3 Data Collection Equipment and Procedures

To collect lateral vehicle position and vehicle operating speed within a single lane, four piezoelectric sensors were placed in accordance with the configuration shown in Figure 3. Piezoelectric sensors are thin, metal devices. The piezoelectric sensors used in this experiment were enclosed in pocket mastic tape to protect them from tire and weather damage and had a height of approximately 1/8 inch. Observations have revealed that the piezoelectric sensor's thin design and mastic tape cover add to its inconspicuity and minimize feedback to the driver when passing over them. These characteristics have been shown by previous research to reduce a sensor device's effect on driver behavior (*46*).

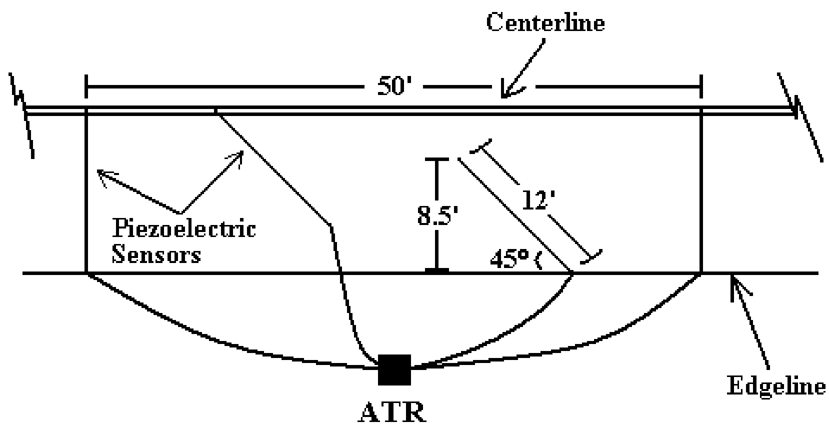

Figure 3. Layout of Sensor Equipment at Trap Location.

Piezoelectric sensors are pressure-sensitive electrical devices that remain "off" when under no external pressure. When a piezoelectric sensor is compressed from the application of a force, such as a tire or tire pair, it produces an electric pulse-generated signal. For the present experiment, the signal is sent to an automatic traffic recorder (ATR). All four sensors were connected to a single ATR that collected a time stamp each instance a vehicle came in contact with a sensor.

The vehicle speed and lateral position data were collected at two trap locations for each site. Each location was arranged with four 12-ft piezoelectric sensors as shown in Figure 3. The speed data were collected using a parallel pair of piezoelectric sensors, installed 90° to the edge lines, with a spacing of approximately 50 ft such that the configuration could be satisfied and a constant speed assumed between the sensors. Another pair of parallel sensors was placed at 45° angles to the lane lines, stretching approximately 8.5 ft from the adjacent line, to record the tire strikes. These time stamps were used to determine the lateral vehicle position.

Each site was setup with a combination of piezoelectric sensors at one location along the tangent and one at the midpoint of the curve to collect vehicle speed and lateral position. Based on the analysis of data from a previous study (*51*), it was determined that the first trap should be located 300 ft before the point of horizontal curvature (PC). This is the location where drivers generally tended to change their speed or vehicle position in the lane in advance of a horizontal curve during a nighttime driving experiment. The second trap was set up at the midpoint of the curve. Nu-Metric Hi-Star magnetic sensors were placed along the tangent and the beginning of the curve at approximately 100- to 150-ft intervals to record a speed profile for each vehicle as it passed through the study site. The first Hi-Star sensor was placed 600 ft in advance of the curve PC. The speed profile was used for the subjective assessment of braking location. One magnetic sensor was also installed in the opposing traffic lane at the midpoint between the two trap locations. This sensor was used to determine if a vehicle was present in the opposing lane at the same time a vehicle is located between the piezoelectric sensor traps. The purpose of documenting this occurrence was to determine if opposing traffic influenced vehicle speed and lateral position in the travel lane of interest. The equipment setup used to collect data at each study site is shown in Figure 4.

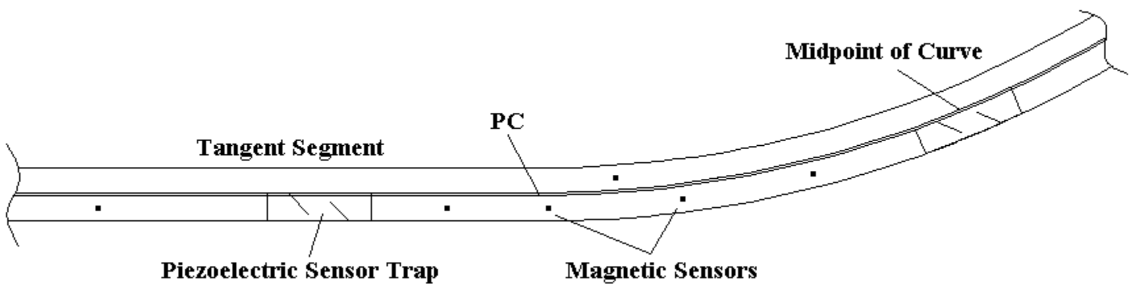

Figure 4. Equipment Layout at Each Data Collection Site (Left Curve).

This data collection method does not measure lateral position directly; rather, it is based on the geometric relationships of the roadway and piezoelectric sensors, and the assumption that vehicles travel at a constant speed while in the experimental section (i.e., from piezoelectric sensor 1 to piezoelectric sensor 4 in Figure 5). The basic equations and relationships used to convert time stamps to lateral vehicle position have been developed in a previous study (*48*). The same methodology was employed in the present study.

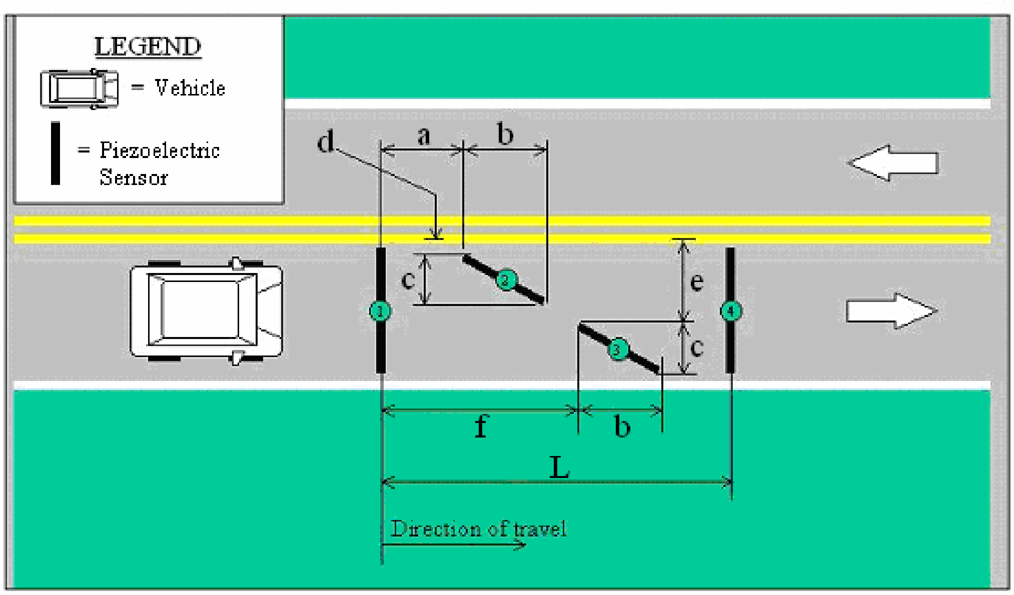

Figure 5. Geometric Layout of Piezoelectric Sensors (*48*).

To identify lane-line encroachments, a human observer was present to record the frequency for both passenger cars and heavy vehicles for a 2-hour period during daylight hours only. The total number of vehicles passing through the data collection site during this same 2-hour period was also noted by the observer. As such, an encroachment proportion was calculated. The observer was hidden from the driver's normal line of sight so that the obsrver's presence did not affect driver behavior.

3.4 Sources of Data Measurement Error

The lateral vehicle position data collected in the present experiment vary about a mean value. The variation is attributable to:

- Errors in the data collection system.
- Variation in lateral position due to the stochastic nature of driver behavior.

An attempt to minimize the former was made during the equipment set-up at each experimental site. The latter was used to determine the appropriate sample size to collect from each site before and after installing wide edge lines in order to make reasonable inferences about the population mean.

The errors stemming from the data collection system were the result of the error due to the piezoelectric sensor's responsiveness and data recorder and the error caused by the inaccurate placement of the piezoelectric sensors by the field data collection team.

The data collection equipment chosen for this study was considered to be very accurate. Therefore, the errors caused by the piezoelectric sensor's responsiveness and the data recorder were very small and can be neglected. The errors caused by the incorrect placement of the piezoelectric sensors are systematic errors (i.e., the errors are the same for every vehicle) and can be corrected for in the lateral position calculations. To correct for these systematic errors, the following equipment set up procedure was used to locate the piezoelectric sensors:

- Step 1. Place the piezoelectric sensors with an effort to achieve the desired dimensions L, a, b, c, d, e, and f in Figure 5.
- Step 2. After the piezoelectric sensors have been placed, re-measure the dimensions L, a, b, c, d, e and f and record the actual values.
- Step 3. Use the actual values in the calculation of speed and lateral position.

The lateral position of vehicles will vary from one vehicle to another due to the stochastic nature of driver behavior. The lateral positions will vary about a mean value. The goal of data collection is to collect a sample that is sufficient to develop a reasonably accurate estimate of the population mean and dispersion. Assuming that the lateral position of vehicles *(x)* follows a normal distribution with mean μ_x and standard deviation σ_x, the standard random variable $z = \frac{\bar{x} - \mu_x}{\sigma_x}$ also follows a normal distribution with $\mu = 0$ and $\sigma = 1$. However, the mean, μ_x, and the standard deviation, σ_x, are unknown. Therefore the sample mean $\bar{x}$ and sample variance, s_x, need to be estimated. If the sample size, N, is large, then the standard random variable

$z = \dfrac{\bar{x} - \mu_x}{\frac{s_x}{\sqrt{N}}}$ also follows a normal distribution with $\mu = 0$ and $\sigma = 1$. This implies that

$\bar{x} \pm (z_{1-\frac{\alpha}{2}} * \frac{s_x}{\sqrt{N}})$ is a large-sample confidence interval for μ_x with a confidence level of 100(1-α)%.

Using the results from a previous study (*48*), $\bar{x}$ has been shown to fall within the range of 4 to 6 inches from the population mean with a 95-percent confidence interval (α=0.05). Therefore,

$$(z_{1-\frac{\alpha}{2}} * \frac{s_x}{\sqrt{N}}) \leq (4 - 6) \text{ inches} \tag{1}$$

A much-larger-than-anticipated estimate of the standard deviation, s_x, would occur when all vehicles in the sample are equally distributed on both sides of a travel lane (i.e., one-half of the sample are positioned with the left tires on the centerline and one-half of the sample are positioned with the right tires on the edge line separating the travel lane and the shoulder). The standard deviation, s_x, for this case is then:

$$s_{x,\max imum} = \frac{1}{2}\sqrt{\frac{N}{N-1}}(W - w) \tag{2}$$

where: $s_{x,\text{ maximum}}$ = sample standard deviation
N = sample size
W = travel lane width
w = average vehicle width

Assuming a lane width, W, of 12 ft and an average vehicle width, w, of 6.5 ft,

$$s_{x,\max imum} = 33 * \sqrt{\frac{N}{N-1}} \text{ inches} \tag{3}$$

When the largest possible standard deviation is assumed,

$$z_{1-\frac{\alpha}{2}} * \frac{33 * \sqrt{\frac{N}{N-1}}}{\sqrt{N}} \leq (4 - 6) \text{ inches} \tag{4}$$

$$z_{1-\frac{\alpha}{2}} * \frac{33}{\sqrt{N-1}} \leq (4 - 6) \text{ inches} \tag{5}$$

$$\frac{z_{1-\frac{\alpha}{2}}}{\sqrt{N-1}} \leq \frac{4}{33} = 0.1212 \qquad \frac{z_{1-\frac{\alpha}{2}}}{\sqrt{N-1}} \leq \frac{6}{33} = 0.1818 \tag{6}$$

For $1-{}^{\alpha}/_{2} = 0.975$, $z = 1.960$,

$$\begin{array}{ll} 1.96/\sqrt{N-1} \leq 0.1212 & 1.96/\sqrt{N-1} \leq 0.1818 \\ N \geq 262.5 & N \geq 117.2 \end{array} \tag{7}$$

Therefore, the estimate sample size is at least 120 observations to detect a sample mean lateral vehicle position estimate within 6 inches of the population mean.

An alternative process was used to determine the sample size when mean speed is the variable of interest (*52*). The process is based on the following equation:

$$N = (S\frac{K}{E})^2 \tag{8}$$

where: N = minimum number of measured speeds
S = estimated sample standard deviation, mph
K = constant corresponding to the desired confidence level
E = permitted error in the average speed estimate, mph

To obtain a range of possible sample sizes, multiple values for the confidence level, *K*, have been input into the equation. The values correspond to confidence levels of 90, 95, and 99 percent. The permitted error in the average speed estimate, *E*, has been input as the most conservative value of ±1 percent. The estimate of sample standard deviation, *S*, is a function of traffic area and highway type. The input value of 5.3 is representative of a rural, two-lane highway (*52*). The resulting sample size estimates, based on the varying input parameters, are summarized in Table 8.

Table 8. Values for Sample-Size Determination.

S	K	E	N
5.3	1.64 (90%)	±1	76
	1.96 (95%)	±1	108
	2.58 (99%)	±1	187

As illustrated by the table, the estimated sample size for the 95-percent confidence interval is approximately 110 samples.

Because free-flow vehicles with headways greater than 4 seconds were used in the analysis, it was determined that at least 12 hours of data would be required to satisfy the minimum sample size requirements. As such, data were collected for at least 6 hours during daylight hours and for at least 6 hours during nighttime hours at all treatment and comparison sites. It should be noted that no sites contained roadway lighting or any other artificial light source during nighttime hours.

4. DATA ANALYSIS METHODOLOGY

Prior to beginning the data analysis, all raw data from the study sites were screened to exclude all vehicles that were not passenger cars and vehicles whose operations may have been affected by the presence of other vehicles. Vehicles were also excluded if they were closely following another vehicle through the study site. Based on a similar previous study, vehicles with a time headway less than 4 seconds were eliminated (*48*). Missing values were excluded from the analysis. Outliers were carefully evaluated to determine if they should be eliminated or included in the analysis. The main issue with outliers was related to observed vehicle speeds. Vehicles traveling less than 35 mph were excluded from the analysis because observation by the data collection team at each site revealed that, on rare occurrences, vehicles from nearby driveways were traveling through the site and were not traveling at desired free-flow speeds. Only 10 vehicles were excluded from the analysis database because of the low operating speed outlier criterion.

4.1 Speed and Lateral Vehicle Position

The data analysis consisted of several steps. Each treatment-comparison site combination was included in a separate analysis database. As such, four analysis databases were created. The first step in the analysis was to determine the distribution of the speed and lateral vehicle position data. Although it is common to assume that both are normally distributed, several tests were performed to confirm this. The Anderson-Darling test was used to test the normality assumption – the null hypothesis is that the speed and lateral vehicle position data are normally distributed. The p-value, at a level of significance of 0.05, was used to apply the decision rule. After the normality assumption was evaluated, an analysis of variance (ANOVA) was performed. Speed and lateral vehicle position were evaluated separately – each was the response variable in the analysis. All main effects were included in the analysis. The categories for each of the factors are as follows:

- Treatment vs. comparison site;
- Before vs. after time period;
- Day vs. night driving conditions;
- Tangent vs. curve measurement location; and
- Indicator for opposing vehicle in the analysis section.

Another key ANOVA assumption is homogeneity of variance across groups of the independent variables. To verify the assumption that there are equal variances among the groups, a Levene's test was performed. The null hypothesis of the test is that error variances are constant across categories of the independent variables. Again, the p-value was used to apply the decision rule. A p-value less than 0.05 results in rejecting the null hypothesis and concluding that the error variances are not constant across groups.

The final ANOVA assumption is that observations are orthogonal or independent. Using only free-flow vehicles in the sample ensured that this assumption was met.

ANOVA provides an F-statistic for each independent variable included in the analysis. This F-statistic tests the significance of the group means (i.e., that the means of the group formed by the independent variables are significantly different from each other). The null hypothesis is that there are no differences among the group means. A failure to reject the null hypothesis (p-value > 0.05) indicates that the independent variables, based on the present experimental design, did not statistically influence the dependent variable. Rejecting the null hypothesis (p-value $\leq$ 0.05) indicates that the independent variables influence the dependent variable, based on the present experimental design.

Planned two-sample t-tests and two-sided F-tests were used to determine how the before/after, treatment/comparison, tangent/curve, and day/night independent variables influenced mean speed, speed variance, mean lateral vehicle position, and lane position variance. The two-sample, independent samples t-test is used to test for differences in sample means and is computed as follows:

$$t = \frac{(\overline{X}_B - \overline{X}_A)}{\sqrt{\frac{s_B^2}{n_B} + \frac{s_A^2}{n_A}}} \tag{9}$$

where:

$\overline{X}_B, \overline{X}_A$ = mean lateral vehicle position or speed for the before and after periods;
s_B, s_A = standard error of speed and lateral position for the before and after periods;
n_B, n_A = sample size in before and after periods.

The degrees of freedom (df) for the independent samples t-test is $n_A + n_B - 2$. The critical value when $\alpha = 0.05$ for a two-tail test is $\pm$ 1.96. The null hypothesis is that the mean speed or mean lateral vehicle position is the same in the before and after periods. When the computed t-test exceeds the critical value, the null hypothesis is rejected and the conclusion is that the mean speed or mean lateral vehicle position differ between the before and after periods. An alternative method to determine the statistical significant of wide edge lines on mean speed or mean lateral vehicle position is the p-value associated with the t-statistic. When the p-value is low (i.e., less than or equal to 0.05), there is a high probability that the wide edge lines influenced mean speed or lane position from the before to the after period. The t-statistic and p-value were computed for each treatment and corresponding comparison site. In addition to the t-statistic and p-value, a 95-percent confidence interval is reported.

A two-sided F-test was used to compare the variances of the lateral vehicle placements for the before and after conditions. The random variable:

$$F = \frac{s_B^2}{s_A^2} \tag{10}$$

which has an F-distribution with $(n_B - 1)$ numerator degrees of freedom and $(n_A - 1)$ denominator degrees of freedom, was used to determine if a difference existed in the variances of the lateral vehicle position and speed during the before and after periods. When the computed F-test exceeds the critical value, the null hypothesis is rejected and the conclusion is that the speed variance or lateral vehicle position variance differ between the before and after periods based on the present experimental design. Again, an alternative method to determine the statistical significance of wide edge lines on speed or lateral vehicle position variance is the p-value associated with the F-statistic.

4.2 Encroachments

As described previously, a human observer was inconspicuously positioned and counted the frequency of centerline and edge line encroachments at each study site during the daytime for the before and after periods. The number of vehicles passing through each study site was also counted by the observer to develop a proportion of encroaching vehicles during the before and after conditions. A z-test of proportions was used to determine if the wide edge line treatment influenced the proportion of edge line or centerline encroachments. The test statistic is as follows:

$$Z = \frac{\hat{p}_B - \hat{p}_A}{\sqrt{\hat{p}_c(1-\hat{p}_c)\left(\frac{1}{n_B} + \frac{1}{n_A}\right)}} \tag{11}$$

where: $\hat{p}_B$ is the estimate of the population proportion in the "before" period;
$\hat{p}_A$ is the estimate of the population proportion in the "after" period;
$\hat{p}_c$ is the pooled estimate of the observed probability;
n_B is the "before" period sample size;
n_A is the "after" period sample size.

The pooled estimate is calculated as follows:

$$\hat{p}_c = \frac{X_B + X_A}{n_B + n_A} \tag{12}$$

where: X_B is the number of encroachments for the "before" sample;
X_A is the number of encroachments of the "after" sample;
n_B is the "before" period sample size (i.e., traffic volume);
n_A is the "after" period sample size (i.e., traffic volume).

The significance level used in the analysis is $\alpha = 0.05$. The critical value of the z-statistic is $\pm$ 1.96 for a two-tailed test. When the calculated z-statistic exceeds the critical value, the null hypothesis is rejected and the conclusion is that there is a statistically significant difference between the two proportions based on the present experiment. When the calculated z-statistic is less than the critical value, the null hypothesis is not rejected. As such, there is no statistically significant difference between the two proportions.

In addition to reporting z-statistics, a p-value and confidence interval are reported. The p-value is the probability of observing a test statistic that is as extreme or more extreme than currently observed, assuming the null hypothesis is true. A small p-value (i.e., 0.05 or less) indicates that the null hypothesis is rejected and, therefore, there is a low probability that a change in the encroachment proportion occurred by chance. In the present study, encroachments were observed only during daytime conditions.

4.3 Braking Location

To evaluate the location of speed reduction or braking with respect to the beginning of a horizontal curve both before and after application of wide edge lines, speed profile plots were developed and evaluated. The profiles contained the longitudinal roadway distance along the horizontal or x-axis, and the 85th percentile operating speed of all observed vehicles on the vertical or y-axis. A visual comparison of the before and after speed profile plots for each treatment and comparison was performed to determine if speed reduction or braking location changes occurred.

5. ANALYSIS RESULTS

This chapter is divided into several sections. The first provides descriptive statistics obtained from each field study site. Included are the sample size, mean speed and lateral vehicle position, and speed and lateral vehicle position variance. The second section contains the results of the normality testing for the observed speed and lateral vehicle position data. The third section describes the results obtained from the speed and lateral vehicle position analyses. Included is a discussion about the change in mean speed, mean lateral vehicle position, speed variance, and lateral vehicle position variance. The fourth section describes the encroachment analysis results and the fifth section contains the speed profile plot analysis used to evaluate the speed reduction or braking location with respect to the beginning of horizontal curve at each study site.

5.1 Descriptive Statistics

The descriptive statistics of interest are the mean speed, speed variance, mean lateral vehicle position, and lateral vehicle position variance for each treatment and comparison site. Additionally, the sample size is also of interest. Each of these descriptive statistics is shown in Table 9 for the vehicle speed data at both the tangent and curve sensor trap locations during the before and after data collection periods. Table 10 shows the lateral vehicle position data at the tangent and curve sensor trap locations during the before and after data collection periods.

As shown in Table 9, there is preliminary evidence that wide edge lines increased mean speed at two treatment sites (SR 14 and SR 87) while wide edge lines decreased mean speeds at two locations (SR 118 and SR 225). There is also preliminary evidence that wide edge lines decreased speed variance at two treatment sites (SR 14 and SR 118); however, the results are varied when comparing the speed variance at the tangent and curve locations at the other two treatment sites (SR 87 and SR 225). Only daytime speed data are available at the SR 118 comparison site because vandals damaged all field data collection equipment before nighttime data could be acquired at the site.

As shown in Table 10, there is preliminary evidence that wide edge lines changed lateral vehicle position in the travel lane at two treatment sites (SR 14 and SR 87) at both the tangent and curve locations. This change was a shift away from the centerline. At the other two treatment sites (SR 118 and SR 225), the lateral vehicle position was less pronounced at either the tangent or curve locations. The lateral vehicle position appears to increase at the SR 118 treatment site while the variance results are varied at the other treatment locations. Again, only daytime lateral vehicle position data are available at the SR 118 comparison site because of the vandalism.

The descriptive statistics indicate that there is preliminary evidence to indicate that wide edge lines do influence mean speed, speed variance, mean lateral vehicle position, and lateral vehicle position variance at some horizontal curve locations. Subsequent sections contain statistical tests to determine the significance of these changes based on the present experiment.

Table 9. Descriptive Speed Data for All Treatment and Comparison Sites.

ID	SR	Designation	Period	Location	Sample Size	Mean (mph)	Variance (mph^2)	Standard Deviation (mph)
1	14	Treatment	Before	Tangent	321	60.93	45.40	6.76
1	14	Treatment	After	Tangent	340	62.81	36.60	6.05
1	14	Treatment	Before	Curve	321	57.98	45.16	6.72
1	14	Treatment	After	Curve	318	59.52	36.84	6.07
2	14	Comparison	Before	Tangent	301	58.94	28.73	5.36
2	14	Comparison	After	Tangent	318	58.66	31.47	5.61
2	14	Comparison	Before	Curve	301	58.41	28.94	5.38
2	14	Comparison	After	Curve	301	58.91	27.77	5.27
3	87	Treatment	Before	Tangent	224	54.87	48.44	6.96
3	87	Treatment	After	Tangent	225	56.07	43.03	6.56
3	87	Treatment	Before	Curve	224	53.55	35.64	5.97
3	87	Treatment	After	Curve	221	54.22	37.45	6.12
4	87	Comparison	Before	Tangent	233	55.97	48.44	6.96
4	87	Comparison	After	Tangent	239	54.89	54.17	7.36
4	87	Comparison	Before	Curve	233	54.86	37.95	6.16
4	87	Comparison	After	Curve	242	54.57	47.75	6.91
5	118	Treatment	Before	Tangent	305	59.32	53.29	7.30
5	118	Treatment	After	Tangent	265	59.01	41.73	6.46
5	118	Treatment	Before	Curve	305	58.80	46.65	6.83
5	118	Treatment	After	Curve	262	58.27	38.94	6.24
6	225	Comparison	Before	Tangent	274	54.57	34.93	5.91
6	225	Comparison	After	Tangent	251	53.86	40.58	6.37
6	225	Comparison	Before	Curve	274	52.37	32.60	5.71
6	225	Comparison	After	Curve	251	52.09	36.36	6.03
7	225	Treatment	Before	Tangent	307	55.51	43.43	6.59
7	225	Treatment	After	Tangent	310	54.64	40.32	6.35
7	225	Treatment	Before	Curve	307	56.41	43.69	6.61
7	225	Treatment	After	Curve	310	54.80	47.06	6.86
8	118	Comparison	Before	Tangent*	180	57.51	36.72	6.06
8	118	Comparison	After	Tangent*	156	55.69	44.09	6.64
8	118	Comparison	Before	Curve*	180	57.18	28.94	5.38
8	118	Comparison	After	Curve*	159	56.85	25.60	5.06

*Data available for daytime condition only

Table 10. Descriptive Lateral Vehicle Position Data for All Treatment and Comparison Sites.

ID	SR	Designation	Period	Location	Sample Size	Mean (in)	Variance (in^2)	Standard Deviation (in)
1	14	Treatment	Before	Tangent	321	60.4	100.00	10.0
1	14	Treatment	After	Tangent	340	62.6	100.00	10.0
1	14	Treatment	Before	Curve	321	67.4	123.21	11.1
1	14	Treatment	After	Curve	318	72.6	104.04	10.2
2	14	Comparison	Before	Tangent	301	60.9	116.64	10.8
2	14	Comparison	After	Tangent	318	62.0	97.81	9.89
2	14	Comparison	Before	Curve	301	71.8	106.09	10.3
2	14	Comparison	After	Curve	301	73.7	127.69	11.3
3	87	Treatment	Before	Tangent	224	51.6	108.16	10.4
3	87	Treatment	After	Tangent	225	55.1	106.09	10.3
3	87	Treatment	Before	Curve	224	54.6	171.61	13.1
3	87	Treatment	After	Curve	221	59.0	174.24	13.2
4	87	Comparison	Before	Tangent	233	60.7	139.24	11.8
4	87	Comparison	After	Tangent	239	62.0	118.81	10.9
4	87	Comparison	Before	Curve	233	57.6	141.61	11.9
4	87	Comparison	After	Curve	242	56.0	121.0	11.0
5	118	Treatment	Before	Tangent	305	74.2	129.96	11.4
5	118	Treatment	After	Tangent	265	74.0	158.76	12.6
5	118	Treatment	Before	Curve	305	65.1	116.64	10.8
5	118	Treatment	After	Curve	262	64.3	132.25	11.5
6	225	Comparison	Before	Tangent	274	58.9	75.17	8.67
6	225	Comparison	After	Tangent	251	63.0	89.11	9.44
6	225	Comparison	Before	Curve	274	54.5	163.84	12.8
6	225	Comparison	After	Curve	251	56.3	190.44	13.8
7	225	Treatment	Before	Tangent	307	60.2	82.08	9.06
7	225	Treatment	After	Tangent	310	60.8	82.99	9.11
7	225	Treatment	Before	Curve	307	70.8	75.34	8.68
7	225	Treatment	After	Curve	310	73.6	112.36	10.6
8	118	Comparison	Before	Tangent*	180	67.5	121.0	11.0
8	118	Comparison	After	Tangent*	156	68.8	104.04	10.2
8	118	Comparison	Before	Curve*	180	71.5	90.82	9.53
8	118	Comparison	After	Curve*	159	76.4	116.64	10.8

*Data available for daytime condition only

5.2 Normality Tests

As described previously, the Anderson-Darling test was used to determine if the mean speed and lateral vehicle position were normally distributed at each treatment and comparison site in both the before and after data collection periods. These tests were run at the tangent and curve midpoint locations. The null hypothesis for the test is that the data are normally distributed. Failure to reject the null hypothesis (p-value > 0.05) indicates that the data are normally distributed. Table 11 shows the result of the Anderson-Darling statistical tests for speed and Table 12 shows the results of the Anderson-Darling statistical tests for lateral vehicle position.

Table 11. Anderson-Darling Normality Tests for Speed.

ID	SR	Designation	Period	Tangent Section		Curve Section	
				A-D Statistic	p-value	A-D Statistic	p-value
1	14	Treatment	Before	1.067	0.008	0.721	0.059*
1	14	Treatment	After	2.357	< 0.005	1.10	0.007
2	14	Comparison	Before	0.597	0.118*	0.570	0.139*
2	14	Comparison	After	1.549	< 0.005	0.552	0.154*
3	87	Treatment	Before	0.929	0.018	0.434	0.298*
3	87	Treatment	After	0.338	0.503*	0.494	0.213*
4	87	Comparison	Before	1.641	< 0.005	0.746	0.051*
4	87	Comparison	After	1.806	< 0.005	1.213	< 0.005
5	118	Treatment	Before	1.080	0.008	1.208	< 0.005
5	118	Treatment	After	1.439	< 0.005	0.552	0.154*
6	225	Comparison	Before	0.552	0.154*	0.720	0.418*
6	225	Comparison	After	0.552	0.154*	0.402	0.357*
7	225	Treatment	Before	0.370	0.423*	0.527	0.178*
7	225	Treatment	After	0.418	0.327*	0.477	0.236*
8	118	Comparison	Before	0.653	0.087*	0.386	0.390*
8	118	Comparison	After	0.382	0.394*	0.442	0.285*
*Data are normally distributed							

As shown in Table 11, 21 of 32 speed normality tests result in rejecting the null hypothesis and thus the distribution is normal. For those instances where the normality assumption is violated, large sample sizes make this less of a concern unless the departure is extreme (*53*). Therefore, the F-test employed in ANOVA is robust against departures from normality. When performing each ANOVA, the histograms of residuals and normal probability plots were examined to be certain that departures from normality were not extreme.

Table 12. Anderson-Darling Normality Tests for Lateral Vehicle Position.

ID	SR	Designation	Period	Tangent Section		Curve Section	
				A-D Statistic	p-value	A-D Statistic	p-value
1	14	Treatment	Before	0.277	0.653*	0.941	0.017
1	14	Treatment	After	2.36	< 0.005	0.885	0.023
2	14	Comparison	Before	0.184	0.909*	0.681	0.075*
2	14	Comparison	After	0.583	0.128*	0.761	0.047
3	87	Treatment	Before	0.402	0.356*	0.379	0.403*
3	87	Treatment	After	0.485	0.225*	0.407	0.346*
4	87	Comparison	Before	0.271	0.671*	0.491	0.217*
4	87	Comparison	After	0.270	0.675*	0.284	0.629*
5	118	Treatment	Before	0.478	0.235*	0.489	0.220*
5	118	Treatment	After	0.642	0.093*	0.757	0.048
6	225	Comparison	Before	0.668	0.080*	0.945	0.017
6	225	Comparison	After	0.668	0.080*	2.400	<0.005
7	225	Treatment	Before	0.702	0.066*	0.632	0.098*
7	225	Treatment	After	0.705	0.065*	0.758	0.048
8	118	Comparison	Before	1.302	< 0.005	0.187	0.904*
8	118	Comparison	After	0.665	0.081*	0.700	0.066*
*Data are normally distributed							

As shown in Table 12, 23 of 32 lateral vehicle position normality tests result in rejecting the null hypothesis and thus the distribution is normal. As in the speed case presented earlier, the ANOVA F-test is robust against departures from normality.

Appendix C contains the before and after frequency distributions for each treatment site at the tangent and curve locations. In each figure, the lateral vehicle position is shown on the x-axis while the observed frequency is shown on the y-axis. The center of the travel lane is denoted as "0" in each figure. Negative lateral position values on the x-axis indicate a position left of the center of the travel lane, while positive values indicate a position right of the center of the travel lane. As shown in all figures in Appendix C, all lateral vehicle position distributions at the treatment site appear normally distributed based on graphic inspection. To illustrate the information contained in Appendix C, consider Figures C-1 and C-2 for the State Route 14 treatment site. The mean lateral vehicle position was 6.18 and 6.58 inches left of the center of the travel lane in the before and after periods, respectively, on the tangent section. At the midpoint curve location, the mean lateral vehicle position was 11.7 and 10.7 inches left of the center of the travel lane in the before and after periods, respectively.

5.3 Speed and Lateral Vehicle Position

This section of the report is divided into subsections based on the study sites. Each subsection contains the results from the statistical analysis for each treatment-comparison site pair. The

ANOVA results are presented as are the independent samples t-test for mean speed and mean lateral vehicle position, and the F-test for the speed variance and lateral vehicle position variance.

5.3.1 State Route 14 Treatment and Comparison

The objective of the analysis was to determine which main effects influence mean speed, speed variance, mean lateral vehicle position, and lateral vehicle position variance. The factors included in the mean speed analysis were an indicator for daytime versus nighttime, an indicator for the tangent versus the curved section, an indicator for before versus after time periods, an indicator for treatment versus comparison site, and an indicator for the presence of a vehicle traveling in the opposing travel lane when the speed measurement was taken. The ANOVA results indicate that there is a statistically significant day/night main effect [F(1, 2382) = 4.60, p-value = 0.032]. This suggests that mean speeds are different when comparing the daytime to nighttime observations. There was also a statistically significant curve/tangent main effect [F(1, 2382) = 50.13, p-value = 0.000] as well as a statistically significant before/after main effect [F(1, 2382) = 10.75, p-value = 0.001]. As such, mean speeds are different when comparing the curve to the tangent observations and when comparing the before/after time periods. There was a statistically significant treatment/comparison main effect [F(1, 2382 = 41.04, p-value = 0.000] indicating that there is a difference in mean speed between the treatment and comparison sites. There was also a statistically significant difference [F(1, 2382) = 4.08, p-value = 0.043] between the mean speeds observed at the treatment site when a vehicle was present in the opposing travel direction as compared to speeds observed when a vehicle was not present in the opposing travel direction. Less than 20 percent of the speed observations were recorded with a vehicle traveling in the opposing travel lane. The mean speed with a vehicle traveling in the opposing lance was 0.5 mph higher than when no vehicle was in the opposing travel lane (60.1 mph vs. 59.6 mph). Independent sample t-tests were then performed to determine the magnitude of the difference between the statistically significant main effects. Table 13 shows the before-after comparison of mean speeds along State Route 14. Included is the treatment versus comparison site designation, the time period (day versus night), and location (tangent versus curve location). For each of the treatment site designations in Table 13, the differences in mean speeds are statistically significant (p-value < 0.05) while all comparison site designations are not statistically significant (p-value > 0.05). The treatment site results indicate that mean speeds increased by 1.16 and 1.35 mph on the curve and tangent locations, respectively, during the day. At night, the mean speeds increased by 2.54 and 3.01 mph on the curve and tangent locations, respectively. The mean speeds are generally higher at night on the tangent and curve sections at the treatment site, and the mean speeds are generally higher at the treatment site than at the comparison site. The comparison site analysis indicates that no change in mean speed occurred from the before to after time period. As such, it is reasonable to conclude that the application of wide edge lines on State Route 14 increased mean speeds during day and night driving conditions and along the approach tangent and within the horizontal curve. The increased speed was greater at night than it was during the day.

Table 13. Before-After Comparison of Mean Speeds along State Route 14.

Designation	Time	Location	Before Mean Speed (mph)	After Mean Speed (mph)	Mean Difference in Speeds (mph)	t-statistic	p-value	95 percent Confidence Interval	
								Lower Bound	Upper Bound
Treatment	Day	Tangent	61.06	62.42	1.35	2.44	0.015	0.26	2.45
Treatment	Night	Tangent	60.70	63.71	3.01	2.97	0.003	1.01	5.01
Treatment	Day	Curve	57.76	58.92	1.16	2.04	0.042	0.04	2.28
Treatment	Night	Curve	58.37	60.90	2.54	2.52	0.013	0.55	4.53
Comparison	Day	Tangent	59.55	58.64	-0.91	-1.81	0.071	-1.90	0.08
Comparison	Night	Tangent	58.01	58.71	0.70	0.80	0.425	-1.03	2.43
Comparison	Day	Curve	58.71	58.86	0.14	0.30	0.768	-0.10	1.09
Comparison	Night	Curve	57.96	59.03	1.06	1.22	0.225	-0.66	2.79

Table 14 shows the before-after speed variance comparison for the treatment and comparison sites along State Route 14. As shown, there is a statistically significant difference (p-value < 0.05) at the treatment site during the daytime period at the tangent and curve locations; however, the speed variance is not different at the treatment site at night. The speed variance at the comparison site is not statistically different when comparing the before and after time periods during daytime or nighttime conditions, or at the tangent or curved section. It is reasonable to conclude that the wide edge lines increase speed variance during the daytime conditions at the State Route 14 treatment site from the before to after period.

Table 14. Before-After Comparison of Speed Variance along State Route 14.

Designation	Period	Location	Before Speed Variance (mph^2)	After Speed Variance (mph^2)	F-statistic	p-value
Treatment	Day	Tangent	28.59	38.17	0.75	0.032
Treatment	Night	Tangent	54.14	59.21	0.91	0.645
Treatment	Day	Curve	29.38	38.76	0.76	0.044
Treatment	Night	Curve	51.55	56.69	0.91	0.632
Comparison	Day	Tangent	25.37	25.20	1.01	0.967
Comparison	Night	Tangent	46.43	32.80	1.42	0.074
Comparison	Day	Curve	21.10	24.02	0.88	0.367
Comparison	Night	Curve	43.05	36.26	1.19	0.378

The factors included in the mean lateral vehicle position analysis were an indicator for daytime versus nighttime, an indicator for the tangent versus curved section, an indicator for before versus after time periods, an indicator for treatment versus comparison site, and an indicator for the presence of a vehicle traveling in the opposing travel lane when the speed measurement was taken. The ANOVA results indicate that there is a statistically significant day/night main effect

[F(1, 2382) = 59.86, p-value = 0.000]. This suggests that mean lateral vehicle position is different when comparing the daytime to nighttime observations. There was also a statistically significant curve/tangent main effect [F(1, 2382) = 569.12, p-value = 0.000] as well as a statistically significant before/after main effect [F(1, 2382) = 38.83, p-value = 0.000]. As such, mean lateral vehicle position is different when comparing the curve to the tangent observations and when comparing the before/after time periods. There was a statistically significant treatment/comparison main effect [F(1, 2382 = 11.64, p-value = 0.001] indicating that there is a difference in mean lateral vehicle position between the treatment and comparison sites. There was also a statistically significant difference [F(1, 2382) = 50.23, p-value = 0.000] between the mean lateral vehicle position measured when a vehicle was present in the opposing travel direction as compared to the lateral vehicle position measured when a vehicle was not present in the opposing travel direction. The mean lateral vehicle position was 70.3 inches when a vehicle was in the opposing travel lane versus 65.6 inches when an opposing vehicle was not present. The distribution of lateral vehicle position at the SR 14 treatment location is shown in Appendix C on the tangent and curve locations both before and after the wide edge line treatment.

Planned independent sample t-tests were performed to determine the magnitude of the difference between the treatment/comparison, day/night, tangent/curve, and before/after data. Table 15 shows the before-after comparison of mean lateral vehicle position along State Route 14. Included is the treatment versus comparison site designation, the time period (day versus night), and location (tangent versus curve location). For all but one of the treatment site designations in Table 15 (tangent at night), the difference in mean lateral vehicle position is statistically significant (p-value < 0.05). It is worth noting that vehicles were generally positioned closer to the roadway centerline at night than during the day at the treatment sites. At the treatment locations, the mean lateral vehicle position increased by 1.28 and 2.27 inches on the tangent during the night and day conditions, respectively. The mean lateral vehicle position increased by 3.66 and 5.79 inches at the curve midpoint during the night and day conditions, respectively. A such, it is reasonable to conclude that wide edge lines contribute to vehicles moving further away from the centerline, particularly at the mid-point of a horizontal curve during both daytime and nighttime conditions. This may suggest that drivers use the wide edge lines as a guide to negotiate the curve and thus move toward it when traversing the curve. It is important to note that the SR 14 treatment curve is a right-hand curve on a road with an 11-foot travel lane. The middle of the travel lane is thus located 66 inches from the centerline. At the treatment site, vehicles are “flattening” the curve by positioning themselves left of the center of the travel lane on the tangent and then “shifting” toward the inside of the curve at the midpoint. This “shift” is more pronounced at night (70.6 – 58.7 = 11.9 inches), but is also significant during the day (73.5 – 64.4 = 9.1 inches), based on computing the mean difference between the tangent and curve locations. Because the data collection plan was designed to “track” individual vehicles, this lateral shift was measured for each vehicle included in the analysis. This issue is discussed in greater detail later in this section. When considering the comparison site, three of the four designations did not show a statistically significant change in mean lateral vehicle position when comparing the before to after periods. Like the treatment site, vehicles were generally positioned closer to the roadway centerline at night than during the day. From this analysis, it is reasonable to conclude that the application of wide edge lines on State Route 14 changed mean lateral vehicle position during daytime driving at tangent and curved roadway sections. The nighttime condition also showed a mean lateral vehicle position change in the after period; however, it was small in magnitude and not statistically significant on the tangent section, but was statistically significant at the midpoint of the horizontal curve.

Table 15. Before-After Comparison of Mean Lateral Vehicle Position along State Route 14.

Designation	Time	Location	Before Mean LVP (in)	After Mean LVP (in)	Mean Difference in LVP (in)	t-statistic	p-value	95 percent Confidence Interval	
								Lower Bound	Upper Bound
Treatment	Day	Tangent	62.1	64.36	2.27	2.37	0.018	0.39	4.18
Treatment	Night	Tangent	57.38	58.66	1.28	1.05	0.294	-1.12	3.67
Treatment	Day	Curve	67.7	73.47	5.79	5.84	0.000	3.84	7.74
Treatment	Night	Curve	67.0	70.6	3.66	2.38	0.018	0.62	6.69
Comparison	Day	Tangent	63.12	63.39	0.27	0.28	0.779	-1.64	2.18
Comparison	Night	Tangent	57.6	58.59	0.95	0.66	0.509	-1.88	3.79
Comparison	Day	Curve	72.58	75.7	3.11	2.99	0.003	1.07	5.16
Comparison	Night	Curve	70.7	69.4	-1.32	-0.85	0.395	-4.39	1.74

Table 16 shows the before-after lateral vehicle position variance comparison for the treatment and comparison sites along State Route 14. As shown, there are no statistically significant differences (p-value < 0.05) for any of the designations shown. The data do, however, indicate that the lateral vehicle position variance decreases in the after period at all treatment sites when compared to the before lateral vehicle position data.

Table 16. Before-After Comparison of Lateral Vehicle Position Variance along State Route 14.

Designation	Time	Location	Sample Size Before	Sample Size After	Before LVP Variance (in^2)	After LVP Variance (in^2)	F-statistic	p-value
Treatment	Day	Tangent	204	237	104.15	99.20	0.95	0.717
Treatment	Night	Tangent	117	103	81.07	80.21	0.99	0.959
Treatment	Day	Curve	204	221	108.77	99.37	0.91	0.511
Treatment	Night	Curve	117	97	147.21	107.85	0.73	0.116
Comparison	Day	Tangent	181	224	94.60	94.57	1.00	0.994
Comparison	Night	Tangent	120	94	132.70	90.37	0.68	0.054
Comparison	Day	Curve	181	208	97.41	112.92	1.16	0.309
Comparison	Night	Curve	120	93	118.90	132.11	1.11	0.586

5.3.2 State Route 87 Treatment and Comparison Sites

The objective of the analysis was to determine which main effects influence mean speed, speed variance, mean lateral vehicle position, and lateral vehicle position variance. The factors included in the mean speed analysis were an indicator for daytime versus nighttime, an indicator for the tangent versus the curved section, an indicator for before versus after time periods, an indicator for treatment versus comparison site, and an indicator for the presence of a vehicle traveling in the opposing travel lane when the speed measurement was taken. The ANOVA results indicate that there is not a statistically significant day/night main effect [F(1, 1719) = 1.28, p-value = 0.257]. This suggests that mean speeds are not different when comparing the daytime to nighttime observations based on the present experiment. There was a statistically significant curve/tangent main effect [F(1, 1719) = 10.32, p-value = 0.001]. The before/after main effect was not statistically significant [F(1, 1719) = 1.33, p-value = 0.249]. There was no treatment/comparison main effect [F(1, 1719 = 2.99, p-value = 0.084] indicating that a statistically significant difference in mean speed between the treatment and comparison sites is not present in the experimental data. There was a statistically significant difference found between the mean speeds observed at the treatment site when a vehicle was present in the opposing travel direction as compared to speeds observed when a vehicle was not present in the opposing travel direction [F(1, 1719) = 4.08, p-value = 0.043]. Approximately 25 percent of all observations were recorded when a vehicle was traveling in the opposing travel lane. The mean speed was 0.7 mph higher when no vehicle was present in the opposing travel lane (54.2 mph vs. 54.9 mph) when compared to mean speeds when a vehicle was present in the opposing travel lane. Although there was no statistically significant difference between the day/night, before/after, or treatment/comparison main effect, the planned t-tests were still computed to show the practical change in mean speed from the before to after time periods based on tangent/curve, day/night, and treatment/comparison conditions. These results are shown in Table 17.

Table 17. Before-After Comparison of Mean Speeds along State Route 87.

Designation	Period	Location	Before Mean Speed (mph)	After Mean Speed (mph)	Mean Difference in Speeds (mph)	t-statistic	p-value	95 percent Confidence Interval	
								Lower bound	Upper bound
Treatment	Day	Tangent	53.56	55.50	1.94	2.58	0.010	0.46	3.42
Treatment	Night	Tangent	57.51	57.21	-0.30	-0.27	0.791	-2.51	1.92
Treatment	Day	Curve	52.49	53.54	1.05	1.63	0.105	-0.22	2.31
Treatment	Night	Curve	55.71	55.60	-0.11	-0.11	0.916	-2.27	2.04
Comparison	Day	Tangent	56.26	55.16	-1.09	-1.45	0.148	-2.57	0.39
Comparison	Night	Tangent	55.24	54.33	-0.91	-0.69	0.493	-3.54	1.71
Comparison	Day	Curve	54.97	54.88	-0.09	-0.13	0.899	-1.42	1.25
Comparison	Night	Curve	54.60	53.93	-0.67	-0.55	0.581	-3.06	1.72

The data provided in Table 17 suggest that the mean speeds increased from the before to after periods during the day at the treatment site tangent and curve locations, while the mean speeds decreased at night on the tangent and curve sites. All mean speeds decreased in the after period at the comparison site. In these cases, the mean speed change from the before to after period was less than 2.0 mph.

Table 18 shows the before-after speed variance comparison for the treatment and comparison sites along State Route 87. As shown, there is a statistically significant difference

(p-value < 0.05) at the treatment site during the daytime and nighttime periods at the tangent location; however, the speed variance is not different at the treatment site at the midpoint of the curve. The speed variance decreases during the day at the tangent treatment location, but increases at night at the same location. As such, it is not clear if wide edge lines influence speed variance at the SR 87 treatment location. The speed variance at the comparison site is not statistically different when comparing the before and after time periods during daytime or nighttime conditions, or at the tangent or curved section.

Table 18. Before-After Comparison of Speed Variance along State Route 87.

Designation	Period	Location	Sample Size Before	Sample Size After	Before Speed Variance (mph^2)	After Speed Variance (mph^2)	F-statistic	p-value
Treatment	Day	Tangent	150	151	49.95	35.31	0.71	0.035
Treatment	Night	Tangent	74	74	35.38	57.50	1.63	0.040
Treatment	Day	Curve	150	148	31.99	29.6	0.93	0.650
Treatment	Night	Curve	74	73	36.45	50.96	1.40	0.156
Comparison	Day	Tangent	166	161	40.63	52.01	1.28	0.116
Comparison	Night	Tangent	67	78	67.81	58.73	0.87	0.541
Comparison	Day	Curve	166	162	35.20	40.18	1.14	0.399
Comparison	Night	Curve	67	80	45.14	63.35	1.40	0.157

The factors included in the mean lateral vehicle position analysis were an indicator for daytime versus nighttime, an indicator for the tangent versus curved section, an indicator for before versus after time periods, an indicator for treatment versus comparison site, and an indicator for the presence of a vehicle traveling in the opposing travel lane when the speed measurement was taken. The ANOVA results indicate that there is a statistically significant day/night main effect [$F(1, 1719) = 139.42$, p-value = 0.000]. This suggests that mean lateral vehicle position is different when comparing the daytime to nighttime observations based on the present experiment. There was not a statistically significant curve/tangent main effect [$F(1, 1719) = 2.64$, p-value = 0.105], but there was a statistically significant before/after main effect [$F(1, 1719) = 16.16$, p-value = 0.000]. As such, mean lateral vehicle position is not different when comparing the curve to the tangent observations in the present experiment, but is different when comparing the before/after time periods. There was a statistically significant treatment/comparison main effect [F(1, 1719 = 54.43, p-value = 0.000] indicating that there is a difference in mean lateral vehicle position between the treatment and comparison sites. There was also a statistically significant difference [$F(1, 1719) = 72.62$, p-value = 0.000] between the mean lateral vehicle position measured when a vehicle was present in the opposing travel direction as compared to the lateral vehicle position measured when a vehicle was not present in the opposing travel direction. The mean lateral vehicle position was further from the roadway centerline when a vehicle was present in the opposing travel lane (62.3 inches) when compared to the mean lateral vehicle position when a vehicle was not present in the opposing travel lane (55.9 inches). The distribution of lateral vehicle position at the SR 87 treatment location is shown in Appendix C on the tangent and curve locations both before and after the wide edge line treatment.

Planned independent sample t-tests were then performed to determine the magnitude of the difference between the tangent/curve, treatment/comparison, before/after, and day/night variables. Table 19 shows the before-after comparison of mean lateral vehicle position along State Route 87. Included is the treatment versus comparison site designation, the time period (day versus night), and location (tangent versus curve location). For all but one of the treatment site designations in Table 19 (tangent at night), the difference in mean lateral vehicle position is statistically significant (p-value < 0.05). At the treatment locations, the mean lateral vehicle position increased by 4.15-inches on the tangent during the daytime. The mean lateral vehicle position increased by 2.85 and 7.52-inches at the curve midpoint during the night and day conditions, respectively. As such, it is reasonable to conclude that wide edge lines contribute to vehicles moving further away from the centerline, particularly at the mid-point of a horizontal curve during both daytime and nighttime conditions. This may suggest that drivers use the wide edge lines as a guide to negotiate the curve and thus move toward it when traversing the curve. It is important to note that the SR 87 treatment curve is a left-hand curve on a road with a 10.5-ft travel lane. The middle of the travel lane is thus located 63 inches from the centerline. At the treatment site, vehicles are "lengthening" the curve by positioning themselves left of the center of the travel lane on the tangent and then "shifting" toward the outside of the curve at the midpoint. The mean lateral vehicle position at the treatment site is closer to the roadway centerline during the nighttime condition than it is during the daytime. When considering the comparison site, no statistically significant change in mean lateral vehicle position is shown in Table 19 when comparing the before to after periods. It is interesting to note, however, that drivers tend to position themselves closer to the roadway centerline at night at the comparison site when compared to the daytime condition. From this analysis, it is reasonable to conclude that the application of wide edge lines on State Route 87 changes mean lateral vehicle position during daytime and nighttime driving at curved roadway sections.

Table 19. Before-After Comparison of Mean Lateral Vehicle Position along State Route 87.

Designation	Period	Location	Before Mean LVP (in)	After Mean LVP (in)	Mean Difference in LVP (in)	t-statistic	p-value	95 percent Confidence Interval	
								Lower bound	Upper bound
Treatment	Day	Tangent	53.64	57.78	4.15	3.72	0.000	1.95	5.34
Treatment	Night	Tangent	47.3	49.6	2.28	1.37	0.172	-1.00	5.56
Treatment	Day	Curve	58.3	61.2	2.85	2.08	0.039	0.15	5.55
Treatment	Night	Curve	47.0	54.5	7.52	3.36	0.001	3.10	11.95
Comparison	Day	Tangent	62.5	64.47	1.99	1.74	0.083	-0.26	4.25
Comparison	Night	Tangent	56.3	56.8	0.50	0.24	0.808	-3.54	4.53
Comparison	Day	Curve	59.7	58.3	-1.42	-1.16	0.246	-3.82	0.98
Comparison	Night	Curve	52.3	51.3	-1.04	-0.57	0.566	-4.62	2.54

Table 20 shows the before-after lateral vehicle position variance comparison for the treatment and comparison sites along State Route 87. As shown, there are no statistically significant differences (p-value < 0.05) for any of the designations and the variance does not consistently change (i.e., increase or decrease) from the before to the after periods at the treatment site. As such, it is reasonable to conclude that the application of wide edge lines does not systematically change lateral vehicle position variance either on the approach to or within a horizontal curve on SR 87.

Table 20. Before-After Comparison of Lateral Vehicle Position Variance along State Route 87.

Designation	Period	Location	Sample Size Before	Sample Size After	Before LVP Variance (in^2)	After LVP Variance (in^2)	F-statistic	p-value
Treatment	Day	Tangent	150	151	95.32	91.71	0.96	0.814
Treatment	Night	Tangent	74	74	109.69	94.39	0.86	0.522
Treatment	Day	Curve	150	148	120.79	159.14	1.32	0.094
Treatment	Night	Curve	74	73	192.05	176.20	0.92	0.715
Comparison	Day	Tangent	166	161	118.57	96.27	0.81	0.186
Comparison	Night	Tangent	67	78	167.65	129.53	0.77	0.275
Comparison	Day	Curve	166	162	132.49	112.04	0.85	0.286
Comparison	Night	Curve	67	80	128.45	108.48	0.84	0.470

5.3.3 State Route 118 Treatment and State Route 225 Comparison Sites

The objective of the analysis was to determine which main effects influence mean speed, speed variance, mean lateral vehicle position, and lateral vehicle position variance. The factors included in the mean speed analysis were an indicator for daytime versus nighttime, an indicator for the tangent versus the curved section, an indicator for before versus after time periods, an indicator for treatment versus comparison site, and an indicator for the presence of a vehicle traveling in the opposing travel lane when the speed measurement was taken. The ANOVA results indicate that there is a statistically significant day/night main effect [F(1, 2180) = 8.74, p-value = 0.003]. This suggests that mean speeds are different when comparing the daytime to nighttime observations. There was also a statistically significant curve/tangent main effect [F(1, 2180) = 22.25, p-value = 0.000] as well as a statistically significant treatment/comparison site main effect [F(1, 2180) = 406.33, p-value = 0.000]. As such, mean speeds are different when comparing the curve to the tangent observations and when comparing the treatment and comparison sites. There was not a statistically significant opposing lane main effect [F(1, 2180 = 0.53, p-value = 0.467] indicating that there is no difference in mean speed when vehicles are present in the opposing lane versus when no vehicle is present in the opposing travel lane based on the present experiment. There was also not a statistically significant difference [F(1, 2180) = 2.21, p-value = 0.137] between the mean speeds observed in the before and after periods.

Planned t-tests to determine the magnitude of the difference between the treatment and comparison sites during the before-after periods at tangent and curve locations for both day and nighttime conditions were carried out. Table 21 shows the before-after comparison of mean speeds at the SR 118 treatment sites and corresponding SR 225 comparison site. Included is the treatment versus comparison site designation, the time period (day versus night), and location (tangent versus curve location). For each of the treatment and comparison site designations in Table 21, the difference in mean speeds is not statistically significant (p-value > 0.05) and is inconsistent in direction. As such, it is reasonable to conclude that the application of wide edge lines on State Route 118 did not consistently change mean speeds along the approach tangent or within the horizontal curve. It is interesting to note that the mean speeds at the treatment site are higher during the day than at night.

Table 21. Before-After Comparison of Mean Speeds along State Route 118 Treatment and State Route 225 Comparison Sites.

Designation	Period	Location	Before Mean Speed (mph)	After Mean Speed (mph)	Mean Difference in Speeds (mph)	t-statistic	p-value	95 percent Confidence Interval	
								Lower bound	Upper bound
Treatment	Day	Tangent	59.84	59.81	-0.03	-0.05	0.961	-1.32	1.26
Treatment	Night	Tangent	58.29	57.68	-0.61	-0.57	0.570	-2.73	1.51
Treatment	Day	Curve	59.21	59.26	0.05	0.08	0.934	-1.19	1.30
Treatment	Night	Curve	57.98	56.61	-1.37	-1.36	0.176	-3.36	0.62
Comparison	Day	Tangent	54.48	53.94	-0.53	-0.83	0.405	-1.79	0.72
Comparison	Night	Tangent	54.73	53.72	-1.00	-1.04	0.298	-2.90	0.89
Comparison	Day	Curve	52.17	52.07	-0.09	-0.15	0.879	-1.30	1.11
Comparison	Night	Curve	52.72	52.12	-0.60	-0.66	0.512	-2.40	1.20

Table 22 shows the before-after speed variance comparison for the treatment and comparison sites along the State Route 118 treatment and State Route 225 comparison sites. As shown, there is a statistically significant difference (p-value < 0.05) at the treatment site during the daytime period at the tangent location; however, the speed variance is not statistically significant at the treatment site during the nighttime condition at either the tangent or curve locations. The speed variance at the treatment site does consistently decrease from the before to after periods. The speed variance at the comparison site is not statistically significant when comparing the before and after time periods during daytime or nighttime conditions. Although lacking statistical significance, there is evidence that speed variance decreases after applying wide edge lines on horizontal curves at the SR 118 treatment site.

Table 22. Before-After Comparison of Speed Variance along State Route 118 Treatment and State Route 225 Comparison Sites.

Designation	Period	Location	Sample Size Before	Sample Size After	Before Speed Variance (mph^2)	After Speed Variance (mph^2)	F-statistic	p-value
Treatment	Day	Tangent	203	165	50.06	30.49	0.61	0.001
Treatment	Night	Tangent	102	100	58.54	57.79	0.99	0.949
Treatment	Day	Curve	203	164	42.06	31.77	0.76	0.062
Treatment	Night	Curve	102	98	55.39	46.89	0.85	0.410
Comparison	Day	Tangent	171	155	32.32	33.79	1.05	0.777
Comparison	Night	Tangent	103	96	39.47	51.92	1.32	0.174
Comparison	Day	Curve	171	155	28.91	31.93	1.10	0.526
Comparison	Night	Curve	103	96	38.77	43.99	1.13	0.530

The factors included in the mean lateral vehicle position analysis were an indicator for daytime versus nighttime, an indicator for the tangent versus curved section, an indicator for before versus after time periods, an indicator for treatment versus comparison site, and an indicator for the presence of a vehicle traveling in the opposing travel lane when the speed measurement was taken. The ANOVA results indicate that there is a statistically significant day/night main effect [$F(1, 2180) = 206.03$, p-value = 0.000]. This suggests that mean lateral vehicle position is different when comparing the daytime to nighttime observations. There was also a statistically significant curve/tangent main effect [$F(1, 2180) = 266.11$, p-value = 0.000] as well as a statistically significant before/after main effect [$F(1, 2180) = 8.46$, p-value = 0.004]. As such, mean lateral vehicle position is different when comparing the curve to the tangent observations and when comparing the before/after time periods. There was a statistically significant treatment/comparison main effect [$F(1, 2180 = 534.14$, p-value = 0.000] indicating that there is a difference in mean lateral vehicle position between the treatment and comparison sites. There was also a statistically significant difference [$F(1, 2180) = 11.13$, p-value = 0.001] between the mean lateral vehicle position measured when a vehicle was present in the opposing travel direction as compared to the lateral vehicle position measured when a vehicle was not present in the opposing travel direction. Less than 20 percent of the observed lateral vehicle position measurements were recorded when a vehicle was traveling in the opposing travel lane. The mean lateral vehicle position was 72.8 inches when a vehicle was present in the opposing travel lane, while the mean lateral vehicle position was 69.3 inches when a vehicle was not present in the opposing travel lane. The distribution of lateral vehicle position at the SR 118 treatment location is shown in Appendix C on the tangent and curve locations both before and after the wide edge line application.

Planned independent sample t-tests were then performed to determine the magnitude of the difference between the statistically significant main effects. Table 23 shows the before-after comparison of mean lateral vehicle position along the State Route 118 treatment site and the State Route 225 comparison site. Included is the treatment versus comparison site designation, the time period (day versus night), and location (tangent versus curve location). For all of the treatment site designations in Table 23, the difference in mean lateral vehicle position is not statistically significant (p-value > 0.05) based on the present experiment. At the tangent section of the comparison site, the mean lateral vehicle position is statistically significant while the mean lateral vehicle position is not statistically significant at the curve location along the comparison site. From this analysis, it is not reasonable to conclude that the application of wide edge lines on State Route 118 changes mean lateral vehicle position during daytime and nighttime driving at tangent or curved roadway sections.

Table 23. Before-After Comparison of Mean Lateral Vehicle Position along State Route 118 Treatment and State Route 225 Comparison Sites.

Designation	**Period**	**Location**	**Before Mean LVP (in)**	**After Mean LVP (in)**	**Mean Difference in LVP (in)**	**t-statistic**	**p-value**	**95 percent Confidence Interval**	
								Lower bound	**Upper bound**
Treatment	Day	Tangent	77.3	77.2	-0.004	-0.00	0.997	-2.23	2.22
Treatment	Night	Tangent	68.26	68.7	0.40	0.24	0.810	-2.91	3.71
Treatment	Day	Curve	68.16	66.97	-1.18	-1.19	0.235	-3.14	0.77
Treatment	Night	Curve	58.9	59.8	0.86	0.51	0.612	-2.47	4.18
Comparison	Day	Tangent	60.83	64.73	3.90	4.08	0.000	2.02	5.78
Comparison	Night	Tangent	55.63	60.3	4.66	3.64	0.000	2.14	7.19
Comparison	Day	Curve	56.9	59.2	2.34	1.92	0.056	-0.06	4.75
Comparison	Night	Curve	50.6	51.5	0.91	0.42	0.678	-3.41	5.24

Table 24 shows the before-after lateral vehicle position variance comparison for the treatment and comparison sites along State Route 118 and State Route 225, respectively. As shown, there is a statistically significant difference ($p\text{-value} < 0.05$) at the treatment sites during the nighttime condition but not during the daytime condition. At the State Route 118 tangent and curve locations during the nighttime condition, the lateral vehicle position variance increased from the before to after period. The lateral vehicle position variance was not statistically significant at the comparison site except on the tangent at night. For this condition, the lateral vehicle position variance increased from the before to after condition. As such, it is not reasonable to conclude that the application of wide edge lines changed lateral vehicle position variance on the tangent at night at the State Route 118 location. There is evidence to suggest that wide edge lines increase lateral vehicle position variance at night at the midpoint of a horizontal curve.

Table 24. Before-After Comparison of Lateral Vehicle Position Variance along State Route 118 Treatment and State Route 225 Comparison Sites.

Designation	Period	Location	Sample Size Before	Sample Size After	Before LVP Variance (in^2)	After LVP Variance (in^2)	F-statistic	p-value
Treatment	Day	Tangent	203	165	120.89	113.14	0.94	0.660
Treatment	Night	Tangent	102	100	93.76	189.35	2.02	0.001
Treatment	Day	Curve	203	164	91.28	88.17	0.97	0.821
Treatment	Night	Curve	102	98	108.53	173.37	1.60	0.020
Comparison	Day	Tangent	171	155	75.96	73.03	0.96	0.805
Comparison	Night	Tangent	103	96	57.58	103.79	1.80	0.004
Comparison	Day	Curve	171	155	124.87	117.75	0.94	0.712
Comparison	Night	Curve	103	96	202.87	272.21	1.34	0.145

5.3.4 State Route 225 Treatment Site and State Route 118 Comparison Site

Day and night speed and lateral vehicle position data were collected at the State Route 225 treatment site; however, only daytime data were collected at the State Route 118 comparison site because vandals damaged the data collection equipment prior to beginning the nighttime data collection effort. Therefore, the factors included in the mean speed analysis were an indicator for the tangent versus the curved section, an indicator for before versus after time periods, an indicator for treatment versus comparison site, and an indicator for the presence of a vehicle traveling in the opposing travel lane when the speed measurement was taken. The ANOVA results indicate that there is a statistically significant before/after main effect [F(1, 1907) = 16.11, p-value = 0.000]. This suggests that mean speeds are different when comparing the before to after observations. There was also a statistically significant treatment/comparison site main effect [F(1, 1907) = 22.12, p-value = 0.000] indicating that mean speeds are different at the treatment and comparison sites. There was not a statistically significant curve/tangent [F(1, 1907) = 2.77, p-value = 0.097] main effect or a statistically significant opposing lane main effect [F(1, 1907) = 0.29, p-value = 0.588].

Planned t-tests were performed to determine the magnitude of the difference between the treatment and comparison sites during the before-after periods on the tangent and curve sections at day and night. Table 25 shows the before-after comparison of mean speeds at the SR 225 treatment site and corresponding SR 118 comparison site. Included is the treatment versus comparison site designation, the time period (day versus night), and location (tangent versus curve location). Only the daytime curve location at the State Route 225 treatment site exhibited a statistically significant change in mean speed from the before to after period. The mean speed decreased by 2.76 mph. It is interesting to note that the mean speeds at the treatment site are higher at night than during the day at both the tangent and curve locations. The daytime tangent location at the comparison site also exhibited a statistically significant change in mean speed from the before to after period. The mean speed at this location decreased by 1.81 mph from the before to after period. As such, it is reasonable to conclude the wide edge lines do not change mean speeds at the State Route 225 treatment site.

Table 25. Before-After Comparison of Mean Speeds along State Route 225 Treatment and State Route 118 Comparison Sites.

Designation	Period	Location	Before Mean Speed (mph)	After Mean Speed (mph)	Mean Difference in Speeds (mph)	t-statistic	p-value	95 percent Confidence Interval	
								Lower Bound	Upper Bound
Treatment	Day	Tangent	54.61	53.45	-1.16	-1.73	0.085	-2.48	0.16
Treatment	Night	Tangent	56.77	56.18	-0.58	-0.73	0.465	-2.15	0.98
Treatment	Day	Curve	55.97	53.22	-2.76	-3.89	0.000	-4.15	-1.36
Treatment	Night	Curve	57.02	56.86	-0.16	-0.19	0.846	-1.75	1.44
Comparison	Day	Tangent	57.51	55.69	-1.81	-2.60	0.010	-3.19	-0.44
Comparison	Night	Tangent	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Comparison	Day	Curve	57.18	56.85	-0.33	-0.58	0.564	-1.44	0.79
Comparison	Night	Curve	N/A	N/A	N/A	N/A	N/A	N/A	N/A

Table 26 shows the before-after speed variance comparison for the treatment and comparison sites along the State Route 225 treatment and State Route 118 comparison sites. As shown, there is not a statistically significant difference (p-value > 0.05) at either the treatment or comparison sites during the daytime or nighttime periods, or at the tangent or curve locations. As such, it is not reasonable to conclude that wide edge lines change speed variance at the SR 225 treatment site.

Table 26. Before-After Comparison of Speed Variance along State Route 225 Treatment and State Route 118 Comparison Sites.

Designation	Period	Location	Sample Size Before	Sample Size After	Before Speed Variance (mph^2)	After Speed Variance (mph^2)	F-statistic	p-value
Treatment	Day	Tangent	179	175	40.27	39.48	0.98	0.896
Treatment	Night	Tangent	128	135	45.60	37.55	0.82	0.268
Treatment	Day	Curve	179	175	39.02	49.77	1.28	0.107
Treatment	Night	Curve	128	135	49.85	36.18	0.73	0.068
Comparison	Day	Tangent	180	156	36.77	44.063	1.20	0.242
Comparison	Night	Tangent	N/A	N/A	N/A	N/A	N/A	N/A
Comparison	Day	Curve	180	159	28.95	25.61	0.88	0.430
Comparison	Night	Curve	N/A	N/A	N/A	N/A	N/A	N/A

The factors included in the mean lateral vehicle position analysis were an indicator for the tangent versus curved section, an indicator for before versus after time periods, an indicator for treatment versus comparison site, and an indicator for the presence of a vehicle traveling in the opposing travel lane when the speed measurement was taken. The ANOVA results indicate that there is a statistically significant before/after main effect [$F(1, 1907) = 22.43$, p-value = 0.000]. This suggests that mean lateral vehicle position is different when comparing the before to after observations. There was also a statistically significant curve/tangent main effect [F(1, 1907) = 447.80, p-value = 0.000] as well as a statistically significant treatment/comparison site main effect [F(1, 1907) = 109.94, p-value = 0.000]. As such, mean lateral vehicle position is different when comparing the curve to the tangent observations and when comparing the treatment to comparison sites. There was a statistically significant opposing lane main effect [F(1, 1907 = 35.06, p-value = 0.000] indicating that there is a difference in mean lateral vehicle position measured when a vehicle was present in the opposing travel direction as compared to the lateral vehicle position measured when a vehicle was not present in the opposing travel direction. Less than 20 percent of the observed mean lateral vehicle position data were recorded with a vehicle traveling in the opposing travel lane. When a vehicle was present, the mean lateral vehicle position was 67.0 inches while it was 61.6 inches when a vehicle was not present in the opposing travel lane. The distribution of lateral vehicle position at the SR 225 treatment location is shown in Appendix C on the tangent and curve locations both before and after the wide edge line application.

Planned independent sample t-tests were then performed to determine the magnitude of the difference between the statistically significant main effects. Table 27 shows the before-after comparison of mean lateral vehicle position along the State Route 225 treatment site and the State Route 118 comparison site. Included is the treatment versus comparison site designation, the time period (day versus night), and location (tangent versus curve location). For the nighttime tangent and daytime curve locations at the treatment site, the difference in mean lateral vehicle position is statistically significant (p-value < 0.05). The mean lateral vehicle position increased by 2.50 inches at the tangent location at night while it increased by 3.45 inches during day at the curve location from the before to after period. The mean lateral vehicle position at night is closer to the roadway centerline than during the daytime. The difference in mean lateral vehicle position, between the before and after period, is statistically significant at the daytime curve section of the comparison site. The mean lateral vehicle position increased by 4.88 inches from the before to after period at this location. Nighttime lateral vehicle position data were not available at the State Route 118 comparison site because vandals damaged the equipment prior to the commencement of nighttime data collection. From this analysis, it is not reasonable to conclude that the application of wide edge lines on State Route 225 changed mean lateral vehicle position when compared to the comparison site.

Table 27. Before-After Comparison of Mean Lateral Vehicle Position along State Route 225 Treatment and State Route 118 Comparison Sites.

Designation	Period	Location	Before Mean LVP (in)	After Mean LVP (in)	Mean Difference in LVP (in)	t-statistic	p-value	95 percent Confidence Interval	
								Lower Bound	Upper Bound
Treatment	Day	Tangent	63.64	63.12	-0.52	-0.59	0.558	-2.26	1.22
Treatment	Night	Tangent	55.34	57.85	2.50	2.37	0.018	0.43	4.58
Treatment	Day	Curve	72.08	75.5	3.45	3.47	0.001	1.49	5.40
Treatment	Night	Curve	69.02	71.0	2.03	1.68	0.094	-0.34	4.40
Comparison	Day	Tangent	67.5	68.8	1.33	1.15	0.251	-0.95	3.61
Comparison	Night	Tangent	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Comparison	Day	Curve	71.49	76.4	4.88	4.39	0.000	2.69	7.06
Comparison	Night	Curve	N/A	N/A	N/A	N/A	N/A	N/A	N/A

Table 28 shows the before-after lateral vehicle position variance comparison for the treatment and comparison sites along State Route 225 and State Route 118, respectively. As shown, there is a statistically significant difference (p-value < 0.05) at the curved treatment site during the daytime and nighttime condition. At the State Route 225 curve locations, the lateral vehicle position variance increased from the before to after period during both the daytime and nighttime conditions. The lateral vehicle position variance was not statistically significant at the comparison site. As such, it is reasonable to conclude that the application of wide edge lines changed lateral vehicle position variance at the State Route 225 curve location, but not at the tangent location.

Table 28. Before-After Comparison of Lateral Vehicle Position Variance along State Route 225 Treatment and State Route 118 Comparison Sites.

Designation	Period	Location	Sample Size Before	Sample Size After	Before LVP Variance (in^2)	After LVP Variance (in^2)	F-statistic	p-value
Treatment	Day	Tangent	179	175	62.43	76.26	1.22	0.185
Treatment	Night	Tangent	128	135	69.99	76.45	1.09	0.616
Treatment	Day	Curve	179	175	68.66	105.56	1.54	0.004
Treatment	Night	Curve	128	135	79.92	111.79	1.40	0.051
Comparison	Day	Tangent	180	156	121.60	103.46	0.85	0.301
Comparison	Night	Tangent	N/A	N/A	N/A	N/A	N/A	N/A
Comparison	Day	Curve	180	159	90.88	116.06	1.28	0.112
Comparison	Night	Curve	N/A	N/A	N/A	N/A	N/A	N/A

5.3.5 Summary

From the speed and lateral vehicle position analysis, it is not reasonable to conclude that wide edge lines consistently influence the performance measures at all treatment locations. At the State Route 14 treatment site, the mean speed increased after the application of wide edge lines at the tangent and curve locations during the day and night. The wide edge line application increased speed variance at the State Route 14 treatment site during the day only. At the State Route 87 treatment site, the mean lateral vehicle position moved away from the centerline at the curve location during the day and night condition. At the State Route 225 treatment location, the lateral vehicle position variance increased at the curve location during both the day and nighttime condition. Because there was not a consistent change in mean speed or lateral vehicle position, or in speed or lateral vehicle position variance, it is not reasonable to conclude that wide edge lines significantly influence driver behavior in the present experiment. Speed and lateral vehicle position differential are evaluated in subsequent sections to further investigate the effect of wide edge lines.

5.4 Speed and Lateral Vehicle Position Differential

Because piezoelectric sensors were installed on the approach tangent and at the midpoint of the horizontal curve, it was possible to "track" a vehicle through a data collection site. As such, each driver's speed and lateral vehicle position differential could be computed per the following equations:

$$\Delta V = V_T - V_{MC} \tag{12}$$

$$\Delta LVP = LVP_T - LVP_{MC} \tag{13}$$

where: ΔV = change in vehicle speed from tangent to midpoint of horizontal curve
V_T = speed at tangent location
V_{MC} = speed at midpoint of horizontal curve
ΔLVP = change in vehicle speed from tangent to midpoint of horizontal curve
LVP_T = speed at tangent location
LVP_{MC} = speed at midpoint of horizontal curve.

Like the speed and lateral vehicle position analysis presented above, the differential speed and lateral vehicle position analyses considered the before/after, treatment/comparison, day/night, and opposing lane effects using the independent samples t-test when comparing the mean values. Only the mean speed and lateral vehicle position were considered in the analysis. The main objective of the analysis was to determine if the change in speed or lateral vehicle position between the tangent and curve midpoint locations changed significantly from the before to after time periods at the treatment or comparison sites. It was hypothesized that a small speed change between the tangent location and midpoint of a horizontal curve, particularly at night, translates into more consistent driver behavior. Likewise, a small change in lateral vehicle position from the tangent section to the midpoint of a horizontal curve may suggest improved driver performance. Driver performance in both cases would possibly indicate that wider edge lines improve curve delineation. The results of the two-sample t-tests for mean speed differential for each treatment and corresponding comparison site are shown in Table 29. As shown, there were several statistically significant changes in mean speed differential from the before to the after period. These changes occurred at the SR 14 comparison site during the day, at the SR 87 treatment site during the day, at the SR 87 comparison site during the day, at the SR 225 treatment site during the day, and at the SR 118 (site #8 in ID column) comparison site during the day. At the two treatment locations where the speed differential changed, the difference between the before and after period mean change was less than 2 mph. The direction of the change was negative, indicating that the speed differential was greater in the after period than it was in the before period. This suggests that drivers increased their speed after treatment of the curves with wide edge lines at two treatment sites during the daytime period. Because of the mixed results in the present experiment, it is not reasonable to conclude that wide edge lines promote improved speed consistency when applied to horizontal curves on two-lane rural highways.

Table 29. Mean Speed Differential Analysis Results.

ID	Site	Designation	Time	Before Mean Speed Diff. (mph)	After Mean Speed Diff. (mph)	Mean Difference in Speed Diff. (mph)	t-statistic	p-value	95 percent Confidence Interval	
									Lower bound	Upper bound
1	Route 14	Treatment	Day	3.30	3.26	0.039	0.16	0.877	-0.459	0.537
1	Route 14	Treatment	Night	2.33	2.90	-0.562	-1.45	0.149	-1.328	0.203
2	Route 14	Comparison	Day	0.84	-0.39	1.221	5.12	0.000	0.752	1.690
2	Route 14	Comparison	Night	0.05	-0.13	0.181	0.47	0.639	-0.579	0.942
3	Route 87	Treatment	Day	1.07	1.99	-0.916	-2.32	0.021	-1.693	-0.138
3	Route 87	Treatment	Night	1.80	1.34	0.461	1.09	0.280	-0.379	1.300
4	Route 87	Comparison	Day	1.28	0.01	1.273	2.84	0.005	0.391	2.155
4	Route 87	Comparison	Night	0.65	-0.39	1.037	1.87	0.063	-0.059	2.133
5	Route 118	Treatment	Day	0.64	0.58	0.058	0.15	0.883	-0.714	0.829
5	Route 118	Treatment	Night	0.30	0.98	-0.676	-1.04	0.398	-1.953	0.602
6	Route 225	Comparison	Day	2.31	1.87	0.439	1.39	0.167	-0.184	1.061
6	Route 225	Comparison	Night	2.00	1.60	0.403	1.35	0.179	-0.186	0.991
7	Route 225	Treatment	Day	-1.36	0.24	-1.596	-3.85	0.000	-2.411	-0.781
7	Route 225	Treatment	Night	-0.25	-0.68	0.425	1.36	0.174	-0.190	1.040
8	Route 118	Comparison	Day	-1.29	0.30	1.594	4.44	0.000	0.887	2.300
8	Route 118	Comparison	Night	N/A	N/A	N/A	N/A	N/A	N/A	N/A

Like the speed differential analysis described previously, a mean lateral vehicle position differential analysis was performed. The results are shown in Table 30. The results of the analysis indicate that there was a change in mean lateral vehicle position differential at the following locations:

- SR 14 treatment site during the day;
- SR 14 comparison site during the day;

- SR 87 comparison site during the day;
- SR 225 treatment site during the day.

In both treatment site cases, the speed differential increased from the before to the after period. This suggests that drivers move away from the centerline a greater distance after application of wide edge lines to horizontal curves. The mean difference in the lateral position differentials at the SR 14 and SR 225 treatment sites was less than 5 inches, suggesting that the lateral shift experienced by drivers between the tangent and midpoint of a horizontal curve is relatively small. Both the SR 14 and SR 225 treatment sites are right-hand curves and therefore the lateral shift is toward the wide edge line, meaning that drivers are "flattening" the curve after application of wide edge lines during the daytime period. The nighttime results at the treatment sites did not reveal any mean speed differential change from the before to after period. Because of the mixed results in the present experiment, it is not reasonable to conclude that wide edge lines promote improved lateral vehicle position consistency when applied to horizontal curves on two-lane rural highways when comparing the before and after periods.

Table 30. Mean Lateral Vehicle Position Differential Analysis Results.

ID	Site	Designation	Time	Before Mean LVP Diff. (in)	After Mean LVP Diff. (in)	Mean Difference in LVP Diff. (in)	t-statistic	p-value	95 percent Confidence Interval	
									Lower bound	Upper bound
1	Route 14	Treatment	Day	-5.6	-9.0	3.397	2.67	0.008	0.893	5.901
1	Route 14	Treatment	Night	-9.6	-12.1	2.494	1.36	0.175	-1.119	6.108
2	Route 14	Comparison	Day	-9.5	-12.2	2.735	2.16	0.032	0.243	5.228
2	Route 14	Comparison	Night	-13.1	-10.5	-2.530	-1.27	0.205	-6.455	1.395
3	Route 87	Treatment	Day	-4.7	-3.4	-1.278	-0.85	0.398	-4.245	1.690
3	Route 87	Treatment	Night	0.4	-4.4	4.747	1.95	0.053	-0.072	9.567
4	Route 87	Comparison	Day	2.8	6.3	-3.533	-2.47	0.014	-6.345	-0.722
4	Route 87	Comparison	Night	4.0	6.2	-2.135	-0.95	0.344	-6.582	2.313
5	Route 118	Treatment	Day	9.1	10.5	-1.448	-1.05	0.295	-4.165	1.269
5	Route 118	Treatment	Night	9.3	9.2	0.114	0.06	0.956	-3.907	4.135
6	Route 225	Comparison	Day	3.9	5.5	-1.556	-1.11	0.270	-4.324	1.213
6	Route 225	Comparison	Night	5.0	8.8	-3.752	-1.65	0.101	-8.244	0.739
7	Route 225	Treatment	Day	-8.4	-12.4	3.966	3.31	0.001	1.605	6.326
7	Route 225	Treatment	Night	-13.7	-13.2	-0.476	-0.32	0.746	-3.363	2.411
8	Route 118	Comparison	Day	-5.1	-7.6	2.442	1.78	0.076	-0.256	5.141
8	Route 118	Comparison	Night	N/A	N/A	N/A	N/A	N/A	N/A	N/A

5.4 Encroachments

A human observer counted the number of encroachments at each treatment and comparison site before and after application of wide edge lines for a 2-hour daytime period ($\geq$ 100 vehicles). An encroachment was defined as an instant when a vehicle came in contact with or crossed the roadway edge line or centerline within a horizontal curve. In addition to collecting encroachment frequency, the human observer counted the number of vehicles passing through the test location. As such, a proportion could be developed and tested according to Equation 11. Table 31 shows the total number of before and after period encroachments, the total traffic volume, and statistical test results for each treatment and comparison site. The negative z-statistic in Table 31 indicates that the encroachment proportion increased in the after period when compared to the before period; however, the results were not statistically significant when comparing the two periods (p-value > 0.05).

Table 31. Total Encroachment Proportion Analysis.

ID	Route	Treatment vs. Comparison	Before Period		After Period		z-statistic	p-value
			Encroachments	Volume	Encroachments	Volume		
1	14	Treatment	64	201	53	157	-0.38	0.702
2	14	Comparison	60	216	58	165	-1.53	0.125
3	87	Treatment	24	104	34	133	-0.44	0.657
4	87	Comparison	29	107	30	107	-0.15	0.878
5	118	Treatment	57	160	41	134	0.92	0.360
6	225	Comparison	36	106	25	104	1.59	0.111
7	225	Treatment	42	142	47	126	-1.34	0.180
8	118	Comparison	42	151	39	136	-0.16	0.871

An edge line encroachment analysis was performed using only passenger car data at the same treatment and comparison sites. The results of the analysis are shown in Table 32. The test of proportions shows that the encroachment proportions did not change statistically from the before to after period at any treatment or comparison site. A negative z-statistic indicates that the after period encroachment proportion is higher than the before period encroachment proportion.

Table 32. Edge Line Encroachment Proportion Analysis.

ID	Route	Treatment vs. Comparison	Before Period		After Period		z-statistic	p-value
			Encroachments	Volume	Encroachments	Volume		
1	14	Treatment	41	175	33	132	-0.32	0.751
2	14	Comparison	37	192	28	123	-0.74	0.460
3	87	Treatment	6	93	9	115	-0.38	0.700
4	87	Comparison	4	88	5	98	-0.18	0.859
5	118	Treatment	10	130	5	99	0.82	0.411
6	225	Comparison	20	91	13	89	1.29	0.198
7	225	Treatment	24	127	31	109	-1.72	0.085
8	118	Comparison	21	121	21	124	0.09	0.931

5.5 Speed Reduction Analysis Using Speed Profiles

Speed profile plots were constructed for each treatment and comparison site during both daytime and nighttime travel conditions. The average (or mean) and 85th-percentile observed operating speeds are shown during the before and after periods. The Nu-metrics Hi-Star sensors were used to plot speeds 600 ft prior to the curve PC, and at evenly spaced increments between the first piezoelectric sensor trap (300 ft prior to the curve PC) and the midpoint of the horizontal curve. Another piezoelectric sensor trap was used to plot the speeds at the horizontal curve midpoint location. Trend lines were used to connect the data points on the speed profiles that are shown in Appendix C. The average/85th-percentile observed speeds were used to subjectively assess where braking or a speed reduction began with respect to the PC of each horizontal curve. These results are shown in Table 33. At the treatment sites, the subjective speed reduction location was generally further from the curve PC location after application of a wide edge line. The only notable exception was at the SR 225 treatment site for the nighttime condition. At the comparison sites, there is not a clear pattern that emerges when comparing the before to after speed reduction location data. The speed reduction location information at night for the treatment sites is further from the curve PC than at the comparison site locations. This suggests that wide edge lines at night may improve horizontal curve delineation and may influence drivers to slow down sooner when compared to standard, 4-inch wide edge lines.

Table 33. Subjective Location of Speed Reduction from Speed Profile Plots.

Subjective Assessment of Braking Location by Curve Comparison						
Route	**Segment**	**Curve Direction**	**Treatment**	**Day/Night**	**Period**	**Speed Reduction Location**
14	210	R	Treatment	Day	Before	-275
					After	>-600
				Night	Before	-250
					After	>-600
14	190	R	Comparison	Day	Before	-210
					After	-200
				Night	Before	-140
					After	-275
87	140	L	Treatment	Day	Before	-275
					After	>-600
				Night	Before	-300
					After	>-600
87	150	L	Comparison	Day	Before	-125
					After	-275
				Night	Before	-275
					After	-250
118	230	L	Treatment	Day	Before	-50
					After	-225
				Night	Before	-50
					After	-200
225	280	L	Comparison	Day	Before	-190
					After	-
				Night	Before	-210
					After	-
225	120	R	Treatment	Day	Before	-200
					After	-250
				Night	Before	-275
					After	-250
118	210	R	Comparison	Day	Before	-250
					After	-175
				Night	Before	-275
					After	-

6. CONCLUSIONS

The present experiment evaluated the effects of wide edge lines on speed and lateral vehicle position on horizontal curves along two-lane rural highways in Pennsylvania. The performance measures used to assess wide edge line effectiveness were mean speed, mean lateral vehicle position, speed variance, lateral vehicle position variance, mean speed differential, mean lateral vehicle position differential, encroachment rate, and the location of deceleration approaching a horizontal curve. Data were collected using a variety of on-road sensors along the approach tangent and within a horizontal curve at four treatment and four corresponding comparison sites. The treatment and comparison sites were evenly split between left- and right-hand curves. Data collection took place during both daytime and nighttime conditions. A summary of the mean speed, speed variance, mean lateral vehicle position, and lateral vehicle position variance findings are shown in Table 34.

The results of the analysis indicate that observed mean speeds increased at one location (SR 14) after application of wide edge lines to a horizontal curve. This increase was less than 1.5 mph during the daytime period at both the tangent and curve data collection locations. The mean speed increase was 2.5 to 3.0 mph at night at both the tangent and curve data collection locations. At all other treatment sites, it is not reasonable to conclude, based on the present experiment, that mean speed changed after application of wide edge lines on horizontal curves. Similar results were obtained for the speed variance analysis. The speed variance increased at the SR 14 treatment site after application of wide edge lines during the day on both the tangent and curved roadway sections. The speed variance decreased on the tangent during the day, but increased on the tangent at night on the SR 87 treatment site. Because the mean speed and speed variance at other treatment sites did not change based on the present experiment, it is not reasonable to conclude that wide edge lines on horizontal curves generally influence these performance measures.

The results of the lateral vehicle position analysis were also mixed. At the SR 14 treatment site, the mean lateral vehicle position did change from the before to the after period. This change was approximately a 2.5-inch shift to the right on the tangent section during the day and a nearly 6-inch shift to the right on the tangent at night. An approximate 4-inch shift to the right occurred on the curve at night. Similar findings occurred at the SR 87 treatment site. An approximately 4-inch shift to the right occurred on the tangent section during the day while a 3-inch and 7.5-inch shift to the right occurred on the curve during the day and night, respectively. It is noteworthy that, although the shift in lateral vehicle position was toward the edge line at both locations, the SR 14 site was a right-hand curve and the SR 87 site was a left-hand curve. The lateral vehicle position variance did not differ significantly from the before to the after period at either of the SR 14 and SR 87 treatment sites when compared to the corresponding comparison sites. The lateral vehicle position, however, did change at the SR 118 and SR 225 treatment sites when compared to their corresponding comparison sites. At both treatment locations, the lateral vehicle position variance increased at night on the tangent and curve sections. Based on the present experiment, there is preliminary evidence that wide edge lines do influence vehicle lateral position. However, the results are not conclusive because two of the four treatment sites exhibited mean lateral vehicle position changes while the other two treatment sites showed an increase in lateral vehicle position variance.

Table 34. Summary of Speed and Lateral Vehicle Position Analyses.

Route	Segment	Designation	Location	Time	Mean Speed	Speed Variance	Mean LVP	LVP Variance
SR 14	210	Treatment	Tangent	Day	X	X	X	
				Night	X			
			Curve	Day	X	X	X	
				Night	X		X	
	190	Comparison	Tangent	Day				
				Night				
			Curve	Day			X	
				Night				
SR 87	140	Treatment	Tangent	Day		X	X	
				Night		X		
			Curve	Day			X	
				Night			X	
	150	Comparison	Tangent	Day				
				Night				
			Curve	Day				
				Night				
SR 118	230	Treatment	Tangent	Day		X		
				Night				
			Curve	Day				
				Night				
SR 225	280	Comparison	Tangent	Day			X	
				Night			X	
			Curve	Day				
				Night				
SR 225	120	Treatment	Tangent	Day				
				Night			X	
			Curve	Day	X		X	X
				Night				
SR 118	210	Comparison	Tangent	Day	X			
				Night				
			Curve	Day			X	
				Night				
X indicates statistically significant change from before to after period								

A speed differential analysis was performed to investigate if large-magnitude speed or lateral position changes were taking place between the tangent and curve midpoint data collection locations at the treatment and corresponding comparison sites. This analysis revealed that there were some changes in mean speed differential at the treatment sites during the day; however, this change was offset by similar changes at the corresponding treatment site.

The encroachment proportion analysis did not reveal any statistically significant changes when considering all encroachments and only edge line encroachments separately. As such, it is reasonable to conclude based on the present experiment that wide edge lines applied to horizontal curves on two-lane rural highways in Pennsylvania do not change centerline or edge line encroachment rates.

Lastly, a subjective evaluation of the location where vehicle deceleration began, with respect to the beginning of a horizontal curve was performed at the wide edge line treatment and corresponding comparison locations. The results of the subjective analysis indicate that there is evidence to suggest that drivers begin to slow down further in advance of the curve at night with wide edge lines when compared to the condition without.

In summary, the present experiment revealed that wide edge lines on horizontal curves did not dramatically alter driver behavior during day or nighttime driving conditions on two-lane rural highways in Pennsylvania. This finding is in agreement with Cottrell (*32*), who studied wide edge line use on two-lane rural highways in Virginia. Future research should consider the safety effects of wide edge lines on horizontal curves using crash-based data.

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49. Miles, J.D., P.J. Carlson, M.P. Pratt, and T.D. Thompson. *Traffic Operational Impacts of Transverse, Centerline, and Edge line Rumble Strips*. Report No. FHWA/TX-05/0-4472-2. Texas Transportation Institute, College Station, TX, March 2005.

50. De la Riva, M. "Development of Deployment Procedures for Highway Safety Flares." Unpublished M.S. Thesis. The Pennsylvania State University, University Park, PA, 2004.

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52. Manual of Transportation Engineering Studies (ed. H. D. Robertson). Institute of Transportation Engineers. Prentice Hall, Englewood Cliffs, NJ, 1994.

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APPENDIX A

Agency Survey Results for the Use of Wider Pavement Markings (*38*)

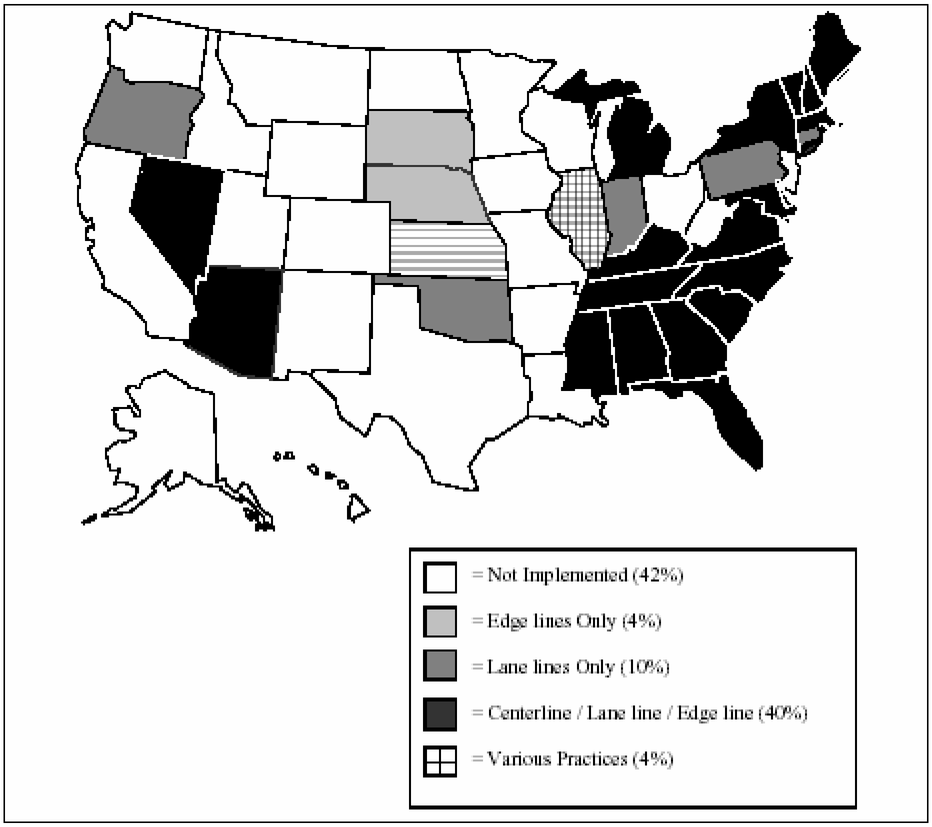

Figure A-1 – Line types for which wider markings are used in state DOTs.

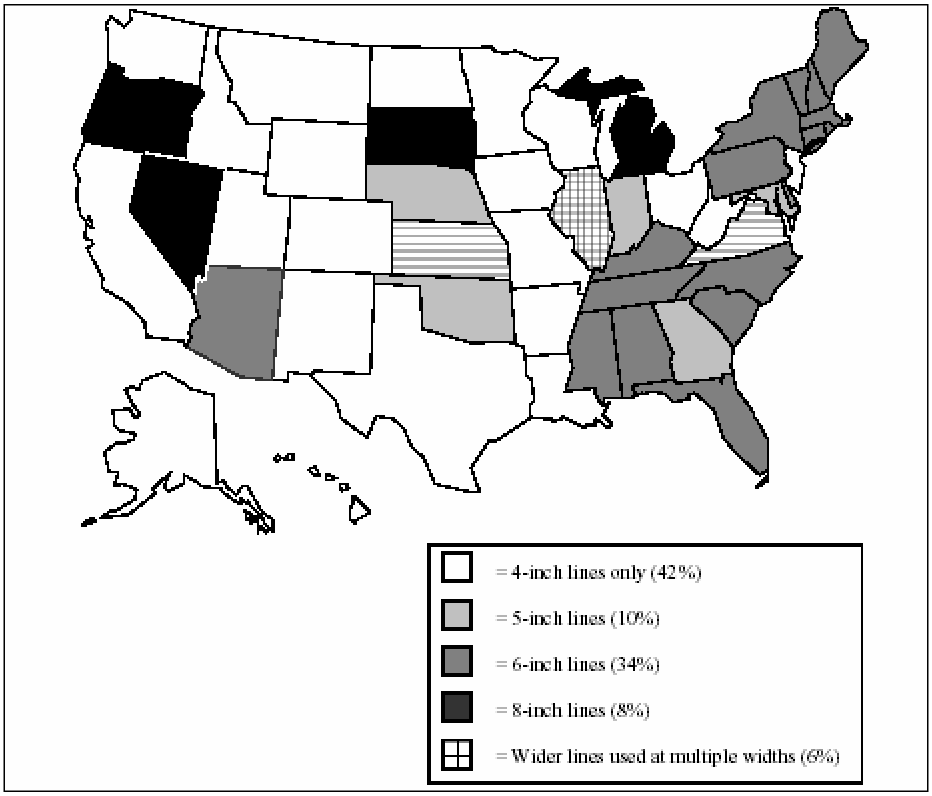

Figure A-2 - Line width usage by state DOT.

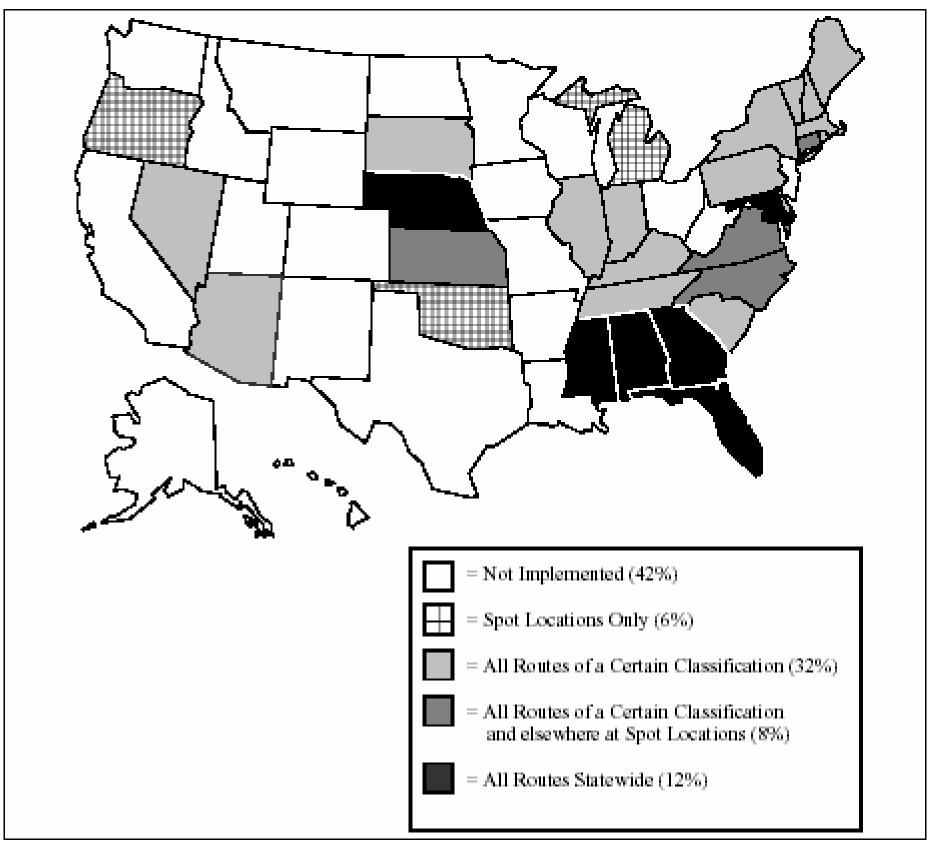

Figure A-3 - Roadways where wider markings are used within state DOTs.

Table A-1 – Reasons for Using Wider Markings (U.S./Canadian Agencies)

Reasons for Using Wider Markings (Percent of Respondents)	
Visibility Improvement	57%
Older Driver Countermeasure	19%
Crash Reduction	14%
Driver Comfort/Aesthetics	8%
Provide Consistency with Nearby Agencies	5%
Driver Fatigue Countermeasure	3%
Service Life Improvement	3%
No Response/Unknown	16%

Note: Many agencies gave multiple responses.

Table A-2 – Basis for Implementation (U.S./Canadian Agencies)

Basis for Implementation (Percent of Respondents)	
Results from Pilot Study	32%
Experience/Satisfaction of Other Agencies or to Provide Consistency	30%
Engineering Judgment	27%
Driver Surveys/Comments	8%
Literature Review	8%
Crash Reductions	3%
Service Life Improvements	3%
No Response/Unknown	24%

Note: Many agencies gave multiple responses.

Table A-3 – Observed Benefits of Wider Markings (U.S./Canadian Agencies)

Observed Benefits (Percent of Respondents)		Observance of Crash Reductions (Percent of Respondents)	
None Measured/Unknown/No Response	57%	Analysis Has Not Been Performed	65%
Favorable Public Response	30%	No Significant Findings	22%
Improved Visibility (mostly subjective)	30%	Significant Crash Reduction	3%
Improved Driver Comfort/Aesthetics	5%	No Response	10%
Crash Reduction	3%		
Improved Service Life	3%		

Note: Many agencies gave multiple responses.

APPENDIX B

PHOTOGRAPHS OF DATA COLLECTION STUDY LOCATIONS AND WIDE EDGE LINE TREATMENT

State Route 14 Treatment and Comparison Sites

(Treatment Site)

(Comparison Site)

State Route 87 Treatment and Comparison Sites

(Treatment Site)

(Comparison Site)

State Route 118 Treatment and State Route 225 Comparison Sites

(Treatment Site)

(Comparison Site)

State Route 225 Treatment and State Route 118 Comparison Sites

(Treatment Site)

(Comparison Site)

Before-After Comparison of Wide Edge Lines

(Before Site)

(After Site)

APPENDIX C

FREQUENCY DISTRIBUTION PLOTS OF LATERAL VEHICLE POSITION AT TREATMENT SITES

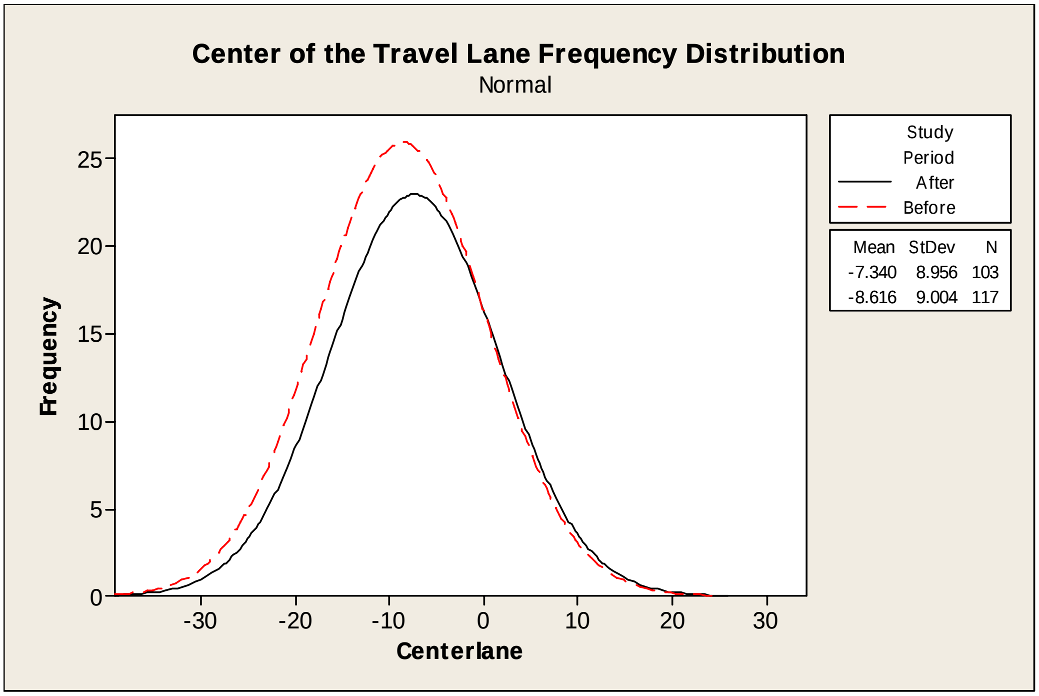

Figure C-1. Frequency Distribution of Lateral Vehicle Position at SR 14 Tangent Location.

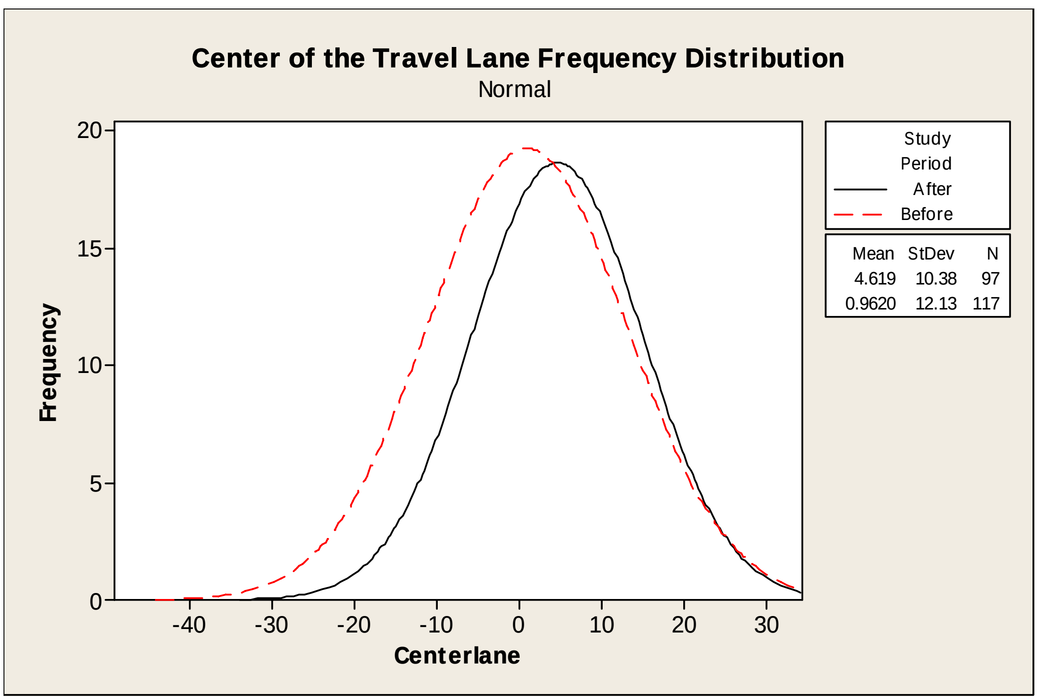

Figure C-2. Frequency Distribution of Lateral Vehicle Position at SR 14 (Right) Curve Location.

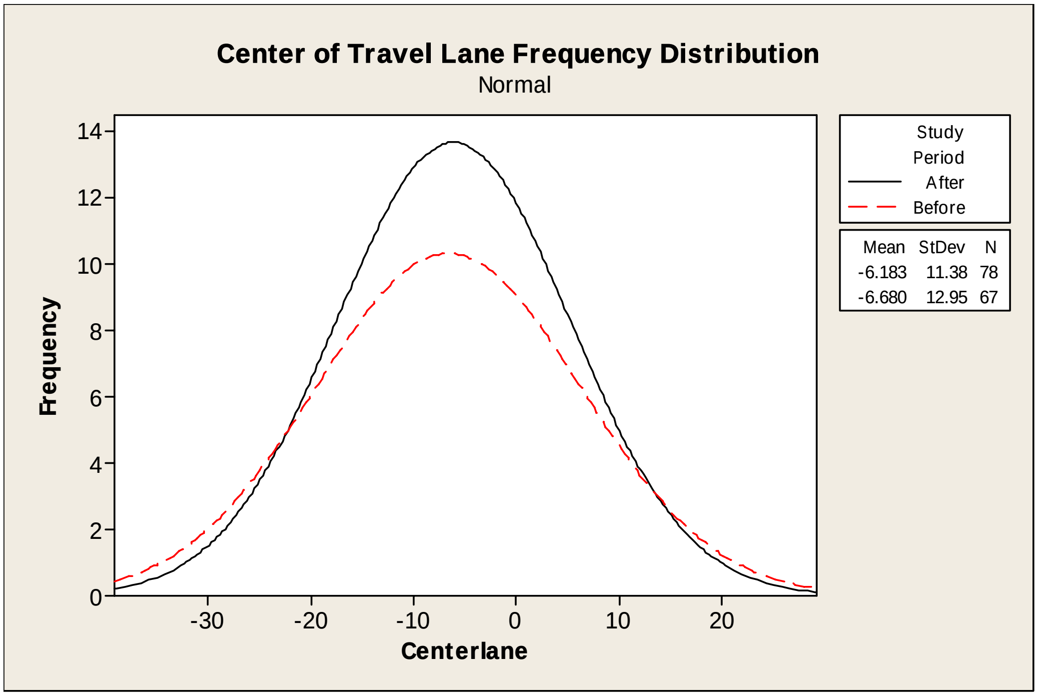

Figure C-3. Frequency Distribution of Lateral Vehicle Position at SR 87 Tangent Location.

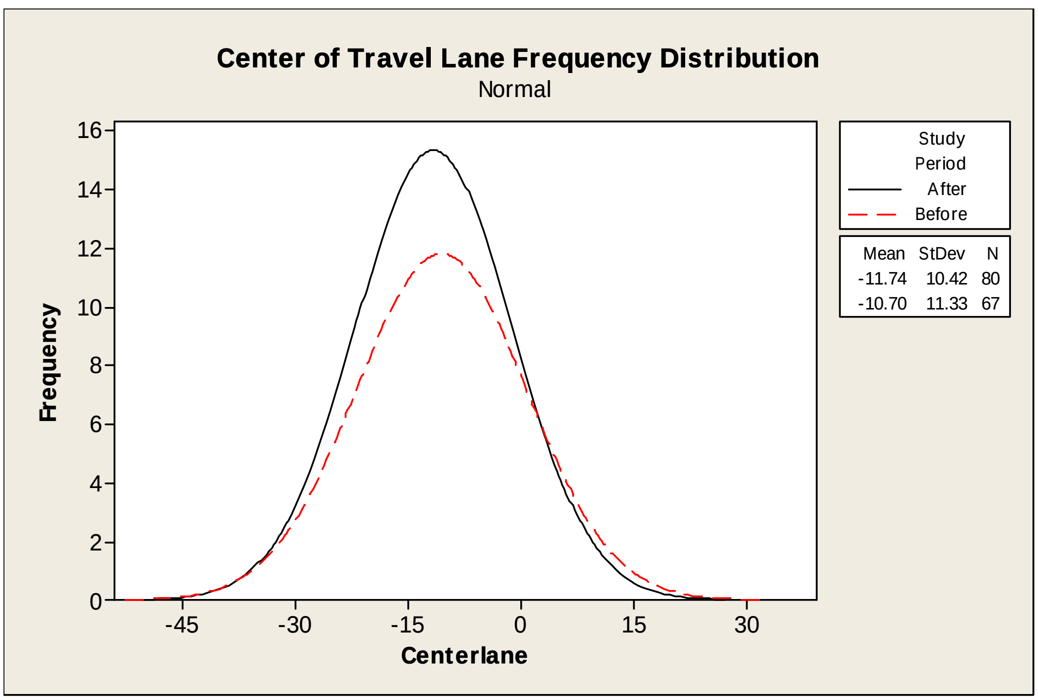

Figure C-4. Frequency Distribution of Lateral Vehicle Position at SR 87 (Left) Curve Location.

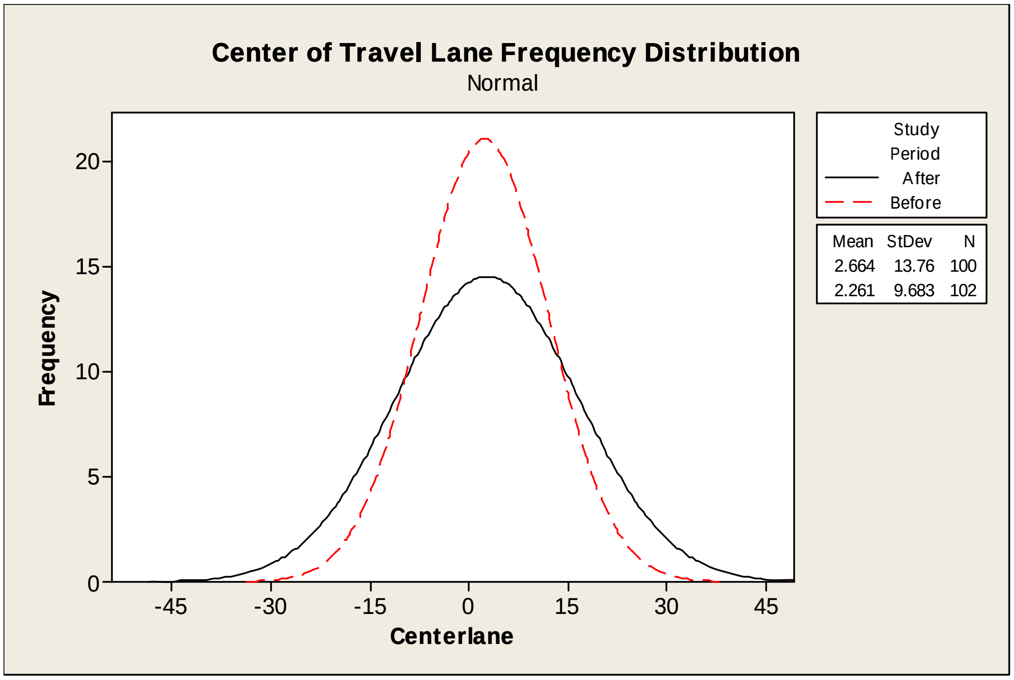

Figure C-5. Frequency Distribution of Lateral Vehicle Position at SR 118 Tangent Location.

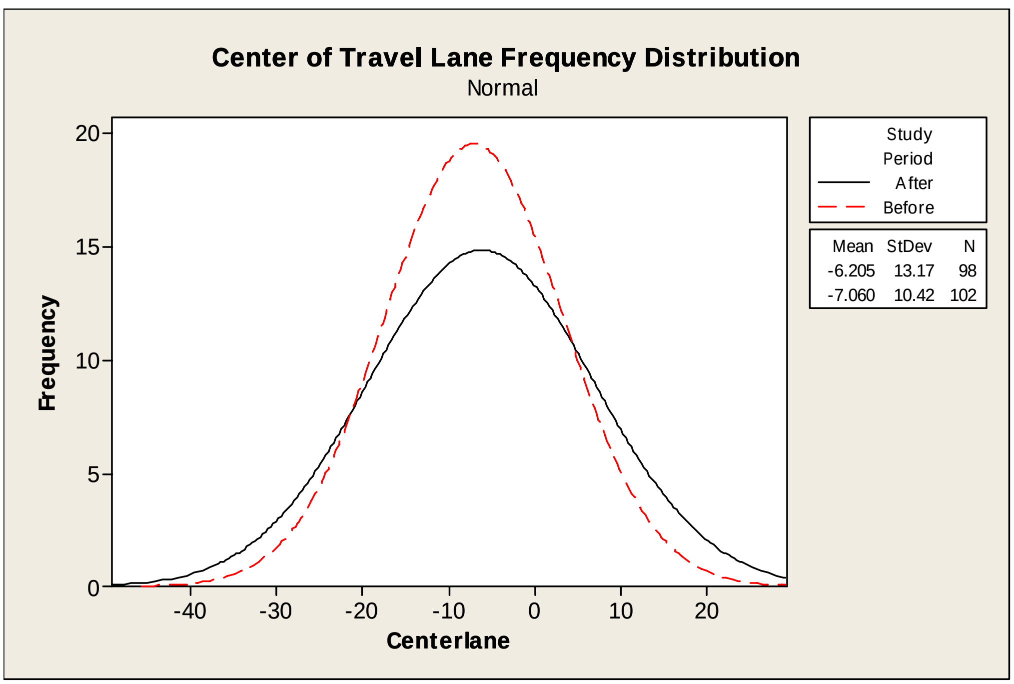

Figure C-6. Frequency Distribution of Lateral Vehicle Position at SR 118 (Left) Curve Location.

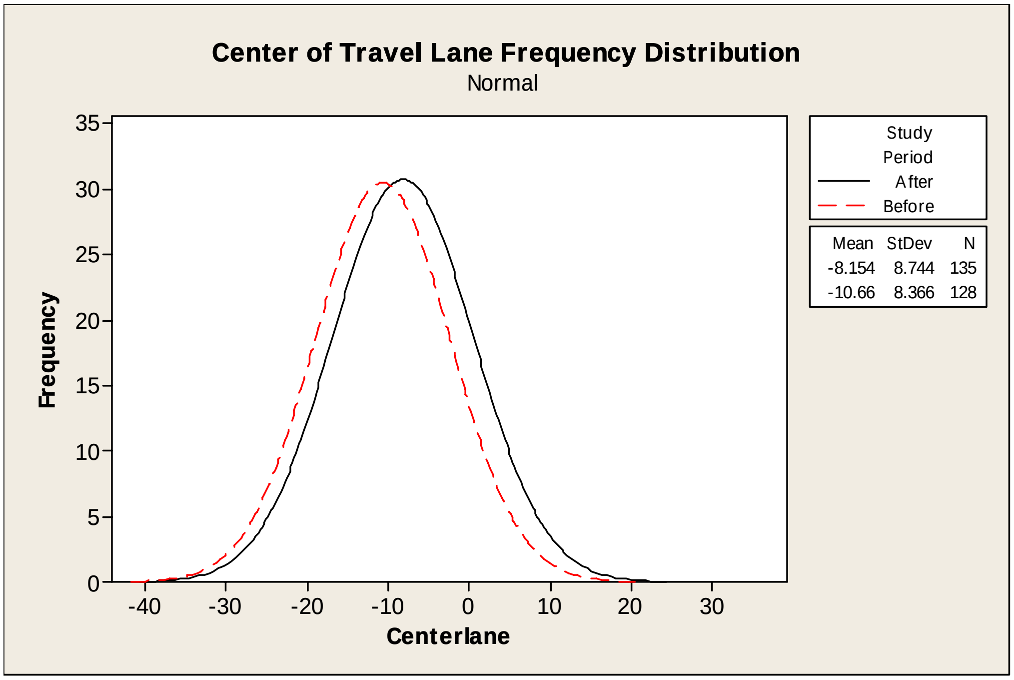

Figure C-7. Frequency Distribution of Lateral Vehicle Position at SR 225 Tangent Location.

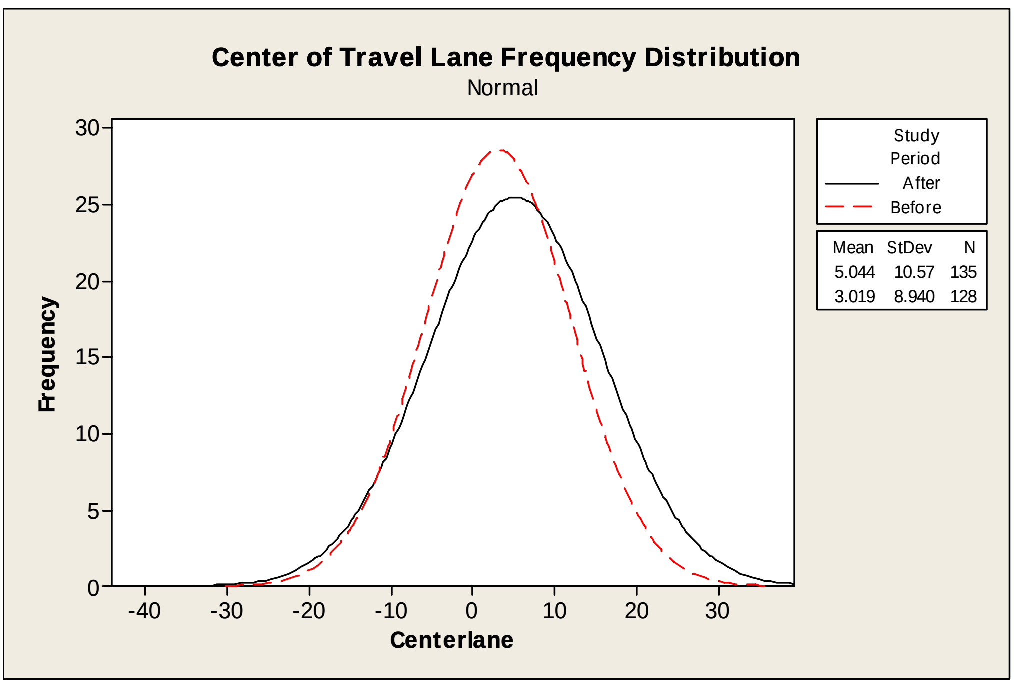

Figure C-8. Frequency Distribution of Lateral Vehicle Position at SR 225 (Right) Curve Location.

APPENDIX D

SPEED PROFILE PLOTS FROM EACH TREATMENT AND COMPARISON SITE

Speed Profiles for SR 0014, Segment 190 (Right Curve – Comparison Section)

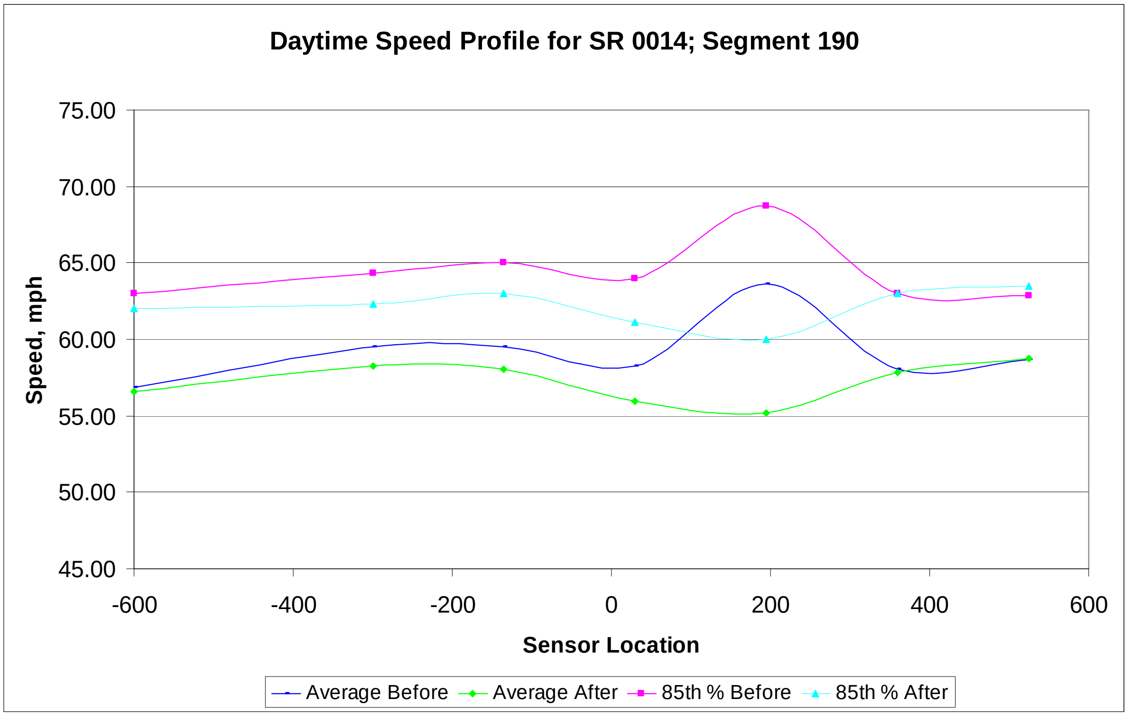

Figure D-1. Daytime Speed Profile for SR 14, Segment 190 (Comparison Site).

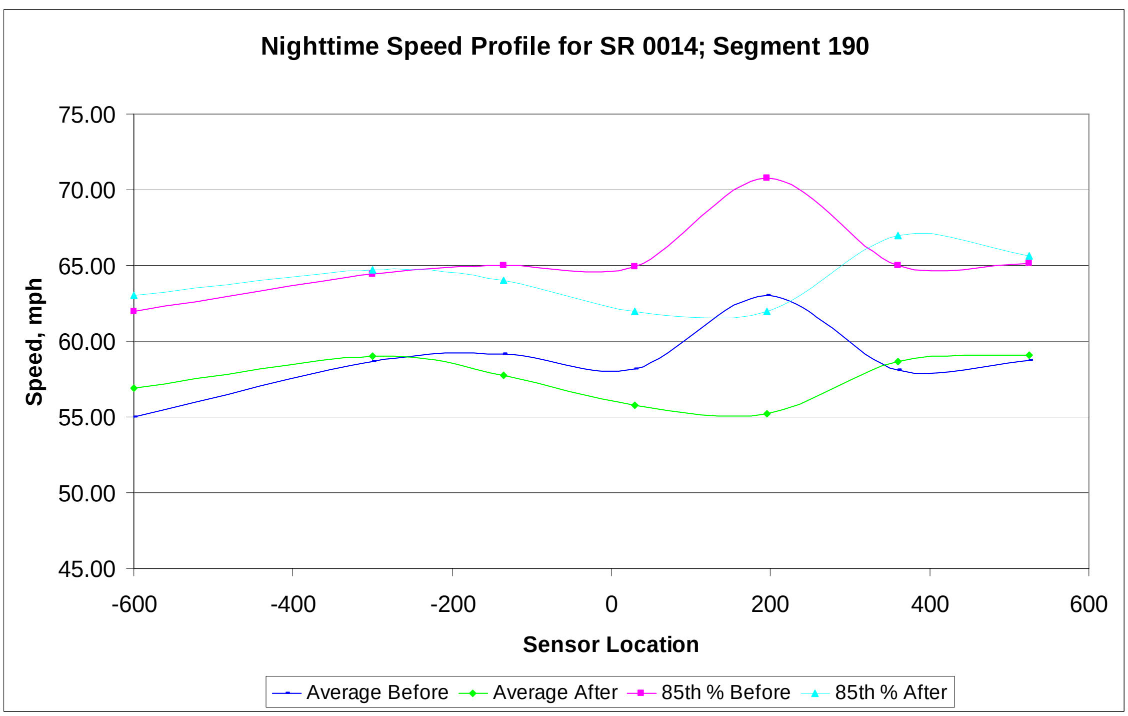

Figure D-2. Nighttime Speed Profile for SR 14, Segment 190 (Comparison Site).

Speed Profiles for SR 0014, Segment 210 (Right Curve – Treatment Section)

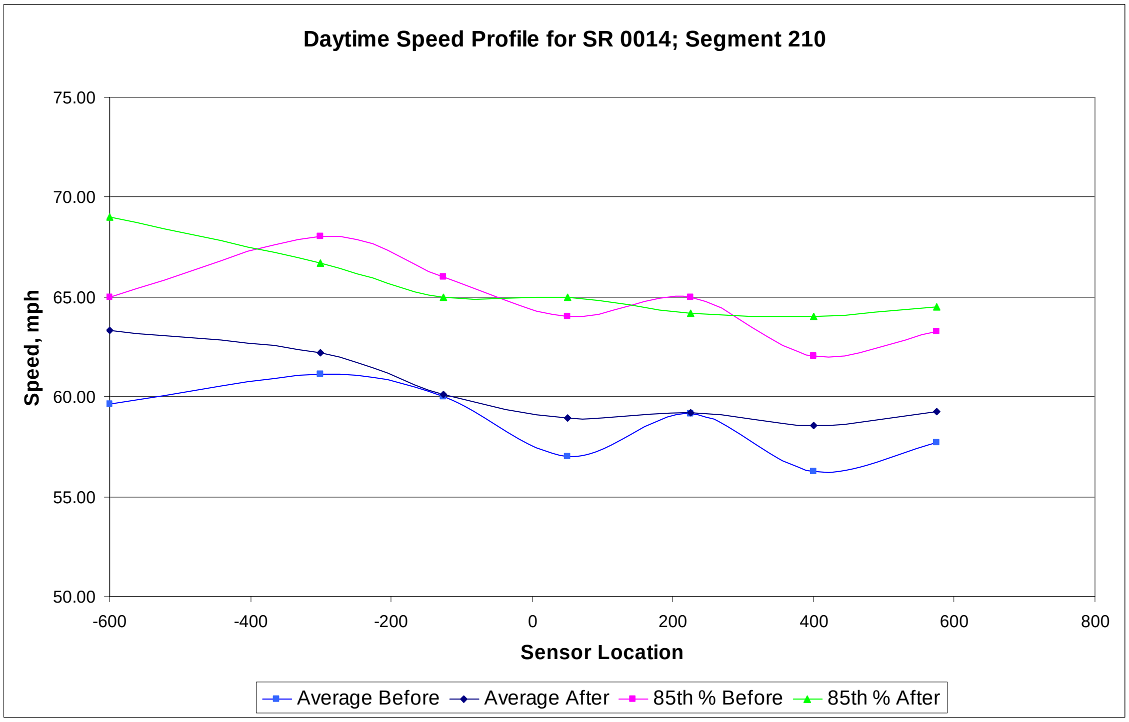

Figure D-3. Daytime Speed Profile for SR 14, Segment 210 (Treatment Site).

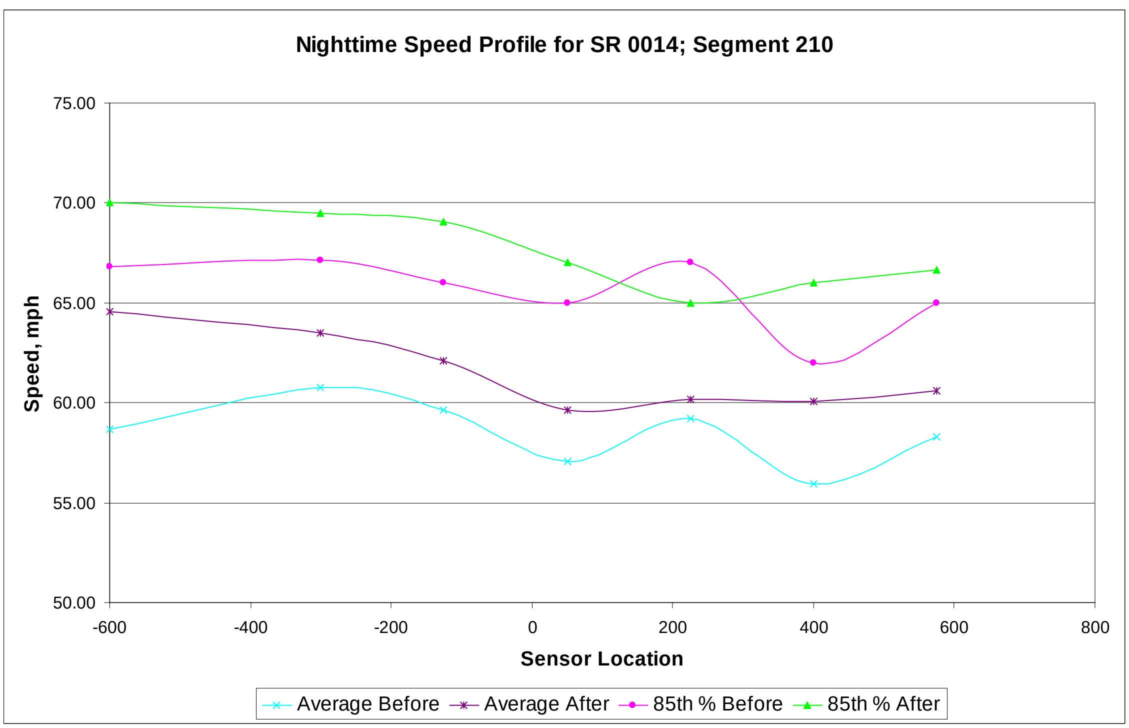

Figure D-4. Nighttime Speed Profile for SR 14, Segment 210 (Treatment Site).

Speed Profile Comparison, SR 0014 Right Curve

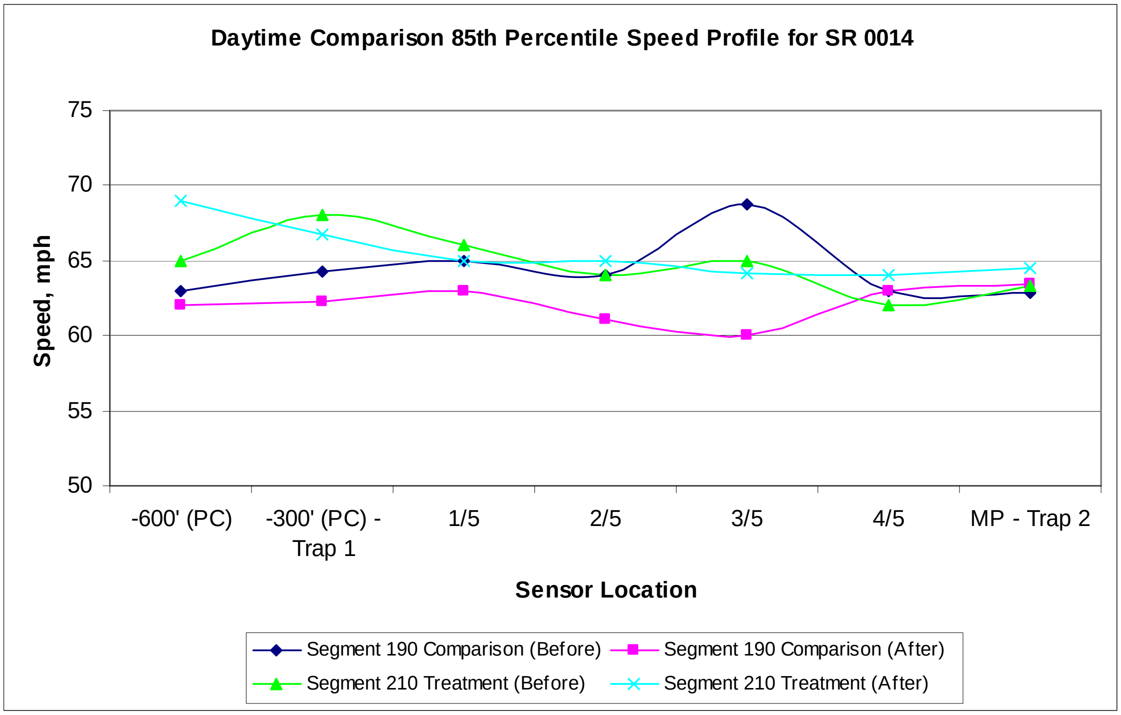

Figure D-5. Daytime Comparison 85th Percentile Speed Profile for SR 14.

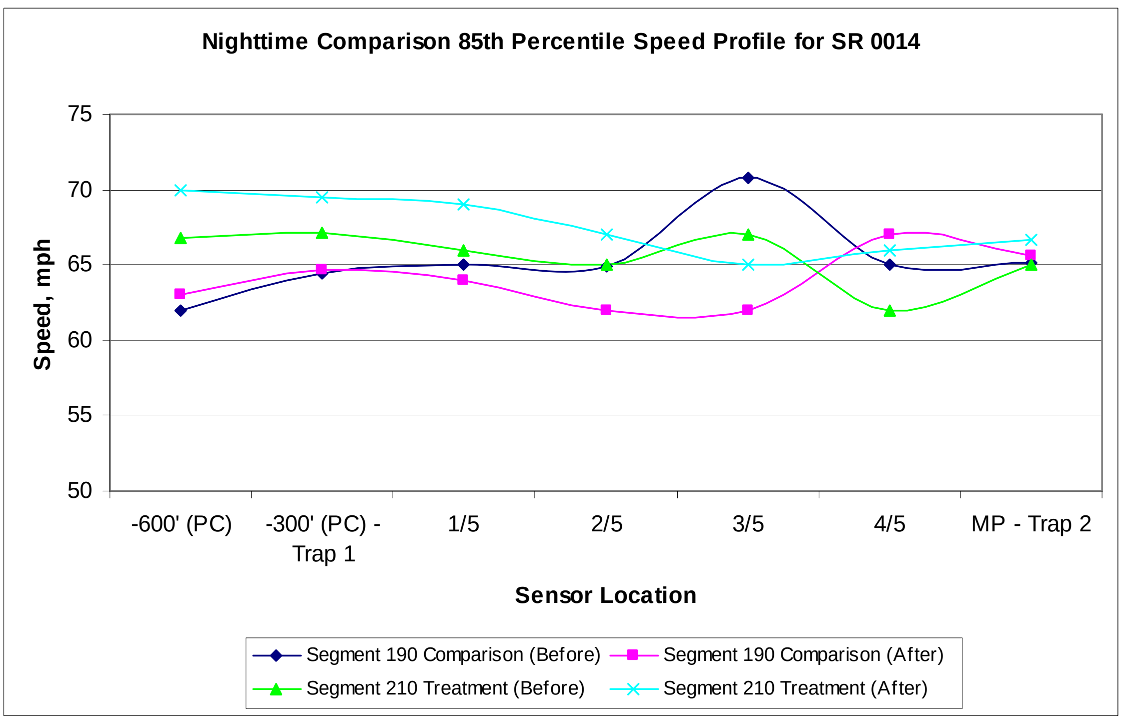

Figure D-6. Nighttime Comparison 85th Percentile Speed Profile for SR 14.

Speed Profiles for SR 0087, Segment 140 (Left Curve – Treatment Section)

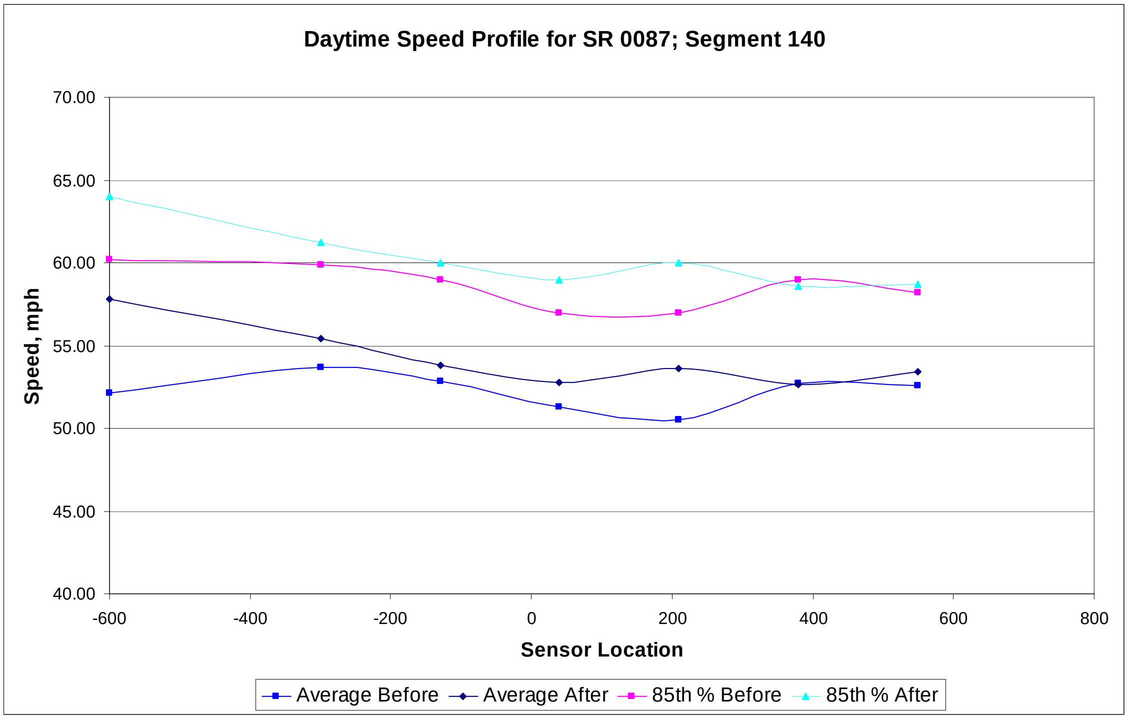

Figure D-7. Daytime Speed Profile for SR 87, Segment 140 (Treatment Site).

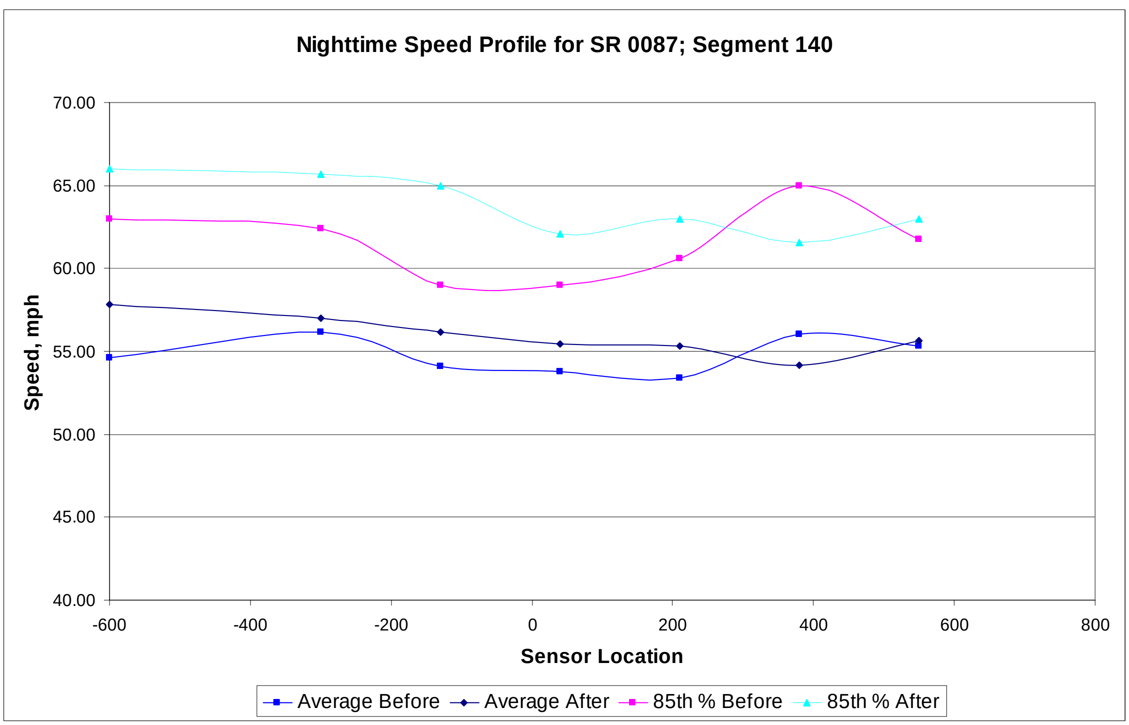

Figure D-8. Nighttime Speed Profile for SR 87, Segment 140 (Treatment Site).

Speed Profiles for SR 0087, Segment 150 (Left Curve – Comparison Section)

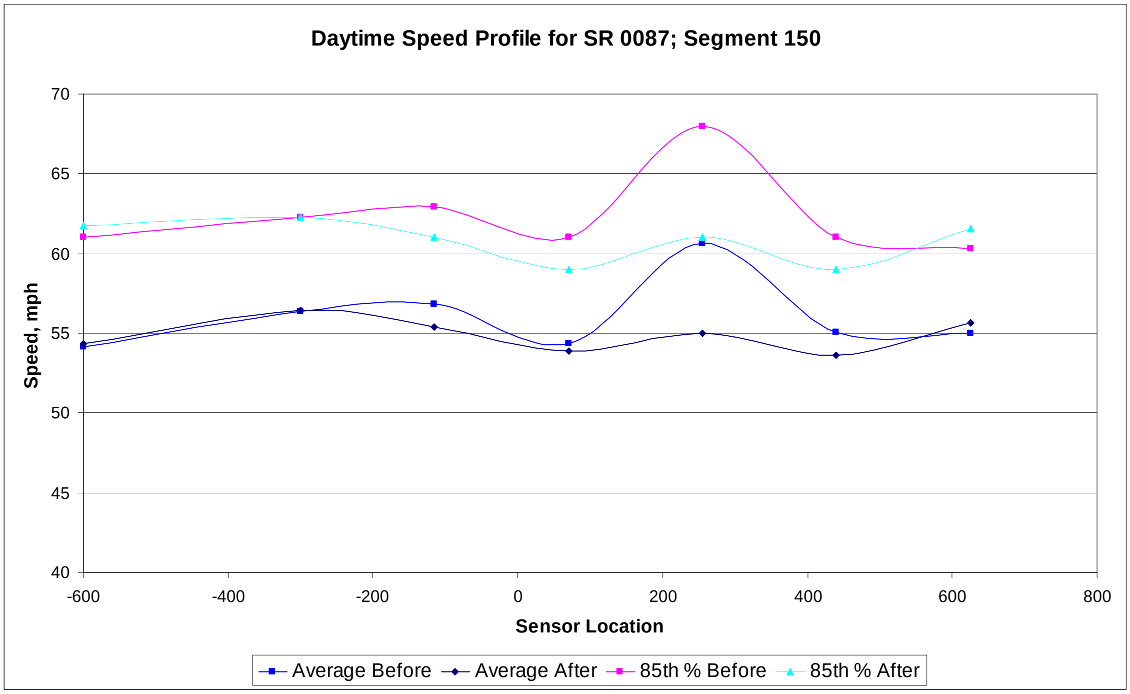

Figure D-9. Daytime Speed Profile for SR 87, Segment 150 (Comparison Site).

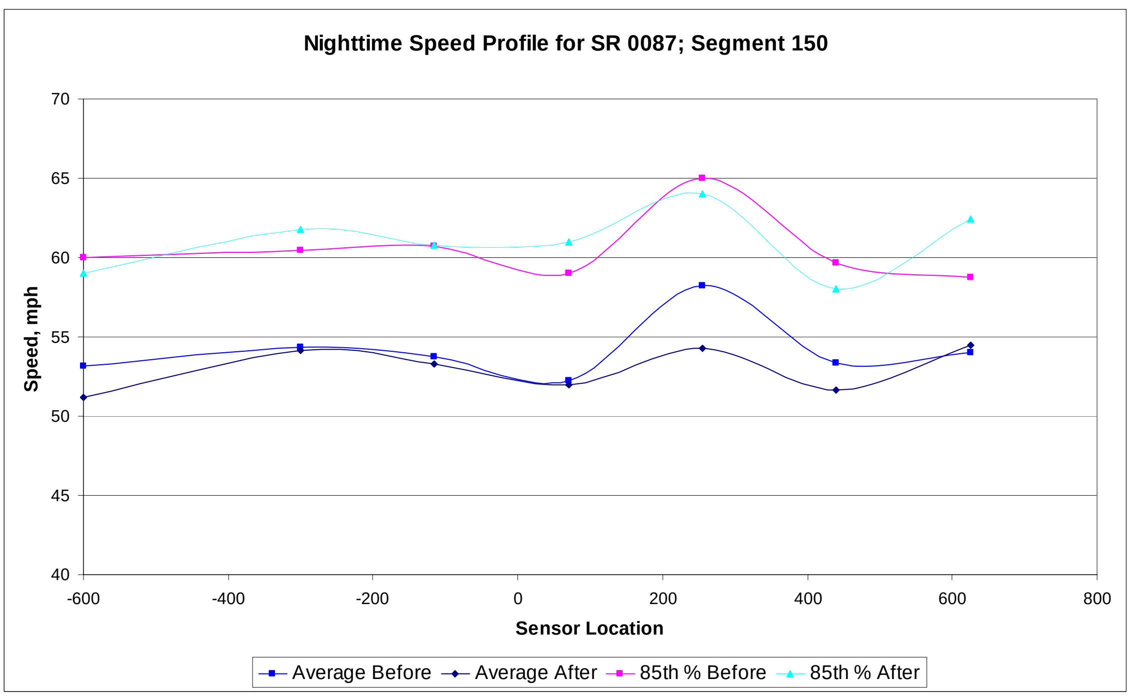

Figure D-10. Nighttime Speed Profile for SR 87, Segment 150 (Comparison Site).

Speed Profile Comparison, SR 0087 Left Curve

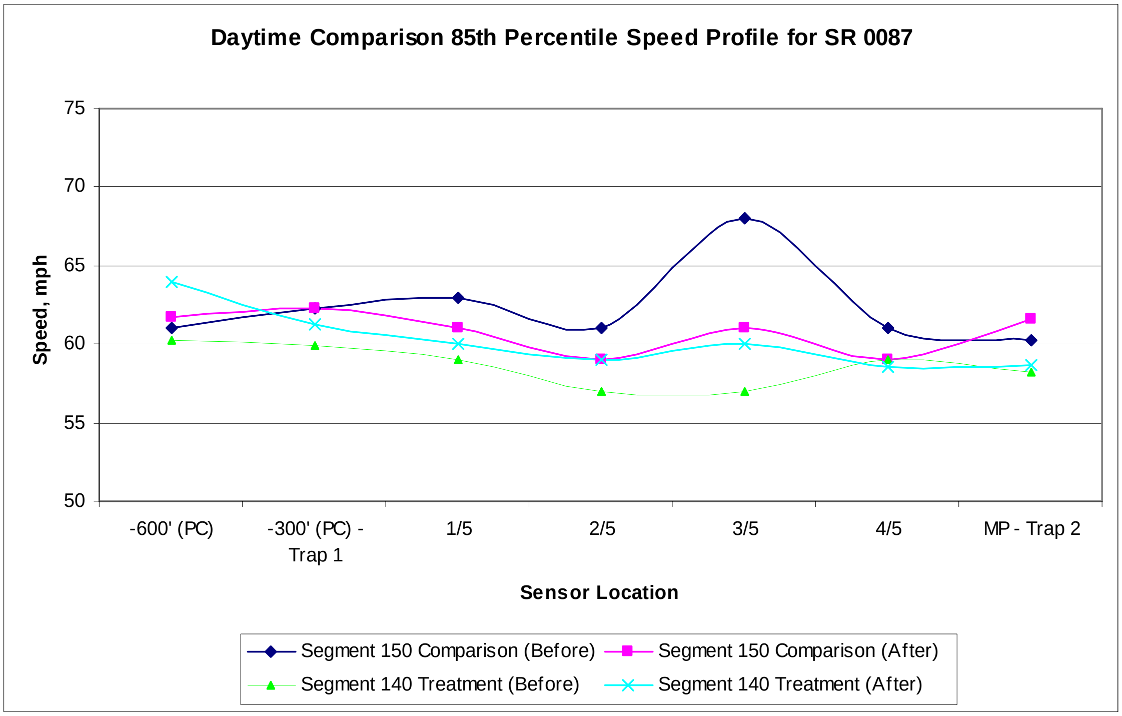

Figure D-11. Daytime Comparison 85th Percentile Speed Profile for SR 87.

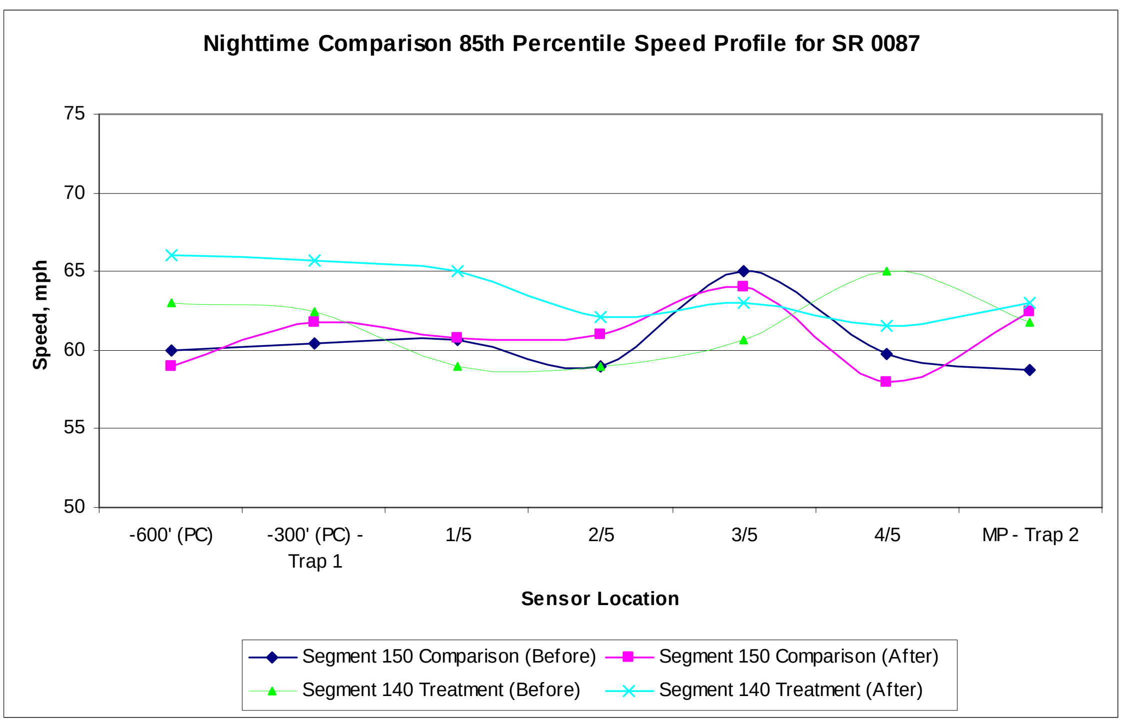

Figure D-12. Nighttime Comparison 85th Percentile Speed Profile for SR 87.

Speed Profiles for SR 0118, Segment 210 (Right Curve – Comparison Section)

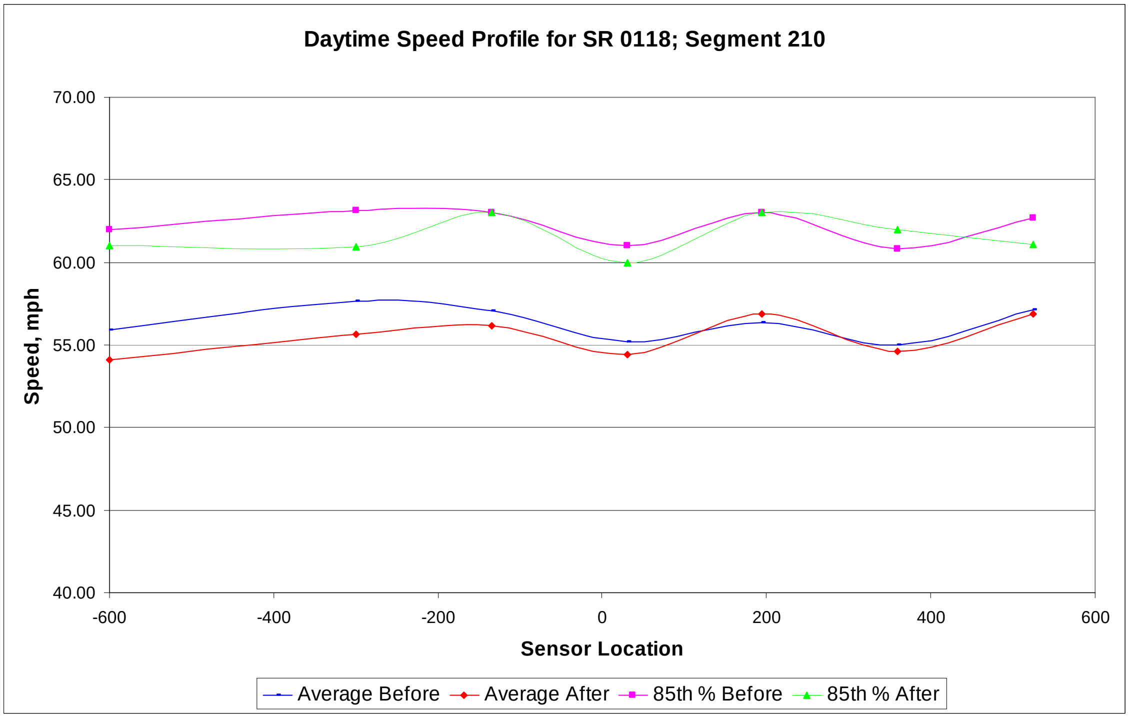

Figure D-13. Daytime Speed Profile for SR 118, Segment 210 (Comparison Site).

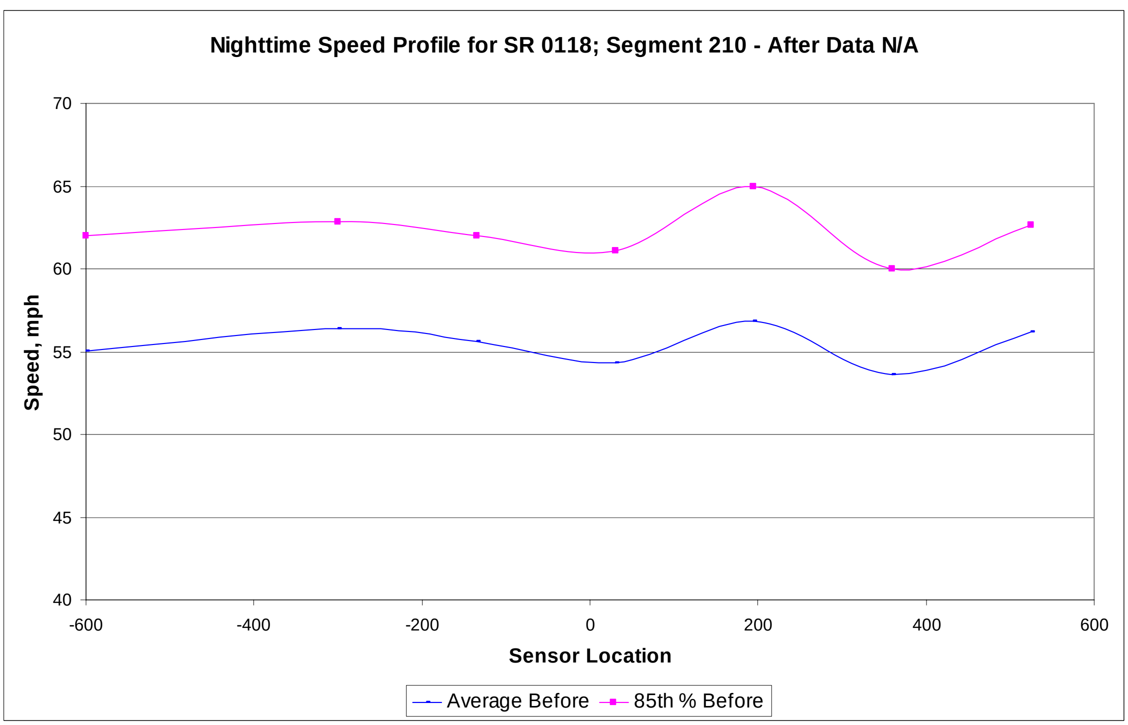

Figure D-14. Nighttime Speed Profile for SR 118, Segment 210 (Comparison Site).

Speed Profiles for SR 0118, Segment 230 (Left Curve – Treatment Section)

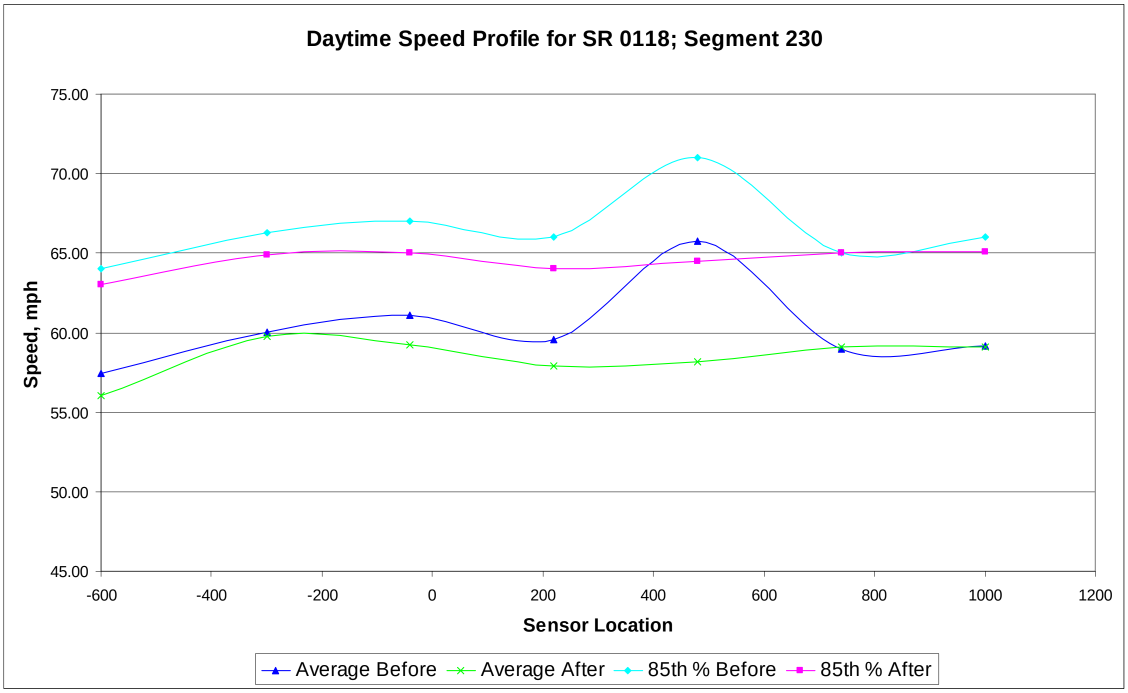

Figure D-15. Daytime Speed Profile for SR 118, Segment 230 (Treatment Site).

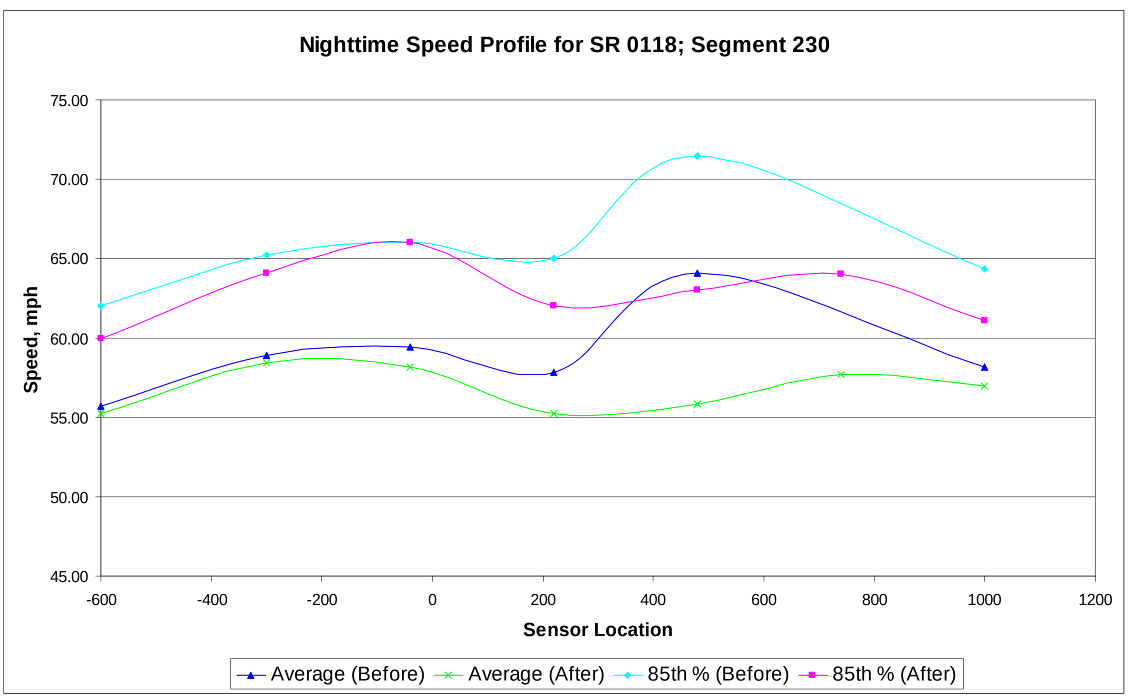

Figure D-16. Nighttime Speed Profile for SR 118, Segment 230 (Treatment Site).

Speed Profiles for SR 0225, Segment 120 (Right Curve – Treatment Section)

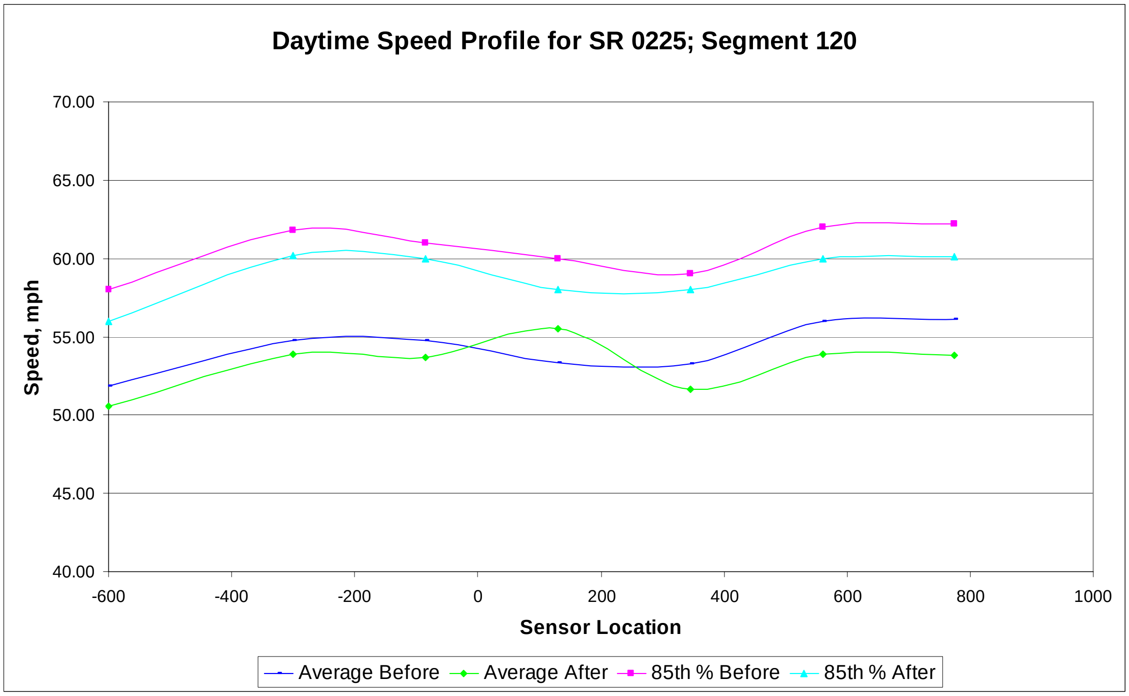

Figure D-17. Daytime Speed Profile for SR 225, Segment 120 (Treatment Site).

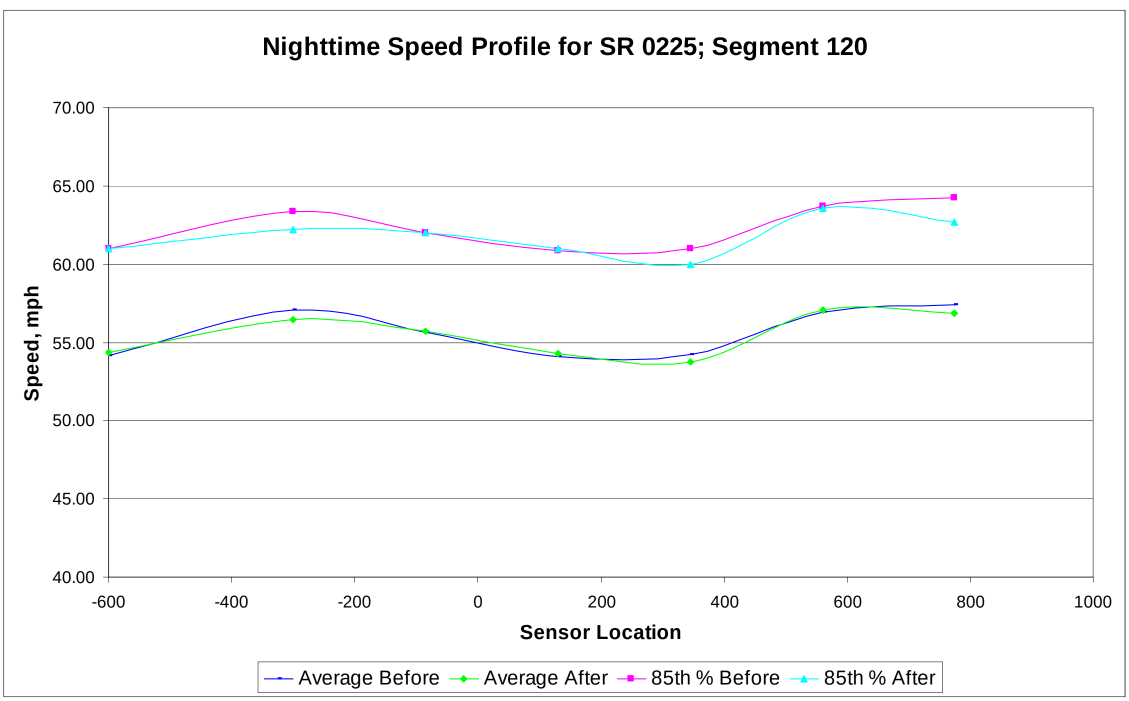

Figure D-18. Nighttime Speed Profile for SR 225, Segment 120 (Treatment Site).

Speed Profiles for SR 0225, Segment 280 (Left Curve – Comparison Section)

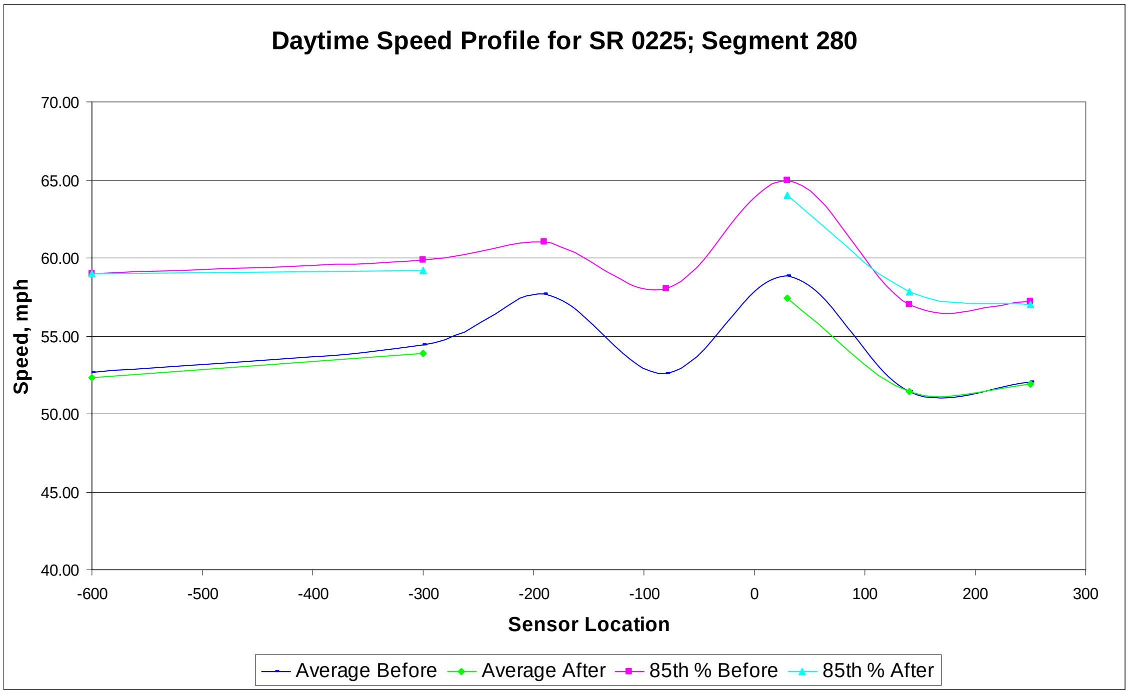

Figure D-19. Daytime Speed Profile for SR 225, Segment 280 (Comparison Site).

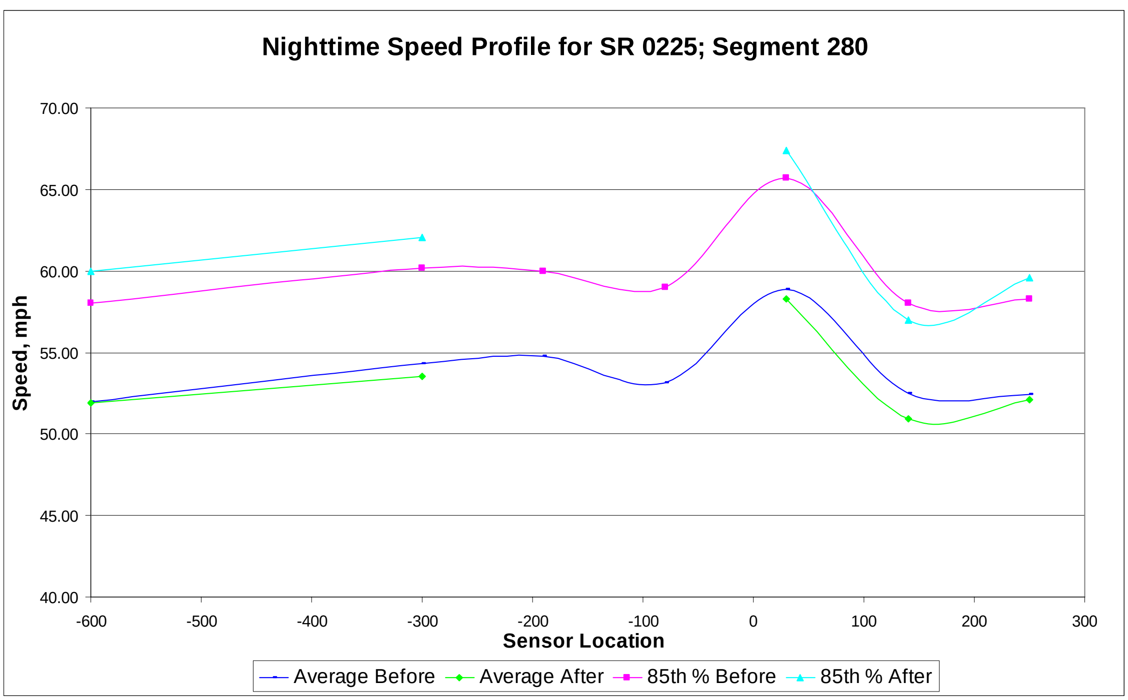

Figure D-20. Nighttime Speed Profile for SR 225, Segment 280 (Comparison Site).

Speed Profile Comparison, SR 0118/0225 Right Curve

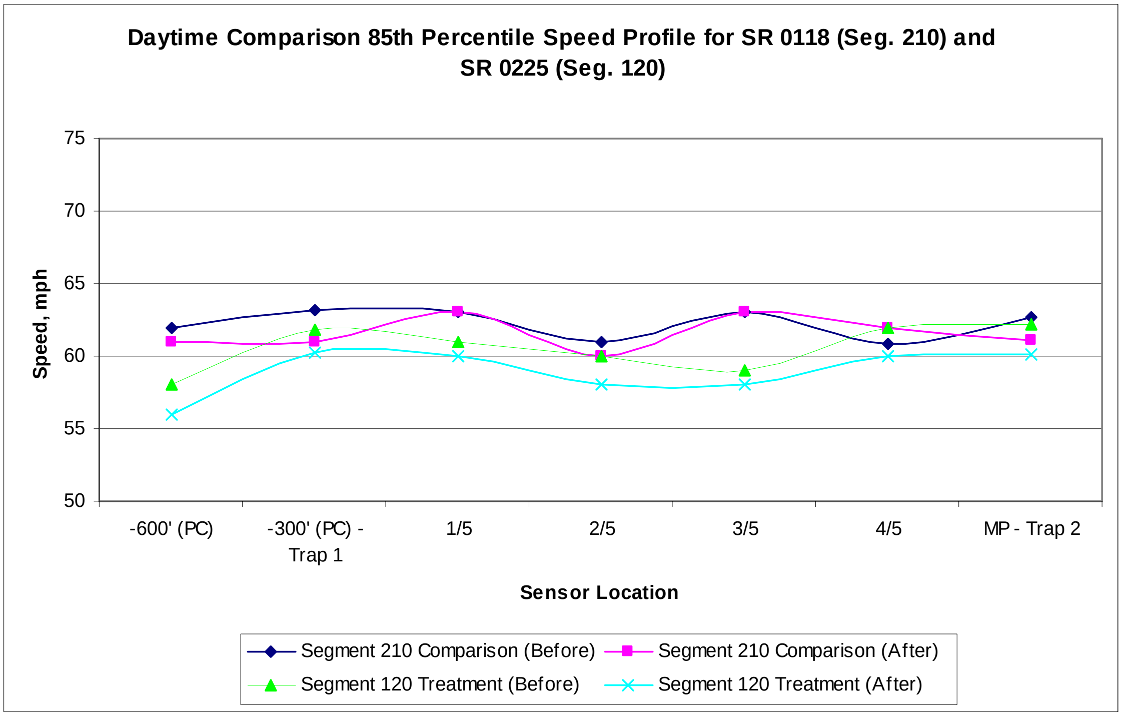

Figure D-21. Daytime Comparison 85th Percentile Speed Profile for SR 118, Segment 210 and SR 225, Segment 120.

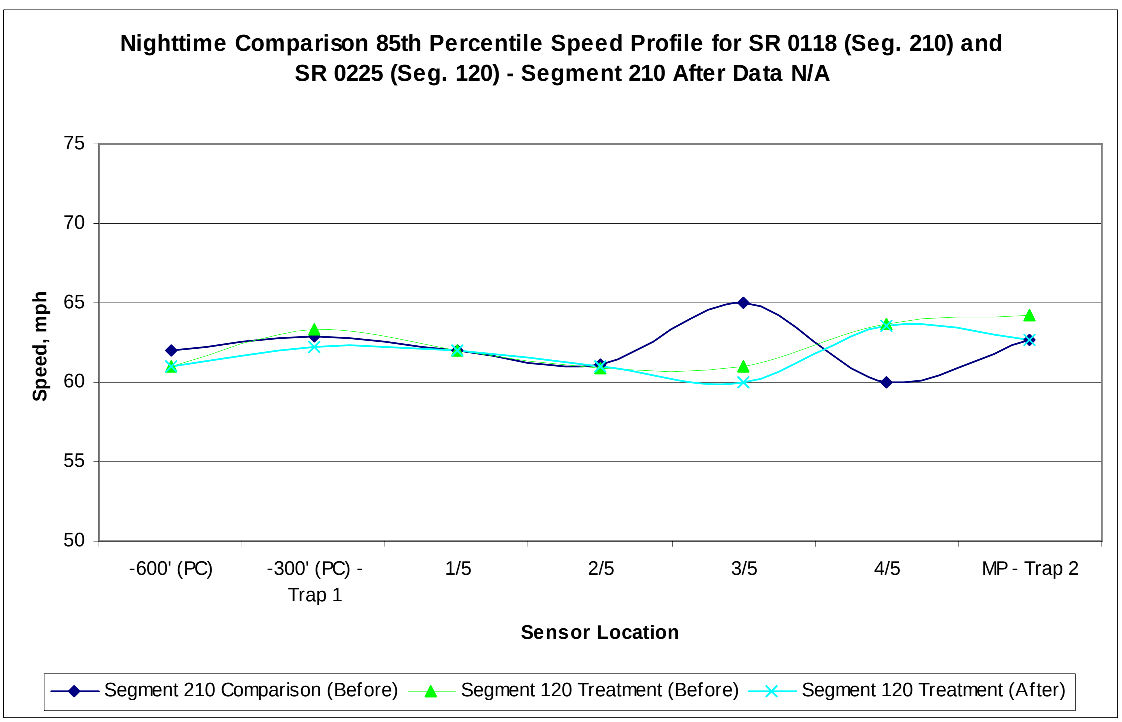

Figure D-22. Nighttime Comparison 85th Percentile Speed Profile for SR 118, Segment 210 and SR 225, Segment 120.

Speed Profile Comparison, SR 0118/0225 Left Curve

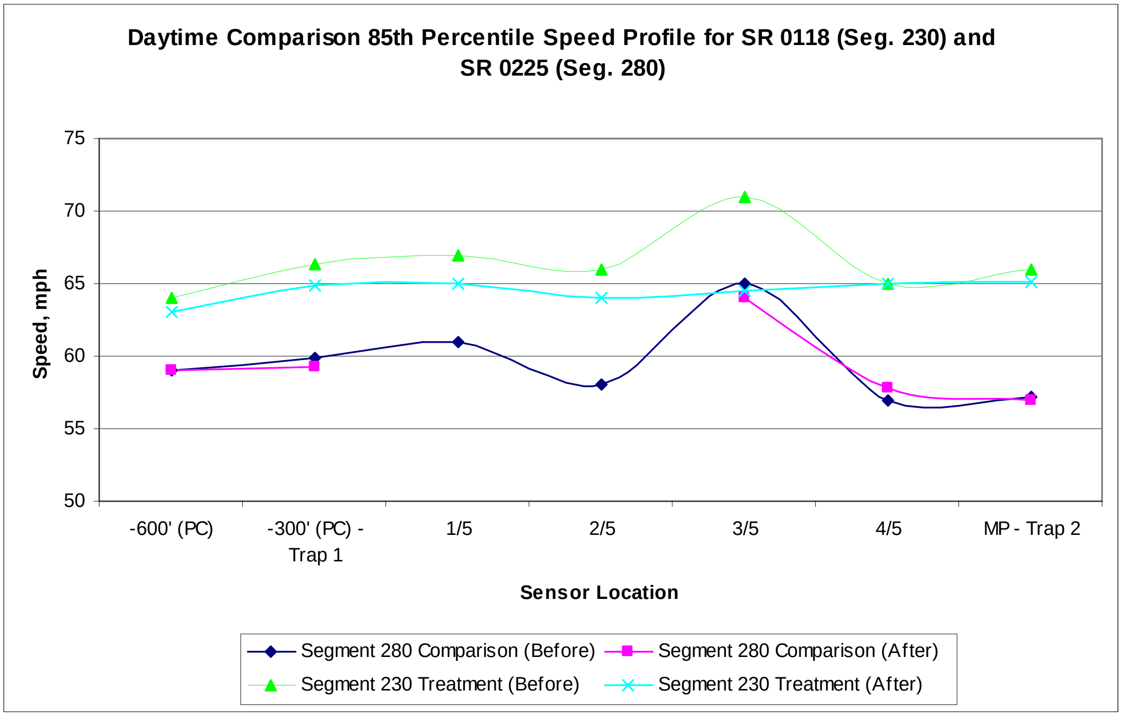

Figure D-23. Daytime Comparison 85th Percentile Speed Profile for SR 118, Segment 230 and SR 225, Segment 280.

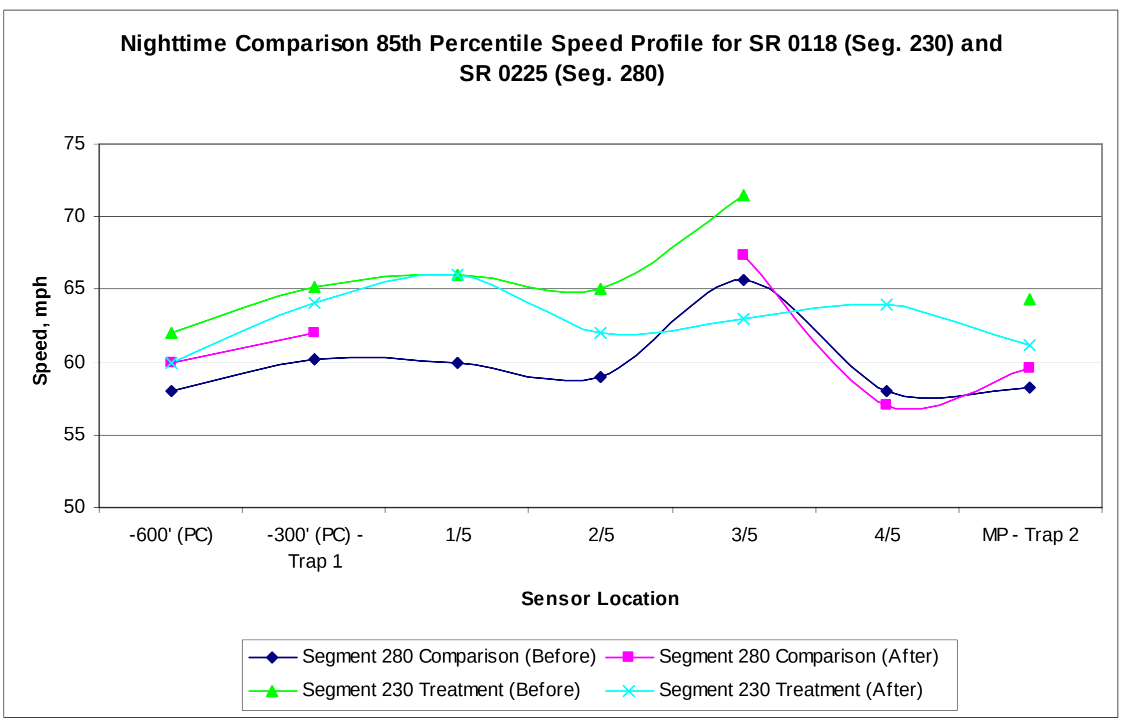

Figure D-24. Nighttime Comparison 85th Percentile Speed Profile for SR 118, Segment 230 and SR 225, Segment 280.