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16. Abstract

This report documents the findings of a 30-month project in which various rumble strip applications were tested. The focus was on the operational aspects of in-lane, transverse rumble strips (TRSs) and centerline rumble strips (CRSs). Operational aspects of edgeline rumble strips (ERSs) were also tested. The researchers reviewed previous studies, interviewed state agencies with significant rumble strip experience, and reviewed available policies. Based on these efforts and input by the Texas Department of Transportation (TxDOT), the researchers then developed initial application guidelines for rumble strips in Texas.

The TRSs were evaluated at stop-controlled intersections and horizontal curve locations throughout the state. Passing operations and vehicle lateral position were evaluated as a function of milled and raised CRSs at sites throughout the state. Shoulder usage was evaluated as a function of milled ERSs.

Researchers used the results of the operational studies, TxDOT input, and the synthesis of previous studies and other state policies to develop recommendations for TxDOT for TRSs, CRSs, and ERSs. These recommendations are contained in Appendix C.

17. Key Words

Rumble Strips, Centerline Rumble Strips, Edgeline Rumble Strips, Shoulder Rumble Strips, Transverse Rumble Strips, In-Lane Rumble Strips, Shoulder Usage, Lateral Position, Passing Operations

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TRAFFIC OPERATIONAL IMPACTS OF TRANSVERSE, CENTERLINE, AND EDGELINE RUMBLE STRIPS

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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 (FHWA) or the Texas Department of Transportation (TxDOT). This report does not constitute a standard, specification, or regulation. The engineer in charge was Paul J. Carlson, P.E. (TX #85402).

The United States Government and the State of Texas do not endorse products or manufacturers. Trade or manufacturers' names appear herein solely because they are considered essential to the object of this report.

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- Kirk Barnes of the Bryan District for his generous cooperation in terms of finding test sites in close proximity to TTI and working with the researchers to install experimental rumble strip designs.

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CHAPTER 1

INTRODUCTION

Research findings have clearly shown that continuous rumble strips along the shoulders of highways have significant benefits in terms of reducing run-off-the-road (ROR) crashes. More recently, studies are beginning to show that continuous rumble strips installed along the centerline (CL) of highways have the potential to impact safety in a positive manner. Less understood, but potentially just as beneficial, are in-lane or transverse rumble strips, which are normally installed on approaches to rural, high-speed intersections, unexpected horizontal curves, or other locations where crashes occur more frequently than expected.

This project included an investigation of these three different types of rumble strips on Texas highways. The primary focus of the project was on the operational aspects of transverse rumble strips (TRSs) and centerline rumble strips (CRSs). Also included in the research scope, but with less emphasis, is the evaluation of edgeline rumble strips (ERSs) on two-lane highways.

This report represents the details of the research performed. An earlier report includes the state-of-the-art review, including:

- interviews with states identified as having significant experience with rumble strips;
- a database of rumble strip specifications, applications, and usage;
- draft guidelines for rumble strips; and
- a benefit-to-cost safety analysis projection for the installation of CRSs and ERSs (*1*).

This report documents the research activities related to TRSs, CRSs, and ERSs. The appendices report detailed statistical analyses along with the recommendations concerning rumble strip applications throughout the state of Texas.

CHAPTER 2

TRANSVERSE RUMBLE STRIPS

PROBLEM STATEMENT

This chapter documents the design of field evaluations for transverse rumble strips, including:

- overall study approach,
- site selection,
- installation of rumble strips, and
- data analysis variables.

Previous studies have examined the effects of rumble strips on approaches to various roadway junctions. The scope of this research was focused on rural stop-controlled intersections and horizontal curves. A review of previous research revealed that the application of rumble strips to similar intersections and horizontal curves produced a statistically significant reduction in mean and 85th percentile approach speeds. However, the actual reductions were on the magnitude of 1 – 4 mph, which is not practically significant (*2*). The goal of this research was not only to determine if the rumble strips help reduce the approach speeds of vehicles, but rather to determine if the rumble strips are effective in warning drivers of an upcoming intersection. Researchers analyzed the changes in drivers' approach speeds to determine if drivers used a more gradual change in approach speed while approaching the intersection in the post-treatment case as opposed to the pre-treatment case.

OBJECTIVES

Reaction to the rumble strips as an advanced warning treatment would be reflected in the deceleration rates, or change of speed on the approach to the intersection or horizontal curve. Larger (but still comfortable) changes in speed, located further upstream, would be an indication that the rumble strips were effective at warning drivers of an approaching intersection or horizontal curve. Smaller changes in speed located further downstream and nearer to the intersection or curve would indicate an improvement as well. An overall indication of improvement would be a more gradual and uniform deceleration profile.

Initial reaction to the rumble strips would be reflected in the speeds of vehicles approaching the intersection or curve. As in previous studies, researchers collected and analyzed approach speeds to determine if drivers utilized lower speeds to the intersection or curve. Lower speeds on the approach to the intersection or curve would indicate an improvement. Another important consideration is drivers' reaction to the rumble strips. Installing new traffic control devices creates the risk of inducing erratic maneuvers if the devices surprise or confuse drivers. In the case of transverse rumble strips, drivers might brake suddenly or swerve to avoid the strips. An installation of transverse rumble strips can be considered a good safety treatment if such maneuvers are minimized.

Previous studies did not differentiate the effect that rumble strips had on unfamiliar or unsuspecting drivers. Another goal of this project was to determine if the rumble strips were more effective on drivers during nighttime periods. Drivers may be more unsuspecting of approaching conditions due to unfamiliarity with the roadway, drowsiness, or other inhibiting factors at night. During these times, rumble strips may be more effective than in daytime periods when there are greater percentages of familiar or suspecting drivers on the roadway.

STUDY DESIGN

Before and After Field Experiments

The basic project approach for this research was to collect and evaluate traffic operations data at given field sites. The experiments were carried out at each site in typical before-and-after fashion. The before treatment case involved collecting traffic operations data while no rumble strips were in place and a Stop-Ahead or Curve-Ahead warning sign was in place. The after treatment case involved collecting data after installing the rumble strips. The Institute of Transportation Engineers (ITE) *Manual of Transportation Engineering Studies* (*3*) recommends before and after experiments both for statistical and practical reasons, including:

- site-to-site variation is eliminated,
- fewer sites are necessary to draw useful conclusions, and
- results make intuitive sense and are easily understood by engineers and non-technical readers alike.

Surrogate Crash Measures

To evaluate the effectiveness of the transverse rumble strips, surrogate crash measures were used. The primary objective of safety expenditures on roadways is to improve the safety along roadways through reductions in crashes and crash severity. The ultimate measure of effectiveness would be an evaluation or analysis of changes in crash experience. Crash-based evaluations are difficult because low crash frequencies require long periods of time to acquire the needed sample sizes. Other complications arise due to bias, inaccuracy, and confounding effects within the crash database (*4*).

To offset the shortcomings of using crash experience as the sole criterion, non-crash measures are used to provide an intermediate measure. Non-crash measures are considered intermediate because they are meant to be a supplement, not a substitute, for–crash-based measures. Some operational non-crash measures that have been identified as surrogates for safety include:

- spot speeds,
- speed profiles,
- delay,
- travel time,
- percentage of vehicles stopping,
- deceleration profile,
- speed changes, and
- queue length.

While the proper use of surrogate crash measures can provide intermediate indications as to the effectiveness of implemented safety projects, their direct relationship to crash occurrence has yet to be established (*5*). Surrogate crash measures are recommended for use as an operational review tool and to improve traffic flow and operations during project planning stages. However, it is recommended that acceptance of non-crash measures as surrogate crash measures should be used with caution until quantitative relationships can be established (*4*). The measures of evaluation used in this research project include speed change and spot speeds.

Erratic Maneuvers

In addition to surrogate crash measures, another safety consideration is the frequency of erratic maneuvers like sudden/hard braking or swerving. As part of this research, video data were collected 24 hours after rumble strip installation at two of the stop-controlled intersection sites and then analyzed to determine the frequency of hard braking, swerving (sudden), or shifting (smooth) maneuvers.

General Field Procedures

For the research described here, a typical data collection effort at a given site was conducted in the following manner:

- Covertly collect traffic operations data (i.e., speeds, driver behavior) in the "before" period with the existing TxDOT warning signs in place.
- Install transverse rumble strips.
- Allow for a minimum three-week "warm up" period to allow novelty effects of the transverse rumble strips to wear off.
- Collect traffic operations data in the "after" period in the same manner as the "before" period.

The data collection effort made every attempt to select sites and design and perform the experiments to minimize biasing factors. With few exceptions, data collection was performed only on Mondays through Thursdays and under clear to partly cloudy weather conditions with dry pavement.

Site Selection

To satisfy the evaluation scenarios, 14 sites were selected and used for field evaluations. These sites included nine approaches to rural stop-controlled intersections and five approaches to horizontal curves. The locations where data were collected are listed in Table 2 and Table 3.

A number of criteria were used for the selection of sites. The main criterion for site selection was evidence of a hazardous condition that could potentially be remedied through the use of rumble strips. The main criteria for hazardous site identification were reports from TxDOT officials of intersections that had known problems, such as higher-than-state-average crash rates, locations of severe crashes, and/or intersections that had received public complaint. TxDOT also selected these sites based on engineering judgment. Traffic control devices such as warning signs had previously been deployed at these sites, but the crash rates and the number of complaints had not subsided as a result of these devices. Because selection of sites was based on the perceived availability of sites in the area and the most efficient way to use resources available for the project, the process was not random. Other selection criteria included:

- long uninterrupted tangent section on approach,
- no evidence of police over-enforcement in the area,
- close proximity to TTI headquarters, and
- feasibility and ease of data collection.

The sites selected contained similar features and controls. The features and controls were kept constant so drivers' speeds would not be influenced by external factors. Table 1 presents a summary of site selection controls. The characteristics for the intersection and curve project sites are displayed in Table 2 and Table 3, respectively. Detailed site descriptions are provided in the Findings section of the report.

Table 1. Site Selection Controls and Criteria.

Control	Criteria
Area Type	Rural
Terrain	No Restriction
Design Classification	Two-Lane on Project Approach
Intersection Control	Stop Ahead on Project Approach
Posted Speed Limit	55 – 70 mph
Traffic Volumes	Low (Less than 3000 vehicles/day [vpd])

Table 2. Characteristics of Rural Stop-Controlled Intersection Sites.

	Sites				
	FM 3118	**FM 50**	**FM 208**	**FM 2154**	**FM 2549**
Intersection Type	Two-way Stop	Two-way Stop	Four-way Stop	Four-way Stop	Two-way Stop
Development	Rural	Rural	Rural	Rural	Rural
Posted Regulatory Speed (mph)	65	65	65	70/65	70
Direction(s)	NB	NB/SB	NB/SB	NB/SB	NB/SB

Table 3. Characteristics of Horizontal Curve Project Sites.

	Sites				
	FM 1179	**FM 3090 (I)**	**FM 3090 (II)**	**FM 244**	**FM 46**
Roadway Type	RTLTW[1]	RTLTW[1]	RTLTW[1]	RTLTW[1]	RTLTW[1]
Right or Left Curve	Right	Left	Left	Left	Right
Posted Regulatory Speed (mph)	65	65	65	70/65	65
Posted Curve Advisory Speed (mph)	35	15	15	40	None

[1] Rural, two-lane, two-way (RTLTW) highway.

Installation of Rumble Strips

After collecting sufficient before speed data, the rumble strips were installed. The Rumbler® rumble strip from Swarco Industries, Incorporated, was used exclusively at all test locations. Swarco Industries produces three types of strips: reflective yellow, reflective white, and black (*6*). The reflective white rumble strip was used in this project.

Rumble Strip Characteristics

Each Rumbler® rumble strip consists of a four-foot-wide piece of white rubber with three raised ridges. The three ridges act to provide the rumble effect and also to provide the audible warning. The reflective white rumble strip, which was used in this project, has a potential to have more warning capabilities because of the added visual effect (*6*). Figure 1 shows a cross-sectional view of the Rumbler® rumble strip.

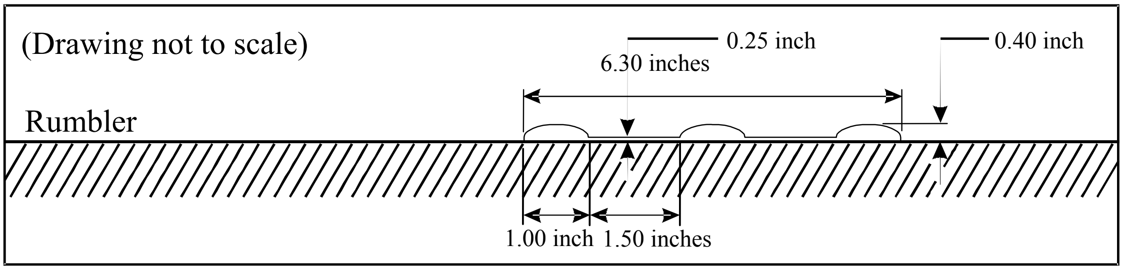


Figure 1. Cross Section of Rumbler® (*7*).

Deployment Configuration

Two sets of Rumbler® rumble strips were installed on the approaches to the stop-controlled intersections and horizontal curves. The sets were spaced 500 feet apart, with the downstream set being 250 feet downstream of the warning sign and the upstream set being 250 feet upstream of the warning sign. Each set contained ten rumble strips, spaced two feet center to center. These strips are four feet long, which leaves space for a gap in the traveled way for motorcycles.

A minimum of a two-foot gap was included in the center of the lane and a six-inch space was left between the edges of the strips and both the edgeline and the centerline. A diagram of a typical deployment for a set of rumble strips is shown in Figure 2.

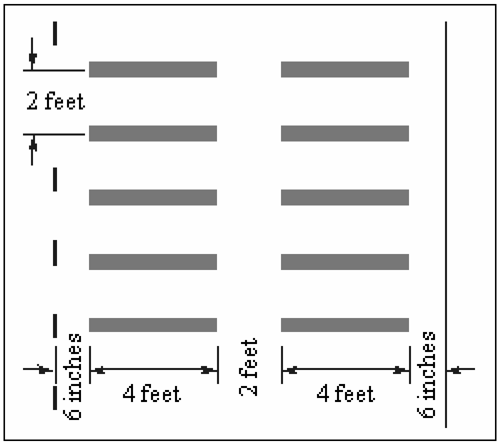


Figure 2. Standard Rumble Strip Layout.

Installation Procedures

For proper installation, the pavement had to be clean, dry, and warmer than 50º F. The pavement was dry, and its temperature just before installation was above 70º F in all cases. Once the pavement was clean, it was marked using a marking line and road chalk for proper placement and layout of the rumble strips. Adhesive, which was supplied by Swarco, was then applied to the pavement with a paint roller and allowed to set for approximately three minutes. After allowing the adhesive to set, seal tape was installed on the areas where the rumble strips would be located. An additional coat of adhesive was applied to the seal tape and allowed three minutes to set. The strips were placed on the seal tape and tamped manually and allowed about ten minutes to adhere to the surface before traffic was allowed to traverse over them. A typical installation is shown in Figure 3 and Figure 4.

Figure 3. Installation of Rumble Strips.

Figure 4. Upstream View of Installed Rumble Strips.

Traffic Operations Data Analysis Variables

The principal objective of this research project was to assess the effectiveness of rumble strips on driver behavior under various field conditions. Therefore, a detailed experiment was devised for each site based on the geometric characteristics. The following sections list descriptions of the independent, covariate, and dependent variables.

Independent Variables

The warning device treatment was the primary independent variable in the data analysis for each site. The null treatment was always the existing sign(s) that were in place. The existing warning treatments were the Stop-Ahead signs (ASTM Type III). The alternative treatments were the placement of rumble strips in addition to the existing warning sign. The null treatment was considered the before case (prior to the rumble strip installation) and the alternative treatment was considered the after case (with the rumble strips installed). Additional independent variables that were included in the analysis were as follows:

- ambient lighting condition (day or night period),
- data collection periods (weekday or weekend),
- vehicle type (only passenger vehicles with headways greater than 15 seconds were included in the analysis), and
- weather condition (data were only collected under clear to partly cloudy weather conditions).

Speed at Upstream Control Point (Covariate)

For the data analyses, the upstream control point speed was used as a covariate. Covariates are random variables that are treated as concomitants or as other influential variables that affect the response (*8*). It is reasonable to assume that the magnitude of drivers' responses to signs, geometric conditions, or intersections varied according to the speed at which they generally chose to drive (i.e., their uninhibited free-flow speed) (*9*). For example, drivers who travel faster on tangent sections will likely travel faster through curves. It was assumed that when approaching a stop-controlled intersection, faster drivers were forced to slow down more than slower drivers.

To provide an explicit measure of uninhibited free-flow driver behavior, initial spot speed measurements were taken on a tangent section upstream of the project site. Upstream speed measurements served as "control" data for the analysis. Upstream control point speed was included as a covariate in the analysis to account for the impact of individual drivers' uninhibited free-flow speed on speeds at the project site.

Dependent Variables (Measures of Effectiveness)

The stop-controlled intersection and horizontal curve studies utilized similar measures of effectiveness (MOEs). Before and after crash data were not available for the evaluations performed. Multiple literature sources have considered speed-related measures (i.e., speeds, decelerations, and speed variance) for vehicles approaching an intersection or curve as appropriate for surrogate crash evaluations. The MOEs were designed to detect changes in driver performance that were believed to be related to traffic safety. Available data collection resources were also considered in MOE development. Direct relationships between MOEs and crash occurrence were not established in the research. The MOEs employed for the stop-controlled intersections and horizontal curve sites included speed changes between data collection points and speeds approaching the intersection or curve.

Erratic Maneuver Data Analysis Variables

A secondary objective of this project was to determine whether installation of transverse rumble strips would induce erratic maneuvers as drivers encounter and pass over the strips. To determine the frequency of erratic maneuvers, video data were collected within 24 hours of strip installation so driver behavior could be observed directly. Data extracted from the footage included traffic volume counts, vehicle classifications, and maneuver classifications. These data were used to determine the frequency of erratic or avoiding maneuvers.

DATA COLLECTION

This section documents the field data collection and analytical procedures for the experiments performed in this project, including:

- determination of sample size,
- data collection procedures, and
- data screening and formatting.

Traffic Operations Data Collection

Traffic operations data were collected to satisfy the measures of effectiveness for each field evaluation. Speeds of free-flowing (> 15-second headway) passenger vehicles were measured for every field evaluation and were the basis for a majority of the MOEs. A 15-second headway was chosen because it was sufficiently large to ensure that drivers were uninfluenced by the brake lights of downstream vehicles. Because the researchers were more interested in the behavior of individual drivers than aggregated spot speeds, speeds of individual vehicles were tracked as they approached and proceeded through the project site. Vehicle tracking allowed speed profiles to be obtained for each vehicle, allowing for a more robust statistical analysis.

Table 4 shows a summary of the traffic operations data that were collected at the project sites to satisfy the measures of effectiveness.

Table 4. Traffic Operations Data Measured at Project Sites.

Curves	Stop-Controlled Intersections
• Vehicle speeds prior to the curve and signs coming into view (control point) • Vehicle speeds on the approach to the curve	• Vehicle speeds prior to intersection or signs coming into view (control point) • Vehicle speeds on the approach to the intersection • Video footage of vehicle traversing the project site

Determination of Sample Size

With project sites selected, the next task was to collect the geometric data of the sites. The geometric layouts of each site, including final placement of rumble strips, are shown in Appendix A. Next, approach speeds were needed prior to installation of rumble strips. The minimum number of individual speed observations required depends on the variation in speeds and the accuracy of the speed measurements. Equation 1 (*10*) was used to estimate the number of speed observations needed to compute mean and 85th percentile speeds at each site:

$$n = \left(\frac{ts}{\varepsilon} \right)^2 \qquad (1)$$

Where,

n = required sample size,
s = standard deviation,
ε = user-specified allowable error, and
t = coefficient of the standard error of the mean that represents user-specified probability level.

The value for standard deviation was estimated from previous studies (*11*,*12*,*13*,*14*, *15*). The estimation was computed prior to the field studies. Levels of statistical precision (t, ε) were user-specified. For the purposes of this report, a 95 percent confidence interval ($t = 1.96$), and an ε value of 1 mph were chosen. The values for standard deviation from previous studies ranged from 5 to 8 mph. Thus, the value for estimated sample size (n) varied from 125 individual vehicle speeds to 250 individual vehicle speeds. A minimum of 250 individual vehicle speeds was determined to be the required sample size at each project location.

Data Collection Equipment

Tracking of individual vehicle speeds through a given site was accomplished by using a series of portable automated vehicle classifiers. Portable automated vehicle classifiers are commonly used by transportation agencies nationwide and allow for a large sample size to be collected. These devices are placed on the roadside and connected to a pair of sensors (pneumatic roadtubes in this case) that are affixed to the pavement surface. The device recorded information for each axle that traversed over the sensors. The device was then able to compute desired information about each vehicle. A light detecting and ranging (LIDAR) device was then used to ensure that the roadtubes were set up properly and recording accurate information.

Speeds of individual vehicles were tracked by the automated vehicle classifiers by placing a number of devices in succession at specific locations throughout the project site. The classifiers and roadtubes were placed at three locations: a control location, at the warning sign, and near the intersection or curve. Time clocks were synchronized for all devices. Individual vehicles were later tracked during the data reduction phase by tracking time stamps and classifications among successive counters.

PEEK™ ADR 2000 traffic counters were used, operating in Raw Data mode. All data were collected using the counters and downloaded into a format that was manageable by Microsoft Excel™. The geometric data (lane widths and distances) were measured using a measuring wheel.

Placement of Counters

As previously mentioned, there were three locations at which the traffic data counters were placed. The control location was placed on the approach at a point where the driver could not see the intersection/curve or warning sign. The control location was used to compare changes in vehicle speeds in the before and after conditions. The second counter, referred to as the warning sign location, was placed at the Stop-Ahead or Curve-Ahead sign. The final counter, referred to as the intersection or curve location, was placed 450 to 500 feet upstream of the warning sign and 100 to 700 feet from the intersection or curve (see Figure 5). The placement of warnings was defined under the guidance of the *Texas Manual on Uniform Traffic Control Devices* (TMUTCD).

These locations were chosen to evaluate driver reaction to the rumble strips. The MOE used to evaluate driver reaction is the change in speed between speed trap locations. Change in speed approaching the stop sign is an appropriate MOE as it is desirable to reduce erratic vehicular decelerations and invoke a more comfortable deceleration profile (*4*, *16*). An indication of improvement would be illustrated by higher (but still comfortable) changes in speed further upstream and lower changes in speed further downstream. Additional MOEs used at the project sites were the comparison of approach speeds to the intersection and/or curve.

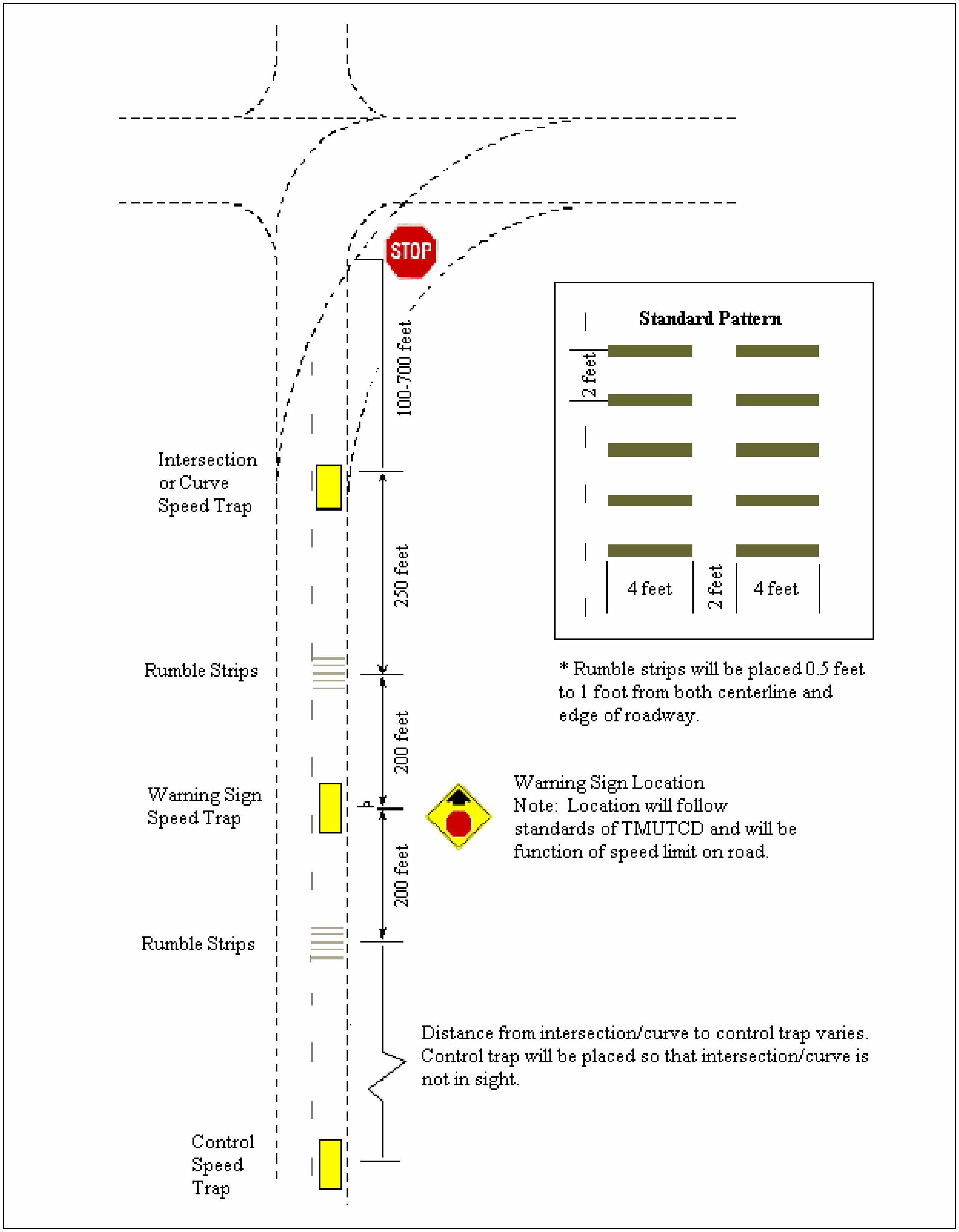


Figure 5. Standard Site Layout.

The Two Tube Class and Speed mode was used to collect the data. After configuring the data files as specified in the PEEK ADR 2000 manual (*17*), the roadtubes were placed within the traveled way. The roadtubes were placed 16 feet apart and perpendicular to the direction of traffic flow, as prescribed by the manual. A typical setup of the traffic counter and roadtubes is shown in Figure 6.

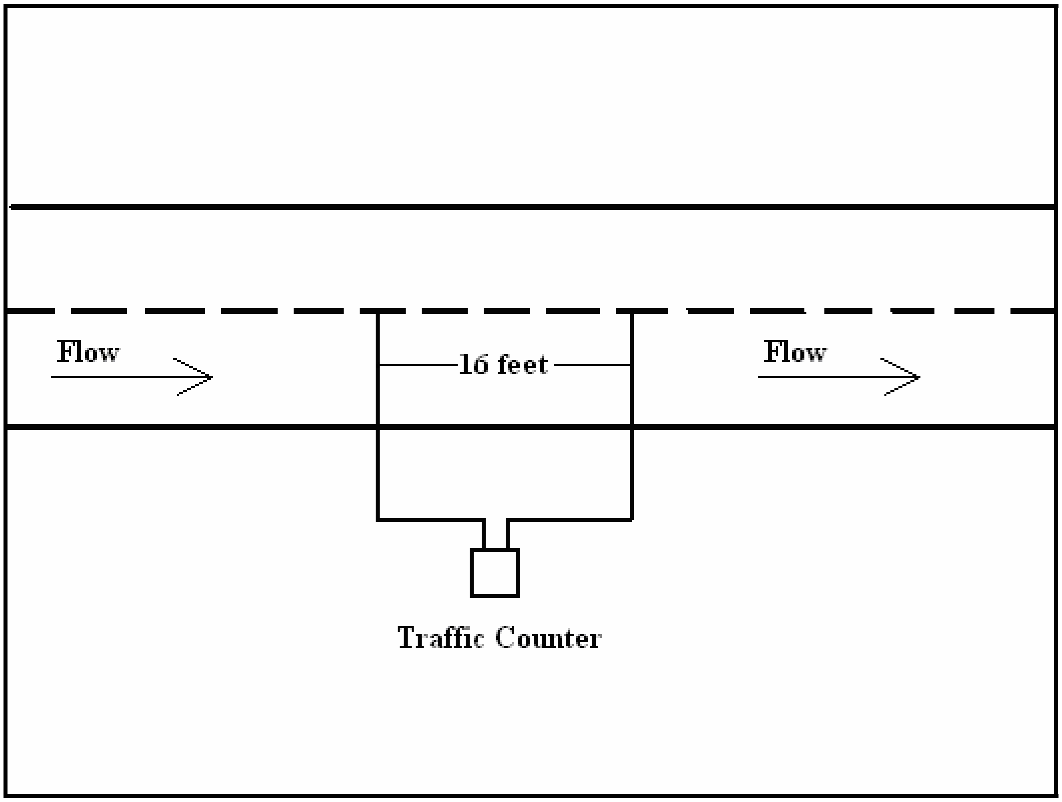


Figure 6. Typical Traffic Counter and Roadtube Configuration.

Duration of Study

A typical data collection period proceeded in the following manner:

- The field crew arrived at the site at approximately 10:00 AM to set up and began observations by 11:00 AM.
- A drive-through of the site was performed to locate the subject intersection, the warning sign, and a location for the control speed trap. The location of the control speed trap depended upon the requirement that drivers could see neither the intersection nor the warning sign.
- Once the location of the control speed trap was located, the traffic counters and roadtubes were placed as shown in Figure 5.

Data were collected during daytime and nighttime periods to determine if the effectiveness of the rumble strips changed throughout the day. The daytime and nighttime periods were defined from the sunrise and sunset times reported in *The Old Farmer's Almanac* (*18*). Generally, daytime was defined as sunrise to sunset and nighttime was defined as sunset to sunrise. Periods in which sunlight was directly in drivers' eyes were removed; however, this was minimal because the sites' roads ran in the north and south directions. The dates of the data collection periods for each site are shown in Table 5.

Table 5. Data Collection Periods.

Location	Before Data Collection		After Data Collection	
	Starting Date	Ending Date	Starting Date	Ending Date
FM 3118	9/23/2003	9/24/2003	11/21/2003	11/24/2003
FM 50	9/5/2003	9/10/2003	12/12/2003	12/16/2003
FM 208	5/12/2003	5/14/2003	6/25/2003	6/26/2003
FM 2154	8/15/2003	8/18/2003	11/18/2003	11/20/2003
FM 2549	8/22/2003	8/25/2003	2/20/2004	2/23/2004
FM 1179	9/16/2003	9/17/2003	12/10/2003	12/11/2003
FM 3090 (I)	5/28/2003	5/30/2003	10/29/2003	10/30/2003
FM 3090 (II)	11/12/2003	11/14/2003	3/24/2004	3/26/2004
FM 244	10/10/2003	10/14/2003	4/5/2004	4/7/2004
FM 46	10/2/2003	10/3/2003	4/7/2004	4/9/2004

Data Screening and Reduction

The raw speed data measured at the project sites were screened to create a random and unbiased sample of speeds for free-flowing, uninhibited passenger vehicles. The objective of the data screening process was to isolate the effect of the transverse rumble strips on driver behavior by identifying and eliminating potentially biased data. Therefore, the main data screening task was to identify anomalous vehicles and exclude them from the final data set.

An additional subset of the data was made to evaluate the effectiveness of rumble strips on drivers that entered the project location at speeds greater than the posted speed limit. After comparing the change in vehicle speed for all passenger vehicles entering the site, the data were subset once more to include only those vehicles whose speed at the control point speed trap exceeded the posted speed limit. The change in vehicle speed between the warning sign speed trap and the intersection speed trap was compared. Evaluations were performed at each site and also for day, night, weekday, and weekend conditions, where applicable.

Definitions of Anomalous and Representative Vehicles

During data collection, the researchers were interested in obtaining data from a sample of free-flowing passenger vehicles that were traveling through the project site without influence by other vehicles. However, a certain percentage of vehicles passing through a site during data collection were influenced by factors external to the experiment and deemed anomalous to the experiment. The researchers made every attempt to identify these anomalous vehicles and to exclude them from that data set. With few exceptions, for all data collected during the field evaluations, researchers defined anomalous vehicle and representative vehicles by the conditions shown in Table 6.

Table 6. Definitions of Anomalous and Representative Vehicles.

Anomalous Vehicles (Excluded from Data Set)	Representative Vehicles (Included in Data Set)
• Non-passenger: – Commercial – Delivery – Bus – Farm equipment • Influenced by other vehicles at the site: – Non-free-flowing (≤ 15-second headway) – Traversing through curve when vehicle is present in opposing lane (encroachment data only) – Approaching Stop sign when queue is present (stop-controlled intersection sites only) • Turning • Towing trailer • Motorcycle • Erratic behavior • Uninhibited upstream speed was deemed excessively slow (e.g., <50 mph for sites with 65-70 mph posted speed limits)	• Passenger: – Car – Pickup truck – Sports Utility Vehicle (SUV) – Van • Uninfluenced by other vehicles • Traversing the entire project site • Greater than 15-second headway • Traveling at an appropriate uninhibited speed upstream of the site (e.g., ≥ 50 mph for sites with 65-70 mph posted speed limits)

Data Formatting

Data collection files from the traffic counters were downloaded and imported into a Microsoft Excel format for the data reduction process. The number of initial observations ranged from 980 vehicles to 5400 vehicles. The following items were collected from the counters:

- date,
- time of day,
- number of vehicles per hour,
- vehicle classification, and
- vehicle speed.

Individual vehicle speeds and classifications were then analyzed to ensure that only free-flowing passenger cars were included in the database. Researchers deleted from the data file any non-passenger car and any vehicle less than fifteen-second headway after the previous vehicle. The percentage of passenger vehicles at each site ranged from 60 to 70 percent of the data set. The percentage of passenger vehicles that were in platoons (non-free-flowing traffic) was less than 10 percent for all sites.

Once in spreadsheet format, timestamps were compared at successive counters in an attempt to "track" vehicles through the project approach. The expected travel times were calculated based on speed and distance between the counters and also assuming a uniform deceleration, or in a few cases, acceleration. The expected travel times were used to estimate a time of arrival at each successive counter. By comparing the estimated time of arrival with the timestamp from the counter, the majority of the vehicles could be uniquely identified as they passed each of the three speed collection points. After tracking the vehicles, the speed change between each speed collection point was determined for each vehicle traveling through the site. Some of the vehicles were not able to be tracked through the site; however, the percentage of the site data that could not be tracked was less than 5 percent for each site. These data were removed.

Data files for each site, which contained only free-flow passenger cars, were then analyzed. The data file included 50 to 60 percent of the original data set and the number of observations ranged from 500 to 2800. A summary of the data is shown in Appendix A (Table 48). This summary includes the following information for each rumble strip location:

- number of speed observations,
- 85th percentile speeds,
- standard deviation of speeds,
- mean speeds,
- minimum speeds,
- maximum speeds, and
- variance of speeds.

ANALYSIS

Upon completion of the data collection and formatting procedures, the data were analyzed to determine statistically significant correlations between the rumble strips and changes in traffic operational characteristics. To analyze the relationships between the variables, appropriate statistical tests were selected for each evaluation. The following subsections describe the statistical tests employed for the analyses. Due to the site-to-site differences, data from each site were analyzed separately. A graphical analysis was also performed to provide a visual indication of any relationships that might exist between the before and after treatment conditions. All statistical tests were performed at a 95 percent confidence level ($\alpha = 0.05$). The histograms and data analyses were completed using Statistical Package for Social Sciences™ (SPSS).

Test for Normality

The initial step in the data analysis was to determine if the data were normally distributed. To test for normal distribution in the data set, the change in speed between the control speed trap and the intersection speed trap was plotted in a histogram for each data set. A normal distribution would be indicated if the data had minimal skewness and followed the bell-shaped distribution that is associated with normally distributed data. This visual assessment of normality was checked using the SPSS software. The SPSS software was also used to generate Q-Q plots to check the assumption of normality.

Speed Data Analysis

To examine the effectiveness of the rumble strips in warning drivers of upcoming decision points, the change in speed was compared in the before and after condition. There were three locations at which speed measurements were collected at all sites for both time periods:

- free flowing (control point),
- warning sign, and
- intersection or curve.

The change in speed parameter was calculated between the warning sign and intersection/curve speed traps for each approach.

To determine if the transverse rumble strips caused a significant reduction in speed changes, a statistical procedure known as the multiple factor analysis of variance (ANOVA) was used. The multifactor ANOVA allows for testing of differences between mean values of multiple populations as a function of independent variables (i.e., before period or after period; day or night light conditions) and the interactions between the independent variables (*8*). The confidence level that was used was 95 percent. Thus, if the p-value was less than 0.05 (5 percent), then the null hypothesis could be rejected. The null and alternative hypotheses that were tested for analysis were:

- Null hypothesis (H_0): the changes in speed or approach speeds were not significantly different for the time periods.
- Alternative hypothesis (H_a): the changes in speed or approach speeds were significantly different for the time periods.

A model was developed for the multifactor ANOVA analyses from the independent and covariate variables that were discussed previously. The model (see Equation 2) tested before and after conditions based on light conditions. The specific comparisons made using Equation 2 were day (before) versus day (after) and night (before) versus night (after). These tests were also done to determine if the rumble strips were more effective during times that drivers might be less attentive or less familiar with the roadway. The following equation was used for the comparisons of all MOEs:

$$\begin{aligned}\text{MOE} &= \beta_0 + \beta_1(\text{Study}) + \beta_2(\text{Light}) + \beta_3(\text{Control Speed}) + \\ &\beta_4(\text{Study} \times \text{Light}) + \beta_5(\text{Light} \times \text{Control Speed}) + \\ &\beta_6(\text{Study} \times \text{Control Speed}) + \beta_7(\text{Study} \times \text{Light} \times \text{Control Speed})\end{aligned} \tag{2}$$

Where,

MOE = the measure of effectiveness (speed change or approach speed),
Study = study period condition (before or after study condition),
Light = ambient light condition (day or night), and
Control Speed = speed at free flow counter.

The control point speed was entered into the analysis as a covariate. Adding the control point speed as a covariate provides a way to account for vehicles having different speeds prior to the driver viewing the intersection. Researchers used the models to compare the before and after conditions. Equation 3 summarizes where the MOE is proportionate to the control speed plus a treatment effect (intercept, α).

$$\text{MOE} = \alpha_i + \beta(\text{Control Speed}) \quad (3)$$

By comparing only one control speed in the ANOVA models, an assumption was made that the relationships (i.e., slope values) for control speed are constant regardless of the control speed. To account for different slopes, two control speeds were chosen to evaluate the models. The control speeds were chosen based on the mean and 85th percentile speeds for each site. If significant differences in approach speeds or speed change occurred at one or both control speeds, those differences would be observed by choosing two different control speeds.

The beta (β) values in the equation represent the regression coefficient estimates, which help predict the speed changes and approach speeds. The estimates were examined as to their significance in the model.

Before periods were denoted by -1 and after periods were denoted by 1 for the linear contrast models in the SPSS analysis. There were series of linear contrasts performed for the data sets. In the case where before daytime data were compared to after daytime data, a value of 1 was coded in for daytime periods and a value of 0 was coded in for nighttime periods. These codes allowed for day (before) versus day (after) comparisons. The nighttime comparisons were coded similarly for the respective linear contrasts.

Graphical Analysis

The graphical analysis consisted of construction of speed-plots of the mean speed at the three designated data collection locations: control (free flow), warning sign, and intersection. The objective of the graphical analysis was to visually compare the pre-treatment approach behavior with the post-treatment behavior.

Erratic Maneuver Data

For the purpose of observing drivers' initial reactions to the installation of the transverse rumble strips, approximately 16 hours (8 during the day and 8 at night) of video data were collected at two of the stop-controlled intersection sites within 24 hours of each installation. The following data were extracted from the footage:

- vehicle counts,
- vehicle classification (passenger vehicle, big truck, pickup with trailer, or motorcycle), and
- maneuver type, including:
    - normal pass, when the vehicle passes directly over the rumble strips (all tires contact the strips),
    - straddle right, when the vehicle is far enough onto the shoulder that either only the left tires pass over the strips, or the left tires straddle the right set of strips but do not contact them,

  - straddle left, when the vehicle is far enough into the opposing traffic lane that either only the right tires pass over the strips, or the right tires straddle the left set of strips but do not contact them,
  - around right, when the vehicle is completely onto the shoulder and no tires pass over the strips, and
  - around left, when the vehicle is completely into the opposing traffic lane and no tires pass over the strips.

Note that these shifting maneuvers are executed smoothly, and thus not considered to be erratic. Figure 7 illustrates these maneuver classifications.

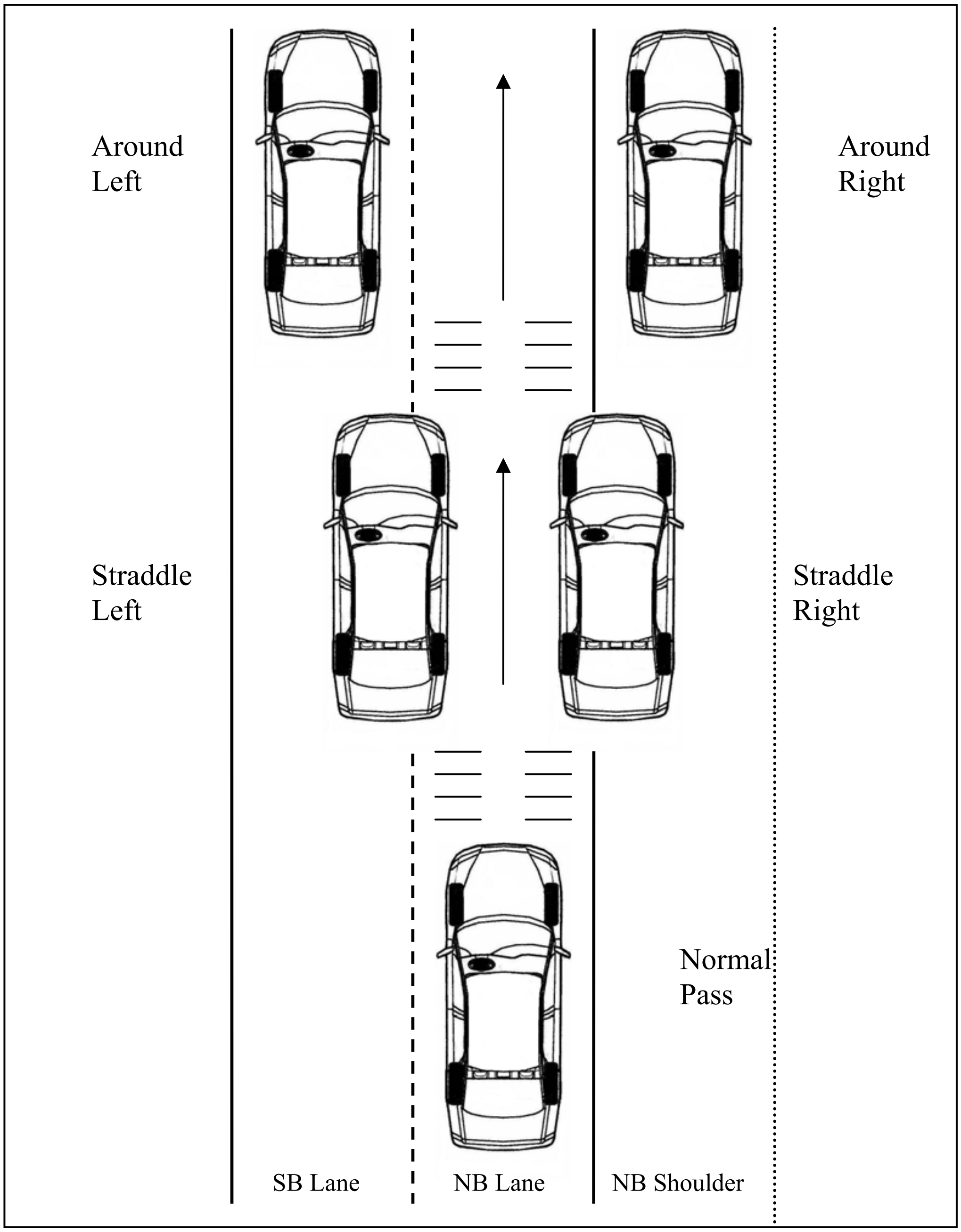


Figure 7. Maneuver Classifications.

From these data, the frequency of each maneuver type was determined for the overall traffic mix and each vehicle classification.

FINDINGS

This section describes the findings of the analysis of the traffic operations data. The findings have been organized based on approach type and site locations, which include:

- stop-controlled intersections
  - Bosque County (FM 3118),
  - Snook (FM 50),
  - Colorado City (FM 208),
  - Millican (FM 2154), and
  - Hearne (FM 2549).
- horizontal curves
  - Steephollow (FM 1179),
  - Navasota I (FM 3090),
  - Navasota II (FM 3090),
  - Keith (FM 244), and
  - Bremond (FM 46).

The statistically significant results are presented for each site and then summarized for all sites following the individual site discussions. Statistical analysis tables are included in Appendix A (Table 49 - Table 102). The erratic maneuver data are also presented for the two sites where they were collected (Snook [FM 50] and Hearne [FM 2549]).

All the coefficients in Equation 3 were found to be significant while performing the multifactor ANOVA. The significant differences between before and after periods were denoted by the study variable and β_1 in Equations 2 and 3. The significant differences between daytime and nighttime periods were denoted by the light variable and β_2 in Equation 2. Thus, the results presented here and in the appendix are categorized by light condition (day or night) and control speed. Additionally, the speed distributions at all sites were found to be normally distributed unless stated otherwise in the specific site findings discussion. Appendix A includes the Q-Q plots generated in SPSS (Figure 71 - Figure 81).

Stop-Controlled Intersection Sites

Bosque County

The Bosque County project site was located at the intersection of FM 3118 and SH 22 near Waco, Texas. The site is a T-intersection near a recreational area that tends to attract many unfamiliar drivers. TXDOT indicated that there were multiple reports of cars driving through the intersection without stopping. The posted speed limit along the approaches was 70 mph.

The statistically significant changes observed at this site were as follows:

- day intersection spot speed decreased by 0.4 mph for the 55-mph control speed,
- day intersection spot speed decreased by 1.1 mph for the 70-mph control speed,

- day warning sign spot speed decreased by 0.5 mph for the 55-mph control speed, and
- night warning sign spot speed increased by 3.7 mph for the 70-mph control speed.

A graphical representation of the speed profiles for the overall before and after periods is shown in Figure 8. As shown, little changed at the intersection and warning sign speed traps, though there was an increase in speeds at the control site.

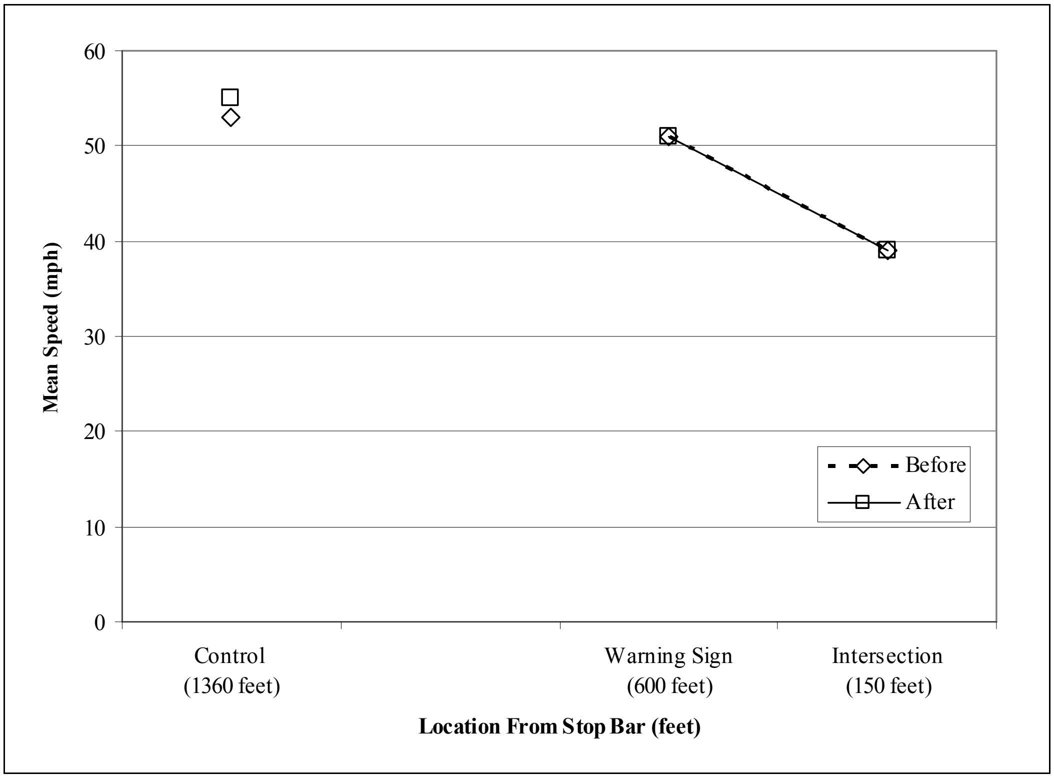


Figure 8. Bosque County (FM 3118) Speed Profile.

Snook

The Snook project site was located at the intersection of FM 50 and FM 60. The site is a two-way stop intersection and is unobstructed; however, the intersection is the first stop in ten miles in both directions and is likely not expected by the driver. The posted speed limit along the approaches was 70 mph.

Southbound Approach

Data from the southbound approach on FM 50 near the Snook site had to be separated into two cases: vehicles entering the highway from a side road (turning vehicles) and through vehicles (highway vehicles). This was due to a bi-modal distribution in the control speeds (see Figure 9). This distribution was due to the control speed trap being located near a side road. The side road was located 420 feet upstream of the control speed trap. Vehicles turning onto FM 50 from the side road would traverse over the control speed trap; however, the speed would be lower than that of a vehicle traveling straight through the site. To analyze the data, the site was split into two groups. A speed of 45 mph was used to separate the groups. The average speeds for the turning vehicles and through vehicles were 33 mph and 68 mph, respectively. The standard deviations for the turning vehicles and the straight through vehicles were 4.0 mph and 8.0 mph, respectively. Taking a range of three standard deviations away from the mean in each case yielded a delineating speed of 45 mph. Once the speed data were split, both subsets (turning and through) were found to be normally distributed.

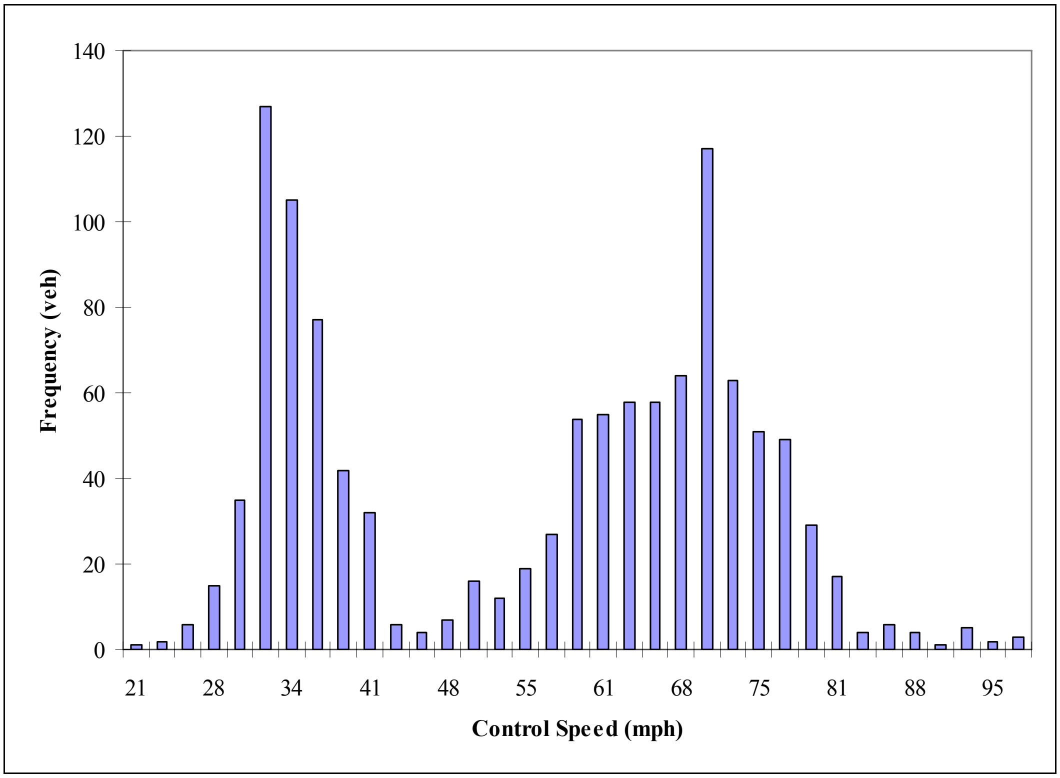


Figure 9. Bi-Modal Distribution of the Southbound Approach at Snook (FM 50).

Turning Vehicles

The statistically significant changes observed for turning vehicles were as follows:

- night speed change between speed traps (intersection and warning sign) decreased by 7.5 mph for the 35-mph control speed,
- night speed change between speed traps decreased by 8.7 mph for the 40-mph control speed,
- night intersection spot speed increased by 4.7 mph for the 35-mph control speed, and
- night warning sign spot speed decreased by 7.5 mph for the 40-mph control speed.

Vehicles traveling at higher than the posted speed limit were not evaluated in this case due to a small sample size of speeding vehicles. A graphical representation of the speed profiles for the overall before and after periods is shown in Figure 10. Very little change was observed at the control site, a small decrease in speeds was observed at the warning sign trap, and a small increase in speeds was observed at the intersection trap.

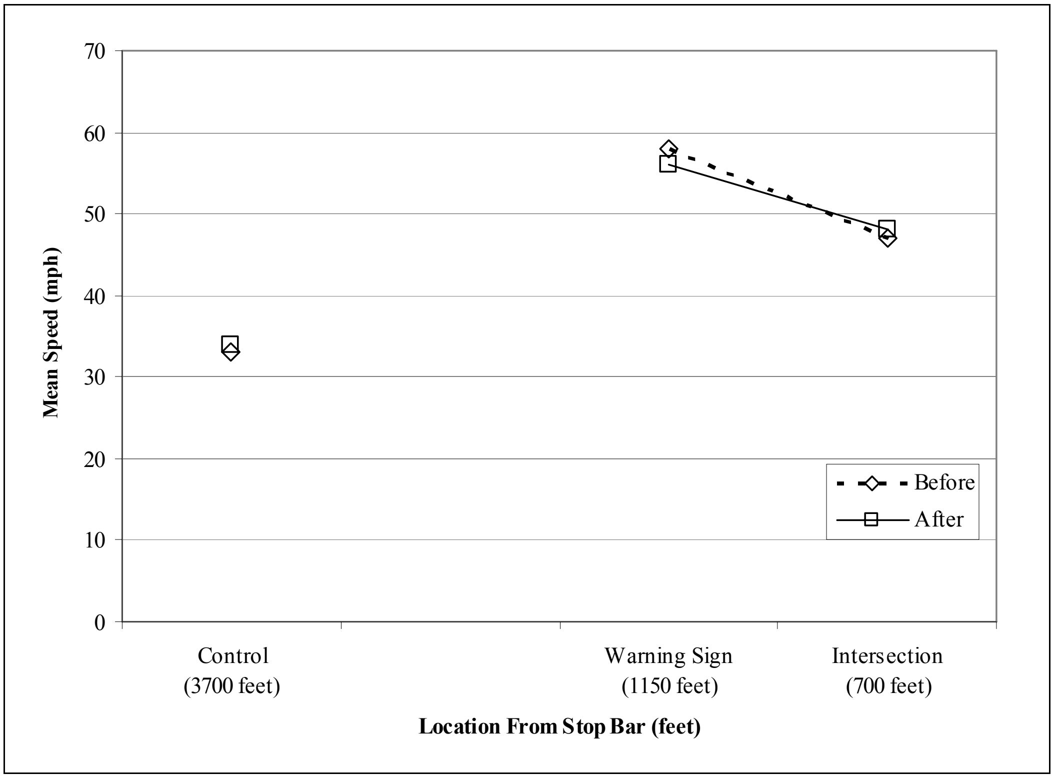


Figure 10. Snook (FM 50 SB turning vehicles) Speed Profile.

Through Vehicles

The statistically significant changes observed for the through vehicles were as follows:

- speed change for speeding vehicles increased by 1.6 mph,
- day warning sign spot speeds increased by 1.9 mph for the 65-mph control speed, and
- night warning sign spot speeds increased by 3.2 mph for the 65-mph control speed.

A graphical representation of the speed profiles for the overall before and after periods is shown in Figure 11. The only changes observed were a small increase in speeds at the warning sign trap and a small decrease at the control site.

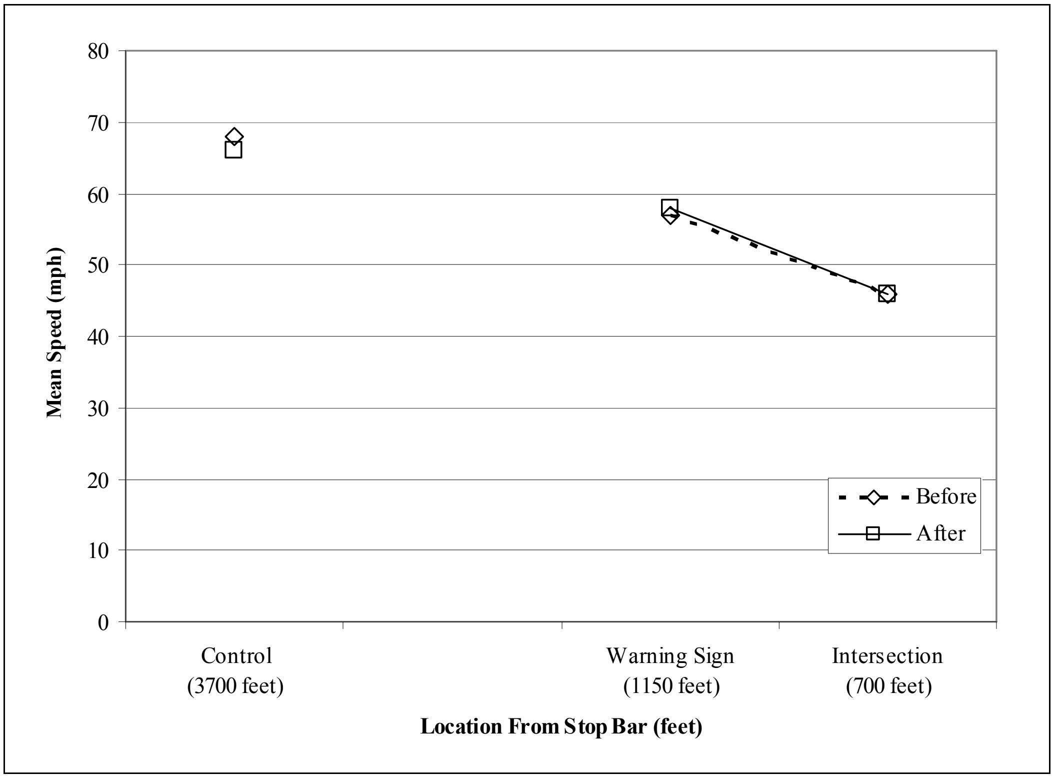


Figure 11. Snook (FM 50 SB through vehicles) Speed Profile.

<ins>Northbound Approach</ins>
The statistically significant changes observed were as follows:

- day speed change increased by 0.6 mph,
- night speed change for speeding vehicles increased by 0.9 mph,
- weekend speed change for speeding vehicles increased by 0.9 mph,
- day intersection spot speeds for the 65-mph and 80-mph control speeds decreased by 3.7 mph and 4.0 mph, respectively,
- night intersection spot speeds decreased by 2.0 mph for the 65-mph control speed,
- day warning sign spot speeds for the 65-mph and 80-mph control speeds decreased by 3.0 mph and 3.6 mph, respectively, and
- night warning sign spot speeds decreased by 2.8 mph for the 65-mph control speed.

A graphical representation of the speed profiles for the overall before and after periods is shown in Figure 12. A small decrease in speeds was observed at both speed traps, while a larger increase was observed at the control site.

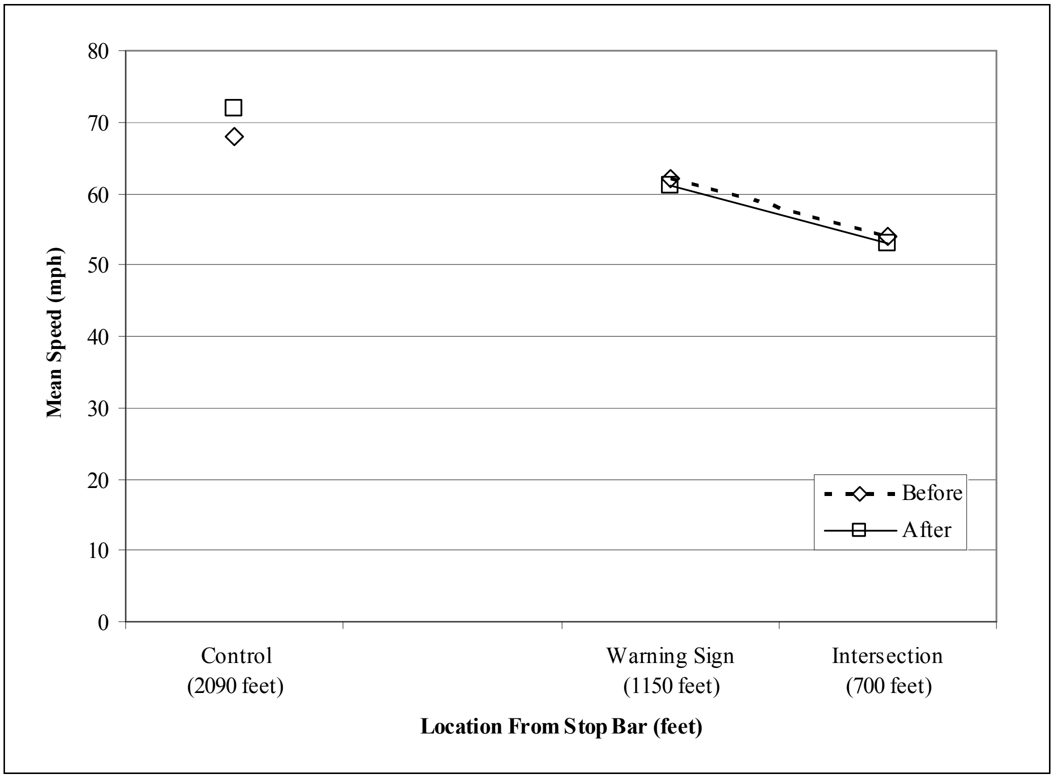


Figure 12. Snook (FM 50 NB) Speed Profile.

Erratic Maneuver Data

Eight hours and twenty-five minutes of video data (10:35 AM – 7:00 PM) from the southbound approach were reviewed to observe the prevalence of erratic or shifting maneuvers at this site. The traffic mix (count and percentage of each vehicle classification) observed is given in Table 7. Note that only one motorcycle was observed in the video footage, which limits the findings with respect to motorcycle driver behavior. Table 8, Figure 13, and Figure 14 provide the maneuver frequency for the vehicle classifications. Figure 14 provides the same information as Figure 13, but with a different x-axis minimum so the rare maneuvers (straddle left, around right, and around left) can be visible. Figure 15 shows the maneuver frequencies for the overall traffic mix.

Table 7. Snook (FM 50) Traffic Mix.

Vehicle Classification	Count	Percentage
Passenger Vehicle	323	77.3
Big Truck	83	19.9
Pickup with Trailer	11	2.6
Motorcycle	1	0.2
All Vehicles	418	100.0

Table 8. Snook (FM 50) Maneuver Frequencies.

Vehicle Classification	Maneuver Frequency (%)				
	Normal Pass	Straddle Right	Straddle Left	Around Right	Around Left
Passenger Vehicle	79.9	18.3	1.5	0.3	0.0
Big Truck	91.6	6.0	1.2	1.2	0.0
Pickup with Trailer	81.8	18.2	0.0	0.0	0.0
Motorcycle	0.0	0.0	0.0	100.0	0.0
All Vehicles	82.1	15.8	1.4	0.7	0.0

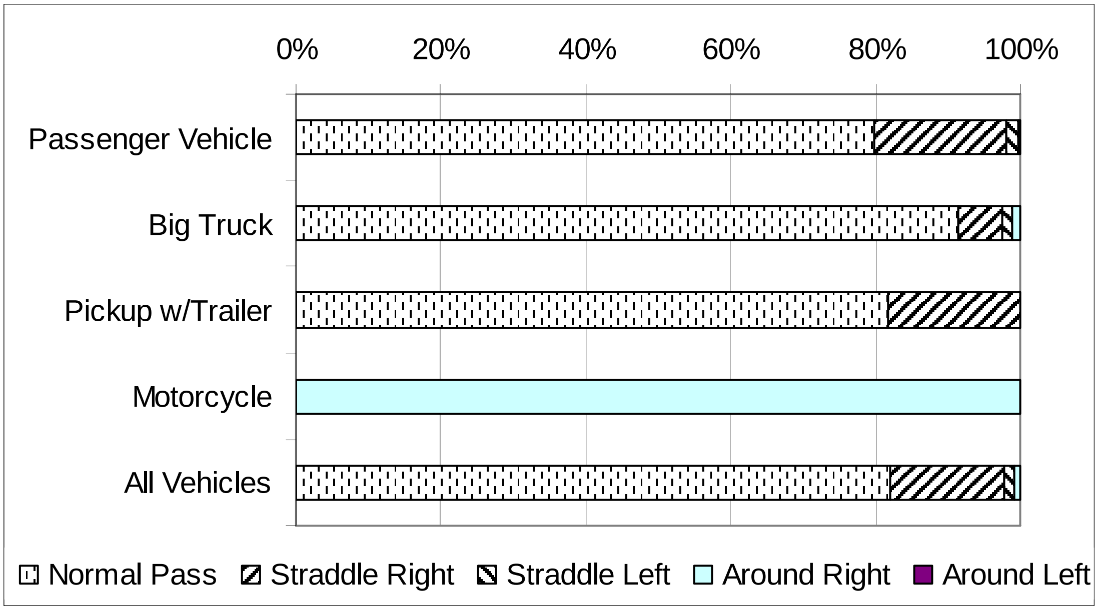


Figure 13. Snook (FM 50) Maneuver Frequencies by Vehicle Classification.

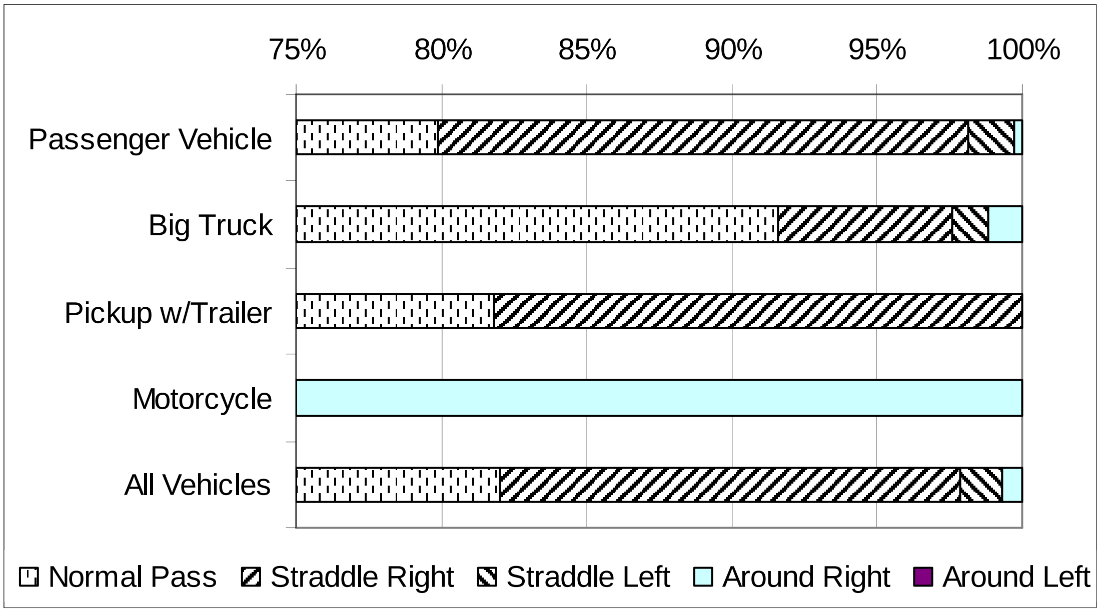


Figure 14. Snook (FM 50) Maneuver Frequencies by Vehicle Classification (Close-up).

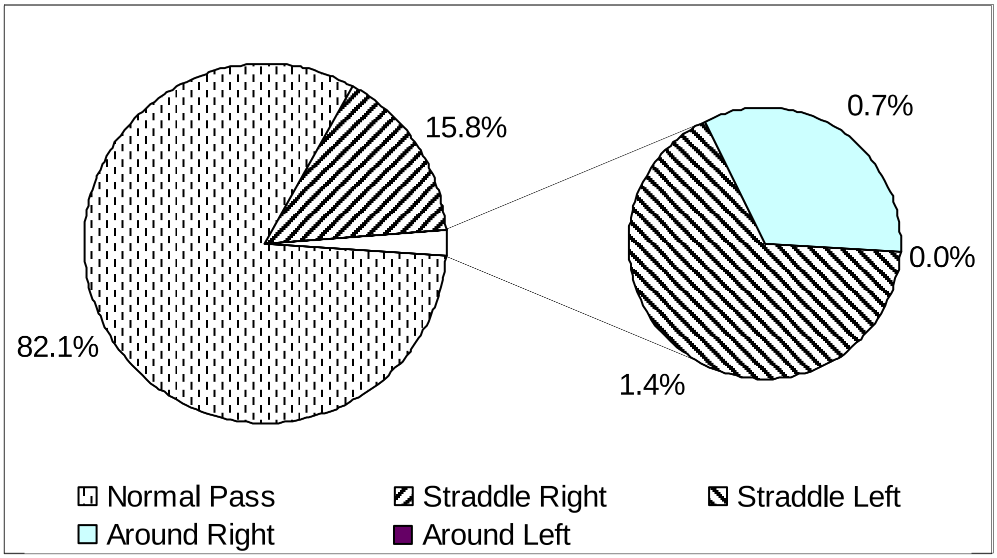


Figure 15. Snook (FM 50) Maneuver Frequencies, All Vehicles.

The majority of vehicles (82.1 percent) passed over the strips normally, and the most common shifting maneuver was straddle right (15.8 percent). This site had ample shoulder space (11 feet) to allow the around right maneuver to occur, yet few drivers were observed trying to shift around to the right. One of the vehicles observed going around right was a motorcycle, despite the two-foot gap left between the strips (see Figure 2 and Figure 4). It was also observed that four drivers (all in passenger vehicles) braked slightly as they encountered the strips. No sudden or hard braking was observed, and no drivers swerved suddenly.

A closer look at the shifting maneuvers provides insight into which vehicle classifications are most likely to execute such maneuvers. Figure 16 provides a breakdown of the straddle right maneuvers by vehicle classification. As shown, 89.4 percent of the straddle right maneuvers were executed by drivers of passenger vehicles, even though passenger vehicles accounted for only 77.3 percent of the traffic mix. In other words, drivers of passenger vehicles account for more than their share of shifting maneuvers. This may be due to passenger cars being more maneuverable than large trucks or vehicles with trailers, or it may be because lighter vehicles experience larger jolts from contacting transverse rumble strips than vehicles with heavier loads.

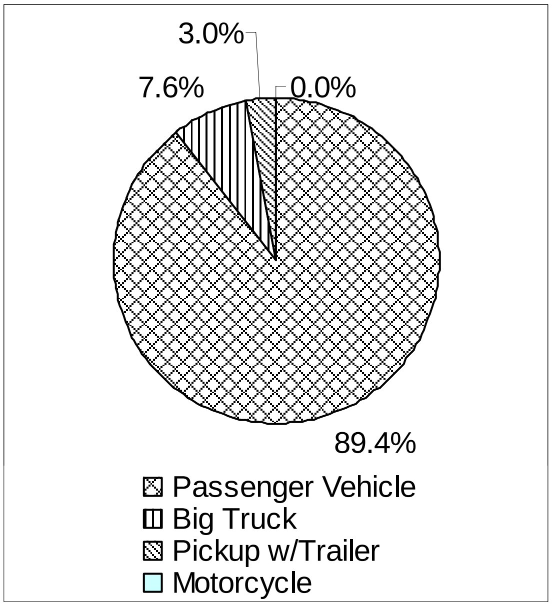


Figure 16. Snook (FM 50) Straddle Right Maneuvers by Vehicle Classification.

Colorado City

The Colorado City project site was located at the intersection of FM 208 and SH 22. The site is a four-way stop-controlled intersection. The intersection is obstructed due to alignment conditions and follows a long tangent that could lead to unexpected conditions for drivers. The posted speed limit along the approaches was 70 mph.

<u>Southbound Approach</u>
The statistically significant changes observed were as follows:

- day intersection spot speeds for the 50-mph and 65-mph control speeds decreased by 4.4 mph and 4.1 mph, respectively;
- night intersection spot speeds decreased by 3.4 mph for the 50-mph control speed;
- day warning sign spot speeds for the 50-mph and 65-mph control speeds decreased by 5.2 mph and 4.8 mph, respectively; and
- night warning sign spot speeds for the 50-mph and 65-mph control speeds decreased by 3.1 mph and 4.1 mph, respectively.

Vehicles traveling at higher than the posted speed limit were not evaluated in this case due to a small sample size of speeding vehicles. A graphical representation of the speed profiles for the overall before and after periods is shown in Figure 17. A decrease of about 4 mph was observed at each speed trap, while an increase of about 5 mph was observed at the control site.

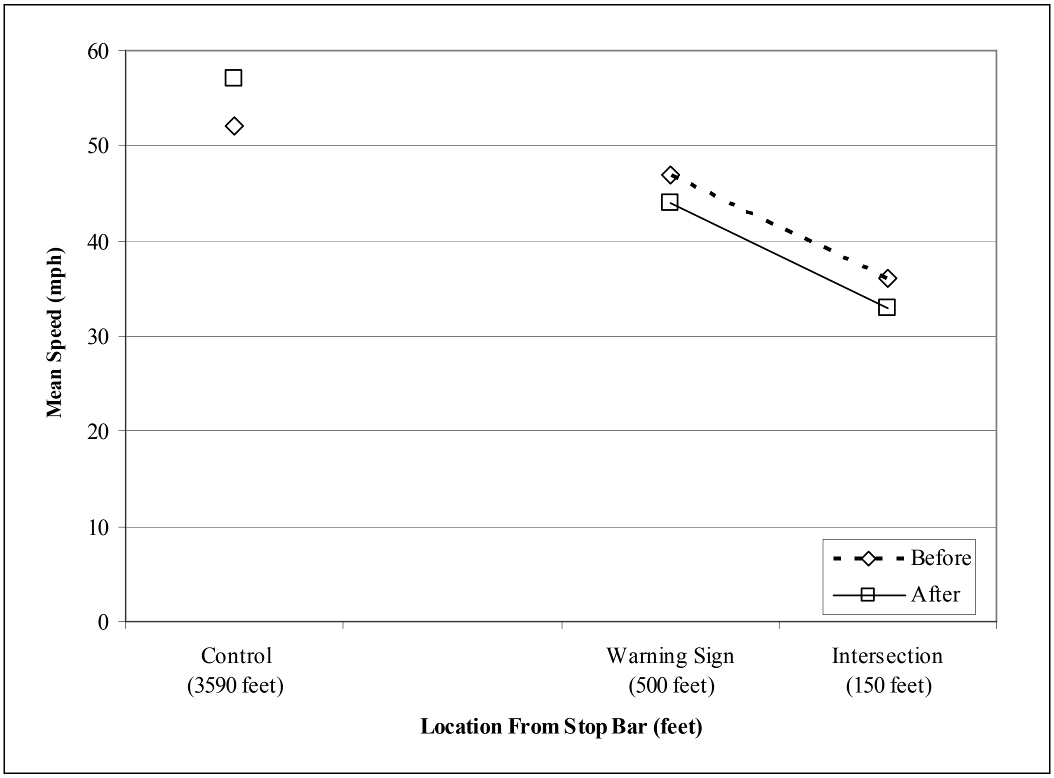


Figure 17. Colorado City (FM 208 SB) Speed Profile.

<u>Northbound Approach</u>

The statistically significant results observed were as follows:

- day speed changes between the speed traps for the 50-mph and 65-mph control speeds decreased by 2.2 mph and 1.9 mph, respectively;
- night speed changes between the speed traps for the 50-mph and 65-mph control speeds decreased by 2.2 mph and 3.5 mph, respectively;
- day intersection spot speeds for the 50-mph and 65-mph control speeds increased by 1.3 mph and 1.8 mph, respectively; and
- night intersection spot speeds increased by 4.7 mph for the 65-mph control speed.

Vehicles traveling at higher than the posted speed limit were not evaluated in this case due to a small sample size of speeding vehicles. A graphical representation of the speed profiles for the overall before and after periods is shown in Figure 18. A decrease of about 4 mph was observed at the control site, while a smaller decrease was observed at the warning sign speed trap with a slight increase at the intersection speed trap.

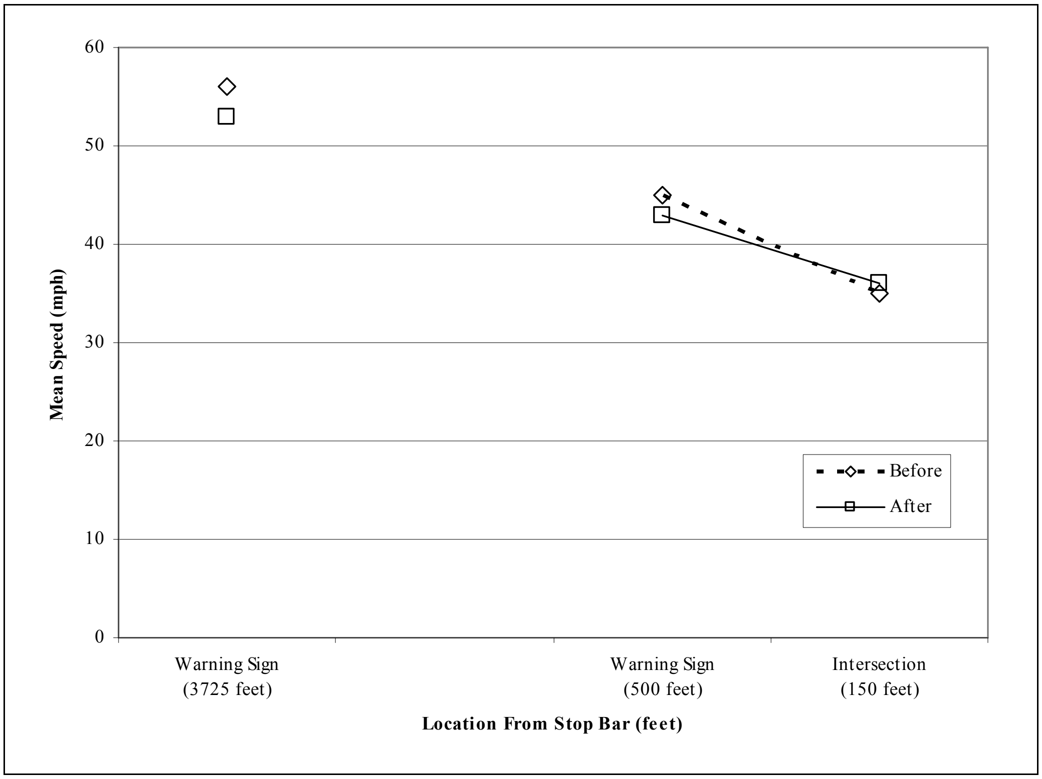


Figure 18. Colorado City (FM 208 NB) Speed Profile.

Millican

The Millican project site was located at the intersection of FM 2154 and FM 159. The site is a four-way stop-controlled intersection that is used by drivers to bypass SH 6, especially in the southbound direction. The intersection was obstructed due to overgrown vegetation near the intersection and sight distance obstructions. The intersection was the first stop for ten miles in the southbound direction, which could be an unexpected intersection to some drivers. One disadvantage to this project site was that a business was located on the west side of the subject roadway (FM 2154). The driveway had low volumes and was assumed to have a very minimal effect on the results. The posted speed limit along the approaches was 70 mph.

Southbound Approach

The statistically significant changes observed were as follows:

- day speed changes for the 65-mph and 75-mph control speeds decreased by 1.3 mph and 1.0 mph, respectively;
- day speed changes for speeding vehicles decreased by 1.1 mph;
- day intersection spot speeds increased by 1.5 mph for the 75-mph control speed;
- night intersection spot speeds increased by 4.2 mph for the 65-mph control speed; and
- night warning sign spot speeds increased by 3.4 mph for the 65-mph control speed.

A graphical representation of the speed profiles for the overall before and after periods is shown in Figure 19. Small increases were observed at all three speed traps (control, warning sign, and intersection).

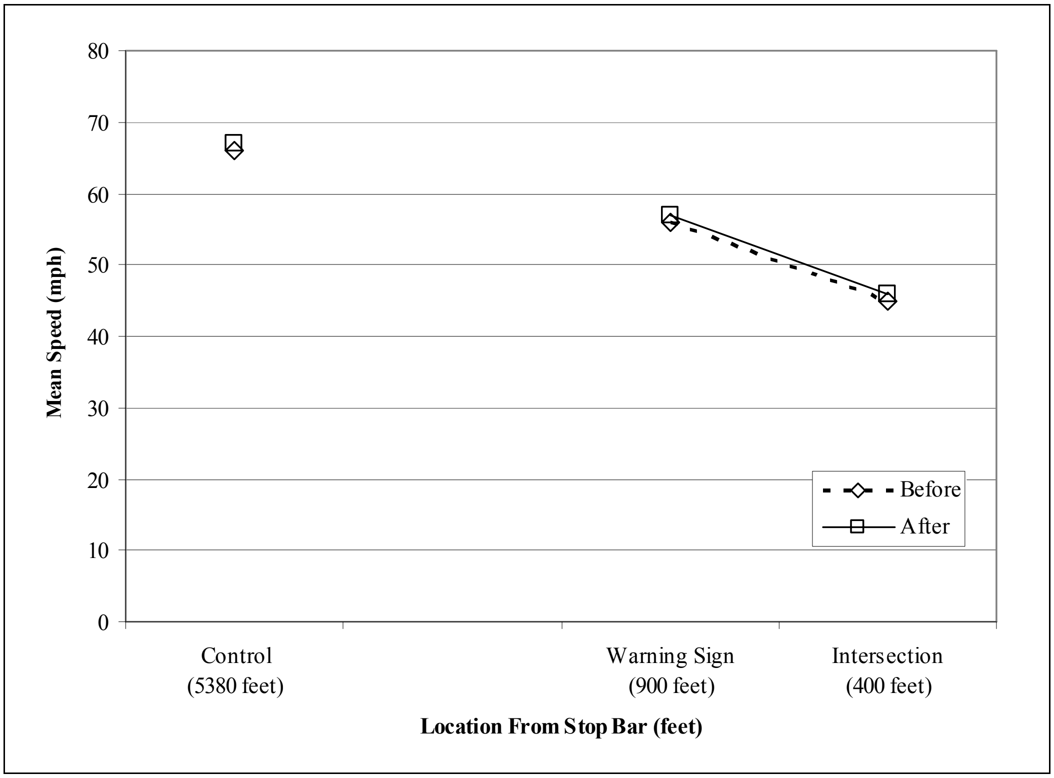


Figure 19. Millican (FM 2154 SB) Speed Profile.

<u>Northbound Approach</u>
The statistically significant results observed were as follows:

- day speed changes decreased by 1.7 mph for the 60-mph control speed;
- night speed changes increased by 4.1 mph for the 75-mph control speed;
- night speed changes for speeding vehicles increased by 3.4 mph;
- day intersection spot speeds for the 60-mph and 75-mph control speeds increased by 1.6 mph and decreased by 1.1 mph, respectively;
- night intersection spot speeds increased by 1.8 mph for the 60-mph control speed; and
- night intersection spot speeds decreased by 4.5 mph for the 75-mph control speed.

A graphical representation of the speed profiles for the overall before and after periods is shown in Figure 20. Small increases were observed at all three speed traps.

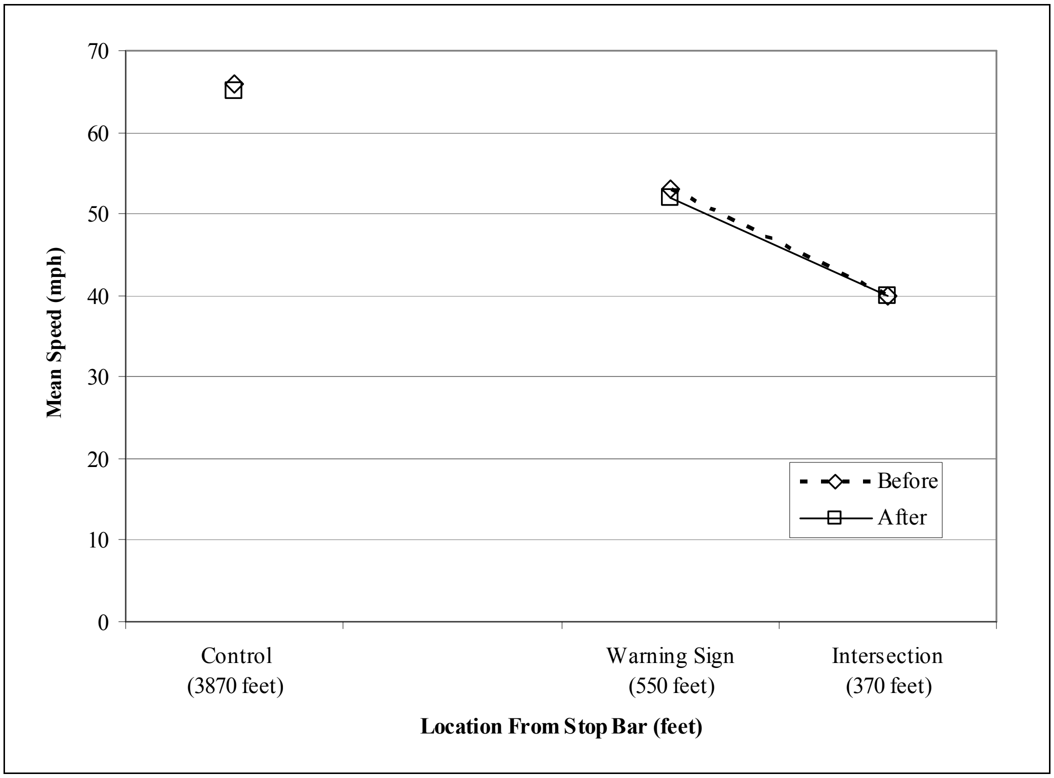


Figure 20. Millican (FM 2154 NB) Speed Profile.

Hearne

The Hearne project site was located at the intersection of FM 2549 and FM 391. The site has a two-way stop and the view of the intersection is obstructed due to the alignment and the vegetation along the approach to the intersection. There are very few cues that an intersection is approaching. There is only standard TXDOT signage along the approach to the intersection. The posted speed limit along both approaches was 70 mph.

Northbound Approach

The only statistically significant change observed was in the weekend speed change for speeding vehicles. This change was an increase of 1.1 mph. A graphical representation of the speed profiles for the overall before and after periods is shown in Figure 21. Small decreases (about 2 mph) were observed at all three speed traps.

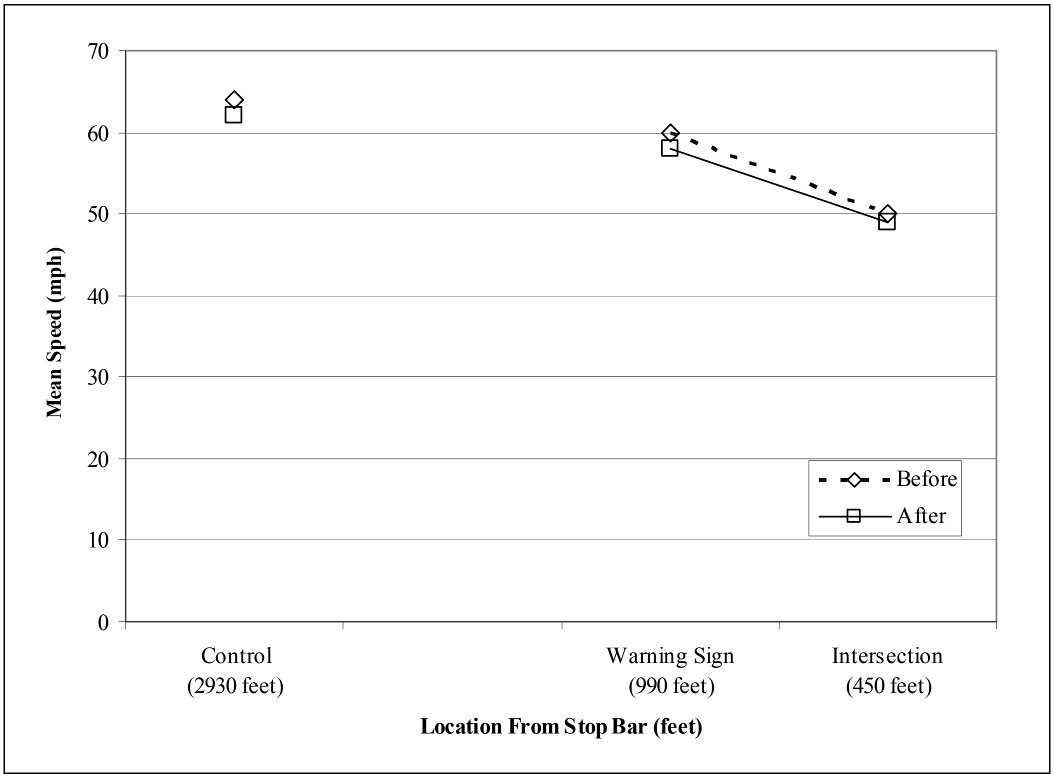


Figure 21. Hearne (FM 2549 NB) Speed Profile.

Southbound Approach
The statistically significant results observed were as follows:

- day speed changes increased by 1.0 mph for the 75-mph control speed;
- day intersection spot speeds for the 60-mph and 75-mph control speeds decreased by 2.9 mph and 2.6 mph, respectively; and
- day warning sign spot speeds decreased by 2.6 mph for the 60-mph control speed.

A graphical representation of the speed profiles for the overall before and after periods is shown in Figure 22. A moderate decrease was observed at the intersection and warning sign speed traps, while a moderate increase was observed at the control site.

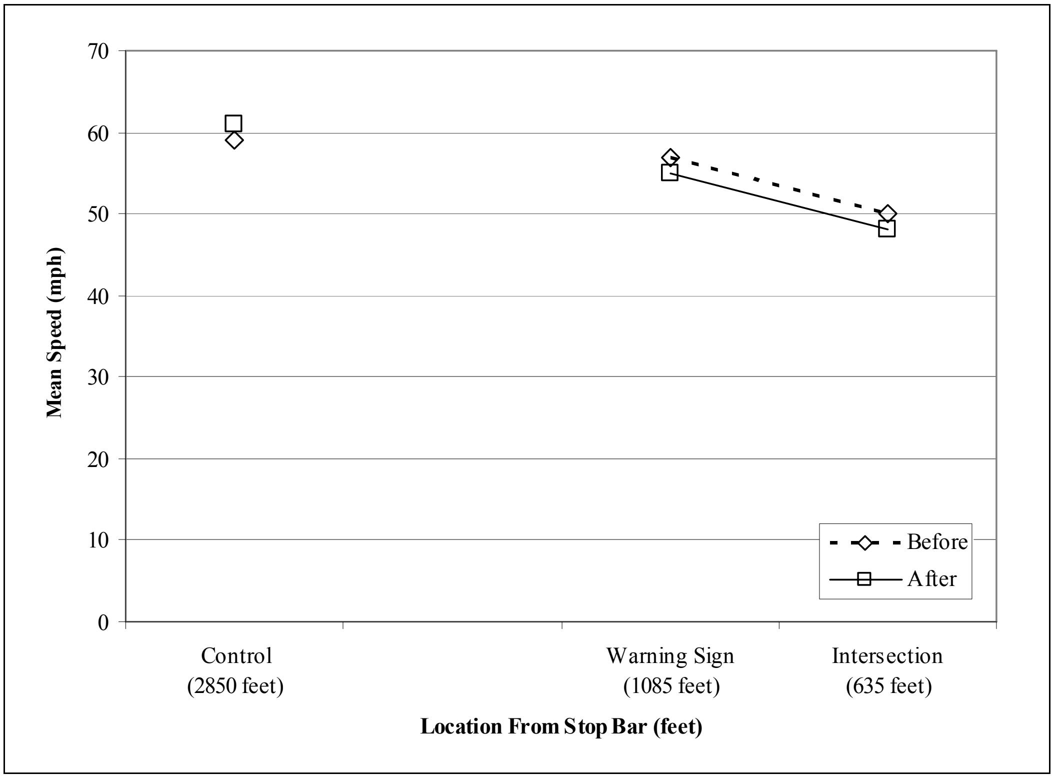


Figure 22. Hearne (FM 2549 SB) Speed Profile.

Erratic Maneuver Data

Seven hours of video data (8:00 AM – 3:00 PM) from the southbound approach were reviewed to observe the prevalence of erratic or shifting maneuvers at this site. Table 9 gives the traffic mix (count and percentage of each vehicle classification) observed. Note that only one motorcycle was observed in the video footage, which limits the findings with respect to motorcycle driver behavior. Table 10, Figure 23, and Figure 24 provide the maneuver frequency for the vehicle classifications. Figure 24 provides the same information as Figure 23, but with a different x-axis minimum so the rare maneuvers (straddle left, around right, and around left) can be visible. Figure 25 shows the maneuver frequencies for the overall traffic mix.

Table 9. Hearne (FM 2549) Traffic Mix.

Vehicle Classification	Count	Percentage
Passenger Vehicle	69	86.3
Big Truck	4	5.0
Pickup with Trailer	6	7.5
Motorcycle	1	1.3
All Vehicles	80	100.0

Table 10. Hearne (FM 2549) Maneuver Frequencies.

Vehicle Classification	Maneuver Frequency (%)				
	Normal Pass	**Straddle Right**	**Straddle Left**	**Around Right**	**Around Left**
Passenger Vehicle	92.8	5.8	1.4	0.0	0.0
Big Truck	100.0	0.0	0.0	0.0	0.0
Pickup with Trailer	100.0	0.0	0.0	0.0	0.0
Motorcycle	100.0	0.0	0.0	0.0	0.0
All Vehicles	93.8	5.0	1.3	0.0	0.0

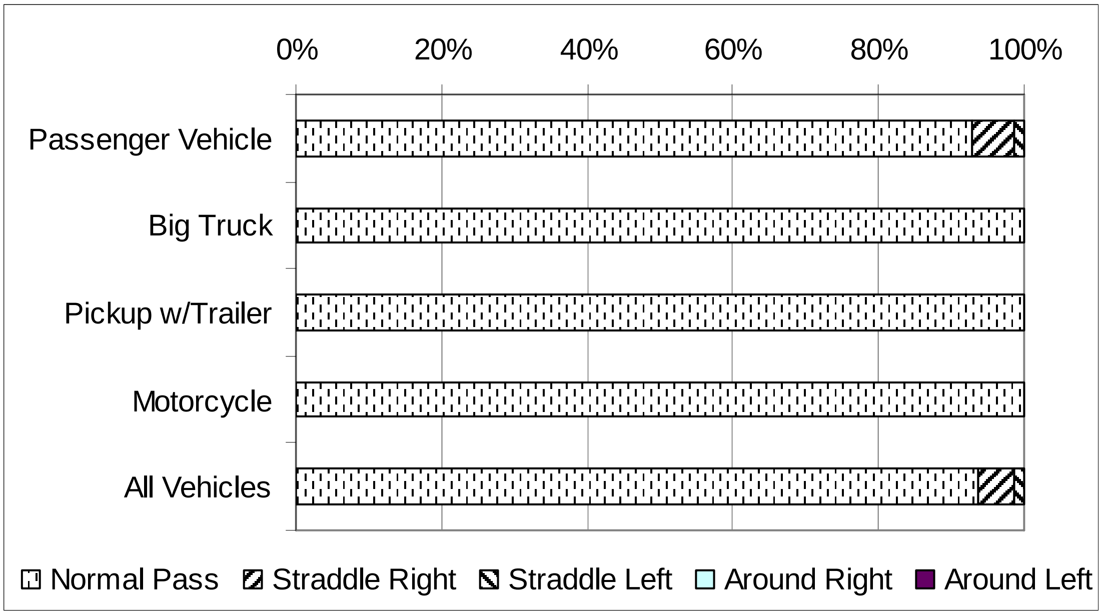


Figure 23. Hearne (FM 2549) Maneuver Frequencies by Vehicle Classification.

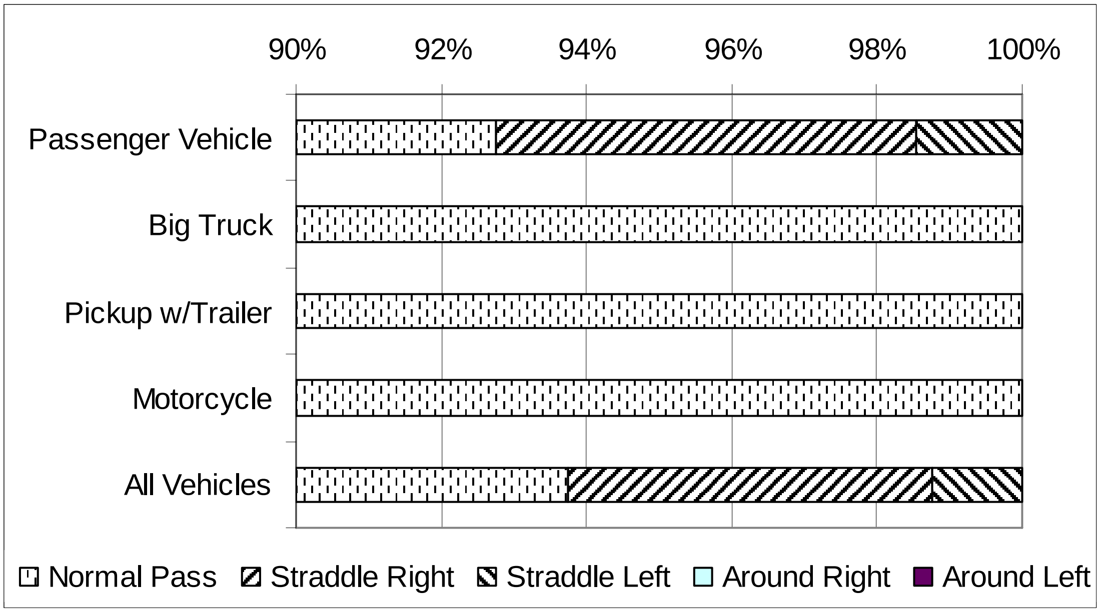


Figure 24. Hearne (FM 2549) Maneuver Frequencies by Vehicle Classification (Close-up).

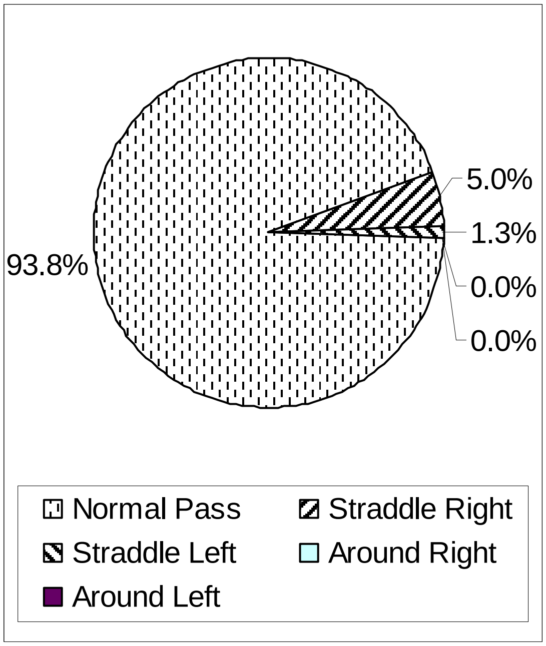


Figure 25. Hearne (FM 2549) Maneuver Frequencies, All Vehicles.

The majority of vehicles (93.8 percent) passed over the strips normally, and the most common shifting maneuver was straddle right (5.0 percent). Only one straddle left maneuver was observed, and no vehicles went around on the right or the left. This site did not have a shoulder, so there was no room for drivers to go around on the right side.

All of the shifting maneuvers observed were executed by drivers of passenger vehicles. All of the vehicles of the other three classifications (big truck, pickup with trailer, and motorcycle) passed normally over the rumble strips. Also, no sudden or hard braking was observed as any of the vehicles passed over the strips, and no swerving maneuvers were observed.

Horizontal Curve Sites

Steephollow

The Steephollow project site was located on FM 1179, a rural two-lane highway near Bryan, Texas. A sharp curve was present at the site and the view of the curve was somewhat obstructed. The posted speed at the site was 65 mph, while the curve advisory speed was 35 mph.

The results for the change in speed, intersection spot speed, and warning sign spot speed comparisons are presented in Table 11, Table 12, and Table 13, respectively. All of the observed changes are statistically significant. Vehicles traveling at higher than the posted speed limit were not evaluated in this case due to a small sample size of speeding vehicles. A graphical representation of the speed profiles for the overall before and after periods is shown in Figure 26.

Table 11. Steephollow (FM 1179) Change in Speed Results.

Light Condition/Period	Overall Sample Size	Control Speed (mph)	Speed Change from Warning to Curve Speed Trap (mph)			
			Before	After	Δ	Significance
Day	2068	60	1.76	4.47	2.71*	0.000
		65	2.05	5.04	2.99*	0.000
Night	409	60	1.30	3.79	2.49*	0.000
		65	1.58	4.83	3.24*	0.000

* Indicates statistically significant at 95 percent level of confidence.

Table 12. Steephollow (FM 1179) Curve Spot Speed Results.

Light Condition/Period	Overall Sample Size	Control Speed (mph)	Curve Speed Trap (mph)			
			Before	After	Δ	Significance
Day	2068	60	54.34	52.71	-1.63*	0.000
		65	57.90	56.47	-1.44*	0.000
Night	409	60	54.53	52.76	-1.77*	0.000
		65	58.02	56.38	-1.64*	0.003

* Indicates statistically significant at 95 percent level of confidence.

Table 13. Steephollow (FM 1179) Warning Sign Spot Speed Results.

Light Condition/Period	Overall Sample Size	Control Speed (mph)	Warning Sign Speed Trap (mph)			
			Before	After	Δ	Significance
Day	2068	60	56.10	57.18	1.08*	0.000
		65	59.96	61.51	1.55*	0.000
Night	409	60	55.83	56.54	0.71*	0.011
		65	59.60	61.20	1.61*	0.000

* Indicates statistically significant at 95 percent level of confidence.

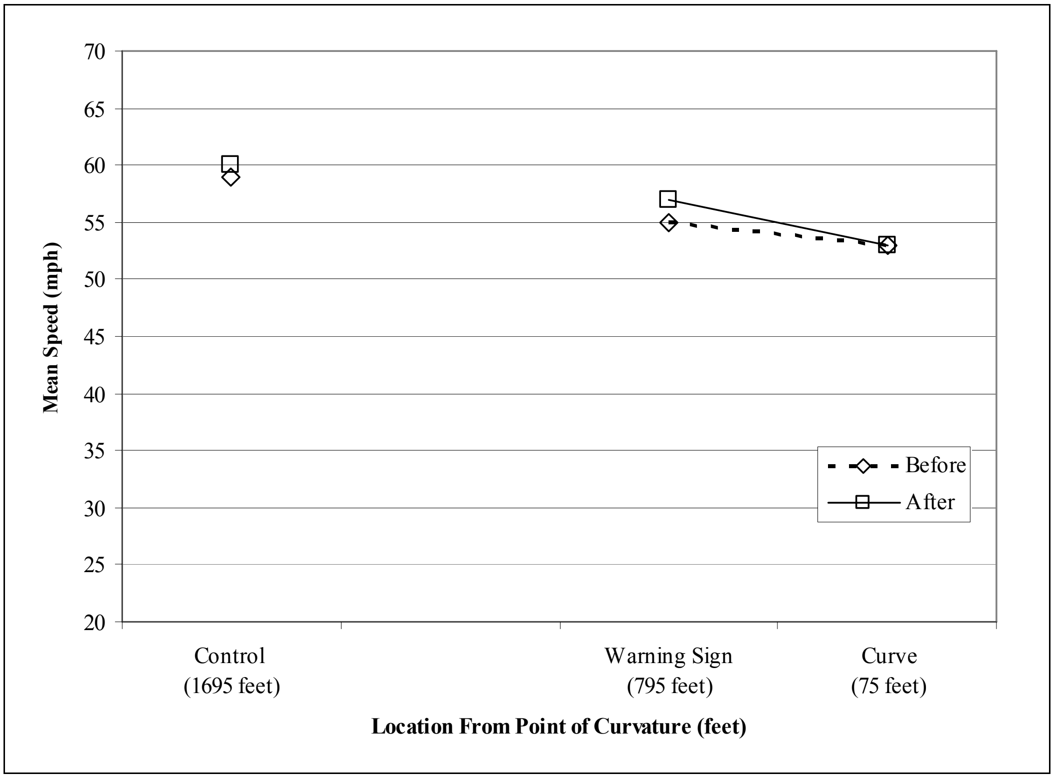


Figure 26. Steephollow (FM 1179) Speed Profile.

Navasota I

The first Navasota project site was located on FM 3090, which is a rural two-lane highway near Navasota, Texas. The curve located at this project site was found to be the sharpest in the Bryan District with a ball bank indicator (BBI) score of 25 mph (*4*). The posted speed at the site was 65 mph, while the curve advisory speed was 15 mph.

The results for the change in speed, intersection spot speed, and warning sign spot speed comparisons are presented in Table 14, Table 15, and Table 16, respectively. All of the observed changes are statistically significant. Vehicles traveling at higher than the posted speed limit were not evaluated in this case due to a small sample size of speeding vehicles. A graphical representation of the speed profiles for the overall before and after periods is shown in Figure 27.

The results at this site were unlike those at any other site. Speeds in the "after" case actually decreased at the warning sign speed trap and increased at the curve speed trap. The change in speed was small at the control site. All of the speed change values listed in Table 14 are large negative values, indicating significant negative deceleration, or positive acceleration, between the speed traps.

Table 14. Navasota I (FM 3090) Change in Speed Results.

Light Condition/Period	Overall Sample Size	Control Speed (mph)	Speed Change from Warning to Curve Speed Trap (mph)			
			Before	After	Δ	Significance
Day	314	55	6.82	-2.77	-9.59*	0.000
		60	7.88	-2.45	-10.33*	0.000
Night	77	55	8.24	-2.39	-10.63*	0.000
		60	10.41	-1.511	-11.92*	0.000

* Indicates statistically significant at 95 percent level of confidence.

Table 15. Navasota I (FM 3090) Curve Spot Speed Results.

Light Condition/Period	Overall Sample Size	Control Speed (mph)	Curve Speed Trap (mph)			
			Before	After	Δ	Significance
Day	314	55	46.47	49.31	2.83*	0.000
		60	49.83	52.10	2.27*	0.001
Night	77	55	45.13	50.10	4.92*	0.000
		60	48.18	54.70	6.53*	0.000

* Indicates statistically significant at 95 percent level of confidence.

Table 16. Navasota I (FM 3090) Warning Sign Spot Speed Results.

Light Condition/Period	Overall Sample Size	Control Speed (mph)	Warning Sign Speed Trap (mph)			
			Before	After	Δ	Significance
Day	314	55	53.29	46.53	-6.75*	0.000
		60	57.71	49.65	-8.06*	0.000
Night	77	55	53.36	47.66	-5.71*	0.000
		60	58.58	53.19	-5.39*	0.002

* Indicates statistically significant at 95 percent level of confidence.

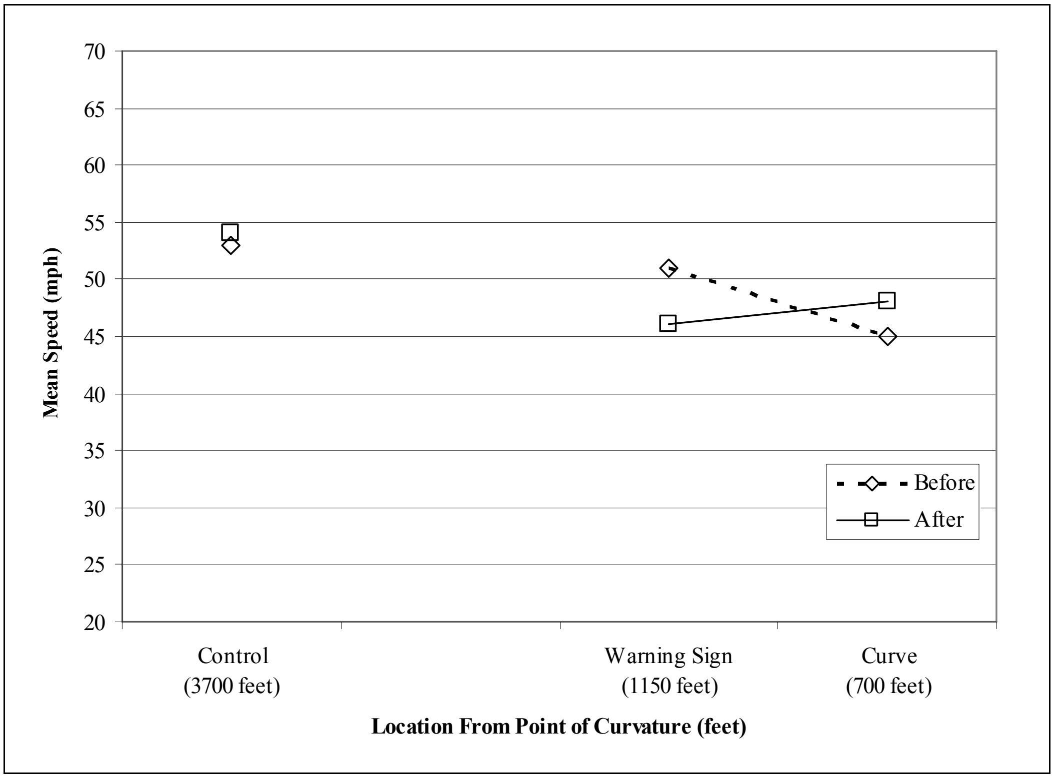


Figure 27. Navasota I (FM 3090) Speed Profile.

Navasota II

The second Navasota project site was also located on FM 3090, a rural two-lane highway near Navasota, Texas. A sharp curve was present at the site and the view of the curve was somewhat obstructed. The posted speed at the site was 65 mph, while the curve advisory speed was 35 mph.

No statistically significant changes were observed at this site. Vehicles traveling during nighttime periods at higher than the posted speed limit were not evaluated in this case due to a small sample size of speeding vehicles. A graphical representation of the speed profiles for the overall before and after periods is shown in Figure 28. Speeds at all three speed traps changed very little. Night comparison could not be made due to lack of data collected during this time period.

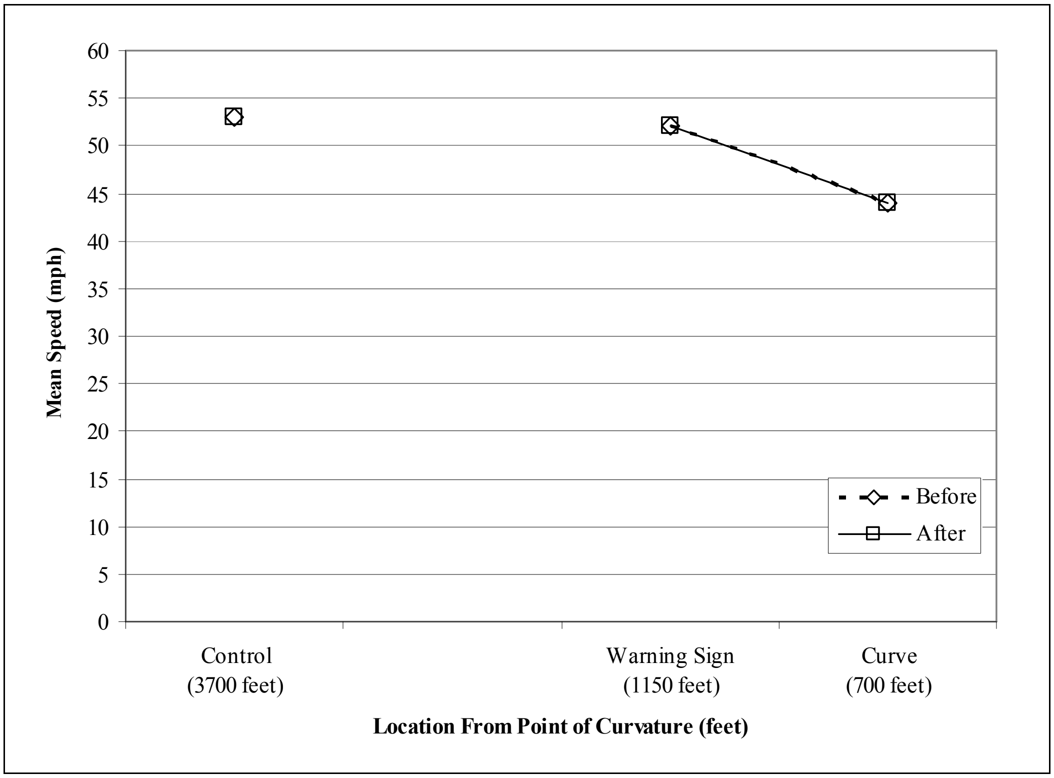


Figure 28. Navasota II (FM 3090) Speed Profile.

Keith

The Keith project site was located on FM 244, a rural two-lane highway near Keith, Texas. A sharp curve was present at the site and the view of the curve was somewhat obstructed. The posted speed at the site was 65 mph, while the curve advisory speed was 40 mph.

The results for the change in speed, intersection spot speed, and warning sign spot speed comparisons are presented in Table 17, Table 18, Table 19, and Table 20, respectively. All of the changes are statistically significant except for the speed changes in speeding vehicles, the day speed change for the 60-mph control speed, and the night speed changes for both control speeds. A graphical representation of the speed profiles for the overall before and after periods is shown in Figure 29. A decrease of about 2.0 mph was observed at the warning sign speed trap, along with a decrease of about 3.0 mph at the curve speed trap and a small decrease at the control site.

Table 17. Keith (FM 244) Change in Speed Results.

Light Condition/Period	Overall Sample Size	Control Speed (mph)	Speed Change from Warning to Curve Speed Trap (mph)			
			Before	After	Δ	Significance
Day	1011	60	2.47	2.76	0.29	0.086
		70	3.41	4.01	0.60*	0.013
Night	227	60	3.13	3.69	0.56	0.157
		70	4.25	5.02	0.77	0.259

* Indicates statistically significant at 95 percent level of confidence.

Table 18. Keith (FM 244) Comparison of Change in Speed for Speeding Vehicles.

Light Condition/Period	Overall Sample Size	Speed Change from Warning to Curve Speed Trap (mph)			
		Before	After	Δ	Significance
Day	498	3.529	3.796	0.267	0.394
Night	276	4.200	4.901	0.701	0.474

* Indicates statistically significant at 95 percent level of confidence. None of the values were statistically significant.

Table 19. Keith (FM 244) Curve Spot Speed Results.

Light Condition/Period	Overall Sample Size	Control Speed (mph)	Curve Speed Trap (mph)			
			Before	After	Δ	Significance
Day	1011	60	57.86	55.84	-2.02*	0.000
		70	64.40	60.44	-3.95*	0.000
Night	227	60	57.98	53.33	-4.64*	0.000
		70	63.51	58.03	-5.47*	0.000

* Indicates statistically significant at 95 percent level of confidence.

Table 20. Keith (FM 244) Warning Sign Spot Speed Results.

Light Condition/Period	Overall Sample Size	Control Speed (mph)	Warning Sign Speed Trap (mph)			
			Before	After	Δ	Significance
Day	1011	60	60.33	58.00	-1.73*	0.000
		70	67.81	64.45	-3.36*	0.000
Night	227	60	61.10	57.03	-4.08*	0.000
		70	67.76	63.06	-4.71*	0.000

* Indicates statistically significant at 95 percent level of confidence.

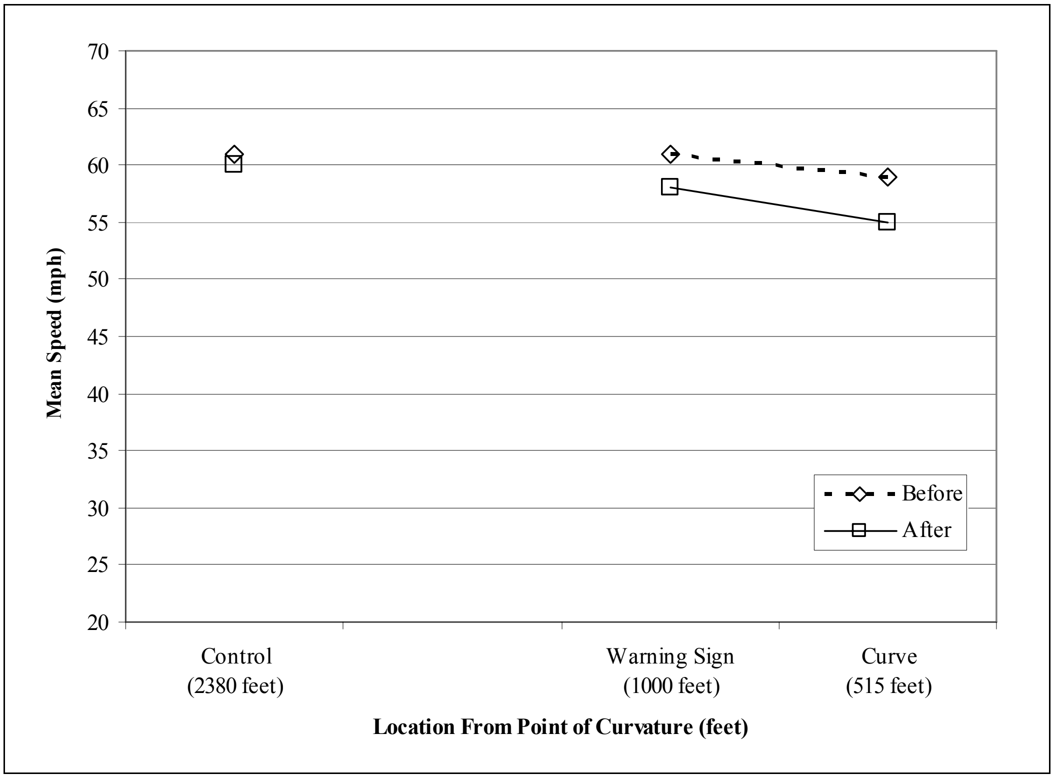


Figure 29. Keith (FM 244) Speed Profile.

Bremond

The Bremond project site was located on FM 46, a rural two-lane highway near Bremond, Texas. A sharp curve was present at the site and the view of the curve was somewhat obstructed. The posted speed at the site was 65 mph, and no curve advisory speed plaque was present at the time of the project.

The statistically significant results observed were as follows:

- day speed changes between the warning sign and curve speed traps decreased by 0.5 mph for the 65-mph control speed,
- day curve spot speeds for the 65-mph control speed decreased by 0.9 mph, and
- night curve spot speeds for the 65-mph control speed decreased by 1.9 mph.

A graphical representation of the speed profiles for the overall before and after periods is shown in Figure 30. A decrease of about 3.0 mph was observed at the warning sign and curve speed traps, while speeds changed very little at the control site.

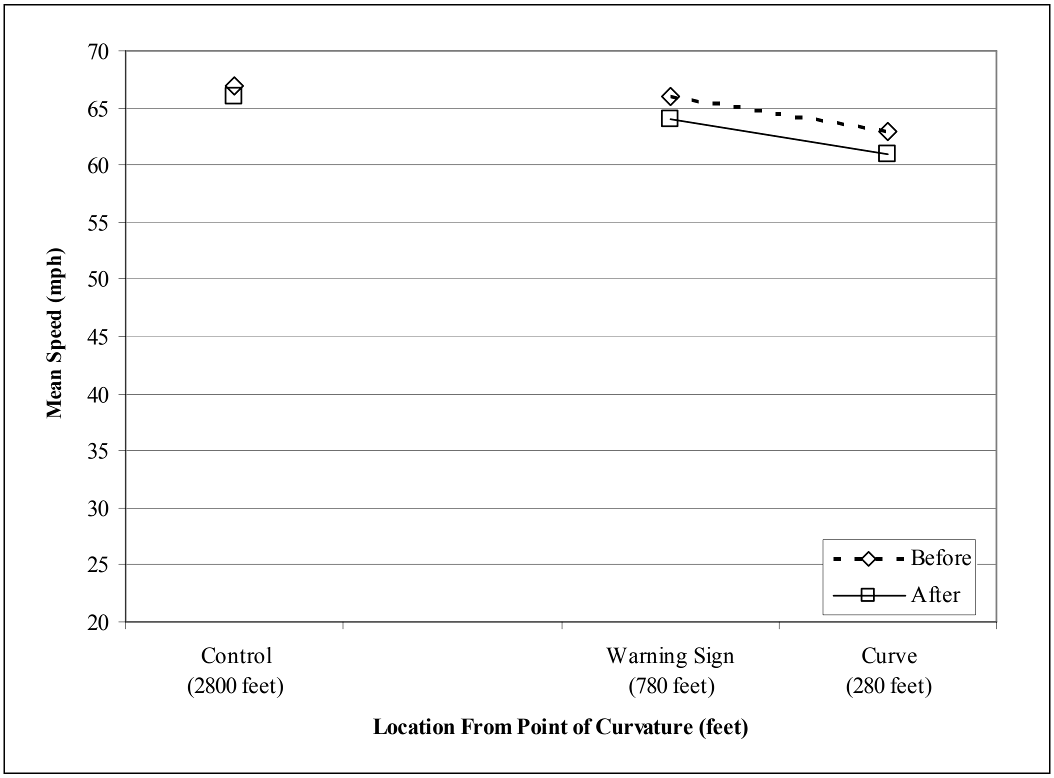


Figure 30. Bremond (FM 46) Speed Profile.

CHAPTER 3

CENTERLINE RUMBLE STRIPS

In 2001, more than half of all fatal multiple vehicle crashes on rural, two-lane, two-way (RTLTW) highways in the US involved drivers traveling in opposite directions (*19*). This is one reason why state departments of transportation (DOT) have recently begun investigating countermeasures for crossover (opposite direction) crashes associated with RTLTW highways.

As engineers investigate possible countermeasures to help mitigate the frequency and severity of crossover crashes, they must consider countermeasures that are both efficient and economical. Centerline rumble strips are a relatively new countermeasure that is one of the least expensive and one of the simplest countermeasures to install and maintain (*20*).

The purpose and design of CRSs are similar to the widely used shoulder rumble strips (SRS), a successful countermeasure for run-off-the-road crashes. As vehicles pass over rumble strips, audible and tactile sensations are generated that warn drivers of changes in roadway alignment and vehicle departures from the travel path. The most common application of CRSs is intermittent, depressed, transverse areas along the centerline pavement markings (*11*, *20*, *21*, *22*). Figure 31 contains a photograph of CRSs from Kansas and a profile view drawing of CRSs.

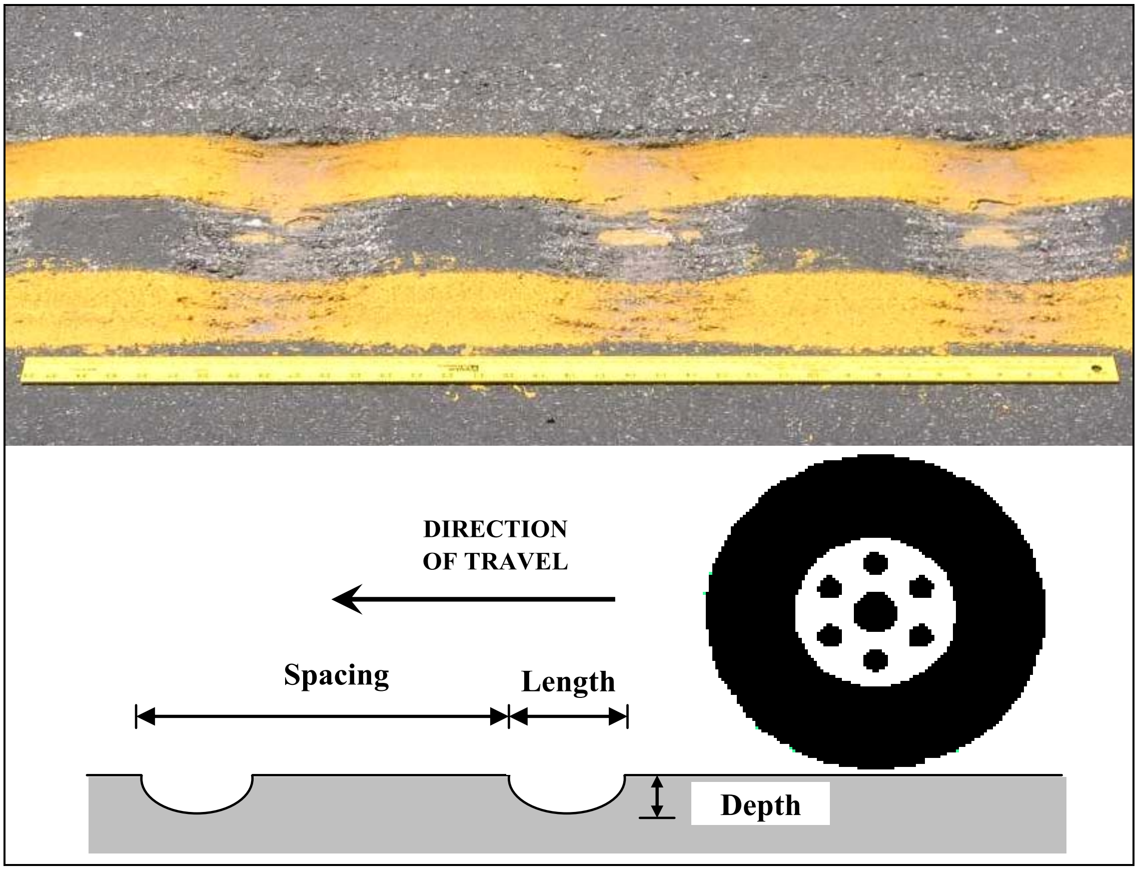


Figure 31. Centerline Rumble Strips.

Various state DOTs, such as Alaska, Delaware, Idaho, Oregon, and Texas, are in the process of installing and testing CRS applications. Early research findings from Delaware indicate that CRSs are effective at reducing not only the number of crashes with increasing average annual daily traffic (AADT), but also the number of fatalities (*23*).

However, most of the current studies that have been published focus on crash data that can neither be used to explain how the traffic flow has changed, nor how the change in traffic flow impacted the improvement in safety by reducing crashes and/or severity of crashes. In particular, no research has been documented on the impact that CRSs may have on driver behavior during a passing maneuver.

PROBLEM STATEMENT

Concerns have been expressed about using CRSs in passing zones because of unknown driver reaction and performance (*20*, *21*, *24*). In particular, state DOT representatives were concerned with the physical reaction of drivers when crossing CRSs in passing zones. Of the 22 state DOTs that have implemented CRSs, only Alaska, Delaware, Kentucky, Maryland, Oregon, Texas and Washington currently have CRSs in passing zones (*20*, *25*, *26*, *27*). This chapter contains the research efforts conducted by TTI to determine the impact that CRSs have on passing behavior for TxDOT's statewide rumble strip project.

A significant portion of the RTLTW highways in Texas is marked for passing, and TxDOT was specifically concerned that drivers may perceive a conflicting message when they cross over CRSs to pass other vehicles, which may result in driver uncertainty and possibly erratic maneuvers during the initial phase of the passing maneuver. There was a need to study driver behavior in the before and after periods along RTLTW highways with CRSs to assess any changes during the initial phases of passing maneuvers.

TxDOT was also concerned with the overall impact CRSs may have on driver behavior such as the use of passing zones and lateral position.

OBJECTIVES

The overall objective of the research detailed in this chapter was to investigate how CRSs impact driver behavior. The specific measures of effectiveness that were used to quantify changes in driver behavior were:

1. number and type of erratic driving movements during the initial stage of a passing maneuver;
2. gap distance between the front end of a passing vehicle and the rear end of a vehicle being passed, prior to completing a passing maneuver;
3. centerline crossing time during the initial stage of a passing maneuver;
4. passing opportunity;
5. percentage of traffic conducting passes along RTLTW highways marked for passing; and
6. lateral position.

The initial stage of passing maneuvers denotes the elapsed time between the point that a passing vehicle first queues behind a vehicle to be passed and the point when the passing vehicle completely crosses into the opposing lane of travel prior to completing a pass.

The research efforts were grouped into different study designs. The first study design required the design and development of an instrumented vehicle that could collect the data required to investigate the MOEs 1 through 5 as they pertained to driver performance during passing maneuvers. This portion of the project is discussed under the subheading of "Effects on Passing Operations." The second study design enabled the researchers to collect data pertaining to vehicular lateral position, and is addressed under the subheading of "Lateral Position."

EFFECTS ON PASSING OPERATIONS

The investigation of how CRSs affect passing operations was limited to an observation of the initial phase of passing maneuvers on US 67, a RTLTW highway in Comanche County, Texas. The project section was 15 miles long and the posted speed limit was 70 mph in the daytime. The average daily traffic (ADT) for the roadway was less than 4122 vpd with approximately 50/50 directional split traffic. One CRS design was tested.

Study Design

Measures of Effectiveness

In order to investigate passing behavior, various MOEs and their respective data collection method were studied (*21*, *27*, *28*, *29*, *30*).

Previous research related to passing operations used distance, time, and speed as MOEs to study passing maneuvers. Passing maneuvers were also subdivided into four different segments for discussion in *A Policy on Geometric Design on Highways and Streets* (*Green Book*) produced by the American Association of State Highway and Transportation Officials (AASHTO) (*31*). Figure 32 is a drawing depicting the passing condition for a single vehicle pass and the terms for distance, d_1 through d_4, as described in the *Green Book*. The system that was developed to collect the data for this report was able to accurately gather data on the second portion (d_2) of passing maneuvers; however, the researchers believed that driver behavior during passing would be most affected during the initial stage of the pass.

Hence, the researchers believed that the use of the passing maneuver criteria, as described in the *Green Book*, was not appropriate for a MOE, and different MOEs were generated that focused solely on the start of passing maneuvers. There were six MOEs selected to investigate driver reaction to CRSs prior to passing. They were:

- erratic movements,
- centerline encroachments,
- gap distance,
- centerline crossing time,
- passing opportunity, and
- percentage passing.

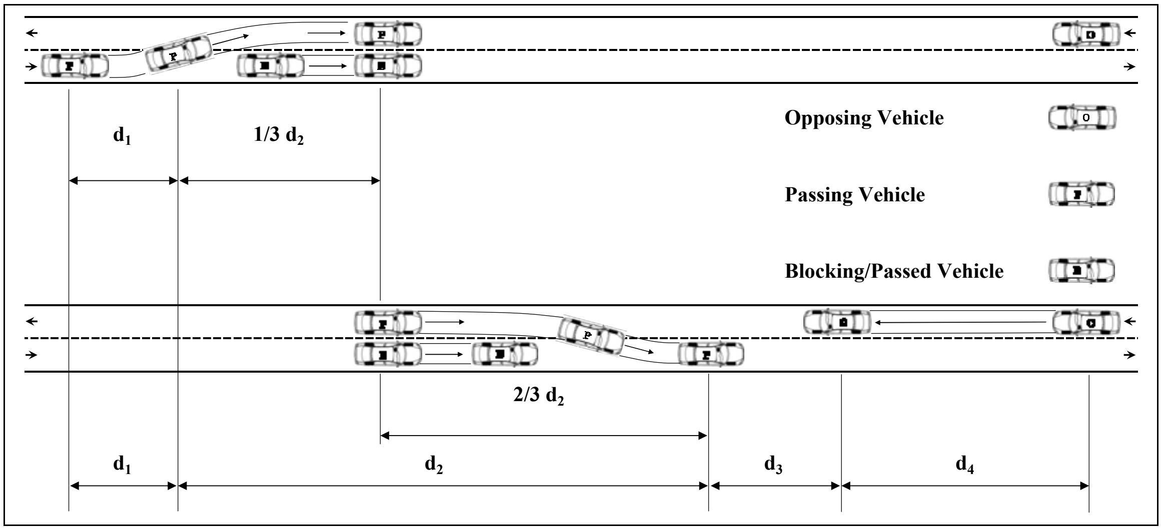


Figure 32. Passing Maneuver Diagram.

Erratic Movements

Erratic movements referred to any movements that appeared to be outside what would be considered normal for the given roadway environment. For example, if a driver appeared to make a rapid alignment change or a wrong corrective action in his/her vehicle's direction of travel, it was recorded as an erratic movement. An example of a wrong corrective action would be a driver initially moving farther to the left rather than to the right when inadvertently contacting CRSs, as speculated by Elango and Noyce (*21*).

Centerline Encroachments

The second MOE was the number of and the time between centerline encroachments. An encroachment referred to any moment that a passing vehicle was in contact with the pavement markings delineating the centerline. The point at which the front, driver-side tire first touched the centerline pavement markings was the start of an encroachment. The end of an encroachment was denoted when the front, driver-side tire last touched the centerline marking when returning to the appropriate lane of travel. Each encroachment was counted, and when multiple encroachments were made by passing drivers prior to completing a pass, the time between encroachments was calculated. The researchers believed that drivers would encroach on the centerline less prior to passing after CRSs were installed.

Gap Distance

The third MOE was gap distance. Gap distance was the distance between a vehicle being passed and a vehicle attempting to pass at the time the passing driver initiated a pass. The researchers thought that gap distance would increase after CRSs were installed for at least two reasons. First, it was possible that drivers would perceive a need to have additional in-lane acceleration distance prior to crossing the CRSs to minimize their exposure to both the traffic in the opposing lane of travel and the sensations associated with crossing CRSs. Another possible reason was that drivers who prefer to encroach on the centerline to scan for on-coming traffic would increase the distance from the vehicle being passed. The additional gap distance would minimize the amount of visual information being processed by the passing driver, so that he or she could focus more on the visual input from the opposing travel lane. Figure 33 depicts of the passing gap distance measurement.

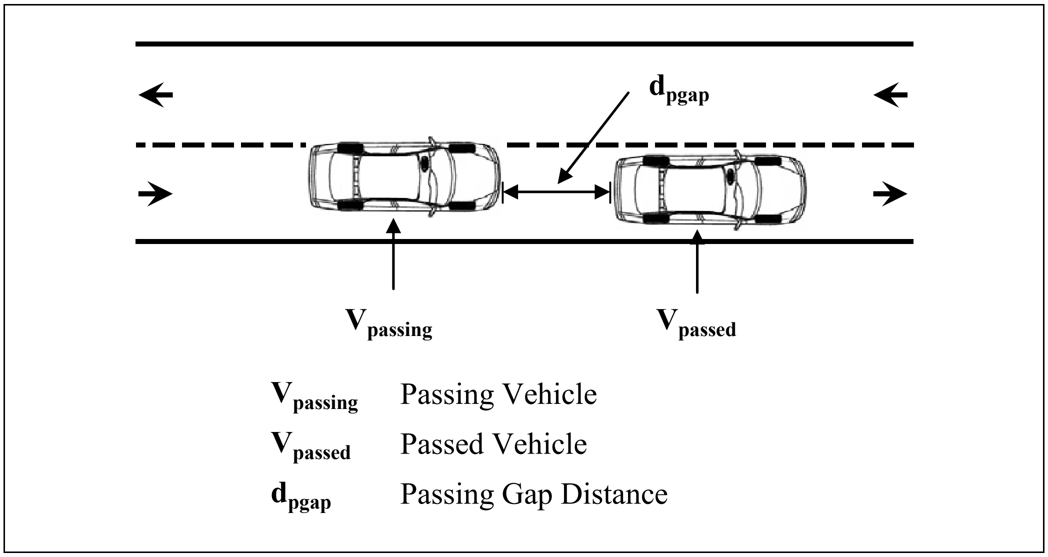
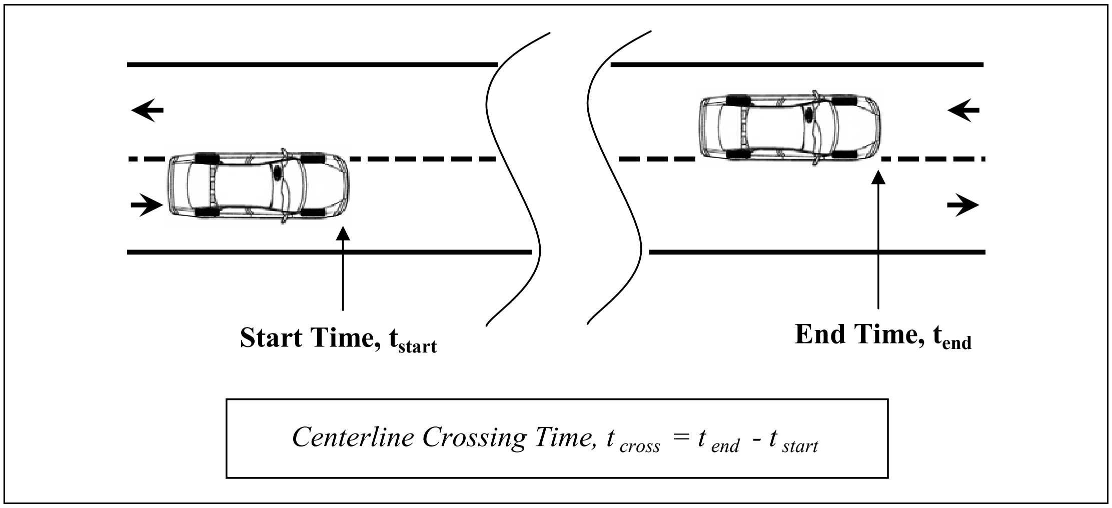


Figure 33. Passing Gap Distance.

Centerline Crossing Time

Centerline crossing time was the fourth MOE, and it denoted the time that was taken by drivers to completely cross the centerline at the beginning of a passing maneuver. The elapsed time started when the front, driver-side tire first contacted the centerline, and it ended when the front, passenger-side tire last touched the centerline during the start of a pass.

This MOE was investigated because the researchers believed that drivers would cross the centerline more quickly when CRSs were present in order to minimize any discomfort that may be experienced by the driver. Figure 34 depicts the previously described scenario, and the figure contains the equation used in this project to calculate the values for centerline crossing time.

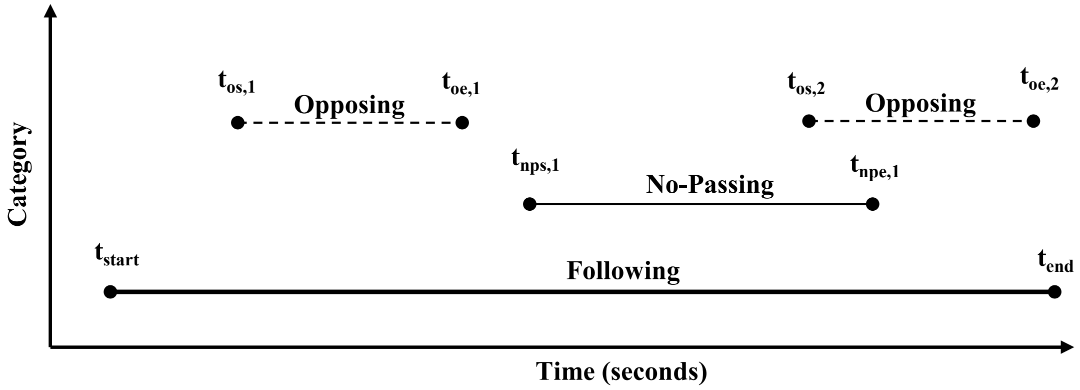


$$\text{Centerline Crossing Time, } t_{cross} = t_{end} - t_{start}$$

Figure 34. Centerline Crossing Time.

Passing Opportunity

Passing opportunity is the amount of time that a passing vehicle is in a passing zone while queued behind a vehicle that the passing driver intends to pass, less the amount of time that there is opposing traffic, and all of this divided by the total amount of time that the passing driver is queued behind the passed vehicle. Figure 35 is a pictorial representation of passing opportunity. DRV represents the data recording vehicle, and in standard passing operations, it represents the vehicle being passed.



t_{start}	time when following vehicle enters threshold (prompt 1)
t_{end}	time when following vehicle begins to pass or leaves threshold
$t_{nps,i}$	time when centerline markings prohibit passing in the direction of travel of the DRV
$t_{npe,i}$	time when centerline markings switch from the prohibited passing to allow for passing
$t_{os,i}$	time when a theoretical vehicle has entered the threshold distance that will not allow for a standard passing maneuver
$t_{oe,i}$	time when a vehicle in the opposing direction of travel is adjacent to a following vehicle
t_{op}	time available to pass
O_{pass}	opportunity to pass (%)

Note: The formula below is unique to the event graphed above and will be adjusted by removing any overlaping times that do not allow for passing.

$$t_{op} = (t_{end} - t_{start}) - (t_{oe,1} - t_{os,1}) - (t_{oe,2} - t_{nps,1})$$

$$O_{pass} = \frac{t_{op}}{(t_{end} - t_{start})} * 100$$

Figure 35. Passing Opportunity.

Percentage Passing

Percentage passing denotes the total number of drivers that conducted single vehicle passes divided by the total number of vehicles that were in a position to complete a single vehicle pass. A single vehicle pass defines the condition when one vehicle that has queued directly behind another vehicle completes a pass around the blocking vehicle. A single vehicle pass was presented in Figure 32.

Research Hypothesis

The general research null hypothesis was that the installation of CRSs in passing zones would not significantly change passing behavior during the initial stage of passing maneuvers on RTLTW highways. It was developed from the concerns of various state DOTs and the research of Elango and Noyce (*21*, *24*, *25*). The general alternative hypothesis was that passing behavior during the initial stage of passing maneuvers would significantly change after the installation of CRSs in passing zones. Passing behavior during the initial stage of passing maneuvers was investigated under the following specific hypotheses:

- Erratic Movements
  - H_0: The number and type of erratic movements made by drivers prior to starting a passing maneuver on a RTLTW highway will be the same or decrease after installing CRSs.
  - H_a: The number and type of erratic movements made by drivers prior to starting a passing maneuver on a RTLTW highway will increase after installing CRSs.
- Encroachments
  - H_0: The number of and time between encroachments on the centerline by drivers prior to starting a passing maneuver on a RTLTW highway will be the same or decrease after installing CRSs.
  - H_a: The number of and time between encroachments of the centerline by drivers prior to starting passing maneuvers on a RTLTW highway will increase after installing CRSs.
- Gap Distance
  - H_0: Gap distance prior to starting a passing maneuver on a RTLTW highway will be the same after installing CRSs.
  - H_a: Gap distance prior to starting a passing maneuver on a RTLTW highway will decrease after installing CRSs.
- Centerline Crossing Time
  - H_0: Centerline crossing time of drivers during the initial stage of a passing maneuver on a RTLTW highway will be the same after installing CRSs.
  - H_a: Centerline crossing time of drivers during the initial stage of a passing maneuver on a RTLTW highway will decrease after installing CRSs.
- Passing Opportunity
  - H_0: Passing opportunity of drivers on a RTLTW highway will be the same after installing CRSs.
  - H_a: Passing opportunity of drivers on a RTLTW highway will increase after installing CRSs.

Data Collection

Previous studies of passing maneuvers were reviewed in detail to determine the potential options for collecting data and their associated advantages and disadvantages. Roadtubes (pneumatic sensors) were used in the earliest studies to collect data (*26*, *27*, *28*). Later studies were conducted using event recorders (*32*, *33*). In some of the more recent studies, passing maneuvers were videotaped from either a moving vehicle (*29*) or a fixed point (*30*).

With the exception of the one study that videotaped passing maneuvers from a fixed point, the researchers believed that the data collection methodologies used previously may have influenced the drivers conducting passes. For instance, roadtubes were placed at 50-foot intervals over approximately 0.5 mile in one of the earliest studies (*26*, *27*, *28*). Drivers would pass over more than 50 roadtubes when passing through the project site, and they would see, hear, and feel each one. Based on the experience of the researchers, this method would impact driving behavior.

While the researchers believed that the method in which a fixed-point video camera was used to record passing maneuvers did not affect driver behavior, this data collection method was also not chosen (*30*). The fixed camera location was from an elevated point, such as a nearby mountain peak or a helicopter. The project location for this report did not provide the topography for monitoring traffic from an overlooking mountain peak, and the use of a helicopter was considered too expensive. Furthermore, the researchers thought that long distance video coverage would not provide sufficient resolution to observe the MOEs.

Subsequently, the review of previous projects did not provide an acceptable means of data collection. Therefore, a unique project approach was developed. Appendix B details the design and calibration of the data collection system. The instrumented vehicle used in this project was referred to as the data recording vehicle.

Field Data Collection

Although the original intent was to collect data at three sites in Texas, TxDOT was only able to install milled CRSs at one location for this portion of the project. Thus, field data were collected at only one site. The site consisted of a 15-mile section of RTLTW highway on US 67 in Comanche County, Texas. US 67 runs approximately north and south. Data were collected in both directions. This section of roadway started at the northern edge of the town of Comanche, Texas, and it ended at the Comanche County line south of Dublin, Texas. The speed limit along this roadway was 70 mph with one short 55-mph speed zone approximately 10 miles north of the southern edge of the test section. The following site-specific details were:

- 44-foot roadway cross section with:
    - 10-foot paved, asphalt concrete shoulders,
    - 12-foot paved, asphalt concrete lanes;
- average daily traffic was:
    - 4122 vehicle per day (vpd),
    - approximately a 50/50 directional split;
- predominately passing zones (greater than 75 percent);
- mean and 85th percentile speed:
    - northbound (63 and 70 mph), and
    - southbound (67 and 73 mph).

The climatic conditions and the timeframes of data collection were different for the before and after periods (see Table 21). This difference was not intended, but instead was the result of various uncontrollable circumstances. The circumstances included:

- scheduling restrictions,
- TxDOT restrictions,
- installation delays, and
- limited financial resources.

The day after the researchers arrived at the project location, it began raining. The researchers decided to continue collecting data for the following reasons:

- The forecasted probability of rain continuing was low, and the rain was to be intermittent.
- Based on the previously mentioned restrictions, data collection would be delayed more than two months until May, and May and June are traditionally rainy months, so further delays would be expected.
- The project funds were limited and the researchers believed that the cost to reschedule once on site would strain the project funds.

Table 21. Data Collection Conditions.

Category	**Before Period**	**After Period**
Number of Sites	1	1
Days of the Week	Wednesday, Thursday, Friday	Friday, Saturday, Sunday, Monday
Period of the Day	7:30 am to 6:00 pm	7:30 am to 6:00 pm
Weather	Ideal (clear skies)	Intermittent Rain
Roadway	Ideal (dry)	Dry to Wet

All of the field data were recorded on videotape. In addition to recording passing maneuvers, supplemental comments related to the field environment during data collection were recorded to videotape through a microphone built into the camera located inside the DRV. These comments included things such as:

- direction of travel,
- location,
- identification of possible erratic movements, and
- acknowledgment of opposing traffic.

Collected Data

The DRV was driven northbound and then southbound along US 67 in Comanche County. Data were recorded continuously to videotape. The DRV induced drivers to pass by driving at 5, 10 and 15 mph below the posted daytime speed limit of 70 mph.

There were two purposes for collecting data at three different speeds. First, it was not certain what speeds would provide a sufficient amount of data within the timeframe of the data collection efforts to conduct statistical testing on the data. Second, it was believed that there would be a difference in the initial phase of the passing maneuvers with respect to the speed of the vehicle being passed.

A total of 723 vehicles were observed during the data collection; however, only 582 actually passed the DRV. Out of 582 passes, 103 vehicles were not analyzed because the passes were conducted by drivers who were in platoons or by drivers conducting multiple vehicle passes. All of the remaining passes recorded to videotape were isolated, single vehicle passes and the resulting sample sizes were:

- DRV traveling at 55 mph:
    - 92 passes before the installation of CRSs,
    - 99 passes after the installation of CRSs,
- DRV traveling at 60 mph:
    - 106 passes before the installation of CRSs,
    - 110 passes after the installation of CRSs,
- DRV traveling at 65 mph:
    - 25 passes before the installation of CRSs,
    - 47 passes after the installation of CRSs,
- Data collapsed regardless of speed:
    - 223 passes before the installation of CRSs, and
    - 256 passes after the installation of CRSs.

Table 22 contains a detailed count of the number of observations recorded to video. The values presented in bold were analyzed with respect to the MOE for this report.

Table 22. Number of Observed Vehicles.

DRV Speed	**55 mph**		**60 mph**		**65 mph**		**Total**	
Period	*Before*	*After*	*Before*	*After*	*Before*	*After*	*Before*	*After*
No Pass[1]	13	15	31	39	13	30	57	84
Pass[1]	**92**	**99**	**106**	**110**	**25**	**47**	**223**	**256**
Platooned Pass[1]	19	15	11	9	1	2	31	26
Multiple Pass[1]	9	10	9	12	4	2	22	24
Total	133	139	157	170	43	81	333	390

[1] No Pass = vehicle did not pass DRV; Pass = vehicle passed DRV; Platooned Pass = vehicle passed the DRV in a platoon; Multiple Pass = a vehicle passed the DRV and at least one other vehicle simultaneously.

Analysis

The data collected from the before and after periods were analyzed using Microsoft Excel and SPSS. The analysis approach detailed in Table 23 was selected after consulting various texts on statistical analysis (*8*, *34*, *35*, *36*).

Table 23. Statistical Analysis Approach.

Method	Purpose
Descriptive Statistics	Mean, standard deviation, variance, range, percentiles
Graphical Analysis	Cumulative distribution, box plot, histogram, normal Q-Q plot
Statistical Tests	Test of Proportions, Wilcoxon Rank Sum, Chi-Square

Variables

Multiple spreadsheets were generated to organize the data and to analyze the data in steps. The first two spreadsheets were created containing all of the raw data for each recorded passing vehicle, and each passing vehicle recorded could have anywhere from 4 to 100 or more lines of data. Hence, summary worksheets were produced to reduce all of the lines of data for each vehicle to one line of data for each represented vehicle. The summary data were the only data analyzed for this report. The variables that were analyzed included:

- number of erratic movements by type,
- number of and time between centerline encroachments,
- gap distance prior to passing,
- crossing centerline time,
- passing opportunity, and
- percentage passing.

Descriptive Statistics

The statistics formulated for each MOE included:

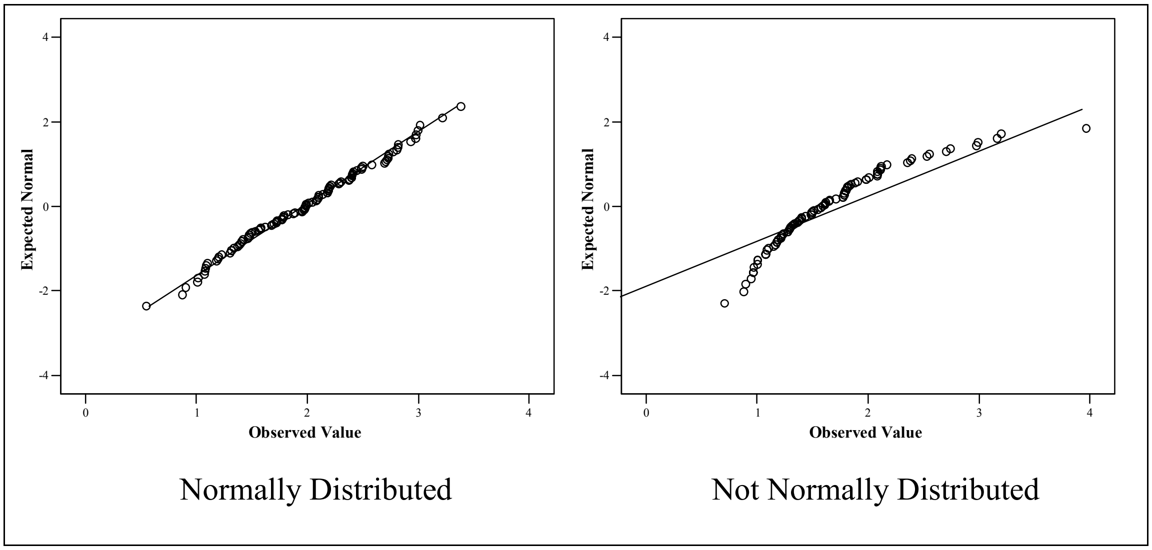
- quantity of data,
- mean, median (50th percentile),
- standard deviation,
- sample variance,
- range,
- minimum,
- maximum,
- skewness,
- kurtosis, and
- percentiles (10th, 15th, 25th, 50th, 75th, 85th, and 90th).

These values were grouped by the before and after periods, DRV speed (55, 60 and 65 mph), and direction of travel. The before period denoted the data collected prior to the installation of CRSs, and the after period defined the data collected after CRSs were installed. These statistics were used in conjunction with various different methods for plotting the data to graphically analyze the data for each MOE.

Graphical Statistics

Cumulative distributions, box plots, histograms, and Q-Q plots were used to analyze the MOEs when applicable. The cumulative distributions and the box plots were two ways of comparing the distribution of the data. While the calculation of the fences in the box plots do not always exactly represent the 25th and 75th percentiles in SPSS, researchers believed that the box plots provided a better way to compare the spread and the location of the center of each data set (*37*). The comparison provided an early insight into probable differences between various data sets.

Histograms and normal Q-Q plots were generated to analyze the distribution of the data. The histograms and the calculated values of skewness and kurtosis provided an early indication of the type of distribution associated with the data. The normal Q-Q plots were used to confirm whether data sets were normally distributed. The quantiles of the data sets with respect to the MOEs were plotted against a line that represented the expected path of a particular distribution, such as a normal distribution in the case of this report (*38*). Figure 36 contains a picture of a data set that is normally distributed on the left and a data set that is not normally distributed on the right.



Normally Distributed

Not Normally Distributed

Figure 36. Normal Q-Q Plot.

Statistical Tests for Significance

The Chi-Square test, test of proportions, and Wilcoxon Rank Sum test were used to examine statistical significance. The Chi-Square test was used to determine whether any dependent variables (i.e., gap distance and centerline crossing time) were associated with each other. If any of the dependent variables were associated, a multivariate analysis would need to be conducted to test for statistical significance.

The test of proportions was used to investigate changes in MOEs based on counted values, such as the number of erratic movements by type and the number of centerline encroachments. The test of proportions is not affected by the distribution of the data. The equation for the test of proportions is:

$$t = \frac{p_1 - p_2}{\sqrt{p_0(1 - p_0)\left(\frac{1}{N_1} + \frac{1}{N_2}\right)}}$$

$$p_0 = \frac{p_1 N_1 + p_2 N_2}{N_1 + N_2}$$

Where,

t = statistic of the t-distribution,
p_i = proportion observed in sample *i*, and
N_i = number of observations in sample *i*.

The Wilcoxon Rank Sum test was used to determine whether there was a change in MOEs based on measured values, such as time between encroachments, gap distance and centerline crossing time. This specific test allowed for the following:

- the data did not need to be normally distributed;
- the data needed to be continuous, but not paired; and
- the number of data points did not need to be equal between the before and after periods.

All tests for significance were conducted assuming a two-tailed, 95 percent confidence interval. A two-tailed test was chosen to statistically test whether the population of the data associated with each MOE after installing CRSs shifted to the right or the left of the data collected prior to installing CRSs. If the test statistic (i.e., t-statistic for the t-test or z-statistic for the z-test) is less than the lower (negative) critical value (i.e., t_{crit} or z_{crit}) for a given level of confidence, the first population (before period) is shifted to the right of the second population (after period), and vice-versa if the test statistic is greater than the upper (positive) critical value. If the first population is shifted to the left of the second population, the overall values of the first population are less than the overall values of the second population. Again, this finding is switched when the test statistic indicates that the first population is shifted to the right.

Findings

Descriptive statistics that are addressed in detail below and the results of the Wilcoxon Rank Sum tests are discussed in this section. The descriptive statistics that are presented are the quantity of data points, the mean, and the 15th, 50th, and the 85th percentile values. The mean values are presented for a comparison with the percentile values, but the focus of the results are on the percentile values. This decision is based on two reasons: 1) the data with respect to each MOE were found to be skewed and so the median (50th percentile) is a better indicator of the center of the data, and 2) the 15th and the 85th percentile values are commonly used in transportation design. The histograms and normal Q-Q plots verified that the data were not normally distributed, which was one of the reasons for using the Wilcoxon Rank Sum test (*34*).

The Chi-Square test was used to test for association between the MOE variables. There was not a sufficient quantity of data to analyze the MOEs for erratic movements or centerline encroachments. Therefore, only centerline crossing time and gap distance were tested for association. No association was found. Consequently, a multivariate analysis was not necessary, and the Wilcoxon Rank Sum test was used to test the data for significant changes between the before and after periods.

The MOEs for gap distance and centerline crossing time were determined with respect to the:

- direction of travel (i.e., northbound and southbound);
- speed of the DRV (i.e., 55, 60, and 65 mph); and
- period (i.e., before and after).

It was found that the data were not statistically different with respect to direction. It was also found that the majority of the data were statistically different with respect to speed of the DRV; however, there did not appear to be any explainable trends. The above findings are documented in Appendix B in Table 103 through Table 106. Subsequently, direction was not considered a factor and the analysis discussed in this report was categorized by speed of the DRV and study period. The material in this chapter was organized by the analysis of each MOE, as follows:

- erratic movements,
- centerline encroachments,
- gap distance,
- centerline crossing time,
- passing opportunity, and
- percentage of passing.

Erratic Movements

While it was originally intended to count the number of erratic movements by type that occurred before and after the installation of CRSs, no erratic movements were recorded after observing 479 passing vehicles between the before and after periods. Furthermore, no drivers were recorded initially shifting left when contacting CRSs prior to returning to the original travel lane. Therefore, it was not possible to conduct statistical tests on erratic movements. However, because no erratic movements were recorded in either project period, the installation of CRSs along US 67 in Comanche County did not induce erratic movements and their installation did not negatively impact passing maneuvers with respect to this MOE.

Centerline Encroachments

The intent of this analysis was to compare differences in the number of and time between centerline encroachments before and after the installation of CRSs; however, the frequency of multiple centerline encroachments was less than expected. Out of 479 observed passing vehicles, only 41 centerline encroachments were recorded in addition to the centerline encroachment required at the start of a pass. Not enough data were available to conduct a Wilcoxon Rank Sum test on the time between encroachments.

A test of proportions was conducted on the number of encroachments. None of the t-statistics fell outside the t_{crit} values of -1.960 and 1.960 (see Table 24). Table 107 in Appendix B contains all of the factors that went into calculating the t-statistics shown in Table 24. The results indicate there was no change in driver behavior with respect to the number of times that a driver encroached on the centerline prior to passing. Subsequently, the installation of CRSs along US 67 in Comanche County did not change driver behavior with respect to encroaching on the centerline prior to initiating a passing maneuver.

Table 24. Test of Proportions for the Number of Centerline Encroachments.

DRV Speed	**55 mph**	**60 mph**	**65 mph**	**Combined**
Sample Size (B/A)	**92/99**	**106/110**	**25/47**	**223/256**
t-statistic	-0.678	-0.102	1.129	-0.026

*Indicates that the t-statistic is significant for a two-tailed, 95 percent confidence interval. There were no statistically significant changes.

Gap Distance

Gap distance was determined by measuring the distance between the front bumper of a passing vehicle and the back bumper of the DRV at the point in which the left tires of a passing vehicle encounter the centerline pavement markings at the start of a successful pass. The results are documented in Table 25 (also see Table 108 in Appendix B). Graphs that were generated to evaluate the spread and distribution of the gap distance data are located in Appendix B (see Figure 91 through Figure 102). The tests for significance associated with gap distance are presented in Table 26 and Table 27 (also see Table 109 and Table 110 in Appendix B).

Table 25. Descriptive Statistics for Gap Distance.

DRV Speed	**55 mph**		**60 mph**		**65 mph**		**Combined**	
Period	**Before**	**After**	**Before**	**After**	**Before**	**After**	**Before**	**After**
Sample Size	**92**	**99**	**106**	**110**	**25**	**47**	**223**	**256**
Mean (feet)	47.8	47.8	46.1	46.4	68.6	43.5	49.3	46.4
15th Percentile (feet)	26	23	28	26	40	29	28	26
50th Percentile (feet)	42	40	44	42	67	41	45	41
85th Percentile (feet)	73	72	67	65	86	63	72	65

The null hypothesis that gap distance after the installation of CRSs is the same as the gap distance before the installation of CRSs was rejected for the data collected with the DRV traveling at 65 mph, but was not rejected at DRV speeds of 55 and 60 mph (see Table 26). Again, the findings are based on a two-tailed, 95 percent confidence interval. An analysis of the data when the DRV was traveling at 65 mph indicated that the gap distance decreased after the installation of the CRSs. The significant decrease indicates drivers accepted smaller gap distances between the passing and passed vehicles when initiating a passing maneuver around a vehicle traveling at 65 mph on US 67 in Comanche County after the installation of CRSs.

Table 26. Wilcoxon Rank Sum Test for Gap Distance.

DRV Speed	**55 mph**	**60 mph**	**65 mph**	**Combined**
Sample Size (B/A)	**92/99**	**106/110**	**25/47**	**223/256**
z-statistic	0.807	0.590	3.822*	2.007*

*Indicates that the z-statistic is significant for a two-tailed, 95 percent confidence interval.

While the Wilcoxon Rank Sum test could not be used to state whether a specific change, such as the mean gap distance, was significant, the results presented in Table 25 appear to emulate the findings of the statistical tests. For instance, 85 percent of the drivers that passed the DRV traveling at 65 mph after the installation of CRSs had a gap distance of 63 feet or less prior to passing versus 86 feet before the installation of CRSs. This result was a reduction of approximately 23 feet. There were also reductions in gap distance after the installation of CRSs for the data collected while the DRV was traveling at 55 and 60 mph. These changes were not considered contradictory to the results of the statistical tests, which did not reject the null hypothesis, because these changes were small relative to the data collected before the installation of CRSs. For example, the 23-foot reduction was approximately a 27-percent decrease in the gap distance used by drivers passing a vehicle traveling at 65 mph. In the case of drivers passing the DRV traveling at 60 mph, there was a reduction of 3 feet, or 3 percent of the gap distance used before the installation of CRSs.

The gap distance data were collapsed and a Wilcoxon Rank Sum test was conducted on the entire data set irrespective of speed. The z-statistic was 2.007, which exceeded the upper end of the two-tailed, 95 percent confidence interval, and the null hypothesis was rejected. The results of the collapsed data show that drivers used a shorter gap distance after the installation of CRSs. Hence, passing drivers along US 67 in Comanche County initiate their passes closer to a vehicle that they are passing after the installation of CRSs.

As stated earlier, possible systematic errors related to the study design may have impacted the results of the data collection efforts described in this report. Therefore, additional tests were conducted to investigate discrepancies. Gap distance data in the after period collected over the weekend were compared to the weekday data for 60 and 65 mph. The specific days of the week and the associated timeframes were the same as discussed previously for the Wilcoxon Rank Sum tests conducted on the centerline crossing time. However, it was found that there was not a statistically significant difference between weekend and weekday data collected at 60 and 65 mph in the after period (see Table 27).

Table 27. Wilcoxon Rank Sum Test for Gap Distance (Weekday vs. Weekend).

DRV Speed	**60 mph**	**65 mph**
Sample Size (B/A)	**24/31**	**13/16**
z-statistic	0.81	-0.97

*Indicates that the z-statistic is significant for a two-tailed, 95 percent confidence interval. There were no statistically significant changes.

The null hypothesis is not rejected for either speed. Both z-statistics did not exceed the lower or upper 95 percent confidence interval z-values of -1.960 and 1.960, respectively. Hence, there was not a significant difference in the gap distance data collected on the weekend or on a weekday. This finding does not dispel the possibility that there may have been an effect on the results in relation to the weather; however, no data were collected before the installation of CRSs to test if there was a statistically significant difference between data collected under dry and wet conditions. Consequently, the differences may be a combination of the variation in the weather and the installation of the CRSs.

Centerline Crossing Time

Researchers investigated centerline crossing time by analyzing the amount of time that each driver that passed the DRV took to cross the centerline pavement markings. Table 28 contains the general results, and a complete list of the descriptive statistics calculated for centerline crossing time is in Table 111 in Appendix B. In addition, the plots that were generated to graphically analyze the data are contained in Appendix B (see Figure 103 through Figure 114). The graphical analysis is not discussed in this chapter because its sole purpose was to choose the proper tests for significance, which was the Wilcoxon Rank Sum test for the centerline crossing time data. The results of the Wilcoxon Rank Sum tests are shown in Table 29 and Table 30.

Table 28. Descriptive Statistics for Centerline Crossing Time.

DRV Speed	**55 mph**		**60 mph**		**65 mph**		**Combined**	
Period	**Before**	**After**	**Before**	**After**	**Before**	**After**	**Before**	**After**
Sample Size	**92**	**99**	**106**	**110**	**25**	**47**	**223**	**256**
Mean (sec)	1.77	2.25	1.97	1.96	2.02	1.77	1.90	2.04
15th Percentile (sec)	1.10	1.51	1.20	1.33	1.34	1.30	1.17	1.39
50th Percentile (sec)	1.58	2.11	1.88	1.98	2.09	1.67	1.79	1.99
85th Percentile (sec)	2.23	2.93	2.72	2.65	2.56	2.32	2.52	2.72

Table 29 contains the z-statistics for verifying any statistically significant changes in centerline crossing time after the installation of CRSs along the RTLTW highway used in this project. The parameters that were used to develop Table 29 are presented in Table 112 in Appendix B.

Table 29. Wilcoxon Rank Sum Test for Centerline Crossing Time.

DRV Speed	**55 mph**	**60 mph**	**65 mph**	**Combined**
Sample Size (B/A)	**92/99**	**106/110**	**25/47**	**223/256**
z-statistic	-5.697*	-1.029	1.722	-3.665*

*Indicates that the z-statistic is significant for a two-tailed, 95 percent confidence interval.

According to the z-statistics, assuming a two-tailed, 95 percent confidence interval, only drivers passing the DRV while it was traveling at 55 mph changed their driving behavior with respect to centerline crossing time at the start of a passing maneuver. The null hypothesis that the centerline crossing time in the after period was the same as the before period was rejected for the data collected at 55 mph, because the z-statistic (-5.697) is less than the z-value (-1.960) for the lower end of the 95 percent confidence interval. Analysis of the data indicated that the crossing time increased significantly. The z-statistics for data collected at 60 and 65 mph were within the 95 percent confidence interval, and they cannot be used to reject the null hypothesis. Therefore, centerline crossing times at 60 and 65 mph after the installation of CRSs are not significantly different from centerline crossing times in passing zones without CRSs.

The results of the descriptive statistics appear to match the results of the statistical testing. The largest change was for the 85th percentile data collected at 55 mph. Before the installation of CRSs, drivers traversed the centerline in 2.23 seconds; and after the installation of CRSs, they crossed the centerline in 2.73 seconds. This was a 0.70-second increase (31 percent). This result supports the earlier statement that the population of the data collected at 55 mph after the installation of CRSs shifted to the right, or increased. Centerline crossing time data collected at 60 and 65 mph decreased for the 85th percentile, and these decreases were 3 and 9 percent, respectively. These changes were smaller than for data collected at 55 mph, which did not appear to contradict the statement that the installation of CRSs did not appear to shift the population of the data. Again, the Wilcoxon Rank Sum test does not allow it to be stated that a particular change of the values presented in Table 28 above was statistically significant.

A Wilcoxon Rank Sum test was also conducted on centerline crossing time data without regard to the speed of the DRV. The test statistic was -3.665, which was outside the two-tailed, 95 percent confidence interval. The overall population of centerline crossing time after the installation of CRSs shifted to the right. Subsequently, driver behavior with respect to centerline crossing time while initiating a passing maneuver changed with drivers taking more time to cross the centerline after the installation of CRSs.

Additional tests were conducted to investigate the possibility of systematic error associated with the differences between the before and after periods other than the installation of the CRSs. The difference in the weather or pavement conditions cannot be fully addressed in this report, because no data were collected in the before period under wet roadway conditions. However, an analysis of after data was completed to determine whether there was a difference between data collected on a weekday versus a weekend.

In particular, centerline crossing time data collected in the after period when the DRV was traveling at 60 mph and 65 mph were analyzed. All of the after data recorded when the DRV was traveling at 55 mph were collected on the weekend, and so a weekend to weekday statistical comparison was not possible. The weekday 60 mph data were collected on a Friday morning from around 7:30 AM to 12:00 PM, and the weekend data were collected the following Saturday during the same timeframe. The weekday 65 mph after data were gathered from approximately 2:00 PM to 6:00 PM on Monday, and the weekend data were gathered the previous day (on Sunday) during the same timeframe. A Wilcoxon Rank Sum test was completed on the reduced data sets and results are listed in Table 30 below (also see Table 113 in Appendix B).

Table 30. Wilcoxon Rank Sum Test for Centerline Crossing Time (Weekday vs. Weekend).

DRV Speed	60 mph	65 mph
Sample Size (B/A)	**24/31**	**13/16**
z-statistic	-4.76*	3.62*

*Indicates that the z-statistic is significant for a two-tailed, 95 percent confidence interval.

The null hypothesis that the centerline crossing time was the same during the weekday and weekend was rejected at both 60 mph and 65 mph. This result is of particular interest because it was presented earlier that the gap distance data collected when the DRV was traveling at 60 and 65 mph did not change significantly after the installation of CRSs (see Table 27). Hence, researchers believe that the significant differences in the centerline crossing time between the before and after periods cannot be said to be solely attributed to the installation of CRSs, but the variations may be a combination of the differences in the weather, the part of the week that the data were collected, and the installation of the CRSs.

Passing Opportunity

Passing opportunity was observed by measuring how long a vehicle was queued immediately behind the DRV while in passing zones, no-passing zones, and when opposing vehicles were present. The formulas used to calculate passing opportunity were presented earlier in Figure 35.

The descriptive statistics are presented in Table 31. The values in the table indicate the percentage of time that was available to a driver prior to making the decision to pass when there was no oncoming traffic and it was legal to pass. Based on the percentages it appears that drivers took more time to pass when traveling behind a vehicle moving at 55 mph than when passing vehicles traveling at higher speeds.

Table 31. Descriptive Statistics for Passing Opportunity.

DRV Speed	**55 mph**		**60 mph**		**65 mph**		**Combined**	
Period	**Before**	**After**	**Before**	**After**	**Before**	**After**	**Before**	**After**
Sample Size	**92**	**99**	**106**	**110**	**25**	**47**	**223**	**256**
Mean	28%	31%	24%	18%	27%	20%	26%	24%
15th Percentile	0%	2%	1%	2%	2%	5%	1%	3%
50th Percentile	11%	18%	14%	11%	14%	14%	12%	13%
85th Percentile	100%	100%	45%	31%	60%	38%	65%	43%

Table 32 contains the z-statistics for verifying any statistically significant changes in passing opportunity after the installation of CRSs along the RTLTW highway used in this project. A complete list of the parameters and their values that were used to develop Table 32 are presented in Table 114 in Appendix B.

The results of the Wilcoxon Rank Sum test are that the only statistically significant change in passing opportunity was for drivers passing a vehicle that was traveling at 55 mph. Statistical significance was established using the z-statistics, assuming a two-tailed, 95 percent confidence interval. Therefore, drivers appear to be waiting longer before passing a vehicle traveling at 55 mph.

Table 32. Wilcoxon Rank Sum Test for Passing Opportunity.

DRV Speed	55 mph	60 mph	65 mph	Combined
Sample Size (B/A)	**92/99**	**106/110**	**25/47**	**223/256**
z-statistic	-2.024*	0.828	0.089	-0.940

*Indicates that the z-statistic is significant for a two-tailed, 95 percent confidence interval.

Percentage of Passing

A test of proportions was used to analyze whether passing decreased after the installation of CRSs. Table 33 contains the results of the tests, and there were not any statistically significant changes in the number of passes between the before and after period (see also Table 115 in Appendix B). The tests for significance were based on a two-tailed, 95 percent confidence interval t-statistic. Consequently, the null hypothesis is not rejected; CRSs did not appear to decrease the number of passes made by drivers at the project location.

Table 33. Test of Proportions for Percentage of Passing.

DRV Speed	55 mph	60 mph	65 mph	Combined
Sample Size (B/A)	**92/99**	**106/110**	**25/47**	**223/256**
t-statistic	-0.678	-0.102	1.129	-0.026

*Indicates that the t-statistic is significant for a two-tailed, 95 percent confidence interval. There were no statistically significant changes.

LATERAL POSITION

Data Collection

There are various technologies available to collect lateral position data and they all vary in cost, accuracy, level of field supervision, and difficulty in data reduction. Based on cost, availability, and required level of accuracy, all of the field data were collected using a TTI camera trailer (see Figure 37). Data were collected during the daytime. The weather was clear to partially cloudy and the pavement was dry. Approximately three hours of video data were recorded for each project site for the before and after periods. The project sites, their geometric configuration, and CRS design are detailed in Table 34. The roadways were all asphalt concrete.

Figure 37. TTI Video Trailer.

Table 34. CRS Lateral Position Project Site Characteristics.

Roadway	Alignment	Number of Lanes	Shoulders	CRS Design
FM 195	Curve 1	2	Yes	Yellow, 4-foot spacing, on each side of CL marking[1]
FM 195	Curve 2	2	Yes	Yellow, 4-foot spacing, on each side of CL marking[1]
FM 969	Tangent	2	No	Black, 4-foot spacing, staggered inside CL marking
FM 969	Curve	2	No	Yellow, 4-foot spacing, on each side of CL marking
FM 1431	Tangent	4	No	Yellow, 4-foot spacing, on each side of CL marking
FM 1431	Curve	4	No	Yellow, 4-foot spacing, on each side of CL marking
FM 2222	Tangent	4	No	Yellow, 4-foot spacing, on each side of CL marking
FM 2222	Curve	4	No	Yellow, 4-foot spacing, on each side of CL marking

[1] This site also included white pavement buttons spaced at 4-foot spacing adjacent to the outside edge of the edgeline, and are therefore raised edgeline rumble strips.

Figure 38 through Figure 41 are general pictures of each roadway that contain key information such as the number of lanes, existence of shoulders, delineation, and CRS design.

Figure 38. FM 195.

Figure 39. FM 969.

Figure 40. FM 1431.

Figure 41. FM 2222.

Tape markers were placed on the pavement at 6-inch intervals from the centerline markings, so that lateral position data could later be extracted (see Figure 42).

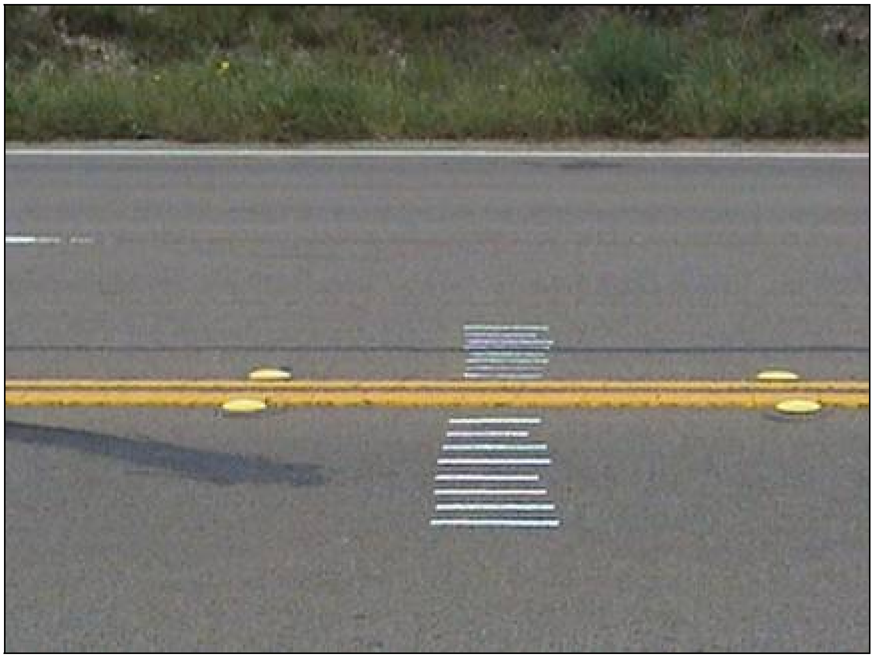


Figure 42. Lateral Position Markers.

Analysis

The data were tabulated into spacing categories that referenced the outside edge of the centerline markings adjacent to a particular lane of travel. Figure 43 contains a picture of the infield marking system that was used to bin the data into spacing categories. The binned data were also broken down by vehicle classification, but not enough data were collected in the sample size to properly analyze the effects of CRSs on lateral position by vehicle classification.

Probability and cumulative distributions were used to analyze the data. General trends were investigated such as shifts in the distribution of the population; however, no comments may be made as to whether a change was statistically significant using this analysis method.

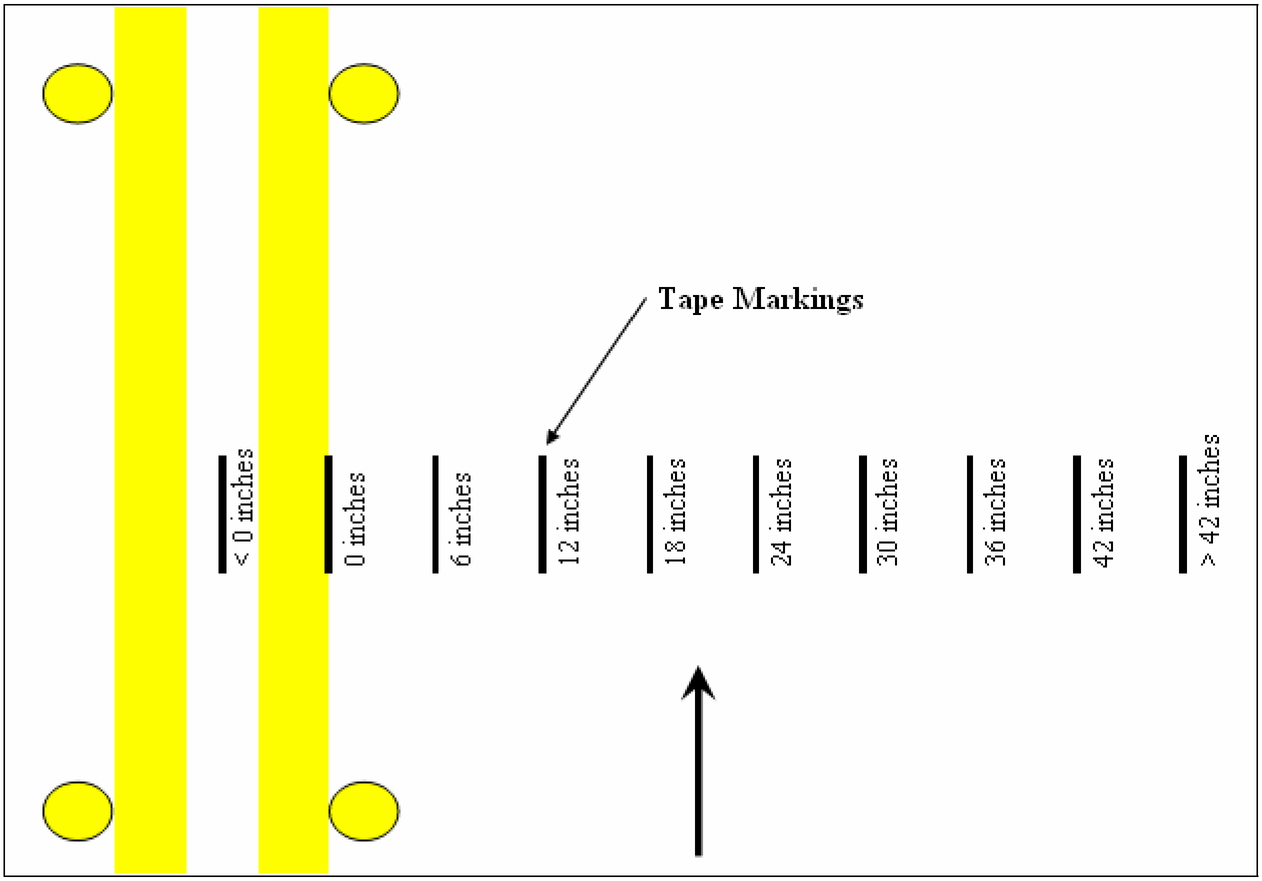


Figure 43. Infield Lateral Position Marking System.

Findings

At all eight project sites, vehicular placement changed. The majority of drivers in the after period moved away from the centerline.

The findings are presented by site location. The term "inside lane" is used to define the travel lane on the inside of a curve, and "outside lane" denotes the travel lane on the outside of a curve. The terms "direction 1" and "direction 2" denote the two different directions of travel for a project site located on a tangent or straight segment of road. Figure 44 is a pictorial description of the previously mentioned terms. All of the descriptive statistics are detailed in Appendix B (Table 116 through Table 132).

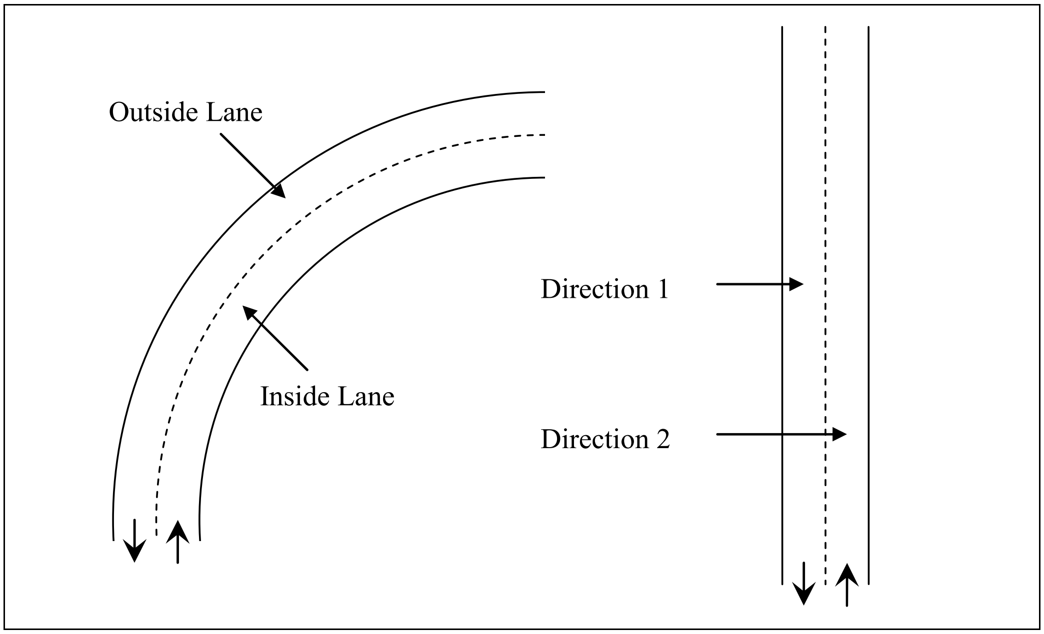


Figure 44. Lane Referencing.

FM 195 (Curve 1)

Figure 45 and Figure 46 contain the distribution of vehicles by lateral position with respect to the centerline at Curve 1 along FM 195. Vehicles traveling in both the inside and outside lanes shifted away from the centerline.

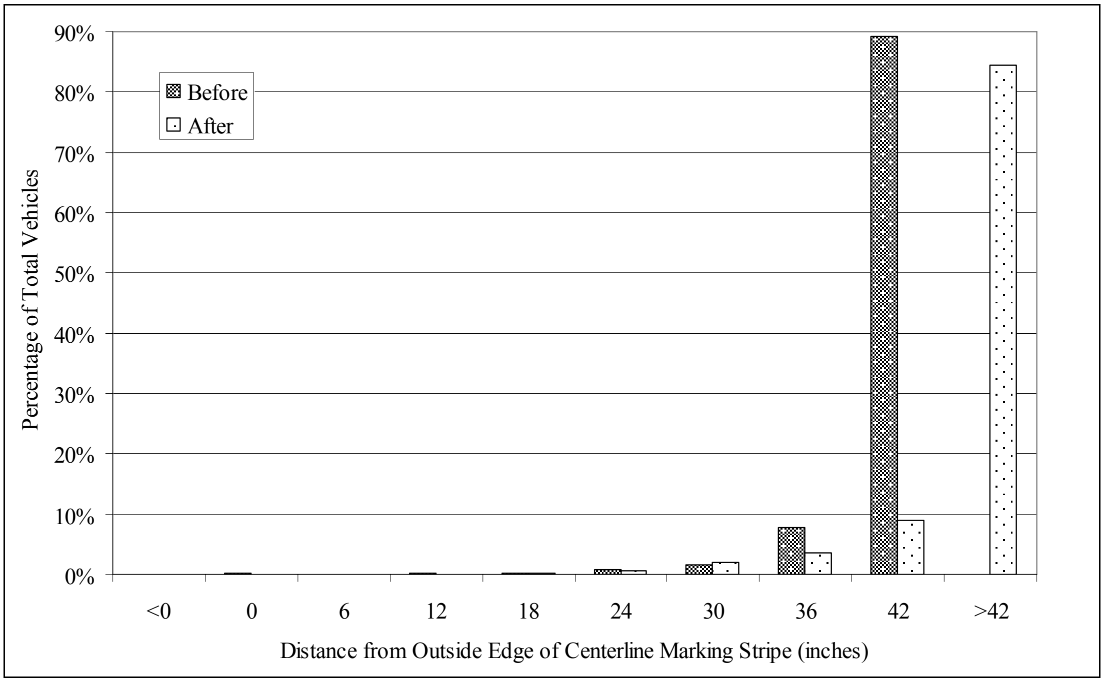


Figure 45. Lateral Position Distribution of All Vehicles on FM 195 (Curve 1, Inside Lane).

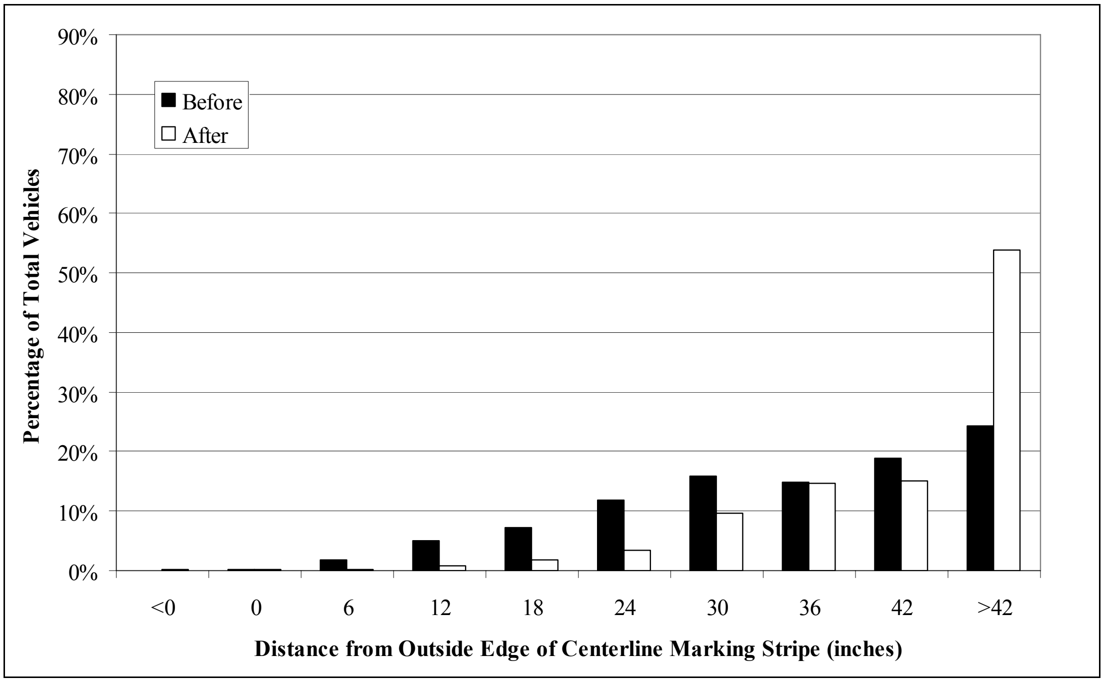


Figure 46. Lateral Position Distribution of All Vehicles on FM 195 (Curve 1, Outside Lane).

For the inside lane of travel, 89 percent of motorists drove with a 42-inch gap between their left tires and the centerline markings in the before period. After the installation of CRSs, 94 percent of the motorists passed through the inside lane with at least a 42-inch gap. It should be noted that no vehicles were recorded passing through the inside lane with a gap greater than 42 inches before the installation of CRSs, while 85 percent of the vehicles were recorded traveling further than 42 inches from the centerline markings.

More than 85 percent of vehicles in the outside lane of travel were at least 24 inches from the centerline markings before the installation of CRSs. In the after period, 84 percent of vehicles were recorded with a gap of at least 36 inches between the left tires and the centerline markings.

FM 195 (Curve 2)

At Curve 2 along FM 195, vehicles also shifted away from the centerline in the inside lane; however, the vehicles in the outside lane shifted toward the centerline (see Figure 47 and Figure 48). Before CRSs were installed, 88 percent of motorists got as close as 12 inches to the centerline markings in the inside lane. Motorists appeared to shift approximately 12 inches from the centerline after the installation with 89 percent of motorists leaving a gap of at least 24 inches between their left tires and the centerline markings.

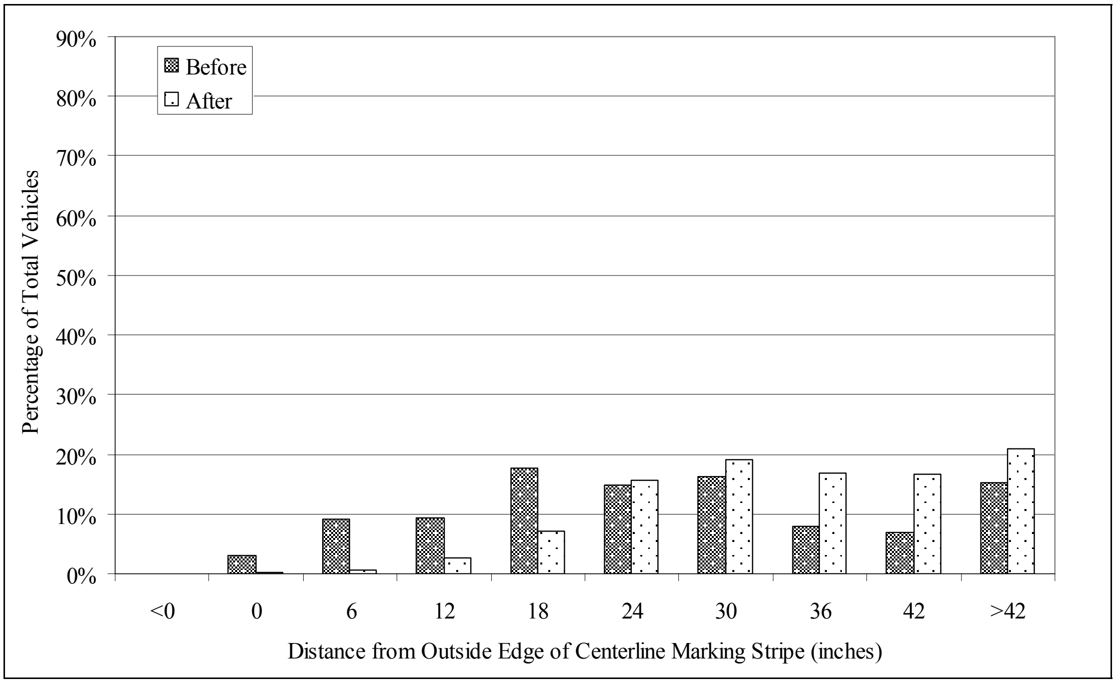


Figure 47. Lateral Position Distribution of All Vehicles on FM 195 (Curve 2, Inside Lane).

The motorists in the outside lane shifted toward the centerline markings by approximately 12 inches with 88 percent of vehicles at 30 or more inches from the centerline before CRSs were installed and 92 percent of vehicles as close as 18 inches to the centerline after the installation.

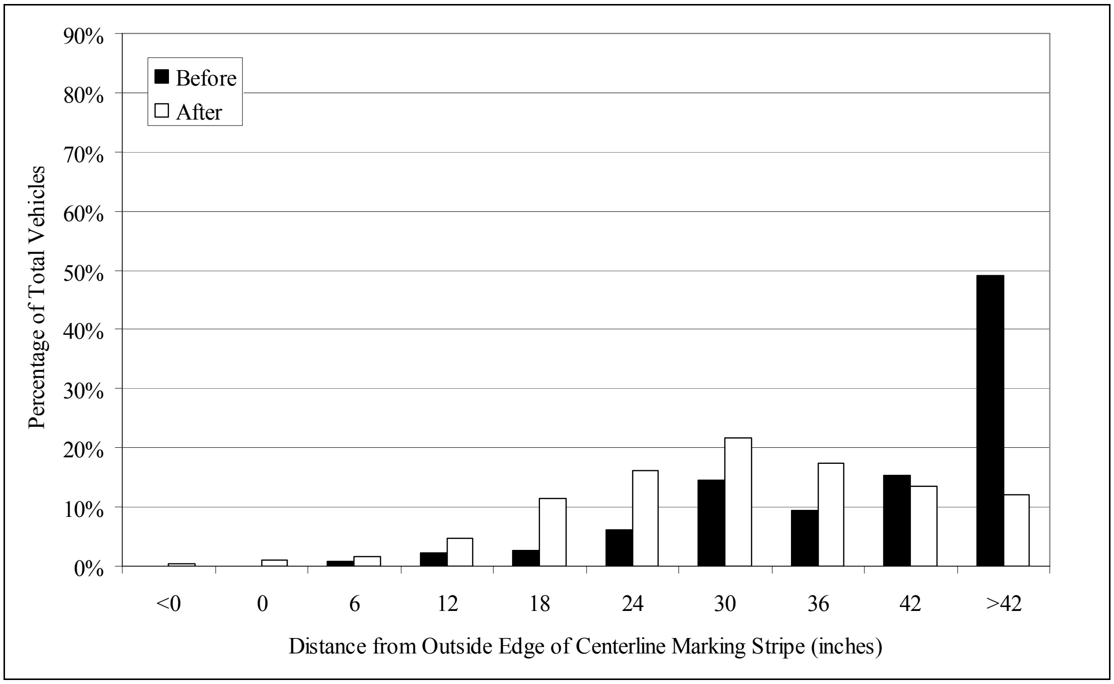


Figure 48. Lateral Position Distribution of All Vehicles on FM 195 (Curve 2, Outside Lane).

It is believed that the inward shift of the outside traffic may be the result of at least two factors. First, motorists in the outside lane may be shifting closer toward the centerline because they shifted in the same direction as the inside traffic. Motorists may shift in this manner because their vehicular placement was based on the location of pavement markings and the location of oncoming traffic. Second, motorists in the outside lane may have been trying to avoid contacting the edgeline rumble strips.

FM 969 (Tangent)

Figure 49 and Figure 50 contain the distribution of vehicles by lateral position with respect to the centerline at the tangent section along FM 969. Vehicles traveling in direction 1 appear to be unaffected by CRSs with respect to lateral position. Before CRSs were installed, 83 percent of traffic maintained a gap of at least 12 inches, as opposed to 80 percent after installation.

Drivers traveling in direction 2 have shifted away from the centerline pavement markings by approximately 6 inches. Vehicles traveling with a gap of 24 inches or more between the left tires and the centerline markings accounted for 82 percent of the travel flow in the before period. After CRSs were installed, 81 percent of the drivers used a gap of 30 or more inches to traverse the project site. These changes are smaller than changes in lateral position recorded for the two FM 195 sites.

The researchers believe there are at least two reasons that these minimal changes may occur. The first possible reason is that the pattern used for the CRSs was less aggressive than the pattern used at other sites. In particular, the pavement buttons were staggered but had the same spacing. Subsequently, there were half as many pavement buttons placed along the centerline. Furthermore, the pavement buttons were placed inside the pavement markings, while at all other sites, the buttons were placed outside of the centerline markings and into the adjacent travel lanes.

A second possible reason for smaller changes in lateral position was that the pavement buttons were black and placed on asphalt concrete pavement. The black buttons may have blended in with the pavement better than the yellow buttons placed at the other project sites so drivers may have been less likely to notice the presence of the CRSs.

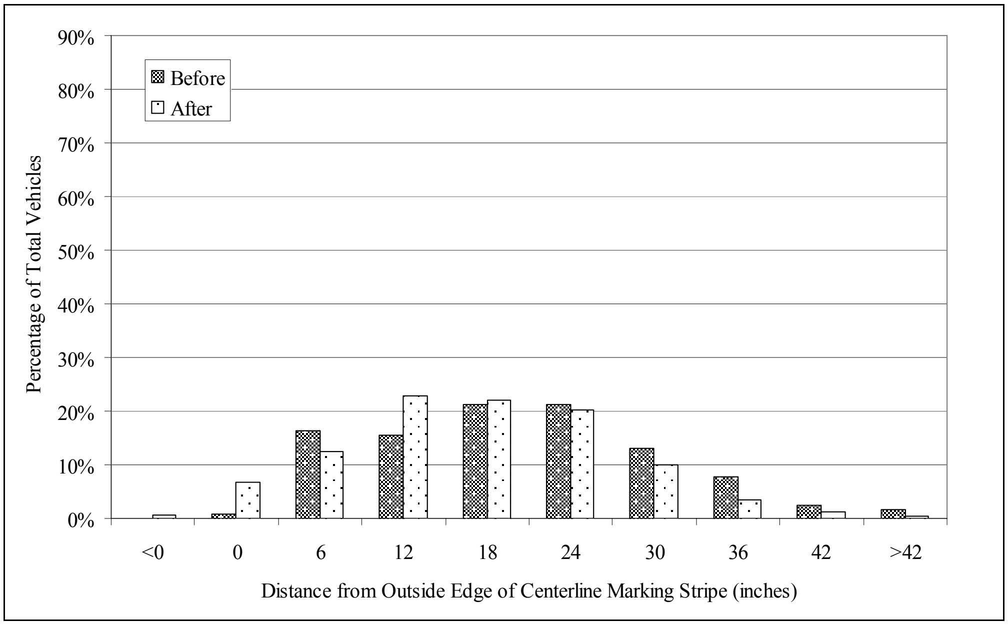


Figure 49. Lateral Position Distribution of All Vehicles on FM 969 (Tangent, Direction 1).

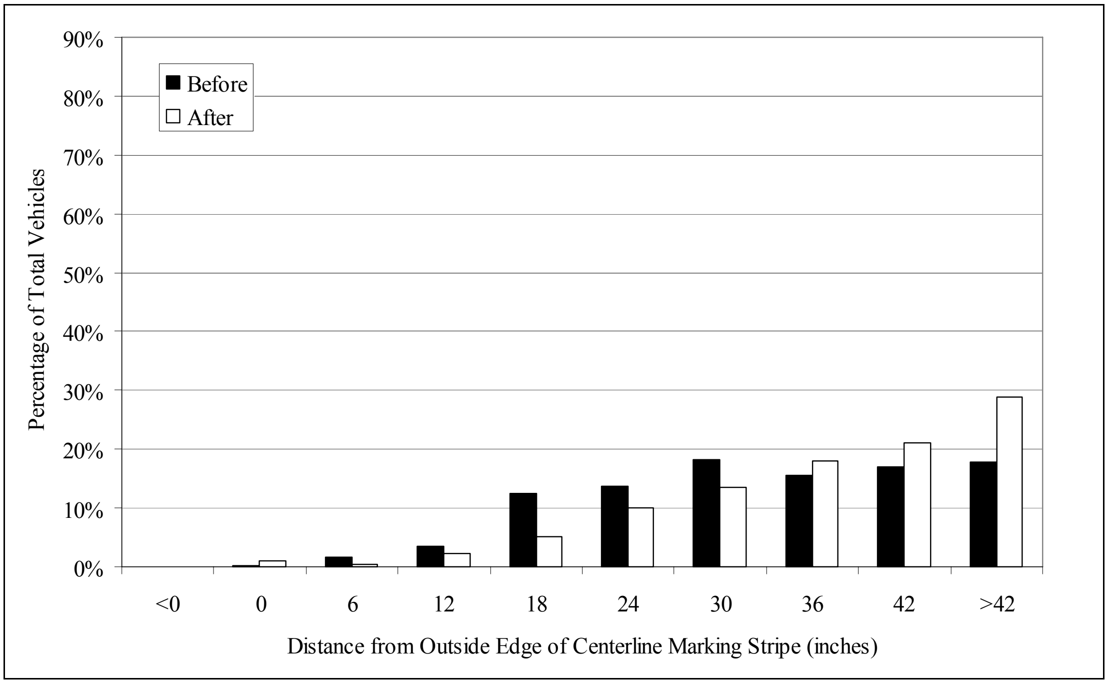


Figure 50. Lateral Position Distribution of All Vehicles on FM 969 (Tangent, Direction 2).

FM 969 (Curve)

Changes in lateral position along the curve project segment of FM 969 were similar to the tangent segment (see Figure 51 and Figure 52). The lateral vehicle position in the outside lane did not appear to change, and the inside lane positioning appeared to move approximately 6 inches away from the centerline markings. There were 80 percent of drivers traveling around the inside lane with at least 12 inches between the centerline markings and their left tires in the before period. After installing CRSs, 85 percent of the vehicles were recorded moving through the inside lane with at least 18 inches between the centerline and their left tires. It is believed that these small changes may have resulted from the less aggressive CRS pattern at this site.

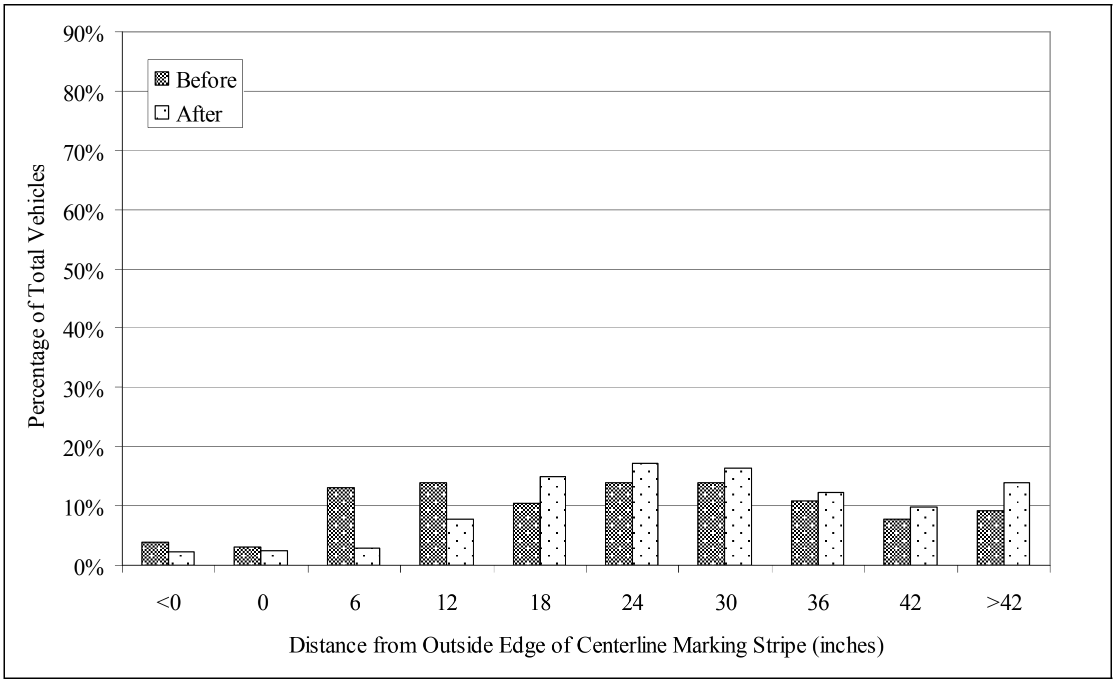


Figure 51. Lateral Position Distribution of All Vehicles on FM 969 (Curve, Inside Lane).

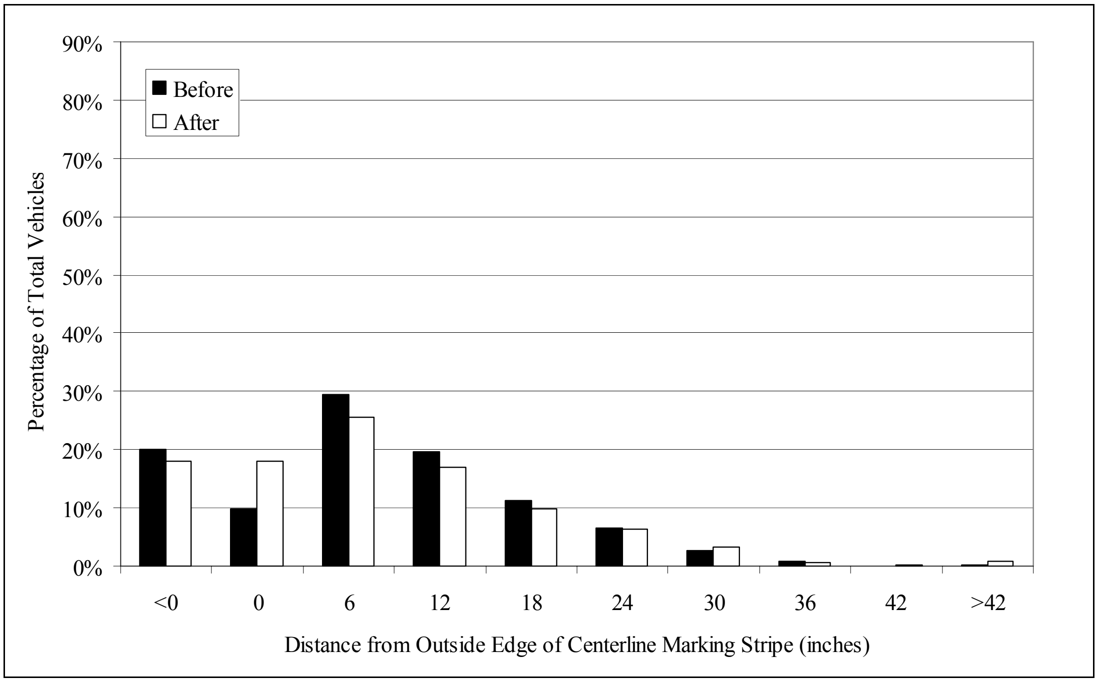


Figure 52. Lateral Position Distribution of All Vehicles on FM 969 (Curve, Outside Lane).

FM 1431 (Tangent)

At the tangent project section along FM 1431, drivers in direction 1 shifted away from the centerline pavement markings; and in direction 2, drivers shifted toward the centerline.

Figure 53 and Figure 54 contain the lateral position distribution of the traffic flow for directions 1 and 2.

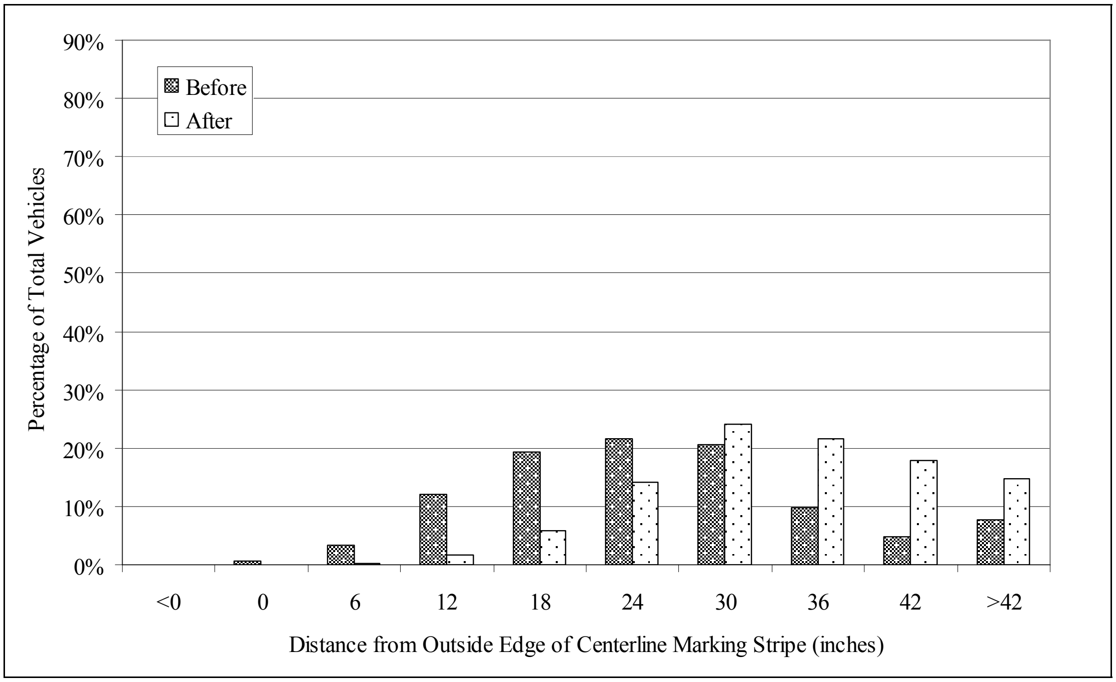


Figure 53. Lateral Position Distribution of All Vehicles on FM 1431 (Tangent, Direction 1).

Drivers moving in direction 1 shifted approximately 12 inches away from the centerline. Before the installation of CRSs, 84 percent of the traffic traveled at least 18 inches from the centerline markings, and 78 percent of the traffic moved through the region at 30 or more inches from the centerline after CRSs were installed.

While vehicles in direction 2 did appear to travel closer to the centerline after the installation of CRSs, the change was minute. Furthermore, the closest a vehicle got to the centerline after installing CRSs was approximately 6 inches. This means that no vehicles were contacting and/or crossing the centerline markings into opposing traffic after the installation of CRSs.

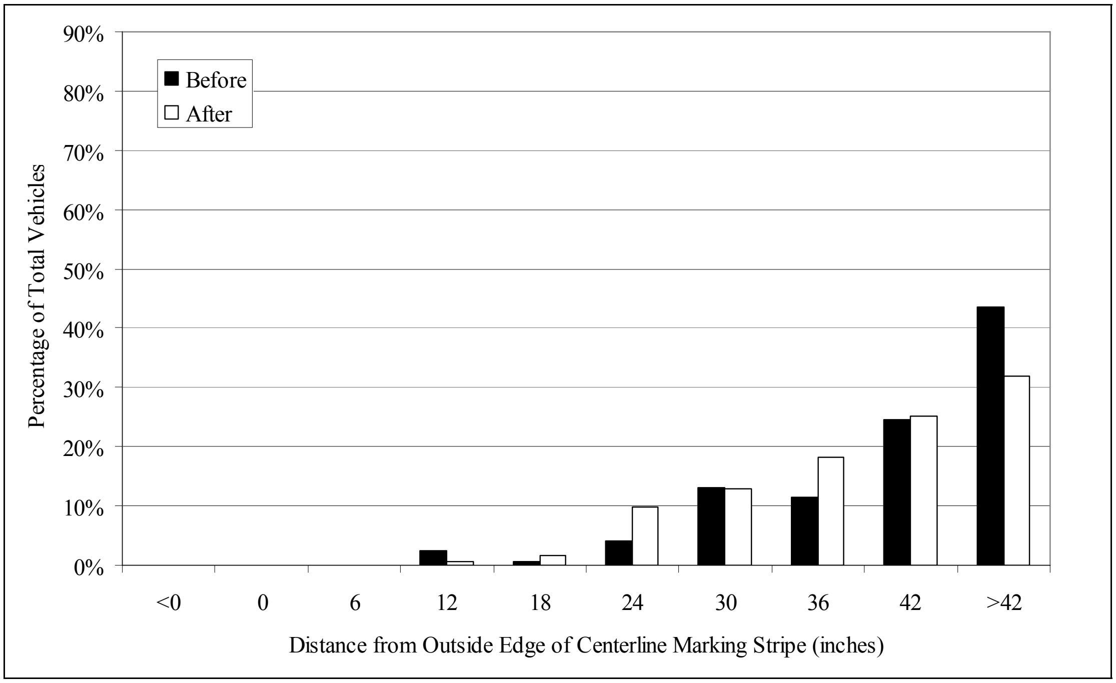


Figure 54. Lateral Position Distribution of All Vehicles on FM 1431 (Tangent, Direction 2).

FM 1431 (Curve)

There was a similar shift for drivers traveling through the curve segment of FM 1431 as was recorded for drivers along the tangent segment. The inside travel lane moved farther from the centerline pavement markings and the outside lane moved closer to the centerline (see Figure 55 and Figure 56). Both directions of travel appear to shift by approximately 6 inches.

There are at least two possible reasons for the traffic in the outside lane shifting toward the centerline. As stated earlier, it is likely that the motorists in the outside lane shifted with the inside traffic to maintain a similar gap distance between opposing traffic streams. This thought is congruent with the similar magnitude of lateral shifting (approximately six inches for each direction of travel). The second possibility is that this project site was a four-lane, undivided highway, and if the far outside lane shifted toward the centerline, it is likely that the adjacent lane closest to the centerline would also shift toward the centerline.

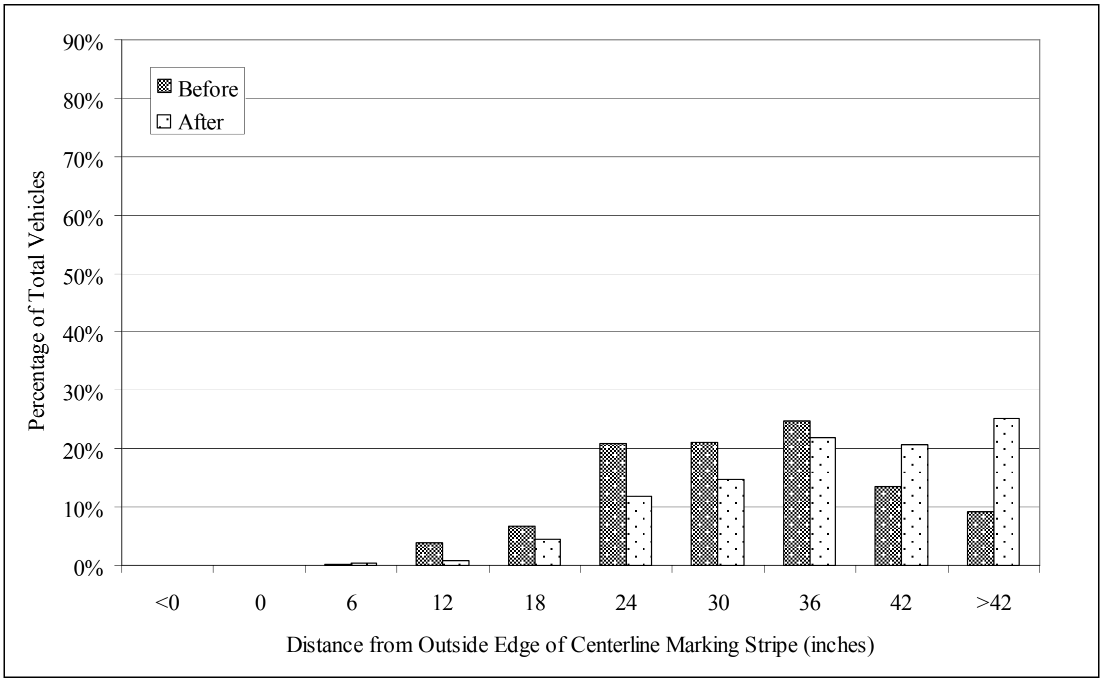


Figure 55. Lateral Position Distribution of All Vehicles on FM 1431 (Curve, Inside Lane).

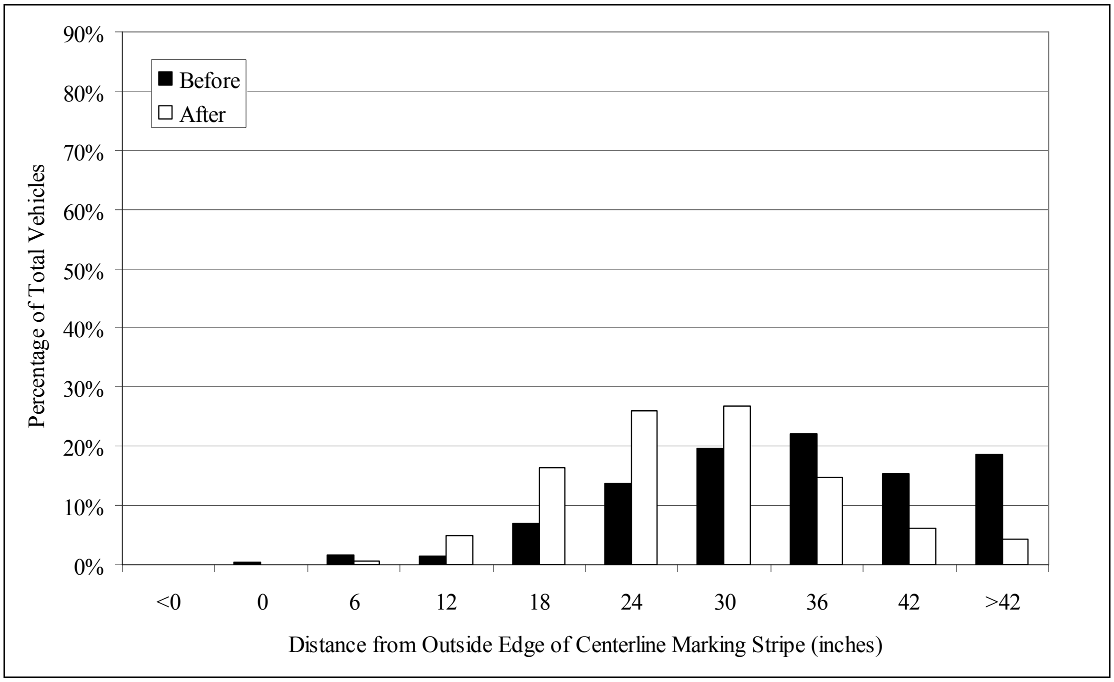


Figure 56. Lateral Position Distribution of All Vehicles on FM 1431 (Curve, Outside Lane).

None of the vehicular traffic contacted the centerline before or after the installation of CRSs. In addition, all vehicles traveled at least 6 inches away from the centerline pavement markings after the installation of CRSs.

FM 2222 (Tangent)

The changes along the FM 2222 tangent section are almost identical in magnitude and type of lateral movement. Figure 57 and Figure 58 contain the distribution of the lateral position data for the tangent project segment along FM 2222. Direction 1 had an approximate shift of 12 inches away from the centerline markings with 95 percent of the traffic at least 6 inches from the centerline before the installation of CRSs and 95 percent at least 18 inches from the centerline after installation.

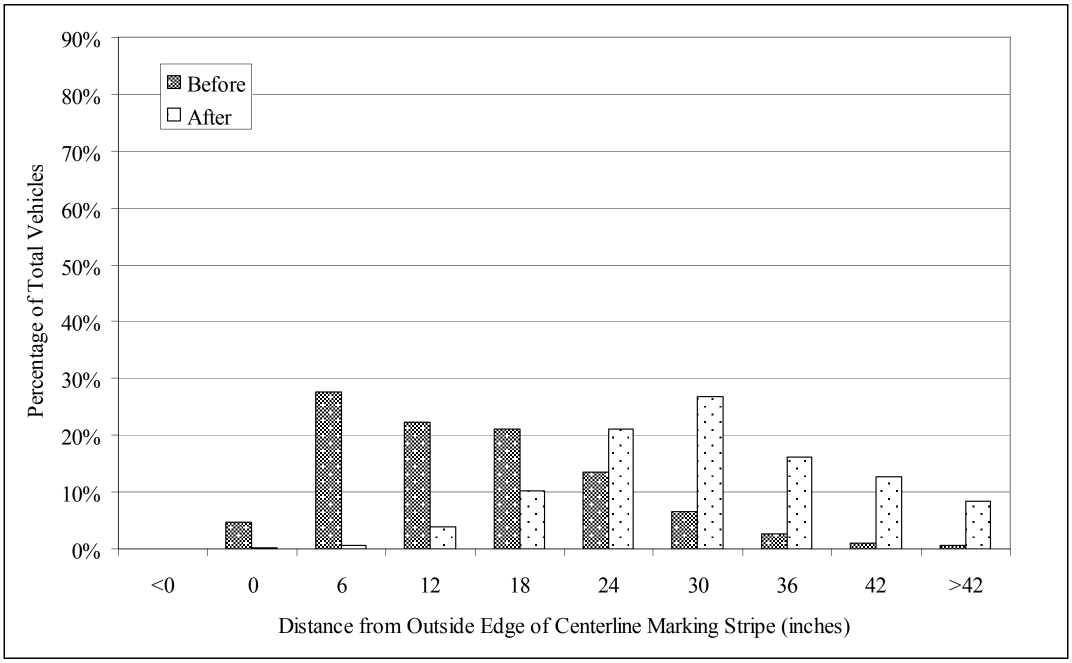


Figure 57. Lateral Position Distribution of All Vehicles at FM 2222 (Tangent, Direction 1).

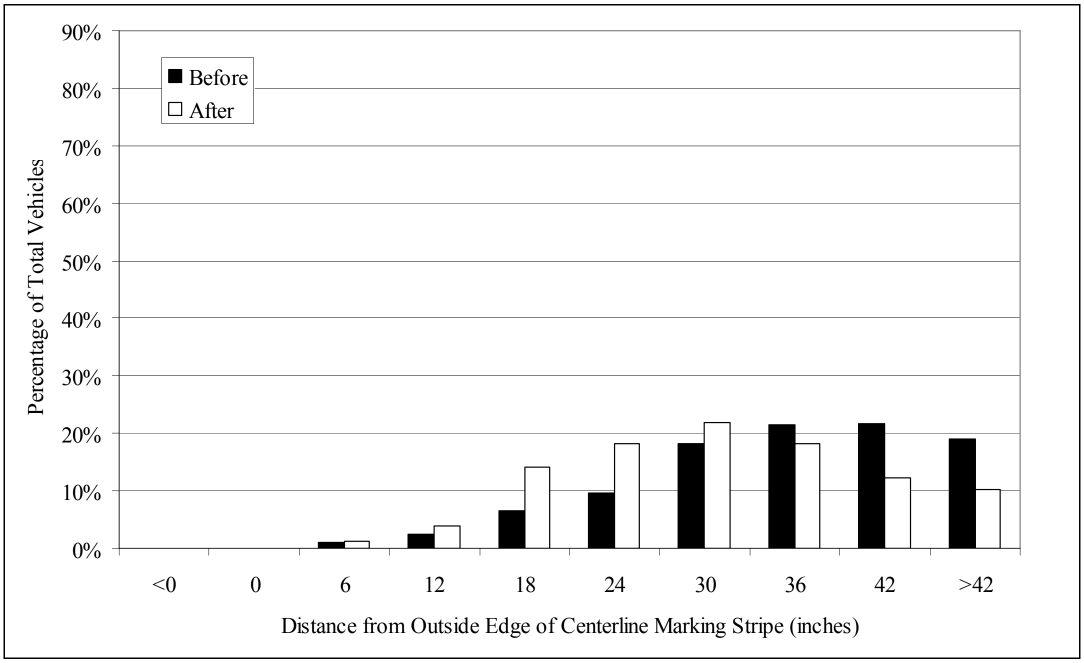


Figure 58. Lateral Position Distribution of All Vehicles on FM 2222 (Tangent, Direction 2).

Direction 2 traffic shifted toward the centerline pavement markings. At least 80 percent of the vehicles were 30 or more inches away from the centerline before CRSs were installed. After installing CRSs, drivers shifted toward the centerline by about 6 inches with 81 percent of the drivers at 24 or more inches from the centerline. Again, it is believed that drivers shifting toward the centerline did so because they were following the lateral shift of vehicles in the opposing lane of travel.

None of the vehicular traffic contacted the centerline before or after the installation of CRSs. In addition, all vehicles traveled at least 6 inches away from the centerline pavement markings after the installation of CRSs.

FM 2222 (Curve)

For the FM 2222 curve project site, both directions of travel shifted away from the centerline (see Figure 59 and Figure 60). It was interesting that this was the only curve site where the largest shift occurred in the outside lane. While drivers traveling along the inside lane did move farther from the centerline pavement markings after the installation of CRSs, the change was minuscule (90 percent of the traffic was at least 42 inches from the centerline before installing CRSs and 94 percent after).

The larger change appeared with the vehicles in the outside lane. There was 91 percent of the traffic at 6 or more inches from the centerline in the before period, and 95 percent at 12 or more inches after the installation of CRSs.

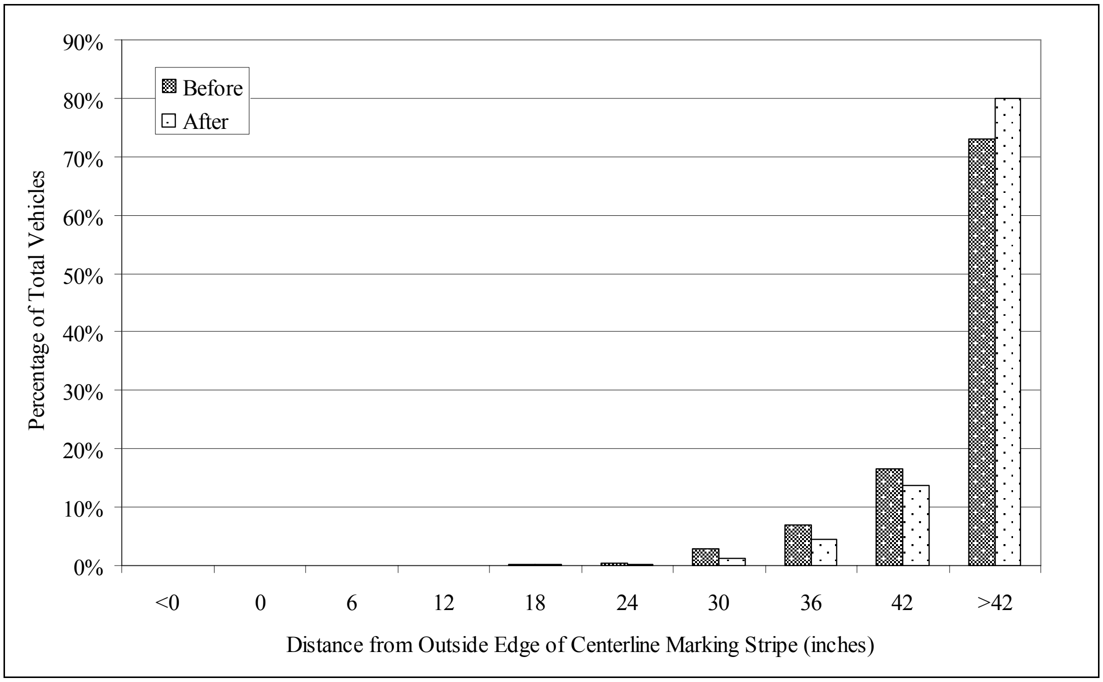


Figure 59. Lateral Position Distribution of All Vehicles on FM 2222 (Curve, Inside Lane).

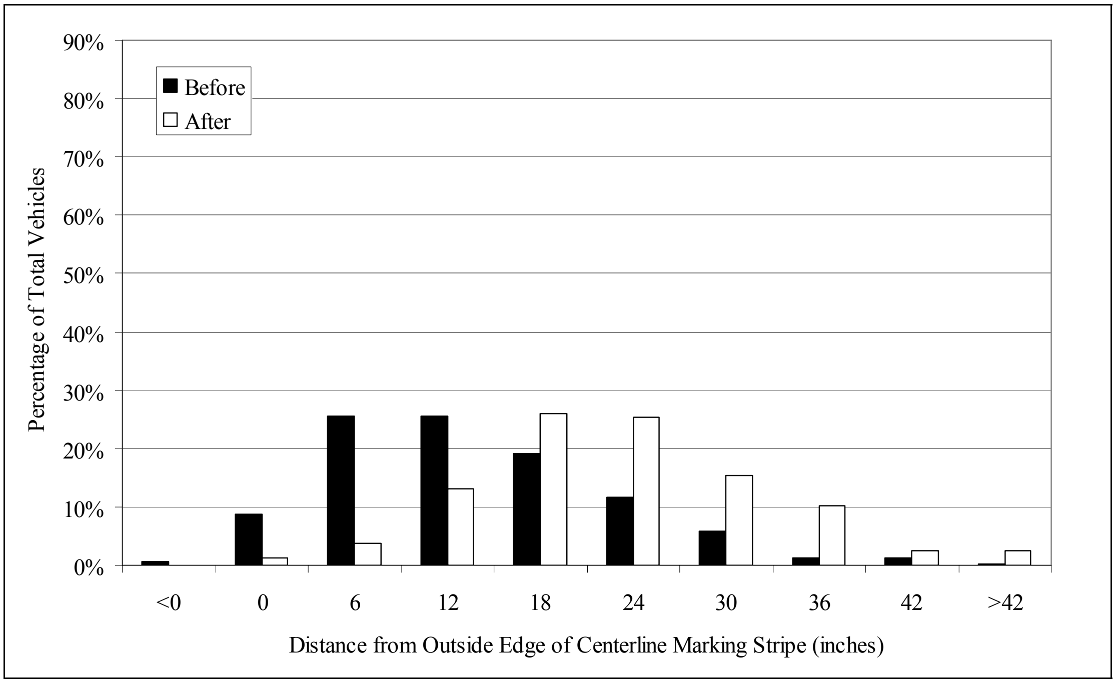


Figure 60. Lateral Position Distribution of All Vehicles on FM 2222 (Curve, Outside Lane).

None of the vehicular traffic contacted the centerline before or after the installation of CRSs.

CHAPTER 4

EDGELINE RUMBLE STRIPS

PROBLEM STATEMENT

This chapter describes the research procedures employed for driver behavior observations before and after edgeline rumble strips (ERSs) were installed in the field. An ERS is a small rut milled into the pavement to create a rough surface. ERSs are similar to shoulder rumble strips (SRSs) that TxDOT often uses, but they differ slightly in placement. SRSs are installed several inches away from the edgeline, while ERSs are installed with a portion of the rumble strip covered by the edgeline. The purpose of this small change is to provide an earlier warning to drivers when they stray off of the traveled lane.

One method to improve road safety is to apply treatments that discourage drivers from straying off of the travel lanes. Crashes can occur if drivers become inattentive and drift onto the shoulder, and then off of the paved surface entirely. To determine the effectiveness of ERSs in reducing such events, a before and after evaluation was performed, and observations were made on shoulder usage. Researchers monitored the volumes of shoulder-encroaching traffic, observed some encroaching maneuvers to determine the circumstances that led to the shoulder usage, and calculated lateral positions of encroaching vehicles. A reduction in shoulder encroachment volumes would indicate an improvement.

OBJECTIVES

The purpose of installing ERSs is to improve road safety by reducing the number of accidental shoulder encroachment maneuvers that occur. When drivers stray out of the travel lane and onto the right shoulder of a highway, they increase their risk of losing control of their vehicles and running off of the road. Rumble strips provide warnings to drivers by creating noise and vibration when vehicles' tires pass over the strips. If the encroachment on the shoulder was unintentional (i.e., the driver was inattentive or drowsy), the noise and vibration can alert the driver to his mistake, so he can then steer back into the travel lane.

This project focused on the volume of shoulder encroachment maneuvers under several circumstances that can induce encroachment, including the:

- presence of emergency vehicles,
- occurrence of dangerous actions by other drivers that require evasive maneuvers,
- desire to let faster vehicles pass, and
- need to avoid turning vehicles.

Data were also analyzed to determine the positions of vehicles on the shoulder during such maneuvers. Observations were made at one site before and after ERSs were installed, to determine the effectiveness of the strips in reducing the frequency of accidental shoulder encroachment.

STUDY DESIGN

This experiment was designed as a simple, one-site before and after experiment to determine the effectiveness of the ERS treatment. Since the data for each case were collected within a few months, when seasonal variations in traffic characteristics are presumably small, it was determined that the use of a control site could be avoided.

Site Characteristics

The site chosen for this project was a five-mile segment of SH 6 between Calvert and Hearne, Texas. This segment of SH 6 is a rural, undivided, two-lane, two-way highway with the following geometric characteristics:

- generally north/south travel alignment;
- one 11-foot travel lane in each direction;
- 9-foot to 9.5-foot shoulders in each direction;
- a 4-foot-wide center segment marked with centerline pavement markings, striped to permit passing 77 percent of the time in each direction; and
- at least two segments in each direction with approximately one-mile sight distance.

See Figure 61 for a picture of the site during installation of the rumble strips.

Figure 61. SH 6 Project Site.

Based on volume data collected during the experiment, the ADT for this highway is approximately 10,800 vpd, with a NB/SB split of 49/51.

Installation Design

The ERSs installed at the site consisted of semicircular ruts milled into the pavement along the edgeline. Each strip measured 12 inches wide and 7 inches long, and they were spaced 12 inches on center. The inside edges of the strips were aligned with the inside edge of the edgeline, such that 4 inches of the strips' widths were on marked edgeline and 8 inches were on shoulder pavement.

Figure 62 and Figure 63 illustrate the design of the ERSs. Note that the design is similar to the CRS design described in Chapter 3.

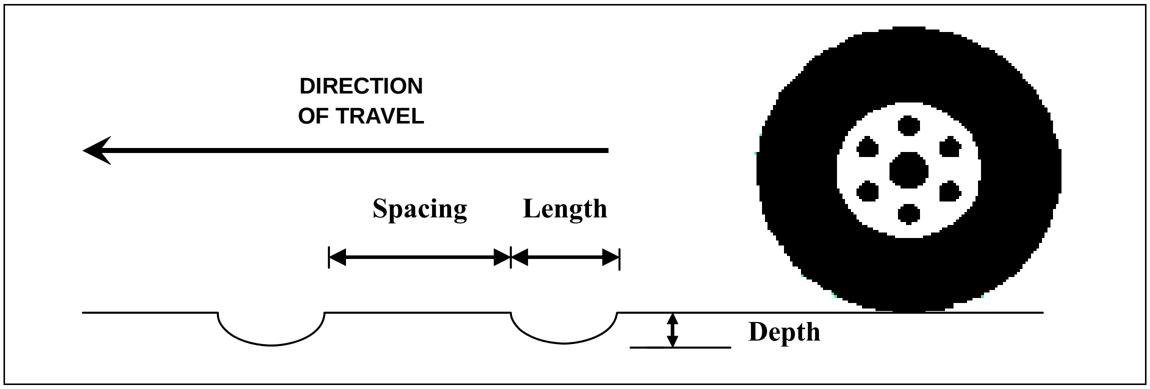


Figure 62. Edgeline Rumble Strip Design.

Figure 63. Picture of Edgeline Rumble Strips.

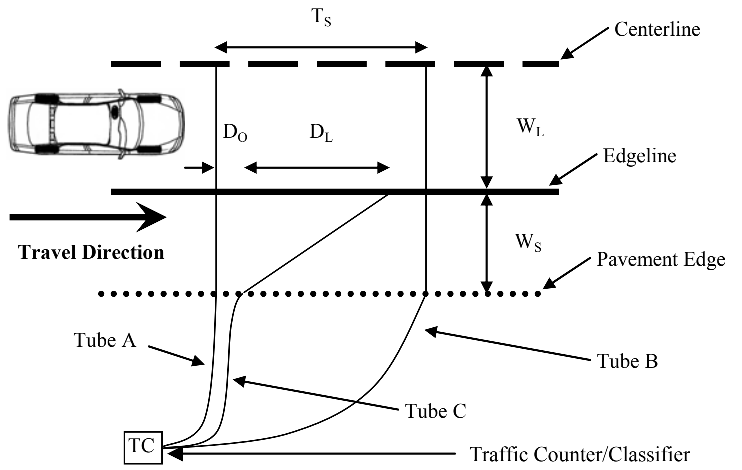
DATA COLLECTION

Data were collected before and after installation of the ERSs to determine the following:

- traffic volumes and speeds;
- frequency of shoulder encroachment maneuvers;
- maneuver classification, including emergency, passing, turning, and other;
- vehicle classification (two-axle or three-axle);
- general time of maneuver (day or night); and
- lateral position of vehicles on the shoulder during encroachment maneuvers.

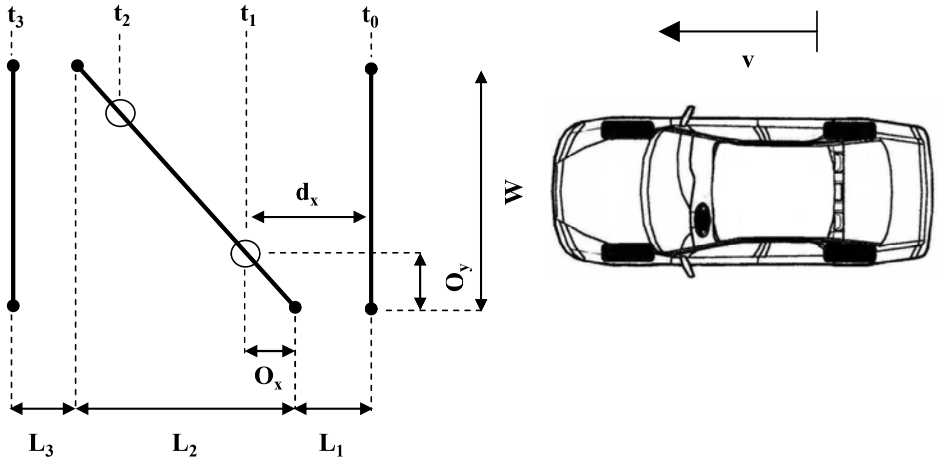
Data Collection Methods

PEEK pneumatic roadtubes were used to collect 1405 hours of lateral position, volume, and speed data. Seven hours of the data had to be discarded because of problems like ruptured tubes and trucks parked on the shoulder. The tubes were arranged in Z patterns, with two tubes extending across the shoulder and the travel lane, and the third placed diagonally across the shoulder only (see Figure 64). The two straight tubes were used to collect speed and volume data. The diagonal tube was used to collect lateral position data; the raw data provided the distance along the tube where vehicles' right front tires crossed the tube, and these measurements were then converted to lateral position using geometry and roadtube time stamp measurements as shown in Figure 65.



Term	Length (ft)	Definition
T_S	8	Roadtube spacing between Tubes A and B
D_L	6	Diagonal length of Tube C with the direction of travel
D_O	1	Diagonal offset of Tube C from Tube A
W_L	12	Width of travel lane
W_S	8	Width of shoulder (and diagonal width of Tube C as measured perpendicular to the direction of travel

Figure 64. Placement of Roadtubes.



L_i = Length over section i (inches)
W = Width (inches)
O_x = offset distance of the first tire contact in the direction of travel (inches)
O_y = offset distance of the first tire contact perpendicular to the direction of travel (inches)
t_i = Time at point i (sec)
v = velocity (inches/sec)

$$v = \frac{L_1 + L_2 + L_3}{t_3 - t_0} \qquad \text{Eq. 1}$$

$$d_x = v(t_1 - t_0) \qquad \text{Eq. 2}$$

$$O_x = d_x - L_1 \qquad \text{Eq. 3}$$

$$O_y = \frac{O_x W}{L_2} \qquad \text{Eq. 4(a)} \qquad O_y = \frac{\left[\left(\frac{L_1 + L_2 + L_3}{t_3 - t_0}\right)(t_1 - t_0) - L_1\right] W}{L_2} \qquad \text{Eq. 4(b)}$$

Figure 65. Lateral Position Calculations from Roadtube Measurements.

During daytime conditions, video footage was collected for the purpose of classifying shoulder encroachment maneuvers. A total of 120 hours of video data was collected.

Sample Size

A total of 2985 shoulder encroachments were observed in the reduced roadtube data. The before data were collected between September 10 and September 22, 2004, and the after data were collected between November 5 and November 17, 2004. The temporal distribution of these observations was as follows:

- 2473 encroachments (82.8 percent) during the daytime period (7 AM – 6 PM),
- 512 encroachments (17.2 percent) during the nighttime period (6 PM – 7 AM),
- 1965 encroachments (65.8 percent) during weekdays, and
- 1020 encroachments (34.2 percent) during weekends.

There were 745 additional encroachment observations that were removed from the data set for analysis because of anomalous results. For unknown reasons, these observations showed shoulder encroachment position values greater than the shoulder width at the location of diagonal roadtube deployment. The maximum value for shoulder encroachment position (measured in inches away from the paved edge of the shoulder) should not be greater than the width of the shoulder.

A total of 1881 encroachments occurred while usable video footage (i.e., filmed during the day) was available to verify the reason for the encroachment. These shoulder encroachments were classified so further analysis could be conducted on shoulder usage.

ANALYSIS

The roadtube data were reduced and analyzed both to provide volume counts for the encroachment volume calculations and to determine the mean lateral positions of vehicles during video-verified encroachment maneuvers. In addition, the video footage was observed to determine if the ERSs induced any erratic maneuvers by drivers. No erratic maneuvers were observed in any of the video data.

Shoulder Encroachment Volume

The field data collected by the straight roadtubes were stratified by time (weekday [WD]/weekend [WE], day/night) and travel direction, and the percentage change in encroachment volumes for each data group were calculated based on percentage of ADT. Statistical t-tests were then performed to determine the significance of each change.

The 1881 shoulder encroachments that were video-verified were further classified to describe the reason for each encroachment maneuver, as follows:

- emergency –vehicles moving onto the shoulder to clear the way for an emergency vehicle, stopping on the shoulder because of breakdown, or pulling onto the shoulder evasively because of dangerous actions by another driver;
- turning –vehicles moving onto the shoulder to avoid a left-turning vehicle in the travel lane, to begin the execution of a right-turn maneuver, or to accelerate back into the traveled way after stopping for any reason;
- passing –vehicles moving onto the shoulder to provide room for faster vehicles to pass; and
- other –vehicles theoretically coming into inadvertent contact with the edgeline because of natural lane shifting, driver inattention or fatigue, swaying motions of trailers, or large load width.

The video-verified observations categorized as “other” or “passing” were further stratified by vehicle type (two axles or three plus axles). The percentage change in encroachment volumes was calculated for each data group based on percentage of ADT to provide insight into the effect of edgeline rumble strips on shoulder usage.

Lateral Position

For the video-verified encroachments, mean lateral positions of vehicles on the shoulder were calculated for both study periods (before and after) to provide additional insight into drivers’ responses to the strips. Lateral position data were extracted from the diagonal roadtube observations. Statistical t-tests were performed on mean position changes to determine significance. Cumulative histogram plots were also drawn. Encroachments classified as "other" or "passing" were further grouped by position category to determine specifically which types of encroachments were most likely to be affected by the installation of rumble strips. The following four position categories were defined for this analysis:

- right tires hit – only the vehicle's right tires pass over the rumble strips,
- straddle – the rumble strips are between the left and right tires such that neither tire is hitting the strips,
- left tires hit – only the vehicle's left tires pass over the strips, and
- around – the vehicle's left tires completely clear the strips on the right side.

The position categories are illustrated in Figure 66.

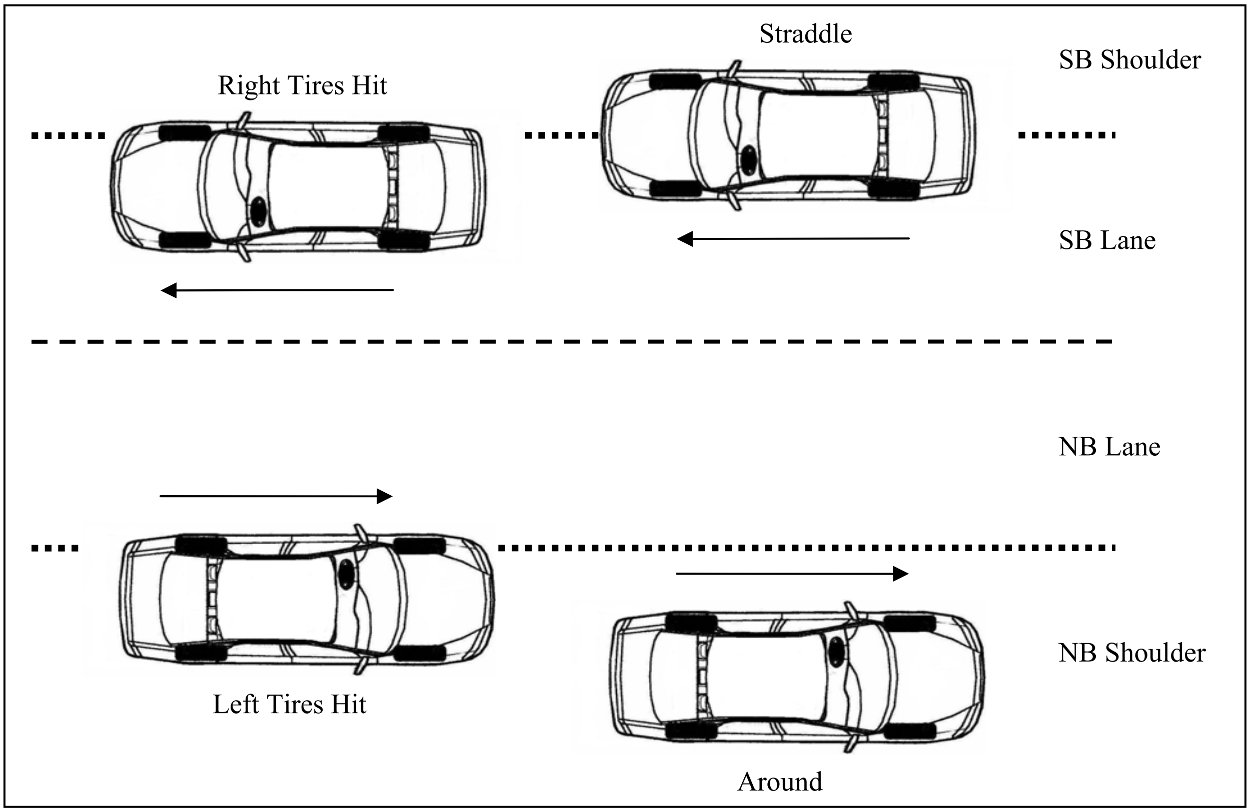


Figure 66. Position Categories for Shoulder Encroachment Maneuvers.

FINDINGS

This section presents the results of the data analysis with respect to shoulder encroachment volume and lateral position. The data are classified by time and travel direction. Encroachments that occurred during the collection of video data are further classified by maneuver type, as the causes of these maneuvers could be verified by the footage.

Shoulder Encroachment Volume

The general trend in the data was a 46.7-percent reduction in shoulder encroachment, as shown in Table 35. This reduction should increase the life span of the marked edgeline stripe because the rumble strips minimize the amount of tire contact with the stripe. The total number of encroachments decreased in the after case, and it is reasonable to assume that the edgeline rumble strips would also reduce the amount of time that drivers keep their tires positioned on the edgeline.

Table 35. Shoulder Encroachment Volumes.

Period	Count	% of ADT	% Change
Before	1923	18.2	-46.7
After	1062	9.7	

Table 36 provides the encroachment maneuver volumes (in % of ADT) during the before and after periods, grouped by time and travel direction. All of the data groups showed a decrease in encroachment volume, and all of the decreases were statistically significant except for the case of weekday night traffic in the northbound direction.

These data also show that shoulder encroachments occurred more often during the day than at night, and more often during weekdays than during weekends. This temporal variation is expected because traffic volumes are higher during the day and during weekdays. Shoulder usage is likely to increase with higher volumes for two reasons:

- a larger number of platoons will form as fast drivers catch up with slower drivers and desire to pass them, and
- the probability of turning conflicts increases.

A left-turning conflict occurs when a driver making a left turn is forced to slow down or stop, to allow a conflicting vehicle in the opposing through lane to clear the intersection. A right-turning conflict occurs when a driver making a right turn is compelled to pull onto the shoulder because a faster-moving through vehicle is approaching from behind. Through- and turning-vehicle arrivals at the project site were random, so the occurrence of turning conflicts was also random, but more likely with higher volumes. See Figure 67 for an illustration of turning conflicts and resulting shoulder encroachment maneuvers.

Table 36. Encroachment Maneuver Volumes.

Travel Direction	WD/WE	Time	Period	Maneuver Count	% of ADT	% Change	Significance
NB	WD	Day	Before	578	5.5	-45.5*	6.73
			After	315	2.9		
		Night	Before	79	0.7	-32.9	1.75
			After	53	0.5		
	WE	Day	Before	213	2.0	-26.8*	2.35
			After	156	1.4		
		Night	Before	62	0.6	-41.9*	1.98
			After	36	0.3		
SB	WD	Day	Before	516	4.9	-44.0*	6.15
			After	289	2.6		
		Night	Before	91	0.9	-51.6*	3.02
			After	44	0.4		
	WE	Day	Before	270	2.5	-49.6*	5.01
			After	136	1.2		
		Night	Before	114	1.1	-71.1*	4.88
			After	33	0.3		

* Indicates statistically significant at 95 percent level of confidence ($t \geq 1.96$).

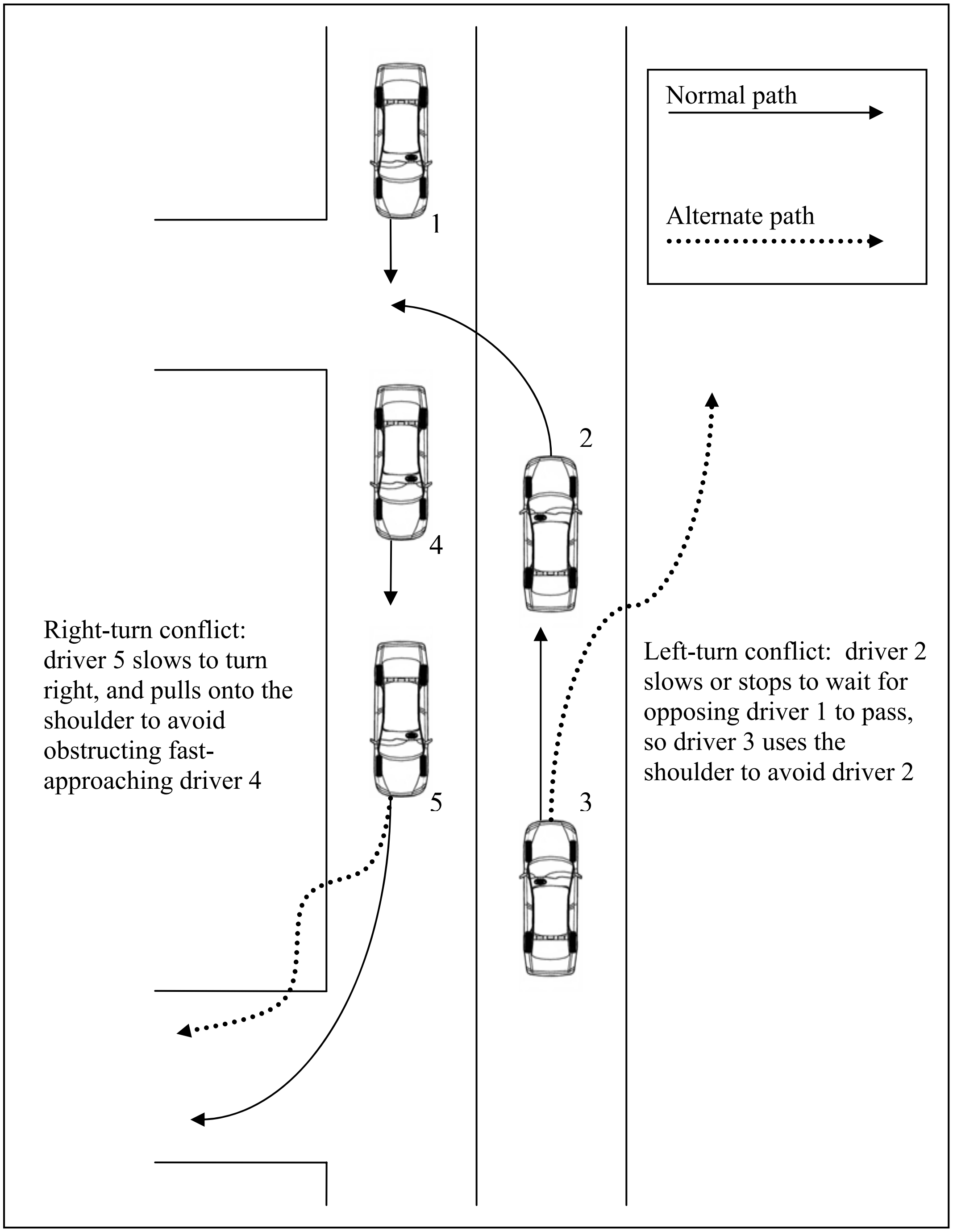


Figure 67. Turning Conflicts.

A total of 1094 video-verified shoulder encroachments were observed in the before period, and 787 in the after period. Figure 68 shows the counts and proportions of each maneuver classification in the before and after cases. Decreases were observed in all four classifications, but the largest proportional decrease was in the “other” case, which includes presumably accidental contact with the edgeline due to driver inattention.

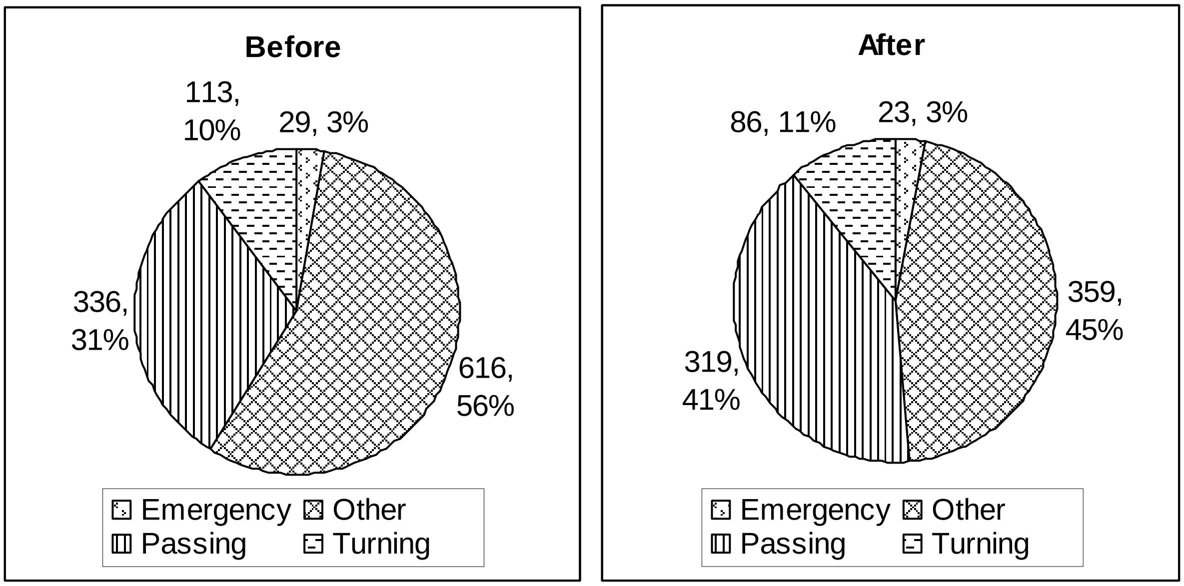


Figure 68. Maneuver Classification Counts and Proportions, Before and After.

Table 37 shows the observed encroachment volumes for emergency and turning maneuvers. There was an observed decrease of 23.5 percent in emergency shoulder encroachments, but this percentage is calculated from numbers that were originally small (29 encroachments before vs. 23 encroachments after). This small decrease can probably be attributed to changes in random events like the number of emergency vehicle arrivals or the number of vehicular breakdowns that occurred during the two study periods (before and after), not the influence of the rumble strips on driver behavior. Furthermore, drivers are highly unlikely to avoid pulling onto the shoulder if the encroachment is part of an evasive maneuver. In drivers' minds, avoiding a crash would certainly take precedence over avoiding brief annoyance experienced when crossing over rumble strips.

Table 37. Shoulder Encroachment Volumes for Emergency and Turning Maneuvers.

Maneuver Classification	Period	Count	% of ADT	% Change	Significance
Emergency	Before	29	0.3	-23.5	0.96
	After	23	0.2		
Turning	Before	113	1.1	-26.6*	2.18
	After	86	0.8		

* Indicates statistically significant at 95 percent level of confidence ($t \geq 1.96$).

The observed 26.6 percent decrease in turning encroachment volumes might be a concern, as the capacity of a road would decrease if turning vehicles blocked the travel lane for longer periods of time, and other drivers chose to wait instead of going around turning vehicles. However, the project site was a two-lane rural road segment with random through-vehicle and turning-vehicle arrivals and random turn-conflict frequencies. The decrease in turning maneuver encroachment volumes might have been caused by a commensurate decrease in turn-conflict frequencies, not the influence of ERSs on driver behavior.

Table 38 shows the observed encroachment volumes for "other" maneuvers, stratified by travel direction and vehicle type. Decreases in encroachment volume were observed for all cases, but the only statistically significant changes occurred in the "other" category in both travel directions for two-axle vehicles and the overall traffic mix. The largest changes were observed in the overall "other" category (-45.0 percent NB and -41.5 percent SB), with much of the change attributed to two-axle vehicles (-59.0 percent NB and -51.8 percent SB) and only modest change attributed to vehicles with three or more axles (-14.4 percent NB and -18.2 percent SB, neither of which was statistically significant). When compared with the overall proportions shown in Figure 68, the results in Table 38 show that the ERSs were particularly effective in reducing "other" maneuvers by two-axle vehicles (including passenger vehicles); this reduction was proportionally the largest.

Table 38. Shoulder Encroachment Volumes for Other Maneuvers.

Travel Direction	Vehicle Type	Period	Count	% of ADT	% Change	Significance
NB	All	Before	400	3.8	-45.0*	5.24
		After	228	2.1		
	2 Axles	Before	275	2.6	-59.0*	5.95
		After	117	1.1		
	3+ Axles	Before	125	1.2	-14.4	0.84
		After	111	1.0		
SB	All	Before	216	2.0	-41.5*	3.50
		After	131	1.2		
	2 Axles	Before	150	1.4	-51.8*	3.75
		After	75	0.7		
	3+ Axles	Before	66	0.6	-18.2	0.79
		After	56	0.5		

* Indicates statistically significant at 95 percent level of confidence ($t \geq 1.96$).

Table 39 shows the observed encroachment volumes for passing maneuvers, stratified by travel direction and vehicle type. The overall change in passing maneuver encroachment volumes is modest (-12.7 percent NB and -2.9 percent SB, neither of which was statistically significant), so the effect of ERSs on such maneuvers is neutral. In other words, the installation of ERSs did not discourage drivers to pull onto the shoulder to allow faster vehicles to pass. The number of three-axle vehicles executing such maneuvers actually increased by 44.6 percent NB and 1.8 percent SB, but it is unknown why this change occurred. The bulk of the increase occurred in the northbound direction, suggesting that the increase is artificially high, and perhaps attributable to a rare event like the passing of a large convoy of slow trucks. It is worth noting that this 44.6-percent increase was calculated from small numbers (32 encroachments before vs. 48 encroachments after), and when the number of passing encroachments by two-axle vehicles (1.1 percent of ADT after) is compared to the number by vehicles with three or more axles (0.4 percent of ADT after), it can be seen that passing encroachments are far more often executed by two-axle vehicles.

Table 39. Shoulder Encroachment Volumes for Passing Maneuvers.

Travel Direction	Vehicle Type	Period	Count	% of ADT	% Change	Significance
NB	All	Before	190	1.8	-12.7	0.92
		After	172	1.6		
	2 Axles	Before	158	1.5	-24.3	1.65
		After	124	1.1		
	3+ Axles	Before	32	0.3	44.6	-1.14
		After	48	0.4		
SB	All	Before	146	1.4	-2.9	0.18
		After	147	1.3		
	2 Axles	Before	110	1.0	-4.5	0.24
		After	109	1.0		
	3+ Axles	Before	36	0.3	1.8	-0.05
		After	38	0.3		

* Indicates statistically significant at 95 percent level of confidence (t ≥ 1.96). No significant changes were observed.

Lateral Position

The video-verified encroachment maneuvers were further analyzed to identify any changes in the lateral positions of vehicles during shoulder usage. Lateral position was defined as distance away from the paved edge of the shoulder, with a position of zero on the paved edge and the maximum position (an average value of 9 feet) on the left edge of the marked edgeline. With few exceptions, the general trend was a decrease in mean lateral position, corresponding to positions farther onto the shoulder. Large standard deviations were also observed in all cases, showing a high level of variability. The following three tables summarize these trends.

Emergency and Turning Maneuvers

Table 40 shows the lateral position calculations for emergency and turning maneuvers. Both changes were small, and neither was statistically significant.

Table 40. Lateral Position Calculations for Emergency and Turning Maneuvers.

Maneuver Classification	Period	Count	Mean Lateral Position (inches)	Standard Deviation (inches)	Change (inches)	Significance
Emergency	Before	29	69.4	34.1	-4.3	0.47
	After	23	65.2	31.3		
Turning	Before	113	47.6	29.2	1.9	-0.43
	After	86	49.5	32.1		

* Indicates statistically significant at 95percent level of confidence (t ≥ 1.96). No significant changes were observed.

Other Maneuvers

Table 41 shows the lateral position calculations for “other” maneuvers, stratified by travel direction and vehicle type. In every case, there was a statistically significant decrease in mean lateral position. The largest decreases were observed for two-axle vehicles (-15.1 inches NB and -18.5 inches SB).

Figure 69 shows the cumulative distribution of lateral positions for all “other” encroachments observed. The origin of the x-axis is defined as the right (outermost) paved edge of the shoulder. Assuming a shoulder width of 9 feet (the actual shoulder width at the project site varied by as much as 7 inches), the vertical dotted lines represent the location of the ERSs. The curves on the graph represent the location of the right edge of the encroaching vehicle’s right front tire as it passes over the diagonal roadtube. Lateral position measurements greater than 108 inches shown in the graph represent observations that occurred where the shoulder width exceeded nine feet.

Table 41. Lateral Position Calculations for Other Maneuvers.

Travel Direction	Vehicle Type	Period	Count	Mean Lateral Position (inches)	Standard Deviation (inches)	Change (inches)	Significance
NB	All	Before	400	94.4	19.9	-10.6*	4.93
		After	228	83.8	28.9		
	2 Axles	Before	275	92.6	20.2	-15.1*	4.70
		After	117	77.5	32.1		
	3+ Axles	Before	125	98.5	18.6	-8.0*	2.90
		After	111	90.4	23.4		
SB	All	Before	216	82.0	32.1	-14.6*	3.89
		After	131	67.4	35.1		
	2 Axles	Before	150	77.2	34.1	-18.5*	3.84
		After	75	58.7	34.0		
	3+ Axles	Before	66	92.9	24.0	-13.9*	2.60
		After	56	79.0	33.3		

* Statistically significant at 95 percent level of confidence (t ≥ 1.96).

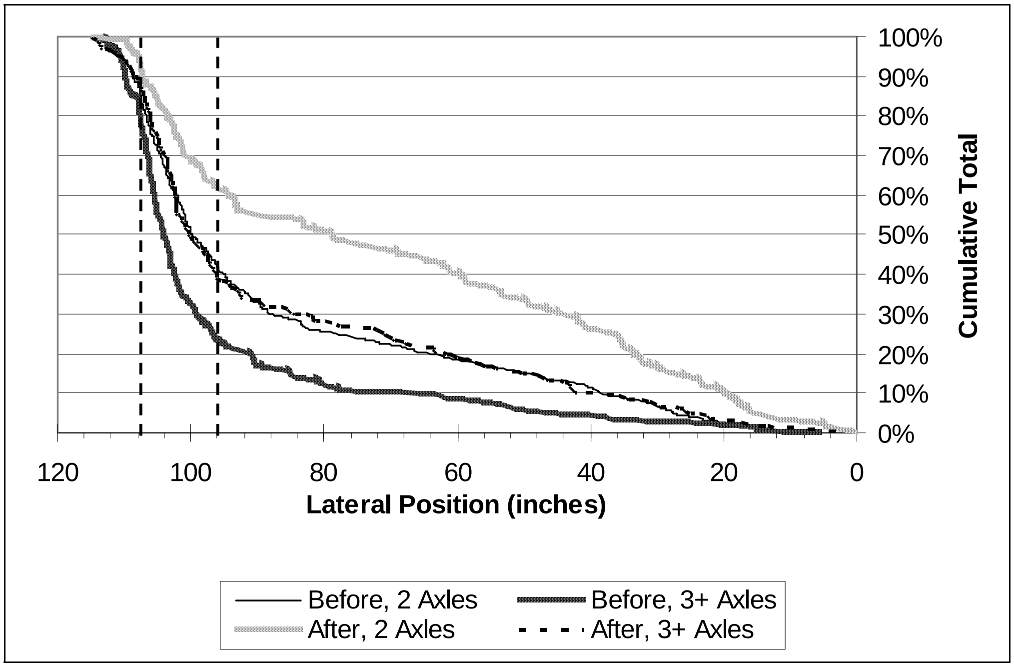


Figure 69. Lateral Position Cumulative Distribution for Other Maneuvers.

The lateral position data graphed in Figure 69 can provide insight into vehicle positions during "other" maneuvers if the following dimensions are assumed:

- tread base (distance from left edge of left tire to right edge of right tire) for two-axle vehicles = 6 feet,
- tread base for vehicles with three or more axles = 8 feet, and
- tire width for all vehicles = 8 inches.

These dimensions are based on recommendations for design vehicle dimensions in Chapter 2 of the *Green Book* (*31*). Table 42 provides the counts of position categories for all of the "other" maneuvers observed during the after study period. The largest total decreases occurred in encroachments when only the right tires contacted the rumble strips, which are relatively minor encroachments likely caused by natural lane shifting or slight driver inattention. Straddling maneuvers decreased for two-axle vehicles but increased for vehicles with three or more axles. One possible explanation for the moderate increase in straddling maneuvers for vehicles with three or more axles is the fact that vehicles with wide loads or swaying trailers are more difficult to position precisely in the middle of a travel lane, and drivers of such vehicles might have chosen to straddle the rumble strips intentionally. Changes for the other two position categories ("left tires hit" and "around") were relatively minor.

Table 42. Position Category Counts for Other Maneuvers.

Position Category	Period	2 Axles			3+ Axles		
		Count	% of ADT	% Change	Count	% of ADT	% Change
Right Tires Hit	Before	298	2.8	-71.8	160	1.5	-31.3
	After	87	0.8		114	1.0	
Straddle	Before	72	0.7	-35.7	27	0.3	71.4
	After	48	0.4		48	0.4	
Left Tires Hit	Before	39	0.4	-23.4	4	0.0	20.5
	After	31	0.3		5	0.0	
Around	Before	16	0.2	56.7	N/A		
	After	26	0.2				

The calculations in Table 42 show that the ERSs did not, in fact, cause more drivers to shift farther onto the shoulder. The apparent rightward shifts shown in Figure 69 are caused by the fact that the rumble strips were most effective in reducing the number of "other" encroachments when only vehicles' right tires contacted the strips, while they were comparatively less effective in reducing the volume of encroachments farther onto the shoulder.

Passing Maneuvers

Table 43 shows the lateral position calculations for passing maneuvers, stratified by travel direction and vehicle type. In every case except southbound two-axle vehicles, there was a decrease of mean lateral position. However, only two of the changes (NB all vehicles and NB two-axle vehicles) are statistically significant. These two shifts were -6.2 inches and -7.3 inches, respectively, which represent less than one tire width.

Table 43. Lateral Position Calculations for Passing Maneuvers.

Travel Direction	Vehicle Type	Period	Count	Mean Lateral Position (inches)	Standard Deviation (inches)	Change (inches)	Significance
NB	All	Before	190	53.6	25.0	-6.2*	2.27
		After	172	47.4	26.8		
	2 Axles	Before	158	53.7	25.9	-7.3*	2.33
		After	124	46.4	26.2		
	3+ Axles	Before	32	53.0	20.8	-3.1	0.57
		After	48	49.9	28.5		
SB	All	Before	146	46.5	22.9	-2.1	0.70
		After	147	44.4	27.7		
	2 Axles	Before	110	42.6	20.3	0.4	-0.12
		After	109	43.0	28.3		
	3+ Axles	Before	36	58.3	26.4	-9.8	1.62
		After	38	48.5	25.7		

*Indicates statistically significant at 95 percent level of confidence (t ≥ 1.96).

Figure 70 shows the cumulative distribution of lateral positions for all passing encroachments observed, with the location of the rumble strips illustrated by the vertical dotted lines. The rightward shift in this graph is less pronounced than the shift in Figure 69, as the mean lateral position changes were smaller than the changes for “other” maneuvers.

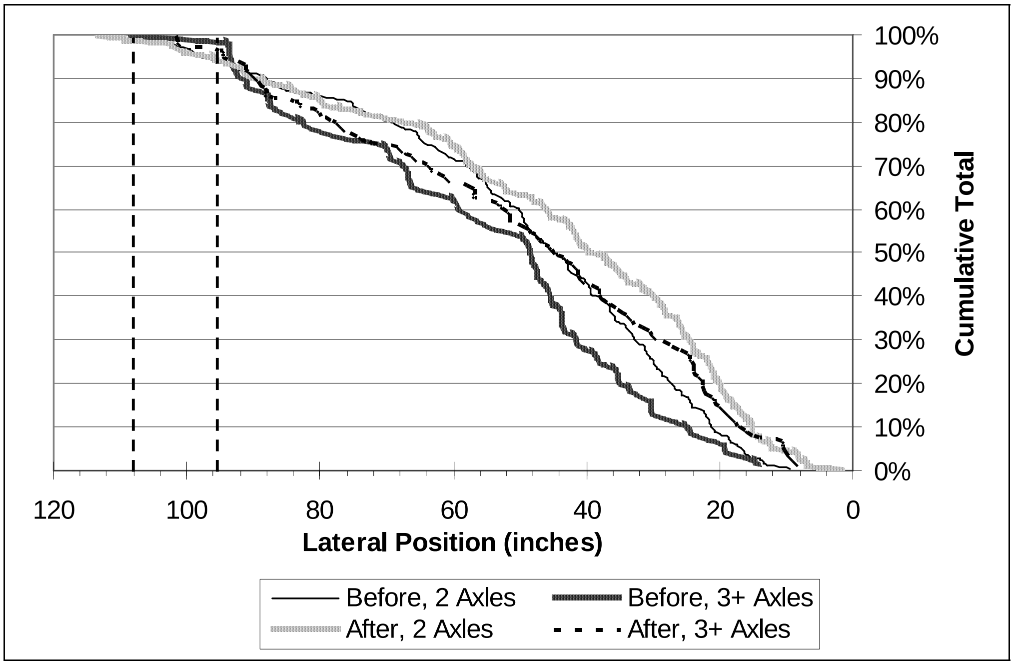


Figure 70. Lateral Position Cumulative Distribution for Passing Maneuvers.

Table 44 shows further analysis of the passing maneuvers grouped by position category. For the two-axle vehicles, there were slight decreases in the counts for "straddle" and "left tires hit" positions, and a moderate increase for the "around" position. In the case of passing maneuvers, drivers intentionally pull onto the shoulder, and all drivers executing such maneuvers will pass over the ERSs. In the before study period, 75.0 percent of drivers in two-axle vehicles either straddled the edgeline or positioned their vehicles such that the left tires were passing along the marked edgeline. Drivers executing such maneuvers typically intend to pull far enough to the right to help a faster vehicle pass, but not necessarily completely onto the shoulder. In the after study period, drivers executing the same maneuvers chose to pull completely onto the shoulder (into the "around" position category) to minimize the annoyance of passing over the rumble strips. This is demonstrated by the increase in the count and frequency of "around" maneuvers in the after study period.

Table 44 shows increases in counts for all three position categories applicable to vehicles with three or more axles. This is consistent with the volumes reported in Table 39. These observations are likely biased because of the seemingly anomalous 44.6 percent increase in passing maneuvers by vehicles with three or more axles in the northbound direction. In addition, a 9-ft shoulder is not wide enough to allow vehicles with three or more axles to encroach in the "around" position, leaving "straddle" as the most likely position for passing maneuvers. Table 44 shows that "straddle" was the most common position before and after installation of the rumble strips, though the frequency of the "straddle" maneuver did decrease slightly. Thus, based on the data collected in this experiment, the effect of ERSs on passing maneuvers by vehicles with three or more axles is neutral.

Table 44. Position Category Volumes for Passing Maneuvers.

Position Category	Period	2 Axles			3+ Axles		
		Count	% of ADT	% Change	Count	% of ADT	% Change
Right Tires Hit	Before	28	0.3	-10.5	10	0.1	6.1
	After	26	0.2		11	0.1	
Straddle	Before	109	1.0	-36.3	54	0.5	12.5
	After	72	0.7		63	0.6	
Left Tires Hit	Before	92	0.9	-24.5	4	0.0	189.3
	After	72	0.7		12	0.1	
Around	Before	39	0.4	55.8	N/A		
	After	63	0.6				

CHAPTER 5

SUMMARY AND RECOMMENDATIONS

This report documents the research conducted by TTI to investigate various types of rumble strips and their impact on drivers along Texas rural highways. Rumble strips are roadway treatments that consist of raised or depressed sections that induce aural and vibratory sensations when tires cross over them. The research efforts consisted of the following general tasks:

- state-of-the-art review (completed in the year 1 report);
- benefit to cost analysis (completed in the year 1 report),
    - centerline rumble strips,
    - edgeline rumble strips (a form of shoulder rumble strips);
- field evaluation,
    - TRSs,
    - CRSs,
    - ERSs;
- generate TxDOT recommendations,
    - design and
    - implementation.

SUMMARY

Transverse Rumble Strips

In this portion of the project, field measured vehicle speeds were used to investigate the impact of TRSs on driver behavior at approaches to rural stop-controlled intersections and horizontal curves. Researchers used the measured speeds to determine the deceleration patterns at each project site. A more uniform deceleration pattern would indicate that drivers had been more adequately alerted to upcoming decision points. The outcomes of previous research have produced varied results. Previous research has reported a statistically significant reduction in speed; however, the reduction in speed has been of the magnitude of 2 to 5 mph, which may not be practically significant.

To accomplish this objective, nine approaches to rural stop-controlled intersections and five approaches to rural horizontal curves were evaluated. Researchers hypothesized that the TRSs would prompt a change in traffic speeds. Speed data were collected and analyzed to evaluate the effectiveness of TRSs on driver behavior and traffic operations.

At stop-controlled intersections, the installation of TRSs produced mostly small changes in traffic operations. Table 45 contains the findings for the stop-controlled intersection project sites. There were some negative driver behavioral impacts (i.e., speed increases) that occurred after the installation of TRSs; however, erratic maneuvers did not occur at either of the project sites selected to investigate such issues, and very few smooth shifting maneuvers were observed.

Table 45. Findings for Stop-Controlled Intersection Sites.

Site	Finding	Beneficial Impact?
Bosque County (FM 3118)	• Approach speeds reduced slightly (less than 1 mph) in most cases • Approach speeds evaluated at night yielded an increase in speed • No significant effect on speed change parameter	No
Snook (FM 50 SB Turning)	• Nighttime and weekend data yielded significant differences (2 – 8 mph) in speed change parameter • Inconsistent effects on approach speeds • No erratic maneuvers; few shifting maneuvers	Marginal
Snook (FM 50 SB Highway)	• Speed change parameter increased slightly (0.6 – 1 mph) • Slight (1 – 2 mph) increases in approach speeds • No erratic maneuvers; few shifting maneuvers	No
Snook (FM 50 NB)	• Inconsistent effect on speed change parameter • Small (less than 1 mph) speed changes yielded significant differences • Approach speeds reduced in all cases • Most speed reductions were reported to be significantly different at a 2 – 3 mph change	Marginal
Colorado City (FM 208 SB)	• No significant differences in speed change parameter • Approach speeds were significantly reduced • Approach speeds reduced from 2 – 5 mph	Yes
Colorado City (FM 208 NB)	• Speed change parameter significantly reduced • Speed change differences were reduced by 2 – 3 mph • Intersection spot speeds increased • Warning sign spot speeds decreased slightly	Marginal
Millican (FM 2154 SB)	• Slight decrease in speed change parameters • Approach speeds increased	No
Millican (FM 2154 NB)	• Inconsistent effects on both speed change and approach speeds • Small (1 mph) changes in both speed change and approach speed parameters	No
Hearne (FM 2549 NB)	• No significant differences in speed change or approach speed parameters • Approach speeds were reduced slightly (less than 1 mph)	No
Hearne (FM 2549 SB)	• Inconsistent effect on speed change parameter • Approach speeds were reduced • No erratic maneuvers; few shifting maneuvers • Approach speeds had significant reductions at 2 – 4 mph	Marginal

Similar results were documented for the horizontal curve sites. Only small changes in traffic operations were observed, such as increases in control speed. Table 46 contains the findings for the horizontal curve project sites.

Table 46. Findings for Horizontal Curve Sites.

Site	Primary Finding	Beneficial Impact?
Steephollow (FM 1179)	• Speed changes significantly (p = 0.05) increased in after case • Spot speeds at warning sign were higher in after case • Slight (1 – 2 mph) decrease in spot speeds near curve	No
Navasota I (FM 3090)	• Statistically significant reductions in speed change (9 – 11 mph) • Spot speeds at warning sign were significantly reduced (6 – 8 mph) • Spot speeds near curve increased	Marginal
Navasota II (FM 3090)	• No significant differences in speed change parameter • No significant differences in approach speeds • Approach speed reductions were less than 2 mph	No
Keith (FM 244)	• Slight (less than 1 mph) differences in speed change • Significant reductions in spot speeds at warning sign • Significant reductions in spot speeds near curve	Yes
Bremond (FM 46)	• Slight (less than 1 mph) difference in speed change • Slight (1 – 2 mph) reductions in spot speeds at warning sign and near curve	No

The general findings were:

- For most of the sites analyzed, the installation of TRSs did not significantly affect the speed change between the warning sign speed trap and intersection speed trap. Of the sites that recorded statistically significant reductions in speed changes, only three sites showed reductions larger than 1 mph. However, the overall trend was small reductions in speed change between the warning sign and intersection speed collection points.
- While statistically significant changes of 2-3 mph in approach speeds were recorded, previous research suggests a reduction of 4 mph is required to be practically significant (*1*). Thus, TRSs did not seem to be successful at reducing approach speeds at the project sites.
- At the two sites where data were collected to determine the prevalence of erratic maneuvers (Snook [FM 50] and Hearne [FM 2549]), no sudden braking, hard braking, or swerving occurred, and all shifting maneuvers were smooth. Thus, the installation of transverse rumble strips did not appear to induce erratic maneuvers.
- Transverse rumble strips are a low-cost treatment and easy to install.

Centerline Rumble Strips

The purpose of this portion of the project was to ascertain how drivers respond to the installation of centerline rumble strips. CRSs were installed along five rural undivided highways. Three designs were used and seven MOEs were investigated. The first six MOEs focused on driver reaction to contacting CRSs during passing operations, and the last MOE focused on whether CRSs affected lateral position of drivers.

Video data were collected using two different data collection methods. In order to investigate how drivers react to contacting CRSs during passing operations, a mobile data collection system was developed and referred to as the data recording vehicle. The DRV collected data that allowed for the analysis of:

- erratic movements,
- number of encroachments prior to passing,
- gap distance prior to passing,
- centerline crossing time during the initial phase of passing,
- passing opportunity, and
- percentage of passing.

There was one project site to investigate the impact of CRSs on passing operations. One design of CRSs was milled continuously in no-passing and passing zones along the marked centerline of US 67, a rural, two-lane, two-way (RTLTW) highway between the cities of Comanche and Dublin in north-central Texas.

Data were also collected to investigate whether CRSs impacted vehicle placement. These data were collected with a TTI video trailer. There were two sites for each roadway studied. The roadways were FM 195, FM 969, FM 1431, and FM 2222.

There were two raised CRS designs evaluated with regard to their impact on vehicle placement. One design used yellow pavement buttons placed adjacent to the outside edges of the centerline markings. The other design consisted of black pavement buttons staggered along the inside edges of the centerline markings.

Passing Operations

- The number of centerline encroachments by a passing vehicle prior to starting a pass did not significantly increase after the installation of CRSs.
- There were not enough data with respect to time between centerline encroachments to analyze if there was a change after the installation of CRSs.
- Gap distance decreased significantly for drivers passing the DRV traveling at 55 mph after the installation of CRSs, but not when the DRV traveled at 60 and 65 mph.
- Gap distance, irrespective of the speed of the DRV, decreased after the installation of CRSs.
- Centerline crossing time increased significantly for drivers passing the DRV traveling at 55 mph after the installation of CRSs, but not when the DRV traveled at 60 and 65 mph.
- Centerline crossing time, irrespective of the speed of the DRV, increased significantly after the installation of CRSs.
- Passing opportunity did not change significantly with the installation of CRSs.
- The percentage of vehicles that pass did not change significantly with the installation of CRSs.

Lateral Position

- Frequency of inadvertent contact with the centerline decreased with the installation of CRSs.
- Yellow pavement buttons placed in the travel lanes adjacent to the outside edge of the centerline markings appeared to have a greater impact on lateral position than staggered black pavement buttons.
- The majority of drivers shifted their vehicles' lateral position farther from the centerline pavement markings after the installation of raised CRSs consisting of pavement buttons.

Overall

- No erratic movements were recorded either before or after the installation of CRSs.
- None of the changes in any of the MOEs were considered to be increases or decreases of a magnitude that merited a practical change in driving characteristics.
- None of the changes in any of the MOEs were considered either to affect the driving environment adversely or to induce unsafe driving practices.

Edgeline Rumble Strips

Milled ERSs were installed at one site in Texas for investigation of their impact on drivers' shoulder usage. Data were collected using a video trailer and roadtubes. The roadtubes were used to observe lateral position of vehicles that encroached on the shoulders, and video data allowed the researchers to ascertain the purpose of encroachment. Shoulder usage was categorized into one of the following four types:

- Emergency – encroaching to allow emergency vehicles to pass, to avoid a collision, or stopping on the shoulder.
- Turning – vehicles encroaching to pass left-turning vehicles on the right, decelerating to turn off the highway, or accelerating up to speed from a stop.
- Passing – vehicles encroaching to allow queued vehicles behind them a better opportunity to pass with more improved sight distance and a decrease in the need for encroaching on the opposing lane of travel.
- Other – vehicles inadvertently contacting with the shoulder due to poor lateral position, intentionally encroaching on the shoulder due to a driver's desire to place more distance between their vehicle and oncoming vehicles (i.e., drivers of vehicles with wide loads, such as manufactured homes), or intentional encroachment of the shoulder by a driver who wishes to drive below the speed limit.

ERSs appeared to have a positive impact on driver lane keeping. The least desirable types of shoulder encroachments were categorized as "other," and they were reduced significantly. Furthermore, no erratic maneuvers were observed. The general findings are bulleted below.

- Shoulder encroachment decreased by almost 50 percent.
- Reductions were recorded regardless of direction, period of the week, or period of the day.

- A statistically significant reduction in "other" traffic was recorded, which includes inadvertent contact with the edgeline caused by natural lane shifting, wide loads, swaying trailers, and driver inattention.
- "Other" drivers shifted 8 to 18.5 inches farther onto the shoulder, and this change was statistically significant for the following reasons:
    - it resulted from the largest reduction in number of encroachments coming from vehicles that only crossed over the edgeline by a few inches (theoretically a decrease in the number of inadvertent encroachments from inattentive drivers),
    - 72 percent reduction for two-axle vehicles,
    - 31 percent reduction for three or more axle vehicles, and
    - 71 percent increase in the three or more axle vehicles that straddle the edgeline, possibly because the drivers of vehicles with wide loads or swaying trailers wished to avoid constant contact with the ERSs and could not keep their vehicles positioned entirely within the lane.
- "Passing" drivers in two-axle vehicles were more likely to pull completely onto the shoulder when allowing a vehicle to pass (56 percent increase) after the ERSs were installed.

RECOMMENDATIONS

Transverse Rumble Strips

Although the data do not support consistent reductions in speed, the data also do not indicate that TRSs cause any need for concern. Furthermore, previous research does support reductions in crashes (*11*). Subsequently, the researchers recommend limited use until at least the first item below is complete:

- conducting crash studies for the project sites,
- studying additional sites for the purpose of comparison with previous studies,
- studying stop compliance at stop-controlled intersections, and
- monitoring long-term maintenance.

Centerline Rumble Strips

There are no findings from the research described in this report to suggest that CRSs negatively impact roadway operations at any of the project sites, and the researchers believe that there is no evidence to recommend removing any of the CRS treatments. Additional recommendations include:

- Survey states that have installed CRSs to document specifically why and where CRSs are installed, and why or where CRSs were not installed in passing zones.
- Analyze available crash data from RTLTW highways with CRSs to continue to document the benefits of CRSs.
- Analyze the various MOEs available to investigate changes in driver behavior associated with safety improvements from the installation of CRSs, in particular, a validation of the MOEs used in this report.
- Conduct an additional research project similar to the one documented in this report of at least three more similar sites that have CRSs installed.

- Conduct a simulator project that focuses specifically on passing behavior.
- Investigate the effects of raised and milled CRSs on lateral position on other rural undivided highways at multiple sites that have varying shoulder widths and lane configurations such as two-lane, three-lane, and four-lane.
- Investigate lateral position interactions along rural undivided highways with CRSs and ERSs or CRSs and shoulder rumble strips.
- Investigate additional benefits of CRSs, such as improvements in:
    - wet-night visibility;
    - nighttime visibility versus reflectorized raised pavement markings and reflectorized, recessed raised pavement markings (i.e., plowable raised pavement markings); and
    - pavement marking life cycle and retroreflectivity with respect to placement over milled rumble strips.

Edgeline Rumble Strips

Based on the findings above, the researchers have no reason to recommend the removal of ERSs along SH 6 between Hearne and Calvert. The researchers have the following recommendations.

- Conduct additional evaluations of ERSs at similar locations to verify whether these findings are unique to SH 6 or consistent with the treatment.
- Investigate whether there is an interaction between shoulder usage and vehicular lateral position along roadways with ERSs as a factor of shoulder width.
- Investigate additional benefits of ERSs, such as:
    - improvements in wet-night visibility,
    - improvements in nighttime visibility, and
    - improvements in pavement marking life cycle and retroreflectivity with respect to placement over milled rumble strips.

Other Recommendations

Previous research (*21*) has raised the question whether drivers would be confused when inadvertently contacting CRSs or SRSs (ERSs are a form of SRSs). Subsequently, it is recommended that CRSs have a set spacing that is different from the spacing of ERSs to minimize the confusion. Appendix C contains a preliminary CRS and ERS design for review by TxDOT, and Appendix D contains a basic safety analysis of rumble strips.

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APPENDIX A

DATA COLLECTION METHODS

Tracking of individual vehicle speeds through a given site was accomplished by the use of a series of portable automated vehicle classifiers. Portable automated vehicle classifiers are commonly used by transportation agencies nationwide and allow for a large sample size to be collected. These devices are placed on the roadside and connected to a pair of sensors (pneumatic sensors, roadtubes in this case) that are affixed to the pavement surface. The device recorded information for each axle that traversed over the sensors. The device was then able to compute desired information about each vehicle.

Speeds of individual vehicles were tracked by the automated vehicle classifiers by placing a number of devices in succession at specific locations throughout the project site. The classifiers and roadtubes were placed at three locations: a control location, at the warning sign, and near the intersection or curve. Time clocks were synchronized for all devices. Individual vehicles were later tracked during the data reduction phase by tracking time stamps and classifications among successive counters.

Another option for the data collection equipment was light detecting and ranging (LIDAR) devices. LIDAR devices measure speed and range of a moving object by sending out hundreds of invisible infrared laser light pulses per second. The laser beams are reflected off the object and directed back to the device. Internal algorithms are then used to derive the speed of the moving object from a successive number of range calculations.

Due to the low traffic volume that was expected at each of the project locations, the automated vehicle classifiers were used. The classifiers were able to minimize the amount of person-hours required at the sites to collect a sufficient sample size and were durable enough to remain in the field during the study periods. A LIDAR device was used to ensure that the setup of the roadtubes was done correctly and that accurate speeds were recorded by the automated vehicle classifiers.

The accuracy of roadtubes as well as other portable speed measurement devices (including LIDAR) has been proven in determining the speed of traveling vehicles. In a study by the Texas Transportation Institute (TTI), the accuracy and precision of five portable speed measurement systems were evaluated in a controlled field evaluation. The researchers found that there was little difference (less than 1.5 mph) in the speed measurement systems. It was also found that all devices were accurate and that speed measurement equipment should be selected to suit the characteristics of a given data collection situation (*39*). A comparison of the advantages and disadvantages of automated vehicle classifiers versus LIDAR is shown in Table 47 (*39*).

Table 47. Advantages and Disadvantages of LIDAR versus Automated Vehicle Classifiers.

	LIDAR	**Automated Vehicle Classifiers**
Advantages	• Accurate, precise, and reliable • Small and lightweight • Simple to use and requires very little training • Greater level of worker safety • Data collector has supervision over measurements, improving reliability • Vehicles may easily be tracked through a site • Very little data reduction	• Accurate, precise, but somewhat less reliable • Large sample sizes are obtained with less effort • Few person-hours are necessary for data collection • Speeds are measured at a precise location for each vehicle • Vehicle/traffic characteristics other than speed may be measured
Disadvantages	• Cosine bias if equipment is offset from vehicle path, such as at curves • Many person-hours needed for large sample size • Difficult to measure speed at a precise location on the roadway • Potential data bias if data collector is visible to drivers • Potential data bias if high percentage of radar/laser detector use by the motoring public	• Equipment failures occasionally occur • Lower level of worker safety • Equipment may be challenging to use • Traffic control required to place/remove equipment • Equipment vandalism • Anomalous vehicles are difficult to determine due to lack of supervision • Potential data bias if sensors are visible to drivers

SITE CHARACTERISTICS

Table 48. Transverse Rumble Strip Site Characteristics.

Location	Number of Observations	85th Percentile Speed (mph)	Standard Deviation (mph)	Mean Speed (mph)	Minimum Speed (mph)	Maximum Speed (mph)	Variance
FM 3118	2616	61	6.9	53.8	8	76	48.2
FM 50	1174	72	17.7	53.9	21	97	314.2
FM 208	3717	76	7.4	69.6	34	109	54.3
FM 2154	1028	60	7.4	53.0	25	83	53.9
FM 2549	561	62	7.3	54.8	30	75	53.1
FM 1179	1093	73	6.3	66.8	36	87	39.6
FM 3090	1941	73	7.4	65.8	33	105	54.2
FM 244	1071	72	9.4	63.3	25	104	89.1
FM 46	871	70	10.3	59.6	18	87	105.9

STATISTICAL ANALYSIS TABLES

Table 49 through Table 102 contain all of the tabulated findings for the TRS project sites.

Table 49. Bosque County (FM 3118) Change in Speed Results.

Light Condition/Period	Overall Sample Size	Control Speed (mph)	Speed Change from Warning to Intersection Speed Trap (mph)			
			Before	After	Δ	Significance
Day	1859	55	12.246	12.181	-0.065	0.714
		70	17.388	17.802	0.414	0.355
Night	261	55	12.839	12.084	-0.755	0.105
		70	16.084	17.422	1.338	0.201

* Indicates statistically significant at 95 percent level of confidence. None of the values were statistically significant.

Table 50. Bosque County (FM 3118) Comparison of Change in Speed for Speeding Vehicles.

Light Condition/Period	Overall Sample Size	Speed Change from Warning to Intersection Speed Trap (mph)			
		Before	After	Δ	Significance
Day	103	18.350	18.272	-0.078	0.940
Night	83	19.000	16.684	-2.316	0.282

* Indicates statistically significant at 95 percent level of confidence. None of the values were statistically significant.

Table 51. Bosque County (FM 3118) Intersection Spot Speed Results.

Light Condition/Period	Overall Sample Size	Control Speed (mph)	Intersection Speed Trap (mph)			
			Before	After	Δ	Significance
Day	1859	55	39.852	39.425	-0.427*	0.044
		70	46.873	45.791	-1.082*	0.044
Night	261	55	39.884	40.250	0.366	0.512
		70	44.117	46.489	2.372	0.059

*Indicates statistically significant at 95 percent level of confidence.

Table 52. Bosque County (FM 3118) Warning Sign Spot Speed Results.

Light Condition/Period	Overall Sample Size	Control Speed (mph)	Warning Sign Speed Trap (mph)			
			Before	After	Δ	Significance
Day	1859	55	52.098	51.606	-0.492*	0.004
		70	64.261	63.593	-0.668	0.126
Night	261	55	52.723	52.334	-0.389	0.392
		70	60.201	63.911	3.710*	0.000

*Indicates statistically significant at 95 percent level of confidence.

Table 53. Snook (FM 50 SB turning vehicles) Change in Speed Results.

Light Condition/Period	Overall Sample Size	Control Speed (mph)	Speed Change from Warning to Intersection Speed Trap (mph)			
			Before	After	Δ	Significance
Day	361	35	10.704	10.358	-0.346	0.653
		40	11.509	9.480	-2.030	0.139
Night	57	35	12.113	4.636	-7.477*	0.000
		40	14.693	6.003	-8.690*	0.005

*Indicates statistically significant at 95 percent level of confidence.

Table 54. Snook (FM 50 SB turning vehicles) Intersection Spot Speed Results.

Light Condition/Period	Overall Sample Size	Control Speed (mph)	Intersection Speed Trap (mph)			
			Before	After	Δ	Significance
Day	361	35	46.846	47.950	1.104	0.217
		40	49.890	49.120	-0.771	0.628
Night	57	35	43.282	47.970	4.688*	0.046
		40	46.136	46.332	1.196	0.737

*Indicates statistically significant at 95 percent level of confidence.

Table 55. Snook (FM 50 SB turning vehicles) Warning Sign Spot Speed Results.

Light Condition/Period	Overall Sample Size	Control Speed (mph)	Warning Sign Speed Trap (mph)			
			Before	After	Δ	Significance
Day	361	35	57.550	58.308	0.758	0.387
		40	61.400	58.599	-2.801	0.073
Night	57	35	55.395	52.606	-2.789	0.226
		40	59.829	52.335	-7.494*	0.033

*Indicates statistically significant at 95 percent level of confidence.

Table 56. Snook (FM 50 SB through vehicles) Change in Speed Results.

Light Condition/Period	Overall Sample Size	Control Speed (mph)	Speed Change from Warning to Intersection Speed Trap (mph)			
			Before	After	Δ	Significance
Day	570	65	10.928	11.827	0.899	0.060
		80	14.014	14.916	0.902	0.298
Night	107	65	9.662	10.262	0.600	0.604
		80	10.613	12.309	1.697	0.432

* Indicates statistically significant at 95 percent level of confidence. None of the values were statistically significant.

Table 57. Snook (FM 50 SB through vehicles) Comparison of Change in Speed for Speeding Vehicles.

Light Condition/Period	Overall Sample Size	Speed Change from Warning to Intersection Speed Trap (mph)			
		Before	After	Δ	Significance
Day	603	11.502	12.650	1.148	0.079
Night	181	9.283	11.310	2.027	0.253
Weekday	400	12.038	13.038	1.000	0.345
Weekend	384	10.778	12.343	1.565*	0.040

*Indicates statistically significant at 95 percent level of confidence.

Table 58. Snook (FM 50 SB through vehicles) Intersection Spot Speed Results.

Light Condition/Period	Overall Sample Size	Control Speed (mph)	Intersection Speed Trap (mph)			
			Before	After	Δ	Significance
Day	570	65	45.040	46.087	1.047	0.078
		80	51.921	51.785	-0.136	0.899
Night	107	65	42.591	45.189	2.598	0.071
		80	50.286	50.165	-0.120	0.964

* Indicates statistically significant at 95 percent level of confidence. None of the values were statistically significant.

Table 59. Snook (FM 50 SB through vehicles) Warning Sign Spot Speed Results.

Light Condition/Period	Overall Sample Size	Control Speed (mph)	Warning Sign Speed Trap (mph)			
			Before	After	Δ	Significance
Day	570	65	55.969	57.914	1.945*	0.000
		80	65.935	66.700	0.766	0.420
Night	107	65	52.253	55.451	3.198*	0.012
		80	60.898	62.475	1.576	0.505

*Indicates statistically significant at 95 percent level of confidence.

Table 60. Snook (FM 50 NB) Change in Speed Results.

Light Condition/Period	Overall Sample Size	Control Speed (mph)	Speed Change from Warning to Intersection Speed Trap (mph)			
			Before	After	Δ	Significance
Day	2455	65	7.012	7.588	0.576*	0.000
		80	9.371	9.752	0.381	0.060
Night	401	65	7.953	7.180	-0.773	0.060
		80	10.125	9.946	-0.180	0.749

*Indicates statistically significant at 95 percent level of confidence.

Table 61. Snook (FM 50 NB) Comparison of Change in Speed for Speeding Vehicles.

Light Condition/Period	Overall Sample Size	Speed Change from Warning to Intersection Speed Trap (mph)			
		Before	After	Δ	Significance
Day	3034	7.873	8.318	-0.339	0.171
Night	1208	8.371	8.031	0.889*	0.000
Weekday	2019	8.442	8.104	-0.339	0.171
Weekend	2223	7.498	8.387	0.889*	0.000

*Indicates statistically significant at 95 percent level of confidence.

Table 62. Snook (FM 50 NB) Intersection Spot Speed Results.

Light Condition/Period	Overall Sample Size	Control Speed (mph)	Intersection Speed Trap (mph)			
			Before	After	Δ	Significance
Day	2455	65	53.022	49.454	-3.568*	0.000
		80	61.018	57.032	-3.986*	0.000
Night	401	65	50.016	47.971	-2.045*	0.004
		80	55.551	54.581	-0.969	0.317

*Indicates statistically significant at 95 percent level of confidence.

Table 63. Snook (FM 50 NB) Warning Sign Spot Speed Results.

Light Condition/Period	Overall Sample Size	Control Speed (mph)	Warning Sign Speed Trap (mph)			
			Before	After	Δ	Significance
Day	2455	65	60.034	57.042	-2.992*	0.000
		80	70.839	66.784	-3.606*	0.000
Night	401	65	57.969	55.151	-2.818*	0.000
		80	65.676	64.527	-1.149	0.235

*Indicates statistically significant at 95 percent level of confidence.

Table 64. Colorado City (FM 208 SB) Change in Speed Results.

Light Condition/Period	Overall Sample Size	Control Speed (mph)	Speed Change from Warning to Intersection Speed Trap (mph)			
			Before	After	Δ	Significance
Day	691	50	10.423	9.534	-0.888	0.072
		65	13.942	13.250	-0.692	0.248
Night	170	50	10.412	10.660	0.248	0.762
		65	13.810	12.212	-1.598	0.194

* Indicates statistically significant at 95 percent level of confidence. None of the values were statistically significant.

Table 65. Colorado City (FM 208 SB) Intersection Spot Speed Results.

Light Condition/Period	Overall Sample Size	Control Speed (mph)	Intersection Speed Trap (mph)			
			Before	After	Δ	Significance
Day	691	50	39.955	31.523	-4.432*	0.000
		65	39.381	35.245	-4.136*	0.000
Night	170	50	33.769	30.406	-3.363*	0.001
		65	36.885	34.377	-2.507	0.091

*Indicates statistically significant at 95 percent level of confidence.

Table 66. Colorado City (FM 208 SB) Warning Sign Spot Speed Results.

Light Condition/Period	Overall Sample Size	Control Speed (mph)	Warning Sign Speed Trap (mph)			
			Before	After	Δ	Significance
Day	691	50	46.378	41.058	-5.230*	0.000
		65	53.323	48.495	-4.827*	0.000
Night	170	50	44.182	41.067	-3.115*	0.007
		65	50.695	46.590	-4.105*	0.019

*Indicates statistically significant at 95 percent level of confidence.

Table 67. Colorado City (FM 208 NB) Change in Speed Results.

Light Condition/Period	Overall Sample Size	Control Speed (mph)	Speed Change from Warning to Intersection Speed Trap (mph)			
			Before	After	Δ	Significance
Day	407	50	8.964	6.781	-2.183*	0.000
		65	10.959	9.017	-1.942*	0.011
Night	109	50	9.014	6.791	-2.223*	0.014
		65	12.153	8.616	-3.537*	0.023

*Indicates statistically significant at 95 percent level of confidence.

Table 68. Colorado City (FM 208 NB) Intersection Spot Speed Results.

Light Condition/Period	Overall Sample Size	Control Speed (mph)	Intersection Speed Trap (mph)			
			Before	After	Δ	Significance
Day	407	50	33.819	35.152	1.333*	0.035
		65	37.474	39.304	1.830*	0.049
Night	109	50	32.735	33.575	0.841	0.440
		65	35.075	39.763	4.688*	0.013

*Indicates statistically significant at 95 percent level of confidence.

Table 69. Colorado City (FM 208 NB) Warning Sign Spot Speed Results.

Light Condition/Period	Overall Sample Size	Control Speed (mph)	Warning Sign Speed Trap (mph)			
			Before	After	Δ	Significance
Day	407	50	42.783	41.933	-0.849	0.145
		65	48.433	48.321	-0.112	0.897
Night	109	50	41.749	40.366	-1.382	0.168
		65	47.229	48.379	1.151	0.506

* Indicates statistically significant at 95 percent level of confidence. None of the values were statistically significant.

Table 70. Millican (FM 2154 SB) Change in Speed Results.

Light Condition/Period	Overall Sample Size	Control Speed (mph)	Speed Change from Warning to Intersection Speed Trap (mph)			
			Before	After	Δ	Significance
Day	794	65	10.190	8.895	-1.294*	0.003
		75	14.573	13.540	-1.033*	0.029
Night	128	65	8.280	7.502	-0.778	0.401
		75	12.055	12.055	0.365	0.762

*Indicates statistically significant at 95 percent level of confidence.

Table 71. Millican (FM 2154 SB) Comparison of Change in Speed for Speeding Vehicles.

Light Condition/Period	Overall Sample Size	Speed Change from Warning to Intersection Speed Trap (mph)			
		Before	After	Δ	Significance
Day	723	13.087	11.989	-1.099*	0.004
Night	423	10.209	10.070	-0.140	0.888

*Indicates statistically significant at 95 percent level of confidence.

Table 72. Millican (FM 2154 SB) Intersection Spot Speed Results.

Light Condition/Period	Overall Sample Size	Control Speed (mph)	Intersection Speed Trap (mph)			
			Before	After	Δ	Significance
Day	794	65	41.723	42.638	0.915	0.093
		75	47.591	49.052	1.460*	0.015
Night	128	65	42.762	46.952	4.190*	0.000
		75	51.077	52.715	1.638	0.286

*Indicates statistically significant at 95 percent level of confidence.

Table 73. Millican (FM 2154 SB) Warning Sign Spot Speed Results.

Light Condition/Period	Overall Sample Size	Control Speed (mph)	Warning Sign Speed Trap (mph)			
			Before	After	Δ	Significance
Day	794	65	51.912	51.533	-0.379	0.482
		75	62.164	62.591	0.427	0.474
Night	128	65	51.041	54.454	3.413*	0.003
		75	63.132	65.135	2.003	0.187

*Indicates statistically significant at 95 percent level of confidence.

Table 74. Millican (FM 2154 NB) Change in Speed Results.

Light Condition/Period	Overall Sample Size	Control Speed (mph)	Speed Change from Warning to Intersection Speed Trap (mph)			
			Before	After	Δ	Significance
Day	1294	60	11.808	10.144	-1.664*	0.001
		75	15.595	16.793	1.198	0.056
Night	378	60	10.126	8.973	-1.153	0.218
		75	13.656	17.750	4.093*	0.004

*Indicates statistically significant at 95 percent level of confidence.

Table 75. Millican (FM 2154 NB) Comparison of Change in Speed for Speeding Vehicles.

Light Condition/Period	Overall Sample Size	Speed Change from Warning to Intersection Speed Trap (mph)			
		Before	After	Δ	Significance
Day	1378	14.432	15.139	0.707	0.195
Night	410	12.119	15.530	3.411*	0.006

*Indicates statistically significant at 95 percent level of confidence.

Table 76. Millican (FM 2154 NB) Intersection Spot Speed Results.

Light Condition/Period	Overall Sample Size	Control Speed (mph)	Intersection Speed Trap (mph)			
			Before	After	Δ	Significance
Day	1294	60	37.757	39.308	1.551*	0.001
		75	41.018	39.896	-1.122*	0.049
Night	378	60	39.487	41.280	1.793*	0.036
		75	44.128	39.629	-4.499*	0.000

*Indicates statistically significant at 95 percent level of confidence.

Table 77. Millican (FM 2154 NB) Warning Sign Spot Speed Results.

Light Condition/Period	Overall Sample Size	Control Speed (mph)	Warning Sign Speed Trap (mph)			
			Before	After	Δ	Significance
Day	1294	60	49.565	49.452	-0.113	0.807
		75	56.613	56.689	0.075	0.897
Night	378	60	49.613	50.253	0.641	0.469
		75	57.784	57.379	-0.406	0.756

* Indicates statistically significant at 95 percent level of confidence. None of the values were statistically significant.

Table 78. Hearne (FM 2549 NB) Change in Speed Results.

Light Condition/Period	Overall Sample Size	Control Speed (mph)	Speed Change from Warning to Intersection Speed Trap (mph)			
			Before	After	Δ	Significance
Day	821	60	8.433	8.493	0.061	0.820
		75	11.696	11.981	0.286	0.494
Night	172	60	9.220	9.578	0.358	0.497
		75	12.598	13.753	1.155	0.241

* Indicates statistically significant at 95 percent level of confidence. None of the values were statistically significant.

Table 79. Hearne (FM 2549 NB) Comparison of Change in Speed for Speeding Vehicles.

Light Condition/Period	Overall Sample Size	Speed Change from Warning to Intersection Speed Trap (mph)			
		Before	After	Δ	Significance
Day	637	10.599	11.145	0.546	0.184
Night	171	11.395	12.225	0.830	0.417
Weekday	427	11.354	11.324	-0.030	0.965
Weekend	381	10.261	11.321	1.060*	0.021

*Indicates statistically significant at 95 percent level of confidence.

Table 80. Hearne (FM 2549 NB) Intersection Spot Speed Results.

Light Condition/Period	Overall Sample Size	Control Speed (mph)	Intersection Speed Trap (mph)			
			Before	After	Δ	Significance
Day	821	60	48.858	48.733	0.148	0.709
		75	54.454	54.298	-0.156	0.802
Night	172	60	47.432	47.420	-0.012	0.988
		75	54.006	52.230	-1.775	0.226

* Indicates statistically significant at 95 percent level of confidence. None of the values were statistically significant.

Table 81. Hearne (FM 2549 NB) Warning Sign Spot Speed Results.

Light Condition/Period	Overall Sample Size	Control Speed (mph)	Warning Sign Speed Trap (mph)			
			Before	After	Δ	Significance
Day	821	60	57.018	57.226	0.208	0.576
		75	66.150	66.280	0.130	0.824
Night	172	60	56.651	56.998	0.346	0.639
		75	66.604	65.984	-0.620	0.653

* Indicates statistically significant at 95 percent level of confidence. None of the values were statistically significant.

Table 82. Hearne (FM 2549 SB) Change in Speed Results.

Light Condition/Period	Overall Sample Size	Control Speed (mph)	Speed Change from Warning to Intersection Speed Trap (mph)			
			Before	After	Δ	Significance
Day	690	60	7.169	7.512	0.343	0.251
		75	9.233	10.278	1.045*	0.045
Night	122	60	6.839	6.698	-0.141	0.844
		75	9.444	9.068	-0.376	0.759

*Indicates statistically significant at 95 percent level of confidence.

Table 83. Hearne (FM 2549 SB) Comparison of Change in Speed for Speeding Vehicles.

Light Condition/Period	Overall Sample Size	Speed Change from Warning to Intersection Speed Trap (mph)			
		Before	After	Δ	Significance
Day	371	8.685	9.019	0.335	0.580
Night	117	7.382	7.938	0.556	0.726
Weekday	578	8.252	8.396	0.144	0.893
Weekend	238	8.919	9.042	0.124	0.856

* Indicates statistically significant at 95 percent level of confidence. None of the values were statistically significant.

Table 84. Hearne (FM 2549 SB) Intersection Spot Speed Results.

Light Condition/Period	Overall Sample Size	Control Speed (mph)	Intersection Speed Trap (mph)			
			Before	After	Δ	Significance
Day	690	60	50.406	47.511	-2.896*	0.000
		75	55.504	52.943	-2.561*	0.004
Night	122	60	48.929	47.548	-1.381	0.260
		75	56.992	54.786	-2.207	0.291

*Indicates statistically significant at 95 percent level of confidence.

Table 85. Hearne (FM 2549 SB) Warning Sign Spot Speed Results.

Light Condition/Period	Overall Sample Size	Control Speed (mph)	Warning Sign Speed Trap (mph)			
			Before	After	Δ	Significance
Day	690	60	57.575	55.023	-2.552*	0.000
		75	64.737	63.221	-1.516	0.108
Night	122	60	55.768	54.246	-1.522	0.242
		75	66.436	63.853	-2.583	0.244

*Indicates statistically significant at 95 percent level of confidence.

Table 86. Steephollow (FM 1179) Change in Speed Results.

Light Condition/Period	Overall Sample Size	Control Speed (mph)	Speed Change from Warning to Curve Speed Trap (mph)			
			Before	After	Δ	Significance
Day	2068	60	1.76	4.47	2.71*	0.000
		65	2.05	5.04	2.99*	0.000
Night	409	60	1.30	3.79	2.49*	0.000
		65	1.58	4.83	3.24*	0.000

* Indicates statistically significant at 95 percent level of confidence.

Table 87. Steephollow (FM 1179) Curve Spot Speed Results.

Light Condition/Period	Overall Sample Size	Control Speed (mph)	Curve Speed Trap (mph)			
			Before	After	Δ	Significance
Day	2068	60	54.34	52.71	-1.63*	0.000
		65	57.90	56.47	-1.44*	0.000
Night	409	60	54.53	52.76	-1.77*	0.000
		65	58.02	56.38	-1.64*	0.003

* Indicates statistically significant at 95 percent level of confidence.

Table 88. Steephollow (FM 1179) Warning Sign Spot Speed Results.

Light Condition/Period	Overall Sample Size	Control Speed (mph)	Warning Sign Speed Trap (mph)			
			Before	After	Δ	Significance
Day	2068	60	56.10	57.18	1.08*	0.000
		65	59.96	61.51	1.55*	0.000
Night	409	60	55.83	56.54	0.71*	0.011
		65	59.60	61.20	1.61*	0.000

* Indicates statistically significant at 95 percent level of confidence.

Table 89. Navasota I (FM 3090) Change in Speed Results.

Light Condition/Period	Overall Sample Size	Control Speed (mph)	Speed Change from Warning to Curve Speed Trap (mph)			
			Before	After	Δ	Significance
Day	314	55	6.82	-2.77	-9.59*	0.000
		60	7.88	-2.45	-10.33*	0.000
Night	77	55	8.24	-2.39	-10.63*	0.000
		60	10.41	-1.511	-11.92*	0.000

*Indicates statistically significant at 95 percent level of confidence.

Table 90. Navasota I (FM 3090) Curve Spot Speed Results.

Light Condition/Period	Overall Sample Size	Control Speed (mph)	Curve Speed Trap (mph)			
			Before	After	Δ	Significance
Day	314	55	46.47	49.31	2.83*	0.000
		60	49.83	52.10	2.27*	0.001
Night	77	55	45.13	50.10	4.92*	0.000
		60	48.18	54.70	6.53*	0.000

*Indicates statistically significant at 95 percent level of confidence.

Table 91. Navasota I (FM 3090) Warning Sign Spot Speed Results.

Light Condition/Period	Overall Sample Size	Control Speed (mph)	Warning Sign Speed Trap (mph)			
			Before	After	Δ	Significance
Day	314	55	53.29	46.53	-6.75*	0.000
		60	57.71	49.65	-8.06*	0.000
Night	77	55	53.36	47.66	-5.71*	0.000
		60	58.58	53.19	-5.39*	0.002

*Indicates statistically significant at 95 percent level of confidence.

Table 92. Navasota II (FM 3090) Change in Speed Results.

Light Condition/Period	Overall Sample Size	Control Speed (mph)	Speed Change from Warning to Curve Speed Trap (mph)			
			Before	After	Δ	Significance
Day	103	55	8.14	8.95	0.816	0.274
		60	9.38	10.15	0.773	0.459

* Indicates statistically significant at 95 percent level of confidence. None of the values were statistically significant.

Table 93. Navasota II (FM 3090) Curve Spot Speed Results.

Light Condition/Period	Overall Sample Size	Control Speed (mph)	Curve Speed Trap (mph)			
			Before	After	Δ	Significance
Day	103	55	44.83	45.51	0.676	0.434
		60	47.77	48.89	1.13	0.352

* Indicates statistically significant at 95 percent level of confidence. None of the values were statistically significant.

Table 94. Navasota II (FM 3090) Warning Sign Spot Speed Results.

Light Condition/Period	Overall Sample Size	Control Speed (mph)	Warning Sign Speed Trap (mph)			
			Before	After	Δ	Significance
Day	103	55	52.97	54.46	1.49	0.086
		60	57.15	59.05	1.90	0.118

* Indicates statistically significant at 95 percent level of confidence. None of the values were statistically significant.

Table 95. Keith (FM 244) Change in Speed Results.

Light Condition/Period	Overall Sample Size	Control Speed (mph)	Speed Change from Warning to Curve Speed Trap (mph)			
			Before	After	Δ	Significance
Day	1011	60	2.47	2.76	0.29	0.086
		70	3.41	4.01	0.60*	0.013
Night	227	60	3.13	3.69	0.56	0.157
		70	4.25	5.02	0.77	0.259

*Indicates statistically significant at 95 percent level of confidence.

Table 96. Keith (FM 244) Comparison of Change in Speed for Speeding Vehicles.

Light Condition/Period	Overall Sample Size	Speed Change from Warning to Curve Speed Trap (mph)			
		Before	After	Δ	Significance
Day	498	3.529	3.796	0.267	0.394
Night	276	4.200	4.901	0.701	0.474

* Indicates statistically significant at 95 percent level of confidence. None of the values were statistically significant.

Table 97. Keith (FM 244) Curve Spot Speed Results.

Light Condition/Period	Overall Sample Size	Control Speed (mph)	Curve Speed Trap (mph)			
			Before	After	Δ	Significance
Day	1011	60	57.86	55.84	-2.02*	0.000
		70	64.40	60.44	-3.95*	0.000
Night	227	60	57.98	53.33	-4.64*	0.000
		70	63.51	58.03	-5.47*	0.000

* Statistically significant at 95 percent level of confidence.

Table 98. Keith (FM 244) Warning Sign Spot Speed Results.

Light Condition/Period	Overall Sample Size	Control Speed (mph)	Warning Sign Speed Trap (mph)			
			Before	After	Δ	Significance
Day	1011	60	60.33	58.00	-1.73*	0.000
		70	67.81	64.45	-3.36*	0.000
Night	227	60	61.10	57.03	-4.08*	0.000
		70	67.76	63.06	-4.71*	0.000

*Indicates statistically significant at 95 percent level of confidence.

Table 99. Bremond (FM 46) Change in Speed Results.

Light Condition/Period	Overall Sample Size	Control Speed (mph)	Speed Change from Warning to Curve Speed Trap (mph)			
			Before	After	Δ	Significance
Day	615	65	2.54	3.04	0.51*	0.012
		75	3.52	3.85	0.33	0.244
Night	103	65	2.72	3.40	0.68	0.146
		75	3.58	4.37	0.79	0.263

*Indicates statistically significant at 95 percent level of confidence.

Table 100. Bremond (FM 46) Comparison of Change in Speed for Speeding Vehicles.

Light Condition/Period	Overall Sample Size	Speed Change from Warning to Curve Speed Trap (mph)			
		Before	After	Δ	Significance
Day	515	2.846	3.134	0.288	0.297
Night	273	2.951	3.600	0.649	0.401

* Indicates statistically significant at 95 percent level of confidence. None of the values were statistically significant.

Table 101. Bremond (FM 46) Curve Spot Speed Results.

Light Condition/Period	Overall Sample Size	Control Speed (mph)	Curve Speed Trap (mph)			
			Before	After	Δ	Significance
Day	615	65	61.34	60.43	-0.91*	0.019
		75	68.45	67.71	-0.74	0.169
Night	103	65	61.51	59.60	-1.91*	0.033
		75	68.85	66.54	-2.31	0.091

*Indicates statistically significant at 95 percent level of confidence.

Table 102. Bremond (FM 46) Warning Sign Spot Speed Results.

Light Condition/Period	Overall Sample Size	Control Speed (mph)	Warning Sign Speed Trap (mph)			
			Before	After	Δ	Significance
Day	615	65	63.88	63.47	-0.40	0.203
		75	71.97	71.56	-0.41	0.346
Night	103	65	64.23	63.00	-1.24	0.091
		75	72.42	70.91	-1.51	0.175

* Indicates statistically significant at 95 percent level of confidence. None of the values were statistically significant.

Q-Q PLOTS FOR NORMALITY TESTING

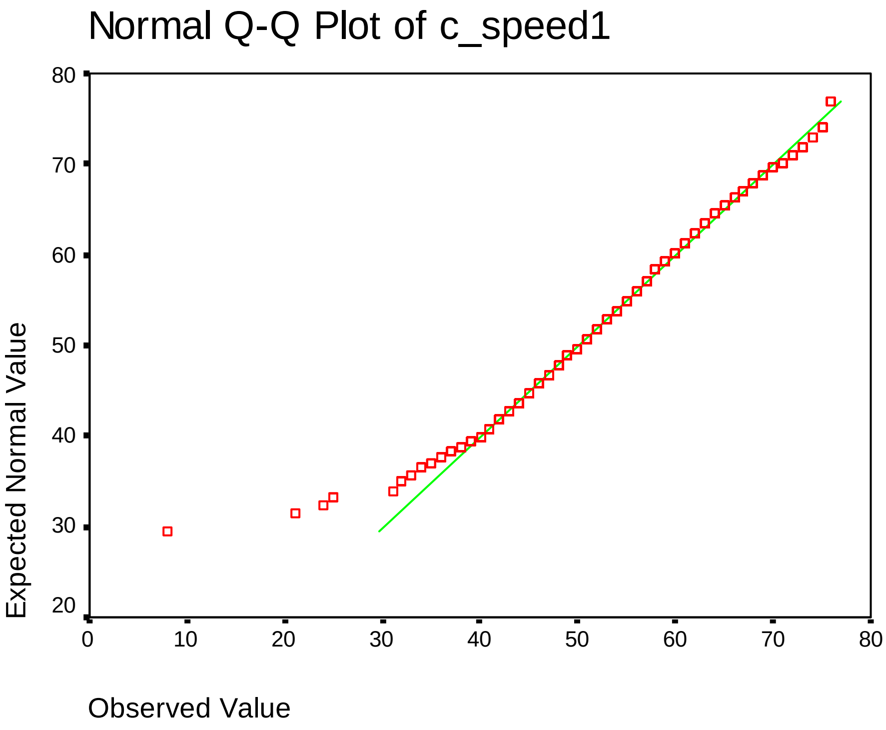


Figure 71. Bosque County (FM 3118) Q-Q Plot.

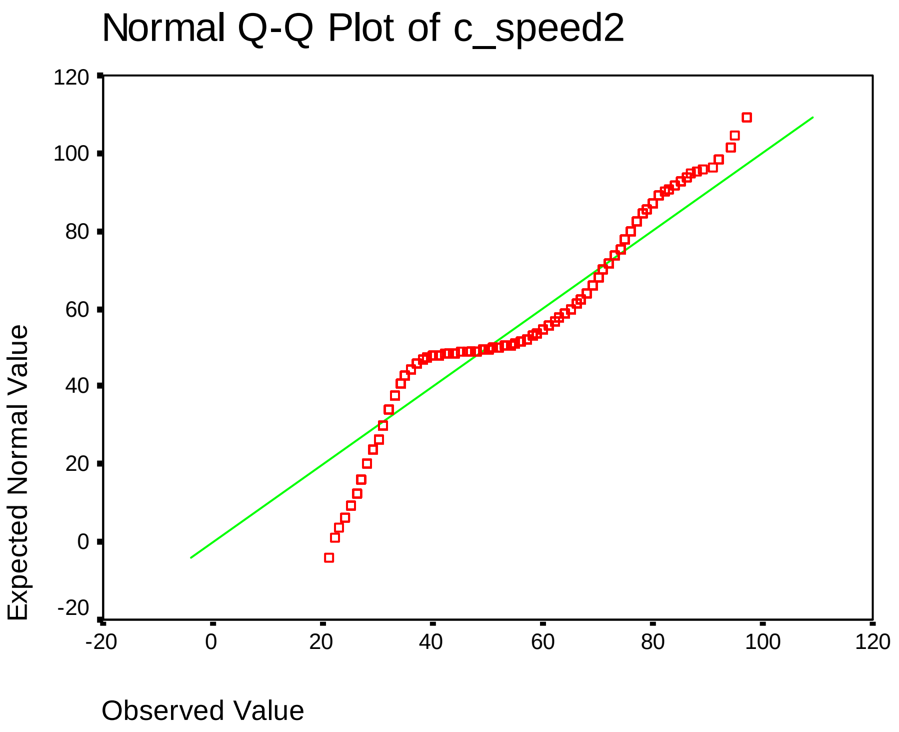


Figure 72. Snook (FM 50 SB) Q-Q Plot.

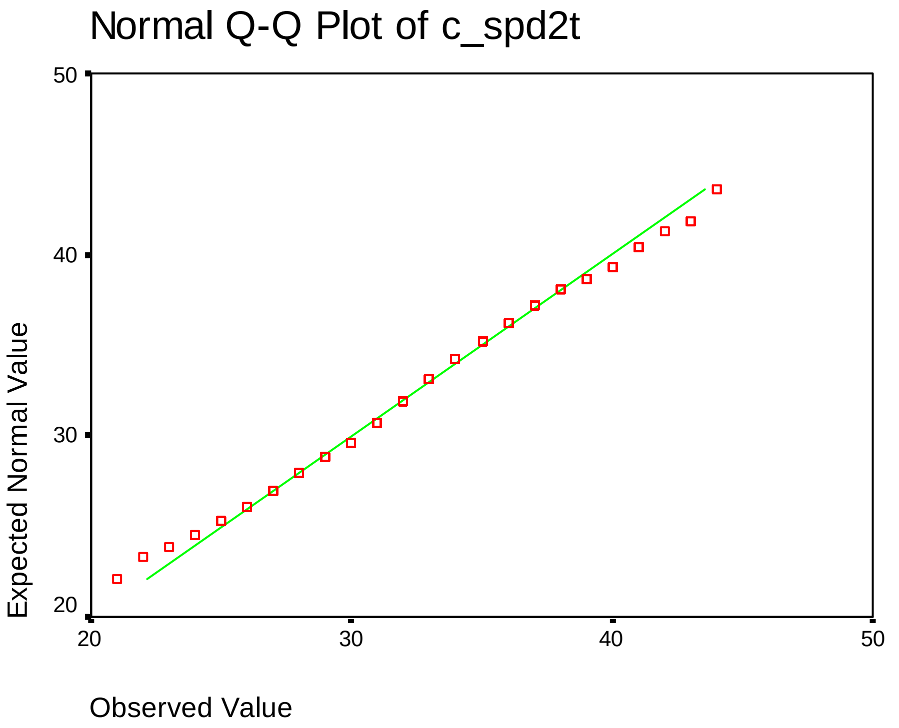


Figure 73. Snook (FM 50 SB turning vehicles) Q-Q Plot.

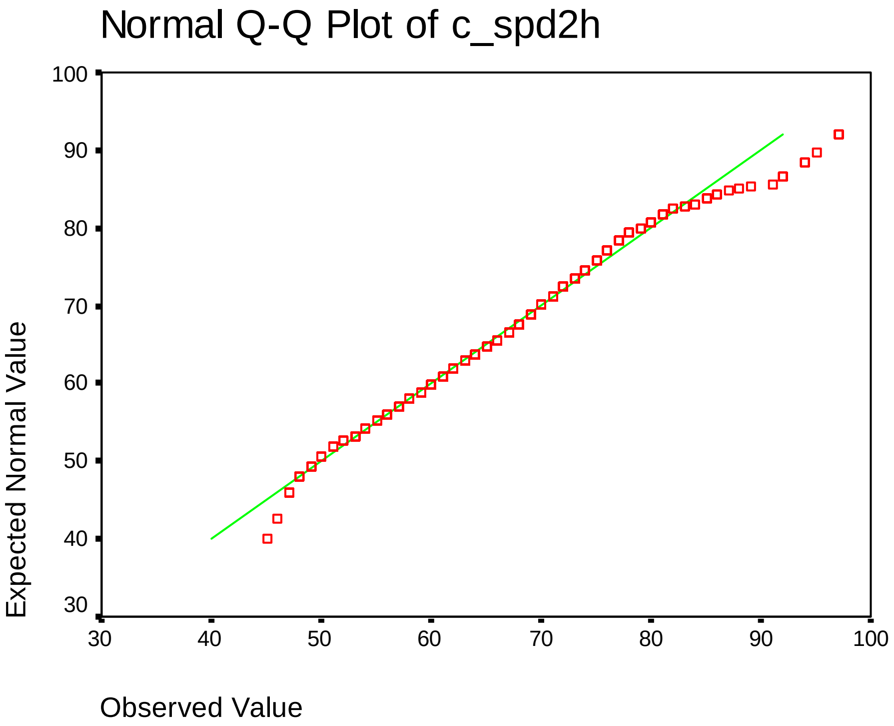


Figure 74. Snook (FM 50 SB through vehicles) Q-Q Plot.

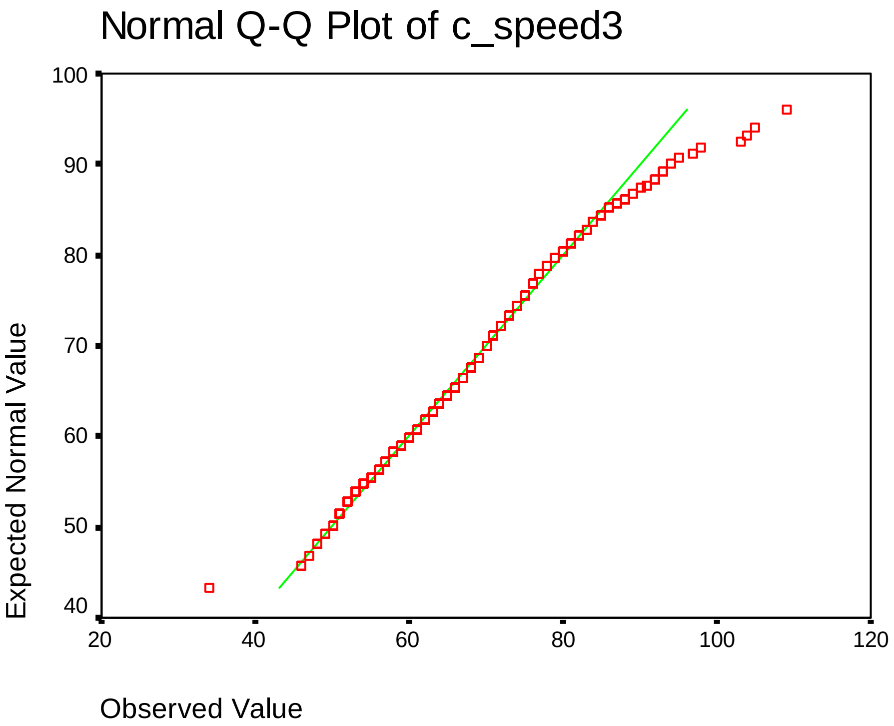


Figure 75. Snook (FM 50 NB) Q-Q Plot.

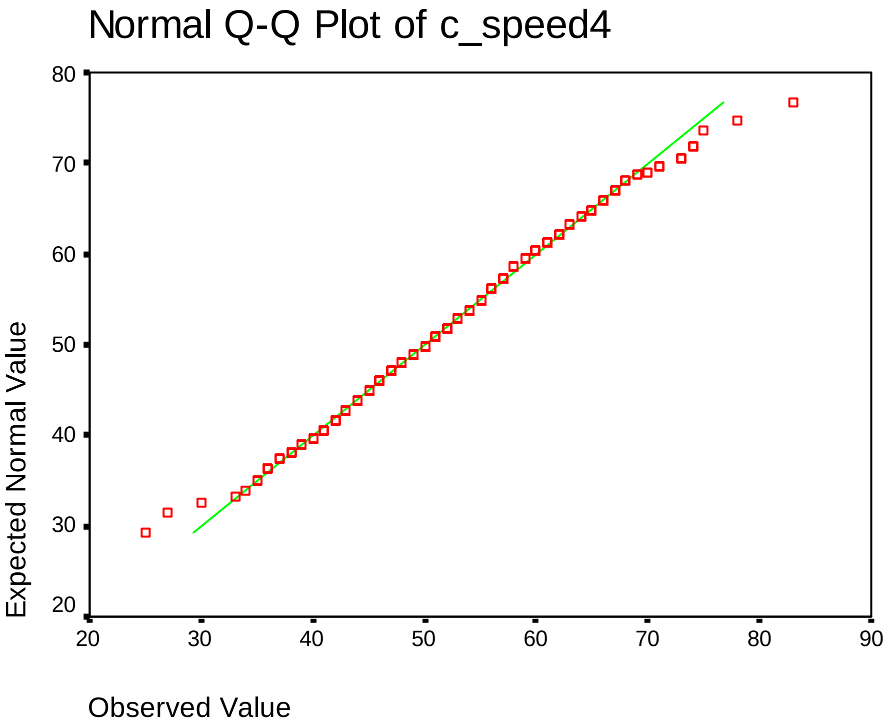


Figure 76. Colorado City (FM 208 SB) Q-Q Plot.

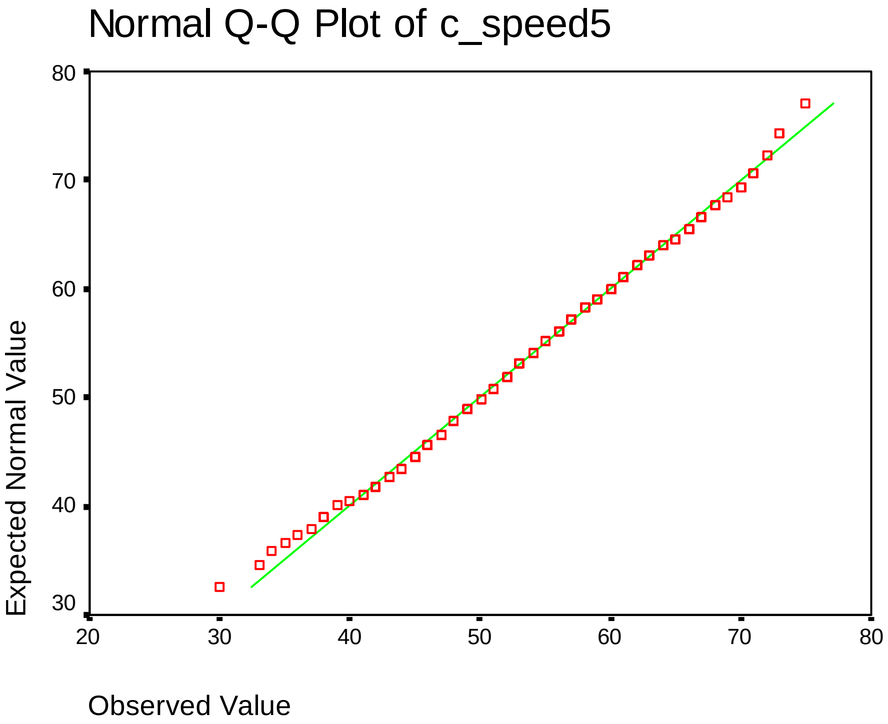


Figure 77. Colorado City (FM 208 NB) Q-Q Plot.

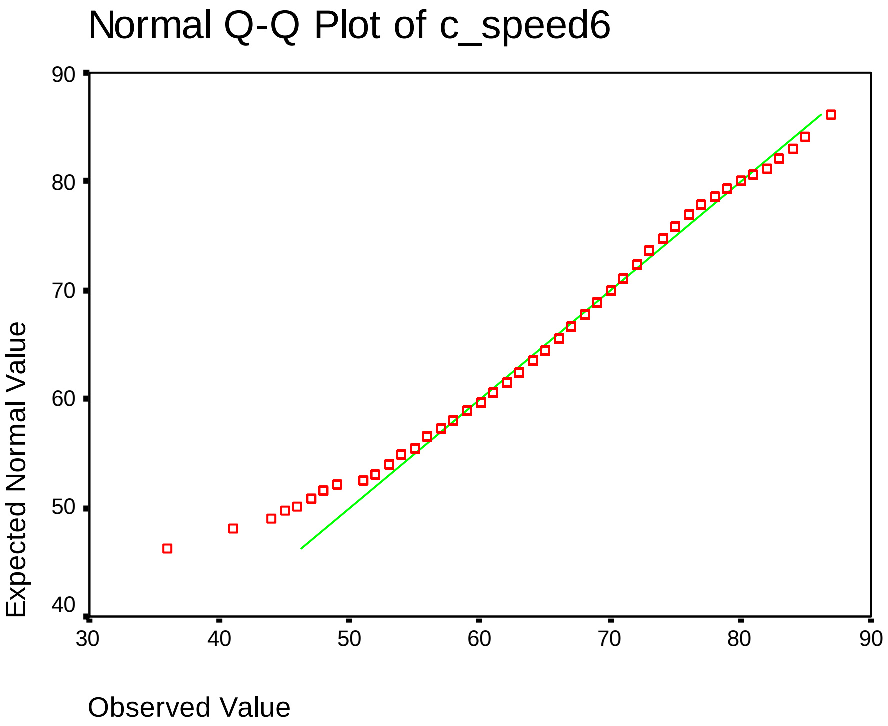


Figure 78. Millican (FM 2154 SB) Q-Q Plot.

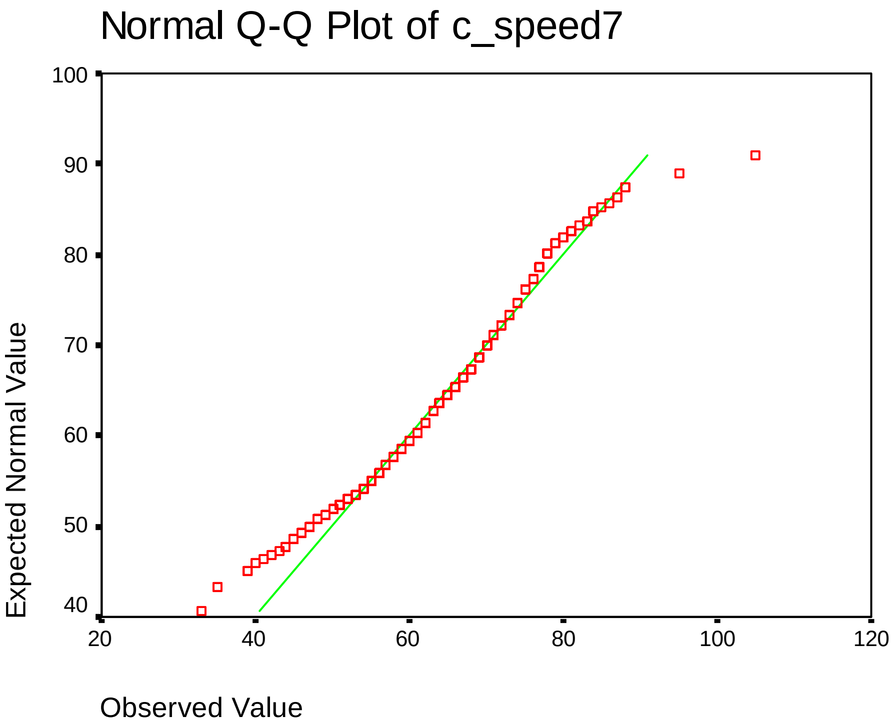


Figure 79. Millican (FM 2154 NB) Q-Q Plot.

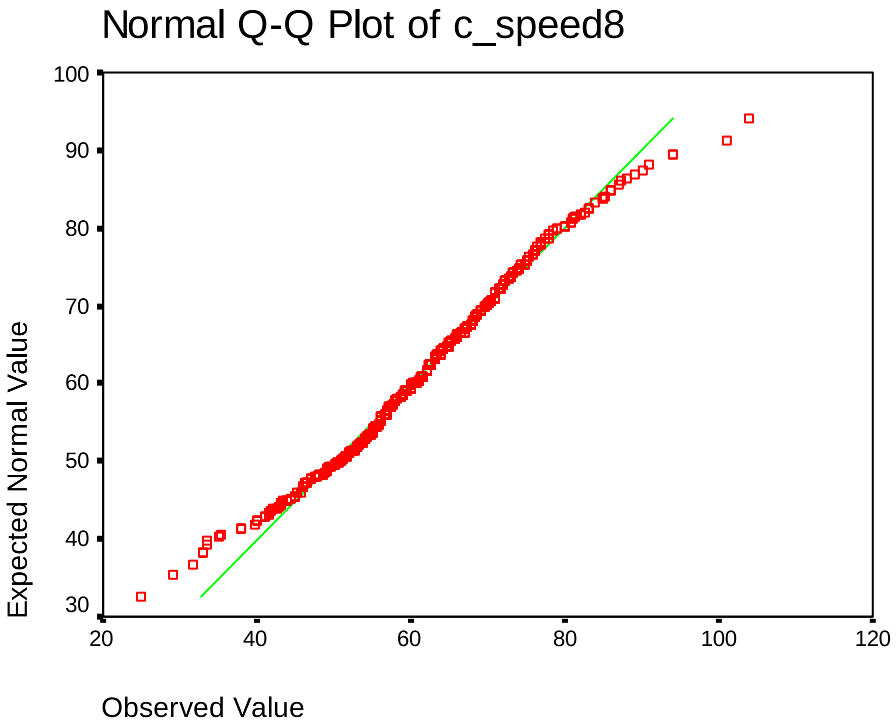


Figure 80. Hearne (FM 2549 NB) Q-Q Plot.

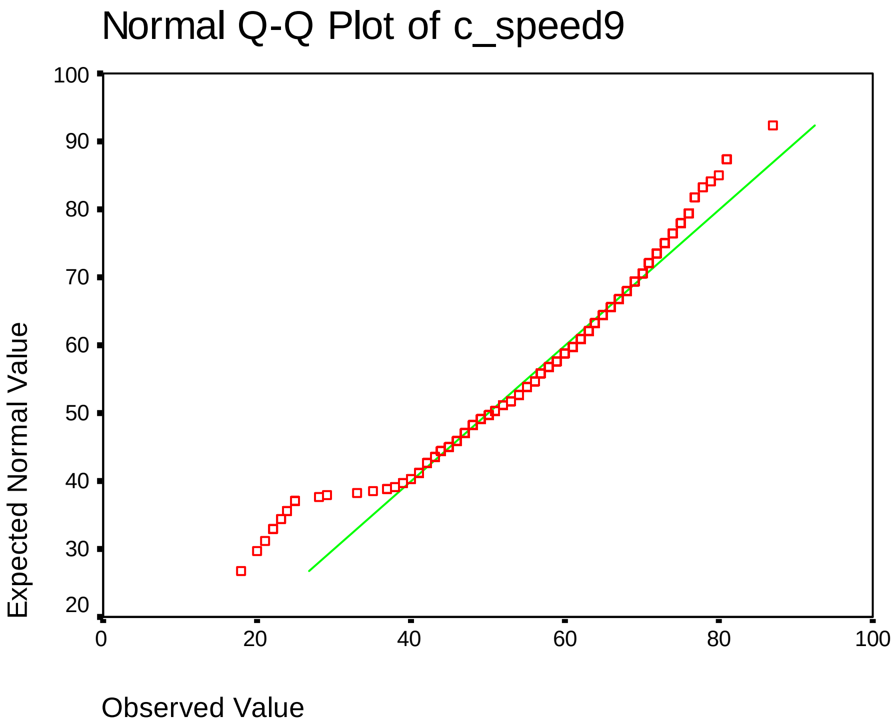


Figure 81. Hearne (FM 2549 SB) Q-Q Plot.

APPENDIX B

DATA COLLECTION SYSTEM DESIGN

The researchers determined that the best form of field data to measure the six MOEs with respect to driver response to CRSs was video footage of passing maneuvers. Since TTI did not have the equipment readily available to collect this type of data, the researchers designed and developed an instrumented vehicle, referred to as the data recording vehicle (DRV). The vehicle, a four-door sedan, had four concealed cameras mounted on it in locations that provided video coverage of vehicles passing around the DRV (see Figure 82). Three of the cameras were placed exterior to the vehicle to monitor passing maneuvers (see Figure 83). The fourth camera was placed inside the DRV, and it recorded the speed of and distances traveled by the DRV. Speeds and distances were calculated and displayed by a distance measuring instrument (DMI) (see Figure 83).

The cameras monitoring passing maneuvers were enclosed in an aerodynamic, hard-body, cargo carrier and carried on the roof of the DRV. Camera "R" faced the rear of the vehicle and recorded onto videotape encroachments and the beginning of passing maneuvers. Camera "S" recorded onto videotape the opposing lane of travel by being placed on the left side of the cargo carrier and angled perpendicular to the travel direction. Camera "F" was affixed at the front of the cargo carrier, and it was angled in the direction of travel of the DRV. This camera recorded oncoming traffic and the completion of passing maneuvers. Figure 82 depicts the general orientation of the camera setup for cameras R, S and F.

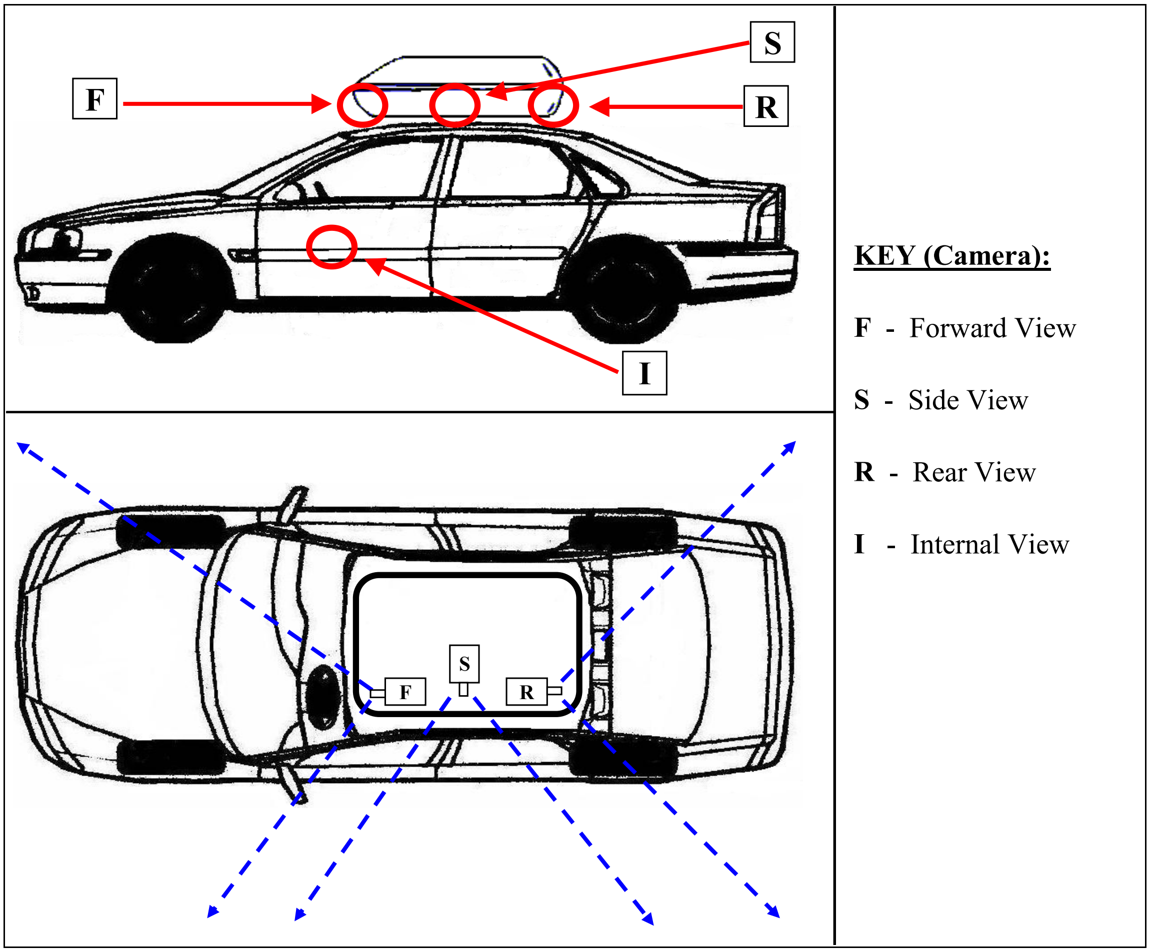


Figure 82. Video Camera Setup.

Cameras R, S, and F

Camera I

Figure 83. Close-up View of Cameras.

Figure 84 is a picture of the fully instrumented DRV.

Figure 84. Data Recording Vehicle.

The three cameras affixed to the interior of the cargo container were mounted in a manner that did not alert drivers to the data collection efforts. The faces of each camera were painted black and symmetrical black ovals were painted on the cargo container to camouflage the viewing ports. Figure 85 contains various pictures of the DRV configuration with close-ups of the camouflaged viewing ports.

Front **Rear**

Side

Figure 85. External Close-up Views.

Furthermore, the viewing angles of the cameras were adjustable to allow for variation in the vehicle height of the DRV being used for data collection (see Figure 83). The forward- and rearward-facing cameras were positioned as close as possible to the left (the driver side of the vehicle) of the cargo carrier to capture the instant that vehicles encroached upon the centerline of the roadway.

The power supply and the video feed cables were sent internally to the vehicle through the trunk of the vehicle. The video recorder was located in the backseat, and it was restrained by harnesses. Power to the recording unit was supplied by a direct current to an alternating current (DC/AC) cigarette lighter power converter.

Camera "I" was placed in the interior of the DRV, and it was mounted on a stable platform with a DMI and a clock (refer back to Figure 83). The stable platform minimized the need to permanently attach any fastening devices to the interior of the vehicle for the camera, DMI and/or clock. The platform was not permanently mounted in the vehicle. Instead, technicians at TTI designed the platform to fit snuggly into the cup holders of the DRV. Consequently, the platform was very stable, yet easy to remove.

The instrumentation of the DRV was calibrated by the researchers in a controlled environment at the Riverside Campus at Texas A&M University in College Station, Texas.

Calibration

The data collection system developed for this report was calibrated to obtain accurate data. One instrument on the DRV that needed calibration was the DMI. This device was calibrated using the manufacturer's recommended calibration method. The other instruments calibrated for this report were the data reduction reviewing monitors (see Figure 86).

The calibration of the reviewing monitors consisted of developing a distance relationship between objects presented on the monitors and the objects in the field. The purpose of this calibration was to allow researchers to estimate distances between objects videotaped in the field (i.e., passing vehicles) by measuring distances off of a reviewing monitor. The estimated gap distance measurements were essential to studying gap distance prior to a vehicle passing the DRV. It is important to note that the distance relationship is not linear and it was developed from meticulous data collection in a controlled environment at a gated research facility.

Figure 86. Reviewing Television Monitor.

The data for the calibration were recorded at the Riverside Campus at Texas A&M University. The DRV was driven north and south on runway 35R. The Erosion and Sediment Control Laboratory Rainfall Simulator located at the south end of runway 35R was used as a fixed reference point. Video footage was collected as the DRV was driven away from and toward the facility along a perpendicular trajectory from the north facing wall of the building (see Figure 87 and Figure 88).

Figure 87. Lab Facility.

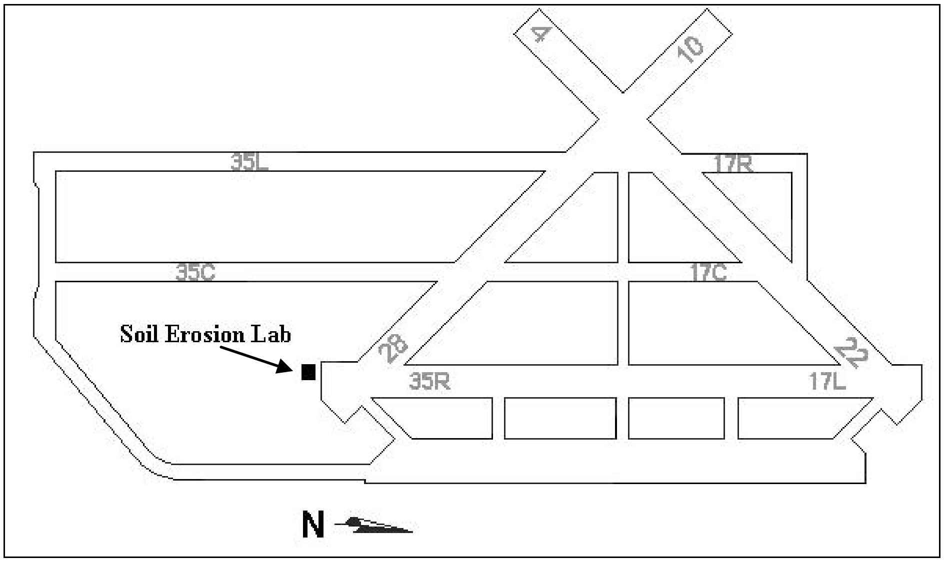


Figure 88. Riverside Campus Layout.

The location of the base (bottom) of the facility was used in conjunction with the distance measures collected from the DMI to establish the gap distance of the front and rear bumpers of the DRV from the north face of the facility. The vertical distance on a reviewing monitor (see Figure 86) between the base of the lab building and the projected horizon of each video camera was measured. The measurements on the reviewing monitor were based on a Society of Automotive Engineers (SAE) scale of 50 (1/50th of an inch). This measure was correlated with the in-field physical distance recorded from the DMI.

Calibration video was taken for the before period and the after period. From this data, empirical formulas were developed for the R1 and F1 cameras (see Figure 89 for R1 curves). The formulas in Figure 89 were developed using Microsoft Excel's regression analysis. Power functions were used because the trend lines appeared to fit the data the best with R2 values greater than 0.99. The differences in the two curves presented in Figure 89 are that the data were reduced on more than one monitor. Consequently, calibration curves were generated for each reviewing monitor to minimize the possibility of systematic data reduction errors. While the formulas generated in the before and after periods could generate non-integer values, only the rounded integer values were used because the distance measures recorded with the DMI were only accurate to whole numbers.

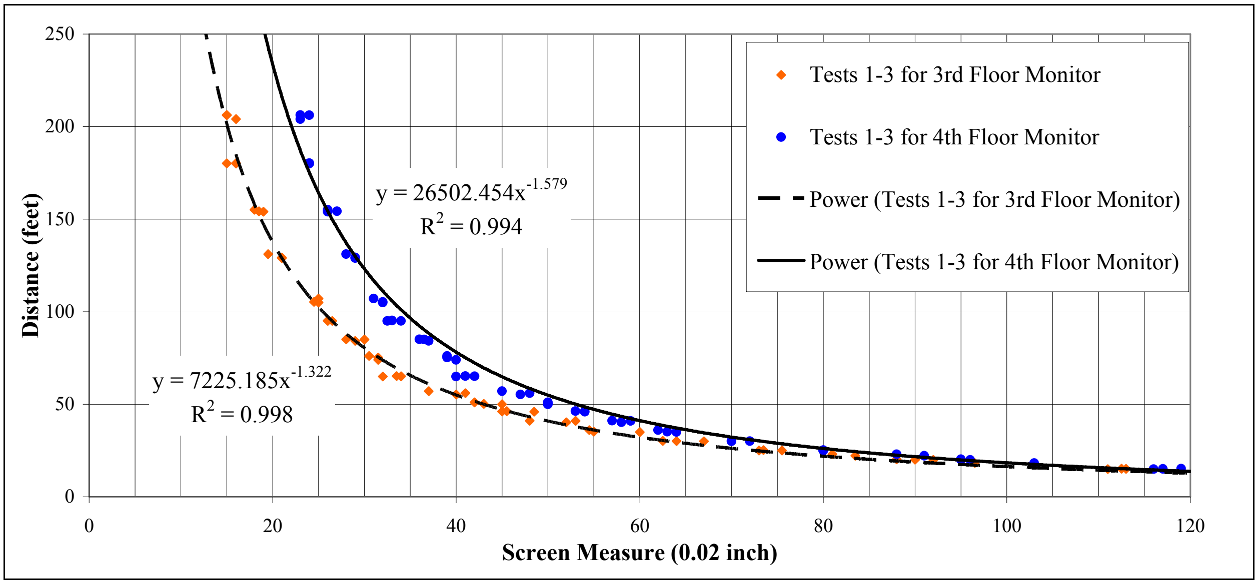


Figure 89. R1 Camera Gap Distance Calibration Curve (after period).

DATA REDUCTION PROCEDURE

This section of the report contains a detailed discussion of the method used to reduce the data from the videotape for the analysis of the MOE, and it is subdivided into the following topics:

- prior to passing maneuver, and
- initial stage of a passing maneuver.

Prior to Passing Maneuver

The MOEs for erratic movements and time between encroachments were investigated from data collected on a tracked vehicle prior to a driver initiating a successful pass. A successful pass was considered any completed pass around the DRV that did not require the driver of the DRV or of an opposing vehicle to leave his/her respective lane of travel to allow the passing vehicle to complete its pass. The reviewer of the video data focused on the tracked vehicle's proximity to the centerline pavement markings to determine whether to collect any data prior to passing on either of the two MOEs mentioned above.

All of these data were reduced from the R1 camera view (see Figure 86). The MOE for erratic movements was a count value, and the MOE for time between encroachments was a calculated value from time measurements.

Erratic Movements

With regard to erratic movements, the reviewer specifically looked for rapid lane shifts or wrong corrective action by the tracked driver. It was believed that a rapid lane shift would be denoted by a downward shift of the front headlight on the side of a tracked vehicle opposite the directional change. This vehicle lean would be caused by the acceleration. It was also presumed that drivers that conducted rapid lane shifts would need to make corrective action to stabilize their respective vehicles in their intended lane of travel.

When a tracked driver inadvertently contacted CRSs and corrected to the left instead of the right, a wrong corrective action was recorded. This specific action was documented by Elango and Noyce (*21*). However, it was decided to further investigate this responsive action, because it was believed that drivers would not continue to respond in this manner with increased exposure. It was thought that a wrong corrective action would appear to be an increase in a tracked vehicle's leftward movement when contacting the CRSs, followed by a rightward shift back into the initial lane of travel. Figure 90 depicts the travel path of the front, driver-side tire of a tracked vehicle with respect to a proposed wrong corrective action. The travel path was not based on field data, and may be more or less conservative than a real-world corrective action.

While it was possible that erratic movements could occur throughout a passing maneuver, it was not believed that the reason for the erratic movement could be solely attributed to the installation of CRSs. For instance, an erratic movement that occurs when a tracked vehicle is in the opposing direction of travel would not be contacting CRSs. Furthermore, a driver that passes would have already made the active decision to cross CRSs, and it was assumed that erratic movements by drivers would occur because of a driver's discomfort with contacting CRSs or the result of inadvertently contacting CRSs. A driver that actively decided to cross CRSs did not inadvertently contact them. Also, it was believed that a driver who was uncomfortable with crossing CRSs would not attempt to complete a pass.

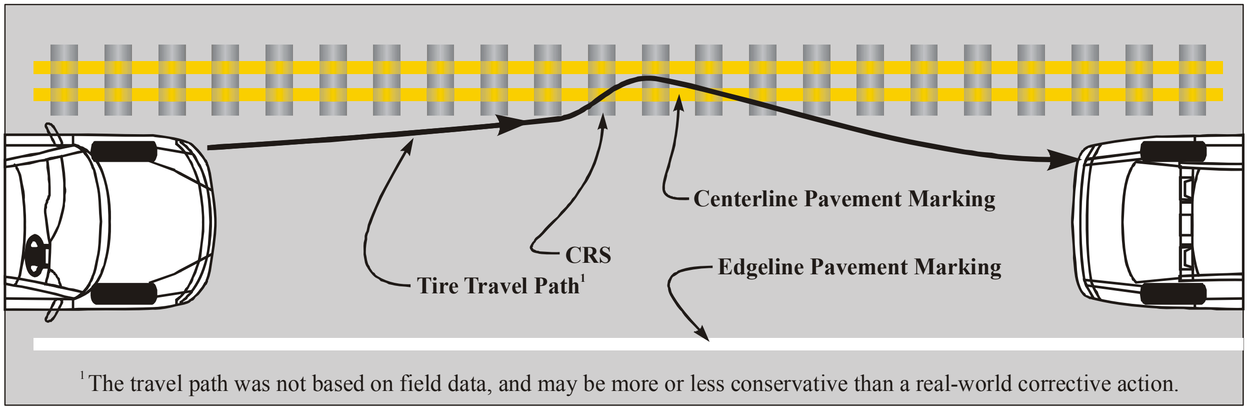


Figure 90. Front, Driver-Side Tire Path for Wrong Corrective Action.

Time between Encroachments

Time between encroachments was the second MOE extracted from the data collected prior to a tracked vehicle completing a successful pass. Data were recorded each time that a tracked vehicle encroached on the centerline markings. This particular MOE was the measure of time between two consecutive encroachments. The starting reference point occurs when the tracked vehicle's front, driver-side tire last touches the centerline pavement marking when the vehicle is returning from an encroachment. The next consecutive encroachment, when the front, driver-side tire contacts the centerline is the ending reference point. The transcribed video data were input into a computer spreadsheet that calculated the difference between these values.

Initial Stage of a Passing Maneuver

Centerline crossing time and gap distance were the two MOEs investigated using the data reduced from successful passing maneuvers. All of the data for both of these MOEs were collected from the R1 camera view. While the initial passing maneuver was normally started prior to crossing the centerline, it was assumed that the start of a pass occurred when the front, driver-side tire first contacted the centerline pavement marking. This was assumed because it was not possible to know the point at which a driver first decided to pass, but it was possible to assume that contacting the centerline at the beginning of a successful pass indicated the intent to pass.

It was thought that the first initial shift toward the centerline may be an indicator of the intent to pass. This was not chosen because early system testing prior to collecting field data indicated that drivers had a tendency to shift in the lane. Consequently, it was believed that it was not possible to clearly differentiate between natural lane shifting within the lane and natural lane shifting into the opposing lane of travel prior to passing.

Centerline Crossing Time

Data were collected at two different points to evaluate centerline crossing time. Data were first transcribed from video when the front, driver-side tire first contacted the centerline. The next set of data was collected when the front, passenger-side tire last contacted the centerline. The elapsed time between these two events was the centerline crossing time value. This value was not calculated during the video data reduction process. These values were input into a computer, and the differences were calculated in a summary spreadsheet.

Gap Distance

The gap distance was recorded at the start of each successful pass. Data were reduced from the video when the front, driver-side tire first contacted the centerline pavement marking. The actual transcribed value was the physical distance from the bottom of the front of a tracked vehicle in the R1 camera view to the marked horizon line. This value was then input into a power function, and a relative distance was computed. These calculations were also conducted internal to a computer spreadsheet based off of the original transcribed video measurement.

STATISTICAL TESTING ON DIRECTION AND SPEED

This section is subdivided by type of analysis, speed, and MOE with respect to the Comanche project site.

Statistical Significance of Direction

This section of the appendix contains all of the tabulated results of the statistical tests on the data with respect to direction (see Table 103 and Table 104). The Wilcoxon Rank Sum test was used. These tests were categorized by speed and period. The general hypothesis and the associated assumptions for significance were:

- H_0: there is not a difference between data collected at speed *i* in northbound direction from the southbound direction at speed *i* in period *j*;
- H_a: there is a statistical difference between data collected at speed *i* in northbound direction from the southbound direction at speed *i* in period *j*;
- 95 percent confidence interval;
- two-tailed test with z-value = 1.960; and
- reject H_0 if -1.960 > z-stat or if z-stat > 1.960.

Table 103. Gap Distance with Respect to Direction.

DRV Speed	55 mph		60 mph		65 mph	
Period	**Before**	**After**	**Before**	**After**	**Before**	**After**
Sum	1212	684	1608	1056	24	186
T	2034.5	2817.5	2781.0	3760.0	95.5	683.0
Count (Northbound)	40	52	53	63	9	29
Count (Southbound)	52	47	53	47	16	18
μ_T	1860.0	2600.0	2835.5	3496.5	117.0	696.0
σ_T^2	16094.9	20352.3	25013.1	27367.5	311.5	2084.3
σ_T	126.9	142.7	158.2	165.4	17.6	45.7
z-stat	1.375	1.525	-0.345	1.593	-1.218	-0.285

*Indicates that the z-statistic is significant for a two-tailed, 95 percent confidence interval. None of the results were statistically significant.

The null hypothesis was not rejected for any of the tested categories in Table 103 above.

Table 104. Centerline Crossing Time with Respect to Direction.

DRV Speed	55 mph		60 mph		65 mph	
Period	**Before**	**After**	**Before**	**After**	**Before**	**After**
Sum	1062	768	1476	1338	18	204
T	2058.5	2561.0	3052.0	3775.0	99.0	743.0
Count (Northbound)	40	52	53	63	9	29
Count (Southbound)	52	47	53	47	16	18
μ_T	1860.0	2600.0	2835.5	3496.5	117.0	696.0
σ_T^2	16098.0	20350.5	25015.9	27361.7	311.6	2083.9
σ_T	126.9	142.7	158.2	165.4	17.7	45.6
z-stat	1.564	-0.273	1.369	1.684	-1.020	1.030

*Indicates that the z-statistic is significant for a two-tailed, 95 percent confidence interval. None of the results were statistically significant.

The null hypothesis was not rejected for any of the tested categories in Table 104.

Statistical Significance of Speed

This section of the appendix contains all of the tabulated results of the statistical tests on the data with respect to speed (see Table 105 and Table 106). The Wilcoxon Rank Sum test was used. These tests were categorized by speed and period. The general hypothesis and the associated assumptions for significance were:

- H_0: there is not a difference between data collected at speed i_1 from the data at speed i_2 in period j,
- H_a: there is a statistical difference between data collected at speed i_1 from the data at speed i_2 in period j,
- 95 percent confidence interval,
- two-tailed test with z-value = 1.960, and
- reject H_0 if -1.960 > z-stat or if z-stat > 1.960.

Table 105. Gap Distance with Respect to Speed.

DRV Speed	**55 and 60 mph**		**60 and 65 mph**		**55 and 65 mph**	
Period	**Before**	**After**	**Before**	**After**	**Before**	**After**
Sum	8796	4674	2220	3348	1644	1944
T	9180.5	10253.0	6374.0	8713.0	4940.0	7213.0
Count (Speed i_1)	92	99	106	110	92	99
Count (Speed i_2)	106	110	25	47	25	47
μ_T	9154.0	10395.0	6996.0	8690.0	5428.0	7276.5
σ_T^2	161537.4	190477.4	29121.2	68012.8	22593.4	56963.6
σ_T	401.9	436.4	170.6	260.8	150.3	238.7
z-stat	0.066	-0.325	-3.645*	0.088	-3.247*	-0.266

The i_1 speed indicates the first speed listed in the speed category and i_2 denotes the second speed. For the first two columns of values, the i_1 equals 55 mph and the i_2 equals 60 mph.
*Indicates that the z-statistic is significant for a two-tailed, 95 percent confidence interval.

Table 106. Centerline Crossing Time with Respect to Speed.

DRV Speed	**55 and 60 mph**		**60 and 65 mph**		**55 and 65 mph**	
Period	**Before**	**After**	**Before**	**After**	**Before**	**After**
Sum	8556	5400	2250	2694	1686	2862
T	8107.0	11603.5	6828.0	9235.0	5064.0	8271.5
Count (Speed i_1)	92	99	106	110	92	99
Count (Speed i_2)	106	110	25	47	25	47
μ_T	9154.0	10395.0	6996.0	8690.0	5428.0	7276.5
σ_T^2	161542.4	190462.3	29120.8	68024.3	22592.9	56946.8
σ_T	401.9	436.4	170.6	260.8	150.3	238.6
z-stat	-2.605*	2.769*	-0.984	2.090*	-2.422*	4.170*

The i_1 speed indicates the first speed listed in the speed category and i_2 denotes the second speed. For the first two columns of values, the i_1 equals 55 mph and the i_2 equals 60 mph.
*Indicates that the z-statistic is significant for a two-tailed, 95 percent confidence interval.

NUMBER OF CENTERLINE ENCROACHMENTS

These results are solely for the Comanche project site.

Table 107. Test of Proportions for the Number of Centerline Encroachments.

DRV Speed	55 mph	60 mph	65 mph	Combined
P_1	0.052	0.102	0.074	0.079
P_2	0.075	0.106	0.021	0.079
P_0	0.064	0.104	0.040	0.079
N_1	97	118	27	242
N_2	107	123	48	278
t-statistic	-0.678	-0.102	1.129	-0.026

P_1 is the proportion of multiple passes that occurred prior to installing CRSs and P_2 is the proportion after the installation of CRSs. P_0 is a combination of P_1 and P_2. N_1 is the number of observed centerline encroachments prior to installing CRSs and N_2 is the number observed after installing CRSs.

*Indicates that the t-statistic is significant for a two-tailed, 95 percent confidence interval. None of the results were statistically significant.

GAP DISTANCE

All of the data analysis detailed in this section is solely for the Comanche project site.

Table 108. Descriptive Statistics.

DRV Speed	**55 mph**		**60 mph**		**65 mph**		**Combined**	
Period	**Before**	**After**	**Before**	**After**	**Before**	**After**	**Before**	**After**
Sample Size	**92**	**99**	**106**	**110**	**25**	**47**	**223**	**256**
Mean (ft)	47.79	47.81	46.08	46.38	68.55	43.48	49.30	46.40
Std. Error (Mean)	2.320	2.837	1.749	2.441	7.055	2.181	1.554	0.040
C.I. Lower Bound[1] (mean)	43.18	42.18	42.61	41.55	53.99	39.09	46.24	43.32
C.I. Upper Bound[1] (mean)	52.40	53.44	49.55	51.22	83.11	47.87	52.37	49.49
5% Trimmed Mean	46.09	44.86	44.73	43.78	64.99	42.96	47.39	43.74
Median	42.41	39.94	44.04	41.82	66.78	41.27	45.21	41.00
Variance	495.117	796.621	324.180	655.199	1244.211	223.491	538.400	628.877
Std. Deviation	22.251	28.224	18.005	25.597	35.273	14.950	23.203	25.077
Minimum	19	12	17	16	17	21	17	12
Maximum	134	164	106	224	199	78	199	224
Range	116	152	89	208	182	58	182	212
Interquartile Range	33	27	21	25	40	23	32	25
10th Percentile	24	21	26	24	36	26	26	23
15th Percentile	26	23	28	26	40	29	28	26
25th Percentile	31	29	32	30	44	32	32	30
50th Percentile	42	40	44	42	67	41	45	41
75th Percentile	64	55	54	55	82	54	63	55
85th Percentile	73	72	67	65	86	63	72	65
90th Percentile	74	87	71	71	96	64	74	73
Skewness	1.262	1.711	1.070	3.451	2.076	0.502	1.912	2.555
Std. Error (skewness)	0.251	0.243	0.235	0.230	0.464	0.347	0.163	0.152
Kurtosis	2.301	3.284	1.091	20.578	7.070	-0.621	7.674	11.656
Std. Error (Kurtosis)	0.498	0.481	0.465	0.457	0.902	0.681	0.324	0.303

[1] A 95 percent confidence interval (CI) for the mean.

Plots

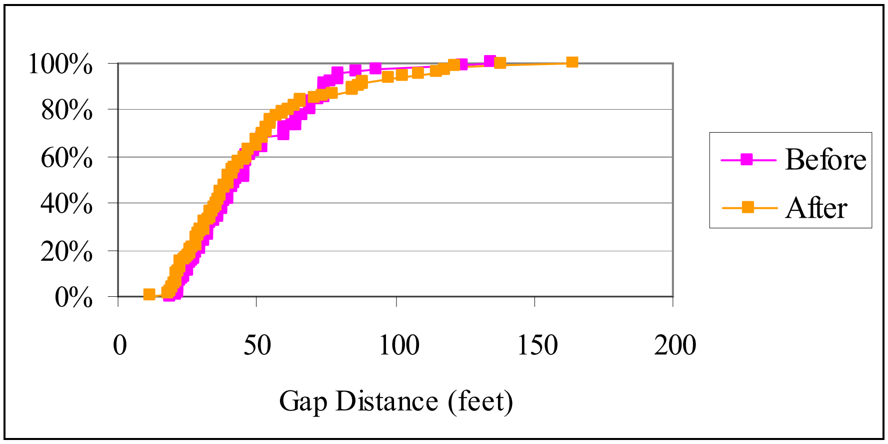


Figure 91. Cumulative Distribution of Gap Distance (55 mph).

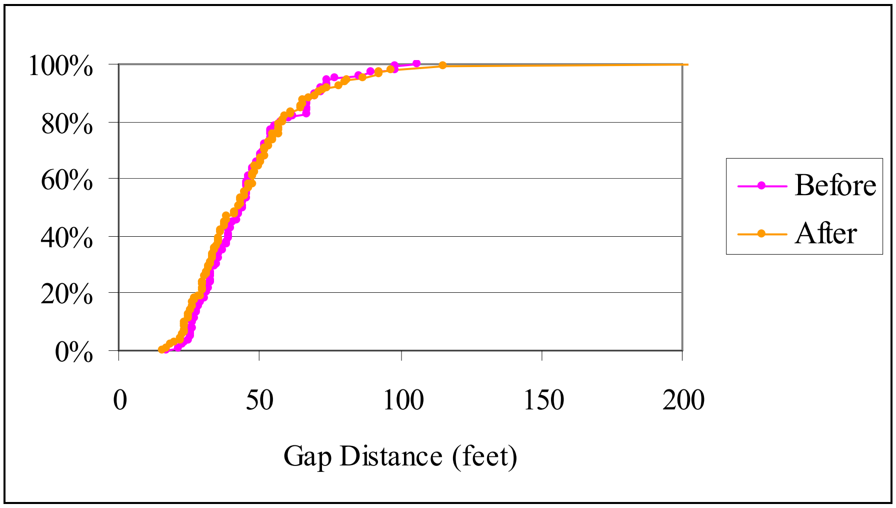


Figure 92. Cumulative Distribution of Gap Distance (60 mph).

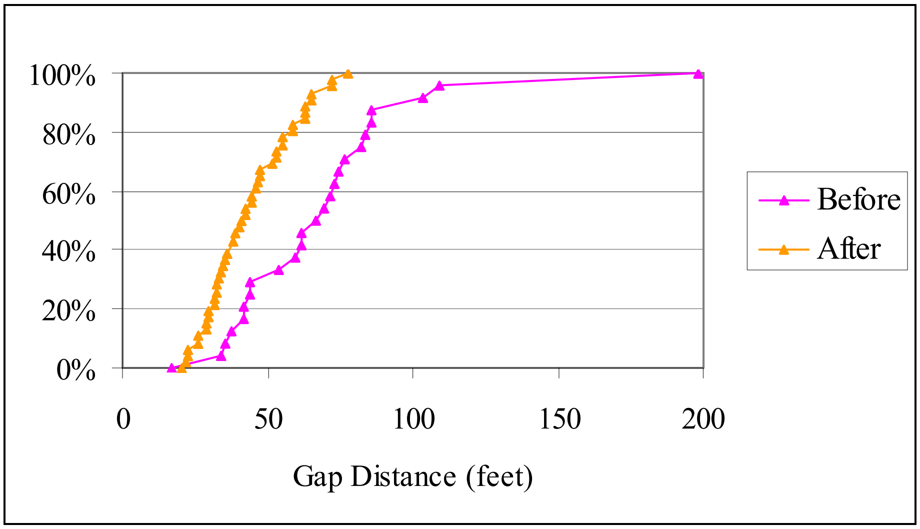


Figure 93. Cumulative Distribution of Gap Distance (65 mph).

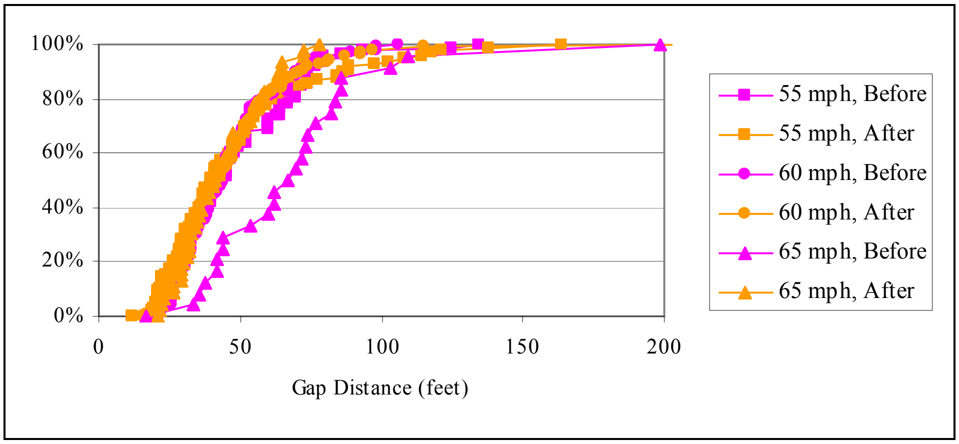


Figure 94. Cumulative Distribution of Gap Distance.

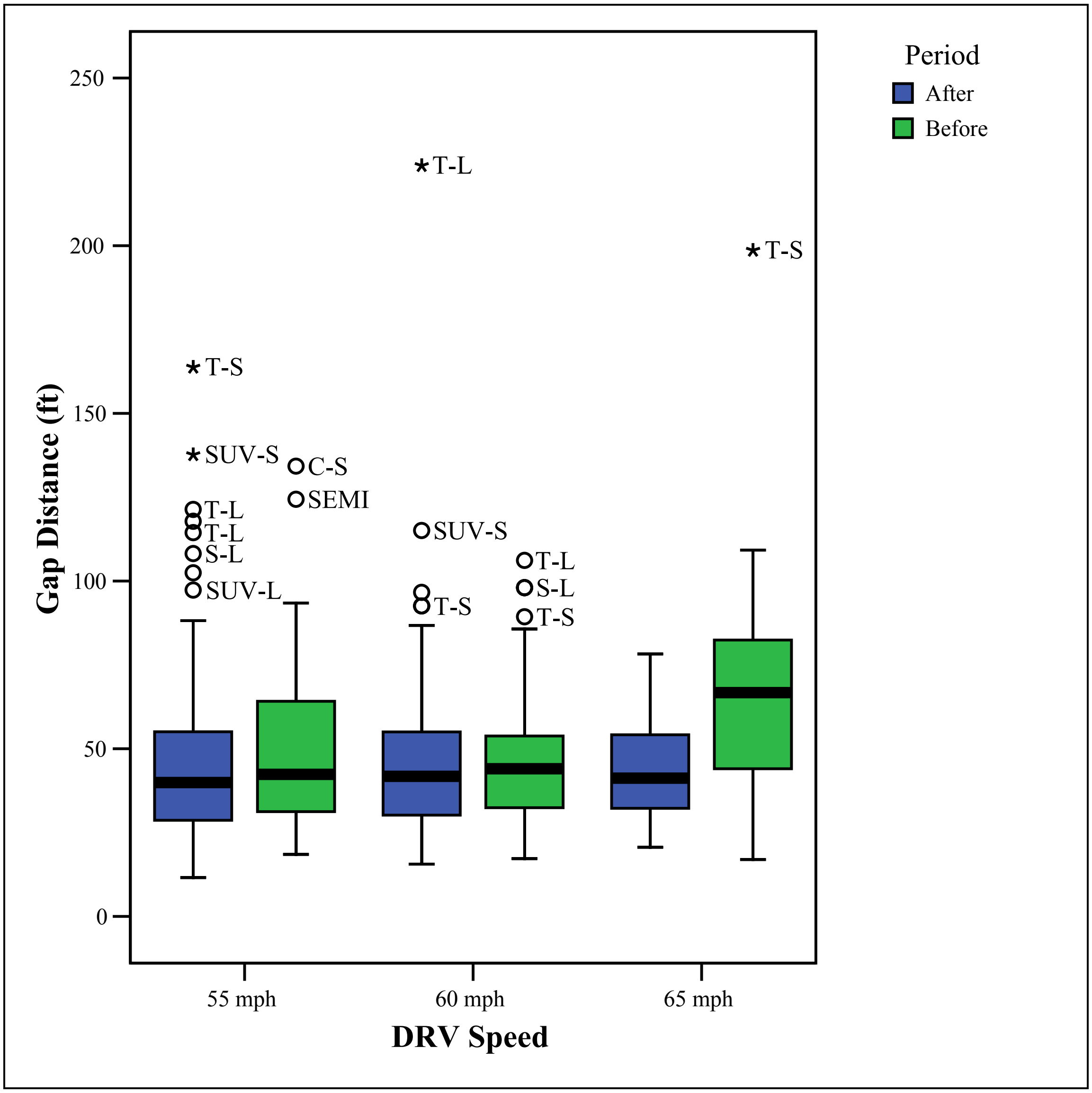


Figure 95. Box Plot of Gap Distance with Respect to Speed.

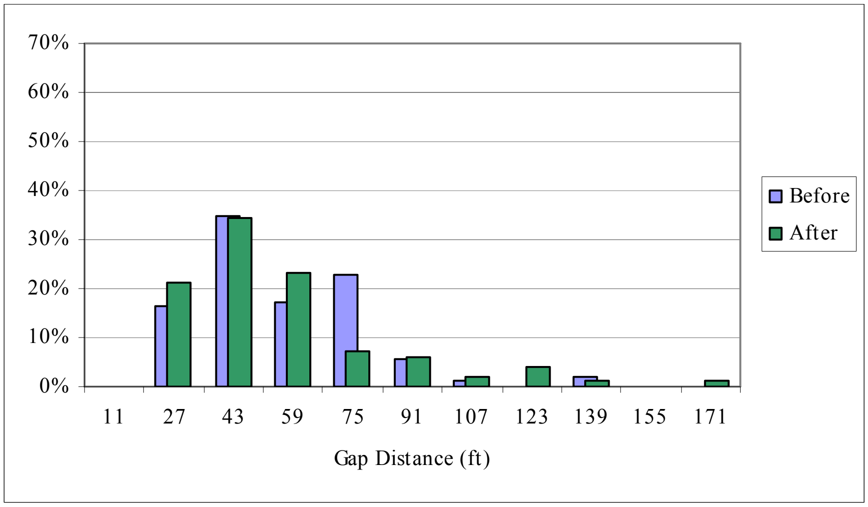


Figure 96. Distribution of Gap Distance (55 mph).

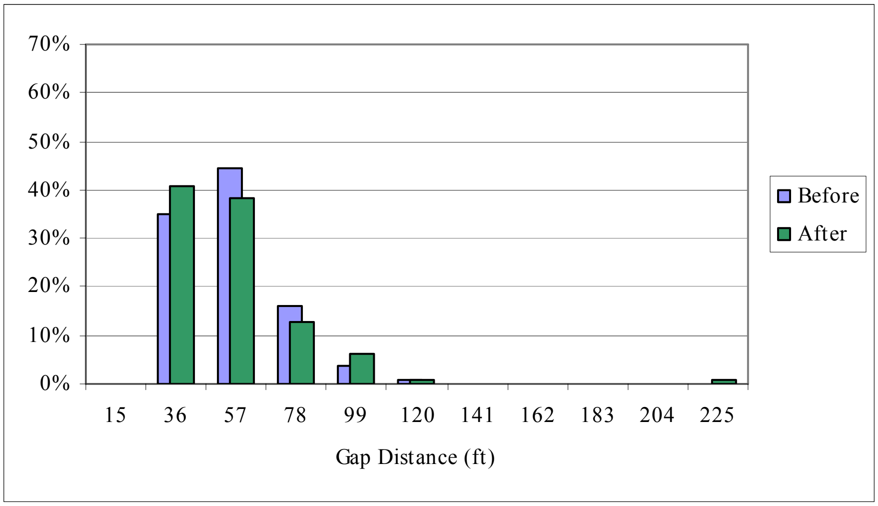


Figure 97. Distribution of Gap Distance (60 mph).

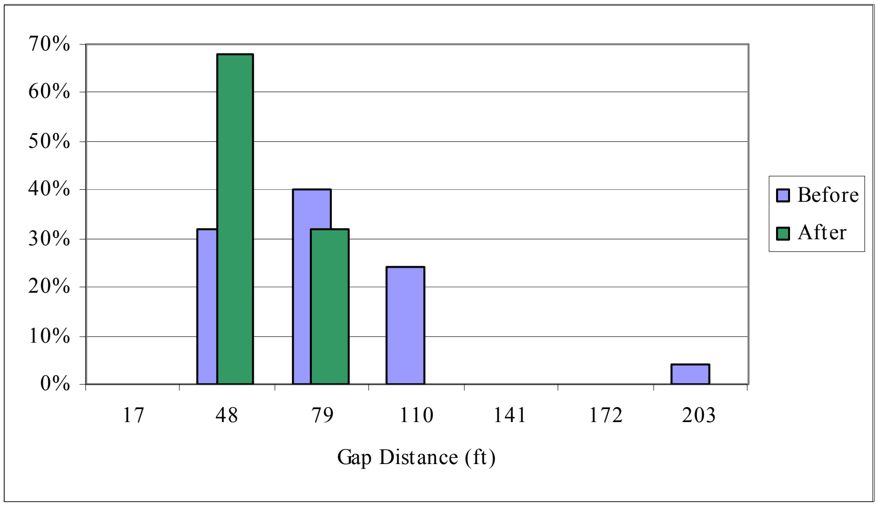


Figure 98. Distribution of Gap Distance (65 mph).

Normality Testing

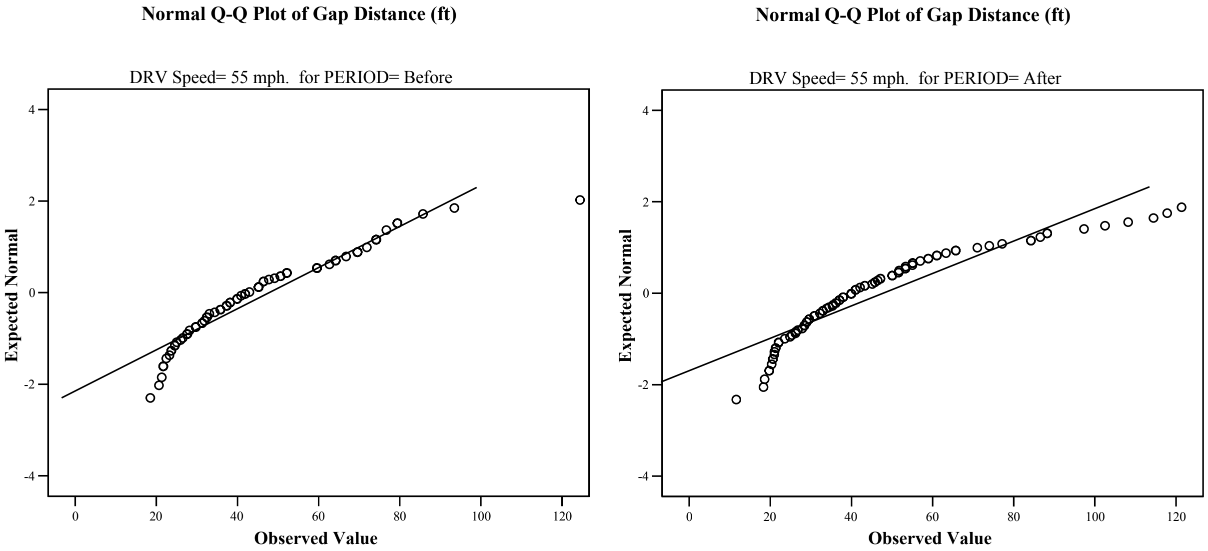


Figure 99. Normal Q-Q Plot of Gap Distance (55 mph).

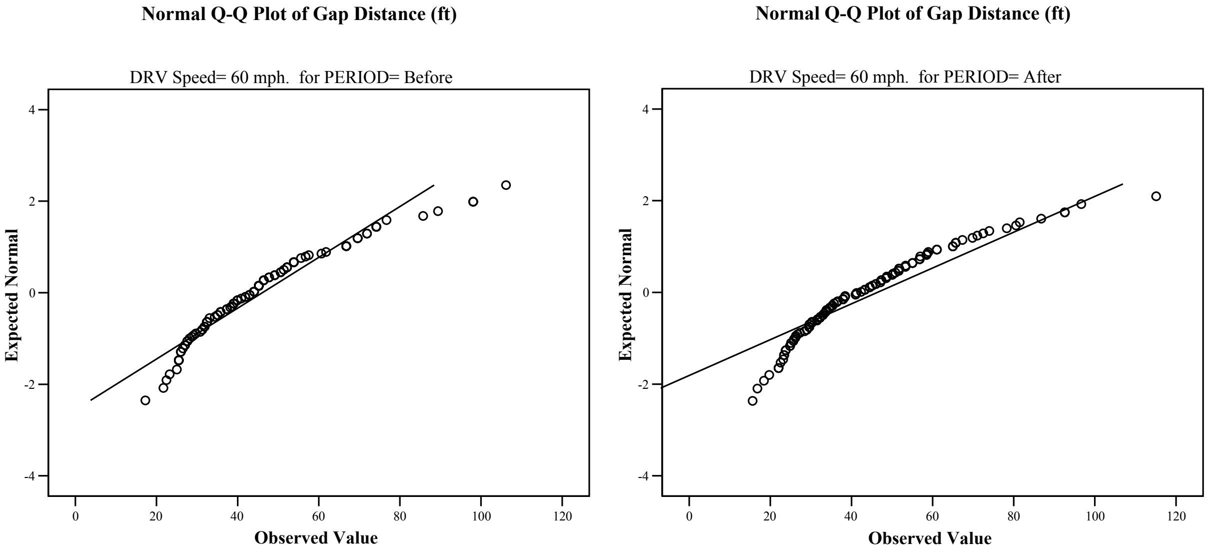
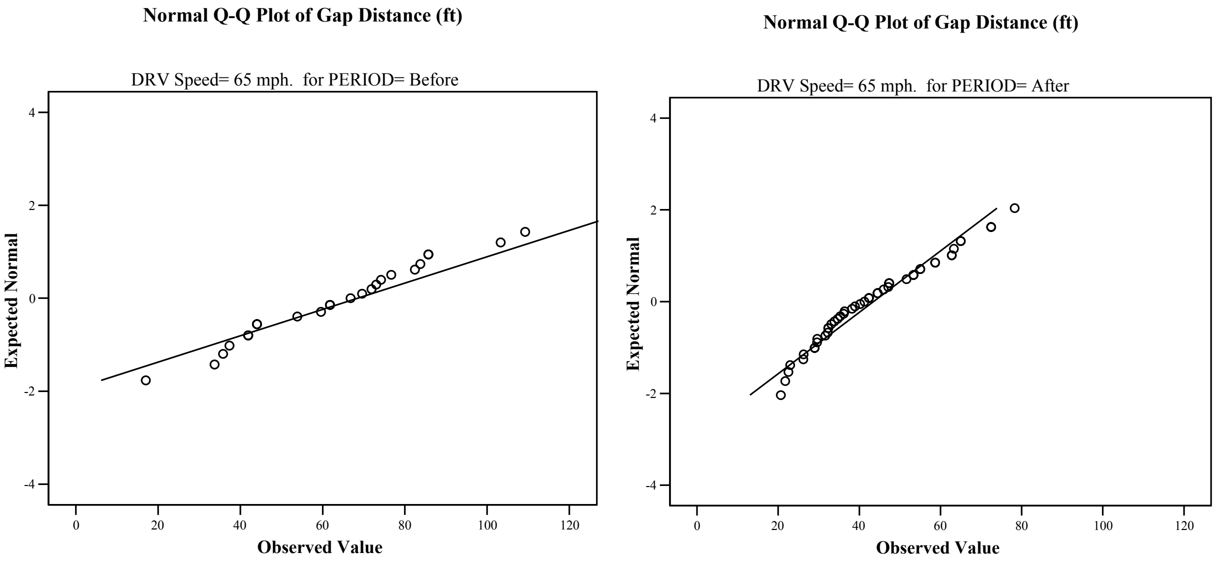


Figure 100. Normal Q-Q Plot of Gap Distance (60 mph).

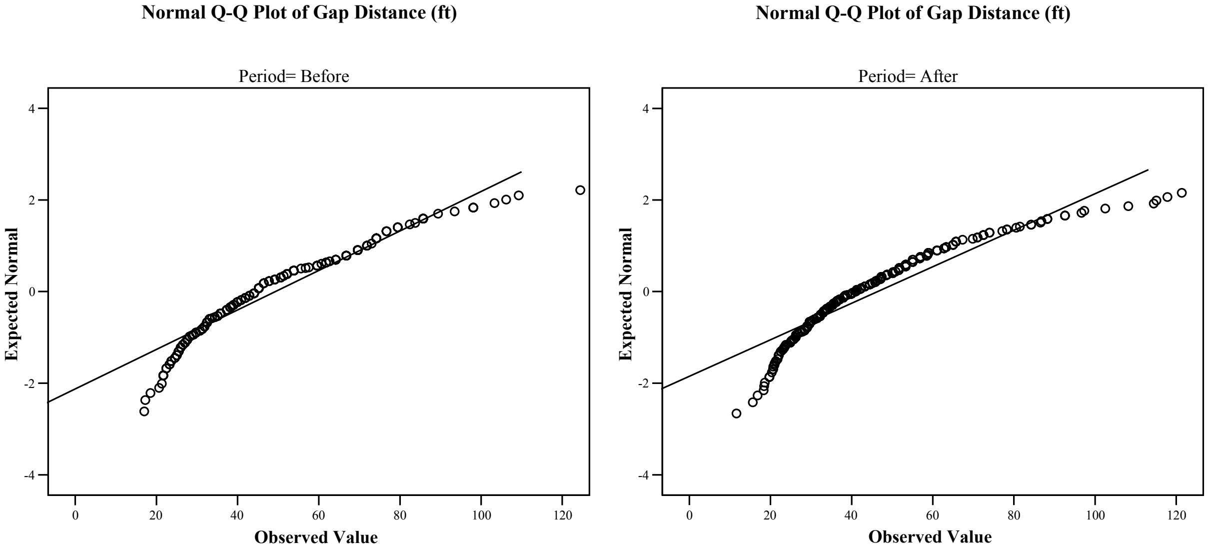

Normal Q-Q Plot of Gap Distance (ft)

DRV Speed= 65 mph. for PERIOD= Before

Normal Q-Q Plot of Gap Distance (ft)

DRV Speed= 65 mph. for PERIOD= After

Figure 101. Normal Q-Q Plot of Gap Distance (65 mph).


Normal Q-Q Plot of Gap Distance (ft)

Period= Before

Normal Q-Q Plot of Gap Distance (ft)

Period= After

Figure 102. Normal Q-Q Plot of Gap Distance (Speeds Combined).

Wilcoxon Rank Sum Test

Table 109 contains the complete Wilcoxon Rank Sum test results conducted on the gap distance data. The general hypothesis and the associated assumptions for significance were:

- H_0: there is not a difference between gap distance data collected at speed *i* between the before and after periods,
- H_1: There is a statistical difference between gap distance data collected at speed *i* between the before and after periods,
- 95 percent confidence interval,
- two-tailed test with z-value = 1.960, and
- reject H_0 if -1.960 > z-stat or if z-stat > 1.960.

Table 109. Gap Distance with Respect to Period.

DRV Speed	55 mph	60 mph	65 mph	Combined
Sum	4596.0	6138.0	342.0	48666.0
T	9140.0	11772.0	1235.5	56552.5
Before	92	106	25	223
After	99	110	47	256
μ_T	8832.0	11501.0	912.5	53520.0
σ_T^2	145631.9	210723.2	7141.4	2282508.8
σ_T	381.6	459.0	84.5	1510.8
z-stat	0.807	0.590	3.822*	2.007*

*Indicates that the z-statistic is significant for a two-tailed, 95 percent confidence interval.

The test results detailed in Table 110 were only from the after period and they did not include all of the data points. Data collected over identical sections of the time on a weekday and a weekend were tested to verify if there was any difference between weekend and weekday data in the after period. No tests were needed for the before data, because the data were collected on weekdays only.

Table 110. Gap Distance with Respect to Weekend and Weekday.

DRV Speed	60 mph	65 mph
Sum	270.0	60.0
T	719.5	173
Weekday	24	13
Weekend	31	16
μ_T	672	195
σ_T^2	3466.4	518.7
σ_T	58.9	22.8
z-stat	0.807	-0.966

*Indicates that the z-statistic is significant for a two-tailed, 95 percent confidence interval. None of the results were statistically significant.

CENTERLINE CROSSING TIME

All of the data analysis detailed in this section is solely for the Comanche project site.

Table 111. Descriptive Statistics for Centerline Crossing Time.

DRV Speed	**55 mph**		**60 mph**		**65 mph**		**Combined**	
Period	**Before**	**After**	**Before**	**After**	**Before**	**After**	**Before**	**After**
Sample Size	92	99	106	110	25	47	223	256
Mean (sec)	1.7706	2.2458	1.9724	1.9612	2.0245	1.7714	1.8950	2.0364
Std. Error (Mean)	0.09784	0.06813	0.08068	0.05594	0.13380	0.07473	0.05787	0.03970
C.I. Lower Bound[1] (mean)	1.5762	2.1106	1.8124	1.8503	1.7484	1.6210	1.7809	1.9582
C.I. Upper Bound[1] (mean)	1.9649	2.3810	2.1324	2.0720	2.3007	1.9218	2.0090	2.1146
5% Trimmed Mean	1.6548	2.2165	1.8879	1.9571	2.0119	1.7459	1.8056	2.0137
Median	1.5826	2.1125	1.8821	1.9830	2.0881	1.6678	1.7851	1.9891
Variance	0.881	0.459	0.690	0.344	0.448	0.262	0.747	0.403
Std. Deviation	0.93843	0.67784	0.83070	0.58674	0.66901	0.51230	0.86425	0.63521
Minimum	0.71	0.88	0.81	0.55	0.80	0.99	0.71	0.55
Maximum	7.93	4.39	6.06	3.39	3.45	3.38	7.93	4.39
Range	7.22	3.51	5.25	2.84	2.65	2.39	7.22	3.84
Interquartile Range	0.77	0.94	0.84	0.92	0.85	0.64	0.82	0.94
10th Percentile	1.01	1.47	1.12	1.19	1.18	1.20	1.09	1.31
15th Percentile	1.10	1.51	1.20	1.33	1.34	1.30	1.17	1.39
25th Percentile	1.23	1.78	1.40	1.48	1.52	1.41	1.32	1.52
50th Percentile	1.58	2.11	1.88	1.98	2.09	1.67	1.79	1.99
75th Percentile	1.99	2.71	2.22	2.39	2.32	2.03	2.12	2.45
85th Percentile	2.23	2.93	2.72	2.65	2.56	2.32	2.52	2.72
90th Percentile	2.55	3.10	2.91	2.74	2.87	2.52	2.81	2.82
Skewness	3.757	0.606	2.030	0.073	0.295	0.892	2.741	0.543
Std. Error (skewness)	0.251	0.243	0.235	0.230	0.464	0.347	0.163	0.152
Kurtosis	20.803	0.258	6.652	-0.546	-0.131	0.885	13.245	0.303
Std. Error (Kurtosis)	0.498	0.481	0.465	0.457	0.902	0.681	0.324	0.303

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[1] Confidence interval (C.I.).

Plots

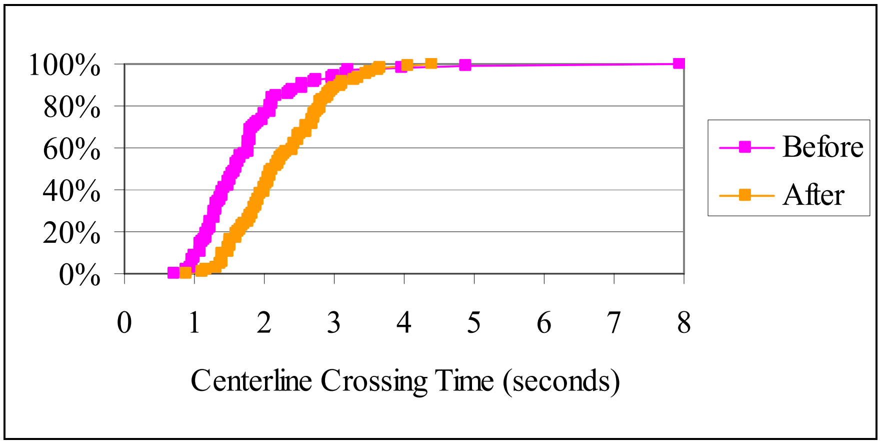


Figure 103. Cumulative Distribution of Centerline Crossing Time (55 mph).

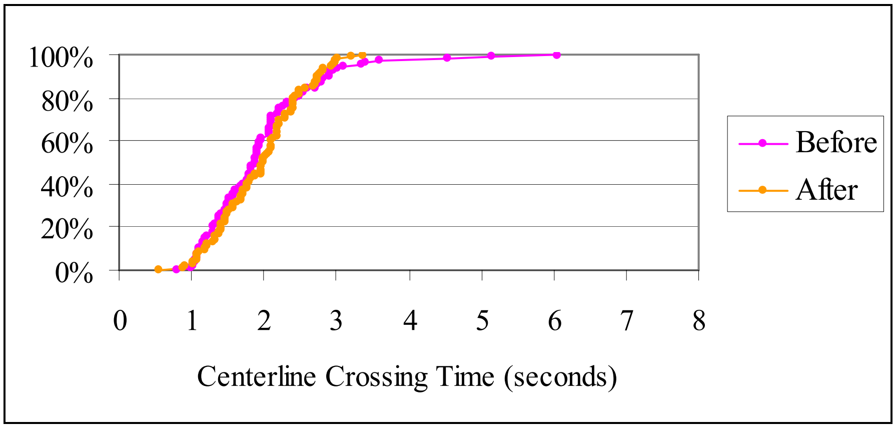


Figure 104. Cumulative Distribution of Centerline Crossing Time (60 mph).

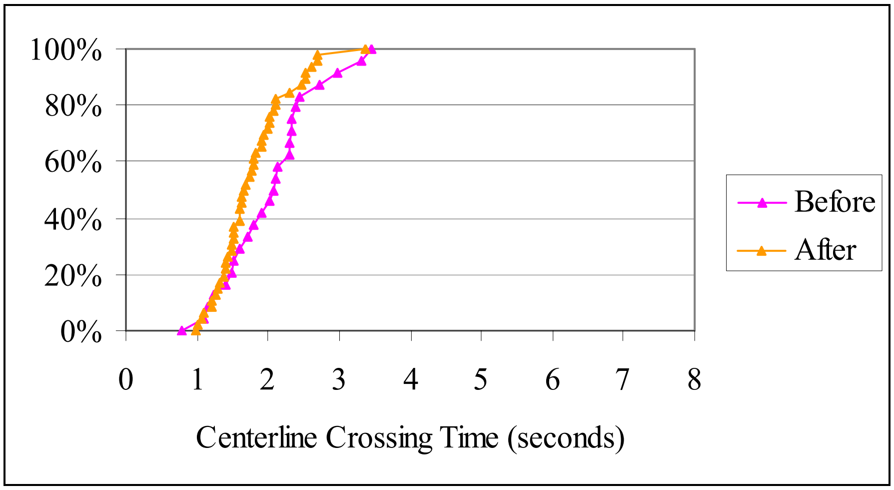


Figure 105. Cumulative Distribution of Centerline Crossing Time (65 mph).

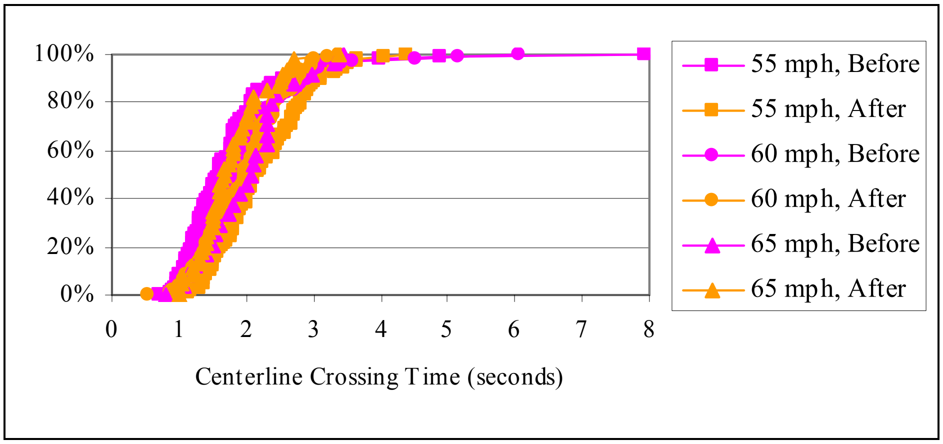


Figure 106. Cumulative Distribution of Centerline Crossing Time.

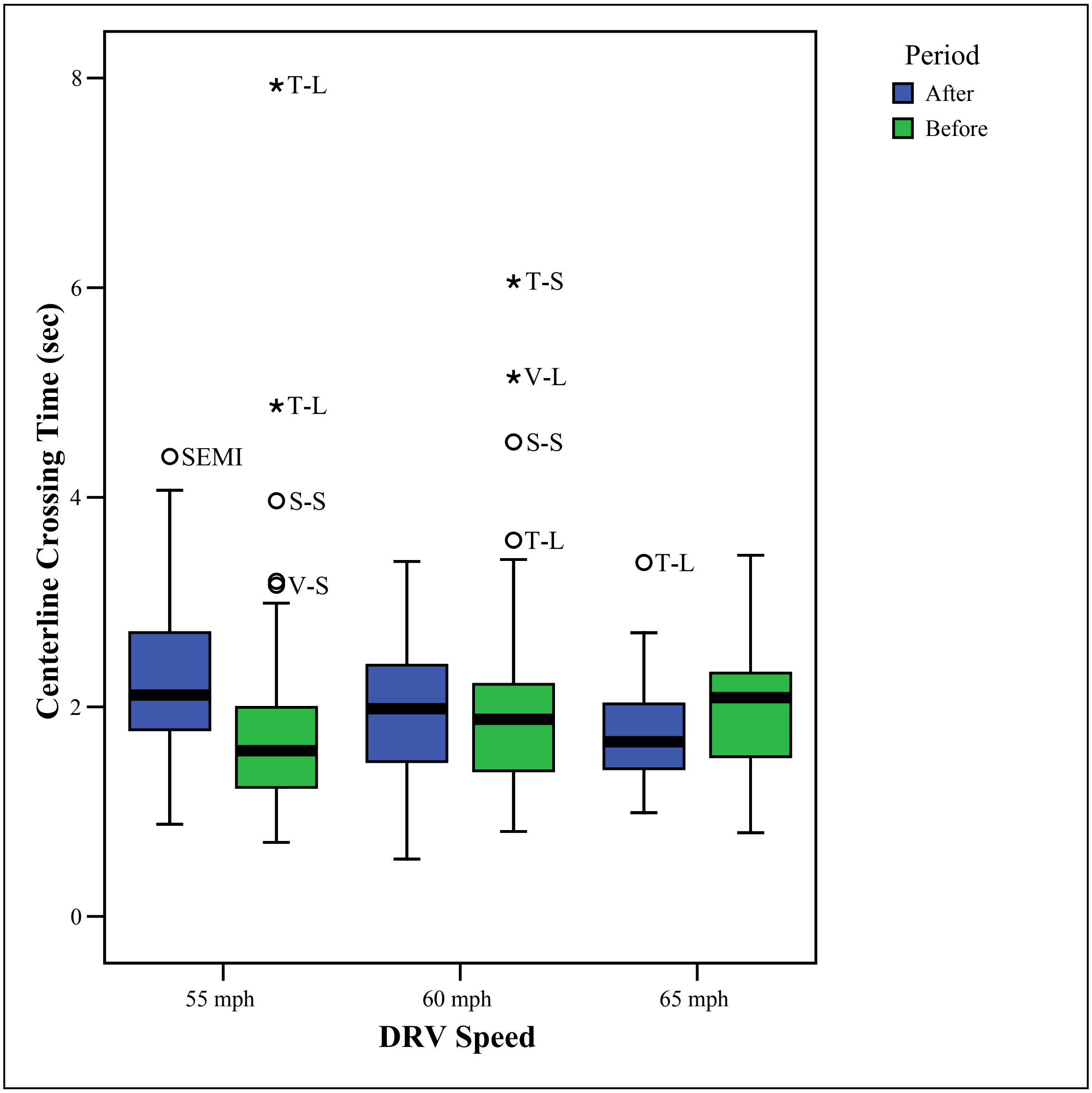


Figure 107. Box Plot of Centerline Crossing Time with Respect to Speed.

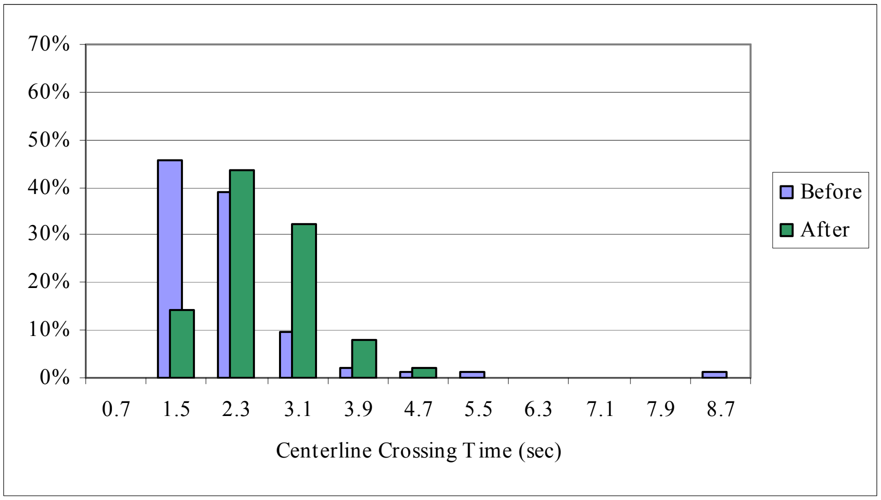


Figure 108. Distribution of Centerline Crossing Time (55 mph).

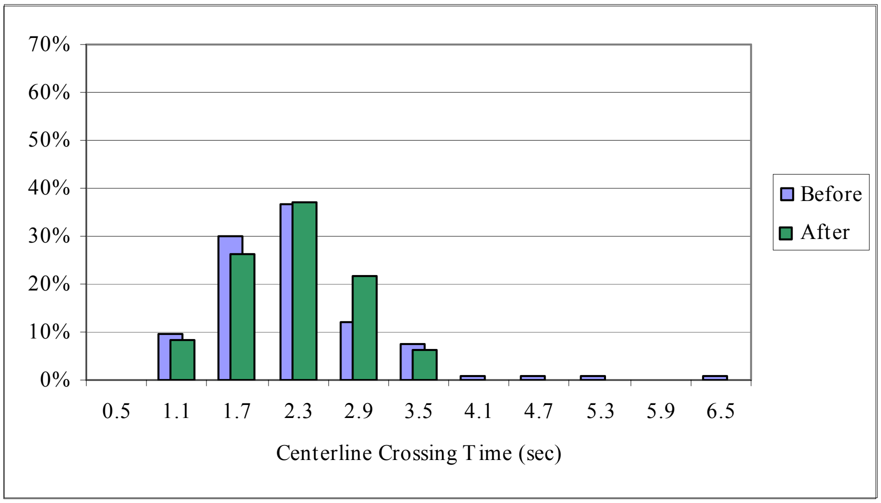


Figure 109. Distribution of Centerline Crossing Time (60 mph).

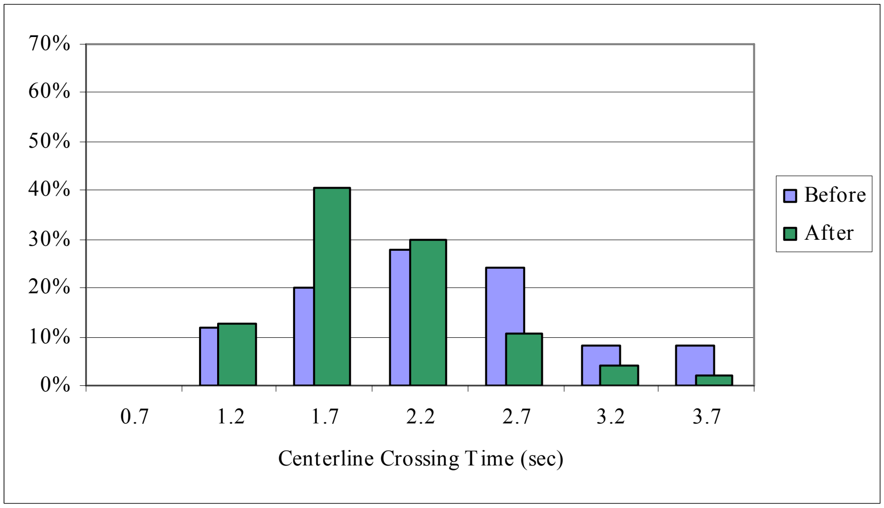
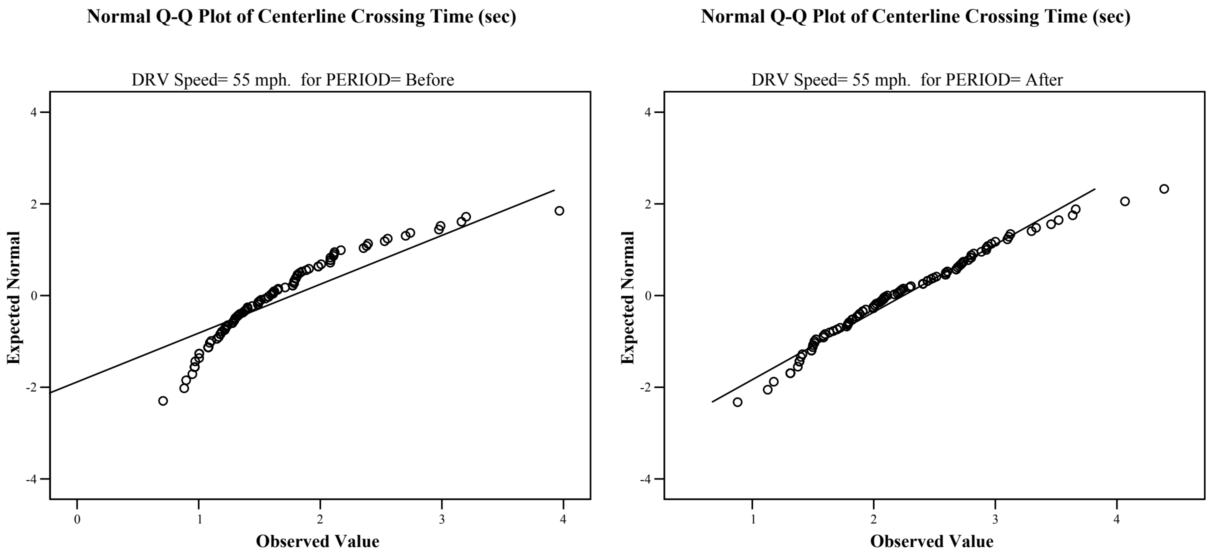


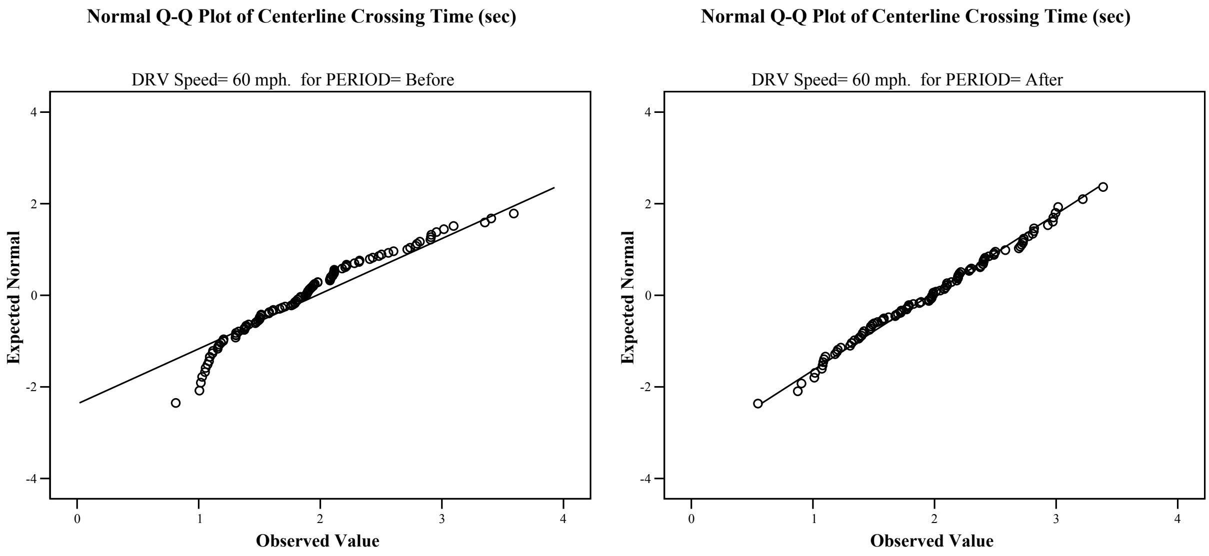
Figure 110. Distribution of Centerline Crossing Time (65 mph).

Normality Testing


Normal Q-Q Plot of Centerline Crossing Time (sec)

Normal Q-Q Plot of Centerline Crossing Time (sec)

Figure 111. Normal Q-Q Plot of Centerline Crossing Time (55 mph).


Normal Q-Q Plot of Centerline Crossing Time (sec)

Normal Q-Q Plot of Centerline Crossing Time (sec)

Figure 112. Normal Q-Q Plot of Centerline Crossing Time (60 mph).

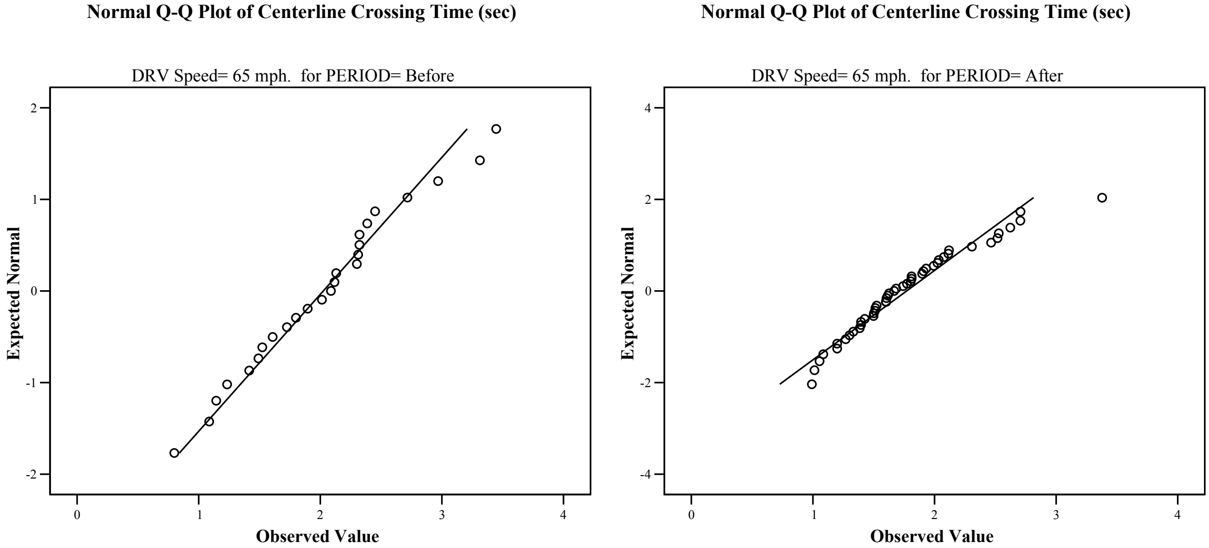


Figure 113. Normal Q-Q Plot of Centerline Crossing Time (65 mph).

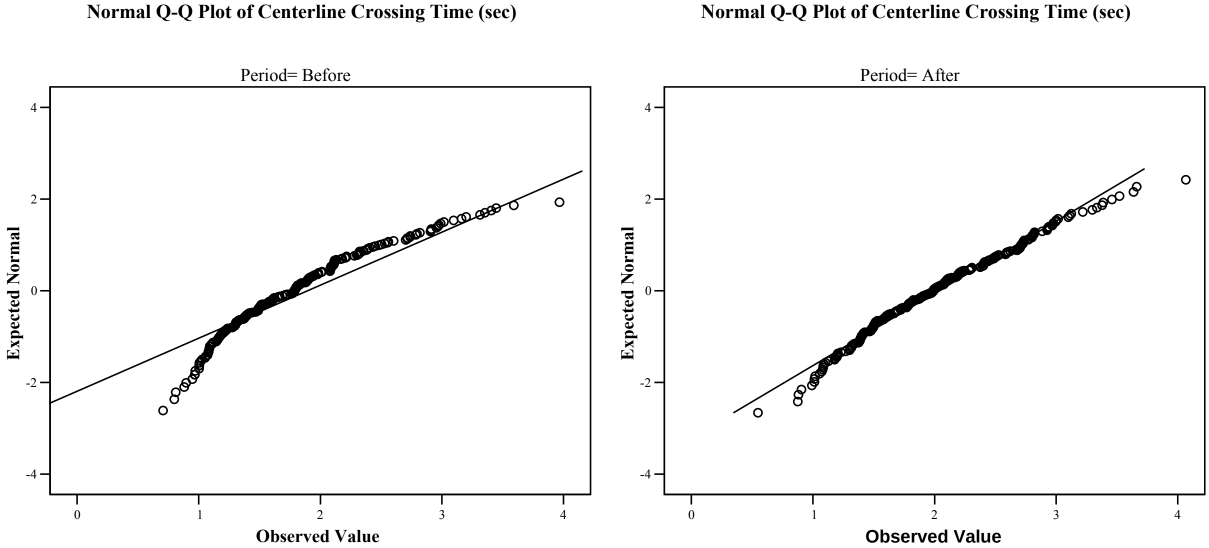


Figure 114. Normal Q-Q Plot of Centerline Crossing Time (Speeds Combined).

Wilcoxon Rank Sum Test

Table 112 contains the complete Wilcoxon Rank Sum test results conducted on the centerline crossing time data. The general hypothesis and the associated assumptions for significance were:

- H_0: there is not a difference between centerline crossing time data collected at speed *i* between the before and after period,
- H_1: there is a statistical difference between centerline crossing time data collected at speed *i* between the before and after period,
- 95 percent confidence interval,
- two-tailed test with z-value = 1.960, and
- reject H_0 if -1.960 > z-stat or if z-stat > 1.960.

Table 112. Centerline Crossing Time with Respect to Period.

DRV Speed	**55 mph**	**60 mph**	**65 mph**	**Combined**
Sum	5154.0	7836.0	522.0	68934.0
T	6658.0	11028.5	1058.0	47998.5
Before	92	106	25	223
After	99	110	47	256
μ_T	8832.0	11501.0	912.5	53520.0
σ_T^2	145620.2	210687.7	7137.9	2282087.7
σ_T	381.6	459.0	84.5	1510.7
z-stat	-5.697*	-1.029	1.722	-3.655*

*Indicates that the z-statistic is significant for a two-tailed, 95 percent confidence interval.

The test results detailed in Table 113 were only from the after period and they did not include all of the data points. Data collected over identical sections of the time on a weekday and a weekend were tested to verify if there was any difference between weekend and weekday data in the after period. No tests were needed for the before data, because the data were collected on weekdays only.

Table 113. Centerline Crossing Time with Respect to Weekday and Weekend.

DRV Speed	**60 mph**	**65 mph**
Sum	240.0	48.0
T	391.5	277.5
Weekday	24	13
Weekend	31	16
μ_T	672	195
σ_T^2	3467.0	519.0
σ_T	58.9	22.8
z-stat	-4.764*	3.621*

*Indicates that the z-statistic is significant for a two-tailed, 95 percent confidence interval.

PASSING OPPORTUNITY

All of the data analysis detailed in this section is solely for the Comanche project site. Table 114 contains the results from a Wilcoxon Rank Sum Test of passing opportunity.

Table 114. Wilcoxon Rank Sum Test for Passing Opportunity.

Parameter	Passing Opportunity			
Speed	55 mph	60 mph	65 mph	Combined
Direction	NB & SB	NB & SB	NB & SB	NB & SB
Sum	42066	19914	714	249240
T	8061.5	11881.0	920.0	52101.5
Before	92	106	25	223
After	99	110	47	256
μ_T	8832.0	11501.0	912.5	53520.0
σ_T^2	144848.2	210435.0	7134.2	2278341.3
σ_T	380.6	458.7	84.5	1509.4
z-stat	-2.024*	0.828	0.089	-0.940

*Indicates that the z-statistic is significant for a two-tailed, 95 percent confidence interval.

PERCENTAGE OF PASSING

All of the data analysis detailed in this section is solely for the Comanche project site. Table 115 contains the results from a test of proportions on the percentage of passing.

Table 115. Test of Proportions for Percentage of Passing.

DRV Speed	**55 mph**		**60 mph**		**65 mph**		**Combined**	
Period	*Before*	*After*	*Before*	*After*	*Before*	*After*	*Before*	*After*
No Pass	13	15	31	39	13	30	57	84
Pass	92	99	106	110	25	47	223	256
% No Pass	12.4%	13.2%	22.6%	26.2%	34.2%	39.0%	20.4%	24.7%
N	105	114	137	149	38	77	280	340
p_0	12.8%		24.5%		37.4%		22.7%	
t-stat	-0.17		-0.70		-0.50		-1.29	

*Indicates that the t-statistic is significant for a two-tailed, 95 percent confidence interval. None of the results were statistically significant.

LATERAL POSITION

All of the data analysis detailed in this section (Table 116 – Table 132) is for the following project sites:

- FM 195 (Curve 1 and 2),
- FM 969 (Tangent and Curve),
- FM 1431 (Tangent and Curve), and
- FM 2222 (Tangent and Curve).

Table 116. Table and Figure Directional Matrix Explanation.

Site	Direction[1]	Direction[2]
FM 195 (Curve #1)	In	Inside
FM 195 (Curve #1)	Out	Outside
FM 195 (Curve #2)	In	Outside
FM 195 (Curve #2)	Out	Inside
FM 969 (Curve)	In	Outside
FM 969 (Curve)	Out	Inside
FM 969 (Tangent)	In	Direction 1
FM 969 (Tangent)	Out	Direction 2
FM 1431 (Curve)	In	Inside
FM 1431 (Curve)	Out	Outside
FM 1431 (Tangent)	In	Direction 1
FM 1431 (Tangent)	Out	Direction 2
FM 2222 (Curve)	In	Outside
FM 2222 (Curve)	Out	Inside
FM 2222 (Tangent)	In	Direction 1
FM 2222 (Tangent)	Out	Direction 2

[1] Vehicles were observed traveling "In" and "Out" of the television screen.
[2] Direction will be referenced in graphs in this manner, and in particular, "Inside" denotes a vehicle on the inside of a horizontal curve and "Direction 1 & 2" only indicates that there were two different directions of travel.

Table 117. Summary Count for FM 195 (Curve 1, Inside Lane).

Roadway	**Alignment**	**Direction**	**Distance (inches)[1]**									
FM 195	**Curve 1**	**In**	**<0**	**0**	**6**	**12**	**18**	**24**	**30**	**36**	**42**	**>42**
Before	Motorcycle	2	0	0	0	0	0	0	0	1	1	0
Before	Passenger Vehicle	648	0	0	0	1	0	2	8	42	595	0
Before	Large Truck	78	0	1	0	0	2	4	4	13	54	0
Before	All	728	0	1	0	1	2	6	12	56	650	0
After	Motorcycle	4	0	0	0	0	0	0	0	1	0	3
After	Passenger Vehicle	509	0	0	0	0	0	0	4	11	32	462
After	Large Truck	75	0	0	0	0	1	4	8	9	21	32
After	All	588	0	0	0	0	1	4	12	21	53	497

[1] Distances were measured from the outside edge of the centerline marking nearest the travel flow for the direction of traffic being observed. The presented values are binned data.

Table 118. Summary Count for FM 195 (Curve 1, Outside Lane).

Roadway	Alignment	Direction	Distance (inches)[1]									
FM 195	**Curve 1**	**Out**	**<0**	**0**	**6**	**12**	**18**	**24**	**30**	**36**	**42**	**>42**
Before	Motorcycle	1	0	0	0	0	0	0	0	0	0	1
Before	Passenger Vehicle	646	0	1	11	31	39	72	103	99	124	166
Before	Large Truck	60	0	0	2	4	12	12	9	6	10	5
Before	All	707	0	1	13	35	51	84	112	105	134	172
After	Motorcycle	0	0	0	0	0	0	0	0	0	0	0
After	Passenger Vehicle	453	1	1	1	3	8	13	41	63	64	258
After	Large Truck	55	0	0	0	1	1	4	8	12	13	16
After	All	508	1	1	1	4	9	17	49	75	77	274

[1] Distances were measured from the outside edge of the centerline marking nearest the travel flow for the direction of traffic being observed. The presented values are binned data.

Table 119. Summary Count for FM 195 (Curve 2, Outside Lane).

Roadway	Alignment	Direction	Distance (inches)[1]									
FM 195	**Curve 2**	**In**	**<0**	**0**	**6**	**12**	**18**	**24**	**30**	**36**	**42**	**>42**
Before	Motorcycle	0	0	0	0	0	0	0	0	0	0	0
Before	Passenger Vehicle	541	0	16	43	53	97	77	88	44	39	84
Before	Large Truck	56	0	2	11	3	8	11	9	3	2	7
Before	All	597	0	18	54	56	105	88	97	47	41	91
After	Motorcycle	5	0	0	0	0	0	0	0	0	1	4
After	Passenger Vehicle	993	0	2	5	25	68	156	184	175	170	208
After	Large Truck	50	1	0	2	3	6	8	17	2	4	7
After	All	1048	1	2	7	28	74	164	201	177	175	219

[1] Distances were measured from the outside edge of the centerline marking nearest the travel flow for the direction of traffic being observed. The presented values are binned data.

Table 120. Summary Count for FM 195 (Curve 2, Inside Lane).

Roadway	Alignment	Direction	Distance (inches)[1]									
FM 195	**Curve 2**	**Out**	**<0**	**0**	**6**	**12**	**18**	**24**	**30**	**36**	**42**	**>42**
Before	Motorcycle	0	0	0	0	0	0	0	0	0	0	0
Before	Passenger Vehicle	449	0	0	2	8	14	26	66	42	70	221
Before	Large Truck	63	0	0	2	3	0	5	8	6	9	30
Before	All	512	0	0	4	11	14	31	74	48	79	251
After	Motorcycle	2	0	0	0	0	0	0	1	0	0	1
After	Passenger Vehicle	1140	3	10	15	50	132	186	246	202	158	138
After	Large Truck	44	1	2	5	6	5	6	9	4	1	5
After	All	1186	4	12	20	56	137	192	256	206	159	144

[1] Distances were measured from the outside edge of the centerline marking nearest the travel flow for the direction of traffic being observed. The presented values are binned data.

Table 121. Summary Count for FM 969 (Tangent, Direction 1).

Roadway	Alignment	Direction	Distance (inches)[1]									
FM 969	**Tangent**	**In**	**<0**	**0**	**6**	**12**	**18**	**24**	**30**	**36**	**42**	**>42**
Before	Motorcycle	0	0	0	0	0	0	0	0	0	0	0
Before	Passenger Vehicle	155	0	1	7	18	26	46	28	19	6	4
Before	Large Truck	90	0	1	33	20	26	6	4	0	0	0
Before	All	245	0	2	40	38	52	52	32	19	6	4
After	Motorcycle	2	0	0	0	0	0	0	0	1	0	1
After	Passenger Vehicle	654	5	43	74	143	150	138	69	23	7	2
After	Large Truck	50	0	5	14	18	6	4	1	1	1	0
After	All	706	5	48	88	161	156	142	70	25	8	3

[1] Distances were measured from the outside edge of the centerline marking nearest the travel flow for the direction of traffic being observed. The presented values are binned data.

Table 122. Summary Count for FM 969 (Tangent, Direction 2).

Roadway	Alignment	Direction	Distance (inches)[1]									
FM 969	**Tangent**	**Out**	**<0**	**0**	**6**	**12**	**18**	**24**	**30**	**36**	**42**	**>42**
Before	Motorcycle	2	0	0	0	0	0	0	0	1	0	1
Before	Passenger Vehicle	295	0	0	1	5	20	29	51	57	65	67
Before	Large Truck	87	0	1	5	8	28	24	19	2	0	0
Before	All	384	0	1	6	13	48	53	70	60	65	68
After	Motorcycle	0	0	0	0	0	0	0	0	0	0	0
After	Passenger Vehicle	267	0	2	0	2	1	22	34	52	65	89
After	Large Truck	45	0	1	1	5	15	9	8	4	1	1
After	All	312	0	3	1	7	16	31	42	56	66	90

[1] Distances were measured from the outside edge of the centerline marking nearest the travel flow for the direction of traffic being observed. The presented values are binned data.

Table 123. Summary Count for FM 969 (Curve, Outside Lane).

Roadway	Alignment	Direction	Distance (inches)[1]									
FM 969	**Curve**	**In**	**<0**	**0**	**6**	**12**	**18**	**24**	**30**	**36**	**42**	**>42**
Before	Motorcycle	1	0	0	0	0	0	1	0	0	0	0
Before	Passenger Vehicle	348	56	26	99	80	46	26	11	3	0	1
Before	Large Truck	70	28	15	24	2	1	0	0	0	0	0
Before	All	419	84	41	123	82	47	27	11	3	0	1
After	Motorcycle	3	0	0	0	1	0	1	0	0	0	1
After	Passenger Vehicle	209	20	31	45	50	27	20	11	2	1	2
After	Large Truck	116	39	28	39	5	5	0	0	0	0	0
After	All	328	59	59	84	56	32	21	11	2	1	3

[1] Distances were measured from the outside edge of the centerline marking nearest the travel flow for the direction of traffic being observed. The presented values are binned data.

Table 124. Summary Count for FM 969 (Curve, Inside Lane).

Roadway	Alignment	Direction	Distance (inches)[1]									
FM 969	**Curve**	**Out**	**<0**	**0**	**6**	**12**	**18**	**24**	**30**	**36**	**42**	**>42**
Before	Motorcycle	2	0	0	0	0	0	1	0	0	0	1
Before	Passenger Vehicle	164	3	4	11	15	15	24	29	25	18	20
Before	Large Truck	64	6	3	19	17	9	7	3	0	0	0
Before	All	230	9	7	30	32	24	32	32	25	18	21
After	Motorcycle	3	0	0	0	0	0	0	0	0	1	2
After	Passenger Vehicle	285	4	1	2	7	37	42	53	47	37	55
After	Large Truck	120	5	9	10	25	24	28	14	3	2	0
After	All	408	9	10	12	32	61	70	67	50	40	57

[1] Distances were measured from the outside edge of the centerline marking nearest the travel flow for the direction of traffic being observed. The presented values are binned data.

Table 125. Summary Count for FM 1431 (Tangent, Direction 1).

Roadway	Alignment	Direction	Distance (inches)[1]									
FM 1431	**Tangent**	**In**	**<0**	**0**	**6**	**12**	**18**	**24**	**30**	**36**	**42**	**>42**
Before	Motorcycle	6	0	0	0	0	0	0	1	0	0	5
Before	Passenger Vehicle	671	0	5	22	78	133	146	141	66	33	47
Before	Large Truck	15	0	0	1	6	1	4	1	1	0	1
Before	All	692	0	5	23	84	134	150	143	67	33	53
After	Motorcycle	3	0	0	0	0	0	0	0	0	0	3
After	Passenger Vehicle	412	0	0	0	7	21	57	100	92	76	59
After	Large Truck	17	0	0	1	0	4	4	4	1	1	2
After	All	432	0	0	1	7	25	61	104	93	77	64

[1] Distances were measured from the outside edge of the centerline marking nearest the travel flow for the direction of traffic being observed. The presented values are binned data.

Table 126. Summary Count for FM 1431 (Tangent, Direction 2).

Roadway	Alignment	Direction	Distance (inches)[1]									
FM 1431	**Tangent**	**Out**	**<0**	**0**	**6**	**12**	**18**	**24**	**30**	**36**	**42**	**>42**
Before	Motorcycle	0	0	0	0	0	0	0	0	0	0	0
Before	Passenger Vehicle	307	0	0	0	8	2	8	41	32	78	138
Before	Large Truck	14	0	0	0	0	0	5	1	5	1	2
Before	All	321	0	0	0	8	2	13	42	37	79	140
After	Motorcycle	0	0	0	0	0	0	0	0	0	0	0
After	Passenger Vehicle	342	0	0	0	0	5	30	43	65	86	113
After	Large Truck	16	0	0	0	2	1	5	3	0	4	1
After	All	358	0	0	0	2	6	35	46	65	90	114

[1] Distances were measured from the outside edge of the centerline marking nearest the travel flow for the direction of traffic being observed. The presented values are binned data.

Table 127. Summary Count for FM 1431 (Curve, Inside Lane).

Roadway	Alignment	Direction	Distance (inches)[1]									
FM 1431	**Curve**	**In**	**<0**	**0**	**6**	**12**	**18**	**24**	**30**	**36**	**42**	**>42**
Before	Motorcycle	3	0	0	0	0	0	0	0	1	0	2
Before	Passenger Vehicle	639	0	0	1	24	44	135	136	159	85	55
Before	Large Truck	6	0	0	0	1	0	0	0	1	2	2
Before	All	648	0	0	1	25	44	135	136	161	87	59
After	Motorcycle	0	0	0	0	0	0	0	0	0	0	0
After	Passenger Vehicle	230	0	0	0	2	8	26	32	51	50	61
After	Large Truck	13	0	0	1	0	3	3	4	2	0	0
After	All	243	0	0	1	2	11	29	36	53	50	61

[1] Distances were measured from the outside edge of the centerline marking nearest the travel flow for the direction of traffic being observed. The presented values are binned data.

Table 128. Summary Count for FM 1431 (Curve, Outside Lane).

Roadway	Alignment	Direction	Distance (inches)[1]									
FM 1431	**Curve**	**Out**	**<0**	**0**	**6**	**12**	**18**	**24**	**30**	**36**	**42**	**>42**
Before	Motorcycle	4	0	0	0	0	0	0	0	1	1	2
Before	Passenger Vehicle	455	0	2	8	5	28	63	90	103	71	85
Before	Large Truck	10	0	0	0	2	5	1	2	0	0	0
Before	All	469	0	2	8	7	33	64	92	104	72	87
After	Motorcycle	2	0	0	0	1	0	0	0	0	0	1
After	Passenger Vehicle	430	0	0	3	19	69	114	118	63	27	17
After	Large Truck	9	0	0	0	2	3	1	0	2	0	1
After	All	441	0	0	3	22	72	115	118	65	27	19

[1] Distances were measured from the outside edge of the centerline marking nearest the travel flow for the direction of traffic being observed. The presented values are binned data.

Table 129. Summary Count for FM 2222 (Tangent, Direction 1).

Roadway	Alignment	Direction	Distance (inches)[1]									
FM 2222	**Tangent**	**In**	**<0**	**0**	**6**	**12**	**18**	**24**	**30**	**36**	**42**	**>42**
Before	Motorcycle	13	0	0	0	0	0	2	1	1	3	6
Before	Passenger Vehicle	1529	1	70	422	346	326	206	101	40	12	5
Before	Large Truck	9	0	2	6	1	0	0	0	0	0	0
Before	All	1551	1	72	428	347	326	208	102	41	15	11
After	Motorcycle	2	0	0	0	0	0	0	0	1	1	0
After	Passenger Vehicle	955	1	2	5	36	94	202	257	154	122	82
After	Large Truck	26	0	0	2	2	6	6	6	3	1	0
After	All	983	1	2	7	38	100	208	263	158	124	82

[1] Distances were measured from the outside edge of the centerline marking nearest the travel flow for the direction of traffic being observed. The presented values are binned data.

Table 130. Summary Count for FM 2222 (Tangent, Direction 2).

Roadway	Alignment	Direction	Distance (inches)[1]									
FM 2222	Tangent	Out	<0	0	6	12	18	24	30	36	42	>42
Before	Motorcycle	9	0	0	0	0	0	0	1	0	1	7
Before	Passenger Vehicle	1040	0	1	11	24	69	99	190	226	226	194
Before	Large Truck	10	0	0	0	1	1	3	2	1	2	0
Before	All	1059	0	1	11	25	70	102	193	227	229	201
After	Motorcycle	8	0	0	0	0	0	0	0	2	1	5
After	Passenger Vehicle	909	0	0	7	36	127	166	204	165	113	91
After	Large Truck	14	0	0	4	0	4	4	0	2	0	0
After	All	931	0	0	11	36	131	170	204	169	114	96

[1] Distances were measured from the outside edge of the centerline marking nearest the travel flow for the direction of traffic being observed. The presented values are binned data.

Table 131. Summary Count for FM 2222 (Curve, Outside Lane).

Roadway	Alignment	Direction	Distance (inches)[1]									
FM 2222	Curve	In	<0	0	6	12	18	24	30	36	42	>42
Before	Motorcycle	4	0	0	0	0	1	1	0	0	2	0
Before	Passenger Vehicle	958	6	83	246	246	184	112	56	12	10	3
Before	Large Truck	5	0	2	1	2	0	0	0	0	0	0
Before	All	967	6	85	247	248	185	113	56	12	12	3
After	Motorcycle	11	0	0	0	0	0	2	2	1	0	6
After	Passenger Vehicle	1041	1	11	39	136	274	265	162	107	26	20
After	Large Truck	10	0	3	1	3	1	2	0	0	0	0
After	All	1062	1	14	40	139	275	269	164	108	26	26

[1] Distances were measured from the outside edge of the centerline marking nearest the travel flow for the direction of traffic being observed. The presented values are binned data.

Table 132. Summary Count for FM 2222 (Curve, Inside Lane).

Roadway	Alignment	Direction	Distance (inches)[1]									
FM 2222	Curve	Out	<0	0	6	12	18	24	30	36	42	>42
Before	Motorcycle	2	0	0	0	0	0	0	0	0	1	1
Before	Passenger Vehicle	887	0	0	0	0	2	3	24	60	148	650
Before	Large Truck	5	0	0	0	0	0	0	1	2	0	2
Before	All	894	0	0	0	0	2	3	25	62	149	653
After	Motorcycle	1	0	0	0	0	0	0	0	0	0	1
After	Passenger Vehicle	1978	0	0	1	0	3	6	21	90	265	1592
After	Large Truck	21	0	0	0	0	0	0	3	2	9	7
After	All	2000	0	0	1	0	3	6	24	92	274	1600

[1] Distances were measured from the outside edge of the centerline marking nearest the travel flow for the direction of traffic being observed. The presented values are binned data.

APPENDIX C

RECOMMENDED DESIGN

This appendix includes the recommended guidelines and designs of the researchers based on the state-of-the-art review, discussions with the project director and advisory panel, and the results of the data analyses. This section is subdivided into three sections:

- definitions,
- guidelines with supporting schematics, and
- standard drawings in MicroStation.

The MicroStation drawings have been converted to jpeg format for inclusion in this report.

Definitions

Rumble strips are devices designed to generate audible and tactile vibrations as vehicles pass over them. They consist of raised (bumps) or lowered (divots) breaks in the level surface of a roadway and are placed in proximity to the edge of a roadway, to the centerline of a roadway, or across the travel lane of a roadway.

Raised rumble strips are created by the placement and forming of additional roadway material or by placing prefabricated materials on the finished roadway surface. For example, one method would be affixing prefabricated material such as high-density-polyurethane (HDPE) plastic strips to the roadway. In some cases, raised pavement markings (RPM) serve as raised rumble strips.

Milled rumble strips are ground (cut) into the finished surface of a roadway and constitute divots.

Rolled rumble strips are rolled into the finished surface of a roadway and constitute divots. This method is only for freshly placed asphalt cement concrete (ACC).

Transverse rumble strips (TRSs) are placed in the lane and generally traverse more than two-thirds of the travel path perpendicular to the direction of travel, and are typically raised rumble strips. TRSs have also been referred to as in-lane rumble strips.

Centerline rumble strips (CRSs) are installed along the specified roadway centerline, and are typically milled.

Shoulder rumble strips (SRSs) are installed along the specified roadway shoulders. Shoulders are the section of paved roadway outside of the delineated edgelines.

Edgeline rumble strips (ERSs) are a type of SRS that are specifically placed along the delineated roadway edgeline, and are typically milled. ERSs may overlap into the lane, but they are typically placed at the start of the edgeline and extend into the shoulder.

Continuous describes an installation of rumble strips that uses a set spacing between individual rumble strips that is consistent from start to finish of the installation treatment. Breaks in the pattern for geometric and operational design considerations such as intersecting roadways and bridges do not negate the term continuous.

Intermittent describes an installation of rumble strips that consists of groupings of rumble strips that are broken up by gaps.

Gap spacing (GS) describes the distance between two sections of rumble strips, and it is associated with intermittent rumble strip placement.

Length (L) is the dimension of an individual rumble strip as it runs parallel to the direction of travel.

Width (W) is the dimension of an individual rumble strip as it runs perpendicular to the direction of travel.

Depth (D) refers to vertical distance of a rumble strip from the roadway surface to the bottom of a rumble strip. For formed, above-ground rumble strips, this dimension will be referred to as height (H).

Spacing is the term for distance in the direction of travel from the front of one rumble strip to the front of the next successive rumble strip.

On-centers spacing (OCS) is the term for the distance in the direction of travel from the center of one rumble strip to the center of the next rumble strip. This term refers to a similar distance that the term spacing refers to, except that the points of measure are different. Spacing is the preferred method of measure for it is simpler and more time efficient with regard to field measures.

Offset is a term that describes the distance that an object (i.e., a pavement marking or rumble strip) may be placed laterally or longitudinally from a referenced location such as from another object (i.e., an edgeline). This distance will be measured from the two closest adjacent inside edges of the object unless specified otherwise.

Two-way-left-turn-lane (TWLTL) is a lane placed along the centerline of the roadway that allows turning in both directions. The center of the TWLTL commonly coincides with the true centerline of the roadway.

Edgeline is the term for pavement marking that delineates the outside edge of the outside lane with the edge of the shoulder of a roadway.

Centerline (CL) is the term for the location of the center of the roadway and is usually delineated by pavement markings on an undivided roadway. The exceptions are turn lanes and TWLTLs. In the exceptions, the pavement delineation may not follow the true centerline of the roadway.

Lane lines are the travel-way delineators between the edgelines and the centerlines on multilane roadways with more than one lane of travel in one direction (this excludes TWLTL).

Figure 115 is a pictorial representation of some of the terms above.

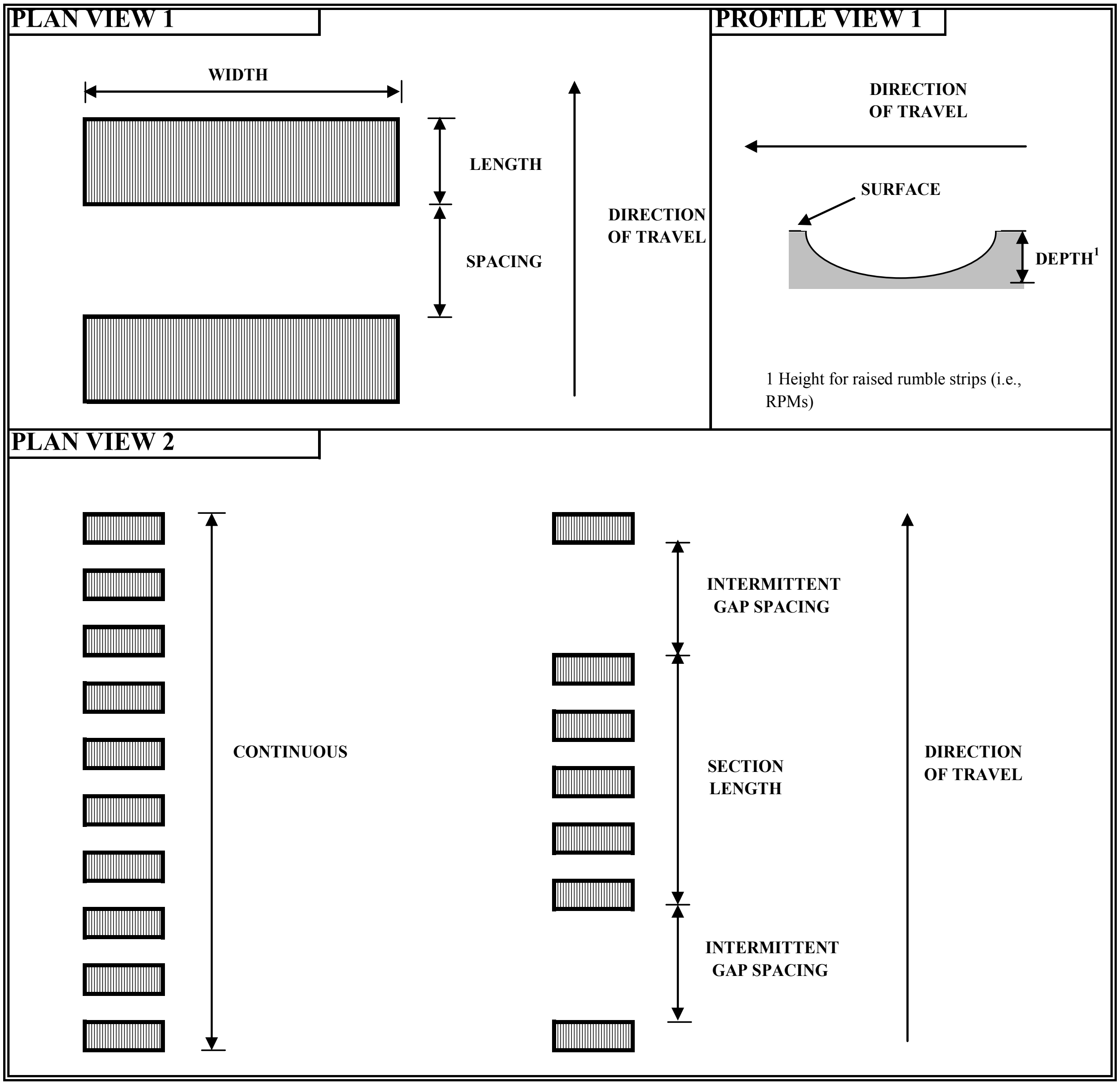


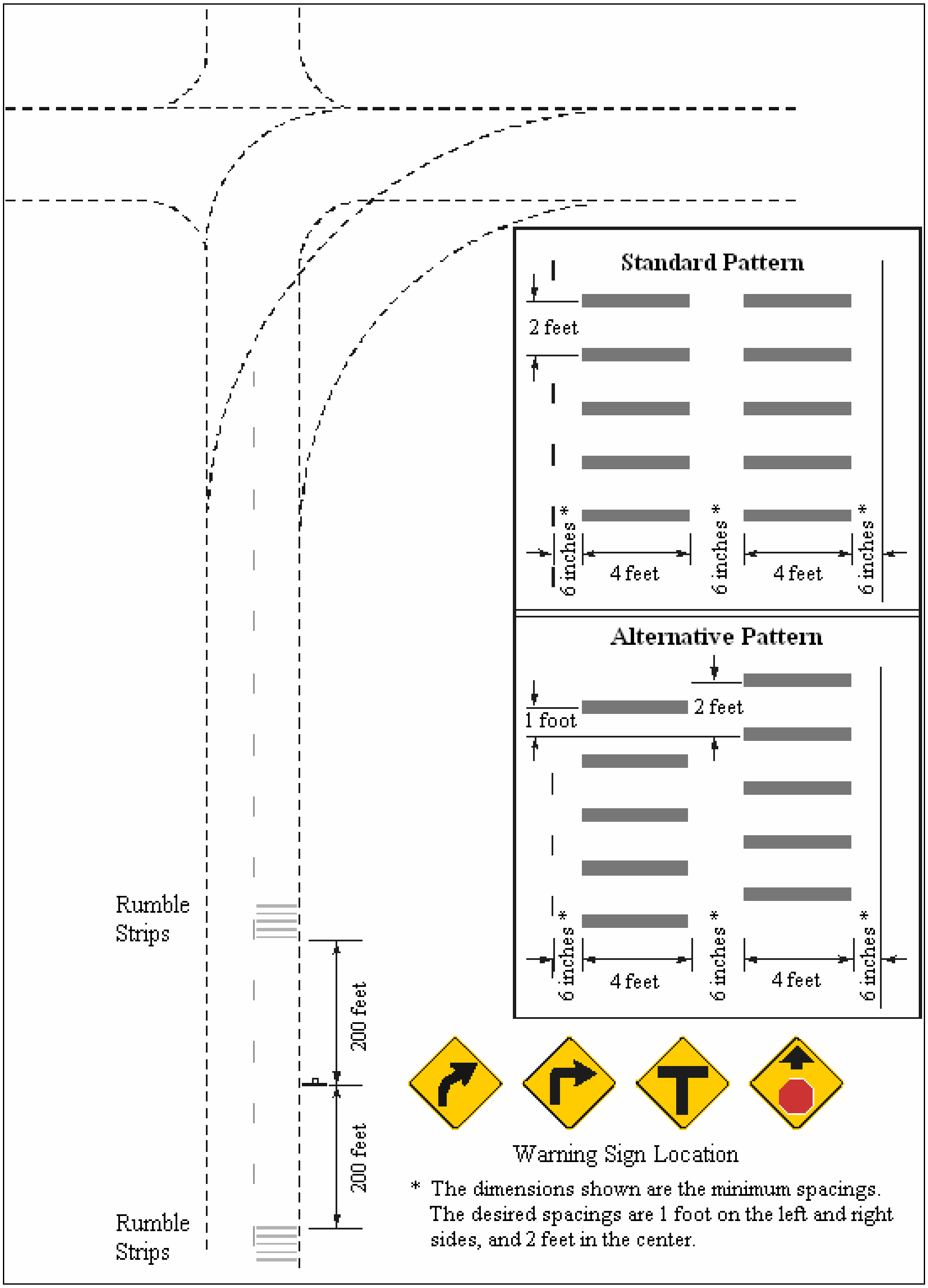
Figure 115. Terms.

RECOMMENDED GUIDELINES

Transverse Rumble Strips

Transverse rumble strips are recommended for limited use based on past studies and the most recent research findings, which do not include robust crash analysis. If further studies including crash analysis show TRSs to be effective, then more widespread implementation should be considered. The purpose of TRSs and recommended guidelines toward their limited implementation are bulleted below, and Figure 116 contains the recommended layout:

- TRSs are a countermeasure designed to reduce the occurrence of single and multi-vehicle crashes that occur as a result of inattentive motorists approaching stop-controlled intersections or horizontal curves. TRSs alert drivers as their vehicle passes over the strips through noise and vibration.
- TRSs should only be used where unexpected traffic stops occur or at high incident locations where all traditional warning devices have been used or proven ineffective through field evaluation.
- If used, preformed, raised rumble strips are recommended and should be white.
- If used, TRSs should be installed as outlined in Figure 116.
- Consideration should be given with regard to the noise levels associated with the installation of TRSs near residential areas, schools, churches, etc.



* The dimensions shown are the minimum spacings. The desired spacings are 1 foot on the left and right sides, and 2 feet in the center.

Figure 116. Recommended Transverse Rumble Strip Layout.

Centerline Rumble Strips

Centerline rumble strips are recommended for use in the state of Texas based upon recent research conducted through the Texas Transportation Institute and previous research conducted by others. The purpose of CRSs and recommended guidelines toward their implementation are bulleted below.

- CRSs are a countermeasure designed to reduce the occurrence of head-on, opposite direction sideswipe and/or single vehicle crossover crashes on two-way, undivided roadways. CRSs alert drivers through noise and vibration as their vehicles cross over the strips. Preliminary safety analysis shows benefit-to-cost (B/C) ratios ranging from 0.95 to 26.42, depending on annual average daily traffic (AADT) volumes.
- CRSs should be placed on two-way, undivided roadways that have shown a high-incidence crash rate with regard to head-on, opposite direction sideswipe and/or single vehicle crossover crashes as a result of inattentive drivers or impaired visibility of positive guidance pavement markings during adverse weather. Any additional installations may be assessed on a case-by-case basis.
- Milled CRSs are preferred over rolled rumble strips. If pavement thickness is less than two inches for asphalt cement concrete or less than two inches between the top of pavement and the top of rebar in Portland cement concrete, milled CRSs should not be used. Raised CRSs consisting of non-reflective raised pavement buttons may be used. Raised CRSs may be affixed to asphalt cement concrete or Portland cement concrete using bituminous or other adhesives, as per the manufacturer's recommendations.
- The following dimensioning should be used (see Figure 117 for milled CRSs and Figure 118 for raised CRSs):
    - Milled CRSs should be cut to a minimum of 0.50 ± 1/8 inch depth, 7 ± 0.50 inch length, and 16 ± 0.50 inch width.
    - Milled CRSs should be spaced at two feet.
    - The dimensions of non-reflective, raised pavement buttons for use as raised rumble strips should be a minimum of four inches in length and width, and 0.50 inch in height prior to adhering to the pavement.
    - Raised CRSs should be spaced at four feet.
- If CRSs are milled into the roadway, then the CL pavement markings shall be washed.
- CRSs shall not be milled or rolled into bridge decks.
- Pavement markings may be applied over milled CRSs. Raised CRSs shall be placed in the travel lane adjacent to the centerline markings. Raised CRSs may be placed over pavement markings.
- CRSs should be continuous, being installed in both passing and no-passing zones.
- Breaks in the CRSs will start at least 50 feet and no more than 150 feet prior to each approach for the following instances:
    - bridges,
    - intersections, and
    - driveways with high usage or large trucks.
- CRSs may be installed along the edgeline delineating pavement stripes for TWLTL. The TWLTL should have at least a 14-foot width from the outside edges of the solid edgelines, and the CRSs will be reduced to 12 inches in width for each edgeline. Alternatively, CRSs may be installed down the middle of a TWLTL.

- In areas where delineated left-turning bays are installed, the CRSs should follow the outside CL pavement marking to the direction of travel with the left-turn bay.
- RPM and lane striping should be placed according to current TxDOT standards as addressed in the Texas Manual on Uniform Traffic Control Devices (TMUTCD) and TxDOT Standard Sheets.
    - When specifying RPM placement, the project engineer should use the standard specifications as depicted in TxDOT standard drawing PM(2)–00A, “Position Guidance Using Raised Pavement Markers” and should not use the supplemental standard PM(3)-00A.
    - The individual CRS closest to the placement of an individual RPM should be skipped, and the RPM should be placed equidistant from the two remaining adjacent CRSs.
- Consideration should be given to the following before installing CRSs:
    - Consider noise impacts when the installation is near residential areas, schools, churches, etc. A minimum of 3/8 inch depth of milled CRSs or rolled CRSs may be considered in these areas.
    - Roadways with significant deterioration and/or raveling (“significant” will be defined by the project engineer with regard to current TxDOT engineering practices) should be resurfaced prior to installation.
    - Coordinate CRS installation with other design projects, such as schedule after roadway resurfacing and prior to pavement striping.

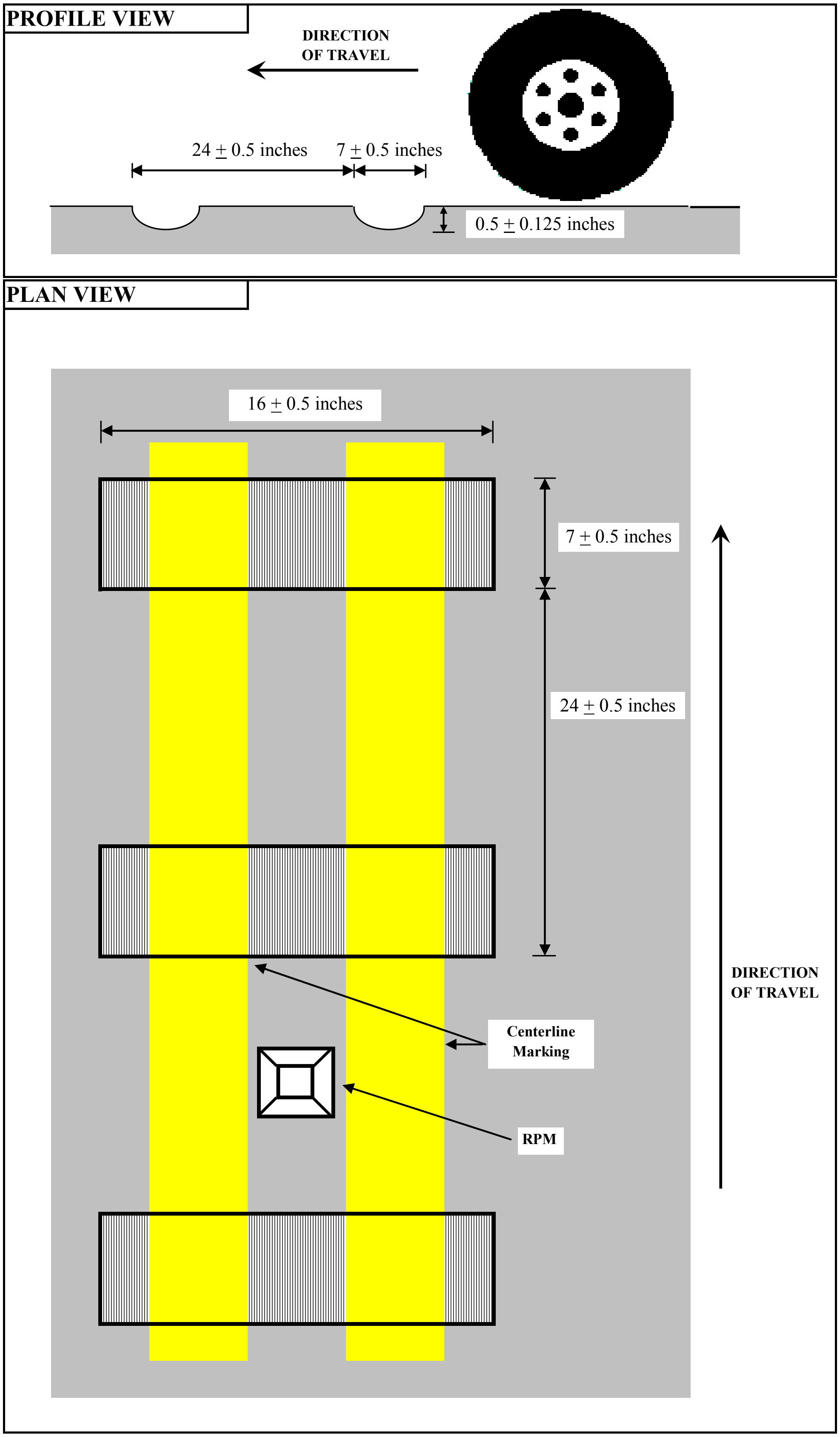


Figure 117. Milled Centerline Rumble Strips.

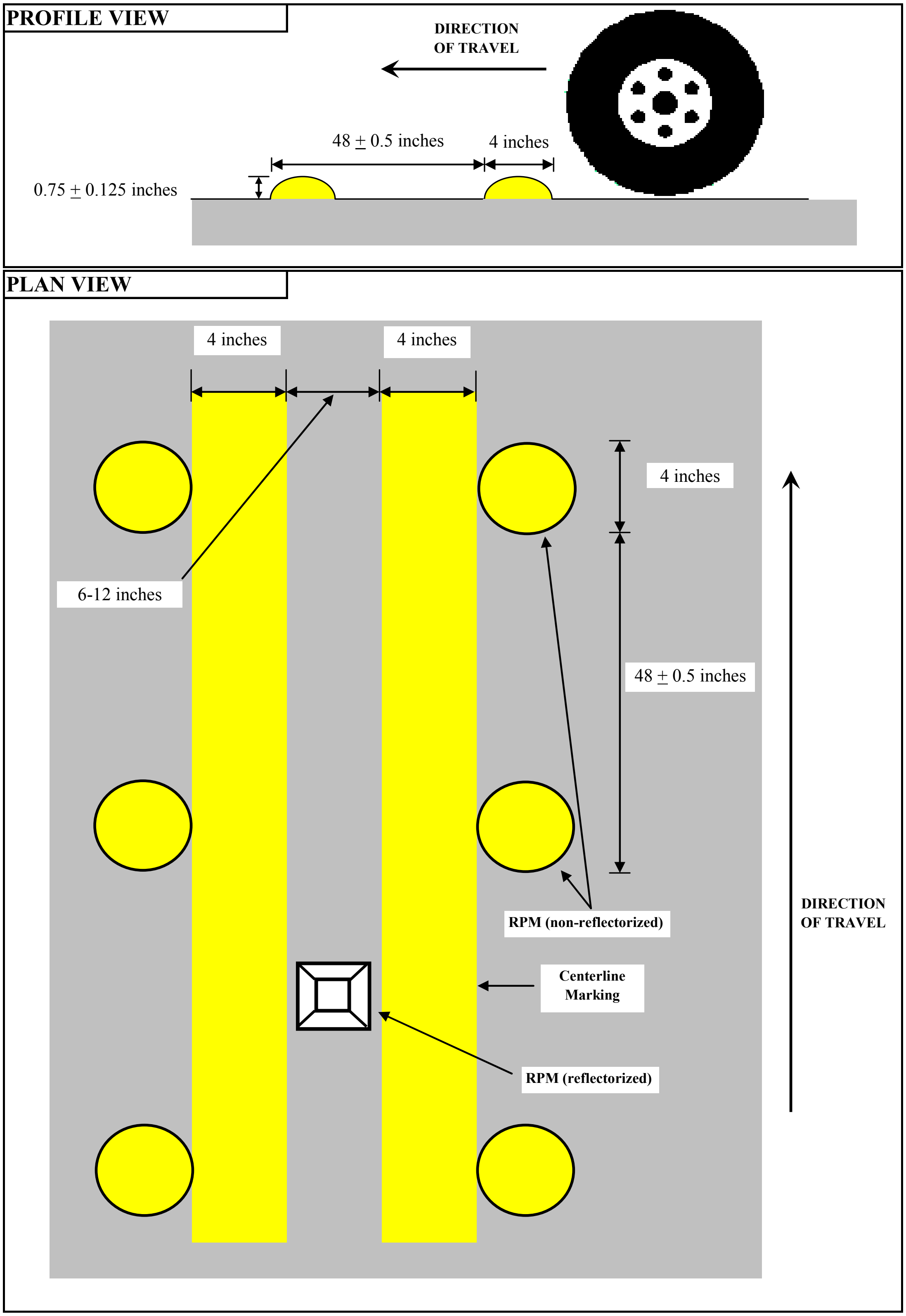


Figure 118. Raised Centerline Rumble Strips.

Edgeline Rumble Strips

Edgeline rumble strips are recommended for use in the state of Texas based upon recent research conducted through the Texas Transportation Institute. The purpose of ERSs and recommended guidelines toward their implementation are bulleted below.

- ERSs are a countermeasure designed to reduce ROR crashes. ERSs alert drivers as their vehicles cross over the strips through noise and vibration. Preliminary safety analysis shows benefit-to-cost ratios ranging from 57 to 200, depending on AADT volumes and shoulder width.
- ERSs should be placed on roadways that have shown a high-incidence crash rate with regard to ROR crashes as a result of inattentive drivers or impaired visibility of positive guidance pavement markings during adverse weather. Any additional installations may be assessed on a case-by-case basis.
- Milled ERSs are preferred over rolled ERSs. If pavement thickness is less than two inches for asphalt cement concrete or less than two inches between the top of pavement and the top of rebar in Portland cement concrete, milled ERSs should not be used. Raised ERSs consisting of non-reflective raised pavement buttons or profile markings may be used. Raised ERSs may be affixed to asphalt cement concrete or Portland cement concrete using bituminous or other adhesives, as per the manufacturer's recommendations.
- The following dimensioning should be used (see Figure 119 for milled ERSs and Figure 120 for raised ERSs):
  - Milled ERSs should be cut to a minimum of 0.50 + 1/8 inch depth, 7 + 0.50 inch length, and 8 + 0.50 inch width.
  - Milled ERSs should be spaced at one foot.
  - The dimensions of non-reflective, raised pavement buttons for use as raised rumble strips should be a minimum of four inches in length and width, and 0.50 inch in height prior to adhering to the pavement.
  - Raised ERSs should be spaced at two feet.
- If ERSs are milled into the roadway, then the edgeline pavement markings shall be washed.
- Pavement markings shall be applied over milled ERSs. Raised ERSs shall be placed in the travel lane adjacent to the edgeline markings. Raised ERSs may be placed over pavement markings.
- ERSs shall not be milled or rolled into bridge decks.
- ERSs should be continuous, being installed in both passing and no-passing zones.
- Breaks in the ERSs will start at least 50 feet and no more than 150 feet prior to each approach for the following instances:
  - bridges,
  - intersections,
  - right turn bays, and
  - driveways with high usage or large trucks.
- RPMs and lane striping should be placed according to current TxDOT standards as addressed in the *Texas Manual on Uniform Traffic Control Devices* and TxDOT Standard Sheets.
  - When specifying RPM placement, the project engineer should use the standard specifications as depicted in TxDOT standard drawing PM(2)–00A, "Position

    Guidance Using Raised Pavement Markers" and should not use the supplemental standard PM(3)-00A.
  - The individual ERS closest to the placement of an individual RPM should be skipped, and the RPM should be placed equidistant from the two remaining adjacent ERSs.
  - Profile markings may be used in conjunction with ERSs.
- Consideration should be given to the following before installing ERSs:
  - Consider noise impacts when the installation is near residential areas, schools, churches, etc. A minimum of 3/8 inch depth of milled ERSs or rolled ERSs may be considered in these areas.
  - Roadways with significant deterioration and/or raveling ("significant" will be defined by the project engineer with regard to current TxDOT engineering practices) should be resurfaced prior to installation.
  - Coordinate ERS installation with other design projects, such as schedule after roadway resurfacing and prior to pavement striping.

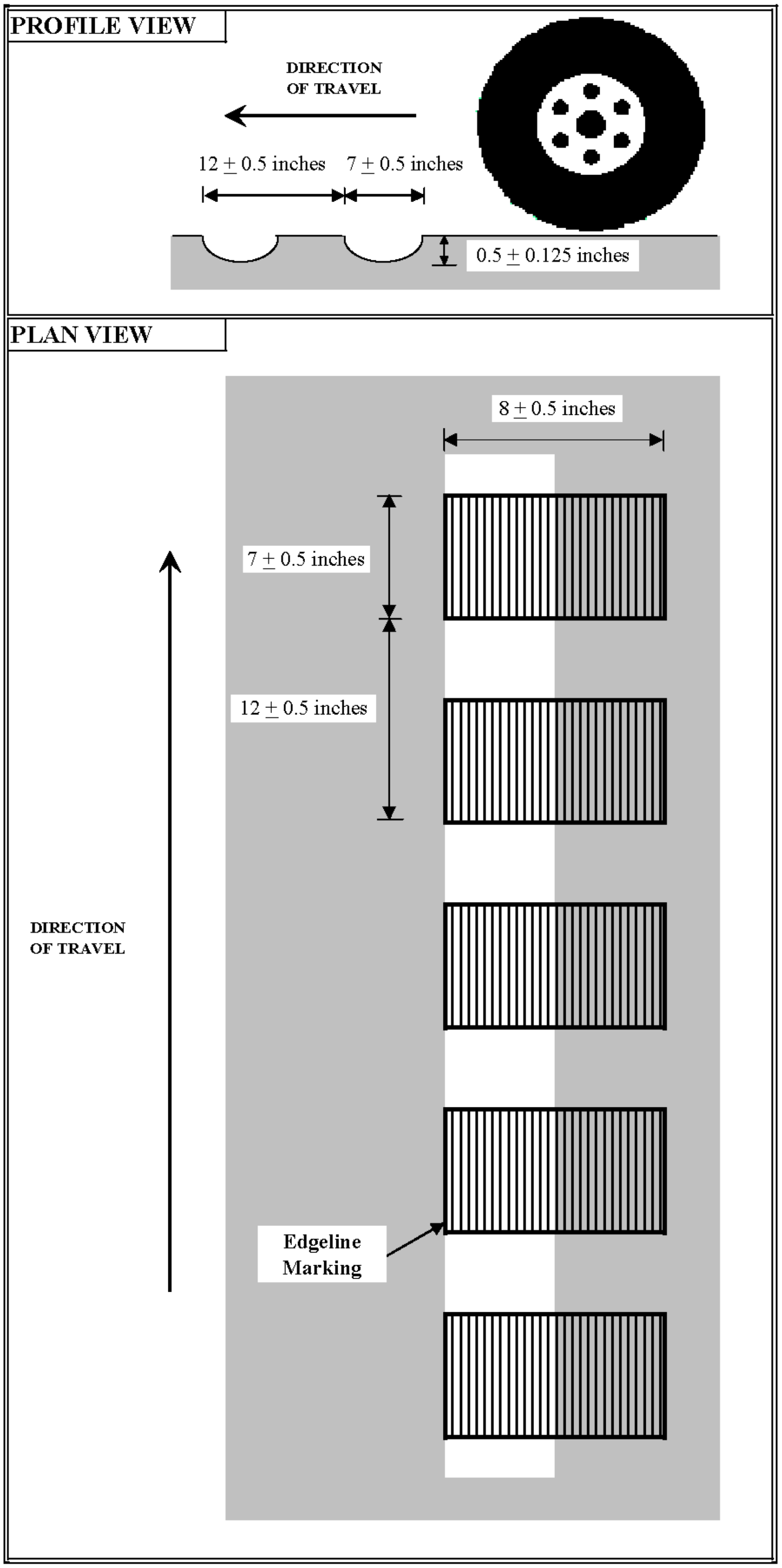


Figure 119. Milled Edgeline Rumble Strips.

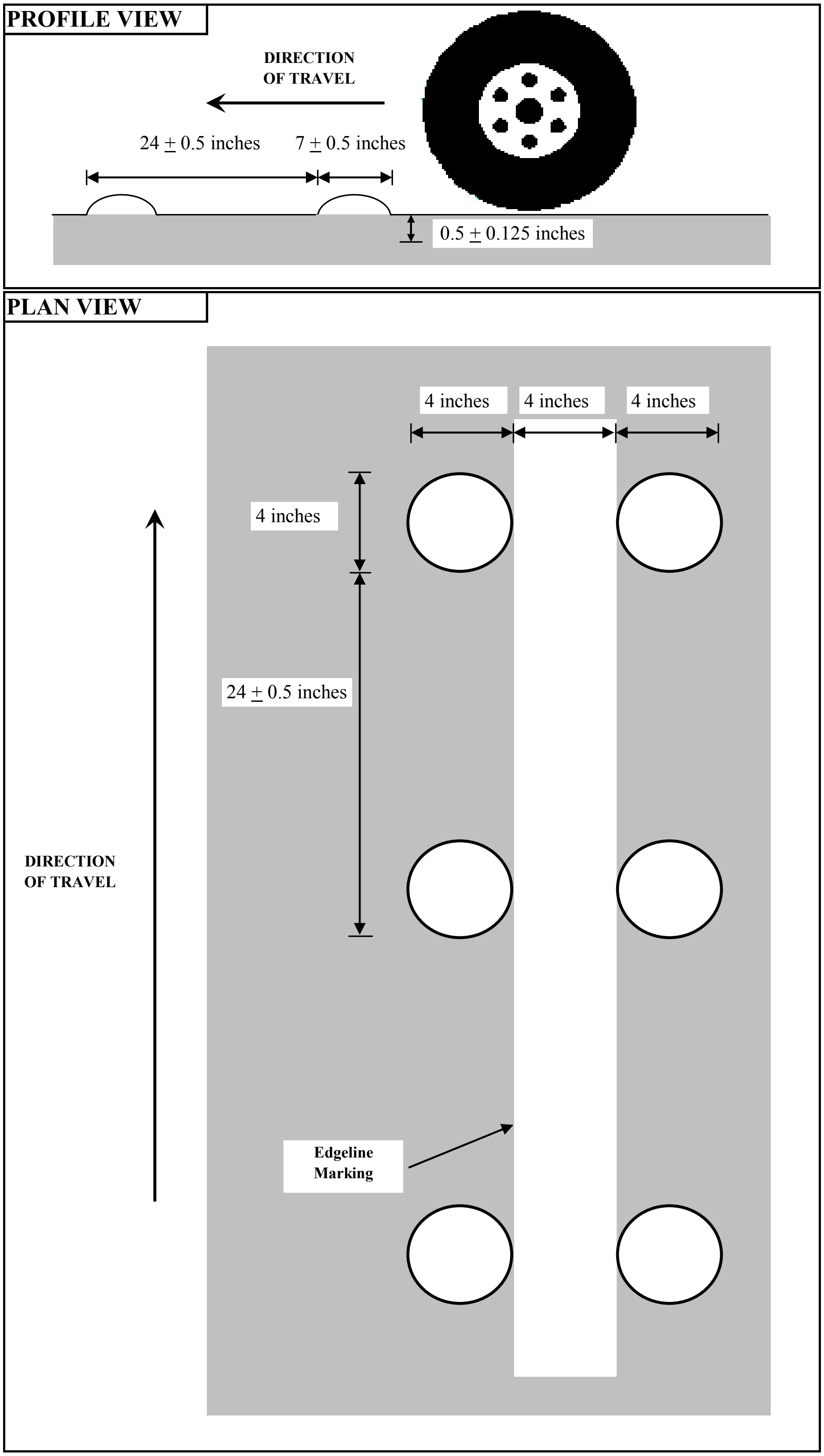
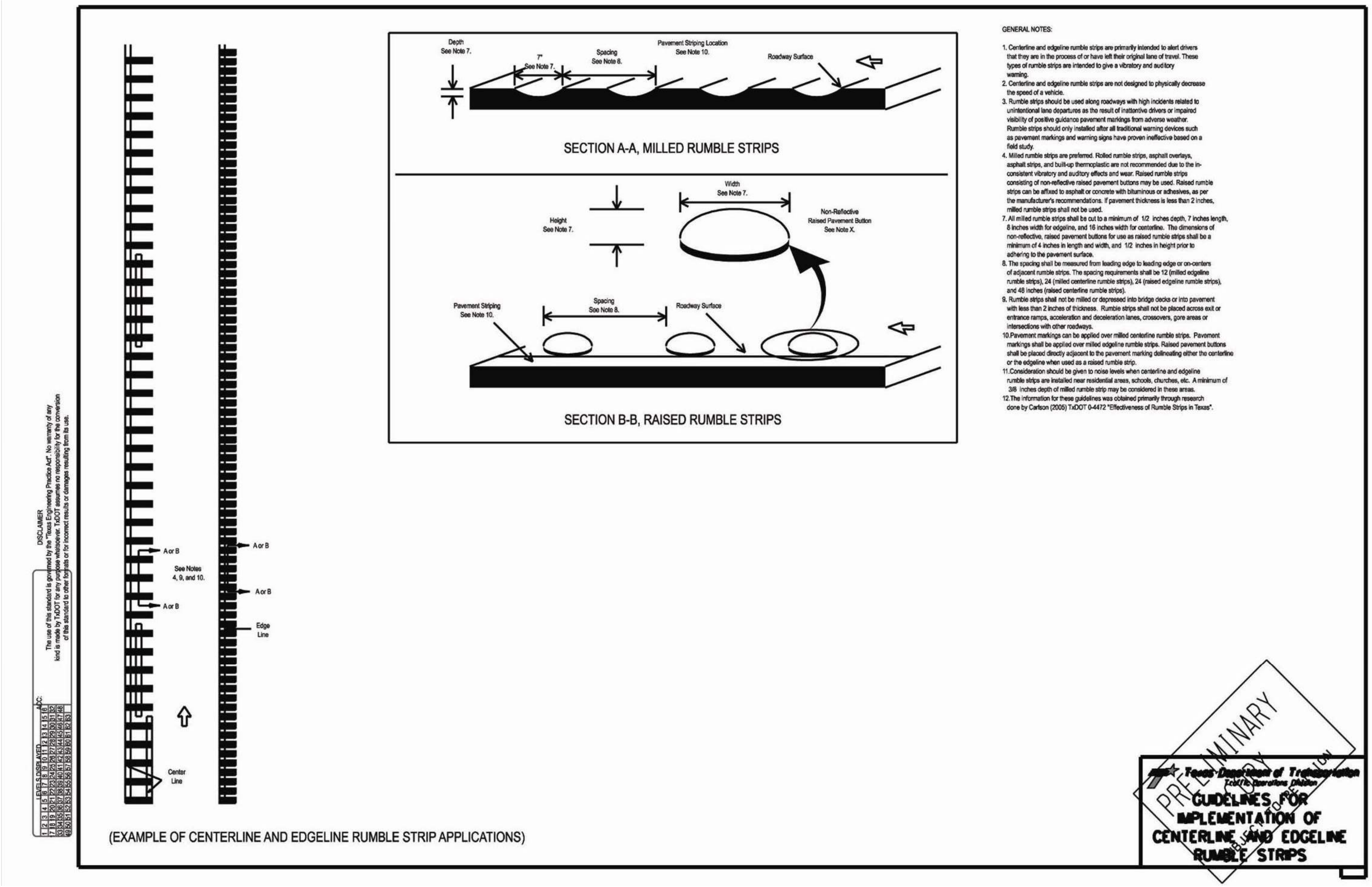


Figure 120. Raised Edgeline Rumble Strips.

Figure 121 is the recommended standard design sheets in MicroStation.

RECOMMENDED STANDARD DESIGN SHEETS



GENERAL NOTES:

1. Centerline and edgeline rumble strips are primarily intended to alert drivers that they are in the process of or have left their original lane of travel. These types of rumble strips are intended to give a vibratory and auditory warning.
2. Centerline and edgeline rumble strips are not designed to physically decrease the speed of a vehicle.
3. Rumble strips should be used along roadways with high incidents related to unintentional lane departures as the result of inattentive drivers or impaired visibility of positive guidance pavement markings from adverse weather. Rumble strips should only installed after all traditional warning devices such as pavement markings and warning signs have proven ineffective based on a field study.
4. Milled rumble strips are preferred. Rolled rumble strips, asphalt overlays, asphalt strips, and built-up thermoplastic are not recommended due to the inconsistent vibratory and auditory effects and wear. Raised rumble strips consisting of non-reflective raised pavement buttons may be used. Raised rumble strips can be affixed to asphalt or concrete with bituminous or adhesives, as per the manufacturer's recommendations. If pavement thickness is less than 2 inches, milled rumble strips shall not be used.
7. All milled rumble strips shall be cut to a minimum of 1/2 inches depth, 7 inches length, 8 inches width for edgeline, and 16 inches width for centerline. The dimensions of non-reflective, raised pavement buttons for use as raised rumble strips shall be a minimum of 4 inches in length and width, and 1/2 inches in height prior to adhering to the pavement surface.
8. The spacing shall be measured from leading edge to leading edge or on-centers of adjacent rumble strips. The spacing requirements shall be 12 (milled edgeline rumble strips), 24 (milled centerline rumble strips), 24 (raised edgeline rumble strips), and 48 inches (raised centerline rumble strips).
9. Rumble strips shall not be milled or depressed into bridge decks or into pavement with less than 2 inches of thickness. Rumble strips shall not be placed across exit or entrance ramps, acceleration and deceleration lanes, crossovers, gore areas or intersections with other roadways.
10. Pavement markings can be applied over milled centerline rumble strips. Pavement markings shall be applied over milled edgeline rumble strips. Raised pavement buttons shall be placed directly adjacent to the pavement marking delineating either the centerline or the edgeline when used as a raised rumble strip.
11. Consideration should be given to noise levels when centerline and edgeline rumble strips are installed near residential areas, schools, churches, etc. A minimum of 3/8 inches depth of milled rumble strip may be considered in these areas.
12. The information for these guidelines was obtained primarily through research done by Carlson (2005) TxDOT 0-4472 "Effectiveness of Rumble Strips in Texas".

Figure 121. Recommended Standard Design Sheet for CRSs and ERSs.

APPENDIX D

SAFETY OF RUMBLE STRIPS

This chapter presents the safety analyses that were conducted in order to determine the relative effectiveness of centerline and edgeline rumble strips in the applications associated with this research. The numbers are compared against other states to show some potential comparisons. It should be noted that the Pennsylvania Department of Transportation provided the numbers for all of the states shown except Texas.

Figure 122 and Figure 123 show the potential safety impacts for centerline rumble strips. The figures are based on the latest statistics for costs for crashes, depending on severity. They are split into four classes of roadway volume and show benefit/cost ratios for each class of roadway volume. The results indicate that the higher the roadway volume, the more benefit of centerline rumble strips.

The B/C ratios shown assume a 20-percent reduction in the pertinent crash rates as a result of the centerline rumble strips. This threshold was chosen based on the literature review presented previously. However, the tables were developed in a spreadsheet format so that this assumption could be studied in sensitivity analysis. The spreadsheet was provided to the project director for additional analyses and policy-making decisions.

Figure 124 and Figure 125 show the potential safety impacts of edgeline rumble strips on two-lane highways. These figures are similar to the previous figures except that they are classified by roadway volume and shoulder width. Unlike the centerline rumble strip results, the results for the edgeline rumble strips vary depending on volume and shoulder width. The reasons for these fluctuations can be traced to the distribution of two-lane mileage in Texas and the related run-off-the-road crashes that occur on them (Figure 126 and Figure 127).

	Costs per Crash ($)
Fatal	3,883,811 *
A Injury	1,043,826
B Injury	69,990
C Injury	5,543
PDO	2,217
Fatalities/Fatal Crash	1.35
Cost of Rumble Strips/Foot	1.50
Reduction from Rumble Strips	0.2

* Cost of Fatal Crashes ($2,882,516) x 1.35 Fatalities/Fatal crash

Table 1: ADT=< 1500

	Head-on and opposing flow side swipe crashes **	WASH	NC	IL	PA	TX
a.	Fatal	3	6	0	8	36
b.	A Injury	6	24	1	23	50
c.	B Injury	7	38	1	43	76
d.	C Injury	3	16	3	79	60
e.	PDO	24	21	3	66	50
f.	Annual Crash Cost	18,474,156	51,149,555	1,137,096	58,672,275	197,771,167
g.	Miles	1,971	13,776	1,325	9,862	41,923
h.	Estimated Rumble Strip Cost/Mile	7,920	7,920	7,920	7,920	7,920
i. (g x h)	Estimated Rumble Strip Total Cost	15,612,696	109,103,544	10,490,832	78,107,040	332,029,764
j.	Estimated Pvmnt Life (yrs)	8	8	8	8	8
k. (f x j)	Total Crash cost over Pvmnt Life	147,793,249	409,196,442	9,096,768	469,378,202	1,582,169,337
l.	Annual Cost Reduction Due to Rumble Strips***	3,694,831	10,229,911	227,419	11,734,455	39,554,233
m. (j x l)	Total Cost reduction over Pvmnt Life	29,558,650	81,839,288	1,819,354	93,875,640	316,433,867
n. (m / i)	**Estimated B/C**	**1.89**	**0.75**	**0.17**	**1.20**	**0.95**
o. (a x 1.35 x 0.2)	Expected Annual Lives Saved	0.81	1.62	0.00	2.16	9.70
p. (j x o)	Expected Lives Saved over life of Pvmnt	6.47	12.93	0.00	17.25	77.61

** Crash data from HSIS except for Pennsylvania and Texas

*** Assumes 20% reduction in head-on and opposing flow side swipe crashes and related costs

Table 2: ADT 1500-2999

	Head-on and opposing flow side swipe crashes **	WASH	NC	IL	PA	TX
a.	Fatal	5	12	7	17	47
b.	A Injury	16	18	18	32	58
c.	B Injury	24	36	15	49	74
d.	C Injury	9	12	0	79	60
e.	PDO	32	14	28	68	74
f.	Annual Crash Cost	37,920,862	68,011,794	47,087,471	103,445,383	248,756,924
g.	Miles	1,197	5,080	2,163	3,182	9,067
h.	Estimated Rumble Strip Cost/Mile	7,920	7,920	7,920	7,920	7,921
i. (g x h)	Estimated Rumble Strip Total Cost	9,478,498	40,232,808	17,128,584	25,201,440	71,815,984
j.	Estimated Pvmnt Life (yrs)	8	8	8	8	9
k. (f x j)	Total Crash cost over Pvmnt Life	303,366,897	544,094,355	376,699,770	827,563,060	2,238,812,320
l.	Annual Cost Reduction Due to Rumble Strips***	7,584,172	13,602,359	9,417,494	20,689,077	49,751,385
m. (j x l)	Total Cost reduction over Pvmnt Life	60,673,379	108,818,871	75,339,954	165,512,612	447,762,464
n. (m / i)	**Estimated B/C**	**6.40**	**2.70**	**4.40**	**6.57**	**6.23**
o. (a x 1.35 x 0.2)	Expected Annual Lives Saved	1.35	3.23	1.89	4.58	12.67
p. (j x o)	Expected Lives Saved over life of Pvmnt	10.78	25.87	15.09	36.65	113.99

** Crash data from HSIS except for Pennsylvania and Texas

*** Assumes 20% reduction in head-on and opposing flow side swipe crashes and related costs

Figure 122. Safety Analysis of Centerline Rumble Strips (1 of 2).

Costs per Crash ($)	
Fatal	0 *
A Injury	1,043,826
B Injury	69,990
C Injury	5,543
PDO	2,217
Fatalities/Fatal Crash	0.00
Cost of Rumble Strips/Foot	1.50
Reduction from Rumble Strips	0.2

* Cost of Fatal Crashes ($2,882,516) x 1.35 Fatalities/Fatal crash

Table 3: ADT 3000-4499

	Head-on and opposing flow side swipe crashes **	WASH	NC	IL	PA	TX
a.	Fatal	9	12	10	17	62
b.	A Injury	17	10	53	27	56
c.	B Injury	20	20	33	53	57
d.	C Injury	15	14	3	61	61
e.	PDO	41	11	28	56	65
f.	Annual Crash Cost	54,273,183	58,545,781	96,549,263	98,379,835	303,722,198
g.	Miles	585	2,370	1,144	1,831	4,575
h.	Estimated Rumble Strip Cost/Mile	7,920	7,920	7,920	7,920	7,921
i. (g x h)	Estimated Rumble Strip Total Cost	4,634,784	18,769,608	9,060,480	14,501,520	36,236,436
j.	Estimated Pvmnt Life (yrs)	8	8	8	8	9
k. (f x j)	Total Crash cost over Pvmnt Life	434,185,466	468,366,251	772,394,107	787,038,676	2,733,499,782
l.	Annual Cost Reduction Due to Rumble Strips***	10,854,637	11,709,156	19,309,853	19,675,967	60,744,440
m. (j x l)	Total Cost reduction over Pvmnt Life	86,837,093	93,673,250	154,478,821	157,407,735	546,699,956
n. (m / i)	**Estimated B/C**	**18.74**	**4.99**	**17.05**	**10.85**	**15.09**
o. (a x 1.35 x 0.2)	Expected Annual Lives Saved	2.43	3.23	2.69	4.58	16.71
p. (j x o)	Expected Lives Saved over life of Pvmnt	19.40	25.87	21.56	36.65	150.37

** Crash data from HSIS except for Pennsylvania and Texas

*** Assumes 20% reduction in head-on and opposing flow side swipe crashes and related costs

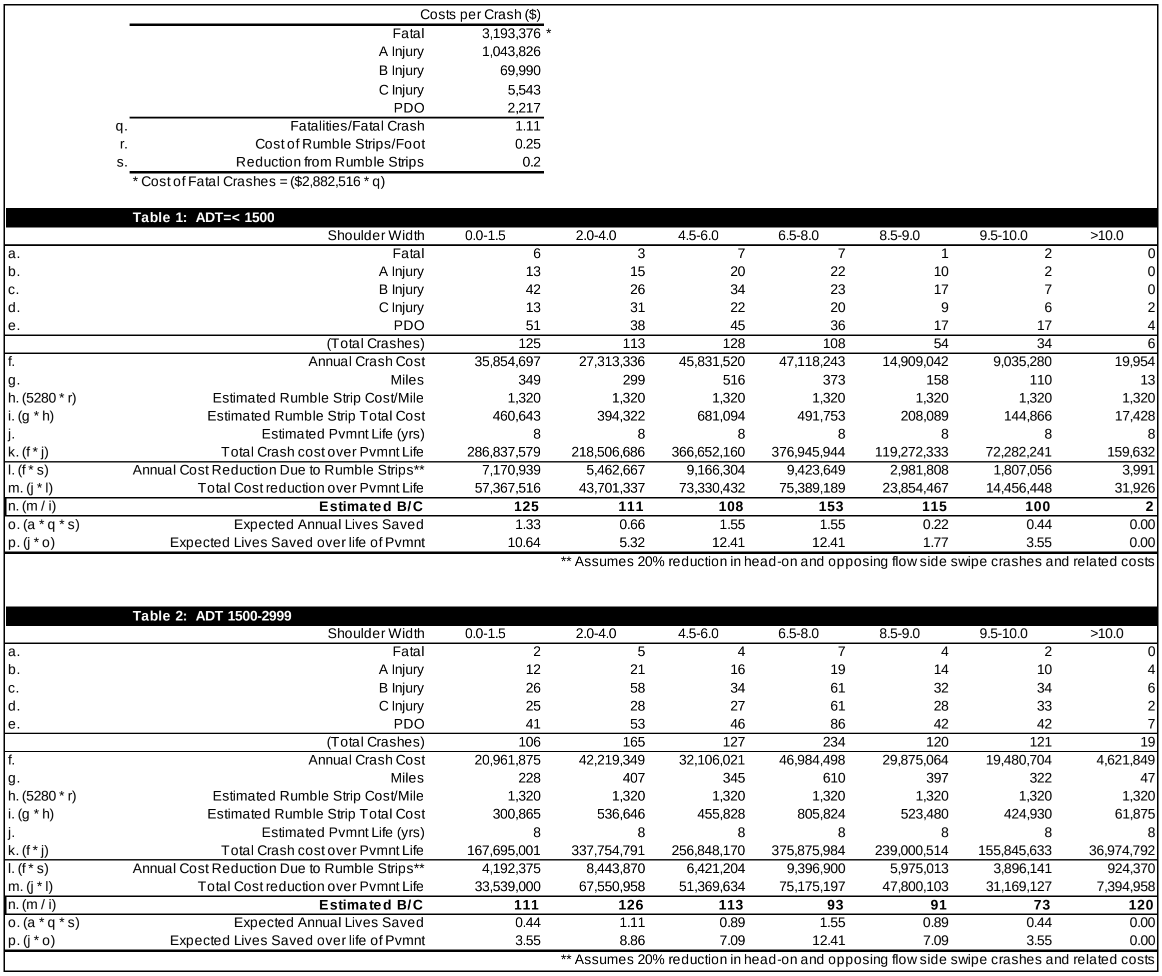
Table 4: ADT >4500

	Head-on and opposing flow side swipe crashes **	WASH	NC	IL	PA	TX
a.	Fatal	33	36	17	65	190
b.	A Injury	54	57	35	94	260
c.	B Injury	66	34	26	133	324
d.	C Injury	58	37	9	193	291
e.	PDO	107	17	50	171	333
f.	Annual Crash Cost	189,710,421	201,937,719	104,539,175	361,324,937	1,034,346,890
g.	Miles	979	3,539	994	2,801	8,897
h.	Estimated Rumble Strip Cost/Mile	7,920	7,920	7,920	7,920	7,921
i. (g x h)	Estimated Rumble Strip Total Cost	7,750,433	28,028,088	7,870,104	22,183,920	70,473,929
j.	Estimated Pvmnt Life (yrs)	8	8	8	8	9
k. (f x j)	Total Crash cost over Pvmnt Life	1,517,683,368	1,615,501,753	836,313,396	2,890,599,496	9,309,122,010
l.	Annual Cost Reduction Due to Rumble Strips***	37,942,084	40,387,544	20,907,835	72,264,987	206,869,378
m. (j x l)	Total Cost reduction over Pvmnt Life	303,536,674	323,100,351	167,262,679	578,119,899	1,861,824,402
n. (m / i)	**Estimated B/C**	**39.16**	**11.53**	**21.25**	**26.06**	**26.42**
o. (a x 1.35 x 0.2)	Expected Annual Lives Saved	8.89	9.70	4.58	17.52	51.20
p. (j x o)	Expected Lives Saved over life of Pvmnt	71.14	77.61	36.65	140.13	460.80

** Crash data from HSIS except for Pennsylvania and Texas

*** Assumes 20% reduction in head-on and opposing flow side swipe crashes and related costs

Figure 123. Safety Analysis of Centerline Rumble Strips (2 of 2).



		Costs per Crash ($)
	Fatal	3,193,376 *
	A Injury	1,043,826
	B Injury	69,990
	C Injury	5,543
	PDO	2,217
q.	Fatalities/Fatal Crash	1.11
r.	Cost of Rumble Strips/Foot	0.25
s.	Reduction from Rumble Strips	0.2

* Cost of Fatal Crashes = ($2,882,516 * q)

Table 1: ADT=< 1500

	Shoulder Width	0.0-1.5	2.0-4.0	4.5-6.0	6.5-8.0	8.5-9.0	9.5-10.0	>10.0
a.	Fatal	6	3	7	7	1	2	0
b.	A Injury	13	15	20	22	10	2	0
c.	B Injury	42	26	34	23	17	7	0
d.	C Injury	13	31	22	20	9	6	2
e.	PDO	51	38	45	36	17	17	4
	(Total Crashes)	125	113	128	108	54	34	6
f.	Annual Crash Cost	35,854,697	27,313,336	45,831,520	47,118,243	14,909,042	9,035,280	19,954
g.	Miles	349	299	516	373	158	110	13
h. (5280 * r)	Estimated Rumble Strip Cost/Mile	1,320	1,320	1,320	1,320	1,320	1,320	1,320
i. (g * h)	Estimated Rumble Strip Total Cost	460,643	394,322	681,094	491,753	208,089	144,866	17,428
j.	Estimated Pvmnt Life (yrs)	8	8	8	8	8	8	8
k. (f * j)	Total Crash cost over Pvmnt Life	286,837,579	218,506,686	366,652,160	376,945,944	119,272,333	72,282,241	159,632
l. (f * s)	Annual Cost Reduction Due to Rumble Strips**	7,170,939	5,462,667	9,166,304	9,423,649	2,981,808	1,807,056	3,991
m. (j * l)	Total Cost reduction over Pvmnt Life	57,367,516	43,701,337	73,330,432	75,389,189	23,854,467	14,456,448	31,926
n. (m / i)	**Estimated B/C**	**125**	**111**	**108**	**153**	**115**	**100**	**2**
o. (a * q * s)	Expected Annual Lives Saved	1.33	0.66	1.55	1.55	0.22	0.44	0.00
p. (j * o)	Expected Lives Saved over life of Pvmnt	10.64	5.32	12.41	12.41	1.77	3.55	0.00

** Assumes 20% reduction in head-on and opposing flow side swipe crashes and related costs

Table 2: ADT 1500-2999

	Shoulder Width	0.0-1.5	2.0-4.0	4.5-6.0	6.5-8.0	8.5-9.0	9.5-10.0	>10.0
a.	Fatal	2	5	4	7	4	2	0
b.	A Injury	12	21	16	19	14	10	4
c.	B Injury	26	58	34	61	32	34	6
d.	C Injury	25	28	27	61	28	33	2
e.	PDO	41	53	46	86	42	42	7
	(Total Crashes)	106	165	127	234	120	121	19
f.	Annual Crash Cost	20,961,875	42,219,349	32,106,021	46,984,498	29,875,064	19,480,704	4,621,849
g.	Miles	228	407	345	610	397	322	47
h. (5280 * r)	Estimated Rumble Strip Cost/Mile	1,320	1,320	1,320	1,320	1,320	1,320	1,320
i. (g * h)	Estimated Rumble Strip Total Cost	300,865	536,646	455,828	805,824	523,480	424,930	61,875
j.	Estimated Pvmnt Life (yrs)	8	8	8	8	8	8	8
k. (f * j)	Total Crash cost over Pvmnt Life	167,695,001	337,754,791	256,848,170	375,875,984	239,000,514	155,845,633	36,974,792
l. (f * s)	Annual Cost Reduction Due to Rumble Strips**	4,192,375	8,443,870	6,421,204	9,396,900	5,975,013	3,896,141	924,370
m. (j * l)	Total Cost reduction over Pvmnt Life	33,539,000	67,550,958	51,369,634	75,175,197	47,800,103	31,169,127	7,394,958
n. (m / i)	**Estimated B/C**	**111**	**126**	**113**	**93**	**91**	**73**	**120**
o. (a * q * s)	Expected Annual Lives Saved	0.44	1.11	0.89	1.55	0.89	0.44	0.00
p. (j * o)	Expected Lives Saved over life of Pvmnt	3.55	8.86	7.09	12.41	7.09	3.55	0.00

** Assumes 20% reduction in head-on and opposing flow side swipe crashes and related costs

Figure 124. Safety Analysis of Edgeline Rumble Strips (1 of 2).

		Costs per Crash ($)
	Fatal	3,193,376 *
	A Injury	1,043,826
	B Injury	69,990
	C Injury	5,543
	PDO	2,217
q.	Fatalities/Fatal Crash	1.11
r.	Cost of Rumble Strips/Foot	0.25
s.	Reduction from Rumble Strips	0.2

* Cost of Fatal Crashes = ($2,882,516 * q)

Table 3: ADT 3000-4499

	Shoulder Width	0.0-1.5	2.0-4.0	4.5-6.0	6.5-8.0	8.5-9.0	9.5-10.0	>10.0
a.	Fatal	0	1	3	7	2	1	1
b.	A Injury	8	9	7	27	18	11	3
c.	B Injury	23	23	28	55	25	23	8
d.	C Injury	23	20	8	40	28	22	1
e.	PDO	29	57	40	63	42	34	8
	(Total Crashes)	83	110	86	192	115	91	21
f.	Annual Crash Cost	10,152,160	14,434,809	18,979,653	54,747,772	27,173,687	16,482,556	6,908,053
g.	Miles	216	230	181	445	237	221	38
h. (5280 * r)	Estimated Rumble Strip Cost/Mile	1,320	1,320	1,320	1,320	1,320	1,320	1,320
i. (g * h)	Estimated Rumble Strip Total Cost	284,828	303,238	239,538	587,690	313,079	291,946	50,089
j.	Estimated Pvmnt Life (yrs)	8	8	8	8	8	8	8
k. (f * j)	Total Crash cost over Pvmnt Life	81,217,280	115,478,469	151,837,222	437,982,176	217,389,497	131,860,445	55,264,421
l. (f * s)	Annual Cost Reduction Due to Rumble Strips**	2,030,432	2,886,962	3,795,931	10,949,554	5,434,737	3,296,511	1,381,611
m. (j * l)	Total Cost reduction over Pvmnt Life	16,243,456	23,095,694	30,367,444	87,596,435	43,477,899	26,372,089	11,052,884
n. (m / i)	**Estimated B/C**	**57**	**76**	**127**	**149**	**139**	**90**	**221**
o. (a * q * s)	Expected Annual Lives Saved	0.00	0.22	0.66	1.55	0.44	0.22	0.22
p. (j * o)	Expected Lives Saved over life of Pvmnt	0.00	1.77	5.32	12.41	3.55	1.77	1.77

** Assumes 20% reduction in head-on and opposing flow side swipe crashes and related costs

Table 4: ADT >4500

	Shoulder Width	0.0-1.5	2.0-4.0	4.5-6.0	6.5-8.0	8.5-9.0	9.5-10.0	>10.0
a.	Fatal	0	2	3	12	7	12	1
b.	A Injury	9	16	16	43	26	38	1
c.	B Injury	30	29	30	103	52	69	13
d.	C Injury	25	25	40	100	45	69	11
e.	PDO	60	55	79	187	87	108	21
	(Total Crashes)	124	127	168	445	217	296	47
f.	Annual Crash Cost	11,765,729	25,378,187	28,777,906	91,382,874	53,574,899	83,437,108	5,254,602
g.	Miles	148	155	342	687	451	505	106
h. (5280 * r)	Estimated Rumble Strip Cost/Mile	1,320	1,320	1,320	1,320	1,320	1,320	1,320
i. (g * h)	Estimated Rumble Strip Total Cost	195,998	204,182	451,292	907,343	594,944	666,048	139,391
j.	Estimated Pvmnt Life (yrs)	8	8	8	8	8	8	8
k. (f * j)	Total Crash cost over Pvmnt Life	94,125,832	203,025,497	230,223,246	731,062,991	428,599,192	667,496,863	42,036,813
l. (f * s)	Annual Cost Reduction Due to Rumble Strips**	2,353,146	5,075,637	5,755,581	18,276,575	10,714,980	16,687,422	1,050,920
m. (j * l)	Total Cost reduction over Pvmnt Life	18,825,166	40,605,099	46,044,649	146,212,598	85,719,838	133,499,373	8,407,363
n. (m / i)	**Estimated B/C**	**96**	**199**	**102**	**161**	**144**	**200**	**60**
o. (a * q * s)	Expected Annual Lives Saved	0.00	0.44	0.66	2.66	1.55	2.66	0.22
p. (j * o)	Expected Lives Saved over life of Pvmnt	0.00	3.55	5.32	21.27	12.41	21.27	1.77

** Assumes 20% reduction in head-on and opposing flow side swipe crashes and related costs

Figure 125. Safety Analysis of Edgeline Rumble Strips (2 of 2).

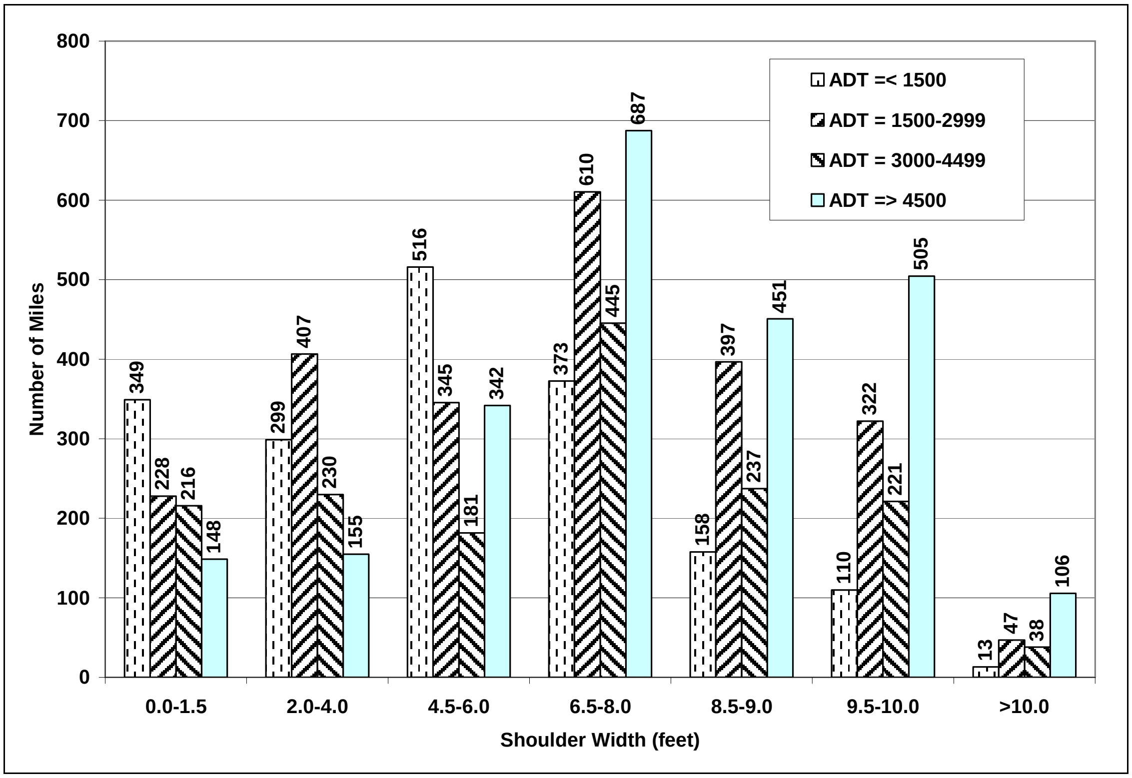


Figure 126. Distribution of Two-Lane Highway Mileage by Shoulder Width.

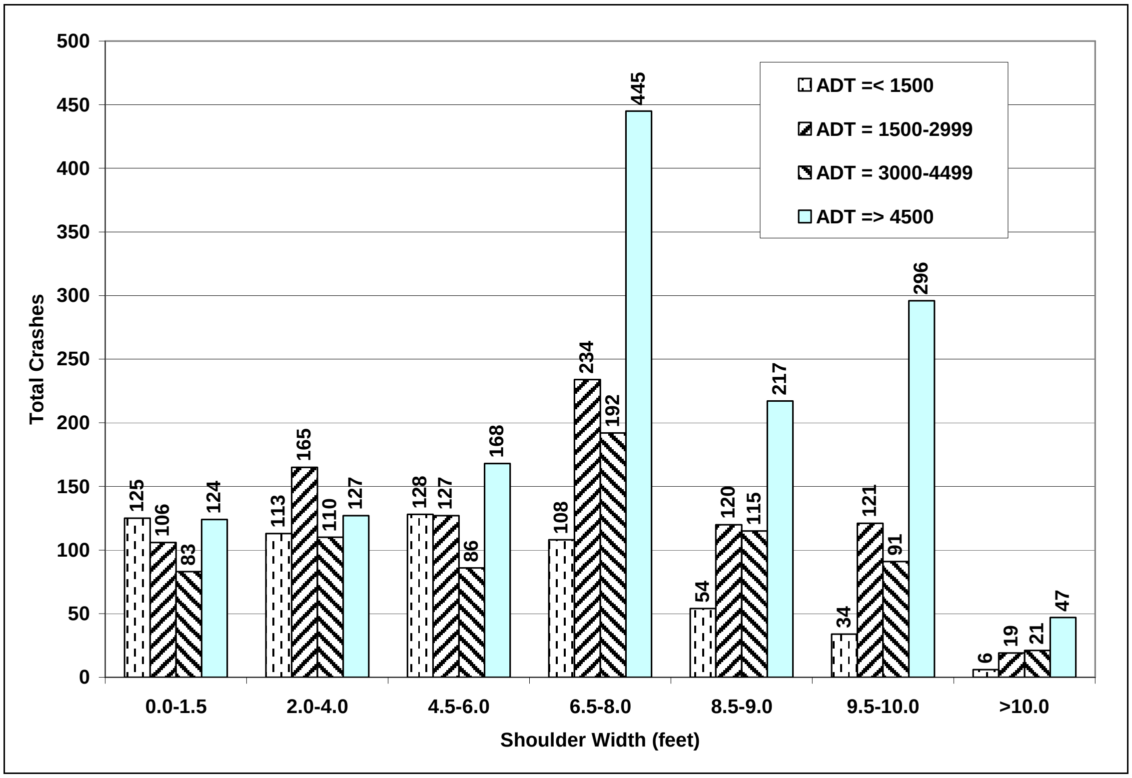


Figure 127. Distribution of Two-Lane Highway Crashes by Shoulder Width.