Technical Report Documentation Page

1. Report No. FHWA/TX-07/0-5090-2	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Before-After Comparison of Edgeline Effects on Rural Two-Lane Highways		5. Report Date November 2006 6. Performing Organization Code
7. Author(s) Alexei R. Tsyganov, Randy B. Machemehl, Nicholas M. Warrenchuk, and Yue Wang		8. Performing Organization Report No. 0-5090-2
9. Performing Organization Name and Address Center for Transportation Research The University of Texas at Austin 3208 Red River, Suite 200 Austin, TX 78705-2650		10. Work Unit No. (TRAIS) 11. Contract or Grant No. 0-5090
12. Sponsoring Agency Name and Address Texas Department of Transportation Research and Technology Implementation Office P.O. Box 5080 Austin, TX 78763-5080		13. Type of Report and Period Covered Technical Report (September 2005–August 2006) 14. Sponsoring Agency Code

15. Supplementary Notes

Project performed in cooperation with the Texas Department of Transportation and the Federal Highway Administration.

16. Abstract

Pavement markings have definite functions in a proper traffic control system. They are applied for the purposes of regulating and guiding the movement of traffic, and promoting safety without diverting the driver's attention from the roadway. It was observed that pavement markings located to the right of the car are detected more easily and at distances farther away when compared with the corresponding markings placed to the left of the car. However, compared to other types of longitudinal markings, the effect of edge lines on safety and driver behavior has been much less investigated.

The conducted crash statistic analysis found that edge-line treatments on rural two-lane roadways may reduce accident frequency up to 26 percent and the highest safety impacts occur on curved segments of roadways with lane widths of 9 to 10 feet.

The next stage was focused on complex investigations of edge lines impacts on driver behavior and reactions, including vehicle navigational and positioning issues, speed selection, and effect on driver visual perception. Stationary traffic observation, test driving, and several laboratory experiments were conducted on the selected rural two-lane highways with different roadway width before and after edge lines placement.

Studies indicated that edge line treatments:

- increase speed on average by 5 mph or 9 percent on both straight and curved highway segments
- moves vehicles toward the pavement edge at both daylight and darkness in an average of 20 inches
- reduce vehicle fluctuation around trajectory center line by 20 percent
- reduce driver mental workload
- improve driver's estimation of roadway curvature
- increase driver's advance time of intersection identification.

17. Key Words Rural two-lane highways, edge lines, safety, pavement markings	18. Distribution Statement No restrictions. This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161; www.ntis.gov.

19. Security Classif. (of report)	20. Security Classif. (of this page)	21. No. of pages	22. Price
Unclassified	Unclassified	105	

Form DOT F 1700.7 (8-72)   Reproduction of completed page authorized

Before-After Comparison of Edgeline Effects on Rural Two-Lane Highways

Alexei R. Tsyganov
Randy B. Machemehl
Nicholas M. Warrenchuk
Yue Wang

CTR Technical Report:	0-5090-2
Report Date:	November 2006
Research Project:	0-5090
Research Project Title:	Analysis of Edge Line Treatments
Sponsoring Agency:	Texas Department of Transportation
Performing Agency:	Center for Transportation Research at The University of Texas at Austin

Project performed in cooperation with the Texas Department of Transportation and the Federal Highway Administration.

Center for Transportation Research
The University of Texas at Austin
3208 Red River
Austin, TX 78705

www.utexas.edu/research/ctr

Disclaimers

Authors' Disclaimer: The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official view or policies of the Federal Highway Administration or the Texas Department of Transportation. This report does not constitute a standard, specification, or regulation.

Patent Disclaimer: There was no invention or discovery conceived or first actually reduced to practice in the course of or under this contract, including any art, method, process, machine manufacture, design or composition of matter, or any new useful improvement thereof, or any variety of plant, which is or may be patentable under the patent laws of the United States of America or any foreign country.

Notice: The United States Government and the State of Texas do not endorse products or manufacturers. If trade or manufacturers' names appear herein, it is solely because they are considered essential to the object of this report.

Engineering Disclaimer

NOT INTENDED FOR CONSTRUCTION, BIDDING, OR PERMIT PURPOSES.

Project Engineer: Randy B. Machemehl
Professional Engineer License State and Number: Texas No. 41921
P.E. Designation: Research Supervisor

Acknowledgments

The authors express their sincere thanks for the support of TxDOT Project Director, Juanita Daniels-West (TYL) as well as all the members of the Project Advisory Panel, and particularly Terry Sams (DAL). The authors acknowledge the great support provided by personnel of TxDOT Tyler district. The authors thank all the people who participated in test driving, whose help was imperative to the success of this project.

Products

Products P2 and P3 are represented in this document as Appendix A and Appendix B, respectively.

Table of Contents

List of Figures

List of Tables

Chapter 1. Introduction and Problem Overview

1.1 Background

In the U.S., two-lane rural roads account for 629,309 miles, which is almost 90 percent of the rural highway system. As highway travel demand grows and funding for new road capacity dwindles, the two-lane highway network may become more important in several ways. Current traffic volumes on many rural segments are very small, while volumes on urban segments are large and growing. Scarce maintenance funds have been traditionally allocated to highways with large and growing traffic demands, which represent a small fraction of the highway system. Thus, rural highways, representing the largest fraction of the total system, are viewed by some as a problematic drain on available maintenance resources. Maximization of the effectiveness of all rural highway maintenance expenditures is therefore very important. Determining the cost-effectiveness of edge line pavement markings on rural two-lane highways is the focus of this research.

This is the second of two research reports documenting an examination of the effectiveness of edge line pavement markings on rural two-lane highways. The first report, the Center for Transportation Research's (CTR) 5090-1, provides a detailed description of the Texas rural two-lane highway inventory. The first report also describes observed and potential safety impacts of edge line markings based upon analyses of accident experiences on Texas rural two lane highways.

This report, CTR 5090-2, presents findings from field observations of drivers on rural two-lane highway sections where edge line markings were added, permitting before-after comparisons. Brief summaries of the Texas rural two lane highway inventory and edge line safety impacts are presented in the following sections as a means of introducing chapters 2 and 3, in which the observational findings are presented.

1.2 Rural Two-Lane Highways in Texas

Two-lane roadways represent the largest fraction of the national rural highway system. In Texas, such roadways number 57,367 miles and comprise more than 70 percent of the highway system maintained by the Texas Department of Transportation (TxDOT).

Based on the existing TxDOT databases, CTR developed the Texas Rural Two-Lane Roadways Inventory (TRTI), summarizing selected dimensions of these highways (Ref.1). The inventory is separated by TxDOT districts and includes information regarding traffic lane and shoulder widths, annual average daily traffic volume (AADT), number of horizontal curves and their radii, and currently-implemented edge lines. The major findings of the TRTI are represented below.

Approximately 98 percent of two-lane rural roadways have lane widths of 9-13 feet, with a predominance of highways with lane widths of 10 and 12 feet, containing 22,134 and 18,243 miles, respectively. Highways with lane widths of 9, 11, and 13 feet each account for approximately 5,000 miles.

Of the 27,650 miles of highways with the narrowest lane widths of 9 or 10 feet, 88 percent have shoulder widths equal to or less than 4 feet, with the most frequent shoulder widths of 4 feet (41 percent). Highways with increased lane widths tend to have wider shoulders. For the

23,333 miles of highways with lane widths of 11 or 12 feet, 97 percent have shoulder widths equal to or less than 10 feet, and for lane widths of 13 feet there is an overwhelming majority of mileage with shoulder widths of 8 or 9 feet. A significant number of highways with lane widths of 9, 10, and 11 feet have no shoulder or a shoulder of only 1 foot, accounting for 20, 26, and 39 percent of total mileage of such highways. Narrow shoulders were observed much less frequently on wider highways with lane widths of 12- and 13-feet, on which shoulder widths of one foot or less represented 11 and 8 percent of the centerline miles, respectively.

For all rural two-lane highways in Texas, the mean AADT is approximately 2,400 vehicles per day and ranges from 700 to almost 6,000 vehicles per day (VPD), with the highest volumes appropriately observed on highways with the most advanced design parameters (widest lanes and shoulders).

Overall, for observed highways, the major curve type was *normal*, which accounts for 96 percent of the over-70,000 existing curves. Other curve types, *point* and *spiral*, represent less than 2 percent each.

Across all rural two-lane highways in the state, the average number of normal curves per highway mile is 1.11 and ranges between 0.46 and 1.97 normal curves per mile. The highest frequency of curves is observed on narrow roadways with 9- and 10-foot lane widths, and such roadways contain an average 1.63 normal curves per mile. Highways with lane widths of 11, 12, and 13 feet show little variance and contain an average 0.95 normal curves per mile. Narrow roadways also have higher frequencies of small-radius curves. For roadways with lane widths of 9-11 feet, the average 15^{th} percentile radius is 600 feet; whereas for highways with 12- and 13-foot lane widths, the value is 1,100 feet.

Across Texas, 59 percent of investigated highways have edge lines, but this percentage varies greatly across districts: values range from 27 percent to 98 percent.

Narrow highways with lane widths of 8, 9, and 10 feet are less frequently treated with edge lines than highways with wider lane widths. Across the state, only 32.2 percent of narrow two-lane roadways have edge lines, but this percentage greatly increases to 84.3 percent for wider highways. Further, the smallest edge-line treatment mileages are found on highways with both narrow lane widths and narrow shoulder widths.

1.3 Safety Impact of Edge Lines on Rural Two-Lane Highways

Crash statistics comparisons were made for Texas rural two-lane highways with and without edge lines focused on highways with lane widths of 9, 10, and 11 feet and shoulder widths of 4 feet or less (Ref. 1). For the crash statistics analysis, these roadways were split into sections of uniform lane width, shoulder width, AADT, and edge-striping. In order to obtain statistically significant findings, a minimum section length of 3 miles was chosen to avoid unreasonably high accident ratios on short highway sections with a small number of crashes. After eliminating sections less than 3 miles in length from analysis, 2,822 sections remained, totaling 12,875 miles.

Crashes occurring on the selected sections between the years of 1998 and 2001 were collected from a crash-statistic database maintained by the Texas Department of Public Safety (DPS).

Because of the significant construction and maintenance activities performed by TxDOT, work-zone related crashes were eliminated from analysis to avoid effects of temporarily uncharacteristic traffic situations. The final crash statistics database contained detailed descriptions for 9,774 crashes that occurred during the 4-year period.

In addition to general crash frequency analysis, varying traffic lane and shoulder widths, roadway curvature, and factors such as crash type, intersection presence, light condition, surface condition, crash-supporting factors, severity, driver age, and driver gender were considered.

The conducted comparative analysis of crash statistics on highways with and without edge lines led to the following conclusions (Ref. 1).

If considering both non-accident and accident-prone (two or more accidents) highway sections together, highways without edge lines are characterized by lower accident frequency than highways with edge lines. This phenomenon was observed for all analyzed parameters and can be explained by the far lower number of vehicle miles traveled on highways without edge lines, which led to many more sections that have zero or one accident compared to sections with edge lines.

However, on accident-prone sections, highways without edge lines have an 8 percent higher mean accident ratio than similar sections with edge lines, supporting the hypothesis that crashes on highways without edge lines are concentrated on certain accident-prone segments.

On crash-prone sections of highways with lane widths of 9 feet, a higher mean accident ratio was observed on highways without edge lines (1.74 AMVMT) than on highways with edge lines (1.60 accidents per million vehicle miles traveled [AMVMT]). For sections with lane widths of 10 feet, the mean accident ratios were 1.59 and 1.60 AMVMT, correspondingly for highways with and without edge lines, and for sections with lane widths of 11 feet, those values were 1.37 and 1.42 AMVMT. Statistical analysis indicated low significance levels (around 0.40) of the observed differences in accident-ratio distributions for highways with and without edge lines, but the general tendency of increased crash frequency on sections without edge line treatments was still noted.

Separate analysis of lane-width impact within highway groups with and without edge lines indicated significantly increased crash frequency with lane-width reduction on roadways without edge lines, while such effect was not observed with edge-line presence. On highways without edge lines, mean values of accident ratios for the analyzed three groups were 1.74, 1.59, and 1.42 AMVMT, respectively, for sections with 9, 10, and 11 feet lane widths, and statistical analysis revealed that these ratios represent statistically significant differences among the three groups (confidence level 0.95).

Similar to the study of varying traffic lane width, shoulder-width analysis began with grouping highways with shoulder widths of 0 to 2 feet and 3 to 4 feet. Each shoulder width group was then analyzed on highways with lane widths of 9, 10, or 11 feet, resulting in six different lane-width/shoulder-width combinations. Conducted analysis did not indicate significant impact of edge lines on crash frequency across all observed shoulder width cases. It is necessary to highlight that the majority of analyzed highway sections without edge lines have the same pavement type for both the travel lane and the shoulder. Therefore, in such situations, the driver perceives all paved surface from the center line to the edge of the roadway as a travel lane, while edge line presence clearly separates the traffic lane and shoulder. This fact reduces the validity of the conducted comparison of roadways with similar traffic lane widths.

Examination of all curved segments without regard to lane-width separation revealed that highways without edge lines had a 25.8 percent higher crash frequency than highways with edge lines (5.80 versus 4.30 AMVMT) with significance of 0.94. For straight segments, the average was 1.81 AMVMT on sections without edge lines versus 1.70 AMVMT for edge-striped sections (6.1 percent difference) with significance of 0.90. Detailed study with separation of highways by lane widths indicated the highest impact of edge lines was on curved segments of highways with lane widths of 9 feet. Such roadways with edge lines had a mean accident ratio of 3.84 AMVMT, while this value was 5.73 AMVMT on such roadways without edge lines (difference of 32.9 percent).

The analysis indicated positive safety impacts of edge lines on curved segments during wet surface conditions. Overall, for all highway classes, the percentage of accidents occurring during wet conditions increases on curved segments compared to straight segments for both highways with and without edge lines, but this increase was observed to be higher on highways without edge lines. On narrow roadways (9-foot lane widths) with edge lines, there are no differences in the proportions of accidents occurring on wet surfaces for straight and curved segments; however, for these types of highways without edge lines, curved segments have higher accident frequencies than straight segments.

Overall, for all lane widths, the frequency of run-off-the-road (ROR) accidents is 11 percent higher on highways without edge lines than with edge lines and the highest difference (12 percent) was observed for lane widths of 9 feet. Occurrences of ROR accidents were observed to be highest on the narrowest highways (lane widths of 9 feet) for both highways with and without edge lines, and the highest overall ROR percentage was found on curved segments with lane widths of 9 feet and no edge lines.

The predominant crash-supporting factor was identified as speeding (40 percent overall for all highways), followed by failure to yield right-of-way (4 percent), disregarding signs and signals (4 percent), and passing inadequacy (2.7 percent), with little variation between highways with and without edge lines. However, on intersections during nighttime, speeding and disregarding signs and signals were noted more frequently on highways without edge lines. Further, comparing daylight and nighttime, the speeding factor increased on both highways with and without edge lines during darkness, but this increase was greater on non-edge-striped sections (16 percent) than on edge-striped sections (6 percent).

For both highways with and without edge lines, over 75 percent of all accidents occur between intersections. Although the proportion of intersection-related accidents was observed to be higher overall of highways with edge lines (24 percent) than without (18 percent), the difference is likely a result of disparities in traffic volume or intersection concentration between highway types. At the same time, slightly higher percentages of intersection-related accidents were observed on curved segments of narrow highways (9-foot lane widths) without edge lines.

Detailed analysis of such crash characteristics as varying lighting conditions, crash severity, and driver age and gender did not indicate significant impacts of edge-line presence.

The findings were summarized as follows:

- edge-line treatments on rural two-lane roadways may reduce accident frequency, with the highest safety impact on curved segments of narrow roadways.
- edge-line presence shows some positive safety impact during darkness that may be related to better driver perception of path and speed.

1.4 Driver Perception of Longitudinal Pavement Markings

Drivers extract necessary visual information from the environment using techniques called "systematic seeing" (Ref.2). This systematic seeing involves three important steps: (1) centering on the travel path, (2) scanning and searching the traffic scene, and (3) checking mirrors and instruments. A considerable amount of research has been devoted to describing driver eye scanning behavior and determining where drivers fixate their eyes when driving.

Figure 1.1 shows the points of driver's eye fixations (Ref.3) and Figure 1.2 represents relative duration of concentration in different areas (Ref.4).

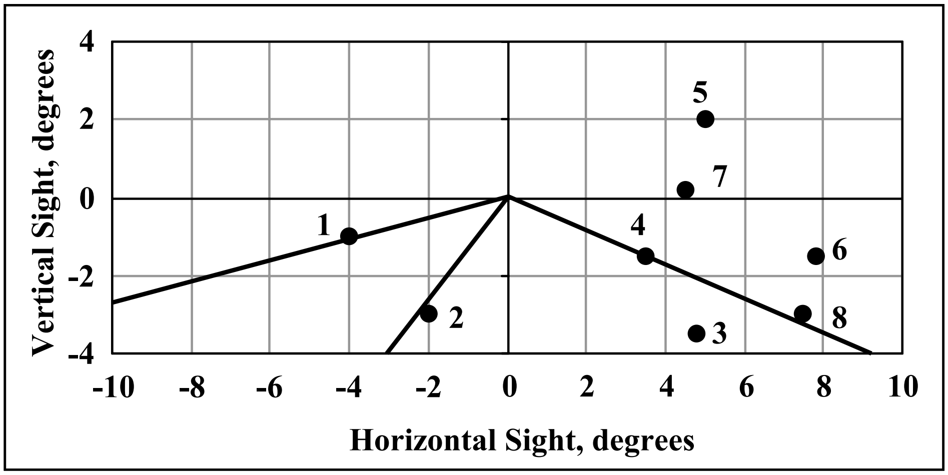


Figure 1.1: Points of Driver's Eye Fixation

The points on the Figure 1.1 represent driver eye fixation for the following purposes:

1 and 6—observation of situation on the left and right adjacent traffic lanes;

2 and 8—control of vehicle position, relative to the left and right lane edges;

3—observation of pavement quality;

4—observation of a leading vehicle;

5—observation of road signs;

7—visual field center of gravity.

As described in Figure 1.2, drivers spent around 14 percent (6.9 percent + 7.2 percent) of total time for conscious estimation of the vehicle's position on the roadway. At high traffic volume, such estimation could take up to 20 percent of the time on tangent highway sections and up to 25 percent on horizontal curve sections (Ref.3, 4).

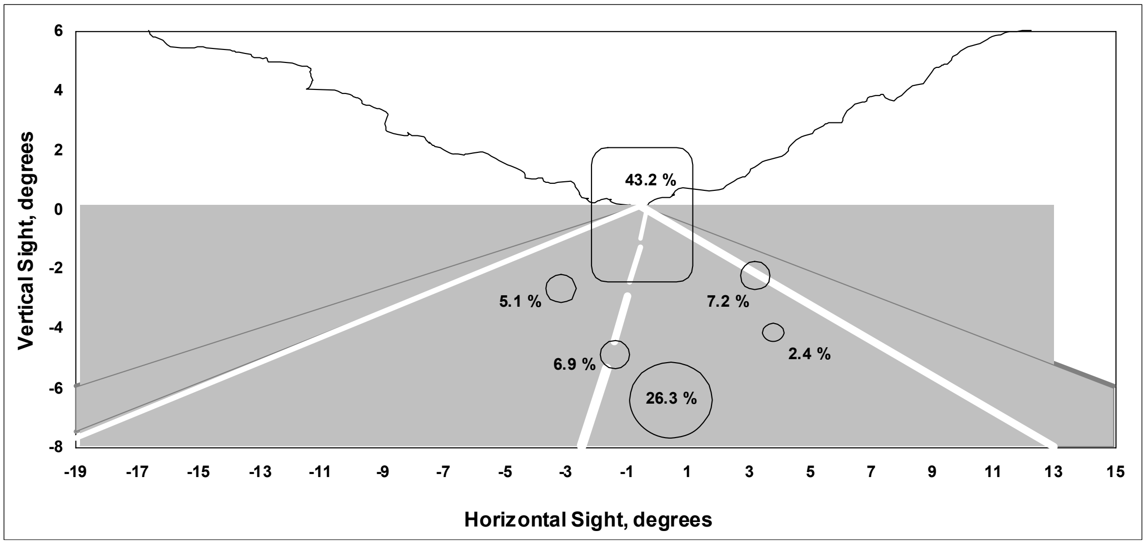


Figure 1.2: Distribution of Driver's Attention among the Different Areas on Two-Lane Rural Roads

At the same time, drivers continuously obtain information about vehicle speed and position through unconscious perception, which is mostly through peripheral vision. The peripheral vision field normally varies from 120 to 180 degrees. As speed increases, the peripheral vision field diminishes. For a speed increase from 48 mph to 60 mph, the horizontal angle of peripheral vision narrows from 65 degrees to less than 40 degrees (Ref.3,4). Therefore, at high speeds and at nighttime, longitudinal markings begin to play a more important role than roadside objects, because they are continuous along the roadway and positioned near the center of the driver's visual field.

The research showed that during nighttime, the lateral lane position of a vehicle is maintained by the driver through peripheral visual cues obtained typically from pavement markings and from the road edge near the vehicle. Navigational decisions are based on visual information obtained by foveal eye fixations on pavement markings at relatively long distances ahead of the vehicle. Pavement marking visibility at night is mainly determined by the marking retroflectivity characteristics and by the level of contrast with the road surface. For rural two-lane driving conditions, the only source of illumination of pavement markings is the automobile headlamps.

A large body of pavement marking research has been conducted around the world under a wide range of pavement marking configurations (edge lines, single solid, double solid, single dashed centerlines) for various line widths (165, 330, and 660 ft) and various retroreflectivities (low, medium, and high). The studies determined that an average detection distance of longitudinal pavement markings at vehicle speed 60 mph is 412 to 425 ft (Ref.5). It was found that driver age has a highly significant effect on pavement marking visibility. The average detection distances ranged from 412 ft (average preview time 5.1 sec for 53 mph) for the old group (average age 68.3 years) under low-beam illumination on the medium-retroreflectivity road to 783 ft (average preview time 9.7 sec for 53 mph) for the young group (average age 23.2 years) under high-beam illumination on the high-retroreflectivity road (Ref.6). The overall average detection distance increased about 55 percent when the old group was compared with the young group (ref.16). On the basis of eye scanning data, it was recommended that a minimum preview time of 3.65 sec. be used to evaluate the photometric adequacy of pavement markings.

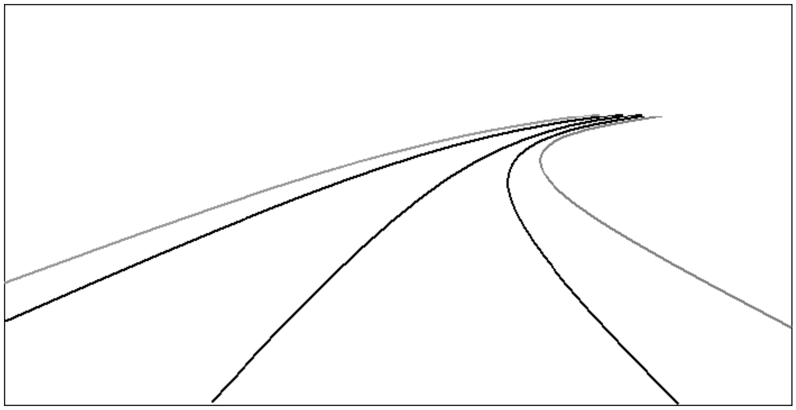
Graham et al. (Ref.7) conducted a low-beam nighttime field study to determine subjective pavement marking retroreflectivity requirements. The results of field evaluation indicated that more than 98 percent of the subjects rated a marking retroreflectance of 93 mcd/m2/lx as adequate or more than adequate for nighttime low-beam driving (Ref.7). This retroreflectivity corresponds to an average luminance of 3.84 cd/m2.

Overall, it was observed that pavement markings located to the right of the car are detected more easily and at distances farther away compared with corresponding markings placed to the left of the car. This could be attributed to the alignment of the automobile low-beams, which point approximately 2 degrees down and 2 degrees to the right, thus favoring the right side (Ref.5). This implies that edge-line pavement marking can have a great impact on driver perception of horizontal curves.

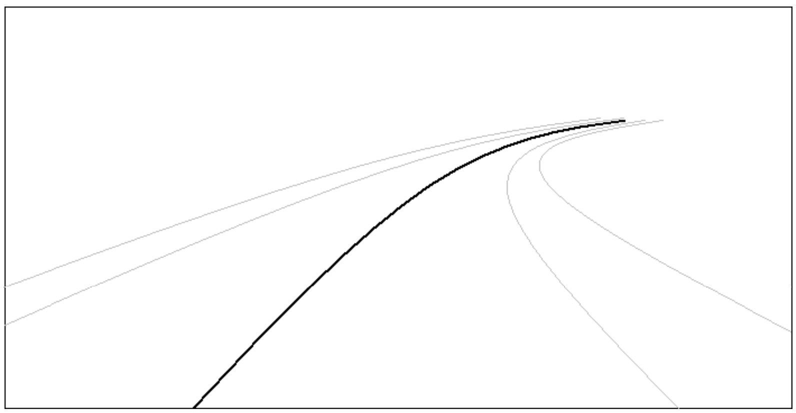
With driving experience, a driver accumulates associations between visual curvature of the horizontal curves and corresponding values of centrifugal force at different speeds. Based on these relations, drivers select the appropriate speed, and so, the adequate speed selection will be greatly determined by the quality of advanced estimation of visual curvature. The main characteristic that provides drivers with information about horizontal curves is the visual curvature of the basic lines in the roadway perspective, and studies show that human subjective estimation of curve radius is more accurate with more basic lines in the perspective view (Ref.4). This phenomenon can be demonstrated by comparing Figure 1.3a, which models a two-lane road with contrasting basic lines (edge-lines and centerline markings), and Figure 1.3b, which is the same road with centerline dominance, caused by low contrast between carriageway and shoulders, and the absence of edge-line markings.

As shown, with only one dominant line, the modeled horizontal curve is perceived differently than it is perceived with the presence of edge lines as well. Therefore, the absence of edge-line pavement markings can create an optical illusion that the curve ahead has a bigger or smaller radius than it actually has and this could lead to inadequate driver behavior, especially at nighttime, when the contrast between road edges and environment is very low.

The investigations of driver psycho-physiology indicated that edge-line pavement markings could have adverse effects as well. Experiments showed that after 0.5 to 1.2 hours of driving on two-lane roads, drivers experienced the first signals of fatigue: some headache, reduced attention level, and increased reaction time. It was observed that during daytime conditions on roads with bright white edge lines, driver reaction times were 10 to 15 percent longer than on similar roads without edge-line pavement markings (ref.14). At the same time, such effects were not observed at nighttime or in bad weather conditions, when edge lines improved driver performance. This phenomenon was explained by the monotonous effect of a continuous white line in the driver's visual field during the daytime. Also, investigations of human visual perception indicated faster eye fatigue in environments overloaded by bright objects. With insufficient lighting conditions, edge-line pavement marking loses its monotonous effect due to increased importance for vehicle lateral position estimation by the driver. Therefore, it was hypothesized that to be most effective, the edge-line pavement marking should have different retroreflectivity characteristics for daytime (reduced) and nighttime (increased) or have smaller width (Ref.4).



a)



b)

Figure 1.3: View of Horizontal Curve on Two-Lane Road
a) with edge-lines and centerline pavement marking, and
b) with dominant centerline caused by absence of edge lines.

This review of principles of driver perception of longitudinal pavement markings might form the basis for the following goals for edge line implementation:

- Delineate the roadway edge to provide the driver with continuous information regarding vehicle lateral position.
- Create a continuous bright object in the driver's visual field to provide a point to focus eyes to minimize the time of the "blinding" effect caused by oncoming vehicle headlights.
- Create more basic lines in the roadway perspective to help the driver adequately estimate the roadway horizontal curvature.

1.5 Evaluation of Edge-Line Pavement Markings

Two principle approaches are currently in use for investigating safety impacts of improvement countermeasures. The first one is based on the hypothesis that absence of reported collisions is indicative of true safety. However, each traffic crash is a random event for which associated conditions are not controlled and many minor crashes are not reported, and certainly many dangerous driver actions do not produce crashes. Considering these facts, the absence of traffic crashes does not guarantee the absence of dangerous traffic conditions or inadequate driver behavior. The second approach to examining the impacts of countermeasures attempts to objectively quantify normal driver behavior and highway conditions that are associated with abnormal driver actions. This criterion defines safety as the absence of systematic abnormal or dangerous driver behavior (Ref.3). Therefore analyzing the driver-vehicle-road-environment (DVRE) system adds a systematic approach to traffic safety studies, with major emphasis on understanding driver behavior and reactions as a key element of the traffic system.

During the first stage of this edge lines evaluation, crash statistics for similar rural two-lane highway sections were examined (Ref.1) and the results are summarized here in section 1.2.

As a next evaluation step, the impacts of edge lines on driver performance were investigated through field studies and findings, described in Chapters 2 and 3.

Based on the principles of driver perception of longitudinal pavement markings and the analysis of crash statistics the following hypotheses were formulated for the field driver responses studies:

- Edge lines may affect vehicle lateral position and speed.
- Edge lines may improve the driver's ability to sense his or her transverse vehicle position on the roadway and this may reduce vehicle transverse position fluctuation around the trajectory centerline.
- Edge lines may reduce driver emotional tension due to enhanced sensing of vehicle transverse position on the roadway, especially when meeting oncoming vehicles.
- During darkness or limited ambient lighting, edge lines may help the driver's eye recover faster after the "blinding" effect of an oncoming vehicle. Therefore edge lines may reduce driver stress level during nighttime driving.
- On two-lane roads, marking of the centerline only (without edge-line pavement marking) may offer inadequate roadway curvature perception, especially at nighttime, when contrast between roadway edges and the environment is very low.
- Breaks in the edge-line pavement marking may increase the distance for intersection advance recognition by drivers.

To test these hypotheses, three approaches were selected: stationary observations, test-driving, and laboratory experiments. These are described in the next chapters.

Chapter 2. Experiment Design and Methods

2.1 Approach and Methodology for Edge-Line Pavement

2.1.1 Markings Evaluation

Two different approaches are often used for investigating safety impacts of improvement countermeasures. One uses recorded crash data to identify problematic road sections, while the other uses objective measures of driver behavior to similarly identify potentially problematic locations. The first approach is based on the hypothesis that the absence of collisions is indicative of safety and is usually focused on the analysis of crash statistics. However, each traffic crash is a random event, and analyses of crash statistics tend to identify only locations having multiple recorded crashes. If analyses depend upon recorded crash data, locations having multiple unreported crashes (property damage only), as well as locations with multiple run-off-the-road events but no crashes, will be overlooked. Therefore, absence of traffic crashes does not guarantee that a road section is hazard free or that it tends to illicit appropriate driver behavior.

The methodology selected for the evaluation of edge line pavement markings was designed to use both crash data and driver behavioral measurements. The driver behavioral criterion defines safety as the absence of systematic potentially dangerous driver actions (Ref.3). During the first stage of the edge lines evaluation, crash statistics for similar rural two-lane highway sections with and without edge lines were compared (Ref.1) and the results are summarized in Section 1.2. As a next evaluation step, the impacts of edge lines on driver performance were investigated, and this chapter presents methodological issues of the conducted studies. Based on the previously reviewed principles of driver perception of longitudinal pavement markings and results of the crash statistics analysis, the following hypotheses were formulated for the driver response study:

- Edge lines may affect vehicle transverse position and speed.
- Edge lines may enhance the driver's perception of his or her vehicle's transverse position on the roadway, and this may be measured as reduced oscillation around the trajectory centerline.
- Edge lines may reduce driver emotional tension due to enhanced transverse position sensing, especially when meeting oncoming vehicles.
- At night, edge lines may allow the driver's eyes to recover faster after the "blinding" effect of oncoming vehicle headlights, which may reduce driver stress level during nighttime driving.
- Edge lines on two-lane roads provide much better driver perception of curvature than centerline markings only (without edge-line pavement marking), especially at nighttime when visual contrast between roadway edges and the environment is very low.
- Discontinuities in the edge-line pavement marking may increase the distance for intersection advance recognition by drivers.

To test the above-mentioned hypotheses, three approaches were selected: stationary observations, test-driving, and laboratory experiments, and these experimental procedures are described in the following section.

2.1.2 Stationary Observations Design

The purpose of the stationary observations is to investigate effects of edge-line pavement marking on speed and vehicle lateral roadway position.

Short duration traffic counts and associated speeds are most often collected via road tubes stretched across one or more highway lanes. However, given the high speeds found on rural, two-lane roadways and the inaccuracies and difficulties with securing road tubes at such speeds, these stationary observations were instead performed via video camera. Using a well-positioned video camera and fiducial marks on the pavement surface, video observations allow for collection of vehicle speed and lateral position data in both daylight and darkness.

Based on information gathered from the TRTI, three rural two-lane roads located near Tyler, Texas with roadway features and traffic volumes typical of roads in the TRTI were selected for video analysis. Consistent with the roadway widths analyzed in the accident statistics study, these three highways, FM 850, FM 15, and FM 13, have roadway widths of 9, 10, and 11 feet, respectively. In addition, these three roadways initially did not have edge markings, which allowed for observations to be made on the same test sites both with and without edge lines. Figure 2.1 represents a general view of the selected highway sections before and after edge line treatment.

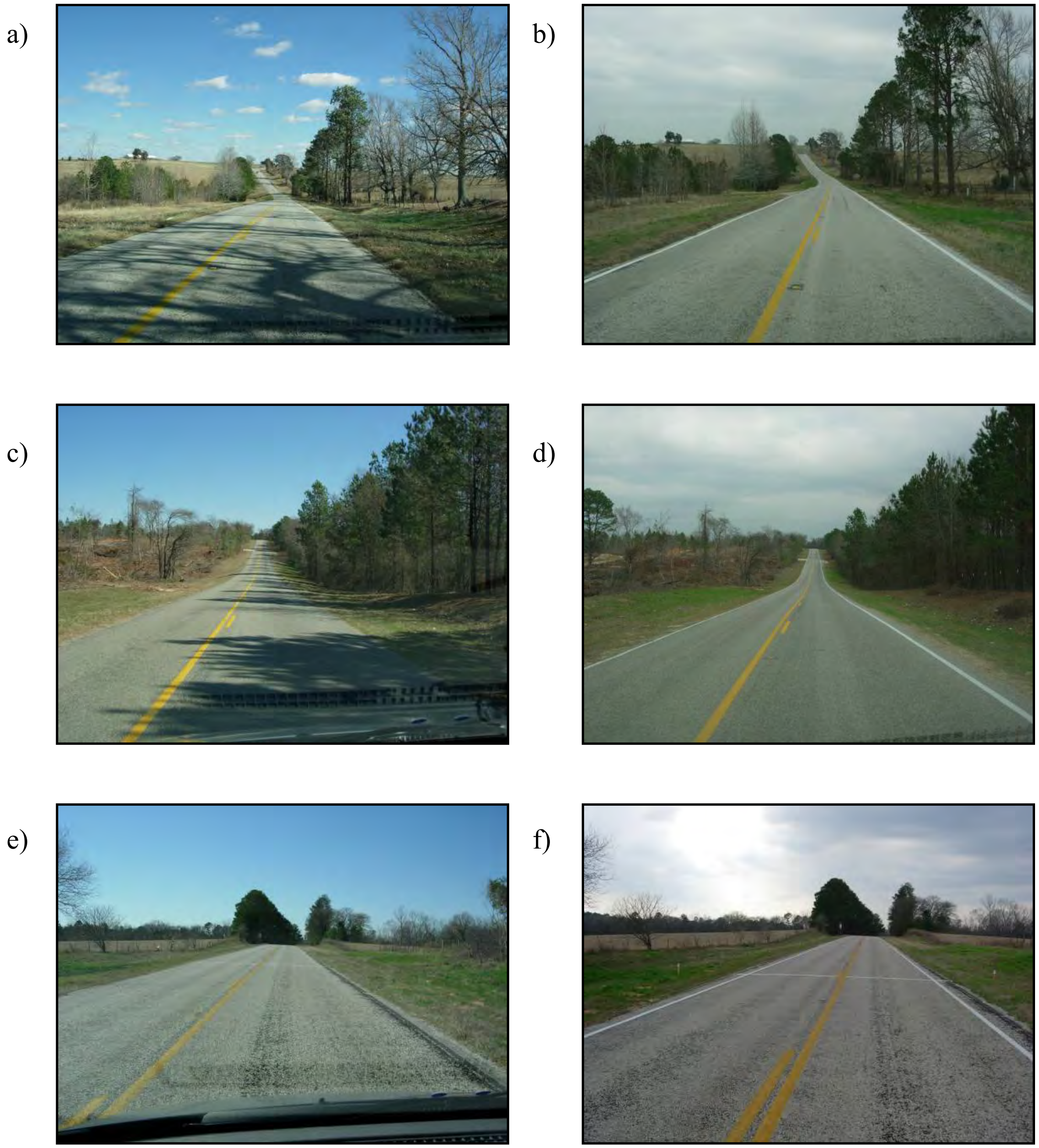


Figure 2.1: Test Sections Representing Roadways with Traffic Lane Width of 9 (a and b), 10 (c and d), and 11(e and f) feet Before (a, c, e) and After (b, d, f) Edge Line Treatment

On each highway, a suitable test site was first selected for analysis and fiducial marks, in the form of two, 4-inch wide white reflective lines, were striped across the roadway test site at an interval of 100 feet as shown in Figure 2.2.

Figure 2.2: Fiducial Marks on FM 850 Test Site

To collect speed and lateral position information, an unmarked vehicle with a video camera was parked off the road, as shown in Figure 2.3, and passing vehicles were recorded. The camera vehicle was positioned in such a manner that the video field of view included both vehicles passing each fiducial mark (allowing for speed measurement) and the position of each vehicle's tires on the roadway with respect to pavement markings (allowing for lateral position measurement).

Figure 2.3: Observer Vehicle Location on FM 15 Test Site (approaching vehicle is on test site)

The position of the test vehicle on each test section was important in order to minimize any possible impact on driving behavior. On FM 15, the unmarked observation vehicle was parked perpendicular to the roadway in a construction site driveway and similarly, on FM 850, the vehicle was placed in a private driveway to simulate a normal vehicle parked in a driveway. In each case, the front of the vehicle was at least 10 feet from the edge of the roadway. On FM 13, no driveway was available, but a large gravel mound used for roadway maintenance provided concealment for the vehicle. On all three test sections, the observation vehicle was located at least 100 yards from the test site to further reduce possible impact upon drivers. At night, an infrared light with an effective range of 150 yards was used in conjunction with the "nightshot" camera mode so that the fiducial marks and pavement markings could be seen on video.

Volumes on all sections are very low (observed as approximately 20 to 50 vehicles per hour), and thus oncoming-vehicle situations and platoons of more than two vehicles were seldom observed. On each section, raised reflective pavement markers (RRPMs) were present along the center of the road and spaced at intervals of 40 feet.

The posted speed limit is 55 mph on the test section on highway FM 850 and is 60 mph during day and 55 mph at night on highways FM 15 and FM 13.

With the observation vehicle in place, data was collected on all roadways, during both daylight and darkness. Observations were first made on all three test sections without edge lines present. Edge lines (4-inch wide) were then striped on all three test sections on a distance of least 1.5 mile upstream and downstream of the test site. Approximately 1 month after data collection without edge lines (3 weeks after striping of edge-lines), observations were made during daylight and darkness on the same test sections but with edge lines now in place. In each case, the observation vehicle was placed in almost exactly the same observation position.

After data collection, videos taken of each test site in the field were analyzed to obtain vehicle speeds and lateral positions.

Vehicle speeds were determined by measuring the time required for a vehicle to pass between the two fiducial marks placed 100 feet apart on each test site. For vehicles headed away from the observation camera, the rear tires were used as a visual guide, and for vehicles headed towards the camera, the front tires served as a guide. However, the video cameras used in this study were time-encoded such that one frame of video corresponds to 1/29.87 of a second (30 frames per second). Given this fact, the visually measured time required for a vehicle to traverse the fiducial marks can only be determined within 2 frames (1 frame for each fiducial mark) or 1/15th of a second of the actual time. Assuming an average vehicle speed of 60 mph, this time error would amount to a random error in speeds of approximately +/- 3 mph.

However, this is only a best-case scenario. Because of problems with parallax, difficult viewing angles, and headlight glare at night, overall fiducial-mark crossing times could only be determined to within 3 frames during daylight and 5 frames overall. This leads to a total random error of approximately +/- 5 mph during daylight and +/- 9 mph during darkness.

Vehicle lateral positions were calculated by viewing the position of a vehicle's driver-side tire with relation to the outside of the centerline when the vehicle passed over the fiducial mark located closest to the observation vehicle. In the case of vehicles headed away from the observation vehicle, the rear driver's side tire was used to determine lateral position, and for vehicles headed towards the camera, the front driver's side tire was used. When viewing the video, hash marks were drawn on the monitor at 0.39 inch intervals along the nearest fiducial mark. Given the hash-mark spacing and the measured distance of the roadway, the real-world lateral position of each vehicle could be determined.

Like vehicle speed measurement, lateral position calculation contains some amount of error due to problems with accurately determining when vehicles crossed the nearest fiducial mark. Because the observation vehicle was positioned at an angle to the roadway, any error in determining precisely when a vehicle’s front or rear tires crossed the fiducial marks will also result in a lateral position error. The random error associated with the near fiducial mark was +/- 1 video frame during daylight and 3 frames during darkness, due to added difficulty in locating vehicle's tires at night. Recalling the speed limit on the test sites, this equates to an error of up to +/- 1 ft during daylight and +/- 2 ft during darkness.

As a result of headlight glare present on the video recordings at nighttime, lateral position unfortunately proved too difficult to determine within a reasonable tolerance for vehicles headed towards the camera during darkness. Thus, lateral position measurements at night are only available for vehicles headed away from the observation camera (approximately 50 percent of all vehicles).

2.1.3 Test Driving Design

The stationary observations provide important but limited information, because changes in speed and trajectory are the last step of the complex process of driver perception and reaction to traffic conditions. The stationary observations provide a means of sampling speed and lateral position for all vehicles composing the traffic stream at the chosen test site location; however, test driving provides a means of monitoring driver speed, position and other characteristics as they change over an extended road section. The test driving allows examination of dynamic driver responses to edge lines as well as driver mental workload history.

Test driving was conducted on the same highways that were chosen for stationary observations near Tyler, Texas. The test route included all three highway sections representing rural two-lane roadways with traffic lane widths of 9 (FM 850), 10 (FM 15), and 11 (FM 13) feet and was designed so that total travel time would not exceed 2 hours, in order to avoid driver fatigue. Figure 2.4 shows the map of the selected test route, which is generally contained with a rural area near Tyler, Texas.

Test Section 1 represents a traffic lane width of 9 feet and is located on eastbound highway FM 850, from the intersection with county road CR 218 on the west side to the intersection with CR 217 on the east. Total test section length is 3 miles and the posted speed limit is 55 mph.

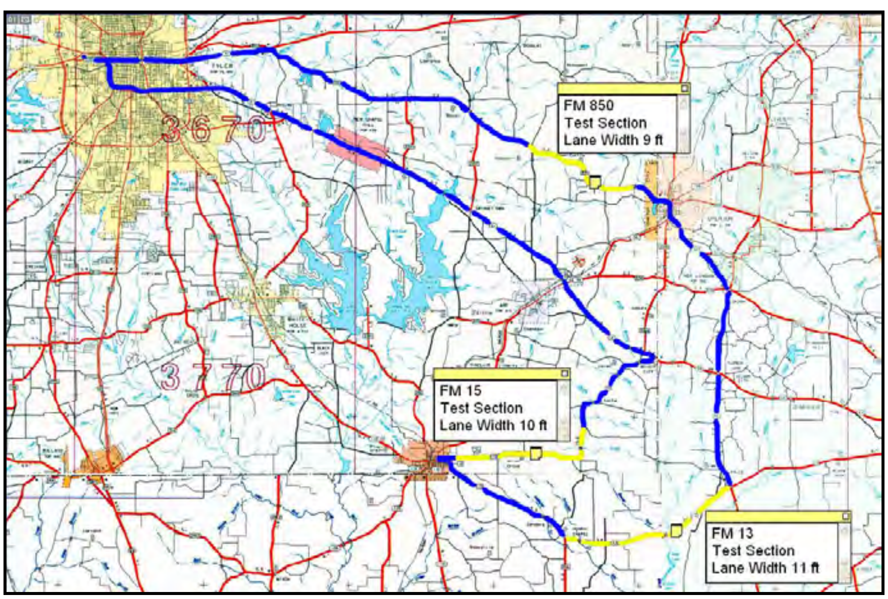


Figure 2.4: Test Route Map and Test Sections Location

Test Section 2 has a length of 4 miles and a traffic lane width of 10 feet. The section is a part of FM 15 eastbound and is bordered by intersections with CR 2156 on the east and CR 2166 on the west. Posted daytime speed limit is 60 mph and 55 mph at night.

Test Section 3 was selected on highway FM 13 westbound from the intersection with Big Springs Cemetery Road on the east to the intersection with FM 856 on the west. Total test section length is 5 miles, traffic lane width is 11 feet, and the posted speed limit is 60 mph (daytime) day and 55 mph at night.

On all three highways, both the solid and dashed centerlines, indicating passing or no passing, are approximately 4 inches wide, with a 4 to 5 inch gap separating the two lines. On each section, raised reflective pavement markers (RRPMs) were present along the center of the road and spaced at intervals of 40 feet.

According to the hypothesis of impacts of edge lines on driver performance stated earlier, the following parameters were selected for continuous monitoring during test driving:

- Vehicle speed and lateral position, for driver behavioral responses analysis
- Driver electrocardiogram (wave form), for estimation of stress level
- Visual stimuli sensed by the driver's eye, for assessment of traffic situation and identification of available stressors.

To capture the above-mentioned parameters, a special portable device developed by CTR was used. This device includes:

- An electronic monitoring module that is connected to the vehicle onboard diagnostic system (OBD) allowing continuous scanning of vehicle systems while driving.
- A digital camcorder for video recording of the driver's field of view,
- A module for monitoring and continuous recording of the driver's psycho-physiological responses, particularly the electrocardiogram (wave form).
- A notebook computer, which records all information.

Figure 2.5 represents a general view and the connection diagram of the vehicle diagnostic module. The vehicle OBD system is easily connected through the vehicle's diagnostic connector using the scan tool unit (device produced by the EASE Diagnostics Co.) to a notebook computer, as a simple "plug-in" operation.

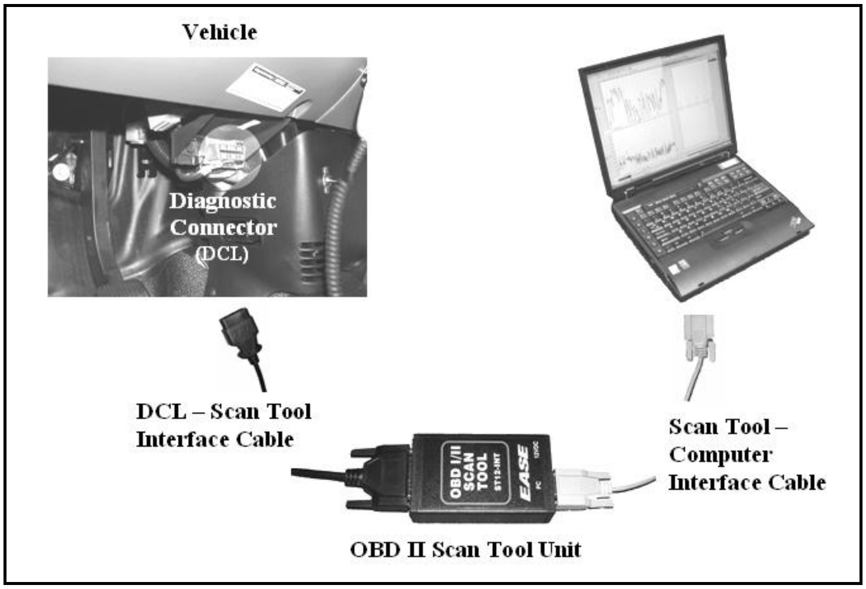


Figure 2.5: Connection Diagram of the Vehicle Diagnostic Module.

Vehicle speed was registered every 0.1 second and recorded in the notebook computer as a text format file along with a time code that was converted into time of day.

For electrocardiogram recording, a unit named PowerLab (model 4/25), manufactured by ADInstruments, was selected. The PowerLab is a smart peripheral device specifically designed to perform all functions needed for data acquisition, signal conditioning, and preprocessing. Together with the bio amplifier unit (BioAmp), this system allows the recording of different biological signals, including an electrocardiogram (ECG), from human sources. The BioAmp has been designed for safe connection to humans and conforms to the requirements of the International Electrotechnical Commission's IEC601-1, its addenda, and various harmonized standards worldwide. Figure 2.6 shows a general view and the connection diagram of the biological module.

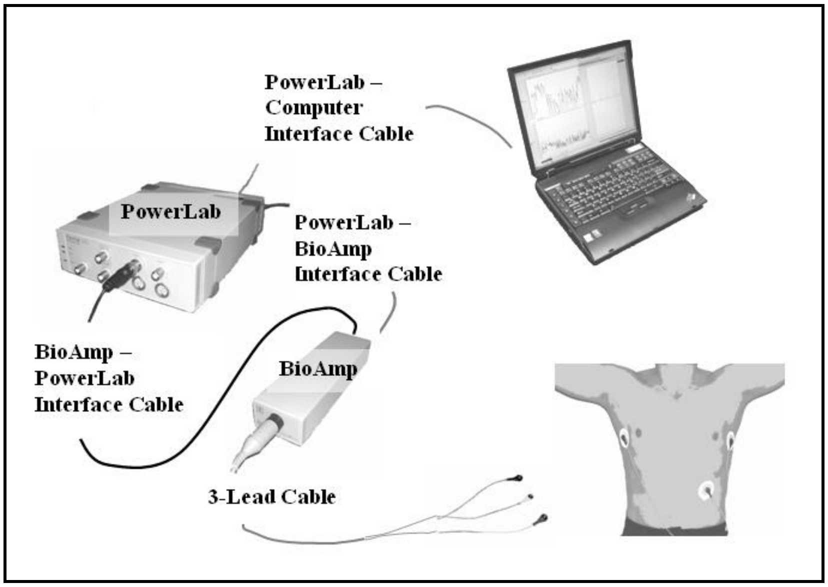


Figure 2.6: Connection Diagram of the Biological Module

Heart electro potentials were scanned with a frequency of 0.01 second and the electrocardiogram wave form was recorded on the notebook computer and plotted versus time.

The review of techniques for measuring driver mental workload indicates that the heart rate and derived parameters (heart rate variability) have proven to be most useful for stress identification from physiological measurements (Refs 3,4,8,9,10).

To avoid the influence of differences in driver psycho-physiological states not related to the driving task, a basic or pre-test electrocardiogram was recorded under non-driving conditions before each test drive. For further analysis, relative characteristics, such as the driver's heart rate at the investigated conditions expressed as a percentage of the basic value, can be used.

Psycho-physiological studies of operator activity find that heart rates over 110 percent of the basic condition indicated increased mental workload (Refs 3,4). Therefore, the frequency of these situations can be a quantitative criterion for comparison of the driving task complexity under different traffic conditions.

For continuous real time assessment of the traffic situation and identification of available stressors not related to the investigated processes, the driver visual field was recorded with a digital camcorder installed on the center of the vehicle dashboard.

For continuous registering of the vehicle lateral position on the roadway, a special technique was implemented. Marks were placed on the vehicle windshield so that they were visible in the video recorded field. The first mark fixes the position of the calibration pavement line on the video screen when the vehicle driver side front wheel is on this line, while the second mark corresponds to the wheel position 3.28 feet to the right of this line. Therefore, analyzing the position of the roadway center line pavement marking on the video screen between these windshield marks, by converting measurements from pixels to centimeters, allows estimating the distance from the vehicle driver side front wheel to the center line, e.g., the vehicle's lateral position on the roadway. Figure 2.7 represents the above-mentioned calibration process and Figure 2.8 shows the data reduction procedure.

Figure 2.7: Developed Technique for Continues Registering Vehicle Lateral Position Using Video Recording

Figure 2.8: Screenshot of Vehicle Lateral Position Data Reduction.

To determine vehicle lateral position measurement error by the above-mentioned technique, a special test was conducted. In total, 100 actual measurements of the distance of vehicle driver side wheels from the pavement marking center line were compared to corresponding values estimated by the video analysis. The obtained data indicated that the 95-percentile measurement difference expressed as an absolute value is 0.26 feet and errors are equally distributed between positive and negative values. So, the error of estimation of vehicle lateral position on the roadway in regard to pavement center line by the implemented technique can be determined as plus/minus 0.13 feet.

Nine test drivers (five males and four females) from the TxDOT Tyler and Atlanta districts participated in the experiments. The average driver age was 45 years, with the youngest 28 and the oldest 62 years.

All drivers were unfamiliar with the test sections or at least were not frequent commuters on the selected test route.

Each driver was directed to drive on the selected route, which included all test sections. Test drivers were informed that the purpose of the observations was general investigation of traffic conditions on rural highways and were asked not to use a car radio or a cell phone. They had no other instructions and did not know about the study objectives or locations of the investigated sections. Test drives were made with the same vehicle (Ford Freestar minivan) and in similar weather conditions during the February and March of 2006.

The first set of test drives were conducted when test sections had no edge lines. Approximately 3 weeks after test sections were treated with edge lines, the second set of test drives was performed. In both sets, each driver drives through the test sections during daylight and darkness.

2.1.4 Laboratory Experiment Design

Laboratory experiments were targeting investigations of edge line impacts on driver perception of roadway curvature and advance recognition of intersections.

As described previously, different numbers of basic longitudinal lines in the visual perspective of a roadway can affect human perception of roadway curvature. Because edge lines may provide more basic lines, or at least more clearly define the pavement edge so that it appears as a longitudinal line, they may help driver's estimate curvature sharpness or actual curve radius.

To test this hypothesis, the perspective view of three highway segments with different curvatures were modeled with one basic line, created by a pavement center line, as well as with two extra basic lines created by the edge lines. Figure 2.9 shows the developed models. The perspectives were modeled based on the dimensions of the driver's eye position while driving a minivan. The first set (Fig. 2.9a) represents a highway section with a curve radius of 500 feet and the second (Fig. 2.9b) and third (Fig. 2.9c) with radii of 300 and 100 feet, respectively.

The developed perspectives were printed in 8 ½ by 11 inches format with black background and white basic lines and sorted into two sets: first with center line only and second with center and edge lines.

During the experiment, the first set of pictures was provided to a human subject with the request to rank each curve as smooth, moderate, or sharp based on "higher-lower" criteria. After approximately 15 minutes after the subject had performed other tasks, the second set was shown with the same request. An observer recorded the subject's responses in both cases.

For the investigation of the effects of edge line discontinuities on intersection recognition, another laboratory experiment was conducted. The driver visual field was video recorded from a moving vehicle at nighttime on a highway section with an intersection. Two samples of the same highway section, before and after edge line implementation, were recorded at nighttime. A digital video camera was placed on the level of the driver's eyes and recording was done with vehicle high beam headlights on.

a)

b)

c)

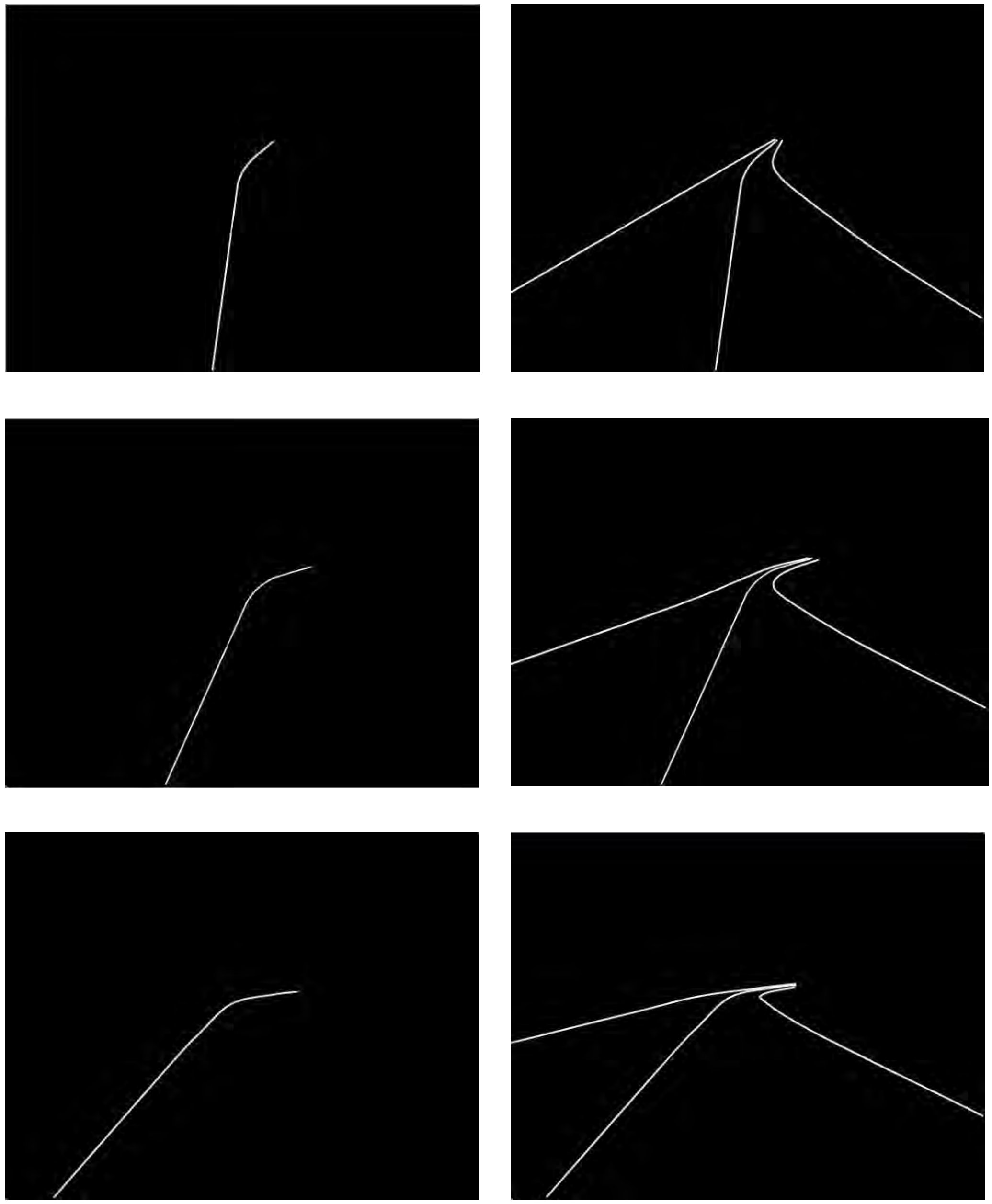


Figure 2.9: Modeled Perspective View of Roadways with Different Curvature (curve radii increases from a to c)

Sample videos were developed in DVD NTSC format and were shown to subjects on a 27-inch TV screen in a dark room.

Participants were asked to watch the video and pause it when he or she recognized an adjacent roadway ahead, and the observer recorded the corresponding time code provided on the video. The time when the subject recognized an adjacent roadway was compared with the actual time that the subject vehicle would pass the intersecting roadway, given a constant speed. The difference in the time measurements permitted estimation of the subject advance recognition time of intersection. The video time code has the accuracy of 0.001 second, but because that one frame of video corresponds to 1/29.87 of a second, the real measurements can be done with accuracy of 0.03 second. To minimize reaction time, the subject was asked to keep his or her finger on the pause button. To avoid subject familiarity with the sample video, one participant was seeing only one video representing sample with or without edge lines.

An additional task for the laboratory experiment was related to application of raised reflective pavement markers (RRPM) on edge lines. As indicated by TxDOT, several agencies have used RRPMs to supplement applied edge lines. This practice, while increasing nighttime visibility of the roadway edge, at the same time creates a concern that the RRPMs may be interpreted by drivers as delineating traffic lanes of the same direction. Taking into account the above-mentioned potential adverse affect, the experiment focused on a special investigation of driver perception of RRPMs on the roadway edges.

RRPMs with spacing of 20 feet were temporarily mounted on the existing 4-inch edge lines on three test sections along a length equal to 15 seconds of driving with the posted speed limit. Figure 2.10 shows RRPM placement on a test highway section.

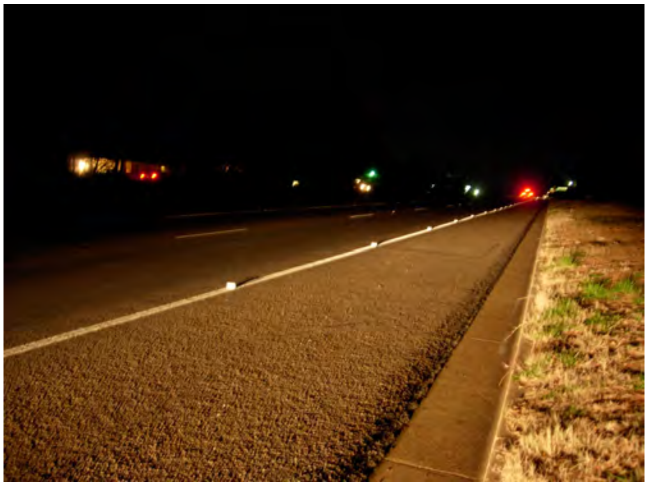


Figure 2.10: Application of RRPM to Supplement Edge Line on Test Section

The first and second sections were selected on two-lane highways without shoulder and with full size (10 feet) shoulder, respectively. The third was on a four-lane highway with full size shoulder.

Sample video of the driver visual field on each section was recorded from a moving vehicle at nighttime with vehicle high beam headlights on. With no special instructions, the videos were shown to participants, followed by the question regarding how many traffic lanes they recognized.

A total of seventy-seven people (forty-one males and thirty-six females) participated in the laboratory experiments. Table 2.1 represents the number of people who participated in the experiments and their general characteristics.

Table 2.1: Laboratory Experiment Participants

Participants	Total Number	Age, years			Average Driving Experience, years
		Average	Minimum	Maximum	
Overall	77	32	21	62	16
Male	41	29	21	62	12
Female	36	36	21	57	21

2.2 Summary

This chapter has described the objectives and design of three sets of observations that were executed to test the following basic hypotheses regarding edge-line treatments:

- Edge lines may affect vehicle transverse position and speed.
- Edge lines may enhance the driver's perception of his or her vehicle's transverse position on the roadway and this may be measured as reduced oscillation around the trajectory centerline.
- Edge lines may reduce driver emotional tension due to enhanced transverse position sensing, especially when meeting oncoming vehicles.
- At night, edge lines may allow the driver's eyes to recover faster after the "blinding" effect of oncoming vehicle headlights and this may reduce driver stress level during nighttime driving.
- Edge lines on two-lane roads provide much better driver perception of curvature than centerline markings only (without edge-line pavement marking), especially at nighttime, when visual contrast between roadway edges and the environment is very low.
- Discontinuities in the edge-line pavement marking may increase the distance for intersection advance recognition by drivers.

The next chapter describes the data, analyses, and recommendations developed using the experiment-based observations.

Chapter 3. Observations of Driver Responses to Edge Line Treatments

The present chapter focuses on the comparison of driver performance on rural two-lane highways before and after implementation of edge lines. All driver responses to the driving environment can be classified as external, which is characterized by the vehicle speed profile and moving trajectory, and internal, characterized by the driver's psycho-physiological reactions.

The external or behavioral responses are corrective actions, that the driver performs during the actual driving situation and are reflected by the vehicle speed and trajectory. For the quantitative description of these responses, parameters such as speed, longitudinal and diametrical acceleration, braking frequency, steering wheel movements, maneuvering frequency, and frequency of gear changing are typically analyzed.

Internal responses reflect driver mental workload and involve both a subjective emotional reaction and specific psycho-physiological changes due to the driving environment.

Taking into account the hypothesis formulated in previous chapters, the following driver responses were selected for detailed analysis:

- Vehicle speed
- Vehicle lateral position on the roadway
- Vehicle fluctuation around trajectory centerline
- Driver heart rate

3.1 Speed Study

The speed study included two parts: stationary observations and test drives on the same highway sections before and after edge lines were placed.

Stationary observations were conducted on highway FMs 850, 15, and 13, representing roadways with traffic lane widths of 9, 10, and 11 feet, respectively, during daytime and nighttime and with and without edge lines.

When analyzing speed, it is important to not only consider the change in overall mean values, but also the speed variation, which can indicate stability of traffic conditions. Speed variances were compared using an F-test, and because sample variances may not be equal, mean speeds were compared using a two-sample t-Test assuming unequal variances (heteroscedastic t-test).

If the variances from both populations are equal, then the F-statistic will be very close to 1, however, as the F-statistic deviates from 1, there is a higher probability that the two samples do not have the same variances. This is reported as P, or the probability of observing an F-statistic value less than the chosen threshold F when the population variances are equal.

T-tests were conducted at a significance level of 95 percent, which yields a critical two-tail t-statistic of approximately 2 (~60 degrees of freedom). The calculated t-statistic was compared to the critical statistic to determine whether the two samples originated from the same population. In addition, the root mean square error (standard error) for each test was calculated and used to determine how the differences in means compared to the expected error due to uncertainties with speed measurement.

Tables 3.1 and 3.2 show in detail the raw speed statistical results for all test sections, separated by lighting condition, highway, and edge line presence.

Table 3.1: Distribution of Vehicle Speeds

Lighting	Highway	Traffic Lane Width, ft	Edge Line Presence	Sample Size	Speed, mph			
					Mean	Std. Dev.	Sample Variance	Std. Error
Daylight	FM 850	9	Without	44	55.1	6.0	36.1	0.9
			With	58	60.2	6.2	38.0	0.8
	FM 15	10	Without	53	58.4	6.0	36.4	0.8
			With	71	58.1	6.6	43.7	0.8
	FM 13	11	Without	42	57.9	5.7	32.5	0.9
			With	58	54.5	6.4	40.9	0.8
Darkness	FM 850	9	Without	33	59.2	6.4	41.0	1.1
			With	36	58.8	6.2	38.1	1.0
	FM 15	10	Without	27	55.7	6.2	38.1	1.2
			With	40	55.3	6.3	40.1	1.0
	FM 13	11	Without	48	63.5	5.9	35.3	0.9
			With	39	63.1	5.3	28.3	0.9

When viewing these measurements, it is important to take into account the random error associated with speed and lateral position measurements, as discussed in Chapter 2. Consider this study as an example: a population exists where all vehicle speeds are exactly at the speed limit. However, due to measurement errors of 5 mph in daylight and 9 mph in darkness (Chapter 2), a sample from the population will still have some variance. Assuming that all samples will fall within the stated error measurement ranges and remembering that 99.7 percent of all samples from a population are within 3 standard deviations of the sample mean, the measurement errors will create a standard deviation in the sample of approximately 2 mph during daylight and 3 mph during darkness.

Table 3.2: Vehicle Speed Before/After Comparison Characteristics

Lighting	Highway	Traffic Lane Width, ft	Total Sample Size	Speed, mph					
				Δ Mean Speed*	t-Value	Ho Rejection Level	|Δ Variance|	F-Value	Ho Rejection Level
Daylight	FM 850	9	102	5.1	4.20	0.99	1.8	0.95	0.23
	FM 15	10	124	-0.3	0.28	0.22	7.3	0.83	0.51
	FM 13	11	100	-3.4	2.76	0.99	8.4	0.80	0.44
Darkness	FM 850	9	69	-0.4	0.26	0.20	-2.9	1.08	0.17
	FM 15	10	67	-0.4	0.24	0.19	2.0	0.95	0.09
	FM 13	11	87	-0.4	0.34	0.26	-7.0	1.25	0.52

* Mean speed with edge lines minus mean speed without edge lines (positive number indicates observed mean speed increase with edge lines)

In comparing sample means and variances for each of the three test sites, it is important to remember that these standard deviation and variance values may exist simply due to random measurement errors. Further, when comparing two samples, these errors will be present in both samples, making bias of two sample comparisons very unlikely. In fact, as noted previously, special care was taken to guarantee before and after measurements were, for each site, performed essentially identically.

First, the narrowest highway (traffic lane width 9 feet), FM 850, was examined and Figure 3.1 shows vehicle speed distributions during daylight and darkness, and this data is tabulated in Tables 3.1 and 3.2.

During daylight, the mean speed increased by 5.1 mph (9 percent) during the test with edge lines, and t-tests showed that both sets of samples (with and without edge lines) originated from different populations with significance levels of 99 percent. Speed differences are greater than the sum of the measurement errors, that is, mean speed differentials exceed the sum of the standard deviations (4 mph) that may have been induced from random measurement error during daytime observations. The F-statistics of 0.95 indicated that vehicles on the FM 850 test section had similar speed variances (variability) both with and without edge markings.

Nighttime comparisons show insignificant mean speed increases with edge-lines (0.4 mph) compared to no edge lines.

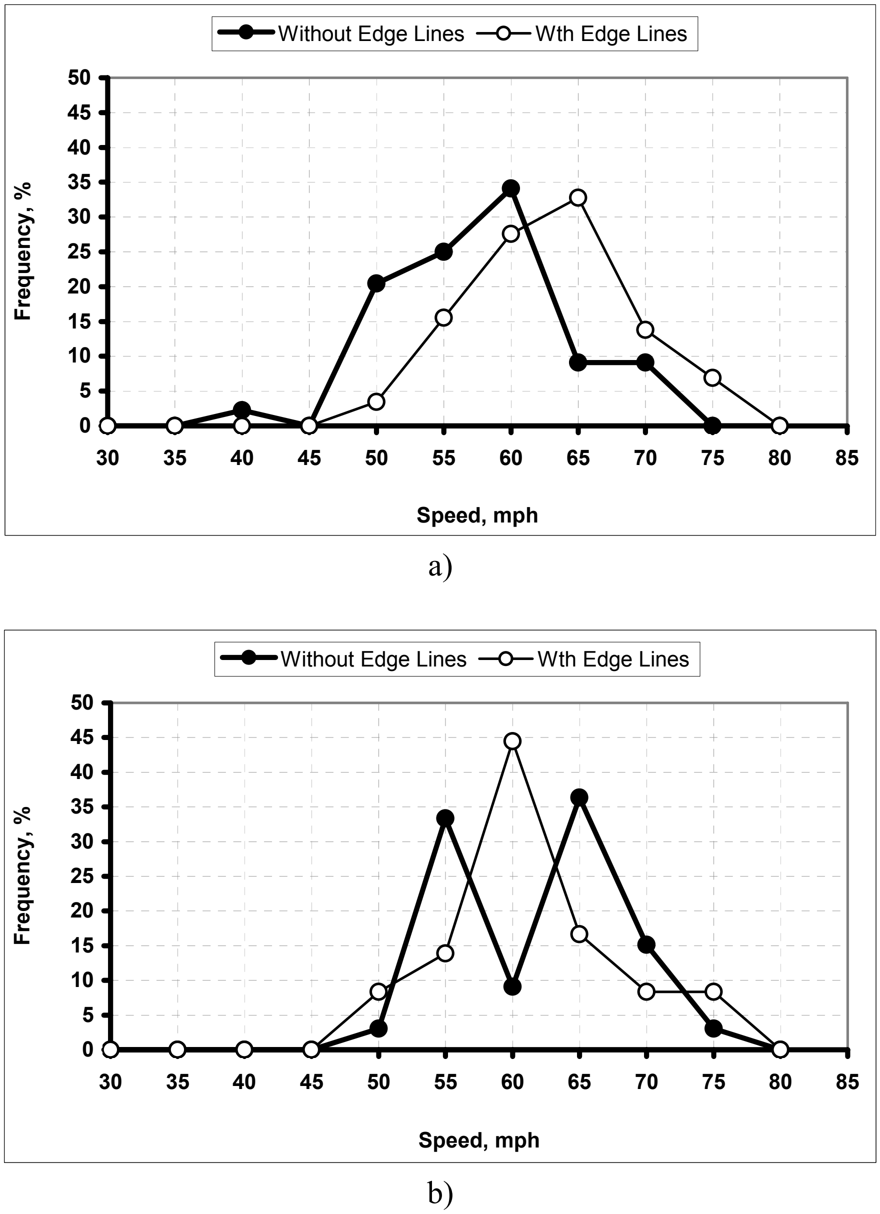
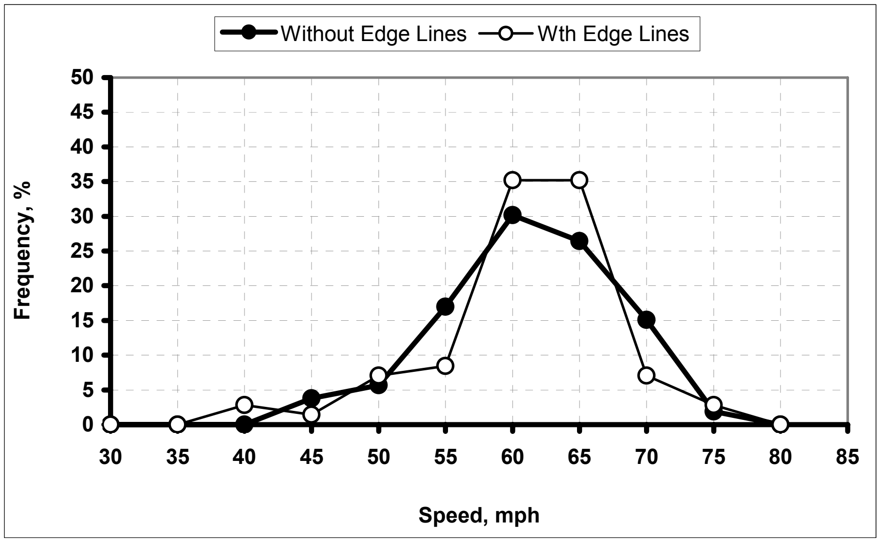
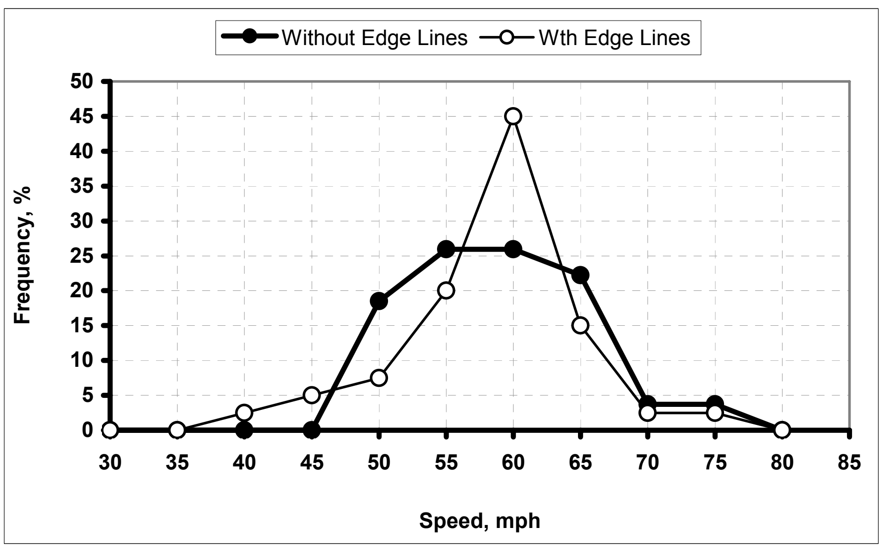


Figure 3.1: Speed Distribution Before and After Edge Line Treatment on Highway with Traffic Lane Width of 9 feet: a) daylight, and b) darkness.

Next, results from FM 15, representing roadways with traffic lane widths of 10 feet, were examined and Figure 3.2 shows vehicle speed distributions during daylight and darkness, with the numerical representation in Tables 3.1 and 3.2.



a)



b)

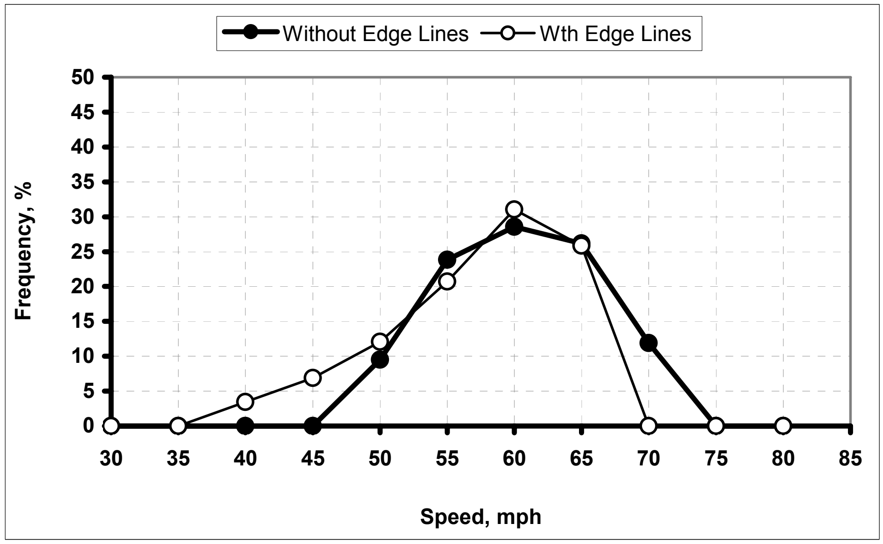
Figure 3.2: Speed Distribution Before and After Edge Lines Treatment on Highway with Traffic Lane Width of 10 feet: a) daylight, and b) darkness.

From daylight observations, only a slight reduction in mean speed for vehicles traveling the edge-striped condition was found (-0.3 mph) and this was not statistically significant.

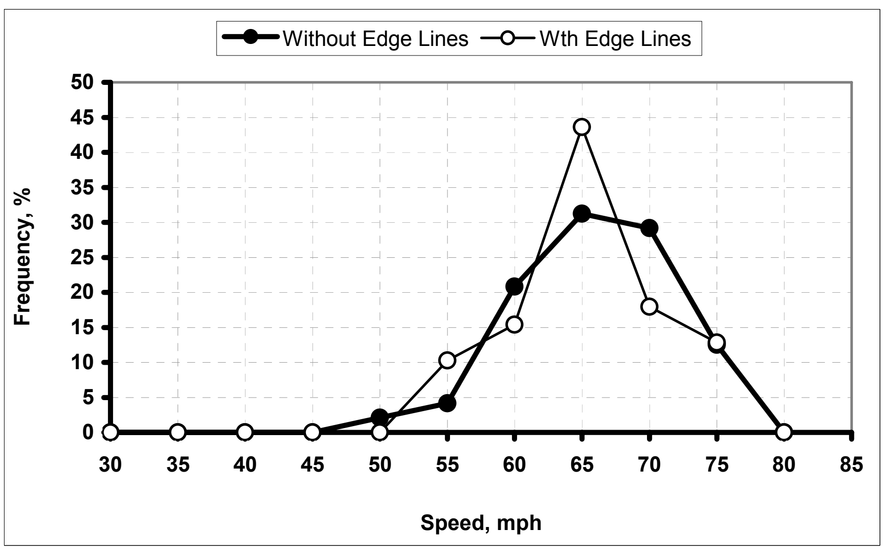
Vehicles speed variances of 44 and 36 were observed for the cases with and without edge lines, respectively. The F-statistic showed that variances for speeds with and without edge lines were not significantly different (significance level 51 percent).

Nighttime comparisons also show insignificant mean speed reduction with edge-lines of 0.4 mph, as well as speed variance.

Next, observations from FM 13 (traffic lane width 11 feet) were analyzed, and resulting vehicle speed distributions during daylight and darkness are represented in Tables 3.1 and 3.2, as well as shown graphically in Figure 3.3.



a)



b)

Figure 3.3: Speed Distribution Before and After Edge Line Treatment on Highway with Traffic Lane Width of 11 feet: a) daylight, and b) darkness.

Daytime observations found that mean speed decreased by 3.4 mph after edge lines were added. This difference was significant at a level of 99 percent and also exceeds the expected error.

Speed variance is higher for observations with edge lines than without edge lines (41 vs. 33), but this difference is not statistically significant (44 percent level).

At nighttime the difference in mean speed between vehicles on the edge-striped and non-edge-striped sections was only + 0.4 mph and insignificant. Speed variance was observed to be higher on highways without edge lines than highways with edge lines (35 versus 28), but again, this is not statistically significant (level 52 percent).

Overall, stationary observations indicated that the presence of edge lines during daylight was associated with increased speeds of 9 percent on the narrowest highway with traffic lane widths of 9 feet, and decreased speeds of 6 percent on roadways with traffic lane widths of 11 feet. No significant impact of edge lines on speeds was observed during darkness for all investigated roadways.

Stationary observations after edge lines were provided seemed to show small increases in speed variation during daylight conditions but a small variation decrease during darkness. Neither day nor night speed variation change was statistically significant (maximum significance level 52 percent).

3.1.2 Speed Observations from Test Driving

To investigate impacts of edge lines on dynamic driver responses, e.g., vehicle speed-time history, test driving was conducted on the same highways that were chosen for stationary observations and was done corresponding with the experimental design described in Chapter 2.2.

Tables 3.3, 3.4, and 3.5 show the resulting speed statistical results for all test sections, separated by highway (traffic lane width), roadway curvature, lighting condition, and edge line presence (before and after). Traffic situations, such as slow-moving vehicles and passing, were eliminated during data reduction and were not considered in the analysis.

Overall, test drivers exhibited slightly higher speeds after edge line application during both daylight and darkness. The daytime average speed increase was 3 mph (7 percent), 4 mph (7 percent), and 3 mph (6 percent) on highways with traffic lane widths of 9, 10, and 11 feet respectively. At nighttime the corresponding values were 3 mph (5 percent), 3 mph (7 percent), and 4 mph (7 percent).

Among the individual drivers who participated, speed increases were varied but generally less then 5 mph. On all observed roadway classes for both daylight and darkness, only two drivers increased their speed by more than 5 mph, with the highest increase at 7 mph. The same characteristics were observed with data separation by roadway horizontal alignment for both straight and curved test section segments.

Table 3.3: Recorded Test Driver Speeds

Driver	Mean Spot Speed, mph											
	Daytime						Nighttime					
	Overall for Test Section		Overall for Segments				Overall for Test Section		Overall for Segments			
			Straight		Curved				Straight		Curved	
	before	after	before	after	before	after	before	after	before	after	before	after
FM 850, Traffic Lane Width of 9 feet												
1	48.18	54.25	48.91	54.89	46.73	51.73	49.02	49.60	49.31	50.55	46.66	47.74
2	51.16	52.80	52.36	53.72	49.77	51.89	47.73	n/a	48.87	n/a	45.36	n/a
3	51.12	53.06	51.77	54.03	49.98	52.16	50.00	55.30	50.77	56.37	49.28	54.24
4	49.86	52.90	51.33	54.48	48.72	51.44	47.60	48.00	49.14	49.24	46.33	46.20
5	54.28	60.89	55.83	61.84	52.92	60.06	51.22	52.69	52.04	53.66	50.51	51.83
6	50.38	54.62	51.97	56.34	48.99	53.12	47.84	51.33	49.33	52.63	46.54	50.19
7	53.57	54.68	54.32	55.54	52.92	53.94	51.57	55.53	52.77	55.93	50.52	55.12
8	45.30	49.74	47.20	51.40	43.63	48.29	n/a	n/a	n/a	n/a	n/a	n/a
9	56.06	57.24	54.87	58.12	57.24	56.47	52.36	56.10	53.27	57.30	51.56	55.05
Overall	51.10	54.47	52.06	55.60	50.10	53.23	49.67	52.65	50.69	53.67	48.35	51.48
FM 15, Traffic Lane Width of 10 feet												
1	49.54	54.19	51.61	52.58	47.23	47.17	46.62	49.49	48.69	51.70	44.03	47.14
2	49.92	52.42	52.05	54.06	47.00	50.17	49.71	n/a	52.69	n/a	46.36	n/a
3	49.73	54.43	51.39	56.49	47.99	51.29	48.12	53.29	49.52	54.87	45.88	51.44
4	47.43	52.21	49.07	53.18	44.21	49.33	47.89	50.56	50.14	52.90	45.61	47.71
5	54.94	61.32	57.54	63.04	53.12	60.12	52.38	53.62	54.22	54.89	51.09	52.73
6	46.87	51.52	49.67	55.08	44.90	49.02	46.19	51.26	49.92	54.39	43.59	49.07
7	50.92	50.99	52.73	52.33	49.66	50.06	48.89	53.10	52.14	57.36	46.61	50.12
8	43.48	47.43	45.66	49.56	41.58	45.30	n/a	n/a	n/a	n/a	n/a	n/a
9	51.24	51.28	53.36	53.55	49.76	49.69	49.33	52.02	52.14	54.16	47.64	50.53
Overall	49.34	52.87	51.45	54.43	47.27	50.24	48.64	51.91	51.18	54.32	46.35	49.82
FM 13, Traffic Lane Width of 11 feet												
1	54.08	58.31	54.40	58.83	52.63	56.95	52.92	56.32	53.65	57.13	51.43	55.09
2	54.59	57.94	55.68	58.43	53.21	57.54	54.39	n/a	55.17	n/a	53.90	n/a
3	54.79	59.93	55.82	60.61	53.84	58.96	56.09	61.38	56.40	62.00	55.18	60.99
4	54.07	59.2	54.86	59.79	52.13	57.69	54.67	55.03	54.74	55.93	53.02	53.66
5	61.41	65.42	62.23	67.1	60.6	63.74	59.57	59.65	60.03	60.91	59.11	58.38
6	53.19	56.79	54.32	58.18	52.06	55.41	53.49	58.18	53.95	58.77	53.04	57.60
7	57.50	58.05	58.05	58.50	57.01	57.61	55.02	62.47	56.13	63.51	53.91	61.42
8	53.01	54.86	54.01	55.46	52.00	54.19	n/a	n/a	n/a	n/a	n/a	n/a
9	59.68	59.80	60.48	60.39	58.89	59.21	56.59	61.03	57.28	61.54	55.89	60.52
Overall	55.81	58.92	56.65	59.70	54.71	57.92	55.34	59.15	55.92	59.97	54.44	58.24

Table 3.4: Recorded Test Driver Speed Variability

Driver	Spot Speed Standard Deviation, mph											
	Daytime						Nighttime					
	Overall for Test Section		Overall for Segments				Overall for Test Section		Overall for Segments			
			Straight		Curved				Straight		Curved	
	before	after	before	after	before	after	before	after	before	after	before	after
FM 850, Traffic Lane Width of 9 feet												
1	3.42	3.90	1.46	1.42	0.81	0.95	3.12	3.72	0.76	1.54	0.96	1.05
2	4.02	3.21	2.06	1.47	0.87	0.88	4.90	n/a	2.38	n/a	1.48	n/a
3	3.27	3.71	1.58	1.42	0.77	0.68	3.36	4.27	1.14	1.47	0.76	0.87
4	3.71	4.10	1.28	1.66	0.91	1.02	3.63	3.83	1.26	1.76	1.11	1.07
5	2.14	1.17	2.83	1.34	1.53	1.02	1.04	0.91	1.14	0.92	0.94	0.91
6	1.06	1.59	1.21	1.55	0.92	1.62	1.24	1.11	1.11	1.11	1.35	1.11
7	0.86	1.13	1.15	1.23	0.60	1.05	1.19	1.41	1.14	1.54	1.24	1.28
8	1.36	1.29	1.69	1.29	1.06	1.30	n/a	n/a	n/a	n/a	n/a	n/a
9	0.91	1.05	1.53	1.20	0.29	0.93	1.05	0.85	0.99	1.03	1.10	0.69
Overall	2.30	2.35	1.64	1.40	0.86	1.05	2.44	2.30	1.24	1.34	1.12	1.00
FM 15, Traffic Lane Width of 10 feet												
1	2.91	3.56	1.08	2.9	1.35	2.23	3.39	3.23	1.20	1.48	1.33	1.51
2	4.72	2.56	2.55	1.09	1.77	1.22	4.36	n/a	1.92	n/a	1.76	n/a
3	3.07	4.23	1.29	1.95	1.01	1.22	2.79	2.79	1.38	1.61	1.04	1.23
4	4.22	3.95	1.70	1.94	1.36	1.05	3.85	3.65	1.85	1.68	1.17	1.60
5	1.60	1.22	1.63	1.26	1.58	1.18	1.56	1.10	1.52	1.11	1.58	1.09
6	1.53	1.79	1.32	1.76	1.67	1.80	1.62	1.58	1.50	1.28	1.71	1.79
7	0.87	1.13	0.69	1.26	1.00	1.04	1.51	1.80	1.22	1.60	1.72	1.94
8	1.18	1.74	1.47	1.70	0.93	1.79	n/a	n/a	n/a	n/a	n/a	n/a
9	1.20	1.15	1.40	1.44	1.05	0.94	1.29	1.33	1.82	1.51	0.97	1.20
Overall	2.37	2.37	1.46	1.70	1.30	1.39	2.55	2.21	1.55	1.47	1.41	1.48
FM 13, Traffic Lane Width of 11 feet												
1	2.23	2.11	1.18	1.23	0.94	0.99	2.80	2.77	1.49	1.66	0.96	1.39
2	3.59	2.39	1.75	1.47	1.25	0.88	3.17	n/a	1.84	n/a	0.89	n/a
3	3.58	2.99	1.28	1.57	1.14	0.76	2.32	2.21	1.46	1.27	0.79	0.84
4	3.18	2.79	1.79	1.5	1.47	1.34	3.65	3.34	2.03	1.94	1.55	1.50
5	1.12	1.65	1.22	1.82	1.01	1.48	1.07	2.02	1.01	1.20	1.12	2.83
6	1.26	1.47	1.38	1.37	1.14	1.58	1.25	1.17	1.35	1.12	1.15	1.21
7	1.02	0.87	1.19	1.11	0.87	0.63	1.35	1.75	1.68	2.16	1.01	1.35
8	1.43	1.21	1.66	1.52	1.19	0.86	n/a	n/a	n/a	n/a	n/a	n/a
9	1.29	1.16	1.45	1.54	1.14	0.78	1.44	1.18	2.03	1.54	0.85	0.81
Overall	2.08	1.85	1.43	1.46	1.13	1.03	2.13	2.06	1.61	1.56	1.04	1.42

Table 3.5: Test Driver Speed Comparisons, Before versus After Edge Lines

Driver	Spot Speed Difference (after minus before)											
	Mean Spot Speed, mph						Spot Speed Standard Deviation, mph					
	Overall for Test Section		Overall for Segments				Overall for Test Section		Overall for Segments			
			Straight		Curved				Straight		Curved	
	day	night	day	night	day	night	day	night	day	night	day	night
FM 850, Traffic Lane Width of 9 feet												
1	6.07	0.58	5.98	1.24	5.00	1.08	0.48	0.60	-0.04	0.78	0.14	0.09
2	1.64	n/a	1.36	n/a	2.12	n/a	-0.81	n/a	-0.59	n/a	0.01	n/a
3	1.94	5.30	2.26	5.60	2.18	4.96	0.44	0.91	-0.16	0.33	-0.09	0.11
4	3.04	0.40	3.15	0.10	2.72	-0.13	0.39	0.20	0.38	0.50	0.11	-0.04
5	6.61	1.47	6.01	1.62	7.14	1.32	-0.97	-0.13	-1.49	-0.22	-0.51	-0.03
6	4.24	3.49	4.37	3.30	4.13	3.65	0.54	-0.13	0.34	-0.01	0.71	-0.24
7	1.11	3.95	1.22	3.16	1.01	4.60	0.28	0.21	0.08	0.40	0.45	0.04
8	4.45	n/a	4.20	n/a	4.67	n/a	-0.06	n/a	-0.41	n/a	0.24	n/a
9	1.18	3.74	3.25	4.03	-0.78	3.49	0.15	-0.20	-0.34	0.04	0.65	-0.41
Overall	3.36	2.70	3.53	2.72	3.13	2.71	0.05	0.21	-0.25	0.26	0.19	-0.07
FM 15, Traffic Lane Width of 10 feet												
1	4.65	2.87	0.97	3.01	-0.06	3.11	0.65	-0.16	1.82	0.28	0.88	0.18
2	2.50	n/a	2.01	n/a	3.17	n/a	-2.16	n/a	-1.46	n/a	-0.55	n/a
3	4.70	5.17	5.10	5.35	3.30	5.56	1.16	0.00	0.66	0.23	0.21	0.19
4	4.78	2.67	4.11	2.76	5.12	2.10	-0.27	-0.20	0.24	-0.17	-0.31	0.43
5	6.38	1.24	5.50	0.67	7.00	1.64	-0.38	-0.46	-0.37	-0.41	-0.40	-0.49
6	4.65	5.07	5.41	4.47	4.12	5.48	0.26	-0.04	0.45	-0.22	0.13	0.08
7	0.07	4.21	-0.40	5.22	0.40	3.50	0.26	0.28	0.57	0.38	0.04	0.22
8	3.95	n/a	3.90	n/a	3.72	n/a	0.56	n/a	0.23	n/a	0.85	n/a
9	0.04	2.70	0.19	2.02	-0.07	2.89	-0.05	0.04	0.04	-0.30	-0.11	0.23
Overall	3.52	3.42	2.98	3.36	2.97	3.47	0.00	-0.08	0.24	-0.03	0.08	0.12
FM 13, Traffic Lane Width of 11 feet												
1	4.23	3.40	4.43	3.48	4.32	3.66	-0.12	-0.03	0.05	0.17	0.05	0.43
2	3.35	n/a	2.75	n/a	4.33	n/a	-1.20	n/a	-0.28	n/a	-0.37	n/a
3	5.14	5.29	4.79	5.60	5.12	5.81	-0.59	-0.11	0.29	-0.19	-0.38	0.05
4	5.13	0.36	4.93	1.19	5.56	0.64	-0.39	-0.31	-0.29	-0.09	-0.13	-0.05
5	4.01	0.08	4.87	0.88	3.14	-0.73	0.53	0.95	0.60	0.19	0.47	1.71
6	3.61	4.69	3.87	4.82	3.35	4.56	0.21	-0.08	-0.01	-0.23	0.43	0.06
7	0.55	7.45	0.44	7.38	0.60	7.51	-0.15	0.41	-0.08	0.48	-0.23	0.34
8	1.86	n/a	1.45	n/a	2.19	n/a	-0.21	n/a	-0.14	n/a	-0.33	n/a
9	0.12	4.45	-0.09	4.27	0.32	4.63	-0.13	-0.26	0.09	-0.48	-0.36	-0.04
Overall	3.11	3.67	3.05	3.95	3.21	3.72	-0.23	0.08	0.03	-0.02	-0.09	0.36

The data also indicated some impact of edge lines on speed variance. On the narrowest investigated roadway (traffic lane width 9 feet), for the majority of drivers, (6 of 9) speed standard deviations increased an average of 23 percent under daytime conditions and 17 percent at night. On highways with traffic lane widths of 11 feet, such edge-lines impacts were observed only for two drivers during both daylight and darkness, while all other test drivers were characterized by reduced speed variance, which averaged 12 percent.

Further data separation by roadway horizontal alignment shows that on highways with traffic lane widths of 9 feet, increased speed variability was observed mostly (7 of 9 drivers) on curved segments during daylight and on straight sections during nighttime. On wider highways (traffic lane widths of 10 and 11 feet), edge lines seem to be related to increases in speed variability most frequently on straight segments during the day and on curves at night.

Comparison of before and after edge-line placement indicated speed variance averages for all drivers on all highways increased from 0.1 to 0.7 mph under daytime conditions and decreased from 0.1 to 0.9 mph under nighttime conditions. No statistically significant relations were identified between speed variance and highway classes, roadway curvature, or lighting conditions.

3.1.3 Summary of Test Drive Findings

After edge-line placement, speed increased for both day and night conditions by approximately 7 percent or 4 mph, on the average, for all drivers and investigated highway classes.

Test drives during both daylight and darkness after edge-line treatment were characterized by changes in speed variance. These observations included an average 20 percent increase in speed variations on 9-feet lane widths and an average 14 percent reduction on wider 10- and 11-feet lanes. On 9-feet lane widths, the increased speed variance was most frequently observed on curved segments during daytime and straight segments at night, while wider roadways tended to display an opposite effect (straight sections during daylight and curves at night).

3.2 Lateral Position Study

Like the speed study, investigation of vehicle lateral positions on the roadway included stationary observations and test drives on the same highway sections before and after edge-line placement. The statistical methodology utilized for stationary speed observations was also applied to lateral positions. Taking into account the random error associated with lateral position measurements was 0.98 feet for daytime lighting conditions and 1.97 feet for nighttime (Chapter 2.1), this translates to standard deviations of 0.33 and 0.66 feet for day and nighttime, respectively.

Tables 3.6, 3.7 and 3.8 detail the raw lateral positions statistical results obtained by the stationary observations for all test sections, separated by lighting condition, highway, and edge-line presence.

Table 3.6: Lateral Positions Statistical Results

Lighting	Highway	Traffic Lane Width, ft	Edge Line Presence	Sample Size	Lateral Position (m) *			
					Mean	Std. Dev.	Sample Variance	Std. Error
Daylight	FM 850	9	Without	41	1.52	0.99	0.99	0.16
			With	47	1.25	0.67	0.45	0.10
	FM 15	10	Without	53	0.93	0.77	0.59	0.11
			With	57	2.53	0.99	0.98	0.13
	FM 13	11	Without	43	2.38	1.00	1.01	0.15
			With	57	3.31	0.78	0.61	0.10
Darkness	FM 850	9	Without	26	1.09	0.78	0.61	0.15
			With	46	1.74	0.93	0.87	0.14
	FM 15	10	Without	36	0.71	0.70	0.49	0.12
			With	43	2.53	1.44	2.07	0.22
	FM 13	11	Without	49	1.85	0.81	0.66	0.12
			With	39	2.87	1.29	1.68	0.21

* Distance from center of driver's side tire to outside edge of nearest centerline

Table 3.7: Distribution of Vehicle Lateral Position

Lighting	Highway	Traffic Lane Width, ft	Total Sample Size	Lateral Position (m) *					
				Δ Mean Lat. Pos.**	t-Value	Ho Rejection Level	|Δ Variance|	F-Value	Ho Rejection Level
Daylight	FM 850	9	88	-0.27	1.45	0.85	0.54	2.20	0.99
	FM 15	10	110	1.59	-9.45	0.99	0.39	0.61	0.99
	FM 13	11	100	0.93	-5.04	0.99	0.40	1.66	0.92
Darkness	FM 850	9	72	0.65	-3.16	0.99	0.26	0.70	0.65
	FM 15	10	79	1.82	-7.34	0.99	1.57	0.24	0.99
	FM 13	11	88	1.02	-4.29	0.99	1.02	0.40	0.99

* Mean lateral position with edge lines minus mean lateral position without edge lines (negative number indicates observed movement towards center of roadway)

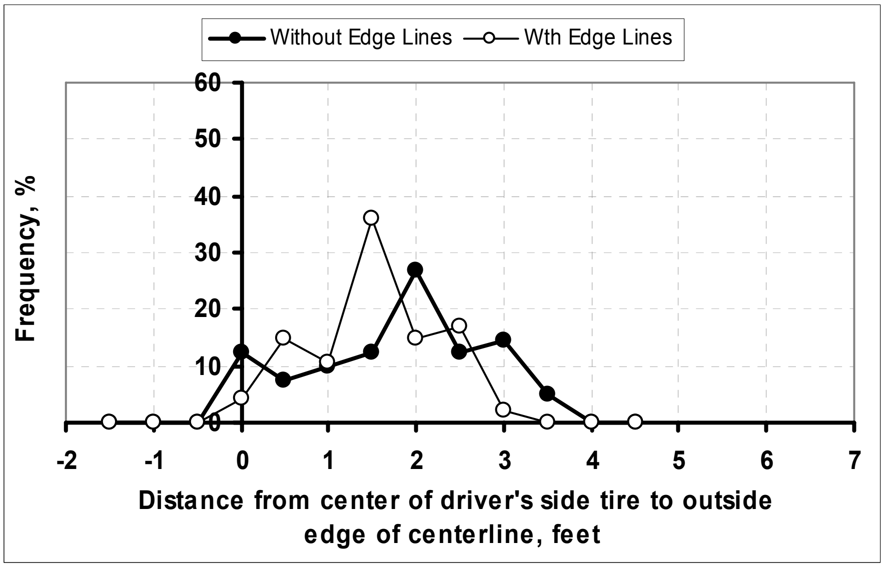
Table 3.8: Vehicle Lateral Position Before/After Comparison Characteristics

Driver	Mean Distance to Centerline, cm											
	Daytime						Nighttime					
	Overall for Test Section		Overall for Segments				Overall for Test Section		Overall for Segments			
			Straight		Curved				Straight		Curved	
	before	after	before	after	before	after	before	after	before	after	before	after
FM 850, Traffic Lane Width of 9 feet												
1	0.93	0.40	0.96	0.33	0.90	0.45	0.34	0.74	0.35	0.71	0.34	0.78
2	0.32	0.59	0.39	0.60	0.25	0.58	0.38	n/a	0.28	n/a	0.50	n/a
3	-0.21	0.27	-0.13	0.20	-0.28	0.34	-0.20	0.06	-0.24	0.00	-0.17	0.12
4	0.05	0.37	-0.08	0.29	0.17	0.44	0.46	0.59	0.59	0.55	0.32	0.63
5	0.36	0.94	0.74	0.91	0.07	0.97	0.78	0.76	0.80	0.78	0.76	0.74
6	0.68	0.74	0.66	0.65	0.70	0.83	0.71	0.66	0.72	0.78	0.71	0.54
7	1.11	1.12	1.11	1.07	1.12	1.15	0.95	1.03	0.94	0.95	0.95	1.11
8	0.97	0.45	0.92	0.49	1.01	0.42	n/a	n/a	n/a	n/a	n/a	n/a
9	1.22	1.13	1.11	1.09	1.33	1.17	1.10	0.90	1.07	0.91	1.12	0.89
Overall	0.60	0.67	0.63	0.63	0.59	0.71	0.56	0.68	0.56	0.67	0.57	0.69
FM 15, Traffic Lane Width of 10 feet												
1	0.54	0.82	0.74	0.87	0.37	0.79	0.56	0.48	0.77	0.55	0.40	0.44
2	0.36	0.85	0.36	0.84	0.35	0.85	0.09	n/a	-0.10	n/a	0.23	n/a
3	-0.03	0.22	0.11	0.37	-0.16	0.12	0.33	0.36	0.41	0.51	0.27	0.26
4	0.54	0.75	0.72	0.79	0.36	0.71	0.68	0.77	0.65	0.81	0.70	0.74
5	1.12	-0.45	1.39	-0.33	0.92	-0.54	1.09	1.12	1.08	1.30	1.10	0.99
6	0.59	0.79	0.70	0.96	0.52	0.68	0.95	0.78	1.10	0.78	0.84	0.78
7	1.67	1.54	1.68	1.63	1.65	1.49	1.38	1.35	1.47	1.20	1.32	1.45
8	1.24	0.51	1.50	0.61	1.01	0.42	n/a	n/a	n/a	n/a	n/a	n/a
9	1.53	1.49	1.58	1.36	1.50	1.59	1.57	1.21	1.96	1.30	1.34	1.15
Overall	0.84	0.73	0.98	0.79	0.72	0.68	0.83	0.87	0.92	0.92	0.78	0.83
FM 13, Traffic Lane Width of 11 feet												
1	1.46	1.05	1.32	0.96	1.59	1.18	0.99	0.93	0.83	0.68	1.15	1.09
2	1.13	1.28	0.90	1.06	1.39	1.51	1.07	n/a	0.96	n/a	1.18	n/a
3	0.64	0.94	0.28	0.88	0.99	1.00	0.74	0.71	0.60	0.56	0.90	0.86
4	0.98	1.29	0.76	1.22	1.22	1.35	1.10	1.23	0.98	1.15	1.20	1.31

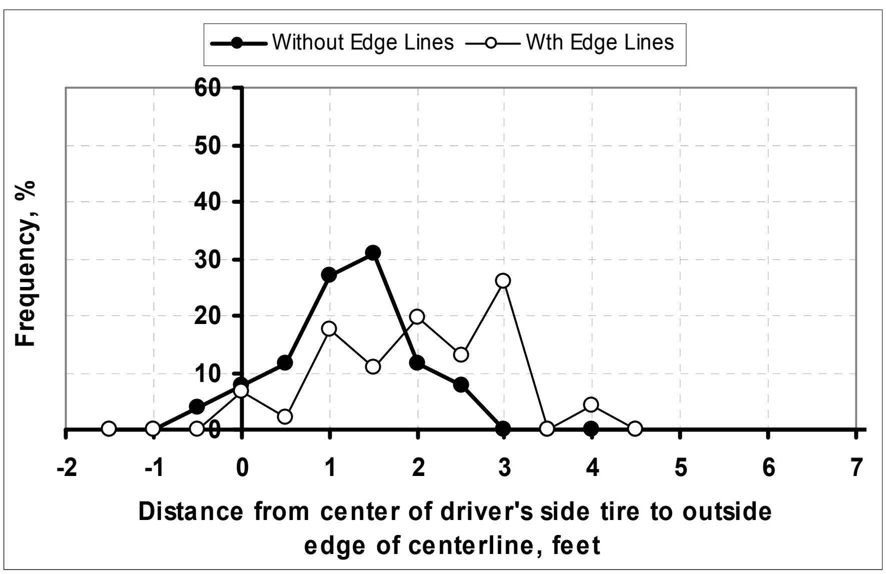
Driver	Mean Distance to Centerline, cm											
	Daytime						Nighttime					
	Overall for Test Section		Overall for Segments				Overall for Test Section		Overall for Segments			
			Straight		Curved				Straight		Curved	
	before	after	before	after	before	after	before	after	before	after	before	after
5	1.54	0.30	1.13	-0.10	1.99	0.65	1.77	1.30	1.56	1.31	1.97	1.30
6	1.86	1.47	1.53	1.21	2.19	1.74	1.70	1.60	1.57	1.42	1.82	1.77
7	2.54	1.98	2.05	1.78	2.97	2.21	2.01	1.73	1.80	1.49	2.25	1.94
8	1.61	1.16	1.49	1.12	1.72	1.20	n/a	n/a	n/a	n/a	n/a	n/a
9	2.60	2.58	2.41	2.45	2.79	2.70	2.29	1.98	1.95	1.88	2.62	2.09
Overall	1.59	1.34	1.32	1.17	1.87	1.50	1.46	1.35	1.28	1.21	1.64	1.48

3.2.2 Observations on FM 850, Lane Width 9 Feet

Figure 3.4 shows vehicle lateral position distributions on the narrowest investigated highway (traffic lane width 9 feet), FM 850, during daylight and darkness, and the numerical data are tabulated in Tables 3.6 and 3.7.



a)



b)

Figure 3.4: Vehicle Lateral Position Distribution Before and After Edge Lines Treatment on Highway with Traffic 9 feet Lane Width: a) daylight, and b) darkness

Though statistically significant, the difference in mean lateral position for the edge lines versus no edge lines conditions does not exceed the expected measurement error. Therefore, differences between vehicle lateral positions with and without edge lines for both daylight and darkness were found to be insignificant.

However, the data indicated that for all daytime observations, the mean lateral position was 0.32 feet closer to the centerline when edge lines were present. Nighttime lateral position observations indicate an opposite movement with overall mean of about 0.66 feet further from the centerline when edge lines were present

3.2.3 Observations on FM 15, Lane Width 10 Feet

Next, results from FM 15, representing roadways with traffic lane widths of 10 feet, were examined and Figure 3.5 shows vehicle lateral position distributions during daylight and darkness, with the data presented in Tables 3.6 and 3.7.

During daylight, vehicles were observed to move closer to the edge of the roadway while edge lines were present. Observations showed an average movement of 1.64 feet towards the edge of the roadway on edge-striped roadways and this change had a significance level of 99 percent and exceeded the expected measurement error.

Lateral position variance for observations with edge lines is higher than for observations without edge lines, and the F-test indicated that the populations have different variances with a significance level of 99 percent.

At nighttime, mean lateral position was observed to be 1.9 feet closer to the edge of the roadway while edge lines were present. This value is significant at a level of 99 percent and is also greater than the expected measurement error of 0.6 feet. Also, lateral position variance was significantly greater for the edge-striped observations with a difference greater than the expected error.

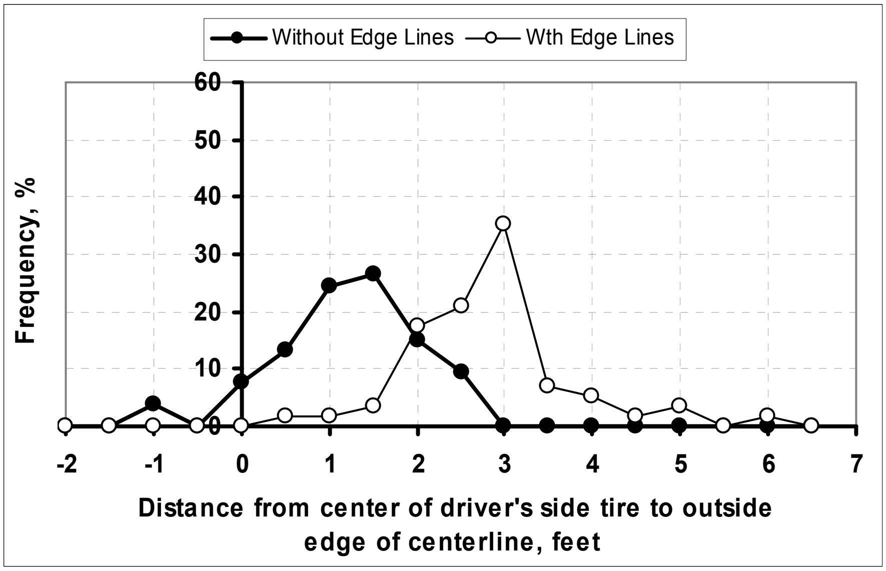
3.2.4 Observations on FM 13, Lane Width 11 Feet

Lateral vehicle positions on FM 13, representing a test section with a traffic lane width of 11 feet, are shown in Figure 3.6 and tabulated in Tables 3.6 and 3.7.

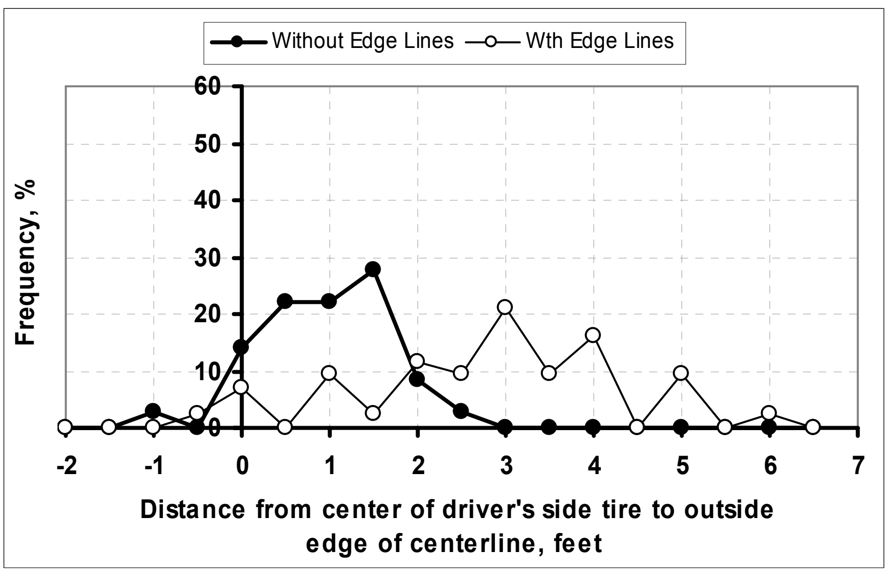
Mean lateral position was 0.66 feet closer to the edge of the roadway for observations with edge lines, but this difference does not exceed the total expected error.

Lateral position variance was greater (89 percent statistical significance level) when edge lines were present: variance without edge lines was 0.09, while variance with edge lines was 0.14.

At night, observations showed that mean lateral position was 0.98 feet closer to the edge of the roadway when edge lines were present. This change had a significance level of 99 percent but was not greater than the expected measurement error. Lateral position variance at night was greater for observations with edge lines than for observations without edge lines (0.16 versus 0.06). The F-test indicated that the sample variances are different with a significance of 99 percent.

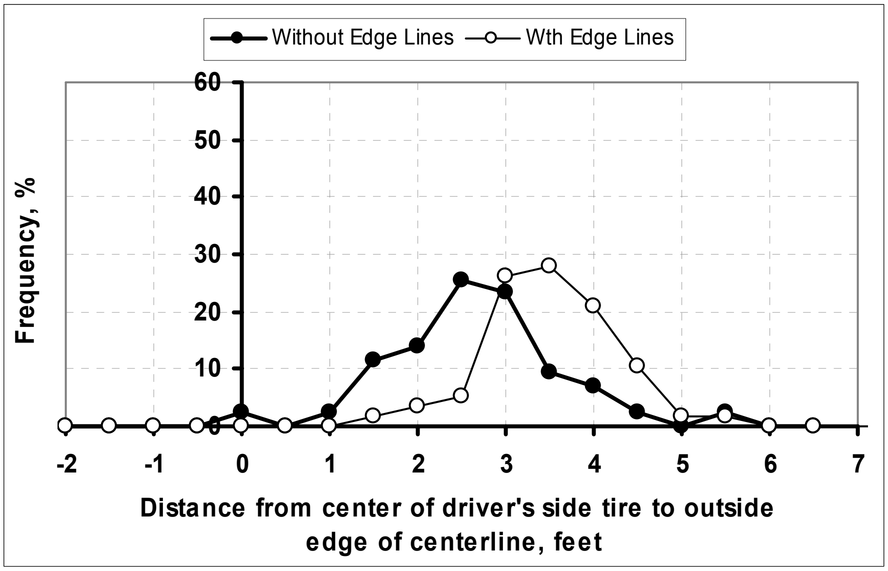


a)

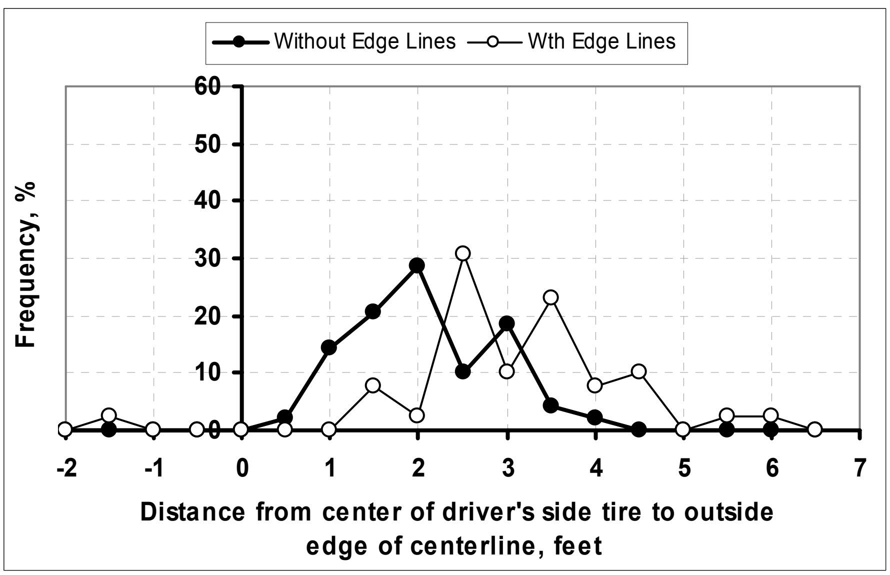


b)

Figure 3.5: Vehicle Lateral Position Distributions Before and After Edge Lines Treatment on Highway with Traffic Lane Width 10 feet: a) daylight, and b) darkness



a)



b)

Figure 3.6: Vehicle Lateral Position Distributions Before and After Edge Lines Treatment on Highway with Traffic Lane Width 11 feet: a) daylight, and b) darkness

On pavements with 9-feet lane widths, the lateral position stationary observations indicated that placement of edge lines did not significantly effect vehicle lateral position in any lighting condition. On wider roadways presence of edge lines was associated with vehicle paths being closer to pavement edge during both daylight and darkness, with the greatest impact where the traffic lane width was 10 feet.

3.2.5 Later Position Measurements from Test Driving

For test drives, the distance from the vehicle's driver-side tire to the outside of the centerline was measured each 1 second during the driving time. Tables 3.9, 3.10, and 3.11 show statistical results for all test sections, separated by highway (traffic lane width), roadway curvature, lighting condition, and edge-line presence (before and after). Like the speed study, all traffic situations that may impact vehicle lateral position but are not related to the investigated processes, such as any obstacles in close proximity to the roadway, speed reduction caused by slow-moving lead vehicles, passing of test vehicle by another car, and meeting an oncoming vehicle (2 seconds before and 2 seconds after) were eliminated from further analysis.

The data indicated that on the highway with a traffic lane width of 9 feet, during daylight, four out of nine drivers moved the vehicle closer to the pavement edge after edge-line placement an average by 0.43 feet. Three drivers had insignificant position changes (mean distance to the centerline less than measurement error of 0.13 feet), and two drivers moved the test vehicle toward the roadway center an average by 0.52 feet. The same trend was observed during nighttime, with a slightly lower value of average distance to centerline increase 0.26 feet.

During daytime on the highway with 10-feet traffic lane width, the majority of drivers (five of nine) moved closer to the roadway edge an average by 0.29 feet, while two drivers moved closer to the roadway center an average by 1.15 feet. Nighttime tests indicated no significant changes in vehicle lateral position due to edge-lines placement.

On the highway with a traffic lane width of 11 feet, test drivers generally moved toward the centerline an average of 0.26 to 0.62 feet during daylight and darkness, respectively.

Data separation by roadway horizontal alignment, in general, is similar to the above-mentioned results and at the same time indicates different impacts of edge lines at daylight and darkness for straight and curved segments.

On straight segments of highways with traffic lane widths of 9 feet, during daytime, the mean distance to the centerline was 0.26 feet closer to the roadway edge after edge-line placement versus 0.52 feet on curves and around 0.29 feet for both during darkness. Also, during nighttime, the impact of edge lines was greatly reduced and more than 50 percent of drivers did not experience significant changes in vehicle lateral position on straight segments. This phenomenon was not observed on the curved segments, where drivers moved closer to the roadway edge during both day and night.

Table 3.9: Vehicle Lateral Position Measured During Test Driving

Driver	Mean Distance to Centerline, cm											
	Daytime						Nighttime					
	Overall for Test Section		Overall for Segments				Overall for Test Section		Overall for Segments			
			Straight		Curved				Straight		Curved	
	before	after	before	after	before	after	before	after	before	after	before	after
FM 850, Traffic Lane Width of 9 feet												
1	0.93	0.40	0.96	0.33	0.90	0.45	0.34	0.74	0.35	0.71	0.34	0.78
2	0.32	0.59	0.39	0.60	0.25	0.58	0.38	n/a	0.28	n/a	0.50	n/a
3	-0.21	0.27	-0.13	0.20	-0.28	0.34	-0.20	0.06	-0.24	0.00	-0.17	0.12
4	0.05	0.37	-0.08	0.29	0.17	0.44	0.46	0.59	0.59	0.55	0.32	0.63
5	0.36	0.94	0.74	0.91	0.07	0.97	0.78	0.76	0.80	0.78	0.76	0.74
6	0.68	0.74	0.66	0.65	0.70	0.83	0.71	0.66	0.72	0.78	0.71	0.54
7	1.11	1.12	1.11	1.07	1.12	1.15	0.95	1.03	0.94	0.95	0.95	1.11
8	0.97	0.45	0.92	0.49	1.01	0.42	n/a	n/a	n/a	n/a	n/a	n/a
9	1.22	1.13	1.11	1.09	1.33	1.17	1.10	0.90	1.07	0.91	1.12	0.89
Overall	0.60	0.67	0.63	0.63	0.59	0.71	0.56	0.68	0.56	0.67	0.57	0.69
FM 15, Traffic Lane Width of 10 feet												
1	0.54	0.82	0.74	0.87	0.37	0.79	0.56	0.48	0.77	0.55	0.40	0.44
2	0.36	0.85	0.36	0.84	0.35	0.85	0.09	n/a	-0.10	n/a	0.23	n/a
3	-0.03	0.22	0.11	0.37	-0.16	0.12	0.33	0.36	0.41	0.51	0.27	0.26
4	0.54	0.75	0.72	0.79	0.36	0.71	0.68	0.77	0.65	0.81	0.70	0.74
5	1.12	-0.45	1.39	-0.33	0.92	-0.54	1.09	1.12	1.08	1.30	1.10	0.99
6	0.59	0.79	0.70	0.96	0.52	0.68	0.95	0.78	1.10	0.78	0.84	0.78
7	1.67	1.54	1.68	1.63	1.65	1.49	1.38	1.35	1.47	1.20	1.32	1.45
8	1.24	0.51	1.50	0.61	1.01	0.42	n/a	n/a	n/a	n/a	n/a	n/a
9	1.53	1.49	1.58	1.36	1.50	1.59	1.57	1.21	1.96	1.30	1.34	1.15
Overall	0.84	0.73	0.98	0.79	0.72	0.68	0.83	0.87	0.92	0.92	0.78	0.83
FM 13, Traffic Lane Width of 11 feet												
1	1.46	1.05	1.32	0.96	1.59	1.18	0.99	0.93	0.83	0.68	1.15	1.09
2	1.13	1.28	0.90	1.06	1.39	1.51	1.07	n/a	0.96	n/a	1.18	n/a
3	0.64	0.94	0.28	0.88	0.99	1.00	0.74	0.71	0.60	0.56	0.90	0.86
4	0.98	1.29	0.76	1.22	1.22	1.35	1.10	1.23	0.98	1.15	1.20	1.31

Driver	Mean Distance to Centerline, cm											
	Daytime						Nighttime					
	Overall for Test Section		Overall for Segments				Overall for Test Section		Overall for Segments			
			Straight		Curved				Straight		Curved	
	before	after	before	after	before	after	before	after	before	after	before	after
5	1.54	0.30	1.13	-0.10	1.99	0.65	1.77	1.30	1.56	1.31	1.97	1.30
6	1.86	1.47	1.53	1.21	2.19	1.74	1.70	1.60	1.57	1.42	1.82	1.77
7	2.54	1.98	2.05	1.78	2.97	2.21	2.01	1.73	1.80	1.49	2.25	1.94
8	1.61	1.16	1.49	1.12	1.72	1.20	n/a	n/a	n/a	n/a	n/a	n/a
9	2.60	2.58	2.41	2.45	2.79	2.70	2.29	1.98	1.95	1.88	2.62	2.09
Overall	1.59	1.34	1.32	1.17	1.87	1.50	1.46	1.35	1.28	1.21	1.64	1.48

Table 3.10: Standard Deviations of Vehicle Lateral Position Measured During Test Driving

Driver	Distance to Centerline Standard Deviation, cm											
	Daytime						Nighttime					
	Overall for Test Section		Overall for Segments				Overall for Test Section		Overall for Segments			
			Straight		Curved				Straight		Curved	
	before	after	before	after	before	after	before	after	before	after	before	after
FM 850, Traffic Lane Width of 9 feet												
1	0.36	0.36	0.40	0.36	0.32	0.36	0.36	0.39	0.33	0.37	0.38	0.42
2	0.33	0.40	0.35	0.35	0.31	0.44	0.37	n/a	0.28	n/a	0.47	n/a
3	0.37	0.45	0.38	0.35	0.37	0.53	0.41	0.36	0.36	0.27	0.45	0.43
4	0.29	0.30	0.29	0.25	0.30	0.34	0.38	0.29	0.39	0.23	0.38	0.34
5	0.62	0.41	0.48	0.46	0.73	0.37	0.40	0.41	0.37	0.32	0.44	0.49
6	0.36	0.43	0.32	0.50	0.38	0.37	0.39	0.33	0.36	0.31	0.41	0.35
7	0.39	0.41	0.42	0.38	0.37	0.43	0.45	0.35	0.37	0.28	0.52	0.41
8	0.39	0.30	0.32	0.28	0.44	0.31	n/a	n/a	n/a	n/a	n/a	n/a
9	0.43	0.36	0.54	0.41	0.32	0.32	0.56	0.40	0.46	0.42	0.63	0.39
Overall	0.39	0.38	0.39	0.37	0.39	0.38	0.41	0.36	0.37	0.31	0.46	0.40
FM 15, Traffic Lane Width of 10 feet												
1	0.46	0.34	0.42	0.38	0.49	0.32	0.49	0.39	0.35	0.26	0.59	0.48
2	0.45	0.39	0.39	0.29	0.50	0.46	0.78	n/a	0.52	n/a	0.95	n/a
3	0.44	0.41	0.40	0.43	0.47	0.40	0.55	0.42	0.43	0.27	0.64	0.53
4	0.39	0.34	0.31	0.33	0.47	0.35	0.53	0.33	0.43	0.19	0.60	0.43
5	0.60	0.77	0.53	0.57	0.67	0.92	0.60	0.56	0.42	0.42	0.72	0.65
6	0.60	0.50	0.54	0.47	0.64	0.52	0.49	0.52	0.46	0.36	0.52	0.64
7	0.69	0.48	0.58	0.46	0.77	0.50	0.60	0.57	0.46	0.41	0.70	0.69
8	0.45	0.38	0.37	0.30	0.52	0.46	n/a	n/a	n/a	n/a	n/a	n/a
9	0.61	0.55	0.55	0.43	0.65	0.65	0.63	0.54	0.45	0.42	0.74	0.62
Overall	0.52	0.46	0.45	0.40	0.58	0.51	0.59	0.48	0.44	0.33	0.68	0.58
FM 13, Traffic Lane Width of 11 feet												
1	0.49	0.42	0.55	0.40	0.43	0.46	0.54	0.37	0.54	0.35	0.54	0.39
2	0.48	0.36	0.48	0.35	0.47	0.37	0.47	n/a	0.44	n/a	0.51	n/a
3	0.49	0.51	0.51	0.48	0.47	0.54	0.40	0.35	0.40	0.32	0.41	0.37
4	0.39	0.34	0.34	0.33	0.45	0.35	0.39	0.30	0.33	0.29	0.43	0.31

Driver	Distance to Centerline Standard Deviation, cm											
	Daytime						Nighttime					
	Overall for Test Section		Overall for Segments				Overall for Test Section		Overall for Segments			
			Straight		Curved				Straight		Curved	
	before	after	before	after	before	after	before	after	before	after	before	after
5	0.84	0.79	0.83	0.67	0.84	0.90	0.59	0.47	0.51	0.40	0.66	0.54
6	0.54	0.64	0.56	0.72	0.52	0.56	0.47	0.48	0.46	0.54	0.49	0.42
7	0.56	0.53	0.53	0.48	0.58	0.59	0.53	0.52	0.52	0.44	0.54	0.58
8	0.48	0.32	0.41	0.33	0.54	0.32	n/a	n/a	n/a	n/a	n/a	n/a
9	0.52	0.54	0.46	0.54	0.58	0.54	0.57	0.44	0.58	0.43	0.56	0.45
Overall	0.53	0.50	0.52	0.48	0.54	0.51	0.50	0.42	0.47	0.40	0.52	0.44

Table 3.11: Differences in Vehicle Lateral Position after Edge-Line Treatment, from Test Driving

Driver	Distance to Centerline Difference (after minus before)											
	Mean Distance to Centerline, cm						Distance to Centerline Standard Deviation, cm					
	Overall for Test Section		Overall for Segments				Overall for Test Section		Overall for Segments			
			Straight		Curved				Straight		Curved	
	day	night	day	night	day	night	day	night	day	night	day	night
FM 850, Traffic Lane Width of 9 feet												
1	-0.53	0.40	-0.63	0.35	-0.45	0.44	0.00	0.03	-0.04	0.03	0.04	0.04
2	0.28	n/a	0.21	n/a	0.33	n/a	0.07	n/a	0.00	n/a	0.14	n/a
3	0.49	0.26	0.34	0.24	0.61	0.29	0.07	-0.05	-0.02	-0.09	0.16	-0.02
4	0.32	0.14	0.37	-0.04	0.27	0.31	0.00	-0.09	-0.04	-0.16	0.04	-0.04
5	0.58	-0.02	0.16	-0.02	0.90	-0.02	-0.21	0.01	-0.02	-0.05	-0.36	0.06
6	0.06	-0.05	-0.01	0.06	0.12	-0.17	0.07	-0.06	0.18	-0.06	-0.02	-0.06
7	0.00	0.08	-0.04	0.02	0.04	0.15	0.02	-0.10	-0.03	-0.09	0.06	-0.10
8	-0.52	n/a	-0.44	n/a	-0.59	n/a	-0.09	n/a	-0.03	n/a	-0.13	n/a
9	-0.09	-0.20	-0.02	-0.16	-0.16	-0.23	-0.07	-0.15	-0.13	-0.05	0.00	-0.24
Overall	0.06	0.09	-0.01	0.06	0.12	0.11	-0.01	-0.06	-0.02	-0.06	-0.01	-0.05
FM 15, Traffic Lane Width of 10 feet												
1	0.28	-0.08	0.12	-0.22	0.42	0.04	-0.11	-0.10	-0.04	-0.09	-0.17	-0.11
2	0.49	n/a	0.48	n/a	0.50	n/a	-0.06	n/a	-0.10	n/a	-0.04	n/a
3	0.25	0.03	0.25	0.10	0.28	-0.02	-0.02	-0.13	0.03	-0.16	-0.07	-0.11
4	0.21	0.09	0.07	0.16	0.36	0.04	-0.05	-0.20	0.02	-0.24	-0.12	-0.18
5	-1.58	0.02	-1.72	0.22	-1.45	-0.11	0.17	-0.04	0.04	0.00	0.25	-0.07
6	0.20	-0.17	0.26	-0.32	0.16	-0.06	-0.10	0.03	-0.07	-0.10	-0.12	0.12
7	-0.12	-0.03	-0.06	-0.27	-0.17	0.13	-0.21	-0.03	-0.12	-0.05	-0.27	-0.01
8	-0.72	n/a	-0.89	n/a	-0.60	n/a	-0.07	n/a	-0.07	n/a	-0.06	n/a
9	-0.04	-0.36	-0.22	-0.66	0.10	-0.20	-0.06	-0.09	-0.12	-0.03	0.00	-0.12
Overall	-0.11	-0.07	-0.19	-0.14	-0.04	-0.03	-0.06	-0.08	-0.05	-0.10	-0.07	-0.07
FM 13, Traffic Lane Width of 11 feet												
1	-0.40	-0.07	-0.36	-0.15	-0.41	-0.06	-0.07	-0.17	-0.16	-0.19	0.03	-0.15
2	0.15	n/a	0.16	n/a	0.12	n/a	-0.12	n/a	-0.13	n/a	-0.10	n/a
3	0.30	-0.03	0.60	-0.03	0.01	-0.04	0.02	-0.06	-0.03	-0.08	0.07	-0.04
4	0.31	0.13	0.46	0.17	0.13	0.12	-0.05	-0.09	-0.01	-0.04	-0.09	-0.12

Driver	Distance to Centerline Difference (after minus before)											
	Mean Distance to Centerline, cm						Distance to Centerline Standard Deviation, cm					
	Overall for Test Section		Overall for Segments				Overall for Test Section		Overall for Segments			
			Straight		Curved				Straight		Curved	
	day	night	day	night	day	night	day	night	day	night	day	night
5	-1.24	-0.46	-1.23	-0.25	-1.34	-0.68	-0.05	-0.12	-0.16	-0.12	0.06	-0.13
6	-0.38	-0.09	-0.32	-0.15	-0.45	-0.05	0.10	0.00	0.16	0.08	0.04	-0.07
7	-0.55	-0.28	-0.27	-0.31	-0.75	-0.31	-0.03	-0.01	-0.05	-0.07	0.01	0.04
8	-0.45	n/a	-0.38	n/a	-0.53	n/a	-0.16	n/a	-0.09	n/a	-0.23	n/a
9	-0.02	-0.31	0.04	-0.08	-0.08	-0.54	0.02	-0.13	0.09	-0.15	-0.04	-0.11
Overall	-0.25	-0.16	-0.15	-0.11	-0.37	-0.22	-0.04	-0.08	-0.04	-0.08	-0.03	-0.08

Edge-lines presence on the highway with 10-feet traffic lane width shows different impacts on vehicle lateral position on straight segments during daylight and darkness. During daytime there was no significant effect, as three drivers moved closer, while three moved farther from the centerline. At nighttime, however, drivers moved closer to the centerline (average change 0.95 feet). On curved segments during daylight, the majority of drivers (five of nine) moved slightly closer (0.19 feet on average) to the roadway edge after edge-lines placement, while no significant effect was observed at nighttime.

On the highway with lane widths of 11 feet, on both straight and curved roadway segments drivers generally moved slightly toward the centerline under both lighting conditions. The average changes in vehicle lateral position were 0.52 and 0.69 feet during daytime and 0.23 and 0.52 feet during darkness, for straight and curved segments, respectively.

On straight segments of all investigated highways, the presence of edge lines, on the average, reduced vehicle lateral position variance by 20 percent during both day and night test drives. For curves, a similar effect was observed in darkness on all highways. On roadways with traffic lane widths of 9 and 11 feet, during daylight more than half the test drivers experienced increased lateral position variance.

In addition to free movements, lateral position of test vehicle while meeting an oncoming vehicle(s) was investigated and the results are represented in Table 3.12. Because of limited frequency of meeting with oncoming traffic on the low-volume rural roads, data was combined without classification by traffic lane width or horizontal alignment.

Table 3.12: Test Vehicle Lateral Position While Meeting Oncoming Traffic

Driver	Total Sample Size	Average Distance to Centerline, cm					
		Daytime			Nighttime		
		before	after	difference	before	after	difference
1	32	1.31	1.15	-0.16	0.92	1.21	0.29
2	30	1.44	1.48	0.03	1.44	n/a	n/a
3	25	0.53	0.97	0.44	0.48	1.01	0.54
4	41	0.98	1.88	0.90	1.50	1.46	-0.04
5	32	1.92	0.50	-1.42	1.47	1.66	0.19
6	31	1.53	1.72	0.19	1.65	1.75	0.10
7	30	2.80	2.01	-0.78	2.37	1.89	-0.48
8	23	2.13	1.78	-0.35	n/a	n/a	n/a
9	34	2.58	2.96	0.38	2.75	2.49	-0.26
Overall		1.69	1.61	-0.09	1.57	1.64	0.07

The data show approximately equal proportions of drivers moving closer to pavement centerline (average 0.66 ft) or to the roadway edge (average 0.49 feet) when meeting an oncoming vehicle. Less impact was observed during nighttime when those values contained 0.33 and 0.26 feet, respectively.

For five out of nine drivers, edge-line presence was associated with a reduction of vehicle lateral position variability while meeting oncoming traffic during daylight (Table 3.13). During darkness, lateral position variability changed very little between the edge-line and no-edge-line cases.

Table 3.13: Standard Deviations of Test Vehicle Lateral Position while Meeting Oncoming Traffic

Driver	Total Sample Size	Standard Deviation of the Distance to Centerline, ft					
		Daytime			Nighttime		
		before	after	difference	before	after	difference
1	32	0.23	0.18	-0.05	n/a	0.25	n/a
2	30	0.30	0.33	0.03	0.39	n/a	n/a
3	25	0.44	0.25	-0.19	0.24	0.30	0.06
4	41	0.44	0.30	-0.13	0.31	0.31	0.00
5	32	0.50	0.50	0.00	0.22	0.24	0.02
6	31	0.29	0.30	0.01	0.35	0.39	0.05
7	30	0.54	0.39	-0.15	0.23	0.27	0.03
8	23	0.31	0.27	-0.04	n/a	n/a	n/a
9	34	0.34	0.37	0.03	0.55	0.41	-0.14
Overall		0.38	0.32	-0.05	0.33	0.32	-0.01

3.2.6 Test Drives Indicated the Following Effects of Edge-Line Treatment

While driving on 9-feet lane width highways, drivers moved their vehicles slightly closer to the roadway edge, with the greatest movements on curved segments.

While driving on 10-feet lane width highways, on straight segments, during daytime drivers showed no consistent lateral position changes, while at nighttime they moved slightly closer to the roadway center. On curved segments drivers tended to move toward the roadway edge during daylight but did not consistently change positions during darkness.

While driving on 11-feet lane width highways, the majority of drivers moved slightly closer to the pavement centerline under all lighting conditions, with the greatest changes occurring on curved segments.

The presence of edge lines tended to reduce vehicle lateral position variability.

3.3 Human Perception Study

As noted in Chapter 2, edge lines may have some impacts on driver perception of the driving environment. Therefore, the objective of the human perception study is to test the following hypotheses:

- The presence of an edge line may reduce driver mental workload due to easier estimation of vehicle lateral position on the roadway, especially at nighttime and when meeting oncoming traffic.
- On two-lane roads, marking of the centerline only (without edge-line pavement marking) may limit the driver's perception of roadway curvature, especially at night when contrast between roadway edges and shoulders is very low, because human estimation of curve radius improves with more basic lines in the perspective view.
- Discontinuities in edge-line pavement markings at intersections may increase the distance for intersection advance recognition by drivers.

- Application of RRPMs to supplement painted edge lines, while increasing nighttime visibility of the roadway edge, may be interpreted by drivers as delineating traffic lanes of the same direction.

The first hypothesis was tested during test driving with continuous recording of driver heart activity as a quantitative indicator of human mental workload. For assessment of the traffic situation and identification of available stressors, the driver visual field was recorded with a digital camcorder and all situations not related to the investigated processes were eliminated from the analysis. In addition, the collected data were separated into free movements and meeting oncoming traffic situations.

To eliminate the influence of differences in driver emotional states not related to the driving task, basic or pre-test electrocardiograms were recorded under nondriving conditions before each test drive, and relative characteristics (driver's heart rate at the investigated conditions expressed as a percentage of the basic value) were used.

Tables 3.14, 3.15, and 3.16 represent some statistical characteristics of driver heart activity during test driving when no oncoming traffic was present. Because of low traffic volume on the investigated highways, the data obtained for meeting oncoming traffic situations were combined for all test sections and the average characteristics are shown in Table 3.17.

Based on results of psycho-physiological studies of operator activity, heart rates exceeding 110 percent of the basic condition were selected as indicating driver increased mental workload related to complexity in the driving task (Chapter 2.2). The frequencies of these situations as percentages of total test driving time were computed, and the resulting data are shown in Table 3.18.

Table 3.14: Driver Heart Rate During Test Driving

Driver	Mean Heart Rate, % to basic											
	Daytime						Nighttime					
	Overall for Test Section		Overall for Segments				Overall for Test Section		Overall for Segments			
			Straight		Curved				Straight		Curved	
	before	after	before	after	before	after	before	after	before	after	before	after
FM 850, Traffic Lane Width of 9 feet												
1	96.33	102.43	96.53	103.54	96.15	101.60	108.16	99.35	109.98	100.19	106.56	98.52
2	107.98	96.79	107.96	96.99	108.00	96.59	103.88	n/a	103.64	n/a	104.17	n/a
3	100.27	108.57	101.11	109.04	99.53	108.15	102.33	102.6	101.82	102.64	102.71	102.57
4	98.46	n/a	98.31	n/a	98.58	n/a	109.34	100.19	109.54	100.35	109.16	100.05
5	98.63	109.01	98.64	107.03	98.62	107.86	106.84	103.84	110.32	104.16	106.67	103.53
6	108.19	97.81	107.63	97.78	108.67	97.84	101.26	97.17	101.14	97.51	101.36	96.83
7	106.23	102.34	106.33	102.31	106.15	102.35	107.66	108.48	107.68	108.06	107.63	108.90
8	105.49	110.10	106.24	112.25	104.94	108.22	n/a	n/a	n/a	n/a	n/a	n/a
9	98.13	97.06	98.48	97.68	97.77	96.53	97.03	96.67	97.44	97.06	96.72	96.33
Overall	102.19	103.01	102.36	103.33	102.04	102.39	104.56	101.19	105.19	101.42	104.37	100.96
FM 15, Traffic Lane Width of 10 feet												
1	90.17	95.26	91.03	95.18	89.5	95.33	103.73	95.85	105.87	98.14	102.23	94.25
2	110.06	98.44	110.13	98.74	110.00	98.23	104.32	n/a	104.02	n/a	104.53	n/a
3	96.58	102.06	94.23	101.86	98.23	102.19	101.52	101.73	101.44	100.79	101.57	102.39
4	92.47	91.37	92.32	92.21	92.59	90.63	103.36	98.21	103.24	99.64	103.44	97.21
5	95.36	104.20	96.01	102.97	94.85	105.06	104.08	98.55	103.01	98.14	104.83	98.84
6	109.56	92.92	110.21	91.43	109.10	93.82	98.54	91.68	98.85	91.73	98.32	91.64
7	105.07	94.06	104.87	93.52	105.21	94.43	106.71	101.60	106.77	101.67	106.67	101.56
8	97.63	106.01	98.42	107.13	97.08	104.89	n/a	n/a	n/a	n/a	n/a	n/a
9	97.44	95.68	97.95	96.19	97.08	95.29	95.40	93.12	95.30	93.55	95.47	92.82
Overall	99.37	97.78	99.46	97.69	99.29	97.76	102.21	97.25	102.31	97.66	102.13	96.96
FM 13, Traffic Lane Width of 11 feet												
1	94.46	99.94	95.52	99.26	93.41	100.70	105.88	98.35	107.38	98.88	104.38	98.00
2	109.36	98.3	109.71	98.14	108.97	98.45	104.00	n/a	103.29	n/a	104.72	n/a
3	100.62	107.16	101.12	107.41	100.12	106.90	101.42	101.83	101.99	102.22	100.79	101.45
4	95.67	97.64	96.02	97.65	95.27	97.63	104.57	97.67	104.83	98.22	104.36	97.05
5	99.86	108.32	101.47	108.85	98.05	107.85	106.22	97.24	106.76	97.34	105.67	97.13
6	108.49	94.56	108.47	94.29	108.52	94.83	99.51	94.66	97.99	94.44	101.03	94.86
7	106.43	97.39	106.34	97.64	106.51	97.11	105.13	105.61	105.32	105.49	104.92	105.73
8	103.63	110.80	101.21	110.71	106.06	110.89	n/a	n/a	n/a	n/a	n/a	n/a
9	98.24	96.51	97.96	96.67	98.51	96.35	95.97	95.16	96.33	95.47	95.61	94.84
Overall	101.86	101.18	101.98	101.18	101.71	101.19	102.84	98.65	102.99	98.87	102.69	98.44

Table 3.15: Driver Heart Rate Standard Deviations During Test Driving

Driver	Heart Rate Standard Deviation, % to basic											
	Daytime						Nighttime					
	Overall for Test Section		Overall for Segments				Overall for Test Section		Overall for Segments			
			Straight		Curved				Straight		Curved	
	before	after	before	after	before	after	before	after	before	after	before	after
FM 850, Traffic Lane Width of 9 feet												
1	5.62	5.34	6.89	5.39	4.50	5.30	4.69	5.88	5.42	6.55	4.04	5.22
2	2.00	1.11	1.22	1.18	2.69	1.04	2.27	n/a	1.25	n/a	3.46	n/a
3	3.24	3.78	3.22	4.17	3.26	3.45	4.12	2.71	4.22	2.89	4.04	2.55
4	2.37	n/a	2.43	n/a	2.31	n/a	3.18	2.30	3.26	2.55	3.10	2.08
5	3.68	4.08	4.00	3.31	3.44	3.47	3.32	2.52	4.79	3.29	3.32	1.76
6	4.93	3.13	5.31	3.61	4.61	2.71	1.61	2.56	1.81	2.83	1.44	2.29
7	1.56	1.64	1.69	1.69	1.44	1.60	0.89	1.76	0.99	1.73	0.78	1.79
8	5.09	4.38	5.26	4.92	4.97	3.91	n/a	n/a	n/a	n/a	n/a	n/a
9	1.09	1.34	1.30	1.11	0.89	1.54	1.42	1.12	1.52	1.33	1.35	0.94
Overall	3.29	3.10	3.48	3.17	3.12	2.88	2.69	2.69	2.91	3.03	2.69	2.38
FM 15, Traffic Lane Width of 10 feet												
1	2.73	5.69	3.41	6.46	2.19	5.03	4.43	5.91	5.39	6.95	3.75	5.19
2	2.60	1.21	1.20	1.48	3.58	1.03	2.22	n/a	3.36	n/a	1.43	n/a
3	5.04	3.45	4.20	3.36	5.63	3.51	4.17	2.98	4.87	3.40	3.69	2.69
4	2.96	2.07	3.50	2.62	2.54	1.58	3.93	4.38	4.29	4.59	3.67	4.24
5	3.69	3.79	4.02	3.64	3.43	3.90	4.09	2.43	4.24	2.88	3.98	2.11
6	3.86	3.79	4.15	4.82	3.65	3.17	2.43	3.55	3.12	3.35	1.95	3.69
7	1.34	1.54	1.39	1.66	1.31	1.45	1.08	1.37	1.18	1.48	1.01	1.30
8	4.54	5.59	4.95	6.18	4.26	5.01	n/a	n/a	n/a	n/a	n/a	n/a
9	1.15	1.05	1.26	1.28	1.07	0.88	1.19	1.33	1.32	1.38	1.11	1.29
Overall	3.10	3.13	3.12	3.50	3.07	2.84	2.94	3.14	3.47	3.43	2.57	2.93
FM 13, Traffic Lane Width of 11 feet												
1	4.66	5.88	5.28	6.78	4.03	4.87	5.39	5.40	6.39	5.67	4.39	5.23
2	3.72	1.94	5.12	2.2	2.15	1.68	3.13	n/a	2.67	n/a	3.59	n/a
3	3.33	4.03	3.31	3.92	3.36	4.15	3.60	3.50	4.23	3.82	2.89	3.17
4	2.76	1.76	3.45	2.07	1.99	1.45	3.28	3.96	3.34	4.19	3.24	3.70
5	4.18	5.25	4.83	5.07	3.45	5.41	3.40	3.96	4.05	4.69	2.75	3.22
6	4.75	4.25	4.88	4.59	4.63	3.74	2.87	2.77	3.06	3.07	2.67	2.51
7	1.30	1.98	1.31	1.95	1.28	2.02	1.06	1.49	1.08	1.71	1.03	1.29
8	5.42	5.13	6.33	5.98	4.52	4.16	n/a	n/a	n/a	n/a	n/a	n/a
9	1.40	1.35	1.39	1.68	1.41	1.02	1.59	1.24	1.63	1.45	1.54	1.04
Overall	3.50	3.51	3.99	3.81	2.98	3.17	3.04	3.19	3.31	3.51	2.76	2.88

Table 3.16: Driver Heart Rate Differences after Edge-Line Treatment

Driver	Heart Rate Difference (after minus before)											
	Mean Heart rate, % to basic						Heart Rate Standard Deviation, % to basic					
	Overall for Test Section		Overall for Segments				Overall for Test Section		Overall for Segments			
			Straight		Curved				Straight		Curved	
	day	night	day	night	day	night	day	night	day	night	day	night
FM 850, Traffic Lane Width of 9 feet												
1	6.10	-8.81	7.01	-9.79	5.45	-8.04	-0.28	1.19	-1.50	1.13	0.80	1.18
2	-11.19	n/a	-10.97	n/a	-11.41	n/a	-0.89	n/a	-0.04	n/a	-1.65	n/a
3	8.30	0.27	7.93	0.82	8.62	-0.14	0.54	-1.41	0.95	-1.33	0.19	-1.49
4	n/a	-9.15	n/a	-9.19	n/a	-9.11	n/a	-0.88	n/a	-0.71	n/a	-1.02
5	10.38	-2.99	8.39	-6.16	9.24	-3.14	0.40	-0.79	-0.69	-1.50	0.03	-1.56
6	-10.38	-4.09	-9.86	-3.63	-10.82	-4.54	-1.80	0.95	-1.70	1.03	-1.90	0.85
7	-3.90	0.82	-4.02	0.39	-3.79	1.26	0.09	0.88	0.00	0.75	0.16	1.01
8	4.60	n/a	6.01	n/a	3.28	n/a	-0.71	n/a	-0.34	n/a	-1.06	n/a
9	-1.06	-0.36	-0.80	-0.37	-1.24	-0.39	0.25	-0.30	-0.19	-0.19	0.65	-0.41
Overall	0.36	-3.47	0.46	-3.99	-0.08	-3.44	-0.30	-0.05	-0.44	-0.12	-0.35	-0.21
FM 15, Traffic Lane Width of 10 feet												
1	5.09	-7.88	4.15	-7.73	5.83	-7.98	2.96	1.48	3.05	1.56	2.84	1.44
2	-11.62	n/a	-11.39	n/a	-11.77	n/a	-1.39	n/a	0.28	n/a	-2.55	n/a
3	5.48	0.21	7.63	-0.65	3.96	0.82	-1.59	-1.19	-0.84	-1.47	-2.12	-1.00
4	-1.10	-5.15	-0.11	-3.60	-1.96	-6.23	-0.89	0.45	-0.88	0.30	-0.96	0.57
5	8.84	-5.53	6.96	-4.87	10.21	-5.99	0.10	-1.66	-0.39	-1.36	0.47	-1.87
6	-16.64	-6.86	-18.79	-7.12	-15.28	-6.67	-0.07	1.12	0.66	0.23	-0.48	1.74
7	-11.01	-5.11	-11.35	-5.10	-10.78	-5.11	0.20	0.29	0.27	0.29	0.14	0.29
8	8.38	n/a	8.71	n/a	7.82	n/a	1.05	n/a	1.23	n/a	0.74	n/a
9	-1.76	-2.28	-1.76	-1.74	-1.80	-2.64	-0.09	0.14	0.02	0.06	-0.19	0.18
Overall	-1.59	-4.66	-1.77	-4.40	-1.53	-4.83	0.03	0.09	0.38	-0.05	-0.23	0.19
FM 13, Traffic Lane Width of 11 feet												
1	5.48	-7.53	3.74	-8.50	7.29	-6.38	1.22	0.01	1.50	-0.72	0.84	0.84
2	-11.06	n/a	-11.57	n/a	-10.52	n/a	-1.78	n/a	-2.92	n/a	-0.47	n/a
3	6.54	0.41	6.29	0.23	6.78	0.66	0.70	-0.10	0.61	-0.41	0.79	0.28
4	1.97	-6.90	1.63	-6.61	2.36	-7.31	-1.00	0.68	-1.38	0.85	-0.54	0.46
5	8.46	-8.98	7.38	-9.42	9.80	-8.55	1.07	0.56	0.23	0.64	1.96	0.47
6	-13.93	-4.85	-14.18	-3.55	-13.68	-6.17	-0.50	-0.10	-0.29	0.01	-0.89	-0.16
7	-9.04	0.48	-8.70	0.17	-9.40	0.80	0.69	0.43	0.64	0.63	0.73	0.27
8	7.16	n/a	9.50	n/a	4.83	n/a	-0.29	n/a	-0.35	n/a	-0.35	n/a
9	-1.73	-0.81	-1.29	-0.86	-2.16	-0.77	-0.05	-0.34	0.29	-0.18	-0.39	-0.50
Overall	-0.68	-4.03	-0.80	-4.08	-0.52	-3.96	0.01	0.16	-0.18	0.12	0.19	0.24

Table 3.17: Driver Heart Rates While Meeting Oncoming Traffic

Driver	Average Heart Rate, % to basic					
	Daytime			Nighttime		
	before	after	difference	before	after	difference
1	95	96	1.00	103	97	-6.00
2	110	98	-12.00	104	n/a	n/a
3	103	105	2.00	99	100	1.00
4	96	98	2.00	105	99	-6.00
5	95.42	109.92	14.50	103.97	99.78	-4.19
6	107.76	92.98	-14.78	99.39	93.95	-5.44
7	106.02	96.71	-9.30	105.69	106.50	0.81
8	100.69	108.93	8.24	n/a	n/a	n/a
9	97.03	95.70	-1.33	95.42	95.43	0.01
Overall	101	100	-1.08	102	99	-3.13

Table 3.18: Frequency of Driver Increased Mental Workload (Heart Rates) During Test Driving

Driver	Percentage of Time with Increased Heart Rate (>110 % to basic)					
	Daytime			Nighttime		
	before	after	difference	before	after	difference
FM 850, Traffic Lane Width of 9 feet						
1	4.76	17.62	12.85	35.92	5.66	-30.26
2	18.18	0.00	-18.18	0.47	n/a	n/a
3	4.08	39.90	35.82	4.46	2.09	-2.36
4	0.00	n/a	n/a	33.18	0.00	-33.18
5	0.53	45.61	45.09	23.35	5.56	-17.79
6	36.36	0.00	-36.36	0.00	0.00	0.00
7	2.14	0.00	-2.14	0.51	21.72	21.20
8	30.73	59.13	28.40	n/a	n/a	n/a
9	0.00	0.00	0.00	0.00	0.00	0.00
Overall	10.8	20.3	9.53	12.2	5.0	-7.23
FM 15, Traffic Lane Width of 10 feet						
1	0.36	2.01	1.66	16.33	4.44	-11.90
2	53.41	0.00	-53.41	0.00	n/a	n/a
3	8.39	5.60	-2.79	6.21	3.30	-2.91
4	0.00	0.35	0.35	11.99	0.70	-11.29
5	0.00	22.36	22.36	9.06	0.00	-9.06
6	48.80	0.00	-48.80	0.00	0.00	0.00
7	0.00	0.00	0.00	6.05	0.00	-6.05
8	1.27	n/a	n/a	n/a	n/a	n/a
9	0.00	0.00	0.00	0.00	0.00	0.00
Overall	12.5	3.8	-8.68	6.2	1.2	-5.00
FM 13, Traffic Lane Width of 11 feet						
1	2.08	9.48	7.40	32.37	3.85	-28.52
2	39.34	0.61	-38.73	4.13	n/a	n/a
3	3.59	20.44	16.85	3.68	2.59	-1.09
4	0.00	0.00	0.00	15.02	0.58	-14.44
5	7.43	46.92	39.49	24.11	0.63	-23.48
6	38.46	0.00	-38.46	0.00	0.00	0.00
7	3.13	0.00	-3.13	4.24	0.33	-3.91
8	15.84	54.49	38.65	n/a	n/a	n/a
9	0.00	0.00	0.00	0.00	0.00	0.00
Overall	12.2	14.7	2.45	10.4	1.1	-9.30

Data represented in Table 3.16 show that, under daytime conditions on all investigated highways, as well as on straight and curved segments, drivers had similar heart rate changes during test driving after edge-line placement compared to the before test. Three or four of nine drivers experienced increased heart rates averaging 8 percent, while two or three drivers show reductions averaging 12 percent. The rest of the drivers do not indicate significant differences (heart rate change less than 5 percent).

During nighttime tests no drivers with increased heart rate were found for all classified roadway groups, and drivers experienced small heart rate reductions. The major effect was observed on the highway with a lane width of 10 feet, where the heart rate of the majority of drivers (five of seven) was reduced on average by 6 percent. The same heart rate reduction was observed for three of seven drivers on straight segments with lane widths of 9 feet and curves with lane widths of 11 feet.

The variability (standard deviation) differences of heart rate were found to be insignificant for all investigated roadway groups during both daylight and darkness.

During meetings with oncoming traffic, data also indicated some reduction of driver emotional tension. At both daytime and night, three drivers experience reduction of heart rate on average by 12 and 6 percent, respectively, and during darkness no significant increases were observed for the rest of the test drivers (Table 3.17).

The frequency of driving with increased mental workload (heart rate) (Table 3.18) shows that the presence of edge lines reduces this driver's heart rate at nighttime on average by 15 percent among the investigated roadway classes. During daytime on all highways, the frequency of such situations for three drivers was reduced on average by 27 percent, while four drivers experienced approximately 21 percent increases.

Comparison of speed and heart rate databases indicated that drivers (noted with numbers 1, 3, 5, and 8) experienced increased emotional tension; however, at the same time, they had the highest speed increases during test driving after edge-lines placement.

So, one might conclude that edge-line striping on all investigated roadways significantly reduces driver mental workload at nighttime at both free driving and meetings with oncoming traffic. During daylight, similar effects were observed as well, but at the same time, some drivers experienced increased emotional tension that may be caused by higher speed.

Three other hypotheses regarding driver perception of curvature, intersection recognition, and RRPM application were tested by the laboratory experiments described in detail in Chapter 2.1.4.

At the first stage of the laboratory experiments, driver perception of curvature with one and three basic lines in the visual field was investigated. The developed perspectives shown in Figure 2.9 were sorted into two sets, first pictures with one basic line and second with three lines. The created perspectives are modeled curves with radius 500, 300 and 100 feet and further referred to as smooth, moderate, and sharp, respectively. Picture sets were shown separately at different times to a human subject with the request to rank each curve as smooth, moderate, or sharp, based on "higher-lower" criteria.

Table 3.19 represents proportions of subjects' correct/incorrect responses sorted by age and gender. In this case, an incorrect response was determined if any curve in the picture set was estimated inadequately. Data in Table 3.20 details inadequacies found during a subject's estimation of curvature, sorted by age and gender.

Table 3.19: Distribution of Subjects' Estimations of Image Sets

Image set	Total Number of Subjects	Responses			
		Correct		Incorrect	
		#	%	#	%
Overall					
1 line	78	29	37.2	49	62.8
3 lines	78	75	96.2	3	3.8
Males only					
1 line	42	16	38.1	26	61.9
3 lines	42	42	100.0	0	0.0
Females only					
1 line	36	13	36.1	23	63.9
3 lines	36	33	91.7	3	8.3
Overall for ages 25 years and under					
1 line	29	10	34.5	19	65.5
3 lines	29	28	96.6	1	3.4
Overall for ages 26 - 35 years					
1 line	25	8	32.00	17	68.0
3 lines	25	25	100.00	0	0.0
Overall for ages 36 and greater					
1 line	23	11	47.8	12	52.2
3 lines	23	21	91.3	2	8.7
Males 25 years and under					
1 line	19	7	36.8	12	63.2
3 lines	19	19	100.0	0	0.0
Males 26 years and greater					
1 line	23	9	39.1	14	60.9
3 lines	23	23	100.0	0	0.0
Females 25 years and under					
1 line	10	3	30.0	7	70.0
3 lines	10	9	90.0	1	10.0
Females 26 years and greater					
1 line	26	10	38.5	16	61.5
3 lines	26	24	92.3	2	7.7

Table 3.20: Distributions of Curves Estimation by Subjects' Gender and Age

Image set	Total Number of Subjects	Tested Curve	Estimation of Tested Curve by Subjects					
			smooth		moderate		sharp	
			#	%	#	%	#	%
Overall								
1 line	78	**Smooth**	**46**	**59.0**	5	6.4	27	34.6
3 lines	78		**77**	**98.7**	1	1.3	0	0.0
1 line	78	**Moderate**	16	20.5	**44**	**56.4**	18	23.1
3 lines	78		1	1.3	**77**	**98.7**	0	0.0
1 line	78	**Sharp**	17	21.8	30	38.5	**31**	**39.7**
3 lines	78		0	0.0	1	1.3	**77**	**98.7**
Overall for ages 25 years and under								
1 line	29	**Smooth**	**16**	**55.2**	1	3.4	12	41.4
3 lines	29		**28**	**96.6**	1	3.4	0	0.0
1 line	29	**Moderate**	3	10.3	**21**	**72.4**	5	17.2
3 lines	29		1	3.4	**28**	**96.6**	0	0.0
1 line	29	**Sharp**	10	34.5	9	31.0	**10**	**34.5**
3 lines	29		0	0.0	0	0.0	**29**	**100.0**
Overall for ages 26 - 35 years								
1 line	25	**Smooth**	**14**	**56.0**	3	12.00	8	32.0
3 lines	25		**25**	**100.0**	0	0.00	0	0.0
1 line	25	**Moderate**	8	32.0	**9**	**36.00**	8	32.0
3 lines	25		0	0.0	**25**	**100.00**	0	0.0
1 line	25	**Sharp**	6	24.0	11	44.00	**8**	**32.0**
3 lines	25		0	0.0	0	0.00	**25**	**100.0**
Overall for ages 36 and greater								
1 line	23	**Smooth**	**16**	**69.6**	0	0.0	7	30.4
3 lines	23		**23**	**100.0**	0	0.0	0	0.0
1 line	23	**Moderate**	4	17.4	**14**	**60.9**	5	21.7
3 lines	23		0	0.0	**23**	**100.0**	0	0.0
1 line	23	**Sharp**	1	4.3	10	43.5	**12**	**52.2**
3 lines	23		0	0.0	1	4.3	**22**	**95.7**
Males Only								
1 line	42	**Smooth**	**25**	**59.5**	3	7.1	14	33.3
3 lines	42		**42**	**100.0**	0	0.0	0	0.0
1 line	42	**Moderate**	6	14.3	**26**	**61.9**	10	23.8
3 lines	42		0	0.0	**42**	**100.0**	0	0.0
1 line	42	**Sharp**	11	26.2	14	33.3	**17**	**40.5**
3 lines	42		0	0.0	0	0.0	**42**	**100.0**
Females Only								
1 line	36	**Smooth**	**21**	**58.3**	2	5.6	13	36.1
3 lines	36		**35**	**97.2**	1	2.8	0	0.0
1 line	36	**Moderate**	10	27.8	**18**	**50.0**	8	22.2
3 lines	36		1	2.8	**35**	**97.2**	0	0.0
1 line	36	**Sharp**	6	16.7	16	44.4	**14**	**38.9**
3 lines	36		0	0.0	1	2.8	**35**	**97.2**

The obtained subjects' responses clearly identify the positive impact of additional basic lines in the visual field on human estimation of curvature. While for the image set with one basic line, 63 percent of subjects had incorrect curvature estimation, for the image set with three lines this percentage drops to only 4 percent. Female subjects showed slightly lower estimation accuracy in both image sets, which may be explained by less experience of driving on low-volume roads at nighttime. Also, among both male and female groups, the highest percentage of errors was observed for ages 25 and under.

The analysis of estimation inadequacies shows that it depended on the curvature level of the provided images. Among three curve models, the percentage of adequate estimation for a "sharp" curve at one basic line was 39.7 percent versus 59.0 percent and 56.4 percent for "smooth" and "moderate" curves, respectively. For the "sharp" curve, 39 percent of the subjects underestimate its curvature on one level down (moderate), and another 22 percent rank it as "smooth". For the "moderate" curve, the percentages of under- and overestimation were identified as 21 percent and 23 percent, respectively, while the predominant error for the "smooth" curve was an estimation at the sharp level (35 percent). The image set with three lines shows very small and an absolutely equal percent of errors for all three curves (1.3 percent).

Among the age groups overall, for provided curves, the best performance showed up in subjects over 36 years old. Subjects of 26 to 35 years tended to inadequately estimate sharper curves ("moderate" and "sharp"), while the youngest group (25 years and under) significantly underestimated "sharp" curves only.

Male and female subjects showed similar proportions of curves estimations, with a slightly lower percentage of female correct responses.

Another test had an objective to investigate the potential impact of edge lines on driver recognition of intersections. Participants were asked to watch a video and pause it when he or she recognized an adjacent roadway ahead, and the observer registered the corresponding time code provided on the video sample.

For the investigation of the effects of edge-line discontinuities on intersection recognition, another laboratory experiment was conducted.

The participant was asked to watch two sample videos of the same highway section before and after the edge line and pause it when he or she recognized an adjacent roadway ahead, and the observer registered the corresponding time code provided on video sample. The time the subject recognized an adjacent roadway was compared to the actual time of roadway passing. The difference in the time measurements permitted estimation of the subject's advance recognition time of intersection. To avoid subject familiarity with the sample video, one participant was seeing only one video representing the sample with or without edge lines. Because of this fact, the number of subjects with classification by gender and age does not allow obtaining statistically valid data and therefore, only overall analysis was conducted.

Table 3.21 represents data regarding proportions of subjects that did not recognize an intersection at all or identified it only when they had passed it.

Table 3.21: Subjects' Identification of Intersection

Video Sample	Total Number of Subjects	Intersection Identification			
		not identified		identified when passing	
		Subjects			
		#	%	#	%
without edge line	40	21	52.5	7	17.5
with edge line	38	5	13.2	1	2.6

Subjects that were shown a video sample of highway section with edge lines, overall in 13.2 percent of cases, did not identify the intersection, while for the sample without edge lines, this proportion was 52.5 percent. The last-moment identification was also much higher for the sample without edge lines (2.6 percent versus 17.5 percent).

Figure 3.7 shows the distributions of intersection advance recognition time for video samples with and without edge lines and the statistical characteristics are represented in Table 3.22.

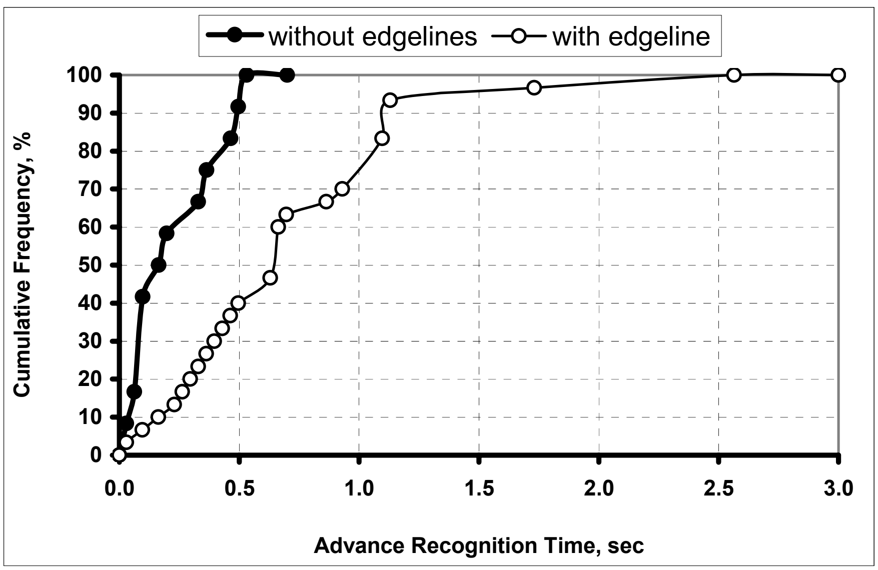


Figure 3.7: Distribution of Intersection Advance Recognition Time with and without Edge-Lines

Table 3.22: Advance Recognition Time Statistics

Video Sample	Sample Size	Advance Recognition Time, sec			t-statistic	
		Mean	Std. Dev.	Std. Error	t-Value	Ho Rejection Level
without edge line	12	0.24	0.18	0.05	-4.48	0.99
with edge line	30	0.73	0.52	0.10		

T-tests showed that both sets of samples originated from different populations with significance levels of 99 percent. So, it can be concluded that the presence of edge lines on video samples increased intersection advance recognition time by 3.

To test driver perception of RRPM application on edge lines, three nighttime video samples were created representing two-lane highways without a shoulder and with a full-size shoulder, and four-lane highways with a full-size shoulder. RRPMs were temporarily mounted on the existing 4-inchedge lines, with spacing of 20 feet, as shown in Figure 2.10. Sample videos were shown to different subjects, followed by the question of how many traffic lanes they recognized. During the conducted test, all participants correctly identified the number of traffic lanes on all provided video samples.

3.3.2 Major Findings in Human Perception Study

Placement of edge lines may reduce driver mental workload at nighttime at both free driving and meetings with oncoming traffic. The percentage of total driving time when drivers experienced increased heart rates, on average, was reduced by 6 percent and the mean heart rate was reduced by 12 percent. During daylight, both reduction and increase of driver mental workload was observed. It was found that the increases of emotional tension are typical for drivers that have the highest speed increases as well.

The presence of additional basic lines created by the edge-line pavement marking in the visual field helped drivers adequately estimate the roadway curvature among the investigated drivers of all age and gender groups.

Discontinuities in the edge-line pavement marking may significantly increase the distance for intersection advance recognition by drivers.

3.4 Summary and Conclusions

The conducted studies identified some impacts of edge lines on a driver's behavior and reactions.

Stationary observations and test drives indicated that edge-line treatment may increase speed, on average, by 5 mph or 9 percent on both straight and curved highway segments. Increases of speed variance, on average by 20 percent on highways with traffic lane widths of 9 feet, and reductions, on average by 14 percent on wider roadways, were observed as well. The study also indicated increases in speed variance in traffic flow as well as in individual vehicle speed history. On highways with traffic lane widths of 9 feet, the increased speed variance was most frequently observed on curved segments during daytime and straight sections at night, on average by 20 percent, while wider roadways had an opposite effect (average increase of 14 percent on straight sections at daylight and curved sections at night). In absolute values, speed standard deviation increases did not exceeded 1 mph.

Numerous studies have shown that crash risk increases with speed growth. So, the identified speed increase after edge-line placement should be analyzed from the perspective of potential impacts on safety. Different studies related to the given problem conducted around the world were summarized in the Federal Highway Administration Research Report "Synthesis of Safety Research Related to Speed and Speed Limits" (Ref. 11). This synthesis highlights the relationships among vehicle speed and safety and shows that crash risk is lowest near the average speed of traffic and increases for vehicles traveling much faster or slower than average. The data represented by Figure 3.8 clearly indicates that the above-mentioned values of speed characteristics increase and have no potential to significantly change the safety situation.

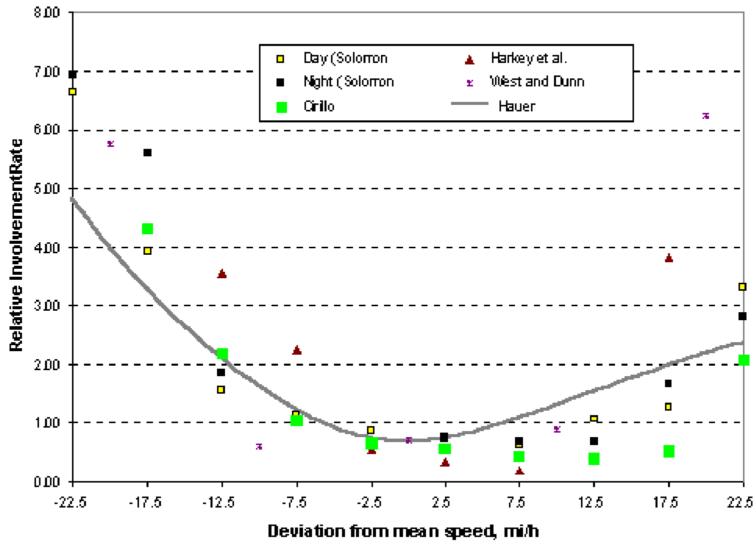


Figure 3.8: Crash Involvement and Overtaking Rates Relative to Average Rate and Speed (Ref. 11)

The obtained distributions of vehicles' lateral positions allow concluding that placement of edge lines has no significant effect on the narrowest investigated roadways with traffic lane widths of 9 feet in any lighting conditions. On wider roadways, presence of edge lines moves vehicles toward the pavement edge in both daylight and darkness at an average of 20 inches, with the greatest impact on highways with traffic lane widths of 10 feet.

Analysis of the lateral position history for individual drivers shows that for all investigated highways at daylight or darkness, three groups of driving behavior can be determined. The first one represents drivers who had no lateral position changes during test drives after edge-line treatment, while the second and third reflect drivers that in "after" tests move vehicle closer or farther away in relation to the centerline pavement marking, respectively. These changes in vehicle lateral position are similar among investigated highway groups and valued during daylight on average at 9 inches towards centerline and 4 inches away. Lateral position changes average 3 in during nighttime driving in both cases.

Edge lines' tendency to move vehicles towards the edge of the roadway may be due to the added visual delineation of the road edge, so drivers feel more comfortable driving farther from the center of the road. Movement towards the center of the roadway was more frequently observed on wider highways. This phenomenon could be explained by the fact that on wider highways, the edge line is not striped quite as closely to the edge of the roadway, which would, in effect, narrow the overall lane width and in turn shift vehicles toward the centerline.

It is necessary to note that the lateral position of a vehicle on low-volume rural highways reflects more the driver's subjective estimation of traffic conditions than real safety situations. For such conditions, some characteristic of a driver's performance of vehicle control task may be a better objective safety criterion. As a quantitative characteristic of this driving task, vehicle fluctuation around the travel trajectory centerline was implemented in this study. The research results indicated that on all investigated highways on straight segments during daytime and night, as well as on curves during darkness, the presence of edge lines on average reduce vehicle lateral position variance by 20 percent. These findings characterized better driver vehicle control and also correspond well with the crash statistic analysis indicating significant reduction of run-off-the-road crashes after edge-line treatment.

An important issue of the present study is determination of the complexity of the driving environment affecting driver's mental workload. As a quantitative characteristic for mental workload estimation, the level of a driver's emotional tension was implemented. Test drives showed that placement of edge lines typically reduces driver mental workload at both free driving and meetings with oncoming traffic, with the greatest effect at nighttime. The percentage of total driving time when driver experience increased emotional tension, on average, was reduced by 6 percent and mean heart rate was reduced by 12 percent.

The human study also found that the presence of additional basic lines created by the edge-line pavement marking in the visual field may significantly improve driver's estimation of roadway curvature.

Other findings related to a driver's recognition of adjacent roadways indicated that the discontinuities in the edge-line pavement markings may significantly increase driver's advance time of intersection identification.

Chapter 4. Summary and Recommendations

4.1 Summary

Based on the hypothesized concepts of driver perception of longitudinal pavement markings and the results of crash statistics analysis the following hypothesis were formulated for testing through the driver response study elements of the project:

- Edge lines may affect vehicle transverse position and speed.
- Edge lines may enhance the driver's perception of his(her) vehicle's transverse position on the roadway and this may be measured as reduced oscillation around the trajectory centerline.
- Edge lines may reduce driver emotional tension due to enhanced transverse position sensing, especially when meeting oncoming vehicles.
- At night, edge lines may allow the driver's eyes to recover faster after the "blinding" effect of oncoming vehicle headlights and this may reduce driver stress level during nighttime driving.
- Edge lines on two-lane roads provide much better driver perception of curvature than centerline markings only (without edge-line pavement marking) especially at nighttime when visual contrast between roadway edges and the environment is very low.
- Discontinuities in the edge-line pavement marking may increase the distance for intersection advance recognition by drivers.

To test the above-mentioned hypothesis three approaches were selected: stationary observations, test-driving, and laboratory experiments. The stationary observations and test driving were conducted as before-after studies in which edge lines were added to two-lane road sections that did not have them during the before experiments.

These studies identified significant impacts of edge lines on driver behavior and reactions.

- Before versus after comparisons of speeds measured through stationary observations, as well as, test drives indicated that edge line treatments were associated with slightly increased speeds. Increases averaged about 5 mph (or 9 percent) on both straight and curved highway segments. As noted in Chapter 3, the average speed change associated with edge line treatments is not considered significant.
- The stationary position measurements of vehicle lateral position indicated that placement of edge lines had no significant effect on the narrowest investigated roadway (lane width 9 feet) in any lighting condition. On wider roadways (lane width 10 and 11 feet), presence of edge lines tended to be associated with vehicle lateral

positions moving toward the pavement edge during both daylight and darkness an average of approximately 1.5 feet.

- Analysis of lateral position histories of test drivers showed that for all investigated highways during both daylight and darkness, approximately equal numbers of drivers had no lateral position changes, moved closer or further away from the center-line. These changes were generally small magnitudes, that is, during daylight toward the center-line moves averaged 0.75 feet and away from centerline moves 0.33 feet. During nighttime, lateral position changes averaged 0.24 feet. Thus, generally speaking, the position histories developed through test driving did not show any consistent pattern of significant movement.
- As a quantitative characteristic of driver consistency and effort (possibly driving stress), fluctuations around the travel trajectory centerline were captured during test driving. On all investigated highways on straight segments during day and night as well as on curves at night, edge lines on average reduced vehicle lateral position fluctuation by about 20 percent. These findings characterize better driver control and correspond well with crash statistics indicating reduction of run-off-the-road crashes after edge-line treatment.
- An important question was how the driving environment affects driver mental workload. As a quantitative characteristic of mental workload, the driver's heart rate and ECG waveform were recorded during test driving. Test drives showed that edge lines typically reduced driver heart rates both during free driving and when meeting oncoming traffic with the greatest effect at night. After edge lines were added, the percentage of total driving time when drivers experienced increased emotional tension on average was reduced 6 percent and the mean heart rate was reduced 12 percent.
- The laboratory study found that additional basic path delineation lines created by edge line pavement markings significantly improved driver perception of roadway curvature.
- The laboratory study also found that driver recognition of crossing roadways improved dramatically when edge lines were provided. Discontinuities, or breaks, in edge-line pavement markings significantly increased the participant's ability to recognize an upcoming intersection providing more time to plan and react properly to a crossing roadway.

4.2 Recommendations.

Based upon these hypotheses, tests, field and laboratory data the following recommendations are offered:

Although pavement widths studied from 18' or wider yielded positive results with the installation of edge lines, for maintenance purposes, 21'-9" should be considered as the standard minimum width for edge line placement. However, if necessary, other widths should be considered as per engineering judgment, after an engineering investigation, or as a specific district policy.

Edge lines might be considered as a possible solution to run off the road accidents where:

- Horizontal curves are problematic due to their sharpness or frequency
- A significant fraction of the users of a highway section are older drivers
- Edge lines might also be considered as a possible treatment for accident prone locations in the vicinity of crossing roadways or major driveways.

References

1. Tsyganov, A.R., Machemehl, R.B., Warrenchuk, N.M., “Safety Impact of Edge Lines on Rural Two-Lane Highways,” Research Report 0-5090-1, Center for Transportation Research, The University of Texas at Austin, 2005, p. 113.

2. Bishop, R.W., Calvin, R.M., and McPherson, K., "Driving: A Task Analysis Approach," Rand McNally & Co., Chicago, Ill., 1975, pp.111-117.

3. Klebelsberg, D., "Verkehrspsychologie", Springer-Verlag, Berlin-Heidelberg-New York, 1982, p.367.

4. Lobanov, E.M., "Highway Design Taking into Consideration Drivers Psycho-Physiology," Transport, Russia, 1980, p.311.

5. Zwahlen, H.T., Schnell, T., “Visibility of New Pavement Markings at Night Under Low-Beam Illumination,” Transportation Research Record, No. 1495, National Research Council, Washington D.C., 1995, pp. 117-127.

6. Zwahlen, H.T., Schnell, T., “Visibility of Road Markings as a Function of Age, Retroreflectivity Under Low-Beam and High-Beam Illumination at Night,” Transportation Research Record, No. 1695, National Research Council, Washington D.C., 1999, pp. 152-163.

7. Graham, J.R., King, L.E., “Retroreflectivity Requirements for Pavement Markings,” Transportation Research Record, No. 1316, National Research Council, Washington D.C., 1991, pp. 18-23.

8. Sadalla, E.,K., Hauser, E., "Psychological and Physiological Consequences of Driving Stress," Arizona State University, Research Report CART-1991-1, Tempe, Arizona, 1991, p.171.

9. Zeitlin, L.R., "Micromodel for Objective Estimation of Driver Mental Workload from Task Data," Transportation Research Record 1631, Washington, D.C., 1998, pp. 28-34.

10. Waard, D., Brookhuis, K.A., "On The Measurement of Driver Mental Workload," Traffic and Transport Psychology: Theory and Application, Galliard Ltd., Great Britain, pp. 161-171.

11. Stuster, J., Coffman, Z., "Synthesis of Safety Research Related to Speed and Speed Management," Research Report FHWA-RD-98-154, FHWA, Washington, D.C., 1998, p.23.

Appendix A: Product 2 (0-5090-P2)

This product consists of the following tables, arranged by TxDOT District:

- Table A.1: Centerline miles and percentage of two lane roads by width indicating those for which edge lines should be considered.
- Table A.2: AADTs of two-lane roads by district and width
- Table A.3: Numbers of curves on two-lane roads by district by width
- Table A.4: Curve radii on two-lane roads by district by width

Table A.1: Centerline miles and percentage of two lane roads by width, indicating those for which edge lines should be considered

TxDOT District			Roadway Width, ft							Roadway Width, ft						
Number	Name	Abr.	18 *	20 **	22 **	24 **	26 ***	28 ***	30 and greater ***	18 *	20 **	22 **	24 **	26 ***	28 ***	30 and greater ***
			Center-line Miles							Percentage of total mileage						
1	Paris	PAR	276.5	1451.3	122.7	481.3	289.1	13.3	17.6	10.39	54.51	4.61	18.08	10.86	0.50	0.66
2	Fort Worth	FTW	102.3	969.1	117.6	487.1	243.6	8.0	26.7	5.24	49.58	6.02	24.92	12.46	0.41	1.36
3	Wichita Falls	WFS	329.5	1081.8	121.6	594.9	139.2	10.4	17.0	14.32	47.03	5.29	25.86	6.05	0.45	0.74
4	Amarillo	AMA	522.6	1075.2	127.7	825.4	500.4	0.6	28.3	16.96	34.90	4.15	26.80	16.24	0.02	0.92
5	Lubbock	LBB	625.3	1729.1	301.7	887.9	515.8	41.6	39.1	15.10	41.76	7.29	21.44	12.45	1.00	0.94
6	Odessa	ODA	126.8	213.6	127.8	1582.6	138.0	0.1	10.7	5.76	9.70	5.80	71.88	6.27	0.00	0.49
7	San Angelo	SJT	268.2	1049.6	170.2	815.4	448.9	1.0	13.4	9.69	37.94	6.15	29.47	16.23	0.04	0.48
8	Abilene	ABI	286.1	1135.0	381.9	774.3	217.1	0.6	17.2	10.17	40.36	13.58	27.53	7.72	0.02	0.61
9	Waco	WAC	431.5	1104.9	253.3	637.3	196.5	8.5	26.0	16.22	41.54	9.52	23.96	7.39	0.32	0.98
10	Tyler	TYL	270.3	1231.2	315.8	741.2	270.1	19.5	25.2	9.41	42.85	10.99	25.79	9.40	0.68	0.88
11	Lufkin	LFK	126.2	811.7	505.0	619.7	218.4	56.5	103.2	5.15	33.12	20.60	25.28	8.91	2.31	4.21
12	Houston	HOU	45.1	161.8	119.9	714.2	3.1	0.9	7.7	4.29	15.37	11.39	67.85	0.29	0.08	0.74
13	Yoakum	YKM	232.5	1104.7	358.6	1077.4	123.9	34.6	35.3	7.84	37.23	12.09	36.31	4.18	1.16	1.19
14	Austin	AUS	104.4	1046.1	169.1	477.6	14.8	8.6	149.5	5.30	53.07	8.58	24.23	0.75	0.43	7.59
15	San Antonio	SAT	117.6	999.6	78.2	1276.5	58.8	1.5	12.4	4.62	39.28	3.07	50.16	2.31	0.06	0.49
16	Corpus Christi	CRP	309.9	631.3	100.4	813.8	161.8	1.1	5.4	15.31	31.20	4.96	40.22	8.00	0.05	0.27
17	Bryan	BRY	60.6	813.9	597.0	590.4	266.0	17.0	77.1	2.45	32.90	24.13	23.86	10.75	0.69	3.12
18	Dallas	DAL	4.1	376.2	558.8	717.0	33.9	5.8	4.2	0.24	22.13	32.87	42.17	2.00	0.34	0.25
19	Atlanta	ATL	80.7	1137.8	120.7	550.2	34.1	41.6	23.4	4.06	57.22	6.07	27.67	1.71	2.09	1.18
20	Beaumont	BMT	255.1	463.5	63.6	505.2	334.2	11.0	20.5	15.31	27.82	3.82	30.32	20.06	0.66	1.23
21	Pharr	PHR	70.3	387.0	3.1	828.7	78.7	32.6	15.5	4.96	27.33	0.22	58.53	5.56	2.30	1.10
22	Laredo	LAR	277.4	590.6	93.4	717.5	88.4	36.3	22.5	15.19	32.34	5.12	39.29	4.84	1.99	1.23
23	Brownwood	BWD	137.1	1170.9	110.2	610.1	256.2	16.5	28.2	5.89	50.26	4.73	26.19	11.00	0.71	1.21
24	El Paso	ELP	236.2	357.2	42.6	457.3	164.9	2.4	18.1	18.47	27.93	3.33	35.76	12.90	0.19	1.42
25	Childress	CHD	219.2	1041.0	129.0	460.0	353.0	5.1	18.3	9.85	46.77	5.79	20.67	15.86	0.23	0.82

* Edge lines placement should be based on engineering investigations

** Edge lines recommended

*** Edge lines required by MUTCD

Table A.2: AADTs of two lane roads by district and width

TxDOT District			Roadway Width, ft						
			18 *	20 **	22 **	24 **	26 ***	28 ***	30 and greater ***
Number	Name	Abr.	AADT (average for roadway class)						
1	Paris	PAR	860	1438	2101	2910	3901	3908	2890
2	Fort Worth	FTW	3392	1934	3338	5116	4469	4755	6236
3	Wichita Falls	WFS	1156	866	1181	1557	1938	1993	2904
4	Amarillo	AMA	308	498	393	1165	1127	445	1713
5	Lubbock	LBB	279	761	931	1157	1393	785	2476
6	Odessa	ODA	190	304	439	1014	1469	420	1554
7	San Angelo	SJT	300	340	885	1323	1907	2033	2225
8	Abilene	ABI	456	1836	618	1377	1414	945	2274
9	Waco	WAC	694	1717	2310	3593	3584	2170	3908
10	Tyler	TYL	1509	1991	2205	3465	5320	3169	4011
11	Lufkin	LFK	631	1762	1802	2402	2559	1740	3111
12	Houston	HOU	2844	5106	3703	5680	10320	5900	8162
13	Yoakum	YKM	755	975	1693	3620	2829	2282	4374
14	Austin	AUS	809	2082	3628	3920	3892	4781	4472
15	San Antonio	SAT	892	1893	1414	3616	4377	4397	7103
16	Corpus Christi	CRP	558	1034	1976	2588	3456	2883	3428
17	Bryan	BRY	1483	1098	2695	2959	4817	4218	4895
18	Dallas	DAL	2569	2080	3651	5401	6046	4200	7568
19	Atlanta	ATL	1070	1534	2350	3157	3846	2964	3775
20	Beaumont	BMT	1574	1845	3727	3378	3828	3662	6742
21	Pharr	PHR	496	942	4283	3259	4049	7279	6852
22	Laredo	LAR	810	569	793	1963	3160	4062	3220
23	Brownwood	BWD	235	628	931	1822	2249	2633	2752
24	El Paso	ELP	242	413	1848	2482	1103	2685	3955
25	Childress	CHD	145	334	487	697	881	756	1595

* Edge lines placement should be based on engineering investigations

** Edge lines recommended

*** Edge lines required by MUTCD

Table A.3: Numbers of curves on two-lane roads by district by width

TxDOT District			Roadway Width, ft						
			18 *	20 **	22 **	24 **	26 ***	28 ***	30 and greater
Number	Name	Abr.	Average Number of Curves per Mile						
1	Paris	PAR	1.94	1.73	1.20	1.33	1.36	1.66	0.88
2	Fort Worth	FTW	0.80	2.06	1.59	1.15	0.94	0.64	1.28
3	Wichita Falls	WFS	1.13	1.52	0.43	0.74	0.60	1.05	0.51
4	Amarillo	AMA	1.13	1.69	0.36	0.76	1.00	0.75	0.35
5	Lubbock	LBB	1.71	1.69	0.78	0.89	1.21	0.82	0.51
6	Odessa	ODA	1.66	1.69	0.89	0.76	0.84	0.00	0.44
7	San Angelo	SJT	1.44	1.52	0.78	0.82	1.22	1.35	0.21
8	Abilene	ABI	1.63	1.41	0.78	0.87	0.84	0.16	0.00
9	Waco	WAC	1.51	1.52	0.78	0.76	1.07	0.79	0.00
10	Tyler	TYL	1.72	1.52	0.78	0.82	1.22	0.77	0.35
11	Lufkin	LFK	1.34	1.52	0.89	0.89	1.07	0.83	0.35
12	Houston	HOU	2.41	1.58	0.89	0.76	2.22	0.00	0.51
13	Yoakum	YKM	1.09	1.52	0.78	0.82	1.07	0.58	0.39
14	Austin	AUS	3.16	4.29	2.23	1.18	1.21	2.99	0.63
15	San Antonio	SAT	1.76	1.52	0.91	0.76	1.22	0.83	0.25
16	Corpus Christi	CRP	0.83	1.92	0.84	0.80	1.63	0.77	0.28
17	Bryan	BRY	1.27	1.69	0.91	0.82	1.42	0.77	0.39
18	Dallas	DAL	1.56	1.32	1.59	1.29	0.45	1.81	0.76
19	Atlanta	ATL	2.92	1.98	1.43	1.32	0.40	0.82	1.39
20	Beaumont	BMT	4.48	1.76	1.70	1.47	0.86	1.29	0.47
21	Pharr	PHR	0.46	0.36	0.00	0.61	0.55	0.44	1.42
22	Laredo	LAR	0.58	0.69	0.48	0.38	0.26	0.82	0.23
23	Brownwood	BWD	2.10	1.55	1.24	1.36	0.70	0.74	2.20
24	El Paso	ELP	1.52	1.89	0.40	0.90	0.80	2.19	1.09
25	Childress	CHD	0.93	0.64	0.61	0.58	0.80	0.00	0.56

* Edge lines placement should be based on engineering investigations

** Edge lines recommended

*** Edge lines required by MUTCD

Table A.4: Curve radii on two-lane roads by district by width

TxDOT District			Roadway Width, ft						
			18 *	20 **	22 **	24 **	26 ***	28 ***	30 and greater ***
Number	Name	Abr.	Average Curve Radius†, feet						
1	Paris	PAR	1480	1307	1516	1921	2401	2057	1895
2	Fort Worth	FTW	1387	1666	1558	1951	1945	2190	2098
3	Wichita Fall	WFS	1222	1853	2405	1501	1976	1709	1591
4	Amarillo	AMA	1757	1739	1742	1997	2133	no data	2022
5	Lubbock	LBB	1317	1778	1736	1772	2274	1869	1785
6	Odessa	ODA	1847	2001	2251	2544	3347	0	1250
7	San Angelo	SJT	1633	1622	1742	1992	1691	1667	910
8	Abilene	ABI	1053	1384	1803	1707	1865	no data	1649
9	Waco	WAC	1150	1648	1883	2159	2015	985	1873
10	Tyler	TYL	1939	1613	1933	2150	2540	2420	1993
11	Lufkin	LFK	1355	1429	1869	2312	1957	1453	1733
12	Houston	HOU	1604	1219	1851	2191	1763	1155	2385
13	Yoakum	YKM	1853	1899	2244	2236	2454	2400	1504
14	Austin	AUS	1372	1596	1880	1771	1472	1535	1872
15	San Antonio	SAT	1422	1929	1986	2063	2539	980	2461
16	Corpus Chris	CRP	1583	1435	2236	1724	2408	no data	1939
17	Bryan	BRY	1445	1576	1890	2076	2267	2486	11
18	Dallas	DAL	510	1131	1302	1778	2606	2375	701
19	Atlanta	ATL	1294	1354	1433	1969	1805	2695	2824
20	Beaumont	BMT	1377	1718	1672	1989	2141	2206	2455
21	Pharr	PHR	1781	1958	0	1497	2053	no data	3217
22	Laredo	LAR	1285	1573	1983	2230	2781	3813	2727
23	Brownwood	BWD	1220	1418	1453	1681	1507	1791	1429
24	El Paso	ELP	1330	1725	1425	1922	1921	425	1541
25	Childress	CHD	1040	1520	1811	2010	2678	0	1963

†Only for curves with radius equal to or less than 5000 ft

* Edge lines placement should be based on engineering investigations

** Edge lines recommended

*** Edge lines required by MUTCD

Appendix B: Product 3 (0-5090-P3)

This product consists of the following tables, arranged by TxDOT District:

- Table B.1: Centerline miles of two-lane roads by width
- Table B.2: Centerline miles of two-lane roads currently with edge lines
- Table B.3: Centerline miles of two-lane roads currently without edge lines, and where edge line implementation is required, recommended, or optional

Table B.1: Centerline miles of two-lane roads by width

TxDOT District			Roadway Width, ft						
			18 *	20 **	22 **	24 **	26 ***	28 ***	30 and greater ***
Number	Name	Abr.	Total Centerline Miles						
1	Paris	PAR	276.5	1451.3	122.7	481.3	289.1	13.3	17.6
2	Fort Worth	FTW	102.3	969.1	117.6	487.1	243.6	8.0	26.7
3	Wichita Falls	WFS	329.5	1081.8	121.6	594.9	139.2	10.4	17.0
4	Amarillo	AMA	522.6	1075.2	127.7	825.4	500.4	0.6	28.3
5	Lubbock	LBB	625.3	1729.1	301.7	887.9	515.8	41.6	39.1
6	Odessa	ODA	126.8	213.6	127.8	1582.6	138.0	0.1	10.7
7	San Angelo	SJT	268.2	1049.6	170.2	815.4	448.9	1.0	13.4
8	Abilene	ABI	286.1	1135.0	381.9	774.3	217.1	0.6	17.2
9	Waco	WAC	431.5	1104.9	253.3	637.3	196.5	8.5	26.0
10	Tyler	TYL	270.3	1231.2	315.8	741.2	270.1	19.5	25.2
11	Lufkin	LFK	126.2	811.7	505.0	619.7	218.4	56.5	103.2
12	Houston	HOU	45.1	161.8	119.9	714.2	3.1	0.9	7.7
13	Yoakum	YKM	232.5	1104.7	358.6	1077.4	123.9	34.6	35.3
14	Austin	AUS	104.4	1046.1	169.1	477.6	14.8	8.6	149.5
15	San Antonio	SAT	117.6	999.6	78.2	1276.5	58.8	1.5	12.4
16	Corpus Christi	CRP	309.9	631.3	100.4	813.8	161.8	1.1	5.4
17	Bryan	BRY	60.6	813.9	597.0	590.4	266.0	17.0	77.1
18	Dallas	DAL	4.1	376.2	558.8	717.0	33.9	5.8	4.2
19	Atlanta	ATL	80.7	1137.8	120.7	550.2	34.1	41.6	23.4
20	Beaumont	BMT	255.1	463.5	63.6	505.2	334.2	11.0	20.5
21	Pharr	PHR	70.3	387.0	3.1	828.7	78.7	32.6	15.5
22	Laredo	LAR	277.4	590.6	93.4	717.5	88.4	36.3	22.5
23	Brownwood	BWD	137.1	1170.9	110.2	610.1	256.2	16.5	28.2
24	El Paso	ELP	236.2	357.2	42.6	457.3	164.9	2.4	18.1
25	Childress	CHD	219.2	1041.0	129.0	460.0	353.0	5.1	18.3

* Edge lines placement should be based on engineering investigations

** Edge lines recommended

*** Edge lines required by MUTCD

Table B.2: Centerline miles of two-lane roads currently with edge lines

TxDOT District			Roadway Width, ft						
			18	20	22	24	26	28	30 and greater
Number	Name	Abr.	Centerline Miles with Edge Lines						
1	Paris	PAR	170.2	333.2	107.1	460.9	287.0	2.8	15.6
2	Fort Worth	FTW	40.7	299.8	9.3	217.7	2.0	6.8	6.8
3	Wichita Falls	WFS	34.5	100.1	101.2	517.9	136.4	8.0	12.9
4	Amarillo	AMA	23.5	68.8	26.0	764.8	484.8	0.0	15.4
5	Lubbock	LBB	146.3	488.9	289.6	776.5	500.8	41.4	32.8
6	Odessa	ODA	101.4	205.8	111.0	1397.1	108.5	0.1	9.2
7	San Angelo	SJT	143.6	591.1	85.2	610.7	237.8	0.4	8.1
8	Abilene	ABI	4.2	183.8	304.7	701.5	215.9	0.4	11.7
9	Waco	WAC	313.7	658.4	199.4	563.5	182.3	8.3	21.4
10	Tyler	TYL	42.9	255.7	152.7	618.8	261.9	9.8	21.1
11	Lufkin	LFK	60.8	227.1	456.8	575.4	191.6	55.8	94.4
12	Houston	HOU	43.7	161.4	116.4	683.7	3.1	0.9	7.1
13	Yoakum	YKM	130.6	797.3	325.9	1003.5	110.4	34.0	27.2
14	Austin	AUS	14.2	169.8	41.2	190.0	102.5	0.6	7.2
15	San Antonio	SAT	0.8	204.8	42.9	774.1	18.0	1.0	6.9
16	Corpus Christi	CRP	69.4	171.5	68.0	729.2	147.1	1.0	3.0
17	Bryan	BRY	14.2	535.7	570.0	551.0	253.3	16.5	76.8
18	Dallas	DAL	3.8	225.3	456.3	617.3	26.4	5.8	4.2
19	Atlanta	ATL	77.5	1115.8	114.6	541.7	33.7	41.6	21.3
20	Beaumont	BMT	79.8	195.3	53.0	481.5	331.3	11.0	19.7
21	Pharr	PHR	17.1	13.6	3.1	723.9	67.4	32.6	15.2
22	Laredo	LAR	2.6	36.6	89.3	651.0	86.9	35.4	12.4
23	Brownwood	BWD	0.0	253.8	62.6	603.8	244.8	11.8	16.8
24	El Paso	ELP	52.7	3.6	25.3	427.9	163.8	1.7	8.4
25	Childress	CHD	0.0	0.0	128.2	459.2	350.6	5.1	16.8

Table B.3: Centerline miles of two-lane roads currently without edge lines, and where edge line implementation is required, recommended, or optional

TxDOT District			Roadway Width, ft							Total Mileage without Edge Lines	Total Mileage where Edge Lines:		
			18 *	20 **	22 **	24 **	26 ***	28 ***	30 and greater ***		Required	Recommended	Optional
Number	Name	Abr.	Center-line Miles without Edge Lines								Center-line Miles		
1	Paris	PAR	106.3	1118.1	15.5	20.4	2.1	10.4	1.9	1274.7	14.4	1154.0	106.3
2	Fort Worth	FTW	61.6	669.3	108.3	269.4	241.6	1.3	19.8	1371.3	262.7	1047.0	61.6
3	Wichita Falls	WFS	295.0	981.7	20.3	77.0	2.8	2.4	4.1	1383.4	9.3	1079.1	295.0
4	Amarillo	AMA	499.1	1006.4	101.7	60.6	15.7	0.6	13.0	1697.1	29.2	1168.8	499.1
5	Lubbock	LBB	478.9	1240.2	12.1	111.4	14.9	0.2	6.3	1864.1	21.4	1363.7	478.9
6	Odessa	ODA	25.4	7.8	16.8	185.6	29.5	0.0	1.5	266.6	31.1	210.1	25.4
7	San Angelo	SJT	124.6	458.6	85.0	204.6	211.2	0.7	5.3	1090.0	217.1	748.2	124.6
8	Abilene	ABI	281.9	951.2	77.3	72.8	1.2	0.2	5.6	1390.1	7.0	1101.3	281.9
9	Waco	WAC	117.8	446.5	53.8	73.8	14.3	0.2	4.6	710.9	19.0	574.1	117.8
10	Tyler	TYL	227.3	975.5	163.1	122.3	8.2	9.7	4.2	1510.4	22.1	1261.0	227.3
11	Lufkin	LFK	65.4	584.6	48.2	44.2	26.8	0.7	8.7	778.7	36.2	677.1	65.4
12	Houston	HOU	1.4	0.4	3.5	30.5	0.0	0.0	0.6	36.5	0.6	34.4	1.4
13	Yoakum	YKM	101.9	307.4	32.7	73.8	13.5	0.5	8.1	537.9	22.1	413.9	101.9
14	Austin	AUS	90.2	876.3	127.8	287.6	-87.7	7.9	142.3	1444.4	62.5	1291.7	90.2
15	San Antonio	SAT	116.8	794.9	35.3	502.4	40.8	0.5	5.5	1496.2	46.8	1332.6	116.8
16	Corpus Christi	CRP	240.4	459.8	32.4	84.6	14.8	0.1	2.4	834.4	17.2	576.7	240.4
17	Bryan	BRY	46.4	278.2	27.0	39.4	12.7	0.5	0.3	404.6	13.5	344.7	46.4
18	Dallas	DAL	0.3	150.9	102.5	99.6	7.6	0.0	0.0	360.9	7.6	353.0	0.3
19	Atlanta	ATL	3.1	22.0	6.0	8.6	0.4	0.0	2.1	42.2	2.5	36.6	3.1
20	Beaumont	BMT	175.4	268.2	10.6	23.7	2.8	0.0	0.8	481.5	3.7	302.5	175.4
21	Pharr	PHR	53.2	373.3	0.0	104.8	11.3	0.0	0.4	542.9	11.6	478.1	53.2
22	Laredo	LAR	274.8	554.0	4.1	66.6	1.5	0.9	10.1	912.0	12.5	624.7	274.8
23	Brownwood	BWD	137.1	917.0	47.7	6.3	11.5	4.7	11.4	1135.7	27.5	971.0	137.1
24	El Paso	ELP	183.5	353.6	17.3	29.5	1.1	0.7	9.7	595.4	11.5	400.4	183.5
25	Childress	CHD	219.2	1041.0	0.8	0.8	2.4	0.0	1.6	1265.7	4.0	1042.5	219.2

* Edge lines placement should be based on engineering investigations

** Edge lines recommended

*** Edge lines required by MUTCD

Appendix C: Pilot Evaluation of LED Delineators on Horizontal Curves

The Texas Department of Transportation Atlanta District initiated a study of the effectiveness of LED post mounted delineators on rural highway horizontal curves. The following describes a test at a field implementation site in which the LED post mounted delineators were studied.

A curved segment of highway FM 127 in the Mt. Pleasant area was selected for this investigation. LED's were attached to chevron posts (2 LED strips on each post) with activation through a radar system so that the LED's would start flashing when the speed of an approaching vehicle exceeded the recommended 35 mph speed. Figure 1 is a general view of the test section and the LED installation is shown in Figure 2.

Figure C.1: General View of the Test Section (Southbound)

Figure C.2: LED Placement on Test Section Posts

The potential operational impact of the LED supplemental delineation was evaluated through before and after field observations as well as by laboratory experiment. The test hypothesis for the field observations was that the LED implementation might effect vehicle speeds and lateral position. The laboratory experiments targeted identification of driver perceptions with and without LED application.

For field observations the investigated highway section was divided onto segments by placement of poles (3 ft height) with reflective plates on top providing fiducial marks for speed analysis. The poles were installed as far as possible from the roadway and practically were not visible by drivers. Four camcorders focused to cover all segments were installed and continuously recorded traffic for several hours during daytime and at night. Each camcorder had a time code with a 1/30 second time resolution. Figure 3 shows the test section segmentations and video recording strategy. The camcorder placements were chosen to insure that drivers could not see them or the human observer.

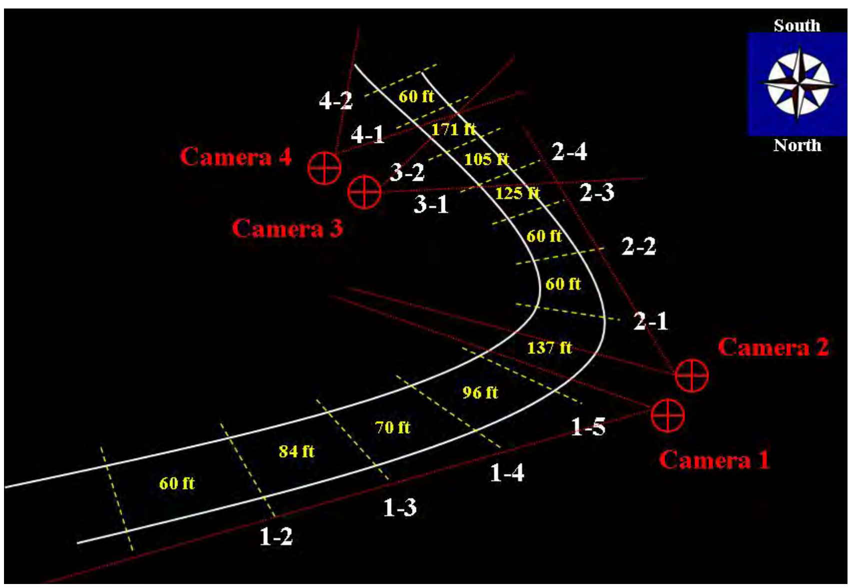
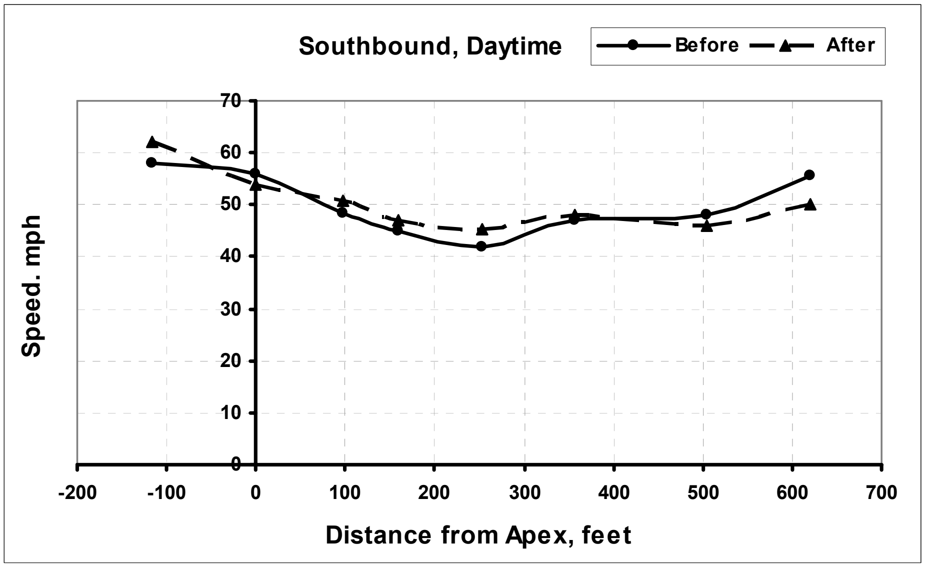


Figure C.3: Test Section Segments and Video Recording Directions

Observations of vehicle passage times between fiducial marks whose spacing was known permitted estimation of vehicle speeds. For vehicle lateral position estimation, a observer replayed the videotaped observations on a computer screen and measured the distance between the vehicle tire and the pavement centerline. A further comparison to verify the estimated distance to the centerline was made using the known traffic lane width. Field observations were conducted during day and nighttime.

The data were separated by the distance to the curve center and the observation sample size was calculated to insure data correspondence to 95-percentile confidence levels.

The field data regarding vehicle speed and lateral position on the roadway before and after LED implementation during daytime and darkness is shown graphically in Figures 4 through 7 and represented in Tables 1, 2, and 3.



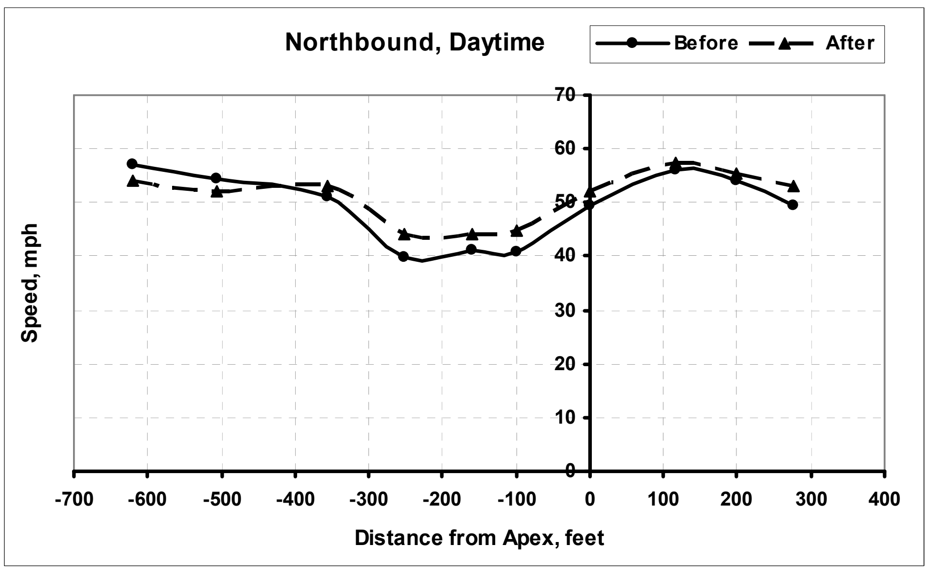


Figure C.4: Before and After Speed Distribution on the Test Section during Daytime

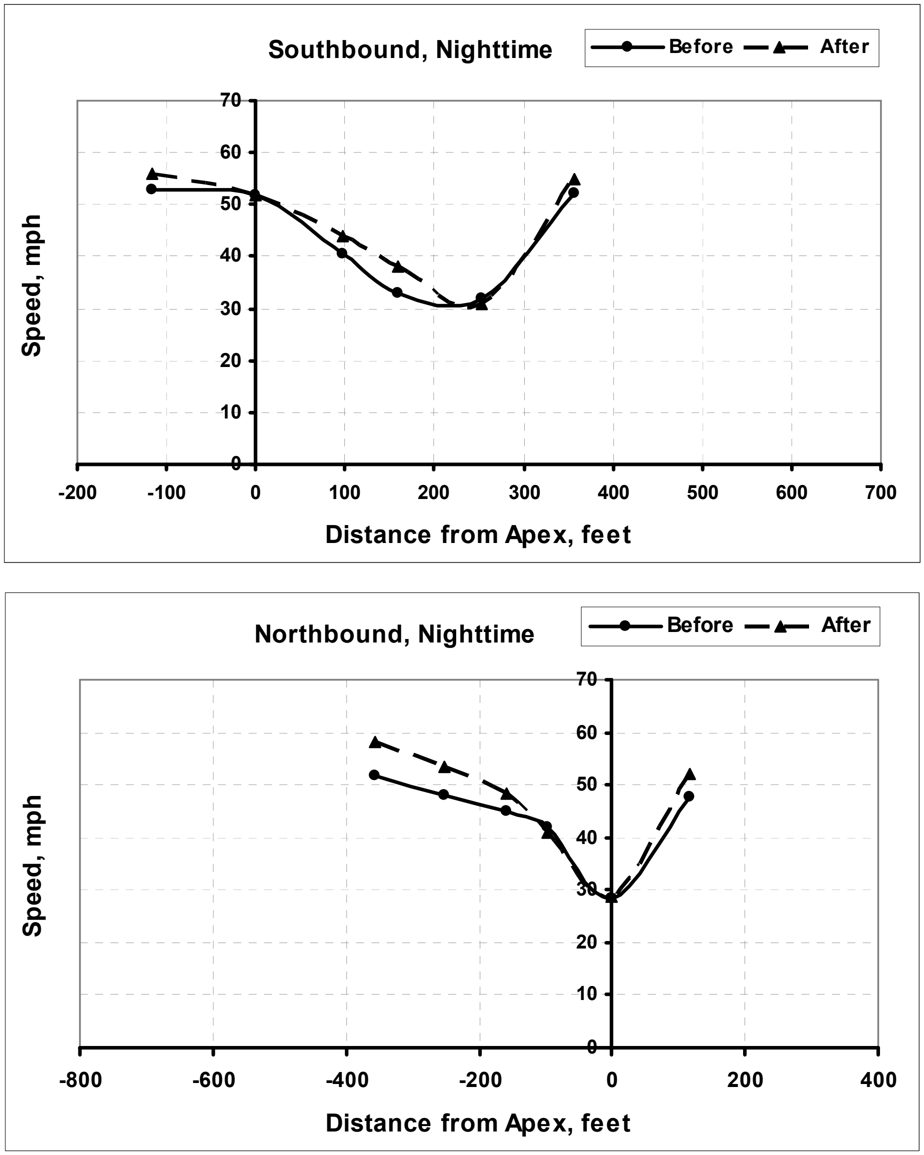
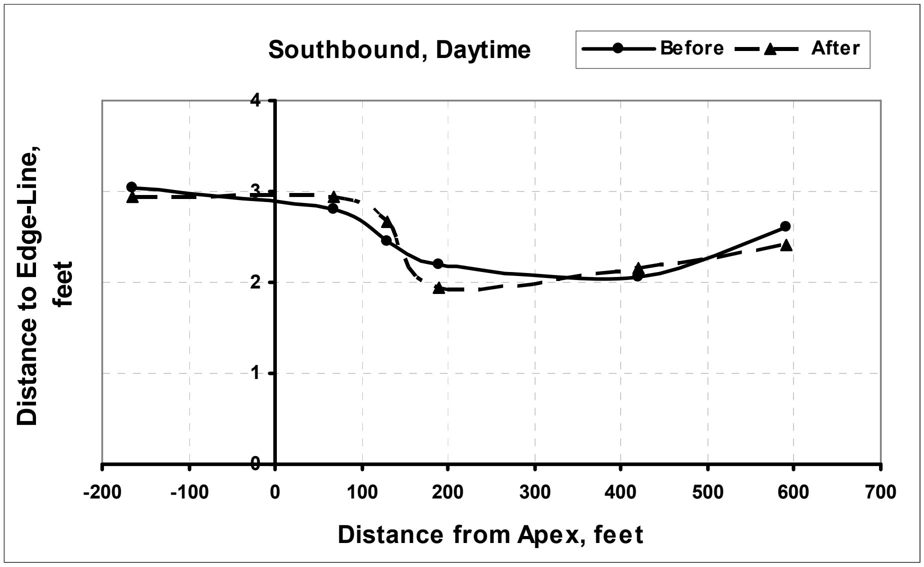


Figure C.5: Before and After Speed Distribution on the Test Section during Nighttime



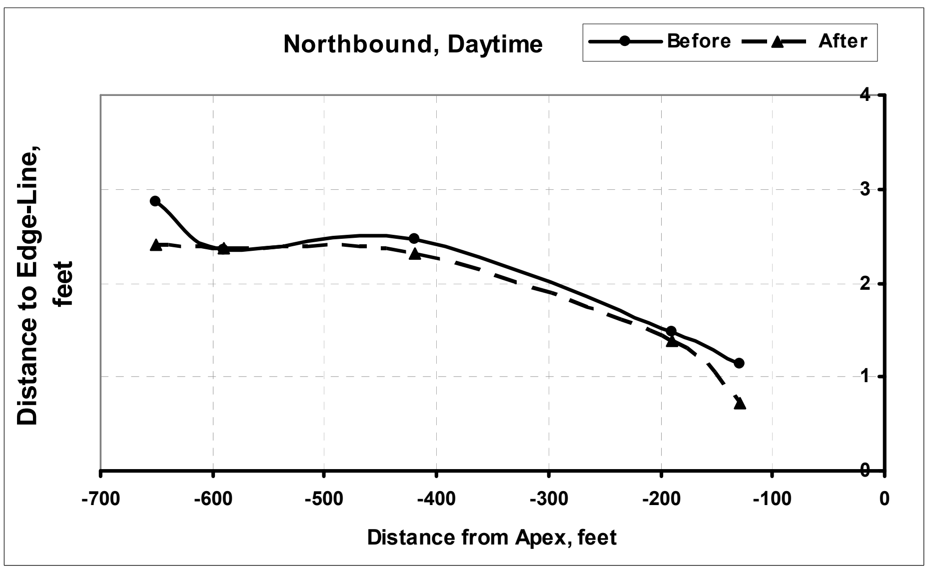
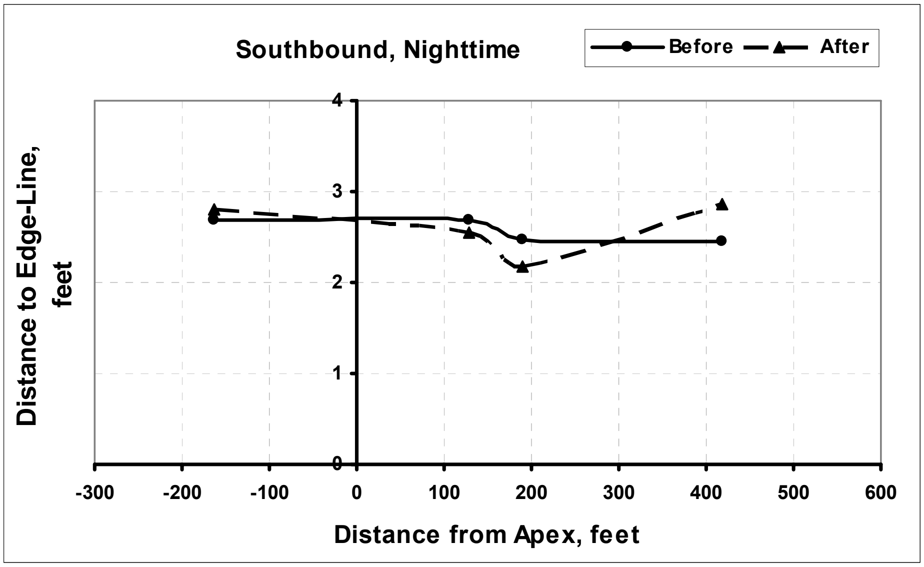


Figure C.6: Before and After Vehicle Lateral Position Distribution on the Test Section during Daytime



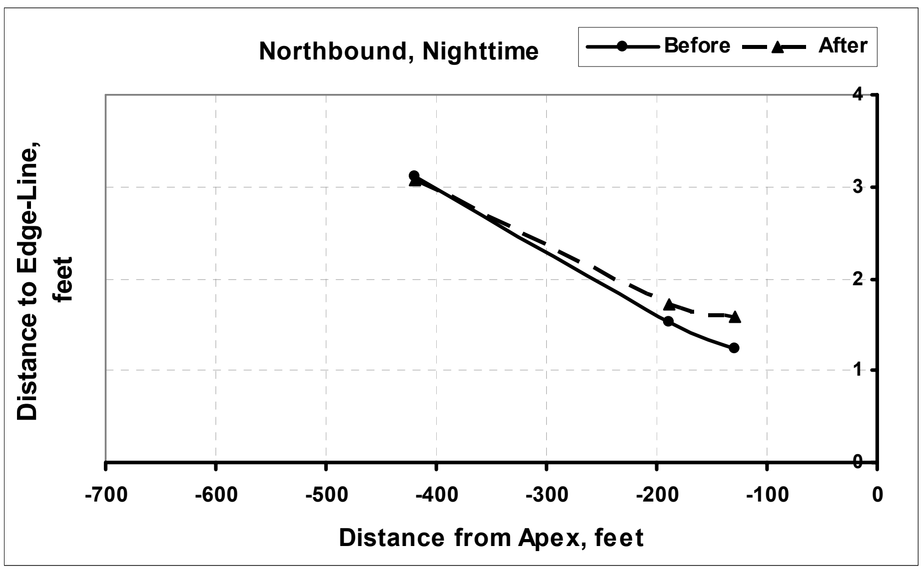


Figure C.7: Before and After Vehicle Lateral Position Distribution on the Test Section during Nighttime

Table C.1: Field Observations Sample Sizes

Sample Size, vehicles			
Day		Night	
LED off	LED on	LED off	LED on
Southbound			
146	153	78	96
Northbound			
123	142	84	72

TableC.2: Before and After Average Speed on Test Section

Position from Cenetr of Curve, ft	Mean Spot Speed, mph			
	Day		Night	
	Before	After	Before	After
Southbound				
-116	58	62	53	56
0	56	54	52	52
98	49	51	41	44
159	45	47	33	38
252	42	45	32	31
357	47	48	52	55
505	48	46	no data	no data
621	56	50	no data	no data
Northbound				
-621	57	54	no data	no data
-505	54	52	no data	no data
-357	51	53	52	58
-252	40	44	48	53
-159	41	44	45	48
-98	41	45	42	41
0	49	52	28	29
116	56	58	48	52
199	54	55	no data	no data
276	49	53	no data	no data

Table C.3: Before and After Vehicle Lateral Positions on Test Section

Position from Cenetr of Curve, ft	Mean Distance to Edge-Line, ft			
	Day		Night	
	LED off	LED on	LED off	LED on
Southbound				
-164	3.0	2.9	2.7	2.8
68	2.8	2.9	no data	no data
129	2.4	2.7	2.7	2.5
189	2.2	1.9	2.5	2.2
419	2.0	2.2	2.4	2.9
590	2.6	2.4	no data	no data
Northbound				
-650	2.9	2.4	no data	no data
-590	2.4	2.4	no data	no data
-419	2.5	2.3	3.1	3.1
-189	1.5	1.4	1.5	1.7
-129	1.1	0.7	1.2	1.6

Field data for both vehicle speed and lateral position, clearly indicated the absence of any statistically significant differences between the before and after LED application cases.

At the next evaluation stage the driver perceptions with and without LED implementation was investigated in a laboratory experiment. Because it is reasonable assume that the major driver perception effect would occur during darkness, only nighttime conditions were considered during the experiment.

The highway section, where field observations were conducted, was video recorded at nighttime from a moving vehicle when the LED post delineators were active and non-active. In both cases the vehicle was driven with a constant speed (50 mph) through whole test section.

Video materials were digitized and formatted as DVD video and shown to human subjects following by a questionnaire survey of his/her subjective perception. During the experiment video was displayed in a dark room on a 36-inch TV monitor with a distance to subject of 5 feet. Participants had no any instruction before the experiment and had no knowledge of the experiment's objective.

Twenty people participated in the computer experiment (10 males and 10 females) with age from 36 to 61 years, and the major findings of the experiment are represented as follows:

The first test hypothesis was that the flashing LED may impact driver speed perception. After videos were shown to the participants, they were asked in which movie vehicle speed was faster. Fifteen subjects answered saying that vehicle speed was faster during Sample-A (active LED) than on Sample-B (non-active LED).

Then the Sample-A video was shown one more time and the researcher provided information regarding the investigated treatment and based on discussion with the participant identified differences in his or her perception of traffic conditions due to LED application. During discussion the researcher and participant may watch both video samples unlimited times to verify any particular ideas regarding potential safety benefits of the LED application. Among the identified responses, several can be highlighted as typical for all participants:

- Flashing LED increases awareness due to association with emergency vehicle lights.
- Flashing lights accentuate attention to the curve.
- The LED treatment could be helpful during adverse weather.
- Appreciation of the LED treatment.

Additionally, almost half of participants noted that the flashing LED did help them to recognize the curve far in advance.

Summarizing the findings of field observations and laboratory experiment, the following major conclusions can be made:

- **There were no significant changes in driver behavior (speed and vehicle lateral position) before versus after LED application. Since most users of the investigated route are daily commuters, this result is predictable. However, considering the driver survey results, the LED's likely produce greater awareness and attention level and this could have positive safety impacts.**

- **On rural highways during nighttime, very low contrast between roadway and roadside objects is typical, so LED placements on chevron posts create bright roadside vertical objects that may affect driver's speed and curvature perception.**

- **LED treatment may be especially effective during adverse weather.**