ASSESSING BENEFITS IN VEHICLE SPEED AND LATERAL POSITION WHEN CHEVRONS WITH FULL RETROREFLECTIVE SIGN POSTS ARE IMPLEMENTED ON RURAL HORIZONTAL CURVES

A Thesis

by

JONATHAN MICHAEL RÉ

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

May 2009

Major Subject: Civil Engineering

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Approved by:

Chair of Committee	H. Gene Hawkins, Jr.
Committee Members,	Yunlong Zhang
	Eric Dumbaugh
Head of Department,	David Rosowsky

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ABSTRACT

Assessing Benefits in Vehicle Speed and Lateral Position when Chevrons with Full Retroreflective Sign Posts are Implemented on Rural Horizontal Curves. (May 2009)

Jonathan Michael Ré, B.S., Michigan State University

Chair of Advisory Committee: Dr. H. Gene Hawkins, Jr.

Driving a horizontal roadway curve requires a change in vehicle alignment and a potential reduction in speed. Curves may present a challenging situation during adverse conditions or to inattentive drivers. Chevron signs provide advanced warning and positive guidance throughout the curve. Some agencies place supplemental retroreflective material on sign posts to enhance the signs' conspicuity and visibility. The objective of this study was to determine any incremental benefits in vehicle speed and lateral lane position when retroreflective material was applied to Chevron sign posts (ChevFull). This study analyzed three separate evaluation scenarios in a before, after, and after-after experimental design. There was an existing Baseline evaluation with no vertical delineation, a standard Chevron evaluation, and an experimental ChevFull treatment evaluation. Data collection measured vehicle speed and lateral position data at the point of curvature and mid-point on two separate curves. Findings showed that both Chevrons and the ChevFull treatment moved vehicles away from oncoming traffic by about 15 inches. Overall, there was little difference between the lateral position findings of the two Chevron treatment scenarios. Chevrons achieved a 1.28 MPH reduction in mean vehicle speed from the Baseline evaluation and the ChevFull treatment obtained a 2.20 MPH reduction. The findings determined that the benefits of the ChevFull treatment were not substantial. The author recommends that the MUTCD should continue to present the ChevFull treatment as an optional delineation tool. Based on this research, the author does not recommend any changes to the MUTCD.

DEDICATION

This thesis is dedicated to my parents for their unending love and support.

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This thesis could not have been completed without the help and support from so many exceptional people. I would like to thank my committee chair Dr. Hawkins for his direction and guidance in my research endeavors. I am grateful to my committee members Dr. Zhang and Dr. Dumbaugh for their time and patience.

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Finally, thanks to my family for their love and support.

NOMENCLATURE

ANOVA	Analysis of Variance
AASTHO	American Association of State Highway and Transportation Officials
ChevFull	Chevrons with Full Length Retroreflective Material on Sign Post
FHWA	Federal Highway Administration
FM	Farm to Market Road
GIS	Geographic Information System
HSD	Honestly Significant Difference
ITE	Institute of Transportation Engineers
K-S	Kolmogorov-Smirnov Test
LED	Light Emitting Diode
MANOVA	Multivariate Analysis of Variance
MDOT	Michigan Department of Transportation
MOE	Measures of Effectiveness
MP	Mid Point of Curve
MPH	Miles per Hour
MUTCD	Manual on Uniform Traffic Control Devices
PC	Point of Curvature
PT	Point of Tangent
PMD	Post-Mounted Delineators
PMD Full	PMD with Full Length Retroreflective Material
RPM	Raised Pavement Markers
SUV	Sports Utility Vehicle
TTI	Texas Transportation Institute
TxDOT	Texas Department of Transportation

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CHAPTER I
INTRODUCTION

A horizontal curve requires a change in vehicle path alignment and a potential reduction in vehicle speed. The change from tangent alignment may present a challenging task during adverse driving conditions or to inattentive drivers. Delineation devices and horizontal curve treatments aid and assist drivers in safe and efficient horizontal curve negotiation. Delineation treatments provide advanced warning on the approach tangent and positive guidance throughout the curve. Chevron signs are a common type of delineation treatment and are widely utilized. Chevron signs are classified as a warning sign (*1*) and are placed on the outside of a curve.

Some agencies have been placing supplemental retroreflective material on the Chevron sign posts to enhance the conspicuity and visibility of the sign. Figure 1 illustrates examples of current uses for the retroreflective material on warning and regulatory sign posts. The retroreflective material is applied with either adhesive backing or attached on a flat panel. There are commercial venders that sell such treatments, which are marketed as "Sign Post Covers" or "Reflective Panels."

The practice of placing supplemental retroreflective material on sign posts became common at passive at-grade railroad crossings. As of 1990, many states began placing a strip of retroreflective material on the front and back of Crossbuck sign posts when there was not an automatic gate that notified drivers of an approaching train (*2*). The retroreflective material is intended to alert drivers of the critical crossing situation and help the drivers to detect the presence of a crossing train. The Federal Highway Administration (FHWA) recommended this treatment for all passive at-grade rail crossings (*1*) and the practice of placing retroreflective material on sign posts spread to other warning and regulatory sign applications.

This thesis follows the style of the *Transportation Research Record.*

Figure 1 Retroreflective Sign Post Examples (*3*)

The only standards that govern the application of retroreflective material on sign posts are contained in the 2003 edition of Manual on Uniform Traffic Control Devices (MUTCD). The MUTCD states in section 2A.21 that "Where engineering judgment indicates a need to draw attention to the sign during nighttime conditions, a strip of retroreflective material may be used on regulatory and warning sign supports" (*1*). The MUTCD specifies that the retroreflective material shall be at least 2 inches in width and shall extend from the bottom of the sign to 2 feet above the roadway surface (*1*). Agencies may utilize the additional retroreflective material as an optional treatment and it is not required by the MUTCD.

The specifications in section 2A.21 covering retroreflective sign posts first appeared in the 2003 edition of the MUTCD. A Notice of Proposed Amendment on May 21, 2003 discussed the new specifications, but it did not provide justification for the added option nor did the final rule provide a research basis for the benefits of using retroreflective post treatments (*4*). The author believes that the standard was added without extensive support or rigorous testing.

Since the addition in the 2003 MUTCD, agencies have been placing retroreflective material on Chevron sign posts (ChevFull) at select locations as an additional treatment to the standard Chevron sign. The ChevFull treatment is intended to increase the visibility and conspicuity of the Chevron sign. Curve negotiation and driver safety may improve as a result of earlier detection and enhanced guidance. The ChevFull treatment is relatively inexpensive, easy to install, and requires no maintenance cost. The additional retroreflective material may be an attractive option due to its simplicity, low-cost, and practicality.

PROBLEM STATEMENT

There has been a recent study that analyzed the change in vehicle speed when the ChevFull treatment was implemented at one curve (*5*). This thesis evaluated both vehicle speed and lateral lane position at two curves to determine the effects of the ChevFull treatment. If the current practice of applying retroreflective material to Chevron sign posts is going to continue, then it is a worthy endeavor to investigate the treatment in a more comprehensive study to ascertain if there are additional benefits in both speed and lateral position.

RESEARCH OBJECTIVES

The objective of this thesis was compare the effects of Chevrons and the ChevFull treatment to a Baseline condition with no treatment in a before and after experimental design and to determine if the ChevFull treatment achieved additional benefits to the Baseline and Chevron evaluations. The research data for this thesis came from a Texas Transportation Institute (TTI) study that was conducted between the fall of 2007 and summer of 2008. The TTI study analyzed multiple delineation treatments in a closed-course test track portion, a laptop survey, and an open-road field evaluation. This thesis focused specifically on the Chevron and the ChevFull treatment results from the field evaluation of the TTI study.

The objective was accomplished by analyzing three separate evaluation scenarios in a before and after experimental design. A before, an after, and an after-after design was used to isolate the specific effects of the treatments. Evaluation scenarios consist of an existing Baseline evaluation (before), a standard Chevron evaluation (after), and an experimental ChevFull treatment evaluation (after). The Baseline evaluation employed no existing vertical delineation, such as Chevron signs and Post-Mounted Delineators (PMD). The analysis compared both Chevron treatment evaluations to the Baseline evaluation to identify any changes in vehicle operations. The results from the ChevFull treatment were compared to the Chevron results to determine if the added retroreflective material achieved additional benefits.

This thesis evaluated the treatments at two test curves. Vehicle speed and lateral position was measured at each curve in the Baseline evaluation. The Texas Department of Transportation (TxDOT) then installed Chevron signs on both test curves. Site 1 had the ChevFull treatment and Site 2 employed standard Chevron signs. The first after analysis repeated the data collection process in an identical manner to the Baseline evaluation. Afterwards, researchers removed the ChevFull treatment from Site 1 and placed it on Site 2. The after-after evaluation completed the final data collection scenario.

Measures of Effectiveness (MOE) assessed the change in vehicle operations between the three evaluation scenarios. A background review of past literature helped to identify appropriate MOE for assessing the benefits of Chevron signs and the ChevFull treatment. Analyzed MOE for both speed and lateral position included the mean, the standard deviation, and the change in individual vehicle data from the PC to the MP. Line lane encroachments and high speed percentages were also assessed.

The data collection process obtained vehicle speed and lateral position data at the Point of Curvature (PC) and at the Mid Point (MP) on both curve approaches of each site. Roadway sensors recorded both vehicle speed and lateral position for around 4 to 7 days during each evaluation scenario. A control speed was measured approximately one mile upstream from each curve approach to determine if vehicle speeds considerably changed between evaluation scenarios. A screening and formatting process transformed the raw data into working vehicle data for the statistical analysis.

Statistical techniques analyzed and determined if the change in MOE amongst the three evaluation scenarios were significantly different. The general testing hypothesis stated that if the treatments did achieve a significant difference, then the null hypothesis was rejected and the alternative hypothesis was accepted. The statistical analysis employed the Multivariate Analysis of Variance (MANOVA), Tukey's Honestly Significant Difference (HSD), the Z-test, and the F-test to test for significance. The statistical analysis performed all tests at a confidence interval of 95 percent or higher.

The author extracted meaningful trends and findings from the statistical analysis. The recommendations addressed the benefits for both Chevrons and the ChevFull treatment over the Baseline Evaluation. This study determined if the ChevFull treatment did or did not achieve significant and substantial benefits over standard Chevrons. In summation, the need for changes in language or treatment practices in the MUTCD was discussed.

CHAPTER II
BACKGROUND

This chapter contains a background review of past studies and practices. Previous research served as a guide and indicated how this study could contribute knowledge to the current transportation practice. This background review started general and then narrowed the focus to establish suitable methods for investigating the ChevFull treatment effects, analyzing the data, and interrupting the results.

A driver must guide his or her vehicle safely through a horizontal curve. Vehicle guidance involves maintaining proper speed and lane placement that does not conflict with roadway constraints or regulations. Vehicle guidance is one of the fundamental tasks in Alexander and Lunenfeld's positive guidance framework. Positive guidance tasks include vehicle control, guidance, and navigation (*6*). Negotiating a horizontal curve involves all three driving tasks. Driver error on a horizontal curve is typically a result of a breakdown in one of the positive guidance tasks.

DRIVER ERROR ON CURVES

Driver error in vehicle guidance is typically attributed to improper vehicle speed or lateral lane position selection. Driver error and inadequate vehicle guidance may increase the chance of a potential hazard.

Improper Speed Selection

Appropriate curve speed is critical for safe vehicle guidance. In a fundamental study, Solomon identified several significant relationships between speed and safety on rural roadways (*7*). The study examined data from 10,000 crashes before the year of 1964. One of the main discoveries revealed that crash rates were significantly higher for vehicles traveling at speeds that were considerably above or below the roadway mean speed. The relationship between vehicle speed and crash rates resembled a U-shape curve. Crash rates were lowest for vehicles traveling near the roadway mean speed and highest when there was a large disparity between the vehicle speed and the roadway mean speed (*7*). The study concluded that variance in speed and speed differential were significant factors that increased the likelihood of a crash.

A study by Nicholas and Ehrhart reconfirmed Solomon's variance in speed and crash relationship (*8*). The study evaluated 15 two-lane rural highways in Virginia between the years of 1993 and 1995. The researchers created a model to determine if the mean speed, speed standard deviation, flow per lane, lane width, or shoulder width were significant contributors to increased crash rates. The results from the model showed that speed standard deviation had the greatest influence on crash rates (*8*). It was determined that crash rates increased exponentially as the standard deviation of travel speed increased. A study in a different part of the county revealed more relationships between speed and crash rates.

At comprehensive crash investigation by the Michigan Department of Transportation (MDOT) explored crash rates on horizontal curves and speed characteristics (*9*). The investigation involved an extensive literature review, an examination of crash data, and a field evaluation of six rural horizontal curves. The most reoccurring speed characteristic that was associated with crash rates was speed differential between the tangent and the curve speed (*9*). The data showed that as the speed differential increased, then so did the crash rates. For instance, crash rates were higher at a curve that required drivers to reduce vehicle speed by 15 MPH, as opposed to 5 MPH. The investigation determined that increased speed differential was strongly correlated to both head-on and single-vehicle crashes (*9*).

Anderson and Krammes further built upon MDOT's speed differential and crash rate relationship (*10*). The researchers developed a model that quantified and illustrated the relationship. The model incorporated speed differential and geometric characteristics from 1,126 rural horizontal curves. A linear regression line plotted the relationship between speed differential and crash rates (*10*). The regression line showed that crash rates were significantly higher on a curve with a 20 MPH speed differential, as opposed to a curve that required a 10 MPH speed reduction. Liner relationships exhibited R^2

values greater than 0.90 and statistical analysis proved that speed differential was a significant contributor to increased crash rates (*10*).

Speed alone is not the only cause or contributor to driver error on a horizontal curve. Vehicle speed and lateral position are related and it is typically a breakdown in both that leads to driver error.

Inadequate Lateral Position

Speed selection greatly influences a vehicle's lateral lane position within a horizontal curve. Centripetal force pushes a vehicle to the outside of a curve when the operating speed exceeds the curve design speed. Moving outwards will increase a vehicle's radius path to compensate for the excessive speed. Adopting a larger radius than the road's intended design radius is called curve flattening. Zador et al. revealed in study that the curve flattening was common at 46 rural horizontal curves in two states (*11*). Researchers collected vehicle speed and lateral lane position at several points along each of the horizontal curves. The results showed that many vehicles shifted towards the edgeline on an outside curve (left-handed curve) and closer to the centerline on an inside curve (right-handed curve).

Spacek determined that curve flattening was more prevalent at curves with large speed differential between the tangent and curve speed (*12*). The study monitored vehicle speed and lateral position at twelve points within a horizontal curve. The researcher also identified another inadequate vehicle path, which was referred to as curve cutting. Vehicles shifted towards the center of a curve during curve cutting. The researcher observed that 37 percent of the total vehicles in the study displayed an inadequate vehicle path (*12*). Spacek determined that the curves with the high rates of improper vehicle paths also exhibited high crash rates (*12*). The study concluded that abruptly overcorrecting for poor lane position was a significant contributor in horizontal curve crashes.

Besides a specific vehicle path, a study in Pennsylvania established a relationship between the lateral position standard deviation and crash rates (*13*). Taylor et al.

evaluated nine rural two-lane curves that exhibited high crash rates. The nine curves varied in crash rates, traffic volumes, geometric characteristics, and driver types. Lateral position data were collected at the PC and at the MP on both directional approaches at each curve. The lateral position mean and standard deviation were generated for each data collection location. The standard deviation indicated the variation in lane position amongst the sampled vehicles. A model determined that crash rates were associated with high lateral position standard deviation values (*13*).

One indication of improper vehicle paths is lane line encroachments. The comprehensive MDOT crash investigation also examined lateral position data and crash rates (*9*). Along with speed differential, the researchers established that lane line encroachments were also a significant contributor to crash rates (*9*). The relationship determined that crash rates increased when total lane line encroachments increased. The correlation was very strong for single-vehicle crashes and edgeline encroachments.

DELINEATION TREATMENTS

Delineation devices are placed on a horizontal curve to curtail improper speed and lateral position by providing advanced warning and guidance. Delineation devices include Raised Pavement Markers (RPM), barrier reflectors, PMD, and Chevron Signs. Implementation is based upon roadway geometry, speed differential, sight distance, and crash history (*1*, *14*).

Curve warning and guidance is achieved through the delineation devices' size, color contrast, and retroreflectivity (*1*). The Retroreflectivity of a delineation device is critical during nighttime or adverse driving conditions. Retroreflection is the physical principle of returning light back to its source (*15*). Light from a vehicle's headlight is redirected back to the driver by means of a retroreflective device. The MUTCD states that delineation "shall be retroreflective devices mounted above the roadway surface and along the side of the roadway in a series to indicate the alignment of the roadway" (*1*).

Two commonly utilized horizontal curve delineation devices are Chevron signs and PMD. Figure 2 depicts an image of both delineation treatments. PMD are approximately 4 foot in length and 4 inches in width with retroreflective material applied at the top of the post. The Chevron signs (W1-8) are classified as a warning sign in the MUTCD and are comprised of a pointed black arrow on a yellow background that indicates the direction of the roadway. Both devices are placed on the outside curve shoulder. Chevrons should be placed so that at least two signs are in the drivers' view throughout the curve (*1*, *16*).

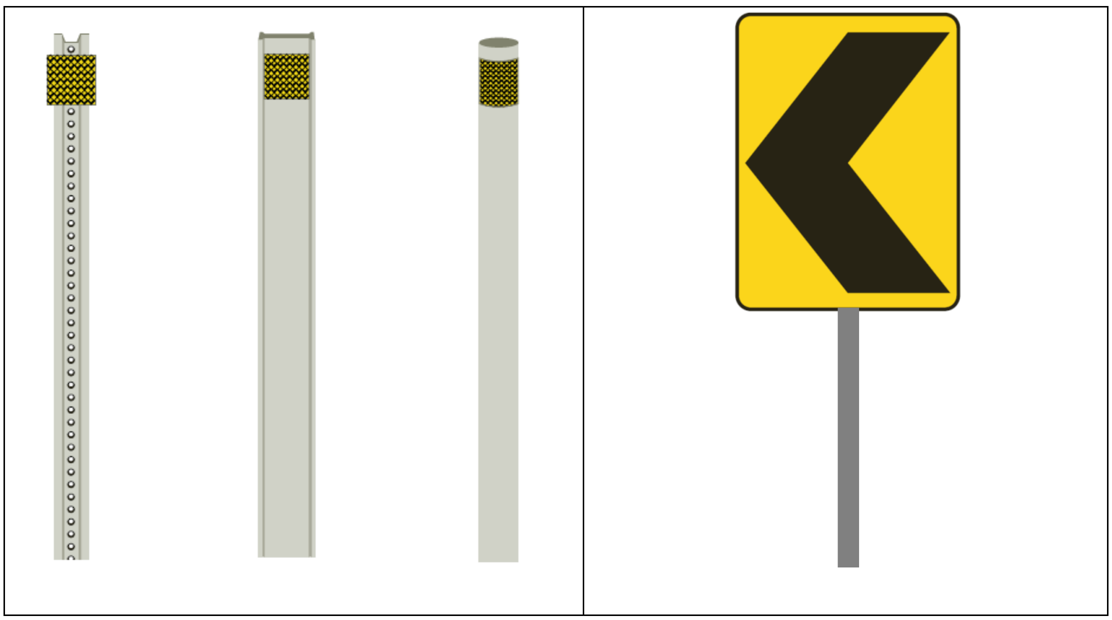

Figure 2 PMD and Chevron Sign (*1*, *16*)

DELINEATION RESEARCH

In 1983 Niessner summarized several field studies that evaluated PMD and Chevrons impacts on vehicle safety and crash rates (*17*). The summary analyzed results from eight different states. All of the reviewed studied were conducted in a before and after experiment design. Each study evaluated crash rates before and after the installation of delineation treatments. Niessner extracted from the studies that Chevrons significantly reduced the fatal crash rate and PMD significantly lowered run-off-the road crashes (*17*). The study concluded that both Chevron and PMD were adequate devices for delineating horizontal rural curves.

The reduced crash rates may be attributed to improved vehicle operations, which were shown in an Australian study conducted in 1983 (*18*). Johnston evaluated the benefits of Chevrons and PMD in a closed-course test track. Delineation treatments were assessed by measuring vehicle lateral position, encroachment rates, and speed. The results showed that the curves without delineation treatments exhibited the least desirable vehicle operations (*18*). Curves employing Chevron signs achieved significantly lower vehicle speed during nighttime and superior lateral position results compared to curves with PMD. It was found that Chevrons moderately increased the mean speed during daytime conditions. Johnston attributed the small speed increase to enhanced driver confidence and comfort (*18*). Nevertheless, mean speeds were significantly lower and vehicles followed a "better" path on curves with Chevrons, as opposed to PMD.

A study in Virginia conducted an open-road field evaluation that was similar to Johnston's study (*19*). Jennings and Demetsky compared the effects of Chevrons, PMD, and a road edge delineator on horizontal curves. Each treatment was placed individually on five curves and vehicle speed and lateral position data were collected at the PC and MP. Results determined that none of the treatments achieved a significant reduction in speed, but benefits were obtained in lateral position (*19*). All treatments shifted drivers away from the edgeline on an outside curve. The researchers concluded that Chevrons promoted a more centralized vehicle path, reduced encroachment rates, and lowered the lateral position variance (*19*).

A study by Agent and Creasey evaluated Chevrons and PMD in a slightly different approach (*20*). The researchers studied the delineation treatments in two parts: a subjective laboratory evaluation and a field evaluation. In the laboratory evaluation, forty subjects were shown curve photographs with PMD and Chevrons varied in spacing, offset, and height. The researchers found that curves were perceived sharper when delineation treatments were taller (*20*). The second part of the study evaluated PMD and

Chevrons at increased heights on the open-road. RPM and pavement markings were also evaluated in the field investigation. The researchers measured vehicle speed and lane line encroachments as treatment MOE. The field investigation concluded that Chevrons achieved a greater reduction in vehicle speeds and lowered centerline encroachment rates then did PMD (*20*).

In 1987, a study by Zador et al. evaluated the short and long-term effects of Chevrons, PMD, and RPM. The study analyzed on vehicle operations at 51 rural curves in Georgia and New Mexico (*11*). Speed and lateral position were measured in a before and after experimental design for short-term and long-term effects. The speed results showed that PMD and RPM generally increased vehicle speeds by 1 to 3 feet per second (*11*). Chevrons did not produce a significant change in vehicle speed in Georgia, but increased vehicle speed by approximately 3 feet per second in New Mexico. Chevrons shifted vehicles away from the centerline in both curve directions and PMD moved them closer to the centerline. Neither treatment significantly corrected the curve cutting. The researchers concluded that the data suggested that short-term changes did not erode over time (*11*). In the end, the researchers could not definitively support one delineation treatment over the other.

ENHANCED DELINEATION TREATMENTS

Most of the reviewed literature dealt with conventional or standard delineation devices. Enhanced or modified delineation devices may be beneficial in certain situations. A study on peripheral visual detection concluded that "where there is a need for early detection, the reflectivity of the target should be increased to assure timely recognition, information processing, decision making, and appropriate control actions" (*21*). Another study that assessed roadway delineation for older drivers also determined that enhanced delineation treatments should be considered in areas with a large population of older drivers or at roadway locations with sharp horizontal curves (*22*).

A study by Pietrucha et al. in 1996 investigated older driver curve perception when standard and enhanced delineation treatments were implemented on horizontal curves (*23*). The objective of the study was to identify effective delineation treatments that increased perception distance and heighten awareness for older drivers. The researchers initially formulated 25 different delineation combinations. The treatments consisted of pavement markings, RPM, Chevrons, standard PMD, PMD with fully retroreflective post, and T-post PMD (*23*). The T-post PMD was an experimental treatment that employed a thin strip of retroreflective material that ran the length of the post from the standard PMD material to the bottom of the device. The PMD with fully retroreflective post was also an enhanced experimental treatment. There were 45 subjects and each was placed in one of three age categories; youth, middle-age, and older drivers.

The first portion of the older driver study evaluated each treatment combination in a driving simulation by measuring the rate of deceleration on the upstream curve approach (*23*). Subjects were also asked to subjectively rank the advanced warning ability of each treatment combination. Treatment combinations that included Chevrons, PMD, and T-post PMD achieved earlier deceleration than curves with just pavement markings or RPM. Chevrons and the T-post PMD were subjectively ranked high by all age groups (*23*). The second portion of the study assessed the 12 most promising treatment combinations by evaluating curve perception distance, cost, and ease of implementation. The treatment combinations that provided the longest perception distance consisted of the T-post PMD and Chevrons (*23*). The effective treatments exhibited large retroreflective targets and retroreflective material that extended from the top of the device to the ground.

The ChevFull treatment was first assessed in a study conducted in 2003 at TTI (*5*). Gates et al. evaluated a 4 inch wide strip of fluorescent yellow prismatic sheeting that extended the entire length of a Chevron sign post. The treatment was placed on all Chevron signs at one rural horizontal curve. Vehicle speed was measured at two upstream tangent points, the PC, and the MP. Overall the ChevFull treatment achieved a slight speed decrease of 1.7 MPH during twilight and 1.6 MPH during nighttime (*5*). The researchers concluded that the "use of fluorescent yellow microprismatic materials on Chevron posts or other curve delineation is recommended on an as-needed basis at spot locations where additional delineation is desired" (*5*).

The parent study to this thesis evaluated the ChevFull treatment in a closed-course test track setting (*24*). Chrysler et al. evaluated five different treatments on four test track curves. The treatments consisted of a Baseline condition with no vertical delineation, PMD with standard retroreflective material, PMD with full length retroreflective material (PMD Full), Chevrons, and the ChevFull treatment. Twenty subjects drove ten laps on the track and saw each treatment at each curve in both directions. An instrumented vehicle measured foot pedal displacement, lateral acceleration, specific Global Positioning System (GPS) location, and vehicle speed.

The PMD Full and the ChevFull treatments showed the most promising results and the least desirable vehicle operations were observed for the Baseline condition (*24*). Subjects were able to detect curves at a greater distance when PMD Full and the ChevFull treatments were implemented on curves (*24*). Subjects also released the acceleration pedal and initiated the brake pedal earlier when PMD Full and ChevFull treatments were present (*24*). It was reasoned that the enhanced delineation achieved a greater detection distance, which allowed drivers to decelerate earlier and minimize lateral acceleration on the vehicle.

BACKGROUND SUMMARY

This background review established that drivers must maintain proper vehicle guidance when traversing a horizontal curve. A driver must select an adequate speed and sustain a lateral lane position that complies with the roadway environment and geometrics. Safety issues may occur if curve speed exceeds the roadway design speed or if lateral position deviates considerably from a centralized lane position.

Appropriate vehicle speed is critical for safe curve negotiation. Solomon showed that crash rates significantly increased when the vehicle speed greatly exceeded the mean roadway speed (*7*). The background review also determined that speed standard deviation and the speed differential were significant contributors to crash rates (*7, 8, 9*).

Promoting more uniform speeds and lowering excessive vehicle speed were deemed to be beneficial safety measurements. Improving vehicle speed on a curve may also be advantageous for lateral lane position and vehicle path.

Excessive speed may force a vehicle to the outside of the curve requiring the driver to adopt a curve flattening strategy to minimize the centrifugal force. Curve flattening was associated with high crash rates (*12*). Curtailing excessive curve speed may mitigate curve flattening and reduce the chance of single-vehicle or head-on crashes. Another improper vehicle path that was linked to crash rates was curve cutting where the driver will shift towards the inside of the curve. Both improper curve flattening and curve cutting may be negated with lowered lateral position standard deviation values and reduced lane line encroachment rates (*12, 13*). It is ideal to achieve a more uniform and centralized lane position at the PC and at the MP.

Past research showed that Chevron signs have achieved beneficial vehicle operations (*18, 19, 20*) and reduced crash rates on horizontal curves (*17*). Some researchers recommended placing enhanced delineation treatments at locations where early curve detection is critical or where there are large populations of older drivers (*21, 22*). Placing retroreflective material on sign posts or on the entire length of the PMD has shown great promise in past studies (*5, 23, 24*). These past studies focused on performance measures of curve detection distance and vehicle speed. Two of the studies were conducted at a close-course test track (*23, 24*) and one evaluated enhanced treatments on a single roadway curve (*5*). This background review determined that there is a need to assess the effects of the ChevFull treatment on both vehicle speed and lateral position in an open-road study with more than one test curve.

CHAPTER III
STUDY DESIGN

This chapter documents the study design and methods utilized for evaluating the effectiveness of the Chevron and the ChevFull treatments on rural horizontal curves. The study design provides the foundation for the data collection and analysis procedures. This chapter documents the study approach, the site selection, and delineation treatment application.

STUDY APPROACH

The study approach details the fundamental structure for the treatment evaluation. It indicates how treatments were assessed and what were the specific criteria used to determine any incremental benefits that were associated with both Chevron treatments.

Experimental Design

This thesis measured vehicle operations in a before and after experimental design, which identified changes in vehicle speed and lateral position that could be attributed to the Chevron treatments. The study design consisted of three separate evaluation scenarios: a before, after, and after-after. The before scenario was an existing Baseline evaluation with no vertical delineation treatment. There were two treatment scenarios that consisted of a standard Chevron evaluation (after) and an experimental ChevFull treatment evaluation (after). Researchers collected vehicle speed and lateral position data at a test site before the addition of a study treatment in the Baseline evaluation. After the Baseline evaluation, Chevron treatments were installed and vehicle data were collected at the same site in an identical manner. Researchers switched the Chevron treatments and the after-after evaluation was conducted. The comparison of vehicle speed and lateral position data between the three evaluation scenarios determined the effects and value of the experimental treatment. The Institute of Transportation

Engineers (ITE) *Manual of Transportation Engineering Studies* acknowledged that before and after experiments are effective and practical for eliminating site-to-site comparisons, reducing the number of sites, and are easily comprehended by engineers and non-technical readers (*25*). Table 1 displays the treatment matrix.

Table 1 Delineation Treatment Matrix

Selected Sites	Before	After	After - After
Site 1	Baseline	ChevFull	Chevrons
Site 2	Baseline	Chevrons	ChevFull

Measures of Effectiveness

Safety benefits can be directly observed with a reduction in crash rates, but in some cases sufficient crash data may not always be accessible. Through years of research, studies have been able to identify surrogates for crashes. Safety surrogate measures establish a relationship between vehicle operations and crashes rates. Surrogates are an accepted intermediate in lieu of the absence or lack of sufficient crash data, but they are not a substitute (*26*).

The background literature review identified suitable MOE that were associated with safety surrogate measures. MOE define the vehicle operations for a given scenario. A comparison between the MOE of two different scenarios reveals the change in vehicle operations. The general testing hypothesis states that if there is relationship between the ChevFull treatment and a beneficial change in MOE, then it is possible to associate the treatment with traffic safety. Figure 3 illustrates the logic and reasoning behind the general hypothesis.

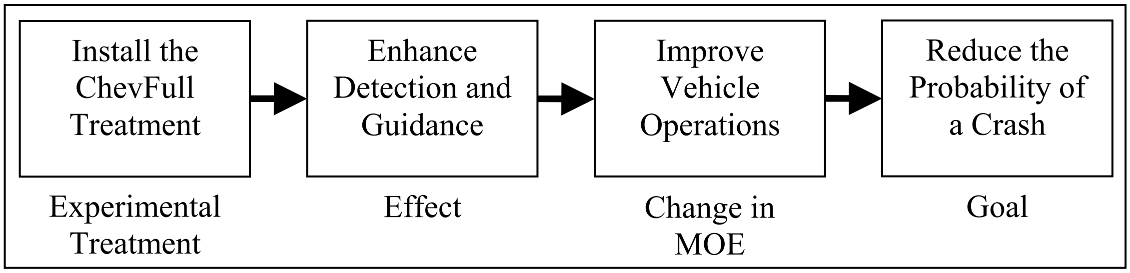

Figure 3 Treatment Effect on MOE and Traffic Safety

MOE included both longitudinal components (speed) and lateral components (lateral lane position). MOE in this thesis were:

- mean lateral position,
- mean change in lateral position from the PC to the MP,
- lateral position standard deviation,
- lane line encroachment rates,
- mean speed,
- mean change in speed from the PC and the MP,
- speed standard deviation , and
- high speed percentages.

Lateral Position Measures of Effectiveness

Justification for the lateral position MOE was derived from the background review. Previous studies determined that high crash rates were associated with overcorrecting improper lateral position due to the curve flatting or curve cutting (*12*). Both incorrect vehicle paths involved vehicles deviating from a centralized path and moving close to or encroaching onto a line lane. Line lane encroachments (*9*) and large variation in lateral position (*13*) also led to higher crash rates. Achieving a more centralized and uniform lateral lane position throughout the curve would reduce improper vehicle paths, line lane encroachments, and lateral position standard deviation.

Therefore, a reduction in improper lateral position characteristics may reduce the likelihood of a crash and ultimately improve safety.

Speed Measures of Effectiveness

Previous research also validated speed MOE. Studies acknowledged that high speeds increased the probability of crashes, such as single-vehicle crashes (*7, 9*). Large disparity between vehicle speed and the roadway mean speed significantly contributed to higher crash rates (*7, 8*). Specifically for a horizontal curve, crash rates were shown to decrease when the tangent speed on the upstream approach was closer to the curve negotiation speed (*9, 10*). Promoting more uniform curve speed close to the appropriate advisory curve speed may reduce the probability of a crash.

SITE SELECTION

The site selection portion of this thesis involved a great deal of effort and focus. The TTI research project had the resources and time to assess the Chevron treatments on two rural horizontal curves. It was highly important that both selected test sites were ideal and satisfactory.

Site Selection Criteria

TxDOT and TTI staff assisted in creating a preliminary list of potential horizontal curve sites. Potential site criteria stated that:

- the roadway shall be classified as a high-speed rural highway with a posted tangent speed of 55 MPH or greater,
- curves should warrant a reduction in speed from the posted speed limit,
- curves shall be located on the TxDOT roadway system, and
- curves should yield volumes of approximately 1,000 or more vehicles per day.

The analysis identified 170 potential curves near Bryan, Texas. Researchers resided within the Bryan area and local sites minimized travel time and conserved resources. Local agencies provided roadway information and curves were plotted on a comprehensive regional map. TTI personnel visited each potential site and digitally filmed the curve for later evaluation. Geometric characteristics, traffic control devices, roadway features, and other relevant information were recorded in a spreadsheet for each curve. The author generated a list of site selection criteria to systematically eliminate any curves that were not ideal. Site selection criteria were that chosen curves:

- shall have edgeline, centerline, and a total travel width greater than 20 feet,
- shall have Curve Warning signs (W1-1 or W1-2) and Advisory Speed plaques (W13-1),
- shall have the same posted tangent speed limit and advisory curve speed on both directional approaches,
- should have minimal interference from intersecting roadways or driveways in the immediate area,
- should all exhibit similar roadway geometry and design characteristics,
- should not be a part of a series of connected curves that are signed with Reverse Curves (W1-3), Reverse Turn (W1-4) ,or Winding Road (W1-5),
- shall be rejected if obstacles, guardrail, construction, railroad crossing, or other objects are deemed likely to influence a driver,
- shall be rejected if vertical delineation devices are presently installed, and
- shall present the opportunity to safely install and maintain data collection equipment.

Site Selection Process

The site selection process reduced the preliminary list to 39 potential curves. The remaining curves were located through Geographic Information System (GIS) software. The author approximated the locations of the PC and the Point of Tangent (PT) on aerial images. GIS applications measured the curve length and deflection angle from the approximated PC and PT locations. Fundamental circular curve equations generated the curve radius.

This thesis did not attempt to isolate two curves with exact geometric characteristics. It was unrealistic to find two curves that both have a radius of 800 feet and a 45 degree deflection angle. For an example, researchers concentrated on identifying curves where the deflection angle would differ by about 5 degrees, as opposed to 45 degrees. Selecting similar curves would minimize uncertainty and strengthen the validity of the results by avoiding curves that were considerably different.

The site selection process grouped similar curves together. The curve groups exhibited similar curve lengths, radii, and deflection angles. Radius was the most critical geometric parameter used to group and compare sites. Posted speed limits and the advisory curve speeds were also compared. Curve film was reviewed and project staff visited each potential site to confirm video observations. A comprehensive list compiled the advantages and disadvantages of each curve. The final outcome generated two suitable sites.

Test Site Characteristics

Site 1 resides on Farm to Market Road (FM) 974 and Site 2 is located on FM 50. Figure 4 indicates the locations of the test sites and APPENDIX A contains detailed curve schematics. Both selected curves employ centerline, edgeline, and RPM with no existing vertical delineation. All upstream approaches to the curves were deemed sufficient in length for vehicles to travel at or near the posted speed limit. Intersecting driveways and roadways exist in the vicinity of both curves but they were reasoned to have a negligible effect on overall traffic operations.

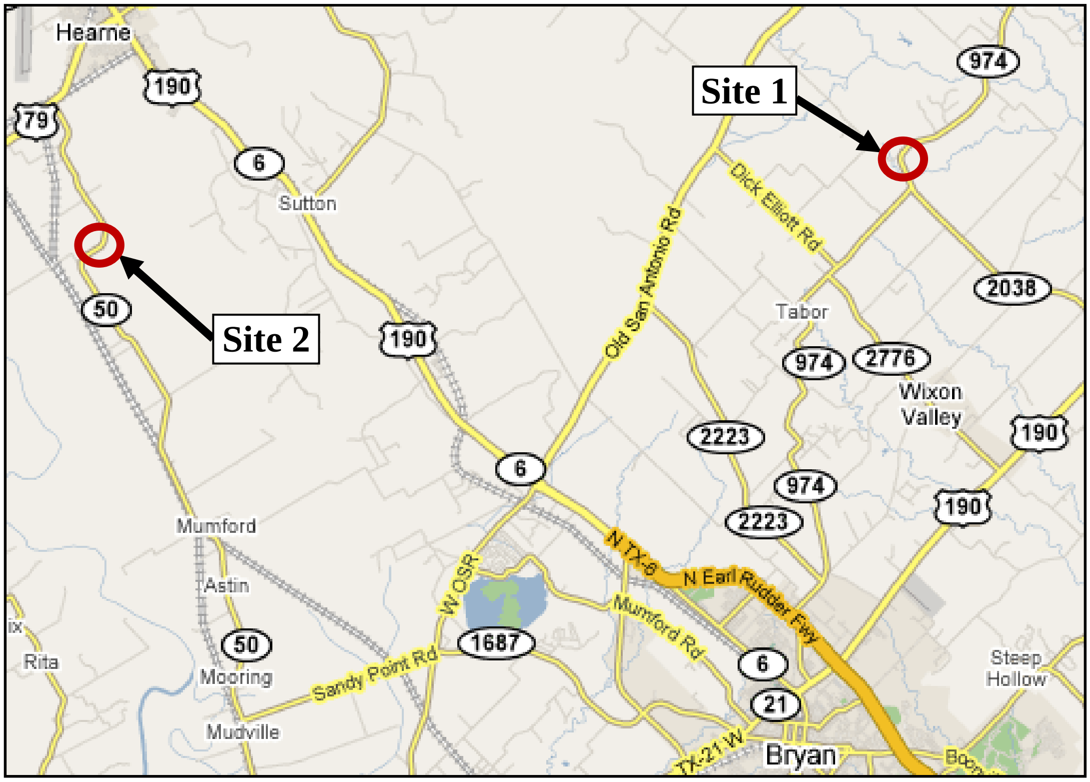

Figure 4 Map of Test Sites

Site 1 and Site 2 employed advisory speed plaques of 45 and 50 MPH, respectively. A comparison between the current advisory speeds and an alternate advisory speed method determined that Site 1 should have an advisory speed of 55 MPH and that the advisory speed at Site 2 is appropriate. The alternate advisory speed was determined using a method in a recent study in 2007 (*27*). Bonneson et al. developed a model from empirical data to estimate the 50th percentile truck speed, which was equivalent to the 40th percentile passenger vehicle speed. Bonneson et al. reasoned that the 50th percentile truck speed was a suitable criterion for selecting an advisory curve speed. The model generates the advisory speed from the 85th percentile tangent speed, curve radius, and superelevation. TxDOT is moving towards officially adopting the Bonneson et al. advisory speed method and the organization is currently providing training sessions for the method (Mike Pratt, Assistant Research Engineer, unpublished data). Table 2 shows pertinent test site characteristic information.

Table 2 Test Site Characteristics

Selected Sites	Name	Deflection Angle (degrees)	Radius (feet)	Length (feet)	Speed Limit (MPH)	Signed Advisory Speed (MPH)	Alternate Advisory Speed* (MPH)	Terrain
FM 974	Site 1	37.5	1071	701	70	45	55	Wooded
FM 50	Site 2	45	1238	972	70	50	50	Farmland

Note: The alternate advisory speed is based on Bonneson et al. (*27*).

DELINEATION TREATMENT APPLICATION

All treatments in this evaluation were in accordance and complied with TxDOT and MUTCD standards. TxDOT staff approved all devices and materials before they were installed on the curves. Types, models, and brands of treatments were obtained impartially and reflected what was currently used by TxDOT.

Studied Delineation Treatments

The standard Chevron assembly consisted of the sign face and the post system. Dimensions for a Chevrons signs (W1-8) on a high-speed conventional road were 24 inches in width by 30 inches in height (*28*). The sign was composed of an aluminum backing with prismatic fluorescent yellow retroreflective sheeting. A wedge anchor assembly was used as the post system, which was specified by TxDOT maintenance staff. TxDOT district offices assumed responsibilities and upkeep of the signs following the completion of the study and it was necessary that all materials met their specifications.

Chevron signs were mounted back-to-back on one sign post and orientated as much as possible towards the direction of travel. A previous ERGO examination determined that sign rotation had a very negligible effect on overall luminance. All Chevron signs had a maximum height of 6.5 feet from the top of the sign to the ground surface, which is the regulation height for a Chevron sign on a wedge anchor post (*29*). Figure 5 shows the TxDOT wedge anchor detail sketch.

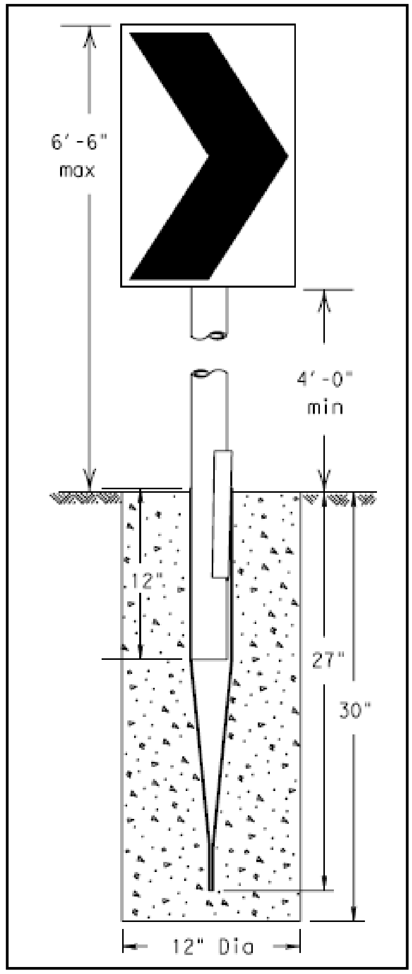

Figure 5 Wedge Anchor Post Assembly (*29*)

The retroreflective material for the ChevFull treatment was flexible prismatic fluorescent yellow sheeting. The sheeting was applied to a section of PVC pipe that was 2.5 inch in diameter and 4 feet in length. The retroreflective PVC pipe was placed over the 2 ⅜ inch sign post and completely encircled the sign post. The retroreflective material was not applied directly to the sign post because removing the sheeting would leave adhesive residue that could collect dirt and debris. The retroreflective PVC pipe proved to be very efficient and economical for changing between Chevrons and the ChevFull treatment.

Application and Installation

Spacing of Chevron treatments was based on the Roadway Delineation section of the Texas MUTCD (*16*). The Texas MUTCD details that Chevron signs are placed throughout the curve between the PC and PT and that one Chevron sign is placed on the entrance and exit tangent. Figure 6 depicts an image of the Chevron sign placement on a horizontal curve. Chevron sign spacing was calculated from both curve radius and curve advisory speed. Calculated values were rounded up to the nearest whole number. Chevron signs were spaced 160 feet apart at both Site 1 and Site 2. Seven Chevron signs were installed on Site 1 and 9 Chevron signs were installed on Site 2.

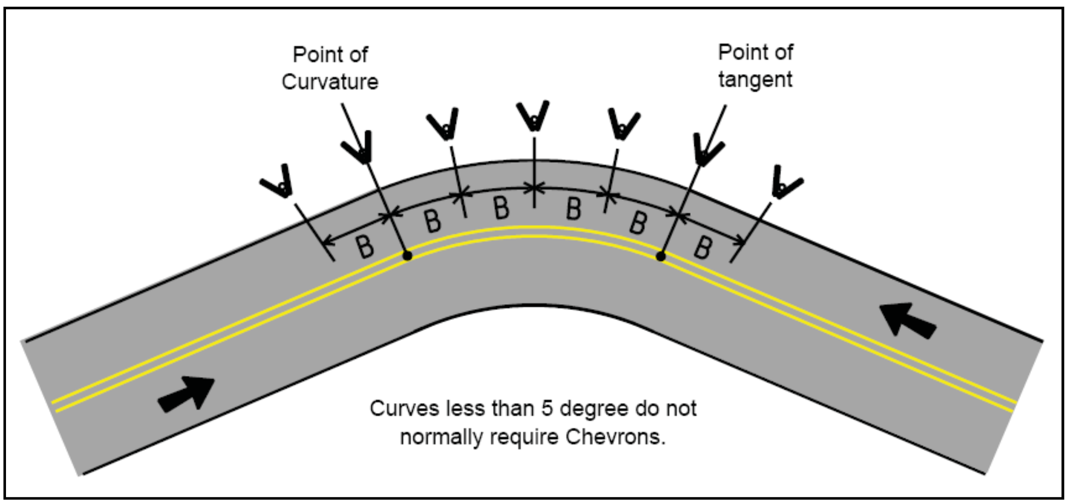

Figure 6 Chevron Spacing on a Curve (*16*)

Signs were located at a 12 foot offset from the nearest travel lane to the nearest edge of the sign (*1, 29*). The author and a TxDOT engineer located all Chevron sign locations. TxDOT field crews installed the Chevron signs in the marked locations. Sign positions and spacing were adjusted within MUTCD requirements to minimize conflicts with driveways, vegetation, objects, etc. Figure 7 and Figure 8 display images of the ChevFull treatment implemented at the test sites.

Figure 7 ChevFull Treatment on Site 1

Figure 8 ChevFull Treatment on Site 2

CHAPTER IV
DATA COLLECTION AND ANALYSIS

Data collection and analysis is the cornerstone of most research studies. Conclusions and observations are irrelevant if datasets are not collected and analyzed in a verifiable, ethical, and candid manner. This chapter documents and details the techniques used to collect and analyze the vehicle speed and lateral position data.

DATA COLLECTION PROCEDURE

The data collection procedure outlines how the vehicle data were acquired. This section describes what methods were utilized to collect the data, where the vehicle speed and lateral position data were measured, and when the data were collected.

Data Collection Equipment

Data collection equipment was comprised of a traffic classifier and three roadway sensors. Piezoelectric roadway sensors were placed on the roadway and detected the presents of a passing vehicle from the pressure of the tires. Piezoelectric sensors consist of a thin metallic wire, which was inserted into pocket tape that adhered to the roadway surface. Three piezoelectric sensors positioned in a pattern that resembles the letter “Z” collected the data and relayed it to the traffic classifier. Traffic classifiers store the vehicle data with an exact time stamp. The time stamp classifies the detected vehicles in a chronological order at an accuracy of one-thousandth of a second. Figure 9 depicts the Z-configuration sensor layout.

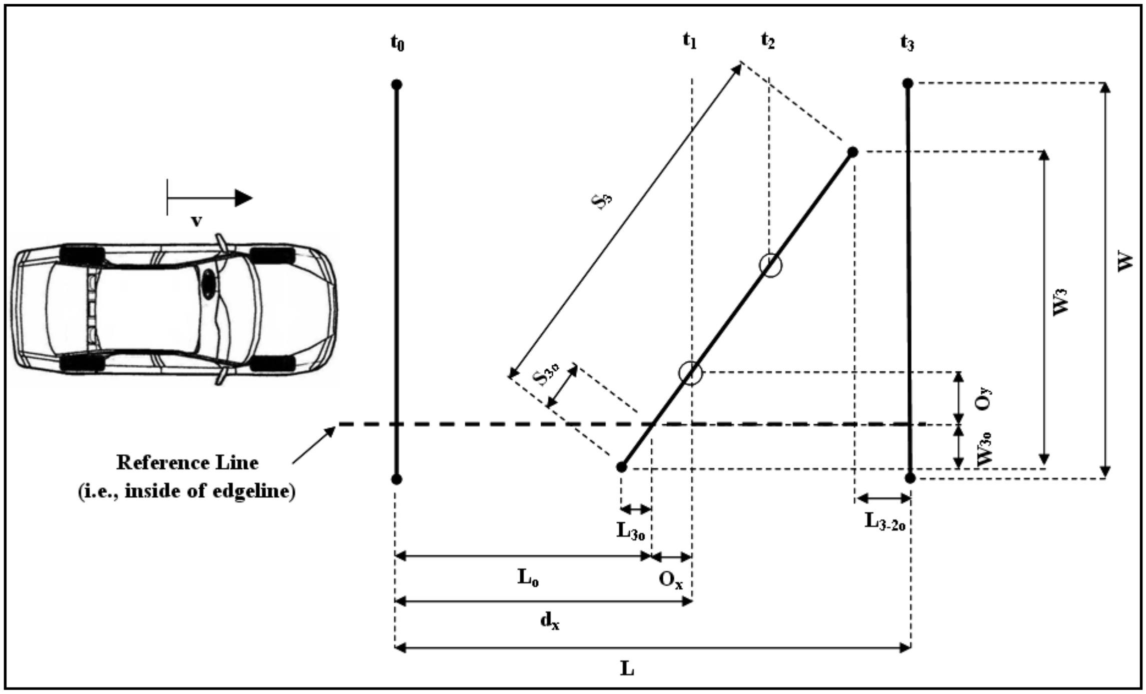

Figure 9 Z-Configuration Sensor Layout (*30*)

Research staff placed the piezoelectric sensors at precise distances on the roadway. The consistent distances ensured the acquisition of reliable and accurate data. The two parallel sensors generated the vehicle speed data. Speed was calculated from the known distance between sensors and the time it took a vehicle to travel across that distance. All three sensors worked simultaneously to produce the lateral position data. Lateral position data were a calculated product from the known geometric proportions of a right triangle, vehicle speed, and sensor time stamps.

Collection Locations

The data collection procedure obtained speed and lateral position data at the PC and MP on both curve approaches. A study by Medina and Tarko determined that vehicle deceleration continues after the PC (*31*). Curve velocity profiles showed that a vehicle decelerated to a comfortable or preferred curve speed between the PC and the MP. Drivers maintained the selected curve speed throughout the remainder of the curve until accelerating on the exiting tangent (*31*). Past studies identified that speed differential between the tangent speed and curve speed was a significant contributor to increased crash rates (*9, 10*). This thesis selected the PC and the MP as data collection locations because they are easily referenced, they provide uniform locations at all sites, and they have served well in past research (*5, 11, 19, 30*). Figure 10 depicts a diagram of data collection locations.

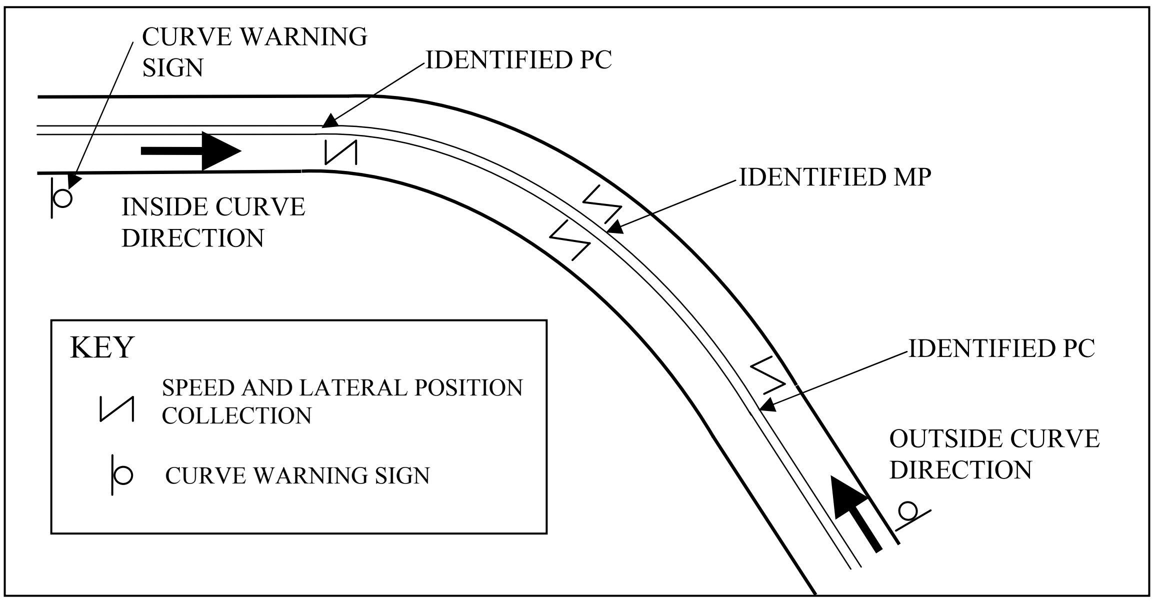

Figure 10 Data Collection Location Diagram

Control points located approximately one mile upstream from the curve measured vehicle speed that was outside the influence of the treatments. Control speeds were obtained in locations where vehicles could achieve an unconstrained free-flow speed at or near the posted speed limit. The control speed was used exclusively as a control point and it was not incorporated into the treatment analyses. The control speed indicated if vehicle speed changed considerably between evaluation scenarios. The control speed assessment is described later in this chapter.

Data Collection Schedule

Following specific steps in the data collection process helped to ensure reliable and verifiable data. The steps in the data collection schedule were:

- collect Baseline data for the before evaluation at both sites,
- install Chevron signs at both test curves and place the ChevFull treatment on Site 1,
- allow for a minimum 10-day acclimation period,
- collect data for the first after evaluation at both sites,
- remove the ChevFull treatment from Site 1 and place it at Site 2,
- repeat the 10-day acclimation period, and
- collect the final after-after evaluation at both sites.

Research staff conducted the before, after, and after-after evaluations in an identical manner. Between each evaluation scenario there was a 10-day acclimation period. The acclimation periods allowed the novelty or surprise effects of the new treatment to subside. Data collection resumed after the 10-day acclimation period.

DATA PROCESSING AND SCREENING

Researchers transferred the raw vehicle data contained in the traffic classifiers onto a computer. The transferred vehicle data at the time were unusable and it required processing and screening before the analysis.

A software program that came with the traffic classifiers quickly generated the vehicle speed data. The software program could not obtain the lateral position data, so research staff conducted the remaining lateral position data formatting with a customized spreadsheet. The spreadsheet distinguished an individual vehicle passing along all three sensors and generated vehicle length, number of axles, and lateral position data. Research staff removed the remaining erroneous data points that the spreadsheet was unable to detect. Erroneous data points included vehicles with a speed of zero, improbable axle spacing, and a lateral position measurement that was greater than the sensor length.

Free-Flowing Vehicles

The free-flowing screening process identified uninhibited vehicles and removed constrained vehicles. The process isolated the effects of the treatments on the vehicles and minimized the influence of lead vehicles. A driver traveling behind a slower moving vehicle may not be traveling at his or her preferred free-flow speed. A previous study identified that speeds of consecutive vehicles on two-lane rural highways were significantly different when there was a headway of 7 seconds or more between the lead and following vehicle (*32*). This study utilized a 7 second headway in the screening process to identify free-flowing vehicles. The screening process removed the following vehicle when there was a headway of 6 seconds or less between the following and the lead vehicle.

Vehicle Type

The vehicle type classification separated passenger vehicles and heavy vehicles into different lists. The vehicle operations of heavy vehicles and passenger vehicles are distinctively different. The vehicle type classification would determine if the treatments produced significantly different effects for different vehicle types. Heavy vehicles were identified by having more than 2 axles or exhibiting single axle spacing greater than 15 feet in length (*33*). Table 3 shows the percentage of heavy vehicle volumes out of the total roadway volumes. The heavy vehicle percentages remained reasonably constant throughout the study, which indicated that vehicle patterns did not change considerably between the evaluation scenarios.

Table 3 Percentage of Heavy Vehicles

Test Site	Before	After	After-After
Site 1	7%	8%	8%
Site 2	27%	25%	28%

Weather Analysis

Research staff documented weather information during collection periods. The information was obtained from the National Oceanic and Atmospheric Administration's National Weather Service website (*34*). A weather station in Bryan, Texas provided the information for both test curves. The daily weather information consisted of a general description of weather conditions, the high and low temperature, the average wind speed, and the amount of precipitation.

Rain fell on three days during the entire data collection period, which amounted to 0.32, 0.23, and 0.02 inches. Each rainfall occurred during different evaluation scenarios. Specific hours of rainfall could not be accurately identified and the removal of vehicle volumes during rainfall was difficult. The author compared the daily speed and lateral position data of rainfall days to non-rainfall days during the same data collection scenario. The comparison indicated that the differences in mean speed and lateral position data were marginal, so vehicles traversing the curve during rainfall were not removed.

Time Classification

The time classification grouped vehicles into nighttime and daytime periods. The nighttime period referred to the hours that were devoid of natural sunlight and the daytime period consisted of hours with ample sunlight. The time classification minimized vehicles arriving in twilight. Twilight is the period where the sun is at the horizon to altitude -18° below the horizon (*35*). Ambient light lingers during twilight, but headlights are required for driving. Vision can be hindered during Twilight and the period is associated with high crash rates (*35*). The time classification process minimized vehicles arriving in twilight. Vehicles were removed 30 minutes before and after sunrise; and vehicles arriving 30 minutes before and after sunset.

The evaluation scenarios occurred at different times in the calendar year which yielded varying durations of daylight. A uniform nighttime period was established for all evaluation scenarios. This approach ensured that the data in the before evaluation do not include high commuter traffic or peak hour volumes. The before evaluation took place in the fall when there was an early sunset. The after and after-after evaluation occurred in the spring when the sunset was later. The results could be negatively comprised if the before evaluation included work commuters and the after and after-after nighttime evaluation did not. The author based the uniform nighttime period on the latest sunset and the earliest sunrise times amongst the three evaluation scenarios. The uniform nighttime period occurred between the hours of 9:00 PM to 6:00 AM for a total of nine hours. Uniform hours were not established for the daytime period since vehicle collection would be limited to the hours between 8:00 AM to 5:00 PM. The limited hours would eliminate a great amount of valuable vehicle data in the after and after-after evaluations.

Control Point Speed Assessment

The screening process compared the control point speeds of different scenarios to determine if free-flow vehicle speed changed considerably between collection periods. The control point indicated if something in addition to the treatments was producing a considerable change in vehicle speed between evaluation scenarios. If a considerable change was observed, then researchers would try to determine the cause of the change and consider repeating the collection period if it led to erroneous data. The independent two-sample T-test analyzed the change in control speed to determine if there was a statistical difference.

Table 4 shows the change in mean control speed between periods and indicates which comparisons were significantly different. A positive value in the table indicates an increase in mean vehicle speed in the later scenario and a negative value signifies a speed decrease. The assessment showed that there were three comparisons that were significantly different. There was a significant speed decrease in the after evaluation on the inside direction of Site 1 and a significant speed increase in the after-after evaluation on the inside direction of Site 2.

Table 4 Control Point Speed Assessment

Location		Change in Mean Speed (MPH)		
		After & Before	After-After & Before	After-After & After
Site 1	Inside	**-1.63**	-1.16	0.47
	Outside	0.99	0.33	-0.66
Site 2	Inside	0.03	**1.71**	**1.68**
	Outside	-0.09	-0.88	-0.79

Note: Significant values are shaded in gray and have bold text.

For clarification, the before control speeds in Table 4 were not collected on the same dates as the before speed and lateral position data. The TTI project originally placed the control speed location at the Curve Warning sign on the tangent approach to the curve. This location was later deemed inadequate. The distance between the Curve Warning sign and the PC varied on each curve approach. Drivers were able to see the treatments at the Curve Warning sign, which could influence his or her vehicle operations and defeat the purpose of the control.

An alternate control speed location was selected to correct the original control location inadequacies. Research staff recollected the before control speed data one mile upstream from the test sites several months after the original before measurements. The different time periods made it difficult to conduct a true control speed comparison. Despite this discrepancy and the three significantly different tests, the author reasoned that the differences in control speeds were not substantial and the data collection periods were not repeated.

FUNCTIONAL DATA FORMATTING

The functional data formatting went beyond the basic screening process and produced lane line encroachment rates and vehicle tracking data. This section describes the process used to generate the encroachment rates and the vehicle tracking data.

Encroachment Rates

Lane line encroachments occurred when the outside edge of a vehicle's tire intruded upon an edgeline or centerline. The functional formatting derived the encroachment rates from the lateral position data and line widths. The encroachment rates were expressed as a percentage of observed encroachments out of the total vehicle number of vehicles. Edgeline encroachment rates were easily established since lateral position measurements were collected from the outside edge of a vehicle's right tire. Centerline encroachment rates could not be directly obtained for each individual vehicle so they were approximated by two aggregated track width values. The author approximated centerline encroachment rates by assigning an 80 and 61 inch track width to all vehicles.

The 80 inch track width was the maximum value from a list of 45 common large commercial Sports Utility Vehicles (SUV), vans, and trucks. All vehicles were 2006 models and data were obtained from the manufactures' website. The larger and more conservative track width would account for the majority of the possible centerline encroachments. Any beneficial reduction in centerline encroachments would not be missed as a result of the large track width. If the treatments decreased centerline encroachment rates for a wider vehicle, then it will decrease the rates for vehicles with a narrower or smaller track width. The 61 inch track width was the average of 14 common passenger vehicles, such as a Toyota Camry, Honda Accord, and Ford Taurus. All vehicles were 2008 models and the author acquired the data from the manufactures' website. The maximum 80 inch and the average 61 inch track widths provided a sufficient representation of possible centerline encroachments.

Vehicle Tracking Through Curve

The author tracked individual vehicles from the PC to the MP. The tracking data provided an exact account of how a single vehicle changed its speed or lateral position when traveling from the PC to the MP. The vehicle tracking was performed for all test sites, evaluation time periods, vehicle types, and treatment evaluations. The author believed this method was more accurate than just finding the difference in means between the PC and MP.

Individual vehicles were tracked from the PC to the MP by matching vehicle characteristics, as such axle spacing, number of axles, and vehicle classification. Matching PC and MP vehicle characteristics were then validated by checking the headway between consecutive vehicles. Vehicle data that could not be matched were removed from the vehicle tracking analysis. The change in vehicle speed and lateral position was calculated with:

$$\Delta = X_{MP} - X_{PC}$$

where:

Δ = change in vehicle speed or lateral position between the PC and the MP,

X_{MP} = speed or lateral position from the MP, and

X_{PC} = speed or lateral position from the PC.

ANALYSIS METHODS

The data analysis utilized common statistical techniques to determine if both Chevron treatments achieved significant differences in the MOE amongst the three evaluations. The statistical methods provided legitimacy and validity to the findings. The statistical methods used in this thesis were well established and approved by expert statisticians.

Multivariate Analysis of Variance

The MANOVA tested for the differences between mean values of multiple populations as a function of independent variables and interactions between the independent variables (*36*). The MANOVA analyzes multiple dependent variables in the same model as opposed to the Univariate Analysis of Variance (ANOVA) test which models only one dependent variable. The MANOVA model was more robust and powerful because it investigated both speed and lateral position dependents simultaneously in the same model (*37*). The dependent variables in the model were speed and lateral position data and the independent variables were:

- site (Site 1 and Site 2),
- location (PC and MP),
- curve direction (right-handed or inside curve and left-handed or outside curve),
- time (night and day),
- vehicle type (passenger vehicle and heavy vehicle), and
- treatment (Baseline, Chevrons, and ChevFull).

The MANOVA used a confidence interval of 95 percent to test for significance. The P-value indicated the probability of concluding significance. If the test produced a P-value less than 0.05 or 5 percent, then the main effects of the independent variables or the variable interactions were considered significant. If findings were significant, then the null hypothesis was rejected and the alternative hypothesis was accepted. The null and alternative hypothesis tests were defined as follows:

- Null hypothesis (H_o): the tested variable or interaction failed to produce a significant difference between means.
- Alternative hypothesis (H_a): the tested variable or interaction produced a significant difference between means.

Tukey's Honestly Significant Difference

Tukey's HSD tested for significance amongst the treatment means. Tukey's HSD is a pairwise comparison which compares the means of subgroups within the MANOVA model. The test is similar to the T-test, except that it corrects for the experiment-wise error rate (*38*). It is based on the standardized range statistic where the means are ordered from smallest to largest and then the differences in means are divided by the standard error of a treatment mean (*38*).

There are many different types of pairwise comparisons with different applications. The Least Significant Difference test is more exploratory while the

Student-Newman-Keuls test is a multi-range and homogeneity test (*38*). Tukey's HSD "provides the best protection against decision errors, along with the strong inference about magnitude and direction of differences" (*38*). Each pairwise comparison has its advantages and disadvantages. The *Statistical Principles of Research Design and Analysis* textbook recommended that "a test should comply with your philosophy and it should be used consistently" (*38*).

Z-test

The Z-test was used to compare proportions (rates) of two samples. The Z-test identified if there was a significant difference in the encroachment rates or high speed comparison. A confidence interval of 95 percent and a value of ± 1.96 were used to test for significance in a two-tailed test. The equation for the test is:

$$Z_0 = \frac{P_B - P_A}{\sqrt{\hat{P}(1-\hat{P})\left(\frac{1}{n_B} + \frac{1}{n_A}\right)}}$$

where:

P_B, P_A = proportions of encroachments for the before and after analyses,

$\hat{P}$ = pooled estimator of the encroachment proportion, and

n_B, n_A = sample size in before and after analysis.

The pooled estimate is calculated as follows:

$$\hat{P} = \frac{X_B + X_A}{n_B + n_A}$$

where:

X_B, X_A = number of encroachments and

n_B, n_A = sample size in before and after analysis.

F-test

The F-test assessed if the speed and lateral position standard deviation values were significantly different. The F-test used a testing value of 1.25 for all comparisons. Expert statisticians acknowledged that the uniform test value of 1.25 was acceptable and conservative (TAMU Statistics Helpdesk, unpublished data). The equation for the F-test is:

$$F = \frac{S^2{}_B}{S^2{}_A}$$

where:

S_B, S_A = standard deviation for the before and after analyses.

Normality of Data

All statistical tests utilized in this thesis were intended for normally distributed data. The normal distribution is a reoccurring phenomenon and is described as "one of the fundamental laws of natural sciences" (*37*). The author examined the speed and lateral position data to determine normality with the One-Sample Kolmogorov-Smirnov (K-S) test. The K-S test was performed for the entire set, for individual test sites, and at each curve location. The K-S test determined that the majority of the speed and lateral data were not normally distributed. The author reasoned that the non-normally distributed data were acceptable. The decision was based on the Central Limit Theorem, which states "the sum of *n* (sample size) independently distributed random variables will tend to be normally distributed as *n* becomes large" (*36*). The tests employed were robust and the sample size was sufficient to achieve acceptable results. Table 5 documents the sample sizes for each evaluation period.

Table 5 Overall Sample Size Summary

Curve Location	Site 1				Site 2			
	Inside		Outside		Inside		Outside	
	PC	MP	PC	MP	PC	MP	PC	MP
Baseline	2673	2948	3155	3063	2590	2401	2570	2389
Chevrons	1848	1769	1831	1790	1016	1061	1058	1051
ChevFull	1193	1151	1005	1134	913	908	944	928

CHAPTER V
FINDINGS

This chapter presents the findings from the statistical analyses. The analysis of the lateral position findings are presented first followed by the speed analysis findings. In each section, the examination starts with a broad overview of the curve findings, the focus is then narrowed to the specific curve locations.

LATERAL POSITION

This section contains all of the lateral position findings. MANOVA and Tukey's HSD results are detailed for each test site and at each curve location. The author details and discusses the vehicle tracking results, the standard deviation data, and the change in encroachment rates. This section summarizes the lateral position results and findings at the end.

Site Findings

Table 6 contains the results of the MANOVA test for the overall data set and for Site 1 and Site 2. Most importantly, the overall MANOVA test determined that the treatments achieved significantly different lateral position results. The main effects of the vehicle type variable and the interaction between vehicle type and treatments were not statistically significant in the overall test. The Site 1 test determined that vehicle type was also not a significant variable. The author reasoned that passenger vehicles and heavy vehicles exhibited similar lateral position traits and the treatments achieved a significant effect for both vehicle types. The tests did determine that curve location, curve direction, and time classification were significant variables.

Table 6 MANOVA Lateral Position Results

Model Variables	Overall P-value	Site 1 P-value	Site 2 P-value
Location	0.00	0.01	0.00
Curve Direction	0.00	0.00	0.00
Time	0.00	0.00	0.00
Vehicle Type	**0.06**	**0.12**	0.00
Treatment	0.00	0.00	0.00
Location & Treatment	0.00	0.00	0.00
Curve Direction & Treatment	0.00	0.00	0.00
Time & Treatment	0.00	0.00	0.00
Vehicle Type & Treatment	**0.09**	0.01	0.00

Note: non-significant values are shaded in gray and have bold text.

Table 7 shows the results from Tukey's HSD test for the overall data set and individually for Site 1 and Site 2. In the table, mean lateral position values in different columns were significantly different. Columns are arranged in increasing order from lowest value on the left side to the highest on the right side. All of the Chevron and the ChevFull treatment mean values were significantly different from the Baseline values, which indicated that both treatments had a considerable effect on vehicle lateral position. In a treatment comparison, the Chevron and the ChevFull treatment mean values were not significantly different in the overall and Site 2 tests. The treatment means in the Site 1 test were significantly different, but the difference was less than 1 inch. Overall, both Chevrons and the ChevFull treatment achieved a difference in mean lateral position by approximately 15 inches from the Baseline evaluation.

Table 7 Tukey's HSD Mean Lateral Position Results

Model Scenario		Lateral Position (inches)		
		Col. 1	Col. 2	Col. 3
Overall	Baseline	87.12		
	Chevrons		**102.59**	
	ChevFull		**102.26**	
Site 1	Baseline	89.13		
	Chevrons			103.60
	ChevFull		102.89	
Site 2	Baseline	85.28		
	Chevrons		**101.36**	
	ChevFull		**101.61**	

Note: non-significant values are shaded in gray and have bold text.

Location Findings

Table 8 shows the lateral position results for the MANOVA tests at specific curve locations. The MANOVA tests determined that both Chevron treatments achieved a significant effect on lateral position at all curve locations. The main effects of vehicle type and time were significant in all but one test. The interaction between treatment and vehicle type was not significant in four tests. This reconfirmed the results in Table 6 and shows that Chevrons and the ChevFull treatment produced the similar mean lateral position values regardless of vehicle type. The interaction between time and treatment was not significant in three tests, which may indicate that the treatment produced a similar effect in both the nighttime and daytime periods.

Table 8 Location MANOVA Lateral Position Results

Model Variables	Site 1 (P-value)				Site 2 (P-value)			
	Inside		Outside		Inside		Outside	
	PC	MP	PC	MP	PC	MP	PC	MP
Time	**0.26**	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Vehicle Type	0.00	0.00	0.01	0.00	0.01	**0.77**	0.00	0.00
Treatment	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Time & Treatment	0.02	0.00	**0.31**	0.01	**0.09**	**0.53**	0.00	0.00
Vehicle Type & Treatment	0.00	**0.55**	**0.06**	**0.11**	0.00	**0.45**	0.04	0.02

Note: non-significant values are shaded in gray and have bold text.

Table 9 shows Tukey's HSD results for the PC and MP curve locations. The results revealed that the mean lateral position values for the Chevron and ChevFull treatments were significantly different from the Baseline values at all locations. The mean values for Chevrons and the ChevFull treatment were not significantly different in six of the eight tests. The largest difference between the Chevron and the ChevFull treatment lateral position means was 2.85 inches. On average, both Chevron treatments moved vehicles away from the centerline by approximately 15 inches from the Baseline evaluation. In a treatment comparison there was an average difference of 0.78 of an inch in difference between Chevrons and the ChevFull treatment values. The author concluded that both Chevron treatments achieved a significant difference from the Baseline evaluation and there was no substantial difference in results between the two Chevron treatments.

Table 9 Location Tukey's HSD Mean Lateral Position Results

Model Scenario		**Inside (inches)**					**Outside (inches)**				
		PC			**MP**		**PC**		**MP**		
		Col. 1	**Col. 2**	**Col. 3**	**Col. 1**	**Col. 2**	**Col. 1**	**Col. 2**	**Col. 1**	**Col. 2**	**Col. 3**
Site 1	Base.	90.94			107.03		85.36		73.56		
	Chev.			104.62		**114.17**		**103.28**			92.50
	C.Full		101.77			**114.77**		**103.60**		91.59	
Site 2	Base.	80.28			88.20		97.40		74.58		
	Chev.		**98.64**			**103.67**		**106.97**		**96.10**	
	C.Full		**98.76**			**104.08**		**107.70**		**95.76**	

Note: non-significant values are in the same column with gray shading and bold text. Base. = Baseline, Chev. = Chevrons, and C.Full = ChevFull treatment.

Table 10 shows the mean lateral position values for the nighttime and daytime periods. The table also identifies the difference in values between the two periods. In the table, a positive value indicates that vehicles moved closer to the edgeline during the nighttime period and a negative value indicates that vehicles moved toward the centerline. The average difference between nighttime and daytime lateral position values was -2.36 inches, which determined that vehicles moved closer to the centerline during the nighttime period. Thirteen of the sixteen Tukey's HSD tests in Table 10 showed that the daytime and nighttime mean lateral position values were significantly different. The time period comparison supports the findings from the MANOVA test, which proved that the interaction between time and treatment was significant. Despite the significant difference between tests, both Chevrons and the ChevFull treatment achieved a considerable shift in lateral position in both the daytime and nighttime periods. Both treatments shifted vehicles approximately 13 inches during the nighttime period and 15 inches during the daytime period. The difference between nighttime and daytime results was minor if one considers the overall change from the Baseline evaluation.

Table 10 Nighttime and Daytime Mean Lateral Position Results

Model Variables		Site 1 (inches)				Site 2 (inches)			
		Inside		Outside		Inside		Outside	
		PC	MP	PC	MP	PC	MP	PC	MP
Chevrons	Nighttime	105.74	112.28	101.19	**91.2**	94.54	102.20	104.93	91.02
	Daytime	104.59	114.60	103.49	**92.63**	99.12	103.84	107.29	96.81
	Difference	1.15	-2.32	-2.30	**-1.43**	-4.58	-1.65	-2.36	-5.79
ChevFull	Nighttime	**101.09**	110.12	100.99	**91.56**	97.32	102.52	106.44	91.56
	Daytime	**101.86**	115.44	103.82	**91.59**	98.95	104.30	107.89	96.29
	Difference	**-0.77**	-5.32	-2.83	**-0.03**	-1.63	-1.78	-1.45	-4.73

Note: non-significant values are shaded in gray and have bold text

Lateral Position Tracking

Vehicle tracking identified the change in lateral position from the PC to the MP. A positive value indicates that a vehicle shifted toward the edgeline at the MP and a negative value represents a shift towards the centerline. Table 11 contains Tukey's HSD results for the mean change in lateral position. Overall, both Chevrons and the ChevFull treatments statistically reduced the change in lateral position. All of the Chevron tests were significantly different from the Baseline values and the ChevFull treatment tests were significant in all but one. In a treatment comparison, there were two of four tests where the Chevron and the ChevFull treatment values were significantly different.

The author removed the negative symbols from the outside curve direction so that all of the mean change values were positive. The values were averaged to provide a broad and simple perspective. The average change values for the Baseline, Chevron, and the ChevFull evaluations were 15.44, 8.29, and 10.70 inches respectively. The Chevron average change value was considerably lower than both the Baseline and the ChevFull treatment values. Chevrons were more effective than the ChevFull treatment in reducing the change in lateral position from the PC to the MP. Nonetheless, both Chevron treatments achieved significant and beneficial reductions in the mean lateral position tracking values.

Table 11 Tukey's HSD Lateral Position Tracking Results

Model Scenario		Inside (inches)			Outside (inches)		
		Sub. 1	Sub. 2	Sub. 3	Sub. 1	Sub. 2	Sub. 3
Site 1	Baseline			17.17	**-12.25**		
	Chevrons	9.49				-6.13	
	ChevFull		12.60		**-12.47**		
Site 2	Baseline		8.12		-24.22		
	Chevrons	**6.40**				**-11.13**	
	ChevFull	**5.40**				**-12.34**	

Note: non-significant values are in the same column with gray shading and bold text.

Lateral Position Standard Deviation

Table 12 contains the lateral position standard deviation values for each curve location. The table shows that all of the treatment standard deviation values were lower than the Baseline values. The reduction in standard deviation values indicated that both treatments achieved more uniform and consistent lane position at both the PC and MP locations. The overall averages for the Baseline, Chevron, and the ChevFull treatments were 13.55, 7.52, and 7.86 inches respectively. The averages showed that both Chevron treatments produced similar standard deviation values which were considerably lower than the Baseline average.

Table 12 Lateral Position Standard Deviations

Curve Location		PC (inches)			MP (inches)		
		Baseline	Chevrons	ChevFull	Baseline	Chevrons	ChevFull
Site 1	Inside	12.27	5.56	7.82	13.95	8.41	8.80
	Outside	11.26	6.19	6.29	14.49	7.57	7.45
Site 2	Inside	12.62	7.38	7.20	14.91	7.08	7.07
	Outside	12.99	7.53	7.98	15.88	10.40	10.28

The F-test proved that Chevrons and the ChevFull treatment produced significantly lower standard deviation values. All of the F-tests between the Baseline values and both Chevron treatment values were significantly different. In a treatment comparison, there was only one F-test where the Chevron and the ChevFull treatment values were significantly different. The one test occurred at the inside curve direction on Site 1 where Chevrons obtained a significant lower value than the ChevFull treatment. Despite this single occurrence, the differences in treatment standard deviation values were very minor. The author concluded that both treatments were significantly effective in lowering the standard deviation values from the Baseline evaluation and that neither Chevron treatment was more beneficial.

Encroachment Rates

The author determined edgeline encroachment rates and estimated centerline encroachment rates for passenger vehicles. The edgeline encroachment rates were derived from the lateral position data and travel lane dimensions at specific curve locations. The centerline encroachment rates were estimated with a conservative track width of 80 inches and an average track width of 61 inches. Table 13 contains the findings for both the centerline and the edgeline encroachments. The values in the table indicate encroachments rates out of the total number of measured vehicles. For example, if there were 100 observed edgeline encroachments out of a total of 1000 vehicles, then the encroachment rate was 10 percent.

Table 13 Encroachment Percentages

Curve Location			Centerline 80 in Track			Centerline 61 in Track			Edgeline		
			Base.	Chev.	C.Full	Base.	Chev.	C.Full	Base.	Chev.	C.Full
Site 1	Inside	PC	9.3%	0.6%	4.4%	2.4%	0.0%	0.0%	0.5%	0.6%	0.7%
		MP	4.1%	0.2%	0.2%	1.2%	0.0%	0.0%	19.7%	31.2%	35.7%
	Outside	PC	29.2%	0.8%	1.0%	2.4%	0.0%	0.0%	0.0%	0.0%	0.0%
		MP	69.1%	6.5%	7.6%	14.4%	0.0%	0.0%	0.0%	0.2%	0.1%
Site 2	Inside	PC	51.5%	2.2%	1.0%	4.8%	0.1%	0.1%	0.3%	0.2%	0.5%
		MP	20.6%	0.8%	0.9%	7.9%	0.0%	0.1%	0.1%	1.3%	0.9%
	Outside	PC	10.0%	1.1%	1.1%	1.5%	0.0%	0.1%	1.1%	1.3%	1.9%
		MP	67.2%	8.8%	8.7%	18.6%	0.4%	0.3%	0.3%	0.2%	0.3%

Chevrons and the ChevFull treatment considerably reduced the centerline encroachment rates for both the 80 and 61 inch vehicle track width. Both treatments reduced the 80 inch track width centerline encroachments at the outside MP locations by approximately 90 percent. On average, Chevrons reduced the centerline 80 inch encroachment rates by approximately 93 percent and the ChevFull treatment reduced it by 88 percent. Both treatments lowered the centerline encroachments for a 61 inch track vehicle to approximately zero at many of the locations. The majority of the edgeline encroachments were lowered or remained approximately unchanged except for the inside MP of Site 1. At this one location, the edgeline encroachment rates increased for both Chevron treatments.

The Z-test determined that all Chevron and the ChevFull centerline encroachment rates were statistically different from the Baseline rates. Both treatments statistically reduced the centerline encroachment rates at all PC and MP locations and for both track widths. The Z-test also compared the Chevron and the ChevFull treatment rates to determine if one treatment was more beneficial in reducing centerline encroachments. The results showed that there were only two tests where the centerline encroachment rates were significantly different. The Z-test confirmed that both Chevrons and the ChevFull treatment statistically reduced centerline encroachments and neither Chevron treatment was more beneficial. The Z-test was performed on the edgeline encroachment rates. Chevrons and the ChevFull treatment statistically increased the rate of edgeline encroachments at the inside MP location of Site 1. This was the only significant difference in edgeline encroachment rates. Apart from this one location, there were no other substantial or significant differences in edgeline encroachment rates.

Lateral Position Summary

The findings showed that both Chevrons and the ChevFull treatment achieved beneficial changes in lateral position MOE. The majority of the statistical tests proved that changes were significantly different and that both Chevron treatments were effective regardless of vehicle type or time classification. On average, both Chevron treatments shifted vehicles away from the centerline and oncoming traffic by about 15 inches. In the vehicle tracking, the change in lateral position from the PC to the MP was reduced from 15.44 inches to 8.29 inches for Chevrons and 10.70 inches for the ChevFull treatment. Estimated centerline encroachments were reduced by approximately 90 percent and the lateral position standard deviations were significantly lowered. In general, both Chevron treatments produced more uniform and consistent lateral lane position results. In a treatment comparison, there was very little difference between the Chevron and the ChevFull results. In summary, the findings indicated that the ChevFull treatment did not produce additional lateral position improvements over standard Chevrons.

SPEED

This section contains the speed findings presented in a format similar to that in the Lateral Position section. The author discusses the MANOVA and Tukey's HSD results for each test site and then at each curve location. In the following order, vehicle tracking, speed standard deviation values, and high speed findings are presented. At the end of the section, a summary of the speed findings follows.

Site Findings

Table 14 contains the speed results of the MANOVA test for the overall data set and for Site 1 and Site 2. The MANOVA test determined that the main effects of the treatments were significant for the overall data set and at both test sites. The main effects of the time variable were not significant for Site 2, which indicated that vehicle speeds were similar in both the nighttime and daytime periods at this specific curve regardless of treatment scenario. The interaction between treatment and curve location was not significant in all three tests, which demonstrates that the treatments produced a similar change in vehicle speed at both the PC and the MP. In the overall test, the interaction between time and the treatment was not significant. This indicated that the treatments achieved a similar change in speed for both nighttime and daytime periods.

Table 14 MANOVA Speed Results

Model Variables	Overall	Site 1	Site 2
	P-value	P-value	P-value
Location	0.00	0.00	0.00
Curve Direction	0.00	0.00	0.00
Time	0.00	0.00	**0.44**
Vehicle Type	0.00	0.00	0.00
Treatment	0.00	0.00	0.00
Location & Treatment	**0.35**	**0.68**	**0.34**
Curve Direction & Treatment	0.02	0.00	0.02
Time & Treatment	**0.24**	0.01	0.01
Vehicle Type & Treatment	0.00	0.00	0.00

Note: non-significant values have gray shading and bold text.

Table 15 shows the mean speed values from Tukey's HSD test for the overall data set and for Site 1 and Site 2. All the mean speed values in Table 15 were significantly different. Results from the three tests were consistent. Both Chevrons and the ChevFull treatment achieved significantly lower mean speeds than in the Baseline evaluation. In the overall test, Chevrons and the ChevFull treatment produced a speed reduction of 1.28 and 2.20 MPH respectively. The ChevFull treatment produced the lowest mean speeds. The ChevFull treatment mean speed values were also closest to the revised advisory curve speeds, which is 55 MPH for Site 1 and 50 MPH for Site 2.

Table 15 Tukey's HSD Mean Speed Results

Model Scenario		Speed (MPH)		
		Col. 1	Col. 2	Col. 3
Overall	Baseline			56.46
	Chevrons		55.18	
	ChevFull	54.26		
Site 1	Baseline			58.28
	Chevrons		56.77	
	ChevFull	56.32		
Site 2	Baseline			54.79
	Chevrons		53.24	
	ChevFull	52.14		

Note: non-significant values are in the same column with gray shading and bold text.

Location Findings

Table 16 shows the MANOVA results for the speed data at specific curve locations. The main effects of the treatments were significant for all tests except for the inside PC location at Site 1. The interaction between time and treatment was not significant in five of eight tests. The treatments produced a similar change in vehicle speed in both the nighttime and daytime periods. The interaction between vehicle type and treatment was not significant for four of the eight tests. The results in Table 16 were similar to the lateral position results in Table 8 where treatment interaction with both vehicle type and time were not significant for about half of the tests.

Table 16 Location MANOVA Speed Results

Model Variables	Site 1				Site 2			
	Inside		Outside		Inside		Outside	
	PC	MP	PC	MP	PC	MP	PC	MP
Time	0.00	0.00	0.00	0.00	0.04	**0.10**	0.00	**0.08**
Vehicle Type	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Treatment	**0.09**	0.00	0.00	0.00	0.00	0.00	0.00	0.01
Time & Treatment	**0.66**	**0.22**	0.02	0.02	**0.95**	**0.93**	0.00	**0.14**
Vehicle Type & Treatment	**0.30**	**0.12**	0.00	0.00	0.00	0.00	**0.26**	**0.20**

Note: non-significant values have gray shading and bold text.

Table 17 contains the mean speed data from the Tukey's HSD test. Both Chevron treatment mean values were significantly different from the Baseline means in all of the tests. The ChevFull treatment achieved significantly lower mean speed values in all of the locations except for the outside MP of Site 1. There were four tests where the mean speed values of Chevrons and the ChevFull treatments were not significantly different. Three of the four non-significant tests occurred at Site 1 where the overall speed difference between treatments was 0.45 MPH. Overall, the ChevFull treatment still achieved lower mean speed values.

Table 17 Location Tukey's HSD Mean Speed Results

Model Scenario		Inside (MPH)						Outside (MPH)				
		PC			MP			PC			MP	
		Col. 1	Col. 2	Col. 3	Col. 1	Col. 2	Col. 3	Col. 1	Col. 2	Col. 3	Col. 1	Col. 2
Site 1	Base.		57.07				57.52		60.42			57.92
	Chev.	**55.99**				55.91		**58.66**			**56.34**	
	C.Full	**55.62**			54.95			**58.19**			**56.67**	
Site 2	Base.			55.88			53.35			55.30		54.40
	Chev.		53.65			51.86			54.32		**53.27**	
	C.Full	52.77			50.56			52.69			**52.61**	

Note: non-significant values are in the same column with gray shading and bold text.

Table 18 shows the time period mean speed values and the differences between values. In the table, a positive value indicates a mean speed increase during nighttime and a negative value signifies a speed reduction. The nighttime and daytime mean speed values were not significantly different for seven of the sixteen tests. In general, vehicle speeds were lowered at nighttime in the majority of the time period comparisons. The average difference between nighttime and daytime mean speed values for the ChevFull treatment and Chevrons were -0.42 and -1.16 MPH respectively. The differences in the time period comparison were minimal and both Chevron treatments were effective in lowering vehicle speed for both nighttime and daytime periods.

Table 18 Nighttime and Daytime Mean Speed Position Results

Model Variables		Site 1 Speed (MPH)				Site 2 Speed (MPH)			
		Inside		Outside		Inside		Outside	
		PC	MP	PC	MP	PC	MP	PC	MP
Chevrons	Nighttime	54.39	54.65	54.81	52.41	**52.99**	**51.50**	56.58	54.34
	Daytime	56.32	56.19	59.04	56.69	**53.72**	**51.90**	53.96	53.12
	Difference	-1.94	-1.54	-4.24	-4.28	**-0.73**	**-0.40**	2.62	1.22
ChevFull	Nighttime	**55.14**	**55.30**	56.09	54.72	**52.09**	**49.88**	53.71	**52.67**
	Daytime	**55.69**	**54.90**	58.36	56.79	**52.86**	**50.65**	52.54	**52.61**
	Difference	**-0.54**	**0.40**	-2.27	-2.07	**-0.77**	**-0.77**	2.62	**0.06**

Note: non-significant values have gray shading and bold text.

Speed Tracking

Table 19 contains the Tukey's HSD tracking results which shows the change in mean speed of individual vehicles from the PC to the MP. It was desirable to reduce the speed differential or achieve a tracking value that was close to zero. In the Chevron and Baseline comparison, three of the four tests were not significantly different. The mean tracking values for all of the ChevFull treatment tests were significantly different from both the Chevron and the Baseline values. The average change in mean speed for the Baseline, Chevron, and the ChevFull scenarios were -1.32, -1.22, and -0.72 MPH respectively. The ChevFull treatment achieved a tracking value that was closer to zero in three of the four curve directions. Overall, the ChevFull treatment achieved more uniform curve speed, while Chevrons did not produce a significant effect from the Baseline evaluation.

Table 19 Tracking Tukey's HSD Mean Speed

Model Scenario		Inside			Outside		
		Col. 1	Col. 2	Col. 3	Col. 1	Col. 2	Col. 3
Site 1	Baseline		**0.12**		**-2.40**		
	Chevrons		**-0.02**		**-2.24**		
	ChevFull	-0.46				-1.78	
Site 2	Baseline	-2.58			**-0.40**		
	Chevrons		-2.06		**-0.57**		
	ChevFull			-0.73		0.10	

Note: non-significant values are in the same column with gray shading and bold text.

Speed Standard Deviation

Table 20 contains the speed standard deviation values for passenger vehicles. All of the Chevron and the ChevFull treatment standard deviation values increased from the Baseline evaluation except for the outside PC location at Site 1. The average standard deviation values increased from 7.80 MPH in the Baseline evaluation to 8.25 MPH for Chevrons and 8.36 MPH for the Chevron treatment. The author analyzed the increase in standard deviation values at an F-test value of 1.25. The analysis concluded that the majority of the Chevron treatment standard deviation values were not significantly different from the Baseline standard deviation. In total, there were three tests out of sixteen that were significantly different. In a treatment comparison, none of the Chevron and the ChevFull treatment standard deviation values were significantly different. The author reasoned that the increase in speed standard deviation values by both Chevron treatments was moderate and not substantial.

Table 20 Speed Standard Deviation

Curve Location		PC Standard Deviation (MPH)			MP Standard Deviation (MPH)		
		Baseline	Chevrons	ChevFull	Baseline	Chevrons	ChevFull
Site 1	Inside	6.91	7.21	7.40	6.86	6.95	7.16
	Outside	7.63	7.59	7.22	6.98	7.13	7.02
Site 2	Inside	9.35	10.41	10.69	7.71	8.65	9.07
	Outside	8.73	9.15	9.34	8.20	8.87	8.95

High Speed Findings

Table 21 compares the curve advisory speeds to the high vehicle speeds. The high vehicle speeds include the 85th percentile speed and the percentage of vehicles exceeding 60, 65, and 70 MPH at the test sites. Majority of the 85th percentile speeds were between 60 and 65 MPH. Similar to the mean speed analysis, treatment 85th percentile speed values were all lower than the Baseline values. The ChevFull treatment further reduced speed values lower than Chevrons. On average, the ChevFull treatment lowered the Baseline 85th percentile speed by 2.2 MPH and Chevrons lowered it by 1.3 MPH.

Both Chevron treatments reduced the percentage of vehicles exceeding speeds of 60, 65, and 70 MPH. On average, Chevrons reduced the high speed percentages by 23 percent and the ChevFull treatment reduced them by 39 percent. The Z-test proved that both Chevrons and the ChevFull treatment reductions were significantly lower than the percentages in the Baseline scenario. In a treatment comparison, the ChevFull treatment significantly reduced high speed percentages further than Chevrons in all but one test. The one exception occurred in the 60 MPH comparison where the 33 percent reduction by the ChevFull treatment was not significantly different than the 34 percent reduction by Chevrons. Overall, the ChevFull treatment consistently reduced the high vehicle speeds further than Chevrons, but the additional reduction was considered to be moderate and not substantial.

Table 21 High Vehicle Curve Speeds

Speed	Site 1			Site 2		
	Baseline	Chevron	ChevFull	Baseline	Chevron	ChevFull
Signed / Alternate Adv. Speed (MPH)	45 / 55			50 / 50		
85^{th} Percentile Speed (MPH)	65.72	64.17	63.80	64.17	63.06	61.91
Percentage of Vehicles Exceeding a Given Speed						
60 MPH	43%	34%	33%	32%	25%	21%
65 MPH	17%	13%	11%	13%	10%	8%
70 MPH	4%	3%	2%	4%	3%	2%

Speed Summary

Both Chevrons and the ChevFull treatment achieved lower vehicle speeds from the Baseline scenario. Similar to the lateral position findings, the majority of the statistical tests proved that changes in the speed MOE were significantly lower. Both treatments produced significantly different results regardless of vehicle type or time classification. In the overall dataset, Chevrons lowered speeds by 1.28 MPH and the ChevFull treatment lowered speeds by 2.20 MPH. Both Chevron treatments lowered the mean vehicle speeds closer to the alternate curve advisory speed. The ChevFull treatment achieved vehicle tracking values that were closer to zero, while Chevrons did not produce a substantial effect from the Baseline evaluation. Both Chevron treatments increased the speed standard deviation values, but the author reasoned that the moderate increase was acceptable. Chevrons reduced the percentages of vehicle exceeding 60, 65, 70 MPH by 23 percent and the ChevFull treatment reduced them by 39 percent. The ChevFull treatment significantly lowered high vehicle speed percentages further than Chevrons. Overall, both Chevron treatments produced significantly lower vehicle speeds from the Baseline scenario and ChevFull treatments speed reductions were significantly lower than the than Chevron values.

FINDINGS SUMMARY

Chevrons and the ChevFull treatment achieved beneficial changes in the MOE from the Baseline evaluation. Both Chevron treatments significantly influenced drivers' speed and lateral lane position. In the after scenarios, the results determined that lateral position results were more uniform and with fewer occasions of lane line encroachments. Chevrons and the ChevFull treatment achieved significantly lower mean speed values that were closer to the alternate curve advisory speed. Overall, both the Chevron treatments achieved vehicle speed and lateral lane position results that were more uniform and desirable.

The findings showed that the Chevron and the ChevFull treatment results were similar. The statistical tests determined that many of the lateral position comparisons between the Chevron and the ChevFull treatment results were not significantly different. Neither treatment appeared to be more beneficial in promoting uniform lane position or correcting improper vehicle paths. The ChevFull treatment did produce significantly lower speed values. Vehicle mean speed values were closer to the alternate curve advisory speed and the vehicle tracking values were closer to zero when the ChevFull treatment was implemented. Nevertheless, the differences in results between the ChevFull treatment and Chevrons were modest and not considered meaningful. The author's final judgment on the ChevFull treatment is provided in the following Conclusion and Recommendations Chapter.

CHAPTER VI
CONCLUSIONS AND RECOMMENDATIONS

This chapter summarizes the key lateral position and speed findings for both the Chevron and the ChevFull treatment evaluations. The author presents his interpretation of the significant results and meaningful inferences. Final comments and treatment recommendations are provided at the end of this chapter.

The purpose of this study was to identify any incremental benefits in vehicle speed and lateral lane position when the ChevFull treatment was implemented on a rural horizontal curve. Speed and lateral position data were collected at the PC and the MP on two curves. The existing Baseline condition, Chevrons, and the ChevFull treatment were evaluated in a before and after experimental design. Evaluated MOE for both speed and lateral position data include the mean, the standard deviation, and the change in individual vehicle data from the PC to the MP. The statistical analyses assessed the change in MOE to determine if the ChevFull treatment achieved significantly different results from the Baseline and Chevron evaluations.

CHEVRON TREATMENT CONCLUSIONS

This section contains a brief summary of the key Chevron treatment results. It details treatment effects on different vehicle types and during different time periods. The lateral position conclusions are presented which are followed by the speed conclusions.

Treatment Application

Both Chevron treatments significantly influenced vehicle operations. Chevrons and the ChevFull treatments affected both passenger and heavy vehicles. The lateral position MANOVA test of the overall dataset determined that the interaction between vehicle type and treatment was not significantly different. This indicated that the Chevron treatments produced a similar change in mean lateral position values for both passenger and heavy vehicles. Many of the speed and lateral position MANOVA tests at specific curve locations reconfirmed this finding. The author reasoned that the benefits of either Chevrons or the ChevFull treatment are not exclusively limited to passenger or heavy vehicles.

The statistical analyses determined that Chevron treatments achieved similar changes in MOE for both the nighttime and the daytime periods. The speed MANOVA test of the overall dataset indicated that the interaction between time and treatment was not significantly different. This indentified that both Chevron treatments produced a similar change in mean speed values in both the nighttime and daytime periods. At specific curve locations, five of the eight speed MANOVA tests were not significant and three of the eight lateral position tests were not significant.

A detailed examination of the speed and lateral position results reconfirmed the previous statistical observation. Drivers typically lowered their curve speeds and moved closer to the centerline during the nighttime period. When compared to the Baseline scenario, both Chevron treatments shifted vehicles away from the centerline by approximately 13 inches during the nighttime period, as opposed to 15 inches during the daytime period. The average difference between nighttime and daytime mean speed values for the ChevFull treatment and Chevrons were -0.42 MPH and -1.16 MPH respectively. There were differences between nighttime and daytime results, but the discrepancies were negligible compared to the overall change in MOE from the Baseline evaluation.

Overall, both the Chevron and the ChevFull treatments were effective in nighttime and daytime periods. The benefits of either treatment are not limited to just nighttime applications. The perception of delineation as an effective guidance and warning device should not exclude or dismiss daytime benefits.

Lateral Position Conclusions

The findings determined that both Chevrons and the ChevFull treatment achieved beneficial changes in lateral position MOE. Both Chevron treatments consistently achieved significant different results from the Baseline evaluation. Chevrons and the ChevFull treatment moved vehicles away from the centerline and from oncoming traffic by approximately 15 inches. The Baseline lateral position standard deviation was nearly divided in half from 13.55 inches to 7.52 inches for Chevrons and 7.86 for the ChevFull treatment. Both Chevron treatments reduced estimated centerline encroachments by approximately 90 percent and edgeline encroachments remained relatively unchanged. Chevrons and the ChevFull treatment achieved more uniform lateral lane position results, which reduced the occurrences of improper vehicle paths that are associated with higher crash rates.

The Chevron and the ChevFull treatment results were quite similar. In the overall dataset, the difference in mean lateral position values between the Chevron treatments was 0.33 of an inch. The majority of the mean and standard deviation statistical comparisons were also not significantly different. The one substantial difference between the Chevron treatments occurred in the vehicle tracking analysis. The change in lateral position from the PC to the MP was lowered from 15.44 inches in the Baseline evaluation to 8.29 inches for Chevrons, as opposed to 10.70 inches for the ChevFull treatment. Chevrons achieved a significantly lower vehicle tracking value than the ChevFull treatment, which indicated that Chevrons were better at producing uniform lane position from the PC to the MP. Both Chevrons treatments were effective in achieving more uniform and beneficial lateral position results, but the ChevFull treatment did not yield substantial gains over Chevrons.

Speed Conclusion

The findings determined that both the Chevron and the ChevFull treatments produced significant changes in speed MOE. Tukey's HSD test identified that both Chevron treatments significantly reduced mean speed values from the Baseline evaluation, which were closer to the alternate curve advisory speed. The results showed that Chevrons and the ChevFull treatment increased the speed standard deviation values from the Baseline evaluation. The average standard deviation values increased from

7.80 MPH in the Baseline evaluation to 8.25 MPH for Chevrons and 8.36 MPH for the ChevFull treatment. The majority of the standard deviation comparisons were not significant. The author deemed the modest increase in standard deviation values caused by both Chevron treatments to be acceptable.

In a treatment comparison, the majority of the ChevFull treatment and Chevron tests were significantly different. The ChevFull treatment consistently produced mean speed values that were closer to the alternate advisory curve speed. In the overall dataset, Chevrons lowered the mean speed by 1.28 MPH from the Baseline evaluation while the ChevFull treatment achieved a reduction of 2.20 MPH. In the vehicle tracking analysis, the ChevFull treatment yielded tracking values that were closer to zero, whereas Chevrons did not produce a substantial effect from the Baseline evaluation. The ChevFull treatment also reduced the percentage of high speed vehicles by 39 percent, as opposed to 23 percent for Chevrons.

While the ChevFull treatment results were significantly lower, the author did not consider the reductions to be overwhelmingly substantial or beneficial to Chevrons results. In the overall dataset, the ChevFull treatment lowered mean speed values further than Chevrons by 0.92 MPH. Despite being significant, this additional reduction was modest and small. A further 1 MPH reduction in mean speed may be substantial in a 20 MPH school-zone where there is an additional 5 percent decrease. At the test sites in this thesis, a 1 MPH reduction only amounted to a 1.7 percent decrease in speed. The additional speed reductions produced by the ChevFull treatment were significant, but not considered substantial. The author concluded that the ChevFull treatment did not achieve substantial benefits in vehicle speed over Chevrons.

RECOMMENDATIONS

Overall, both Chevrons and the ChevFull treatment achieved beneficial changes in speed and lateral position MOE in both the daytime and nighttime periods. In a treatment comparison, the ChevFull treatment did not produce substantial gains over Chevrons. The lateral position results for both Chevron treatments were very similar.

The ChevFull treatment achieved statistically significantly different speed results, but the differences were not substantial to declare superior performance over Chevrons. Agencies using the ChevFull treatment in a similar roadway situation may not experience substantial benefits over Chevrons. Although the ChevFull did not achieve incremental benefits, the findings did not indicate that the treatment had a detrimental impact on vehicle operations. The ChevFull treatment may have value in situations that are different from those evaluated in this thesis. The current MUTCD language allows agencies to implement the ChevFull treatment as an optional tool at their discretion. The author recommends that the MUTCD should continue to present the ChevFull treatment as an optional delineation tool. Based on this research, the author does not recommend any changes to the MUTCD.

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APPENDIX A

CURVE MAPS AND SCHEMATICS

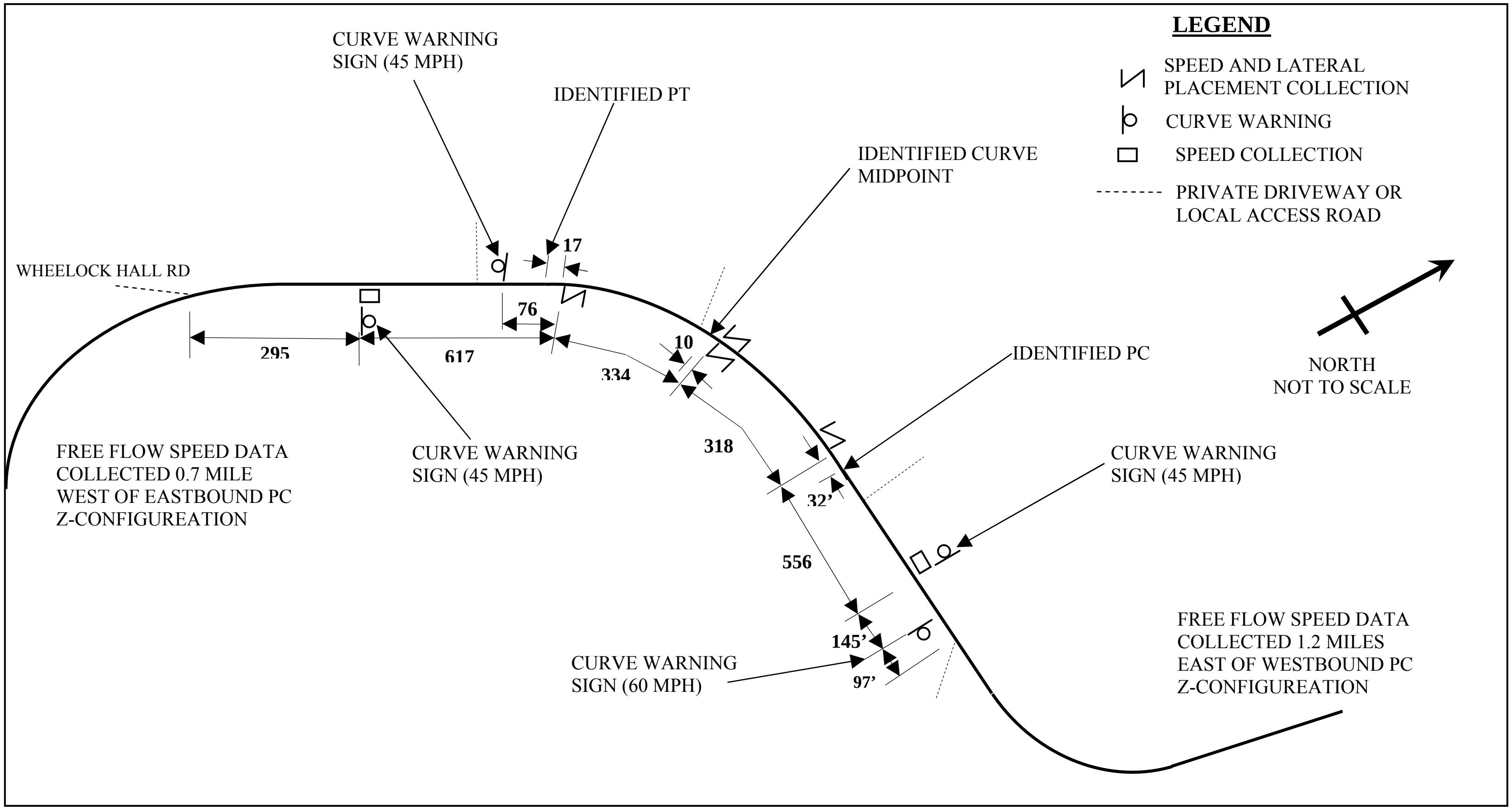

Figure 11 FM 974 Curve Schematic

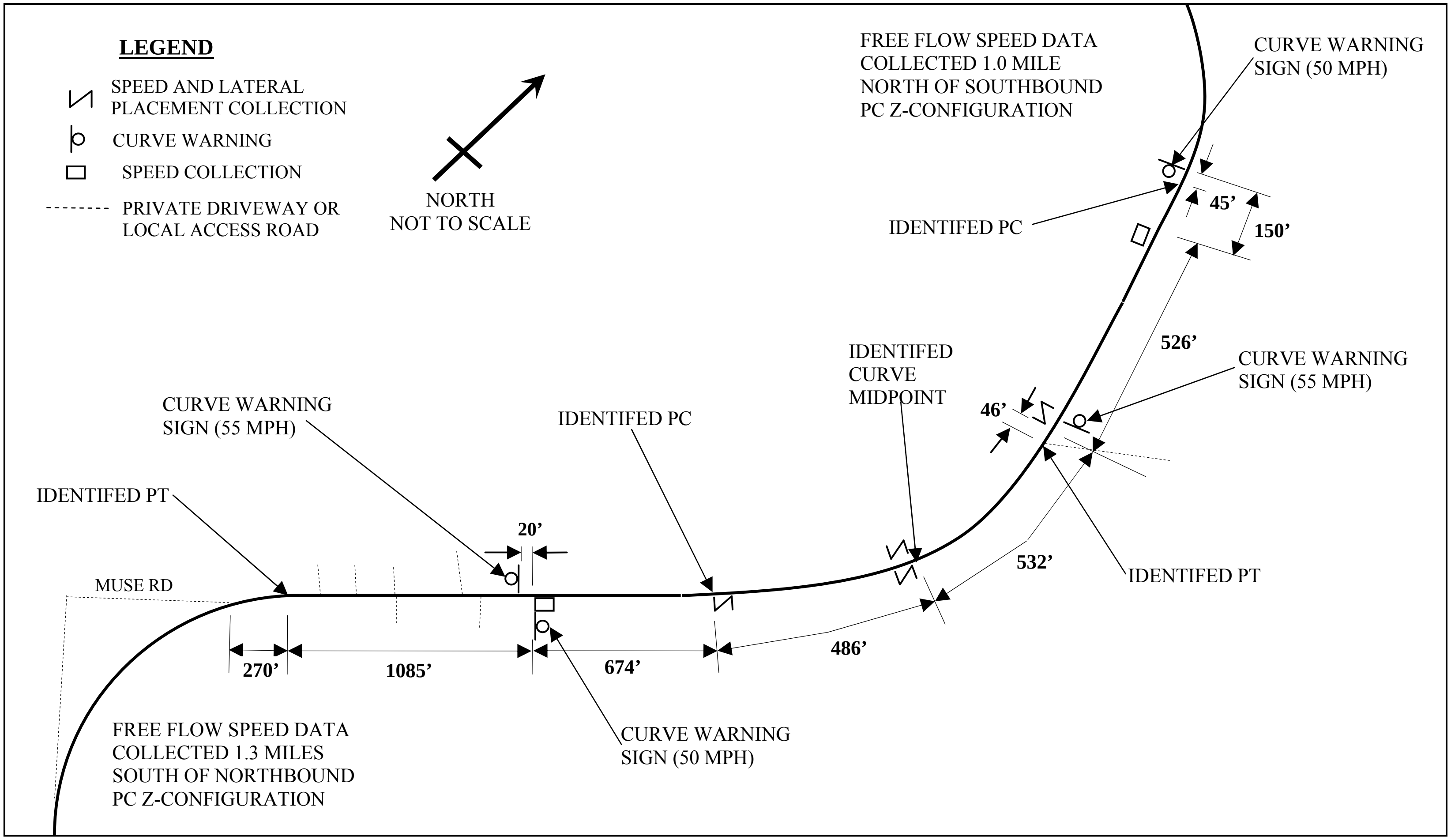

Figure 12 FM 50 Schematic

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