Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
FHWA/TX-04/0-4052-1		

4. Title and Subtitle	5. Report Date
SIMPLIFYING DELINEATOR AND CHEVRON APPLICATIONS FOR HORIZONTAL CURVES	March 2004
	6. Performing Organization Code
7. Author(s) Paul J. Carlson, Elisabeth R. Rose, Susan T. Chrysler, Austin L. Bischoff	8. Performing Organization Report No. Report 0-4052-1
9. Performing Organization Name and Address Texas Transportation Institute The Texas A&M University System College Station, Texas 77843-3135	10. Work Unit No. (TRAIS) 11. Contract or Grant No. Project No. 0-4052
12. Sponsoring Agency Name and Address Texas Department of Transportation Research and Technology Implementation Office P. O. Box 5080 Austin, Texas 78763-5080	13. Type of Report and Period Covered Research: September 2002 – February 2004 14. Sponsoring Agency Code

15. Supplementary Notes

Research performed in cooperation with the Texas Department of Transportation and the U.S. Department of Transportation, Federal Highway Administration.
Research Project Title: Guidelines for the Use and Spacing of Delineators and Chevrons

16. Abstract

This research effort focuses on the investigation of methods to simplify horizontal curve delineation treatments without jeopardizing safety. The specific objectives of the research were to simplify delineator and Chevron spacing along horizontal curves, determine a radius above which a horizontal curve on a freeway or expressway may be delineated as a tangent, and explore whether there is any new benefit in using double delineators.

The researchers reviewed the Manual on Uniform Traffic Control Devices (MUTCD) evolution with respect to delineation. They also performed a literature review and conducted a state Department of Transportation survey to determine other policies and practices. The research team visited curves throughout the state of Texas to assess the current state-of-the-practice in terms of delineation treatments and test and develop alternative delineation treatment procedures. The researchers also performed a field study to determine drivers' response to an increase in the number of Chevrons installed along horizontal curves. Finally, the researchers performed a closed-course delineator visibility study at the Texas A&M University Riverside campus to assess the need for variable delineator approach and departure spacing on horizontal curves and the need for double delineators (versus single delineators).

Using the findings from the previously described activities, the researchers recommended a simplified delineator and Chevron spacing table that is based on the radius or the advisory speed value. Researchers also developed a simple-to-use and accurate field device for measuring the radius of a horizontal curve.

17. Key Words	18. Distribution Statement
Delineation, Delineator, Chevron, Spacing, Radius, Horizontal Curve, Advisory Speed, Ball Bank Indicator, Lateral Acceleration, Traffic Control Device	No restrictions. This document is available to the public through NTIS: National Technical Information Service 5285 Port Royal Road Springfield, Virginia 22161

19. Security Classif.(of this report)	20. Security Classif.(of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	236	

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

SIMPLIFYING DELINEATOR AND CHEVRON APPLICATIONS FOR HORIZONTAL CURVES

by

Paul J. Carlson, Ph.D., P.E.
Associate Research Engineer
Texas Transportation Institute

Elisabeth R. Rose
Assistant Transportation Researcher
Texas Transportation Institute

Susan T. Chrysler, Ph.D.
Associate Research Scientist
Texas Transportation Institute

and

Austin L. Bischoff
Assistant Transportation Researcher
Texas Transportation Institute

Report 0-4052-1
Project Number 0-4052
Research Project Title: Guidelines for the Use and Spacing of Delineators and Chevrons

Sponsored by the
Texas Department of Transportation
In Cooperation with the
U.S. Department of Transportation
Federal Highway Administration

March 2004

TEXAS TRANSPORTATION INSTITUTE
The Texas A&M University System
College Station, Texas 77843-3135

DISCLAIMER

The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official view or policies of the Federal Highway Administration (FHWA) or the Texas Department of Transportation (TxDOT). This report does not constitute a standard, specification, or regulation. The engineer in charge was Paul J. Carlson, P.E. (TX # 85402).

ACKNOWLEDGMENTS

This project was conducted in cooperation with TxDOT and the FHWA. The authors would like to thank the project director, Larry Colclasure of the TxDOT Waco District, for providing guidance and expertise on this project. The authors would also like to thank other members of the TxDOT Advisory Panel for their assistance:

- Howard Holland, TxDOT Brownwood District
- Brian Stanford, TxDOT Traffic Operations Division
- Kathy Pirkle, TxDOT Traffic Operations Division
- Davis Powell, TxDOT Wichita Falls District
- Kathy Wood, TxDOT Fort Worth District
- Richard Kirby, TxDOT Maintenance Division
- Wade Odell, TxDOT Research and Technology Implementation Office

At least three other TxDOT engineers provided significant assistance during this research project – Kirk Barnes of the Bryan District, Carlos Ibarra of the Atlanta District, and Chris Freeman of the Amarillo District.

Special thanks also goes out to Dick Zimmer of TTI for helping to equipment test vehicles with various electronics for this project. Mr. Zimmer also helped design and build the Radiusmeter.

TABLE OF CONTENTS

Page

LIST OF TABLES

Page

LIST OF FIGURES

Page

CHAPTER 1:
INTRODUCTION

The Manual on Uniform Traffic Control Devices (MUTCD) contains the basic principles that govern the design and use of traffic control devices to promote highway safety and efficiency (*1*). The MUTCD states that traffic control devices should be appropriately positioned with respect to the location, object, or situation to which it applies. The MUTCD also states that traffic control devices should be placed and operated in a uniform and consistent manner.

The 2003 Texas Manual on Uniform Traffic Control Devices (Texas MUTCD) (*2*), which became effective on January 17, 2003, and superseded the 1980 Texas MUTCD and all previous editions thereof, was based on the Millennium Edition of the national MUTCD. The Texas MUTCD is similar in many ways and is in substantial conformance with the Millennium Edition of the national MUTCD.

The two types of traffic control devices under study herein include delineators and Chevrons. Delineators are described in Section 3D of the MUTCD, and Chevrons are described in Section 2C. Both types of traffic control devices are typically used to delineate the horizontal alignment of roadways. While the MUTCD provides guidance in terms of their uniform application, the guidance is different for delineators as compared to Chevrons. Furthermore, the guidance is difficult for field personnel to implement because of the criteria needed beforehand and the subjectivity. There are also other pertinent issues related to delineators that need to be researched such as the need to distinguish between single and double delineators.

OBJECTIVES

The objectives of this project were to simplify methods for determining delineation and Chevron spacing on horizontal curves, determine if there is a radius above which a horizontal curve may be treated as a tangent with respect to delineation, and investigate if there is any net benefit in the use of double (or vertically elongated) delineators.

BACKGROUND

During a research project evaluating drivers' information needs for guide signs on rural highways, Texas Transportation Institute (TTI) researchers and TxDOT engineers identified the need for a document prepared specifically for TxDOT sign crews. This led to the development of the TxDOT Sign Crew Field Book (*3*). The Field Book addresses several significant areas including:

- placement of regulatory, warning, and guide signs.
- location and placement of object markers, delineators, and barrier reflectors.
- location and installation of mail boxes.

The Field Book does not supersede the Texas MUTCD, but it provides additional guidance with respect to standards, recommended practices, or other requirements established by TxDOT documents.

Researchers identified many of the issues addressed within the scope of this research project while developing the Field Book chapter on delineation treatments. At the time, there was not sufficient support to make fundamentally sound decisions regarding these issues. Therefore, researchers envisioned that this project would address these issues, which may lead to a need to revise part of the Field Book, and other TxDOT documents, depending on the results.

This section of the report includes the specific MUTCD language that has led to this research. It is this language that may need to be changed as a result of this research. The specific issues that were addressed in this research are highlighted in text boxes immediately following the specific language of the MUTCD that was of concern. Researchers have provided references when material from other sources is presented and discussed.

Chevrons

According to the MUTCD, the Chevron Alignment sign *should* be spaced such that the road user always has at least two in view, until the change in alignment eliminates the need for the signs. Chevron Alignment signs should be visible for a sufficient distance to provide the road user with adequate time to react to the change in alignment.

Research Issue: The current guidelines concerning the number and spacing of Chevrons allow adequate flexibility but at the same time are difficult for field crews to implement. An easy-to-apply set of guidelines concerning the spacing along horizontal curves needs to be identified and tested.

Delineation Treatments for Horizontal Curves

Section 3D of the MUTCD addresses delineation applications, including horizontal curves. In 3D-1, the MUTCD reads, "Road delineators are light-retroreflecting devices mounted at the side of the roadway, in series, to indicate the roadway alignment. Delineators are effective aids for night driving and are to be considered as guidance devices rather than warning devices. Delineators may be used on long continuous sections of highway or through short stretches where there are changes in horizontal alignment, particularly where the alignment might be confusing, or at pavement width transition areas. An important advantage of delineators, in certain areas, is that they remain visible when the roadway is wet or snow-covered (*1*)." The MUTCD standards and guidelines associated with delineation along horizontal curves are summarized below. References are provided when material from other sources is presented and discussed.

Delineator Application

The MUTCD gives the following guidelines and standards for delineator applications on expressway and freeways:

- Single delineators shall be provided on the right side of expressway and freeway roadways and on at least one side of interchange ramps. They may be provided on other classes of roadways.
- Roadside delineators shall be optional on tangent sections of expressway and freeway roadways when all of the following conditions are met:
  - Raised pavement markers are used continuously on lane lines throughout all curves and on all tangents to supplement markings.
  - Where whole routes or substantial portions of routes have large sections of tangent alignment.

- Where, if roadside delineators were not required on tangents, only short sections of curved alignment would need delineators.
- Roadside delineators are used to lead into all curves as shown in Table 1 of this report.

The MUTCD also provides the following guidance in terms of delineator application on crossovers and acceleration and deceleration lanes:

- "Where median crossovers are provided for official or emergency use on divided highways and where these crossovers are to be marked, a double yellow delineator should be placed on the left side of the through roadway on the far side of the crossover for each roadway (*1*)."
- "Double or vertically elongated delineators should be installed at 30 m (100 ft) intervals along acceleration and deceleration lanes (*1*)."

Research Issue: The MUTCD implicitly requires single delineators on the right side of all curved sections of expressway and freeway roadways. While right side delineation is required for all expressway and freeway roadways, an option exists for using raised pavement markers where certain conditions are met. There should be a point of minimum curvature that should allow for the raised pavement marker option in lieu of right side delineation. For example, is it reasonable to require right side delineation on a curve with a deflection angle as small as 0E15' when raised pavement markers may perform as adequately as they do on tangent sections?

Research Issue: The MUTCD suggests using double delineators at crossovers and along acceleration and deceleration lanes. TTI Researchers did not know whether motorists could distinguish double delineators from single delineators, and, if they could, researchers did not known that they perceived a difference between the two, especially with the mixed use of retroreflective materials. A single delineator with an efficient retroreflective material can look brighter than a double delineator with less efficient retroreflective material.

Table 1. Suggested Spacing for Highway Delineators on Horizontal Curves (*1*).

Radius of Curve (ft)	Spacing on Curve, S (ft)
50	20
150	30
200	35
250	40
300	50
400	55
500	65
600	70
700	75
800	80
900	85
1000	90

Spacing for specific radii not shown may be interpolated from Table 1. The minimum spacing should be 20 feet. The spacing on curves should not exceed 300 feet. In advance of or beyond a curve, and proceeding away from the end of the curve, the spacing of the first delineator is 2×S, the second 3×S, and the third 6×S but not to exceed 300 feet. S refers to the delineator spacing for specific radii computed from the formula: $S = 3\sqrt{R - 50}$.

Delineator Placement and Spacing

The MUTCD recommends that normal spacing of delineators should be 200 to 528 feet. Spacing should be adjusted on approaches and throughout horizontal curves so that several delineators are always visible to the driver. MUTCD's Table III-1 (reproduced herein as Table 1) shows suggested spacing for delineators on horizontal curves.

Research Issue: The spacing of delineation varies on the approach to and the departure from a horizontal curve. The justification for this varied spacing is not provided and has changed over time. It is possible that equal approach and departure spacing would provide the driver the same cues about the alignment change as varied spacing does. If so, implementation of curve delineation would be considerably less complicated. In consequence, more consistent applications would be provided.

Research Issue: The spacing for delineation is based on a radius-dependent formula. TxDOT maintenance crews responsible for installing and maintaining delineators typically do not have curve radii information readily available. An easier-to-apply method for spacing delineators is needed.

Research Issue: The spacing for delineation is based on the formula above and depends on curve radius. However, the guidelines for Chevron spacing simply recommend that two Chevrons be visible to the motorist until the change in alignment eliminates the need for the signs. There needs to be more consistent guidance regarding the spacing of these two elements.

ORGANIZATION

In order to satisfy the objectives listed above, the researchers reviewed the literature and contacted researchers performing research that was identified as being potentially or directly related to this project. Chapter 2 of this report describes the results of this effort.

Because this project focused on practices in Texas, the researchers developed and administered a survey in order to identify practices and policies in use in the remaining 49 states. Chapter 3 describes the survey and the findings.

In another early effort of this research project, the researchers visited various curves around the state of Texas to assess the current state-of-the-practice. The researchers measured delineator and Chevron spacing, curve radius, superelevation, ball bank indicator speeds, and other related curve characteristics. Chapter 4 describes these efforts and the results of these efforts.

One of the main efforts of this research was to develop a simple method for field personnel to identify the proper spacing of delineators. Chapter 5 describes the initial efforts that were tested and the subsequent results.

Based on the results of the initial efforts to identify alternative spacing criteria, as described in Chapter 5, researchers embarked on a more focused effort to fully develop the two most feasible options. One of these options was using the advisory speed value of a curve to set the spacing and the other was a radius measuring device built by the researchers to measure the radius of a horizontal curve from a vehicle traversing the curve at highway speed. Chapter 6 describes these efforts and the pertinent findings.

Chapter 7 of the report describes the researchers' efforts to determine how Chevron spacing impacts vehicle approach speed to horizontal curves. This research was conducted on the open road with cooperation from the TxDOT Bryan and Waco District offices.

The researchers also performed a battery of delineator visibility tests at the Texas A&M Riverside campus. These tests included the evaluation of driver perception of curve severity as a function of radius, delineator size, and approach delineator spacing. The tests also included an assessment of how well drivers understand delineator color and how the size and color of the delineator affects driver detection distances. Chapter 8 describes these research activities and findings.

Chapter 9 includes a summary of the research and the researcher team's recommendations to simplify delineator and Chevron applications. The references are then included as well as the appendices which supplement the individual chapters as described above.

CHAPTER 2:
LITERATURE REVIEW

INTRODUCTION

Research has consistently shown an over representation of run-off-the-road accidents in rural areas on horizontal curves (*4*). In some cases, these types of accidents can account for 40 percent of all accidents on rural roads with nearly half of these involving personal injury or fatality (*5*). One study found that on two-lane rural highways the degree of curvature of a horizontal curve is the strongest geometric variable related to accident rates (*6*). Due to these findings, many devices and treatments have been developed and tested over the years to try and reduce these types of accidents. Two of these devices are Chevron Alignment signs (W1-8) and post-mounted delineators (PMD). Chevrons and PMD provide a preview of roadway features ahead. The MUTCD defines the Chevron Alignment sign as a warning sign (*1*). It states that the Chevron Alignment signs are intended to "provide additional emphasis and guidance for a change in horizontal alignment." Delineators, on the other hand, are strictly considered a guidance device rather than a warning device. Several studies have analyzed the effectiveness of these devices; however, only a few studies have examined spacing variations. Though little information was found in regards to Chevron or delineator spacing, the history of the spacing requirements for these devices and the finding of the many studies that evaluated their effectiveness may provide insight to direct researchers toward a more uniform and uncomplicated spacing system.

Driver Behavior on Horizontal Curves

Accidents on horizontal curves have been considered a problem for many years. In response to this problem, many treatments for horizontal curves have been developed and tested. Researchers have also conducted human behavior studies on curves to identify how drivers progress through a horizontal curve and where their vehicles are located with respect to the center of the lane during their travel through the curve. Human behavior has also been studied to determine how drivers estimate the curvature of a horizontal curve and when the drivers notice a curve. This section summarizes these human performance studies.

In Shinar's study (*4*), participants underestimated curvature for arcs that were less than 90 degrees. For example, the participants thought the radius was larger than it actually was, which would indicate that they perceived the curve to be softer than it actually was. Thus, if they were driving and felt that the curve was not as sharp as it is in reality, they may be going too fast. A Triggs and Fildes study, showed subjects' drawings of curves from the perspective of the driver. The subjects were students with legal driver's licenses. Subjects were asked to set the exit angle (in plan view), which they perceived from slides. Subjects tended to overestimate the exit angle when shown curves with smaller (8 and 15 degrees) degrees of curvature. Also, subjects were more accurate at estimating the exit direction of right-hand curves than left-hand curves. Since the study was performed in Australia, where they drive on the left side of the road, it can be inferred that these results contradict the results of Shinar's curve study.

The goal of Nemeth et al.'s report *(7)* was to develop a cost-effective methodology to compare the effectiveness of different delineation treatments for horizontal curves on rural roads in a laboratory setting. Subjects were shown a video taken of the road as a vehicle was driving toward a curve. Subjects were asked to stop the videotape when they were first able to detect the curve and then tell the direction of the curve (left or right). Researchers found that subjects tend to perceive right-hand curves quicker and with a lot more certainty than left-hand curves. The authors claim that the results of the laboratory studies are supported by the results from several field studies. However, a FHWA flyer reports a field study that contradicts Nemeth et al.'s finding that drivers tend to perceive right-hand curves quicker and with a lot more certainty than left-hand curves. In this field test, subjects drove a field research vehicle on a rural two-lane highway that contained frequent horizontal curves but very little vertical curvature. Then, the participant rode as a passenger along the same stretch of road and, when prompted, gave a subjective safety evaluation. The road contained untreated and chevron-treated horizontal curves. Participants chose slower speeds to traverse the right untreated curves than the left untreated curves. The study interpreted this result to mean the participants perceived these curves to be less safe. On chevron-treated right curves, drivers were even more cautious. The report did not offer any explanation as to why drivers were more cautious on right curves with chevrons.

According to Zador *(5)*, most researchers have interpreted that the delineation of a curve leads to a "decrease in the variability of the vehicle speed and lateral position" on a curve. Zador also found that drivers use a curve-flattening strategy. In other words, the driver takes a path that does not follow the radius of the curve. On left-turning curves, researchers found that vehicles were closer to the centerline of the road at the midpoint of the curve and closer to the edgeline of the roadway on right-turning curves.

Felipe and Navine *(6)* found that for curves with large radii the drivers followed the center of the lane in both directions. However, for smaller radii curves, the drivers "cut" the curves in both directions. In order to minimize the speed change, the drivers "flattened out the bends" by driving on the shoulder or in the other travel lane.

Overall, the past research on driver behavior while approaching and while driving through a curve has mixed results. However, most of the research does conclude that there is a perception problem for drivers on small radii curves (curves less than 15 degrees). Also drivers do not stay in the center of the travel lane on small radii curves, which poses a problem from a safety standpoint because drivers are getting too close to the center of the roadway and could hit other vehicles head-on or they are getting too close to the edge of the roadway and could run off the road. Delineation has been used in the past to try and minimize these issues and increase safety. The effectiveness of post-mounted delineators and chevrons used on horizontal curves at certain spacings has been studied by several agencies and will be discussed in the next two sections.

POST-MOUNTED DELINEATORS

This section gives a history of when post-mounted delineators (PMDs) came into the MUTCD and how the regulations have changed over time. This section also describes research findings concerning the effectiveness of post-mounted delineators at given spacings and how PMD spacings differ among agencies and countries.

MUTCD History – Delineator Spacing

The following paragraphs describe the evolution of PMD requirements in the MUTCD. Requirements that changed in the next chronological MUTCD are italicized for ease of identification. Delineators first appeared in the 1948 edition of the MUTCD *(8)*.

In this edition, the following requirements related to delineator spacing:

- Delineators should be spaced 200 ft apart normally. (Tangent sections)
- On approaches to and throughout horizontal curves, delineators should be spaced such that five are always visible to the right of the road.
- Delineators on horizontal curves were recommended to be spaced according to the following equation: $S = 1.2\sqrt{R+18}$

  Where: S = spacing on the curve, and

  R = radius
- The spacing to the first delineator in advance of and beyond the curve was 1.8S, to the next delineator 3S, and to the next 6S, but not to exceed 200 ft.

This edition also included recommended spacing for delineators on vertical curves.

In the 1961 edition of the MUTCD, the following changes were made in regards to delineator spacing (*9*):

- Delineators should normally be 200 to 400 ft apart. (Tangent sections)
- On approaches to and throughout horizontal curves, delineators should be spaced such that several are always visible on the curve ahead of the driver.
- Delineators on horizontal curves were recommended to be spaced according to the following equation: $S = 2\sqrt{R-50}$
- The minimum delineator spacing should be 10 ft.

The 1961 MUTCD eliminated recommended delineator spacing on vertical curves.

In the 1971 edition of the MUTCD additional changes were made. Delineator spacing recommendations were again adjusted as follows (*1*):

- Delineators should normally be spaced 200 to 528 ft apart. (Tangent section)
- Delineators on horizontal curves were recommended to be spaced according to the following equation: $S = 3\sqrt{R-50}$
- The spacing to the first delineator in advance of and beyond the curve should be 2S.
- The spacing on curves should not exceed 300 ft.
- The minimum spacing on curves should be 20 ft.

Delineator spacing experienced minor changes unrelated to the scope of this project since the 1971 edition of the MUTCD. No literature justifying changes to the equation for delineation spacing on horizontal curves or changing the maximum spacing on horizontal curves has been found. When asked, the Federal Highway Administration could not provide documentation describing the changes to delineation application. Table 2 shows how the recommended spacings for delineation have changed in the MUTCD. The recommended delineator spacings have increased over each successive edition of the MUTCD.

Table 2. Spacing Changes for Delineators in the MUTCD.

MUTCD Edition	Recommended Spacing for Delineators
1948	$S = 1.2\sqrt{R + 18}$
1961	$S = 2\sqrt{R - 50}$
1971	$S = 3\sqrt{R - 50}$

Past Research

Most field studies evaluating the effectiveness of delineators analyzed one or more of the following variables: change in speed, change in lateral placement, and change in the speed variance. Longitudinal spacing of delineators was not tested; however, many agencies used spacings that differed from the recommended spacing in the MUTCD when they tested for effectiveness. Some studies tested the effects of varying the height of the delineator from the ground or varying the lateral placement of the delineator from the edge of the pavement. Also included in this section are different agencies' spacing methods used today for horizontal curves to show how the spacings differ across different agencies.

Vertical (ascending) and lateral (in-out) spacing was evaluated by Rockwell and Hungerford in 1979, and discussed in a literature review by Johnston. The study found that a combination of varying vertical and lateral placement of delineators induced the most consistent judgment of apparent sharpness in a laboratory comparison test. In a field test, this configuration resulted in a significant increase in the amount of deceleration between the approach and the curve entry when compared to a before curve without delineators. It is important to note that the spacing of the posts was always constant and not based on curve radius (*10*).

In Appendix M of NCHRP Report 130, David (*11*) compared post-mounted delineators to retroreflective pavement markings. In this study, post-mounted delineators were spaced according to PennDOT specifications. The equation used to space the post-mounted delineators was $S = 2\sqrt{R}$. These spacing requirements are slightly less conservative than the maximum spacing values obtained from the equation in the 1961 MUTCD, but considerably more conservative than the spacing calculated from the 1971 MUTCD equation. Researchers recorded lateral placement and speed in the curve for 50 vehicles in each direction. The data were only collected between Monday and Thursday. The change in variance for lateral placement and speed was not significant. The report concluded that adding post-mounted delineators to a curve with a freshly painted centerline would provide marginal improvements at best.

Post-mounted delineators were evaluated at two different spacings and compared to a base condition (standard centerline and edgelines only) in Stimpson et al. (*12*). The study site was in Maine, and the data were collected using detection traps made of three coaxial cables. These cables were used to collect speed and lateral placement data for a sample size between 125-150 vehicles. The base condition was labeled level 1; level 2 was used to describe the condition where delineators were placed at 528 ft apart in tangent sections and at two times the recommended spacing on horizontal curves; and level 3 denoted the condition where delineators were placed at half the distance of the level 2 spacing (MUTCD spacing on horizontal curves). The study found that adding PMD at the level 2 spacing reduced speed variance by 20 percent, and doubling the delineation to the level 3 condition reduced speed variance 8 percent from the level 2 condition. The researchers recommended delineator spacing on tangents to be increased to 400-528 ft, but also recommended that the MUTCD suggested spacing for curves be retained.

Agent and Creasey (*13*) varied the heights, lateral placement from the edge of pavement, and spacing for both post-mounted delineators and chevrons. Photographs of the varied configurations were shown to 40 subjects, and the subjects answered a questionnaire based on their perception of the curve. They were asked to choose three configurations with the sharpest curves and three configurations with the flattest curves. The questionnaire results determined which configurations would be tested in the field. These results indicated that curves appeared sharper when the height of the sign was varied, but the lateral placement and spacing between posts remained constant. The curves perceived to be the sharpest were field tested. Chevrons were recommended over post-mounted delineators because vehicle speeds were lower with chevrons. Researchers made no spacing recommendations in this study.

In a study done by Hall (*14*), delineators were spaced at $S = 2\sqrt{R}$. Hall found that there was no difference in the speeds over the different delineation treatments. In another treatment, he doubled the spacing but still found no difference in the lateral placement of the vehicles or the speeds. Overall, the post-mounted delineators did not change the speed of the motorists or the mean lateral placement. However, on outside curves, PMDs helped reduce the variance of the lateral placement of the vehicles.

In Freedman et al.'s study (*15*), the authors state that the suggested spacing for post-mounted delineators be determined based on the radius of the curve and applying the formula $S = 3\sqrt{R-50}$ and that the spacings should be no less than 20 ft and no greater than 300 ft. Although it is not stated in the report, the formula used for the spacings appears to have been the same formula from the latest version of the MUTCD. This study also found that post-mounted delineators had the greatest speed increase in the comparative study between PMD, Rasied Retroreflective Pavement Markers (RRPM), and Chevrons. The authors found that the speed increased 2 to 2.5 ft per second and that post-mounted delineators caused vehicles to shift away from the centerline of right curves whereas Chevrons tended to shift vehicles away from the centerline on left and right curves. One of the conclusions from the visual simulation study in this report is that delineation treatments that include the use of post-mounted delineators lead to lower overall speeds and speed variances, lower acceleration, and steadier lane tracking closer to the centerline for left horizontal curves.

Zwahlen's study (*16*) looked at both the height and spacings of post-mounted delineators and compared them to see if the spacings and heights had a significant impact on the detection of the delineators. The study compared three different lateral offsets of the post-mounted delineators and found that the offsets did not significantly affect the detection distances of the delineators. At the time of this study, the Ohio Manual on Uniform Traffic Control Devices stated that the spacing of post-mounted delineators be placed based on using the radius of the curve and the formula $S = \sqrt{R-50}$. After analyzing the effects of different sheeting materials on the visibility of the delineators, they recommended the following spacings for two-lane rural roads:

- For encapsulated lens sheeting, the spacing should be $10\sqrt[3]{R-43}$,
- For prismatic sheeting with retroreflectivity levels of 825 cd/fc/ft^2, the spacing should be $11.5\sqrt[3]{R-44}$, and
- For prismatic sheeting with retroreflectivity levels of 1483 cd/fc/ft^2, the spacing should be $13\sqrt[3]{R-46}$.

All values should be rounded to the nearest 5 ft. These formulas are based of photometric calculations for left curves along two-lane rural roads with an assumed lanes width of 12 ft and an offset of 2 ft. The values produced by these formulas fit the results obtained in the study fairly well for radii from 500 to over 2000 ft.

The spacings for other countries vary considerably. Austroads (*17*) suggests that chevrons and delineators be spaced by the following equations: $S = 0.03R + 5$ for radii up to 500 m and $S = 0.06R$ for radii over 500 m. These spacings must not exceed 150 m or 60 m in areas subject to fog. The guide also states that if the radius of the curve is unknown that it should be estimated by using the middle ordinate offset from the chord of the curve. For the most part, the European countries use a spacing that is one-half that of the MUTCD's recommended spacing. However, there was no formula given for where the spacings came from for these countries. However, the British Road Marking Panel, in 1965, did recommend that maximum distance between delineators be 33 m or 100 ft (*18*).

The spacings used by some agencies in the United States vary but resemble the MUTCD recommended spacings in some instances. In the Roadway Delineation Practices Handbook, the FHWA specifies that delineators should be placed on the outside of curves with a radius of 1000 ft or less. The recommended spacings for the delineators are shown in a table and are derived from following equation: $S = 3\sqrt{R-50}$. It also states that the three PMDs should be placed in advance of the curve and three after the curve and should be placed so that three are visible at all times to the driver. Also the spacing of the PMDs should not be less than 20 ft or exceed 300 ft (*19*). In the California Department of Transportation Handbook, there is a diagram and table that shows how post-mounted delineators should be spaced based on the radius of the curve. The spacing table is based off of the formula, $S = 1.6\sqrt{R}$, and anyone spacing along the curve should not exceed 48 m (*20*).

The Local Technical Assistance Program (LTAP) document titled Delineation of Turns and Curves (*21*) has a table that gives guidance for the spacing requirements for post-mounted delineators. The spacings in this table were developed using the following formula, $S = \sqrt{R - 50}$, and that the shortest spacing should be 20 ft and that the spacings should not exceed 300 ft. This table also states the recommended spacings for post-mounted delineators to be used before the curve starts and after the curve ends.

Overall, there are considerable differences in the spacings being used by different agencies in the United States as well as by other countries. Unfortunately, there have been no published studies on the effectiveness of these different spacings and methods used by these agencies. For those delineation treatments, that were studied there is variation in whether or not the different delineation treatments are effective in reducing crashes. Some studies found a decrease in the speeds and position of the vehicles whereas other studies found no significant difference in the different delineation treatments. More research should be done on the effectiveness of these different delineation treatments and how they relate to accidents on rural horizontal curves.

CHEVRONS

This section discusses the history of the chevron in the MUTCD as well as changes that have occurred to the regulations. Also discussed is past research on the effects of chevrons on the driver's behavior as well as the effectiveness of chevrons. Finally, some of the different spacing techniques used by different agencies are discussed if the spacings differ from those of the standard post-mounted delineator.

MUTCD History – Chevrons

Chevrons were added to the MUTCD in the Official Rulings on Requests for Interpretations, Changes, and Experimentations in 1977 due to successful experiments performed in the state of Georgia and Oregon (*22*). The suggested spacing has not changed. In the 2000 MUTCD, the spacing requirements for chevrons remain that the driver must be able to view two chevron signs until the change in alignment eliminates the need for the signs.

Past Research

Zwahlen and Park performed a study to determine the optimum number of chevrons that a driver needs to be able to accurately estimate the sharpness of the curve (*23*). Ten young drivers sat in a black booth a saw a slide of a standard curve with 12 chevrons equally spaced around the curve for 2 s. Then, they turned 90 degrees to view the test curves. They found that the judgment accuracy increased as the number of chevrons was increased up to four, and there was no basic difference between four and eight chevrons. Also, from a practical standpoint, having more than four chevrons in view in a visual field of about 11 degrees was not practical. From the results, they concluded that "four equally spaced delineation devices, such as chevrons, within a total visual field of about 11 degrees provided adequate curve radius estimation cues for unfamiliar drivers." They also concluded that having four delineation devices instead of three, while it improves perceptual accuracy slightly, would be better because if a chevron was missing, the driver would still have three chevrons visible, which would allow higher accuracy levels than with just two visible.

Jennings and Demetsky tested PMDs, special delineators, and Chevrons for effectiveness (*24*). In the results, the authors found chevron signs to reduce speed and speed variance, and promote more desirable lateral placement. Chevrons spaced at two times the MUTCD was the recommended delineator spacing. Researchers wrote that this spacing reduced the wall effect that often occurs when chevrons are spaced according to MUTCD recommendations for delineators. Using twice the MUTCD spacing also allowed two or three signs to be visible throughout the curve. Other states also found this spacing to be the best. The research concluded that Chevron signs (WI-8) should be used for curves over 7 degrees and that standard edge delineators could be used for curves less than that. They also recommended that the spacing for chevrons be twice the distance for standard delineators.

For Zador et al. study (*5*), chevrons were placed such that three were always in view on rural curves in Georgia and New Mexico. Coaxial cables were used to collect speed and lateral placement data 100 ft before the curve and 100 ft after the beginning of the curve (instead of center). The presence of delineation modifications significantly influenced both vehicle speeds and lateral placement, and the long-term measurements indicate that the benefits do not erode over time. However, there "was no convincing evidence to support a preferential choice" between any of the devices tested in this study. Also, there was no recommended spacing distance given or a recommended number of delineation devices that should be in view throughout a horizontal curve. Modification had no effect on corner-cutting behavior, but the author stated that raised pavement markers reduced corner cutting at night but increased it during the day for left curves. All of the studies cited in this report stated that drivers preferred to use a corner-cutting strategy. This strategy can reduce the peak friction demand on the curve because of the reduction in the lateral acceleration, but it can bring vehicles closer to the boundaries of the roadway, thus reducing the margin of safety while traveling the curve.

Niessner states in his report that he found chevrons made with a yellow background and black legend were very noticeable in both day and night situations (*25*). He also found that at night the chevrons were very visible and the line of the chevrons, consisting of three in view, delineated the curve. West Virginia used a chevron spacing two times the recommended spacing from the MUTCD. The data collected for this study also shows that chevrons significantly reduced the total fatal accident rate from the before and after periods. The study also showed a decrease in the number of run-off-the-road accidents when just delineators were used.

The Roadway Delineation Practices Handbook states that Chevrons should be spaced so that two are in view at all times (*26*). This must be maintained until the alignment of the roadway changes to where the signs are no longer needed. The chevrons should also be visible for at least 500 ft before the beginning of the horizontal curve. The LTAP publication for Pennsylvania states that chevrons should be used in a series on turns and curves with curvature greater than 7 degrees. This document also states that "chevrons must be used in a series of at least three," but the document does not state what spacings to use or what method to use for determining the recommended spacings (*21*).

Zwhalen's study (*27*) found that some curves had increased speeds and some with decreased speeds after chevrons were used. Overall, there was a slight speed reduction, but it was not statistically significant. The study concludes that visual guidance does not significantly affect approach speeds of drivers. Also, the study states that the center speeds were not significantly affected by the presence of delineation devices.

Unfortunately, only one document could be found with equations used for chevron spacings. According to the handbook published by the Center for Transportation Research and Education (CTRE), the Kansas Department of Transportation uses the following guidelines to space chevrons along a horizontal curve:

1. Determine the distance from the beginning of the curve,
2. Lookup the proper spacing value from a set table of spacings that were developed using the equation $S = 4.5\sqrt{R - 50}$,
3. Determine the number of spaces by dividing the distance from the beginning to the end of the curve by the spacing value from the table and round this value to the nearest reasonable whole number, and
4. Determine the spacing distance of the chevrons by dividing the measured distance from the beginning to the end of the curve by the rounded number of spaces (*19*).

A diagram of how the CTRE recommends placing of chevron signs and the table of spacings are located in Figure 1 and Table 3 respectively.

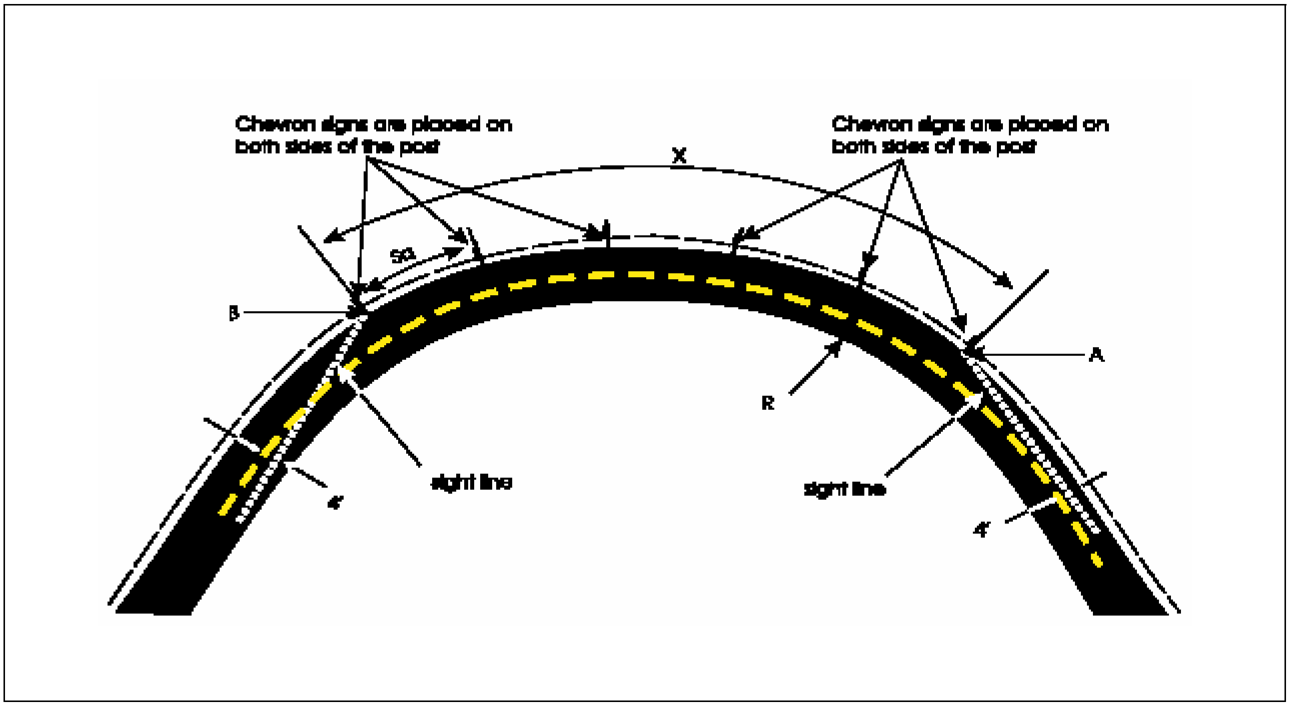

Figure 1. Diagram to Illustrate Placing of Chevron Signs on Curves (*19*).

Table 3. Suggested Spacing for Chevron Signs (*19*).

Suggested spacing for Chevron signs

Design Speed (0.08 Max Super)	Degree (D)	Radius (R)	Spacing Distance (Sc)
60 mph	1°00'	5730'	200'
60 mph	2°00'	2865'	200'
60 mph	3°00'	1910'	200'
60 mph	4°00'	1432'	150'
50 mph	5°00'	1146'	150'
50 mph	6°00'	955'	125'
50 mph	7°00'	819'	125'
40 mph	8°00'	716'	125'
40 mph	9°00'	637'	100'
40 mph	10°00'	573'	100'
40 mph	11°00'	521'	100'
40 mh	12°00'	477'	100'
30 mph	13°00'	441'	100'
30 mph	14°00'	409'	75'
30 mph	15°00'	382'	75'
30 mph	16°00'	358'	75'
30 mph	17°00'	337'	75'
30 mph	18°00'	318'	75'
30 mph	19°00'	302'	75'
30 mph	20°00'	286'	75'

Overall, the results on whether or not chevrons are effective are mixed. However, according to Niessner's study (*25*), there was a reduction in the number of run-off-the-road accidents where chevrons were used to delineate curves. In Jennings et. al.'s research, they found that chevrons reduced the speed and speed variance while following a horizontal curve (*24*). They also found that the chevrons caused drivers to follow the curve better. However, there are also results that state there were no significant results from using chevrons over other delineation methods. But given the results of the research, it can be determined that chevrons do provide some reduction in the speeds and speed variances and, therefore, add some safety for drivers.

Most of the research discussed here used the MUTCD recommended spacing or two times the recommended spacing. Also, the research states that at least two or three must be in view of the driver at all times. Unfortunately, there was only one document that specified spacings for chevrons in the form of an equation. However, some of the agencies and the studies used the post-mounted delineator spacings for those of chevrons as well. Table 4 shows an example of the mixed opinions and findings regarding spacing.

The past research overall does not clearly show whether or not post-mounted delineators and chevrons improve safety on rural horizontal curves. There are mixed results for both methods but there appear to be more benefits from using post-mounted delineators or chevrons than not using them even though there is no trend one way or another from past research. The MUTCD needs to be more clearly defined, and more research should be done on what spacings will work the best for both chevrons and post-mounted delineators. Having two or three chevrons or post-mounted delineators "in view" of the driver throughout the curve is too vague and needs to be clarified so that there is no discrepancy on what is or is not "in view" of the driver. Using equations to specify the spacings may not be the best option, but perhaps a range of values depending on different configurations and sight-distance problems would provide more flexibility for rural curves that are not typical. More research should be done to determine what the minimum requirements are for post-mounted delineators and chevrons on a standard rural horizontal curve.

Table 4. Chevron Spacing Summary.

Recommended or studied spacing	Reference
Two in view	MUTCD *(22)*
Four in view	Zwahlen and Park *(23)*
Twice the recommended delineator spacing	Jennings et. al *(24)*
Three in view	Zador et. al *(5)*
Three in view	Niessner *(25)*
Two in view	Roadway Delineation Practices Handbook *(26)*
$S = 4.5\sqrt{R - 50}$	CTRE *(19)*

CHAPTER 3:
STATE SURVEY

TTI researchers developed and administered a state survey in order to determine how various states interpret some of the vague MUTCD language associated with the delineation of horizontal curves. Specifically, the survey was designed to determine if and when agencies interpret Section 3D.03 such that gentle horizontal curves on expressways and freeways can be considered tangent sections and, therefore, do not require delineation (as long as the appropriate exemptions from Section 3D.03 are satisfied), how agencies use and classify single and double delineators, and finally, how agencies expect their field crews to set the spacing for delineators and Chevrons.

Figure 2 shows the survey instrument. It was sent to the state representatives on the American Association of State Highway and Transportation Officials (AASHTO) Maintenance Engineering subcommittee and the AASHTO Traffic Engineering subcommittee. A total of 34 states responded to the survey.

The first question of the survey was aimed at determining whether agencies that use Retroreflective Raised Pavement Markings (RRPMs) on their freeways and expressways delineate gentle curves on these limited access facilities as tangents, and if so, at what point they make this distinction. This question was important because the wording of the MUTCD implies that all curves on freeways and expressways require post-mounted delineators, regardless of the radius.

Twenty-seven states responded to this question. Of these, 17 states indicated that they do delineate horizontal curves as tangents at some point. The point at which a distinction is made ranged from a radius of 2865 ft (or a 2-degree curve) to 14,000 ft (or a 0.41-degree curve). The average was a radius of 6413 ft (or a 0.89-degree curve).

The next question of the survey was aimed at determining whether there is a real need to distinguish between single and double delineators for various applications. Even though this was thought to be a minor issue, it is not hard to find delineators in the field that have the wrong number of reflector units on them.

The Texas Transportation Institute is conducting research for the Texas Department of Transportation regarding delineation practices along horizontal curves. The research is specifically focused on delineators and Chevrons. One of the objectives is to provide spacing guidelines for delineators and Chevrons that can be easily applied in the field without prior knowledge of curve radii or other features difficult to determine without a set of plans. I would be extremely grateful if you or one of your staff could take a few minutes to answer the following questions pertaining to the MUTCD and horizontal curve delineation. **If you could, please respond by May 31.**

---

1. Section 3D.03 implies that delineators are required on the right side of all curves on expressways and freeways. In many states such as Texas, RRPMs are used on lane lines such that the delineators are not needed on tangent sections of expressways and freeways. These types of facilities are also built to the highest standards, which translates to very gentle horizontal curvature. Does your agency interpret Section 3D.03 such that gentle horizontal curves may be considered tangent and therefore do not require delineators (as long as the appropriate exemptions of Section 3D.03 are satisfied)? If so, please indicate the point (i.e., radius or degree of curve) at which your agency delineates curves as tangent sections on expressways and freeways. For example, your agency may use the spacing table in the MUTCD (Table 3D-1) which stops at 1000 ft radius curves (approximately 5.7 deg). If not, at what point (i.e., radius or degree of curve) would you consider acceptable practice to delineate an expressway or freeway curve as a tangent section?

2. Section 3D.03 indicates specific uses for single and double delineators. Does your agency distinguish between single and double delineators? Do you feel that it is necessary to distinguish between single and double delineators? How many classes of delineators does your agency use and what are their intended meanings?

3. Section 3D.04 provides guidelines for delineator spacing. The spacing depends on the radius or degree of curve. Does your agency use something other than radius or degree of curve to determine spacing? If not, how do your field personnel determine the pertinent information to select the appropriate spacing? Does your agency vary the approach and departure spacing as suggested in Section 3D.04?

4. Section 2C.10 addresses the Chevron sign. It says that Chevron spacing "should be such that the road user always has at least two in view . . ." How does your agency space Chevrons in horizontal curves?

Please send your agency's related guidelines, practices, and/or specifications, particularly if they differ from the national MUTCD.

Also, please include your name and phone number so that we may call you to follow up, if needed. Each response will be kept confidential in that only percentages and trends will ever be published as a result of this survey.

Thank you, in advance, for your cooperation. If you have any questions, please contact me.

Paul J. Carlson, Ph.D., P.E.
Program Manager
Texas Transportation Institute
3135 TAMU
College Station, TX 77843-3135
PH: (979) 845-1728
FX: (979) 845-6006
Email: paul-carlson@tamu.edu

Figure 2. State Survey Instrument.

Thirty-two states responded to this question. Of these, 25 states reported that they do distinguish between single and double delineators. Only 12 states expressed their opinions regarding whether there was a need to make the single versus double delineator distinction. Interestingly, the results were split.

The third question of the survey was designed to reveal the difficulty in applying the delineator spacing criteria as shown in the MUTCD. The MUTCD spacing table is based on the curve radius or degree of curve. While this may be adequate for the roadway design engineers, it is not convenient for field personnel who typically do not have easy access to this information or have a way to measure it in the field. Additionally, the MUTCD provides guidelines for variable delineator spacing on the approach and departure to horizontal curves. The states were asked if they practiced this guidance.

Twenty-eight states answered this question. Of these, 26 states reported that they use either the curve radius or the degree of curve, exclusively. Two states reported that they use the advisory speed value of the curve to set the delineator spacing, and one other state reported that they use a constant spacing for all curves, regardless of the radius.

Only seven of the 26 states that reported using either the curve radius of degree of curve to set delineator spacing in curves responded to the question of how their field personnel obtain the information (i.e., radius or degree of curve) to set the proper spacing. Surprisingly, three states reported that they use the chord method, which is a rather laborious and inaccurate procedure that puts the field personnel on the road to make the measurements (this method, and others, are more fully described in the following chapter). As reported above, two states use the advisory speed value and another uses constant spacing in all curves.

Of the 28 states that responded, 19 reported that they use some form of variable delineator spacing on the approach and departure to horizontal curves. Some unique variations were provided. For instance, one state uses only one delineator on the approach and departure, and it is spaced as 2×S (where S is the spacing in the curve). Another state uses the MUTCD guidance but omits the third delineator on the approach and departure to the curve. Yet another practice reported by one of the states makes use of two delineators on the approach and departure, but their spacing is 2×S rather than 2S and then 3S (as per the MUTCD).

The fourth and final question of the survey focused on Chevron spacing in horizontal curves. The question was asked to determine if there are states using more objective spacing criteria than MUTCD's guidance of having at least two in view.

Half of the 32 states that responded to the Chevron spacing question reported that they use the MUTCD criteria of two in view. Three states reported that they use the same concept as the MUTCD criteria except they try to provide three in view. Three states use a table based on the advisory speed value to space Chevrons. Two states use the MUTCD delineator spacing table without modifications, and one state reported that they double the spacing of the MUTCD delineator spacing table for their Chevron spacing. Other states reported various formulas or radius-dependent tables. Appendix A shows the spacing tables that were provided by the states, for both delineators and Chevrons.

CHAPTER 4: STATE-OF-THE-PRACTICE

One of the early fundamental issues associated with this research was determining the state-of-the-practice with respect to the installation and maintenance of delineators and Chevrons along horizontal curves. Therefore, TTI researchers visited horizontal curves on state-maintained highways to assess the current installation and maintenance practices used by TxDOT field crews. Researchers then compared the findings to TxDOT standards and guidelines. Part of the reason for these activities was to understand the current difficulties and to determine the potential for making improvements to the current practices.

CURVE LOCATIONS AND CHARACTERISTICS

Researchers visited 58 curves in various areas of Texas including the Bryan, Waco, Amarillo, and Atlanta Districts. One of the required curve characteristics was the presence of an advisory speed. Researchers used TxDOT Road Inventory Logs (RI logs) or as-built plans to identify or calculate geometric curve characteristics such as length, deflection angle, and radii. Traffic control characteristics, such as delineation type and spacing, and posted and advisory speed values were recorded at each location. Researchers also collected roadway characteristics such as number of lanes, width of lanes, and width of shoulders. Of the 58 curves, the advisory speed ranged from 15 mph to 65 mph, and the radii ranged from 180 ft to almost 2000 ft.

MEASURED DELINEATOR SPACING

In order to determine how delineators in the field were spaced and how that compared to the Texas MUTCD recommendations, the distance between the delineators was measured and then compared to the following Texas MUTCD criteria: "The spacing of delineators should be adjusted on approaches to and throughout horizontal curves so that several delineators are always simultaneously visible to the road user (*2*)."

Table 5 shows the delineator spacing table from the Texas MUTCD (*2*). The recommended spacing on the approach of the curve in each direction is 2S for the first delineator just before the point of curvature (PC) or just after the point of tangency (PT) of the curve, 3S for the second delineator, and 6S for the third delineator (where S is the spacing in the curve). The

Texas MUTCD also recommends that delineator spacing should not be less than 20 ft or more than 300 ft.

Table 5. Table 3D-1 from the Texas MUTCD.

Radius of Curve (ft)	Approximate Spacing (S) on Curve (ft)
50	20
115	25
180	35
250	40
300	50
400	55
500	65
600	70
700	75
800	80
900	85
1000	90

As shown in Table 6, researchers collected data on 35 curves with delineators. None of the curves examined had delineators spaced at 2S, 3S, or 6S on the tangent approach or departure to or from the curve. On most of these curves, there was one delineator in advance of the point of curvature and beyond the point of tangency. All the curves had at least three delineators in view at any point on the curve. Table 6 also includes the average field spacing and the spacing recommended by the Texas MUTCD.

Table 6. Delineator Spacing as Measured in the Field.

	Curve Locations	Speed Limit (mph)			Delineator Spacing				
		Posted Speed Limit	Advisory Speed	Change in Speed	Number of Delineators	Average Spacing	Standard Deviation	Radius	Tx MUTCD Recommended Spacing
1	FM 1671	60	25	35	6	133	9	190	35
2	FM 1404	55	35	20	11	90	25.6	320	49
3	FM 449	55	35	20	10	80	57.2	441	59
4	FM 168	55	35	20	21	66	14.7	500	64
5	FM 1860	60	40	20	11	96	10.2	567	68
6	FM 556	60	40	20	15	100	49.6	573	69
7	FM 285	55	40	15	28	72	40.8	574	69
8	FM 935	55	40	15	9	114	34.6	637	73
9	SH 207 (Armstrong, South)	50	40	10	15	67	41.0	717	77
10	SH 207 (Armstrong, Middle)	50	40	10	25	66	38.1	717	77
11	FM 159	60	40	20	9	79	0.8	721	78
12	SH 207 (Armstrong, North)	50	40	10	19	79	57.5	818	83
13	FM 285	55	45	10	16	125	38.3	595	70
14	FM 293 (West)	70	45	25	22	99	75.9	717	77
15	FM 293 (East)	70	45	25	14	130	148.0	718	78
16	FM 46	60	45	15	16	117	57.3	1027	94
17	FM 1258 (North)	70	50	20	10	155	83.9	960	90
18	FM 1258 (South)	70	50	20	10	165	93.1	1003	93
19	FM 2300	70	55	15	18	75	57.6	820	83
20	FM 2161 (North)	70	55	15	15	64	13.4	956	90
21	FM1258	70	55	15	32	81	45.6	956	90
22	FM 2385 (East)	70	55	15	20	99	71.0	957	90
23	FM 2385 (West)	70	55	15	24	93	74.2	958	90
24	FM 2161 (South)	70	55	15	16	76	35.4	959	90
25	FM 1151 (East)	70	55	15	31	97	36.9	1143	99
26	FM 1151 (West)	70	55	15	34	103	45.9	1147	99
27	FM 1342 (West)	70	60	10	11	97	56.3	1145	99
28	FM 294	70	60	10	28	107	75.8	1147	99
29	FM 1342 (East)	70	60	10	9	96	50.6	1155	100
30	SH 207 (Carson, South)	70	60	10	11	154	63.2	1901	129
31	FM 293 (East)	70	65	5	4	135	50.5	1425	111
32	FM 293 (West)	70	65	5	4	133	1.89	1443	112
33	FM 2386 (Middle)	70	65	5	11	103	30.1	1906	129
34	FM 2386 (North)	70	65	5	7	181	164.6	1913	129
35	FM 2386 (South)	70	65	5	11	115	48.8	1916	130

The data in Table 6 show that the delineator spacing on the curves, on average, isfairly consistent with the guidelines in the MUTCD. On average, the difference was only 12 ft. However, there are some clear examples that show differences between the guidelines and field measurements of over 50 ft. Despite these differences, as Figure 3 shows, the curves all had several delineators in view throughout the curve. At night, most of the delineators should be easily seen because of the reflective aspects of the delineator.

Figure 3. Example of Curve with Delineators.

MEASURED CHEVRON SPACING

Data were collected on 15 curves with Chevrons. The distance between each Chevron was measured to identify any placement patterns in the field. In most cases, the Chevrons were spaced approximately equally. When a road intersected within a curve, a Chevron was often omitted. Table 7 shows several curve characteristics of the curves with Chevrons.

Table 7. Chevron Spacing as Measured in the Field.

		Speed Limit (mph)			Chevron Spacing (ft)			
	Curve Locations	Posted	Advis.	Change in Speed	Number of Chevrons	Average	Standard Deviation	Curve Radius
1	FM 3090 Curve 1	60	15	45	5	48	3.8	191
2	FM 185	Unknown	25		4	91	25.7	179
3	FM 974 Curve 2	60	30	30	5	93	3.5	316
4	FM 450	55	30	25	7	83	29.5	318
5	FM 852	55	30	25	8	74	29.9	472
6	FM 974 Curve 3	60	30	30	5	75	4.6	478
7	FM 1237	60	35	25	7	119	34.8	409
8	FM 1179 Curve 1	65	35	30	2	124	N/A	474
9	FM 3090 Curve 2	60	35	25	5	78	7.4	478
10	FM 1179 Curve 2	65	35	30	3	195	43.1	482
11	FM 487 Curve 2	55	40	15	6	136	32.7	409
12	FM 487 Curve 1	55	40	15	6	135	26.9	410
13	FM 2038	70	45	25	5	177	20.8	1142
14	FM 2223	70	50	20	5	188	3.8	958
15	SH 207 (Carson, North)	70	60	10	9	100	0.9	1426

The data in Table 7 shows the average spacing between Chevrons. The Texas MUTCD and the FHWA MUTCD both recommend spacing Chevrons such that there are "at least two in view, until a change in alignment eliminates the need for the signs." Therefore, there are no quantitative spacing guidelines to compare with the field data. Figures 4 and 5 show examples indicating that that the Chevron spacing on two of these curves meets the Texas MUTCD criteria of having at least two Chevrons in view (as did all of the sites visited). Researchers observed that the Chevrons were placed approximately at the point of curvature and ended at approximately the point of tangency. Researchers also discovered that there was a large difference between the Chevron spacing from district to district.

Figure 4. An Example of Chevrons along a Curve.

Figure 5. Another Example of Chevrons along a Curve.

Figure 6 was developed to illustrate the relationship that exists between the radius and the average Chevron or delineator spacing from the data collected in the field. Figure 6 shows that Chevrons are almost exclusively reserved for curves with radii of 500 ft or less while delineators appear to be used more on curves above 500 ft radii. The other point here is that there is very little correlation between the radii of horizontal curves and the spacing that is used in the field. For the delineators, the coefficient of determination for the linear model shown was only 29 percent and for Chevrons the relation was even weaker (18 percent).

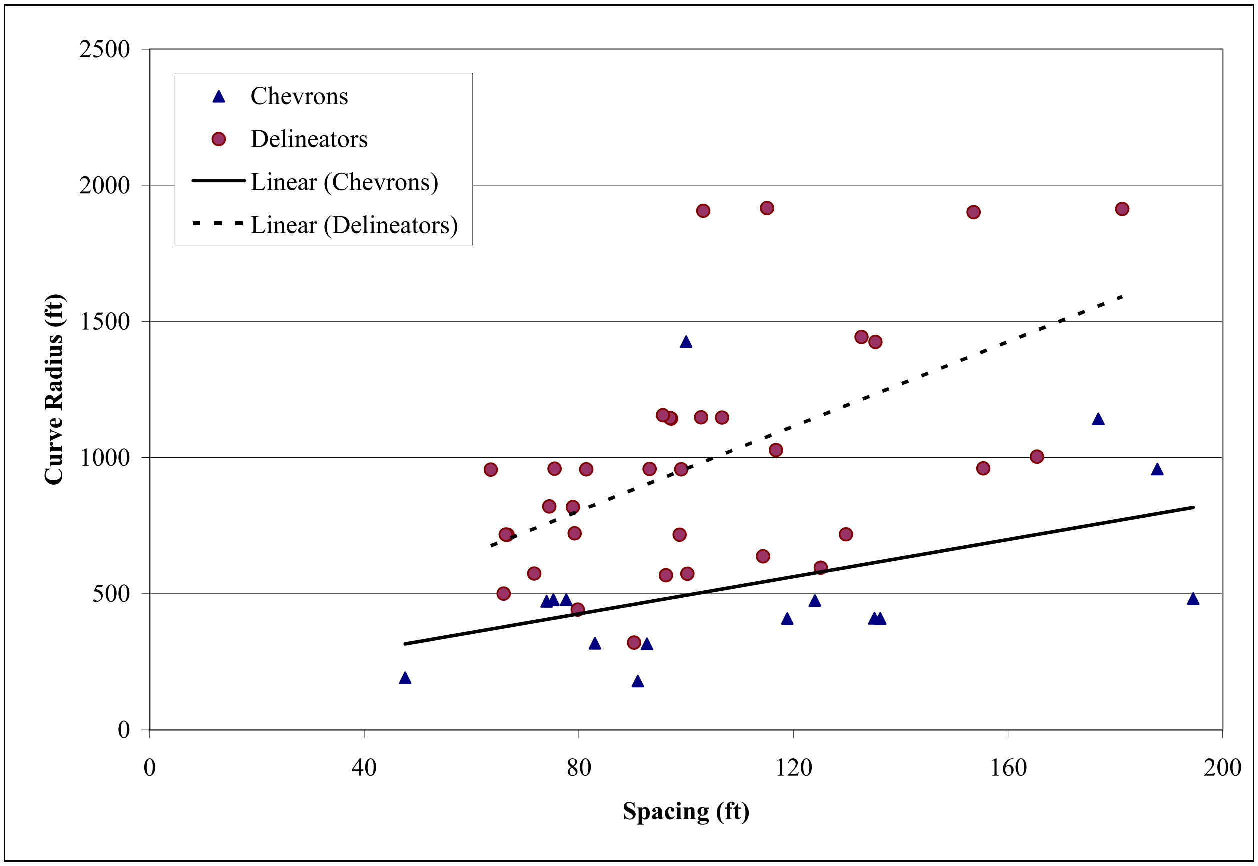

Figure 6. Chevron and Delineator Spacing versus Radius.

APPLICATION OF DELINEATORS

Table 8 shows the TxDOT guidelines for curve delineation treatment use. These guidelines can be found in the Traffic Operations Manual - Signing & Markings Volume (*28*).

Table 8. TxDOT Guidelines for Curve Treatments.

Difference Between Posted Speed and Advisory Speed (mph)	Recommended Curve Delineation Treatment
0-14	RRPMs
15-24	RRPMs and Delineators
25 and above	RRPMs and Chevrons

For curves with differences of less that 15 mph between the posted and advisory speed, TxDOT guidelines suggest the use of RRPMs for delineators, exclusively. All of the eight curves that the researchers visited with no delineators or Chevrons fell within this group.

However, 13 of the 35 curves with delineators had speed differences less than 15 mph and one of the 15 curves with Chevrons had a speed difference less than 15 mph. For curves with speed differences of 15 to 24 mph, the TxDOT guidelines suggest adding delineators to the RRPMs along the curves. Only 19 of the 35 curves visited by the researchers that had delineators fell within this criteria and three of the 15 Chevron curves fell into this criteria. On curves where the difference between the speed limit and the advisory speed is 25 mph or more, the TxDOT policy is to use Chevrons with RRPMs. Ten of the 15 curves with Chevrons fell into this group and two of the 35 curves with delineators fell into this category.

MEASURED SUPERELEVATION

Superelevation is an important feature of horizontal curves, not only in terms of countering lateral acceleration, but also when it comes to estimating radius, depending on the method of choice. For instance, ball bank indicators (BBI), which are typically used to determine advisory speed values, can also be used to estimate curve radius. However, superelevation is an important factor because it affects the ball bank indicator reading. The ball bank indicator reading (α) is the result of the combined effects of the lateral acceleration angle (θ), the superelevation angle (ϕ), and the body-roll angle (ρ). The equation for the BBI reading is: $\alpha = \theta - \phi + \rho$. This equality and its use to estimate horizontal curve radius is further explained in Chapter 5.

The superelevation was measured along a sample of the visited curves in the Bryan and Waco Districts so that an understanding of the variation could be developed as this is an important aspect to the determination of radius using ball bank indicators. The hope was to eventually develop an empirical relationship that could be used to estimate superelevation so that it would not need to be measured but would still provide a reasonably accurate value if needed.

Researchers measured the superelevation at each chevron or delineator. The superelevation was measured every 200 ft on curves that only had curve warning signs and advisory speed plates. The average superelevation was calculated on each curve by visually inspecting the superelevation profile and averaging the superelevation measurements that seemed to represent full superelevation. Figure 7 illustrates this method. The point of curvature and the point of tangency are placed in an estimated position based on the length of the curve calculated from the RI log and the distance between the third and seventh delineators.

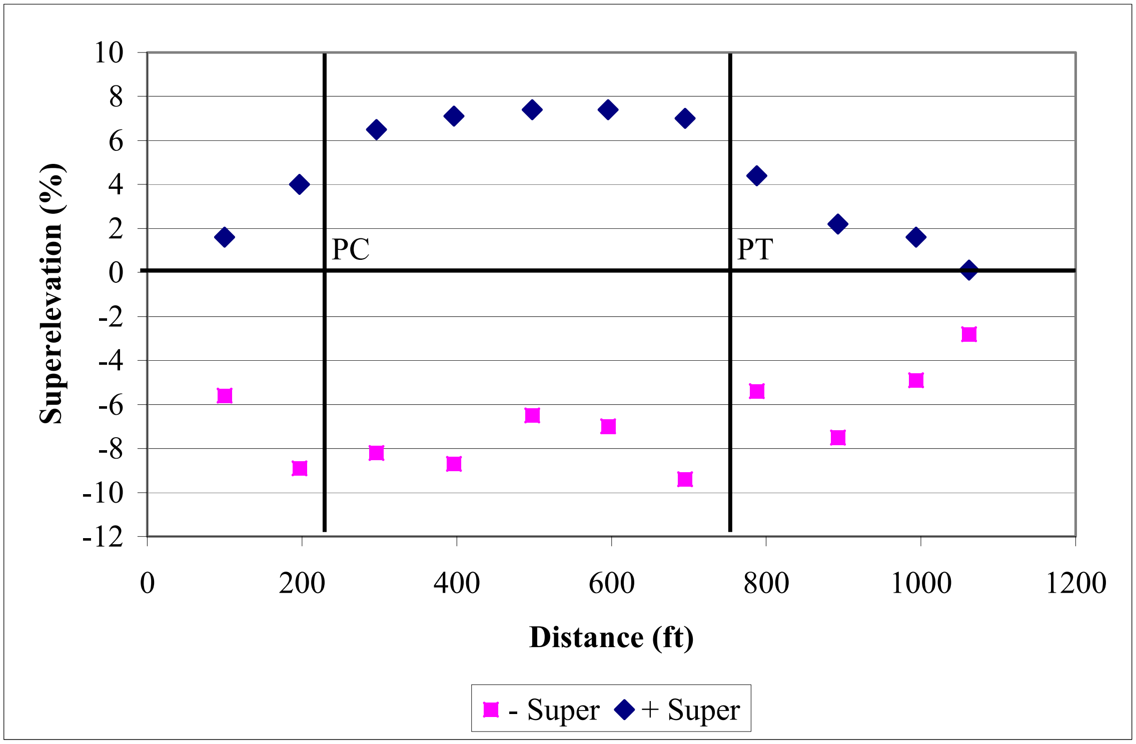

Figure 7. Superelevation within the Curve on FM 1860.

Figure 7 shows an example of how the superelevation on a curve changes as a function of distance. The positive superelevation measurements are approximately what one would expect to see. Slightly in advance of and just after the beginning of the curve, the road would be approaching full superelevation (i.e., be in superelevation run out [SRO]). At approximately the third delineator, the superelevation starts to flatten out. The third through seventh delineators seem to make up the plateau (full superelevation), and then the superelevation begins to approach normal -2 percent grade. The average superelevation calculation is an average of the delineator superelevation measurements that appear to be at full superelevation. These averages were calculated for each curve, and the data are given in Tables 9 and 10.

The negative superelevation measurements for this curve illustrate an additional point. While many superelevation profiles observed appeared to follow the expected pattern, there were also several cases where there was variation in the superelevation measurements. This result is not surprising. Uneven settlement or wear on pavements could account for this type of variation. However, this outcome makes it difficult to form statistically valid predictions for superelevation. Figures 8 and 9 present the data graphically.

Table 9. Average Superelevation on Curves in the Bryan District.

Bryan District Curves	Speed Limit			Curve Attributes			Superelevation							
	Posted Speed	Advis. Speed	Change in Speed	Length (ft)	R_{RILOG} (ft)	Delin. (Device)	Average		Standard Deviation		e_{min}		e_{max}	
							High[1]	Low[2]	High[1]	Low[2]	High[1]	Low[2]	High[1]	Low[2]
FM 1179 Curve 1	65	35	30	417	474	Chev.	Curve too short.							
FM 1179 Curve 2	65	35	30	444	482	Chev.	Curve too short.							
FM 2223	70	50	20	766	958	Chev.	2.6	-6.1	1.7	1.0	1.2	-6.9	4.5	-4.9
FM 974 Curve 2	60	30	30	496	316	Chev.	5.8	-11.0	1.4	2.3	4.3	-13.7	7.0	-9.3
FM 974 Curve 3	60	30	30	528	478	Chev.	5.5	-7.9	0.8	0.4	4.8	-8.4	6.3	-7.6
FM 2038	70	45	25	940	1142	Chev.	3.4	-6.1	1.4	2.0	2.0	-8.4	10.2	-18.3
FM 159	60	40	20	343	721	Delin.	3.9	-5.2	0.5	0.0	3.4	-5.2	4.3	-5.2
FM 3090 Curve 1	60	15	45	248	191	Chev.	8.2	-8.0	0.4	0.4	7.9	-8.4	8.7	-7.7
FM 3090 Curve 2	60	35	25	597	478	Chev.	6.5	-7.3	0.9	0.6	5.9	-7.7	7.5	-6.6
FM 46	60	45	15	950	1027	Delin.	5.0	-7.0	1.2	1.1	3.4	-5.7	6.3	-8.5

1. High side of curve, positive superelevation.
2. Low side of curve, negative superelevation.

Table 10. Average Superelevation on Curves in the Waco District.

Waco District Curves	Speed Limit			Curve Attributes			Superelevation							
	Posted Speed	Advis. Speed	Change in Speed	Length (ft)	R_{RILOG} (ft)	Delin. (Device)	Average		Standard Deviation		e_{min}		e_{max}	
							High[1]	Low[2]	High[1]	Low[2]	High[1]	Low[2]	High[1]	Low[2]
FM 487 Curve 1	55	40	15	644	410	Chev.	4.1	-6.1	0.4	1.1	3.8	-4.7	4.6	-7.1
FM 487 Curve 2	55	40	15	649	409	Chev.	6.7	-8.3	1.2	0.5	5.4	-7.7	8.1	-9.0
FM 1237	60	35	25	649	409	Chev.	5.0	-6.7	1.0	0.8	3.9	-5.4	6.2	-7.4
FM 935	55	40	15	644	410	Delin.	5.5	-8.6	0.7	1.6	4.7	-7.2	6.4	-10.8
FM 1860	60	40	20	544	567	Delin.	7.1	-8.0	0.4	1.2	6.5	-6.5	7.4	-9.4
FM 2086	60	50	10	1014	637	Ad. Spd	6.9	-9.5	0.7	1.6	5.9	-8.2	7.6	-11.6
FM 2113	60	55	5	961	956	Ad. Spd	5.2	-4.8	0.9	1.1	4.0	-3.6	5.9	-6.2
FM 2311	60	55	5	496	955	Ad. Spd	6.1	-10.2	0.1	0.6	6.0	-9.8	6.1	-10.6

1. High side of curve, positive superelevation.
2. Low side of curve, negative superelevation.

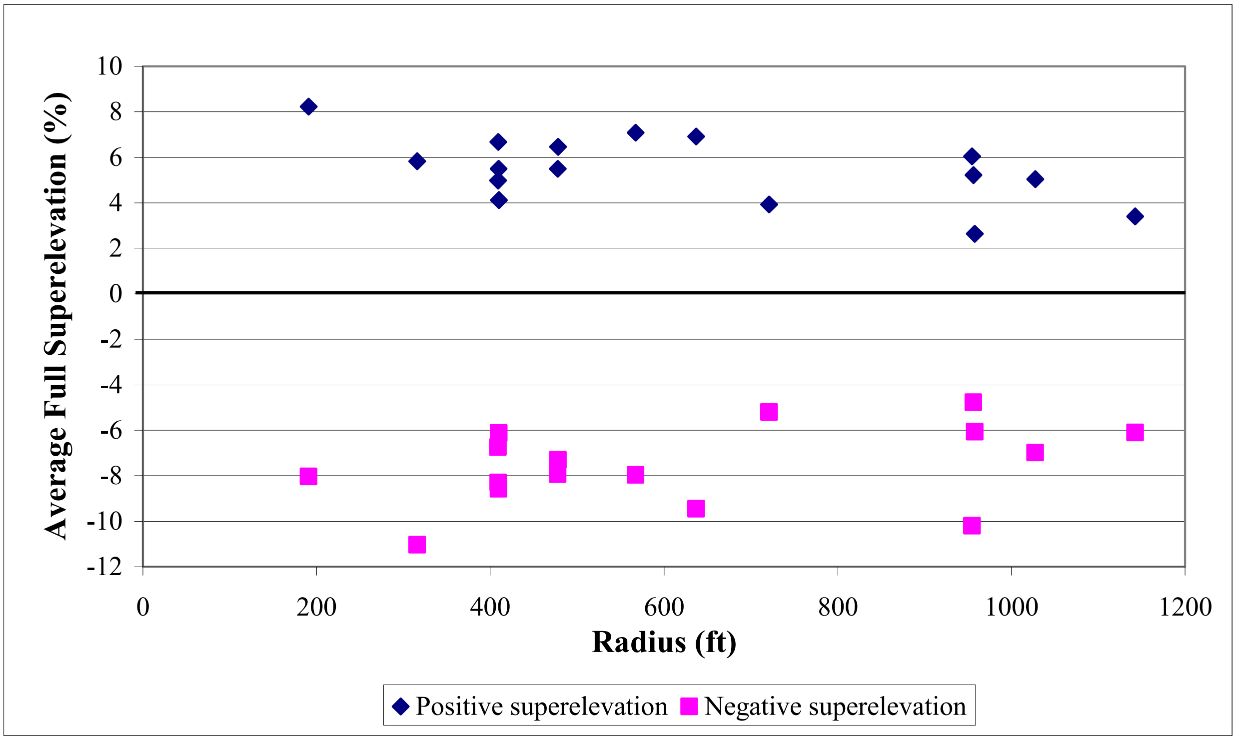

Figure 8. Radius versus the Average Superelevation.

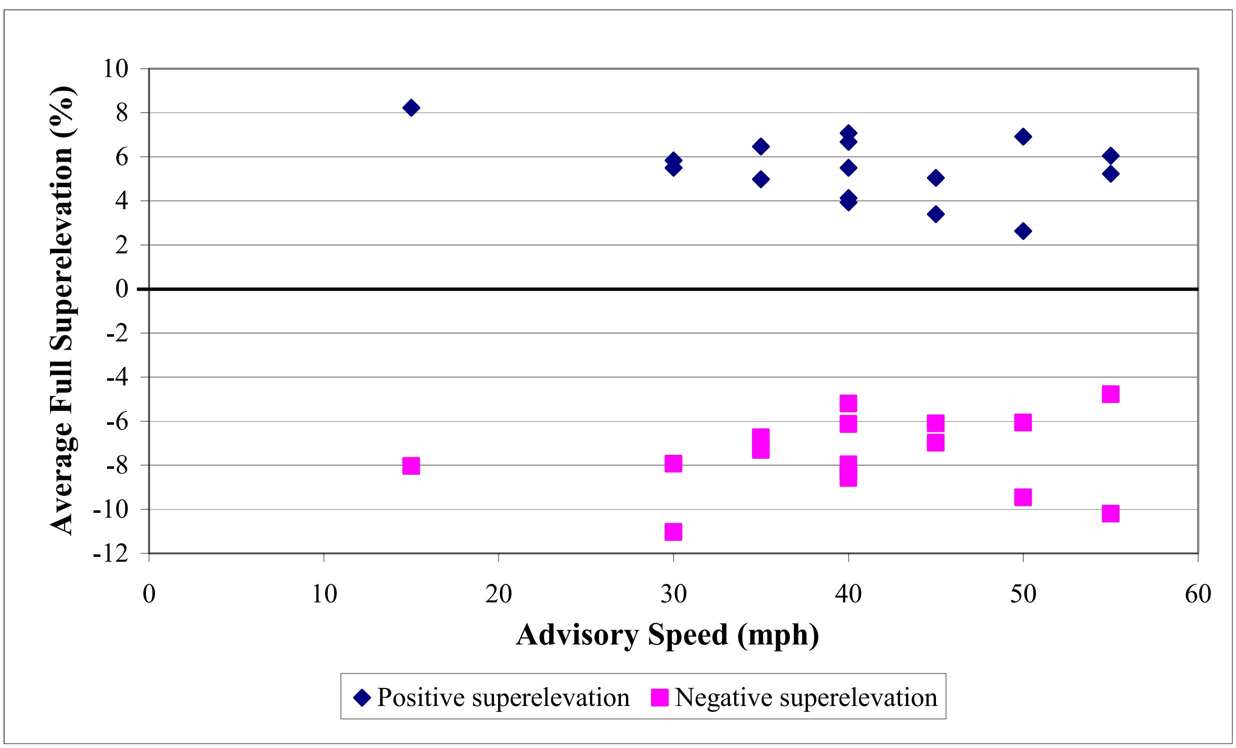

Figure 9. Advisory Speed versus the Average Superelevation.

BBI COMPARISON

For a sample of the curve visited, researchers obtained ball bank indicator measurements from three different BBI instruments simultaneously. The rational behind using three instruments was to determine if they provided consistent results. Figure 10 shows a photograph of all three instruments. The top ball bank indicator in Figure 10 was a Rieker manual ball bank indicator. It is the standard BBI issued from the TxDOT warehouse. Besides the low resolution markings on this device, another drawback is that it requires two people to set the advisory speed – one person to drive and the other to read the ball bank indicator. A solution to this problem is the electronic ball bank indicator, the bottom BBI shown in Figure 10, which has been used by some districts in TxDOT. An advantage of the electronic ball bank indicator is that it can be set to audibly alert the driver when the ball bank indicator reading exceeds 10 degrees; therefore, it only requires one person to set advisory speeds on curves. The third ball bank indicator was a Slopemeter manual ball bank indicator, the middle BBI in Figure 10. It is larger than the Rieker manual BBI, and tick marks denote every degree between -28 and +28. The larger face and additional tick marks made this instrument easier to read than the Rieker manual.

Figure 10. Ball Bank Indicators.

(from top: Rieker Manual, Slopemeter, Rieker Electronic)

The ball bank indicator data were compared to identify any differences between the three instruments. Tables 11 and 12 show the ball bank indicator data for each instrument and the linearly interpolated speed at a ball bank indicator reading of 10 degrees.

Table 11. Ball Bank Indicator Data for the Curves in the Bryan District.

Curve Location	Velocity* (mph)	Slopemeter (degrees)		BBI =10 ° (mph)		Rieker Mech. (degrees)		BBI =10 ° (mph)		Rieker Digital (degrees)		BBI =10 ° (mph)	
Brazos Co.													
FM 1179 Curve 1		**NEB**	**SWB**	**NEB**	**SWB**	**NEB**	**SWB**	**NEB**	**SWB**	**NEB**	**SWB**	**NEB**	**SWB**
	30	5	-5			5	-5			4	-6		
	35	9	-8	36	37	8	-9	37	37	7	-8	39	38
	40	12	-12			12	-12			11	-11		
	45	18	-16			18	-15			14	-15		
FM 1179 Curve 2	30	-5	5			-5	5			-5	5		
	35	-8	8	37	37	-8	9	37	37	-9	5	37	39
	40	-12	11			-12	12			-13	11		
	45	-18	17			-17	17			-14	14		
FM 2223		**NB**	**SB**	**NB**	**SB**	**NB**	**SB**	**NB**	**SB**	**NB**	**SB**	**NB**	**SB**
	45	-8	8			-7	7			-8	8		
	50	-11	10			-10	11			-10	9		
	55	-12	13	49	50	-12	13	51	50	-12	13	50	50
	60	-16	14			-15	16			-16	14		
	65	-18	17			-18	19			-20	17		
FM 974 Curve 2		**NB**	**SB**	**NB**	**SB**	**NB**	**SB**	**NB**	**SB**	**NB**	**SB**	**NB**	**SB**
	25	5	-4			5	-4			3	-3		
	30	9	-7			8	-7			7	-7		
	35	14	-11	31	32	12	-11	32	33	10	-11	33	33
	40	19	-17			18	-16			18	-16		
	45	25	-24			+20	+20			23	-23		
FM 974 Curve 3		**NB**	**SB**			**NB**	**SB**			**NB**	**SB**	**NB**	**SB**
	25	-3	5			-3	4			-2	2		
	30	-5	5			-4	5			-4	3		
	35	-6	9	39	34	-6	8	39	36	-6	8	39	37
	40	-10	14			-10	12			-9	12		
	45	-15	19			-15	18			-15	16		
FM 2038		**NB**	**SB**	**NB**	**SB**	**NB**	**SB**	**NB**	**SB**	**NB**	**SB**	**NB**	**SB**
	40	-5	6			-5	6			-5	4		
	45	-7	7			-7	7			-7	5		
	50	-8	11	52	50	-8	10	53	52	-11	9	50	52
	55	-11	12			-11	11			-13	11		
	60	-14	14			-13	13			-13	15		
FM 159		**NB**	**SB**	**NB**	**SB**	**NB**	**SB**	**NB**	**SB**	**NB**	**SB**	**NB**	**SB**
	35	-5	6			-4	5			-4	5		
	40	-7	7			-7	7			-7	7		
	45	-10	11	45	44	-9	10	47	45	-9	8	47	47
	50	-12	14			-11	13			-11	11		
	55	-15	16			-15	15			-14	14		

Table 11 Continued.

		Ball Bank Indicator Data											
Curve Location	**Velocity* (mph)**	**Slopemeter (degrees)**		**BBI =10 ° (mph)**		**Rieker Mech. (degrees)**		**BBI =10 ° (mph)**		**Rieker Digital (degrees)**		**BBI =10 ° (mph)**	
Grimes Co.													
		NB	**SB**	**NB**	**SB**	**NB**	**SB**	**NB**	**SB**	**NB**	**SB**	**NB**	**SB**
FM 3090	***15***	-4	2			-3	2			-3	2		
Curve 1	20	-7	5	22	23	-7	5	23	23	-7	3	23	25
	25	-11	10			-10	9			-11	7		
	30	-22	20			-20	20			-19	17		
		NB	**SB**	**NB**	**SB**	**NB**	**SB**	**NB**	**SB**	**NB**	**SB**	**NB**	**SB**
	25	-5	6			-5	6			-5	5		
FM 3090	30	-10	10			-10	10			-10	7		
Curve 2	***35***	-10	11	33	31	-10	10	33	32		9	35	35
	40	-15	16			-14	15			-14	13		
	45	-18	18			-18	18			-18	15		
Robertson Co.													
		NB	**SB**	**NB**	**SB**	**NB**	**SB**	**NB**	**SB**	**NB**	**SB**	**NB**	**SB**
	35	-5	6			-4	5			-4	6		
	40	-7	10			-6	9			-8	8		
FM 46	***45***	-10	13	44	41	-9	12	46	42	-9	10	45	43
	50	-14	16			-13	15			-14	13		
	55	-17	20			-15	19			-16	18		

* Bold italicized speeds represent the posted advisory speed.

Table 12. Ball Bank Indicator Data for Curves in the Waco District.

Curve Location	Velocity* (mph)	Slopemeter (degrees)		BBI =10 ° (mph)		Rieker Mech. (degrees)		BBI =10 ° (mph)		Rieker Digital (degrees)		BBI =10 ° (mph)	
FM 2086		**EB**	**WB**	**EB**	**WB**	**EB**	**WB**	**EB**	**WB**	**EB**	**WB**	**EB**	**WB**
	45	-12	13	44	40	-11	12	44	42	-14	11	42	43
	50	-15	16			-14	15			-14	13		
	55	-21	19			-19	18			-19	16		
FM 1237		**EB**	**WB**	**EB**	**WB**	**EB**	**WB**	**EB**	**WB**	**EB**	**WB**	**EB**	**WB**
	30	9	-9	31	33	10	-8	37	34	7	-9	34	33
	35	14	-10			13	-10			11	-10		
	40	17	-14			16	-13			14	-14		
	45	22	-17				-17			18	-17		
FM 1860		**NB**	**SB**	**NB**	**SB**	**NB**	**SB**	**NB**	**SB**	**NB**	**SB**	**NB**	**SB**
	35	-5	6	43	40	-4	6	44	41	-5	5	44	45
	40	-8	10			-7	9			-8	9		
	45	-11	15			-11	14			-9	13		
	50	-15	17			-15	16			-14	14		
	55	-19	23			-18	21			-18	0		
FM 2113		**EB**	**WB**	**EB**	**WB**	**EB**	**WB**	**EB**	**WB**	**EB**	**WB**	**EB**	**WB**
	50	9	-10	51	50	8	-9	53	51	7	-10	56	50
	55	13	-14			11	-13			10	-13		
	60	15	-16			14	-14			12	-15		
FM 2311		**NB**	**SB**	**NB**	**SB**	**NB**	**SB**	**NB**	**SB**	**NB**	**SB**	**NB**	**SB**
	50	9	-7	52	55	8	-7	54	57	7	-8	56	55
	55	11	-12			11	-10			10	-11		
	60	14	-12			13	-11			12	-11		
	65	17	-14			17	-13			15	-13		
FM 487 Curve 1		**WB**	**EB**	**WB**	**EB**	**WB**	**EB**	**WB**	**EB**	**WB**	**EB**	**WB**	**EB**
	35	-9	10	36	35	-9	10	37	35	-9	8	36	37
	40	-13	15			-12	14			-13	13		
	45	-16	20			-16	19			-15	17		
FM 487 Curve 2		**WB**	**EB**	**WB**	**EB**	**WB**	**EB**	**WB**	**EB**	**WB**	**EB**	**WB**	**EB**
	35	10	-8	35	37	9	-8	36	38	7	-8	38	38
	40	15	-12			13	-12			12	-12		
	45	18	-17			17	-16			16	-16		
FM 935		**WB**	**EB**	**WB**	**EB**	**WB**	**EB**	**WB**	**EB**	**WB**	**EB**	**WB**	**EB**
	35	-8	11	38	34	-7	10	39	35	-8	9	37	37
	40	-12	17			-11	16			-13	14		
	45	-16	20			-16	20			-17	17		
	50	-21	27			-20	+20			-21	25		

* Bold italicized speeds represent the posted advisory speed.

In most cases, the ball bank indicator readings are within two degrees when different instruments were compared at the same speed and in the same direction on a curve. This translates into a one to two mph difference between the interpolated speeds. There are only a few cases where there is more than a two mph difference between the interpolated speeds. The differences in the ball bank indicator readings appear random. There is no indication that one instrument is consistently higher or lower than another.

ADVISORY SPEED VALUE VERSUS BALL BANK INDICATOR

This section of the report discusses the research activities performed to determine whether the advisory speed values were appropriately set along the curves visited by the researchers. Advisory speeds are set by driving trial runs around a curve starting at five mph less than an estimated safe speed. The sequential runs are driven at five mph greater than the previous run until the ball bank indicator meets or exceeds 10 degrees. The advisory speed is then set at the speed at which the ball bank indicator reads 10 degrees or five mph less than the speed at which the ball bank indicator first exceeded 10 degrees. Ten degrees is considered a safe and comfortable ball bank indicator reading limit.

Using the three BBI devices described in the previous section, researchers collected BBI data on 10 curves in the Bryan District and eight curves in the Waco District. All BBI data were collected in a 2000 Ford Taurus. The ball bank indicator data were plotted at each speed. Tables 11 and 12 in the previous section provide a complete set of the ball bank indicator data collected, as well as the interpolated speed at a ball bank indicator reading of 10 degrees. This interpolation was computed twice for each curve, once using the data from the high side of the curve (the outside of the curve, positively superelevated) and once using the data from the low side of the curve (the inside of the curve, negatively superelevated). The interpolated speed was then used to determine if the advisory speed had been set appropriately. Researchers deemed the advisory speed appropriately set in both directions if the linearly derived speed at 10 degrees was greater than or equal to the advisory speed and less than the advisory speed plus five mph.

It could be argued that using one advisory speed per curve (i.e., one advisory speed for both directions on the curve) is what motorists expect so the advisory speed should be considered appropriately set if one direction is correct, but the advisory speed in the opposite direction is lower than the appropriate advisory speed for the first direction. Tables 13 and 14 show a list of the curves for each district and whether each curve is set appropriately on each side of the curve based on the criteria in the above paragraph. The last column shows if the advisory speed is set appropriately for both sides of the curve. The advisory speed is considered to be set appropriately for both sides of the curve if one side of the curve, based on the criteria in the previous paragraph, is set appropriately and the other side of the curve is considered to have been set low. If, however, the advisory speed for either direction was set too high, the advisory speed was considered too liberal, and thus, did not meet the "appropriately set" criteria for the column labeled "Both."

Table 13. Advisory Speed Set Appropriately for Both Directions (Curves in Bryan District)?

	Curve Location	Interpolated BBI Reading: 10 Degrees (High Side)	Appropriate Advisory Speed (High Side)?	Interpolated BBI Reading: 10 Degrees (Low Side)	Appropriate Advisory Speed (Low Side)?	Appropriate Advisory Speed (Both Sides)?
1	FM 1179 Curve 1	Advisory Speed:				35 mph
	Slopemeter	36	Yes	37	Yes	Yes
	Rieker Mech.	37	Yes	37	Yes	Yes
	Rieker Digital	39	Yes	38	Yes	Yes
2	FM 1179 Curve 2	Advisory Speed:				35 mph
	Slopemeter	37	Yes	37	Yes	Yes
	Rieker Mech.	37	Yes	37	Yes	Yes
	Rieker Digital	39	Yes	37	Yes	Yes
3	FM 2223	Advisory Speed:				50 mph
	Slopemeter	50	Yes	49	HIGH	HIGH
	Rieker Mech.	50	Yes	51	Yes	Yes
	Rieker Digital	50	Yes	50	Yes	Yes
4	FM 974 Curve 2	Advisory Speed:				30 mph
	Slopemeter	31	Yes	32	Yes	Yes
	Rieker Mech.	32	Yes	33	Yes	Yes
	Rieker Digital	33	Yes	33	Yes	Yes
5	FM 974 Curve 3	Advisory Speed:				30 mph
	Slopemeter	34	Yes	39	LOW	Yes
	Rieker Mech.	36	LOW	39	LOW	LOW
	Rieker Digital	37	LOW	39	LOW	LOW
6	FM 2038	Advisory Speed:				45 mph
	Slopemeter	50	LOW	52	LOW	LOW
	Rieker Mech.	52	LOW	53	LOW	LOW
	Rieker Digital	52	LOW	50	LOW	LOW
7	FM 159	Advisory Speed:				40 mph
	Slopemeter	44	Yes	45	LOW	Yes
	Rieker Mech.	45	LOW	47	LOW	LOW
	Rieker Digital	47	LOW	47	LOW	LOW

Table 13. Continued.

	Curve Location	Interpolated BBI Reading: 10 Degrees (High Side)	Appropriate Advisory Speed (High Side)?	Interpolated BBI Reading: 10 Degrees (Low Side)	Appropriate Advisory Speed (Low Side)?	Appropriate Advisory Speed (Both Sides)?
8	FM 3090 Curve 1	Advisory Speed:				15 mph
	Slopemeter	23	LOW	22	LOW	LOW
	Rieker Mech.	23	LOW	23	LOW	LOW
	Rieker Digital	25	LOW	23	LOW	LOW
9	FM 3090 Curve 2	Advisory Speed:				35 mph
	Slopemeter	36	Yes	38	Yes	Yes
	Rieker Mech.	37	Yes	38	Yes	Yes
	Rieker Digital	40	LOW	37	Yes	Yes
10	FM 46	Advisory Speed:				45 mph
	Slopemeter	41	HIGH	49	Yes	HIGH
	Rieker Mech.	42	HIGH	51	LOW	HIGH
	Rieker Digital	43	HIGH	50	LOW	HIGH

Table 14. Advisory Speed Set Appropriately for Both Directions (Curves in Waco District)?

	Curve Location	Interpolated BBI Reading: 10 Degrees (High Side)	Appropriate Advisory Speed (High Side)?	Interpolated BBI Reading: 10 Degrees (Low Side)	Appropriate Advisory Speed (Low Side)?	Appropriate Advisory Speed (Both Sides)?
1	FM 487 Curve 1	Advisory Speed:				40 mph
	Slopemeter	34	HIGH	37	HIGH	HIGH
	Rieker Manual	34	HIGH	38	HIGH	HIGH
	Rieker Digital	42	Yes	38	HIGH	HIGH
2	FM 487 Curve 2	Advisory Speed:				40 mph
	Slopemeter	35	HIGH	37	HIGH	HIGH
	Rieker Manual	36	HIGH	38	HIGH	HIGH
	Rieker Digital	37	HIGH	38	HIGH	HIGH
3	FM 1237	Advisory Speed:				35 mph
	Slopemeter	31	HIGH	33	HIGH	HIGH
	Rieker Manual	30	HIGH	34	HIGH	HIGH
	Rieker Digital	34	HIGH	33	HIGH	HIGH
4	FM 935	Advisory Speed:				40 mph
	Slopemeter	34	HIGH	38	HIGH	HIGH
	Rieker Manual	35	HIGH	39	HIGH	HIGH
	Rieker Digital	37	HIGH	37	HIGH	HIGH
5	FM 2086	Advisory Speed:				50 mph
	Slopemeter	40	HIGH	44	HIGH	HIGH
	Rieker Manual	42	HIGH	44	HIGH	HIGH
	Rieker Digital	43	HIGH	42	HIGH	HIGH
6	FM 2113	Advisory Speed:				55 mph
	Slopemeter	51	HIGH	50	HIGH	HIGH
	Rieker Manual	53	HIGH	51	HIGH	HIGH
	Rieker Digital	56	Yes	50	HIGH	HIGH
7	FM 2311	Advisory Speed:				55 mph
	Slopemeter	50	HIGH	60	Yes	HIGH
	Rieker Manual	50	HIGH	60	LOW	HIGH
	Rieker Digital	54	HIGH	60	Yes	HIGH
8	FM 1860	Advisory Speed:				40 mph
	Slopemeter	40	Yes	43	Yes	Yes
	Rieker Manual	41	Yes	44	Yes	Yes
	Rieker Digital	42	Yes	44	Yes	Yes

Out of the total number of curves examined, researchers found that about 29 percent set appropriately by all three ball bank indicators. Researchers also found that approximately 47 percent of the curves examined were considered to be set appropriately by at least one ball bank indicator.

Some curves were set appropriately in one direction, but not in the other direction. This could be caused by several factors including uneven pavement surfaces on one side of the road, or inconsistent path driven by the researcher. A third reason for differing interpolated advisory speeds is the high side of the curve has a larger radius than the low side of the curve; thus, the low side of the curve is a tighter curve, and a lower advisory speed could be expected. However, a close comparison between the interpolated advisory speed on the high side of the curve and the interpolated advisory speed on the low side of the curve indicates the low side of the curve has a higher interpolated advisory speed for several different curves. FM 2311 and FM 935 are both examples of this result (see Table 12). Since this result was counterintuitive, researchers examined the superelevation characteristics for these curves. Tables 15 and 16 list the average superelevation on the high side and the low side for each curve. These tables also list the absolute value of the difference between the high side superelevation and the low side superelevation. In some cases, for example FM 2311 and FM 935, the large difference between the high side superelevation and the low side superelevation is likely the reason the interpolated advisory speed on the low side of the curve is higher than the interpolated advisory speed on the high side of the curve.

Table 15. Difference between Average Superelevation on the High Side and the Low Side of the Curve for Curves in the Bryan District.

Curve Location Bryan District	Speed Limit (mph)			Curve Attributes			Superelevation (%)		
	Posted	Advis.	Change in Speed	Length (ft)	R_{RILOG} (ft)	Delin. (device)	Average High	Average Low	Difference
FM 1179 Curve 1	65	35	30	417	474	Chev.	2.0	-4.6	2.6
FM 1179 Curve 2	65	35	30	444	482	Chev.	3.2	-5.3	2.1
FM 2223	70	50	20	766	958	Chev.	2.6	-6.1	3.4
FM 974 Curve 2	60	30	30	496	316	Chev.	5.8	-11.0	5.2
FM 974 Curve 3	60	30	30	528	478	Chev.	5.5	-7.9	2.4
FM 2038	70	45	25	940	1142	Chev.	3.4	-6.1	2.7
FM 159	60	40	20	343	721	Delin.	3.9	-5.2	1.3
FM 3090 Curve 1	60	15	45	248	191	Chev.	8.2	-8.0	0.2
FM 3090 Curve 2	60	35	25	597	478	Chev.	6.5	-7.3	0.8
FM 46	60	45	15	950	1027	Delin.	5.0	-7.0	1.9

Table 16. Difference between Average Superelevation on the High Side and the Low Side of the Curve for Curves in the Waco District.

Curve Location Waco District	Speed Limit (mph)			Curve Attributes			Superelevation (%)		
	Posted	Advis.	Change in Speed	Length (ft)	R_{RILOG} (ft)	Delin. (device)	Average High	Average Low	Difference
FM 487 Curve 1	55	40	15	644	410	Chev.	4.1	-6.1	2.0
FM 487 Curve 2	55	40	15	649	409	Chev.	6.7	-8.3	1.6
FM 1237	60	35	25	649	409	Chev.	5.0	-6.7	1.8
FM 935	55	40	15	644	410	Delin.	5.5	-8.6	3.1
FM 1860	60	40	20	544	567	Delin.	7.1	-8.0	0.9
FM 2086	60	50	10	1014	637	Ad. Spd	6.9	-9.5	2.5
FM 2113	60	55	5	961	956	Ad. Spd	5.2	-4.8	0.4
FM 2311	60	55	5	496	955	Ad. Spd	6.1	-10.2	4.2

It should also be noted from Tables 15 and 16 that large differences between the superelevation of the high and low side of the curve do not always have as obvious an effect on the advisory speed as it does on FM 2311. For example, the difference between the high and low side superelevation on curve 2 on FM 974 is 5.2 percent; however, the difference between the advisory speeds for the high and low side of the curve was at most 1 mph (depending on which ball bank indicator instrument was used). In many cases, only a 1 to 2 mph difference was noted when the absolute value of the superelevation on the low side of the curve was greater than the superelevation on the high side of the curve.

CHAPTER 5: PILOT STUDIES

This chapter presents the methods used to estimate radius. Early in the project, the researchers brainstormed to identify methods that could be used to estimate horizontal curve radius. The criteria that had to be satisfied in order for the researchers to consider the radius estimating method were only that they had to be safe and easy to implement, and preferably low cost. Table 17 shows the initial list of potential methods with brief descriptions.

Table 17. Preliminary Methods to Estimate Curve Radius.

Method	Brief Description
Ball Bank Indicator 1	Use theoretical curve dynamic relationships to estimate the radius using speed and measured ball bank indicator readings. Assume superelevation and neglect bodyroll.
Ball Bank Indicator 2	Use an empirical relationship between speed and measured ball bank indicator readings to estimate radius. Assume superelevation and account for bodyroll in derived empirical relationship.
Lateral Acceleration 1	Use theoretical curve dynamic relationships to estimate the radius using speed and measured lateral acceleration. Assume superelevation and neglect bodyroll.
Lateral Acceleration 2	Same as Lateral Acceleration #1 method except this method includes a measurement of bodyroll and superelevation.
Advisory Speed Value	Derive an empirical relationship between advisory speed value and radius.
Yaw Rate Transducer	Measure deflection angle of curve using a yaw rate transducer and simultaneously measure length of curve with a distance measuring device. Calculate radius.
Compass	Same as Yaw Rate Transducer method except this method is done with a compass.
Chord Length	Stretch a known length of chord along an arc concentric to the radius. Measure the offset at the midpoint. Calculate radius.
GPS	Use data that can be acquired from Global Positioning System (GPS) while driving a curve to determine radius.

Although the first five methods listed in Table 17 depend on the superelevation and bodyroll of the vehicle, they do not require personnel to get out of the vehicle. Therefore, safety is not compromised using these methods to estimate radius. In fact, the only two methods that require field personnel to leave their vehicle were the Compass and Chord Length methods. Consequently, because of safety, these methods were eliminated from further consideration. The remaining methods were explored further to determine their feasibility with respect to TxDOT's needs.

The remainder of this chapter describes each of the curve estimating methods that were tested. Specifically, the methods for estimating the radius are described as well as the results that were obtained. It should be noted that the curves that were tested were the same ones as those used to determine the state-of-the-practice.

A final section of this chapter compares the field spacing as measured and described in the previous chapter to the theoretical spacing if the methods explored in this chapter would have been implemented. This comparison demonstrates the potential usefulness of these methods compared to the status quo.

BALL BANK INDICATOR METHODS

The ball bank indicator is the most commonly used device to select a posted advisory speed on existing horizontal curves. In a recent survey, 88 percent of the states, cities, and counties that responded indicated that they use the ball bank indicator to set safe speeds (*29*). Therefore, if a method could be determined to estimate radius using the ball bank indicator, no additional equipment purchase would be needed. Combined with its ease of use, it was initially thought that a curve estimating radius method using a ball bank indicator had a lot of promise.

The ball bank indicator is a curved level that when properly mounted in a vehicle measures the combined eaffects of the body roll angle (ρ), lateral acceleration angle (θ), and superelevation angle (ϕ). The relationship between the ball bank indicator reading and the aforementioned angles can be expressed by the following equation:

Equation 1: $$\alpha = \theta - \phi + \rho$$

where:

α = ball bank indicator reading, (degrees)
ρ = body roll angle, (degrees)
ϕ = superelevation angle, (degrees)
θ = lateral acceleration angle. (degrees)

In order to understand how the ball bank indicator reading can be used to estimate radius, it is important to review the fundamentals of horizontal curve design.

Horizontal Curve Design

As a particle moves in a circular path of constant radius with constant speed, the acceleration is directed toward the center of the circle, perpendicular to the instantaneous velocity. This is called centripetal acceleration and is equivalent to the instantaneous normal acceleration, or:

Equation 2: $$a_{\perp} = \frac{v^2}{R}$$

where:

a_z = centripetal acceleration, (m/s^2)

v = speed of vehicle, (m/s)

R = radius of horizontal curve, (m)

According to Newton's second law (ΣF=ma), the acceleration must be caused by a force also directed toward the center of the curve. The net radial force on a particle of mass (m) traveling in uniform circular motion is:

Equation 3: $$F = ma_{\perp} = m\frac{v^2}{R}$$

where:

F = net radial force, (N=kg·m/s^2)

m = mass of vehicle, (kg)

The centripetal acceleration shown in Equation 2 is referred to as lateral acceleration in highway engineering. Lateral acceleration is generated as a vehicle negotiates a horizontal curve with constant radius and is counterbalanced by the vehicle weight component related to the roadway superelevation and/or the side friction developed between the tires and pavement surface.

The point mass model is used by the *Green Book* (*30*) to determine the minimum radius of a curve for a specified superelevation so that the lateral acceleration is kept within comfortable limits. On a superelevated curve, the superelevation offsets a portion of the lateral acceleration, such that:

Equation 4: $$a_{net} = \frac{v^2}{127\,R} - \frac{e}{100}$$

where:

a_{net} = unbalanced lateral acceleration in g's, (9.807 m/s^2)

e = superelevation in percent, (m/m)

The unbalanced portion of lateral acceleration of the vehicle is a measure of the forces acting on the vehicle that tend to make it skid off the road (*31*). Using Newton's second law, the point mass model used to represent vehicle operation on a horizontal curve is the following:

Equation 5:

$$\frac{e}{100} + f = \frac{v^2}{127\,R}$$

The left-hand side of Equation 4 represents the amount of lateral acceleration supplied while the right-hand side is the demanded lateral acceleration. In other words, the side friction demand of the vehicle is mathematically equivalent to the unbalanced lateral acceleration (a_{net}). The tendency of the vehicle to skid must be resisted by tire/pavement friction. The vehicle will skid off the road unless the tire/pavement friction coefficient exceeds the side frictional demand. The side friction factor, f, of the supplied lateral acceleration is based on perceived vehicle occupants' tolerable limits and is far below the threshold of tipping or sliding out for a typical passenger car.

Therefore, if it were not for the body-roll angle, the ball bank indicator reading would be a direct measure of lateral acceleration. In other words, α from the ball bank indicator would be equal to the side friction factor f used in the point mass equation of the *Green Book.*

A criticism of the ball bank indicator's usage for setting safe speeds on existing curves is the influence of the test vehicle's body-roll. A comprehensive study of the ball bank indicator (*9*) concluded that "The extreme effect of the body-roll of various model and makes of cars is only about 1 degree in the ball bank angle and provides a difference of about 2 km/h (3 mph) in speed." The report recommended neglecting the body-roll influence as long as "The observers understand the effect of body-roll and make due allowance for it in case cars with extreme values are used for the driving tests." However, according to the *Green Book*, "A correction must be made for that portion of force taken up in the small body-roll." Therefore, due to the uncertainty of the influence of body-roll, this research also investigated the significance of body-roll and how it affects the reading of the ball bank indicator.

Ball Bank Indicator Method 1

This method is referred to as the physics ball bank indicator method from hereon after because it is based on the laws of physics. This method neglects the body-roll angle, and, if deemed promising, would require some sort of empirically derived assumption for the superelevation component.

Because of the dismissal of body-roll, the ball bank indictor reading, α, equals the side friction factor, f, of the point mass model used in highway design to determine horizontal curve radius. If the speed of the vehicle and the ball bank indicator value are both simultaneously known, then the radius can be calculated using the following relationship:

Equation 6:
$$R = \frac{V^2}{15(e + f)}$$

where:

R = radius, (ft)

e = superelevation, (ft/ft) and

f = side friction factor (ft/ft) = ball bank indicator reading (α).

It is important to note that this method relies on the superelevation. For the pilot testing of the method, the researchers measured the superelevation. If this method proved promising and worth fully developing, the researchers anticipated the need to develop an empirical relationship to minimize the error associated with guessing the superelevation. Initial, but unexplored, thoughts were setting the superelevation to a single value such as an average value or developing a relationship between superelevation and strongly correlated factors such as highway type, speed limit, or advisory speed value.

Justification for neglecting the body-roll angle is provided by Moyer and Berry (*32*). They recommended neglecting body-roll because "the extreme effect of body-roll of various models and makes of cars is only about 1 degree in the ball bank indicator." It should be noted that this conclusion was made in the 1940s when vehicles had much looser suspensions than today's typical vehicles. More recent justification was provided in 1999 by Carlson and Mason (*31*). These researchers concluded that ". . . the results indicate that body-roll does not significantly influence the readings provided by the ball bank indicator." Because all the data for the project reported in this report were collected using one type of vehicle, a 1998 Ford Taurus from the TTI fleet, there is little reason to suspect that body-roll would play a significant part in the errors.

Researchers collected ball bank indicator data using all three different types of ball bank indicators described in Chapter 4. The ball bank indicators were mounted to a wooden board and secured in the front seat between the driver and passenger seats. One person sat in the back seat and recorded the three ball bank indicators as the driver traversed each test curve. The curve was driven at the advisory speed, and four more times: at the advisory speed minus 5 mph, plus 5 mph, plus 10 mph, and plus 15 mph (only if the driver felt safe). The estimated radius was calculated using the data collected at each speed and for each direction of travel. Thus, the estimated radius at each speed were summed and averaged for each direction. The final average is an average of the radii from both directions at all of the data collection speeds. Table 18 is included to as an example of the calculations described.

Table 18. Radius Estimation of Calculations for Curve 1 on FM 1179.

Velocity	BBI readings		Average Superelevation		Radius	
(mph)	(degrees)		(percent)		(feet)	
	Slopemeter					
	NB	SB	NB	SB	NB	SB
30	5	-5	2.0	-4.6	642.9	371.1
35	9	-8	2.0	-4.6	482.3	373.4
40	12	-12	2.0	-4.6	471.3	361.9
45	18	-16	2.0	-4.6	396.7	364.2
Directional Average:					498.3	367.6
Final Average:					433.0	

In Table 18, the radius is calculated using Equation 6. Body-roll is ignored for the physics method, so the side friction factor is assumed to be the ball bank indicator reading converted into radians. Average superelevation is also converted to radians for radius estimates. The dashed line box represents the radius estimates included in the final average calculation. The solid line boxes represent the radius estimates that are included in the directional average calculation. The measure of effectiveness was how close the radius estimates came to the assumed actual radius. The assumed actual radius was the radius calculated from the information given in the RI log. The percent difference between the average radius and RI log radius was calculated for each curve.

Ball Bank Indicator Method 2

The second ball bank indicator method for estimating radius uses an equation developed by Carlson and Mason (*31*). This method will be referred to as the empirical ball bank indicator method because it was derived from actual field measurements of lateral acceleration, ball bank indicator readings, superelevation, and body-roll. It was hypothesized that because this ball bank indicator method was based on empirical data that it might yield more accurate results than the physics method, which relies entirely on the theoretical laws of physics. The derived relationship relates the ball bank indicator reading to the unbalanced lateral acceleration or the side friction factor.

Equation 7: $$\alpha = 1.115 + 52.627 \times (ULA)$$

where:

α = ball bank indicator reading (degrees)

$ULA = f$ = unbalanced lateral acceleration = side friction factor (g).

The radius for the empirical method was calculated similar to the radius estimate from the physics method. The same equation was used to estimate the radius, Equation 6, however, the empirical method used the equation developed by Carlson and Mason (31) to estimate the side friction factor (Equation 7) instead of ignoring body-roll. The effectiveness of the empirical ball bank indicator method was analyzed the same as the measure of effectiveness of the physics method. Table 19 shows the percent error calculated for each curve surveyed in the Bryan District using both ball bank indicator methods for estimating radius, and Table 20 shows the same for the curves surveyed in the Waco District.

Table 19. Radius Calculations Using the Physics and the Empirical Methods for Curves in Bryan District.

Road/ Description	Curve Character.		Radius Given on RI Log	Method	Average Radius Physics	% Diff.	Radius Empirical	% Diff.
	L	Δ						
FM 1179 Curve 1 Northernmost Curve	417.1	50.4	474.5	Slopemeter	452.8	4.6	433.0	8.7
				Rieker Mech.	457.3	3.6	439.3	7.4
				Rieker Digital	499.2	5.2	466.0	1.8
FM 1179 Curve 2 Southernmost Curve	443.5	52.7	481.9	Slopemeter	436.5	9.4	418.9	13.1
				Rieker Mech.	429.0	11.0	409.5	15.0
				Rieker Digital	475.6	1.3	466.0	3.3
FM 2223	765.6	45.8	957.8	Slopemeter	773.7	19.2	734.4	23.3
				Rieker Mech.	773.2	19.3	731.1	23.7
				Rieker Digital	780.1	18.6	743.5	22.4
FM 974 Curve 2	496.3	90.1	315.8	Slopemeter	266.0	15.8	253.6	19.7
				Rieker Mech.	277.0	12.3	266.8	15.5
				Rieker Digital	296.4	6.1	289.1	8.5
FM 974 Curve 3	528.0	63.3	477.7	Slopemeter	374.3	21.6	355.5	25.6
				Rieker Mech.	392.5	17.8	375.4	21.4
				Rieker Digital	431.0	9.8	425.2	11.0
FM 2038	939.8	47.1	1142.5	Slopemeter	793.4	30.6	753.9	34.0
				Rieker Mech.	816.5	28.5	778.4	31.9
				Rieker Digital	836.8	26.8	821.8	28.1
FM 3090 Curve 1	248.2	30.0	191.0	Slopemeter	137.7	27.9	134.0	29.9
				Rieker Mech.	108.0	43.4	139.2	27.1
				Rieker Digital	145.1	24.0	155.7	18.5

Table 19 Continued.

Road/ Description	Curve Character.		Radius Given on RI Log	Method	Average Radius Physics	% Diff.	Radius Empirical	% Diff.
	L	Δ						
FM 3090 Curve 2	596.6	71.5	478.1					
				Slopemeter	391.4	18.1	369.2	22.8
				Rieker Mech.	398.8	16.6	376.7	21.2
				Rieker Digital	420.9	12.0	403.7	15.6
FM 46	950.4	53.0	1027.4					
				Slopemeter	520.8	49.3	488.7	52.4
				Rieker Mech.	565.1	45.0	531.5	48.3
				Rieker Digital	564.1	45.1	534.1	48.0
FM 159	343.2	27.3	721.2					
				Slopemeter	610.7	15.3	576.2	20.1
				Rieker Mech.	648.8	10.0	614.1	14.9
				Rieker Digital	678.5	5.9	646.7	10.3

Table 20. Radius Calculations Using the Physics and the Empirical Methods for Curves in Waco District.

Road/ Description	Curve Character. L	Curve Character. Δ	Radius Given on RI Log	Method	Average Radius Physics	% Diff.	Radius Empirical	% Diff.
FM 487 Curve 1	644.2	90.1	409.9	Slopemeter	368.3	10.1	344.6	15.9
				Rieker Mech.	381.3	7.0	355.2	13.3
				Rieker Digital	408.4	0.4	378.8	7.6
FM 487 Curve 2	649.4	91.0	409.1	Slopemeter	357.6	12.6	335.9	17.9
				Rieker Mech.	368.5	9.9	348.4	14.8
				Rieker Digital	382.8	6.4	365.4	10.7
FM 1237	649.4	91.0	409.1	Slopemeter	326.1	20.3	292.0	28.6
				Rieker Mech.	324.0	20.8	303.0	25.9
				Rieker Digital	352.3	13.9	324.3	20.7
FM 935	644.2	90.1	409.6	Slopemeter	344.3	15.9	319.7	21.9
				Rieker Mech.	359.5	12.2	336.4	17.9
				Rieker Digital	363.6	11.2	340.1	17.0
FM 1860	543.8	54.9	567.4	Slopemeter	464.1	18.2	435.3	23.3
				Rieker Mech.	487.4	14.1	457.2	19.4
				Rieker Digital	503.8	11.2	477.7	15.8

Table 20 Continued.

Road/ Description	Curve Character. L	Curve Character. Δ	Radius Given on	Method	Average Radius	% Diff.	Radius Empirical	% Diff.
FM 2086	1013.8	91.2	637.1	Slopemeter	482.3	24.3	437.4	31.3
				Rieker Mech.	494.4	22.4	463.6	27.2
				Rieker Digital	531.7	16.5	485.8	23.8
FM 2113	961.0	57.6	956.4	Slopemeter	743.0	22.3	699.7	26.8
				Rieker Mech.	812.3	15.1	767.9	19.7
				Rieker Digital	837.0	12.5	802.4	16.1
FM 2311	496.3	29.8	954.8	Slopemeter	764.3	20.0	724.7	24.1
				Rieker Mech.	793.2	16.9	759.6	20.4
				Rieker Digital	819.2	14.2	788.6	17.4

A cumulative percent error was then calculated for each ball bank indicator used for both the empirical and the physics radius calculation methods. Table 21 gives the cumulative percent error for both the physics method and the empirical method of estimating the radius for each BBI instrument used.

Table 21. Percent Differences between Radius Estimates and Actual Radius Using Ball Bank Indicator Methods and Instruments.

	Physics			Empirical		
	Slope-meter	Rieker Mech.	Rieker Digital	Slope-meter	Rieker Mech.	Rieker Digital
Average Percent Difference	19.8	18.1	13.4	24.4	21.4	16.5

The percent difference between the estimated radius with a specific ball bank indicator and the RI log radius was calculated, and the percent differences on all the curves were averaged to obtain the average percent difference for each ball bank indicator. Table 21 shows that the average percent difference for the radius estimate obtained using the physics method and the Rieker digital ball bank indicator produced estimates that were closest to the radius information found in the RI log. The physics method produced closer estimates than the empirical method for each type of ball bank indicator.

From a practical standpoint, the goal of this project is to develop an easier way to space Chevrons and delineators so that the spacing used conforms to the Texas MUTCD spacing recommendations. Thus, the equation given in Table 3D-1 of the Texas MUTCD: $3*(R-50)^{1/2}$ was used to calculate the recommended spacing for the actual radius and the recommended spacing for the expected radius. Tables 22-27 show the results of this analysis. Table 28 summarizes the average spacing error for each method and instrument. Each graph shows the results from one ball bank indicator method (either physics or empirical) and one instrument (Slopemeter, Rieker mechanical, or Rieker digital). The data in these tables show that the error between the spacing recommended at the estimated radius and the spacing recommended at the actual radius is less than the error between the estimated radius and the actual radius. Thus, medium differences between the radius estimate and actual radius often become small differences between the spacing recommended at the estimated radius and the spacing recommended at the actual radius.

Table 22. Spacing Percent Error Using Physics BBI Method (Slopemeter).

Road/Description	Actual Radius (ft)	TxMUTCD Recommended Spacing (ft)	Average Radius Physics (ft)	TxMUTCD Recommended Spacing (ft)	Percent Difference (%)
FM 3090 Curve 1	191	36	138	28	21.2
FM 974 Curve 2	316	49	266	44	9.9
FM 974 Curve 3	478	62	374	54	12.9
FM 1237	409	57	313	49	14.4
FM 1179 Curve 1	474	62	453	60	2.6
FM 3090 Curve 2	478	62	391	55	10.7
FM 1179 Curve 2	482	62	437	59	5.4
FM 487 Curve 2	409	57	358	53	7.5
FM 935	410	57	344	51	9.7
FM 487 Curve 1	410	57	368	54	5.9
FM 1860	567	68	464	61	10.5
FM 159	721	78	611	71	8.6
FM 46	1027	94	521	65	30.6
FM 2038	1142	99	793	82	17.5
FM 2086	637	73	465	61	16.0
FM 2223	958	90	774	81	10.7
FM 2311	955	90	790	82	9.5
FM 2113	956	90	743	79	12.6

Table 23. Spacing Percent Error Using Empirical BBI Method (Slopemeter).

Road/Description	Actual Radius (ft)	TxMUTCD Recommended Spacing (ft)	Radius Empirical (ft)	TxMUTCD Recommended Spacing (ft)	Percent Difference (%)
FM 3090 Curve 1	191	36	134	27	22.8
FM 974 Curve 2	316	49	254	43	12.5
FM 974 Curve 3	478	62	355	52	15.5
FM 1237	409	57	292	47	17.9
FM 1179 Curve 1	474	62	433	59	5.0
FM 3090 Curve 2	478	62	369	54	13.7
FM 1179 Curve 2	482	62	419	58	7.6
FM 487 Curve 2	409	57	336	51	10.8
FM 935	410	57	320	49	13.4
FM 487 Curve 1	410	57	345	51	9.5
FM 1860	567	68	435	59	13.7
FM 159	721	78	576	69	11.5
FM 46	1027	94	489	63	33.0
FM 2038	1142	99	754	80	19.7
FM 2086	637	73	437	59	18.8
FM 2223	958	90	734	78	13.2
FM 2311	955	90	732	78	13.2
FM 2113	956	90	700	76	15.3

Table 24. Spacing Percent Error Using Physics BBI Method (Rieker Mechanical).

Road/Description	Actual Radius (ft)	TxMUTCD Recommended Spacing (ft)	Average Radius Physics (ft)	TxMUTCD Recommended Spacing (ft)	Percent Difference (%)
FM 3090 Curve 1	191	36	108	23	35.9
FM 974 Curve 2	316	49	277	45	7.6
FM 974 Curve 3	478	62	392	56	10.5
FM 1237	409	57	313	49	14.4
FM 1179 Curve 1	474	62	457	61	2.0
FM 3090 Curve 2	478	62	399	56	9.7
FM 1179 Curve 2	482	62	429	58	6.3
FM 487 Curve 2	409	57	369	54	5.8
FM 935	410	57	359	53	7.2
FM 487 Curve 1	410	57	381	55	4.0
FM 1860	567	68	487	63	8.1
FM 159	721	78	649	73	5.5
FM 46	1027	94	565	68	27.4
FM 2038	1142	99	816	83	16.2
FM 2086	637	73	492	63	13.2
FM 2223	958	90	773	81	10.7
FM 2311	955	90	795	82	9.2
FM 2113	956	90	812	83	8.3

Table 25. Spacing Percent Error Using Empirical BBI Method (Rieker Mechanical).

Road/Description	Actual Radius (ft)	TxMUTCD Recommended Spacing (ft)	Radius Empirical (ft)	TxMUTCD Recommended Spacing (ft)	Percent Difference (%)
FM 3090 Curve 1	191	36	139	28	20.5
FM 974 Curve 2	316	49	267	44	9.7
FM 974 Curve 3	478	62	375	54	12.8
FM 1237	409	57	297	47	17.0
FM 1179 Curve 1	474	62	439	59	4.2
FM 3090 Curve 2	478	62	377	54	12.6
FM 1179 Curve 2	482	62	409	57	8.8
FM 487 Curve 2	409	57	348	52	8.8
FM 935	410	57	336	51	10.8
FM 487 Curve 1	410	57	355	52	7.9
FM 1860	567	68	457	61	11.3
FM 159	721	78	614	71	8.3
FM 46	1027	94	532	66	29.8
FM 2038	1142	99	778	81	18.3
FM 2086	637	73	464	61	16.1
FM 2223	958	90	731	78	13.4
FM 2311	955	90	739	79	12.8
FM 2113	956	90	768	80	11.0

Table 26. Spacing Percent Error Using Physics BBI Method (Rieker Digital).

Road/Description	Actual Radius (ft)	TxMUTCD Recommended Spacing (ft)	Average Radius Physics (ft)	TxMUTCD Recommended Spacing (ft)	Percent Difference (%)
FM 3090 Curve 1	191	36	145	29	17.9
FM 974 Curve 2	316	49	296	47	3.7
FM 974 Curve 3	478	62	431	59	5.6
FM 1237	409	57	342	51	9.8
FM 1179 Curve 1	474	62	499	64	2.9
FM 3090 Curve 2	478	62	421	58	6.9
FM 1179 Curve 2	482	62	476	62	0.7
FM 487 Curve 2	409	57	383	55	3.7
FM 935	410	57	361	53	6.9
FM 487 Curve 1	410	57	408	57	0.2
FM 1860	567	68	504	64	6.3
FM 159	721	78	678	75	3.2
FM 46	1027	94	564	68	27.5
FM 2038	1142	99	837	84	15.1
FM 2086	637	73	504	64	12.1
FM 2223	958	90	780	81	10.3
FM 2311	955	90	843	85	6.4
FM 2113	956	90	837	84	6.8

Table 27. Spacing Percent Error Using Empirical BBI Method (Rieker Digital).

Road/Description	Actual Radius (ft)	TxMUTCD Recommended Spacing (ft)	Radius Empirical (ft)	TxMUTCD Recommended Spacing (ft)	Percent Difference (%)
FM 3090 Curve 1	191	36	156	31	13.4
FM 974 Curve 2	316	49	289	46	5.2
FM 974 Curve 3	478	62	425	58	6.3
FM 1237	409	57	324	50	12.6
FM 3090 Curve 2	474	62	466	61	1.0
FM 3090 Curve 2	478	62	404	56	9.1
FM 487 Curve 2	482	62	466	61	1.9
FM 487 Curve 2	409	57	365	53	6.3
FM 935	410	57	340	51	10.2
FM 487 Curve 1	410	57	379	54	4.4
FM 1860	567	68	478	62	9.1
FM 159	721	78	647	73	5.7
FM 46	1027	94	534	66	29.6
FM 2038	1142	99	822	83	15.9
FM 2086	637	73	479	62	14.5
FM 2311	958	90	744	79	12.6
FM 2311	955	90	793	82	9.4
FM 2113	956	90	802	82	8.9

Table 28. Summary of Spacing Percent Error for the Physics and Empirical Ball Bank Indicator Methods.

	Physics			Empirical		
	Slopemeter	Rieker Mech.	Rieker Digital	Slopemeter	Rieker Mech.	Rieker Digital
Average Percent Difference	12.0	11.2	8.1	14.8	13.0	9.8

When Table 28 is compared to Table 21, it is evident that the error between the spacing recommended at the actual radius and the spacing recommended at the estimated radius using any of these methods will be considerably less than the error between the actual radius and the estimated radius. Note, however, even though the average error dropped substantially between Table 21 and Table 28, there are several curves where the percent difference for an individual curve is a great deal more than the average percent difference.

The benefit of this method is that no new equipment is required, except perhaps a digital ball bank indicator if one is not already available. One disadvantage of this method is that several runs at several different speeds are required to estimate the average radius with the accuracy obtained by this project. Another disadvantage is that collecting this data becomes a two-person job. Even when using the Rieker digital ball bank indicator, one person would need to drive and the other would have to record the ball bank indicator reading at each speed for each direction. Also, the average error is a little high. Other methods require a larger initial investment but have smaller percent error, and require less manpower.

LATERAL ACCELERATION METHODS

The lateral acceleration methods are similar to the ball indicator methods in that the measurement is the unbalanced lateral acceleration rate, or the side friction factor. This assumes that body-roll is neglected and superelevation is known or can be estimated. This method was tested for several reasons. First, the measurement of lateral acceleration rates is digital, precise, and stored to a file every 0.01 seconds along with speed and distance. Compared to the ball bank indicator, this advantage in of itself was thought to possibly provide more accurate curve radii estimates. The other advantage is that features are available that when incorporated with the lateral acceleration device were hoped to provide profiles of the superelevation and bodyroll as the test vehicle traversed the test curves.

Figure 11 shows a picture of the lateral accelerometer used in this project.

Figure 11. Lateral Accelerometer.

Figure 12 shows a sample of the data obtained from an accelerometer. This example data shows that there was no lateral acceleration from 500 to approximately 1700 ft (i.e. the curve is approximately flat and lateral acceleration was approximately zero). At about 1700 ft, lateral acceleration was generated (in other words, at this point the driver was traversing the curve). The data in Figure 12 represent four passes of the curve at speeds from 35 to 50 mph. The lateral acceleration increases as the speed increases.

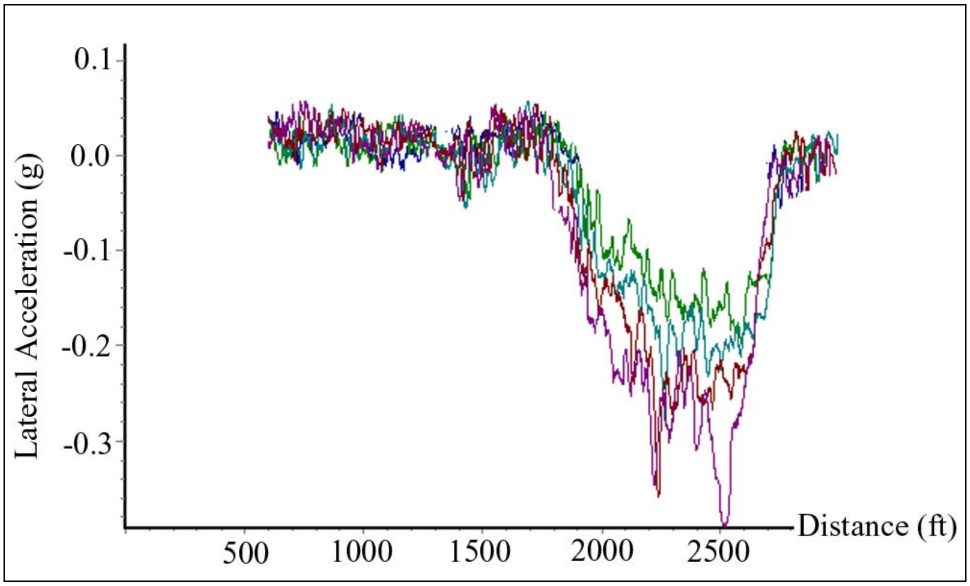

Figure 12. Measured Lateral Acceleration Rates.

Researchers used an approximately average lateral acceleration for calculations. The maximum acceleration was not used because of the likelihood that the curves were not driven in an exactly uniform radius. These determinations were made visually by inspecting each set of lateral acceleration profiles.

Lateral Acceleration Method 1

Again, this method is similar to Ball Bank Indicator Method 1 except that the measured lateral acceleration rate is substituted in the equation below to determine the radius:

Equation 8: $$R = \frac{V^2}{15(e+f)}$$

where:

R = radius, (ft)

e = superelevation, (ft/ft)

f = side friction factor (ft/ft) = measured lateral acceleration

It is important to note that this method relies on the superelevation. For the pilot testing of the method, the researchers measured the superelevation with a digital level. If this method proved promising and worth fully developing, the researchers anticipated the need to develop an empirical relationship to minimize the error associated with guessing the superelevation.

Lateral acceleration data were collected on eight curves in the Bryan District and seven curves in the Waco District. The resulting radius estimates were analyzed the same way the ball bank indictor radius estimates were analyzed.

Lateral Acceleration Method 2

This method was the same as Lateral Acceleration Method 1 except it included the addition of two roll-rate sensors, which were used in an attempt to create profiles of the superelevation along the curve and the bod-yroll of the test vehicle. One roll-rate sensor was positioned on the fixed suspension of a 1995 Ford Mustang (see Figure 13) and the other sensor was positioned on the sprung mass of the vehicle (see Figure 14). The theory was that the roll-rate sensor positioned on the sprung mass of the vehicle would measure the body-roll of the vehicle plus the superelevation while the roll-rate sensor positioned on the fixed suspension of the vehicle would measure just the superelevation.

Figure 13. Roll-Rate Sensor Position on the Fixed Suspension.

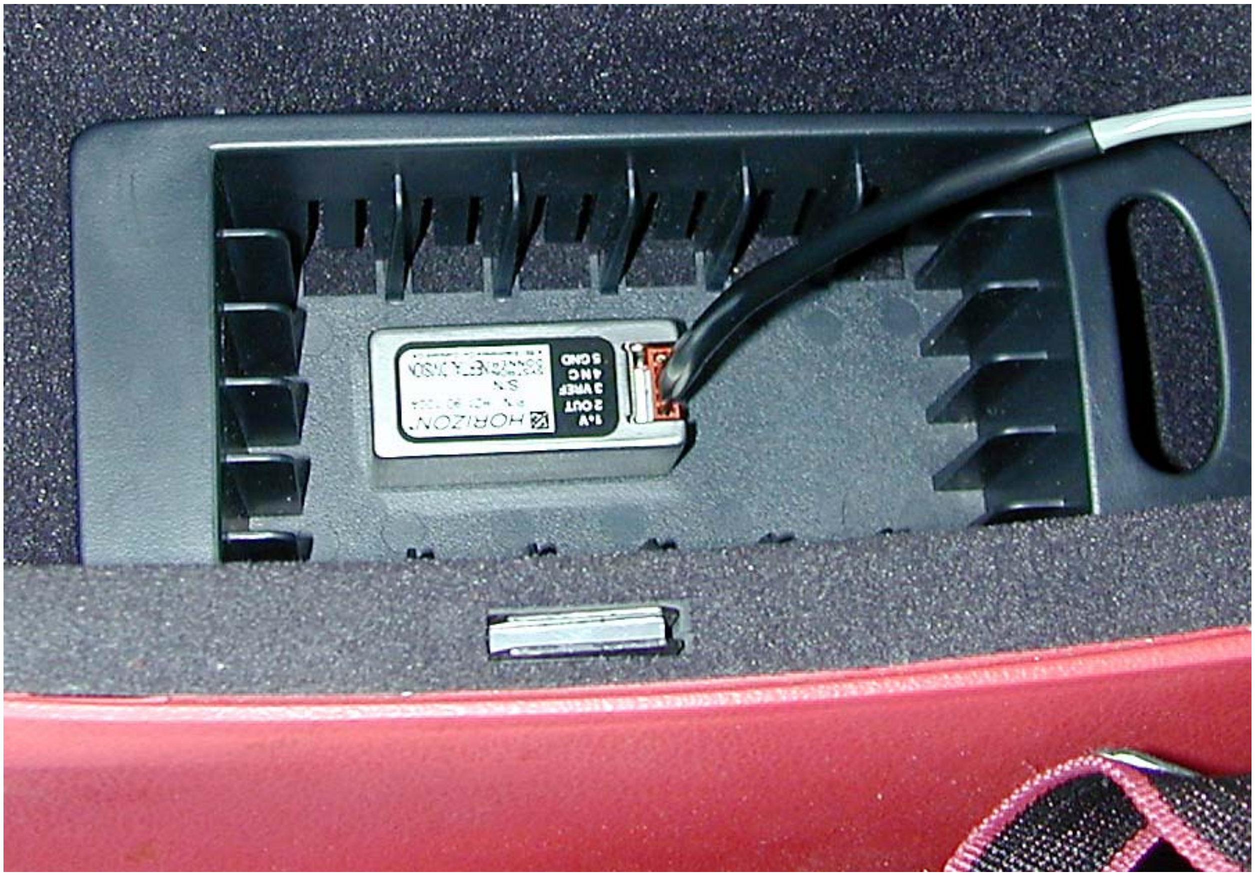

Figure 14. Roll-Rate Sensor on the Vehicle Sprung Mass.

Knowing the profile of the superelevation would provide an accurate measurement of superelevation and alleviate the need for either field crew to get out of their vehicle and measure it or use a crude estimate. Therefore, the safety of this method appeared promising as well as the potential for increasing the accuracy of the radii estimates.

The body-roll of the vehicle could be calculated by taking the difference between the data collected from the sensor on the sprung mass of the vehicle and the data collected on the fixed suspension of the vehicle. This would alleviate the need to make assumptions about the body roll of the vehicle. Unfortunately, the data collected by the rollrate sensors had excessive noise, and it was determined that the data were not useful. Figure 15 shows an example of a roll-rate graph generated with data collected on FM 935 at 45 mph. The figure shows largeband widths for superelevation. The only data that can be deduced from the graph is that the superelevation at any point is probably between 8 percent and -7 percent. The excess noise is probably due to excessive vehicle vibrations. The results for the rest of the curves are similar to the results shown for FM 935.

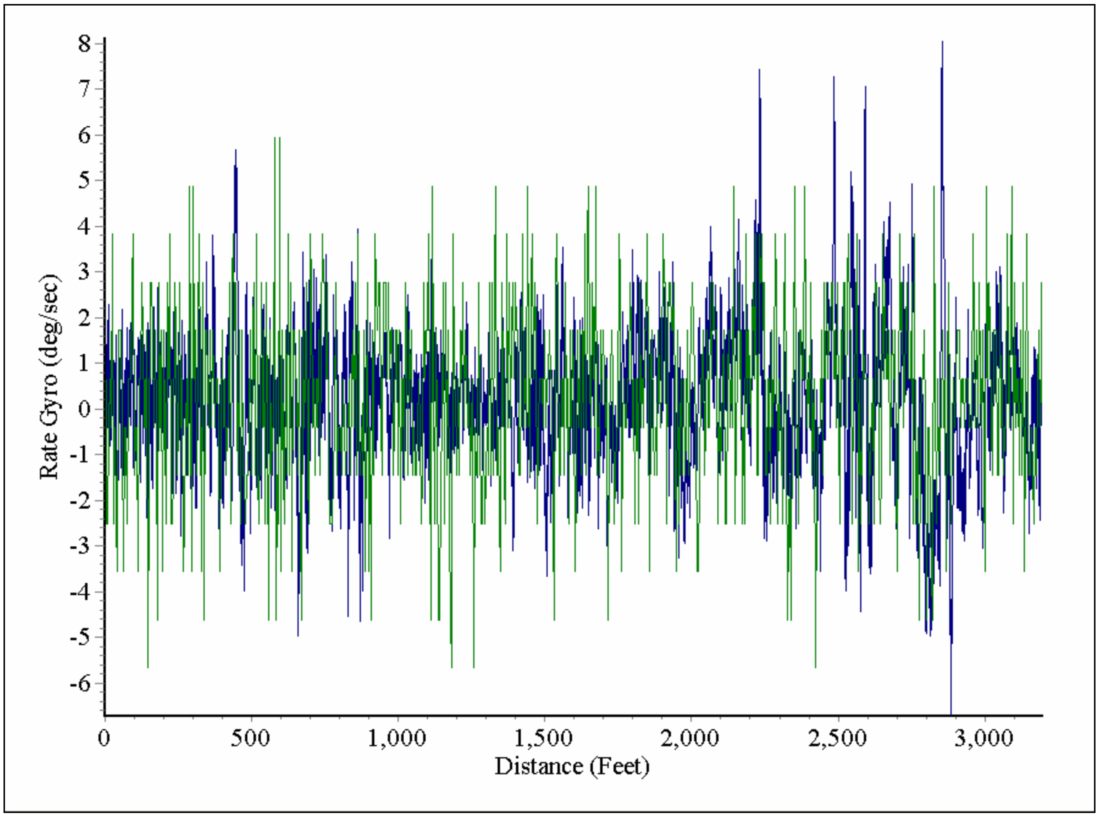

Figure 15. Noise of Roll-Rate Sensor on a Curve at 45 mph.

The lateral acceleration data were considered very useful. The radius estimates calculated using this data gave closer estimates to the RI log radius than the radius estimates from the ball bank indicator data. Tables 29 and 30 show the average lateral acceleration data collected for each curve as well as the average radius calculated using the lateral acceleration data. Tables 29 and 30 represent data calculated using Lateral Acceleration Method 1 for estimating radius. These tables also include the percent error and the RI log radius data for each curve.

Table 29. Lateral Acceleration Data for Curves in Bryan District (Method 1).

Curve/ Description	Speed (mph)	Average Lateral Acceleration (g)		Average Superelevation (%)		Radius Considering Superelevation (ft)		Average	RI Log Radius (ft)	% Diff
		NB	SB	NB	SB	NB	SB			
FM 2223	45	-0.1	0.12	-6.07	2.63	840.1	922.8	888.8	957.8	7.2
	50	-0.14	0.14			830.4	1002.2			
	55	-0.18	0.18			837.8	977.5			
	60	-0.24	0.24			798.1	901.2			
	65	-0.28	0.27			826.7	950.6			
		NB	SB	NB	SB	NB	SB			
FM 1179 (Curve 1)	30	0.12	-0.09	1.95	-4.55	430.1	442.8	457.2	474.5	3.6
	35	0.17	-0.12			431.0	493.5			
	40	0.2	-0.19			486.0	452.9			
	45	0.26	-0.25			483.0	456.9			
	50	0.34	-0.34			463.6	432.3			
		NB	SB	NB	SB	NB	SB			
FM 1179 (Curve 2)	30	-0.07	0.1	-4.97	4.23	501.3	421.6	446.2	481.9	7.4
	35	-0.12	0.16			481.2	403.7			
	40	-0.18	0.2			464.4	440.2			
	45	-0.26	0.26			435.9	446.6			
	50	-0.36	0.32			406.8	460.0			
		NB	SB	NB	SB	NB	SB			
FM 974 (Curve 2)	25	0.06	-0.05	5.83	-11.03	352.2	259.9	292.1	315.8	7.5
	30	0.13	-0.12			318.6	260.5			
	35	0.23	-0.18			283.3	281.3			
	40	0.3	-0.28			297.7	273.3			
	45	0.4	-0.34			294.6	299.8			
		NB	SB	NB	SB	NB	SB			
FM 974 (Curve 3)	25		0.05	-7.93	5.5		396.8	415.9	477.7	12.9
	30	-0.07	0.1			401.9	387.1			
	35	-0.11	0.13			431.4	441.4			
	40	-0.19	0.2			396.1	418.3			
	45	-0.24	0.26			422.8	428.6			
		NB	SB	NB	SB	NB	SB			
FM 159	35	-0.06	0.09	-5.2	3.93	729.2	631.6	702.1	721.2	2.7
	40	-0.1	0.11			701.8	714.4			
	45	-0.14	0.15			703.1	713.2			
	50	-0.18	0.2			718.4	696.5			
	55	-0.24	0.24			690.6	722.0			

Table 29 **Continued.**

Curve/ Description	Speed (mph)	Average Lateral Acceleration (g)		Average Superelevation (%)		Radius Considering Superelevation (ft)		Average	RI Log Radius (ft)	% Diff
		NB	**SB**	**NB**	**SB**	**NB**	**SB**			
FM 3090 (Curve 1)	15	0.02	-0.02	8.23	-8.03	146.6	149.6	166.0	191	13.1
	20	0.06	-0.09			187.4	156.6			
	25	0.12	-0.16			206.0	173.4			
	30	0.28	-0.34			165.6	142.8			
		NB	**SB**	**NB**	**SB**	**NB**	**SB**			
FM 3090 (Curve 2)	35	-0.07	0.06	-7.3	6.47	571.1	654.9	614.8	478.1	28.6
	40	-0.11	0.11			582.9	610.6			
	45	-0.15	0.14			605.4	659.5			
	50	-0.2	0.21			610.5	606.7			
	55	-0.26	0.25			605.6	640.8			

Table 30. Lateral Acceleration Data for Curves in Waco District (Method 1).

Curve/ Description	Speed (mph)	Average Lateral Acceleration (g)		Average Superelevation (%)		Radius Considering Superelevation (ft)		Average	RI Log Radius (ft)	% Diff
FM 1237		EB	WB	EB	WB	EB	WB	385.7	409.1	5.7
	30	0.11	-0.1	4.98	-6.74	375.5	358.4			
	35	0.16	-0.14			389.3	393.8			
	40	0.21	-0.2			410.6	398.9			
	45	0.3	-0.27			385.9	400.1			
	50	0.42	-0.36			354.8	390.0			
FM 1860		NB	SB	NB	SB	NB	SB	564.2	567.4	0.6
	35	-0.07	0.07	-7.7	5.75	555.6	640.5			
	40	-0.11	0.13			570.4	568.9			
	45	-0.17	0.17			546.6	593.4			
	50	-0.24	0.25			525.8	542.0			
	55	-0.3	0.3			534.9	564.1			
FM 2086		EB	WB	EB	WB	EB	WB	591.2	637.1	7.2
	45	-0.13	0.15	-9.46	6.92	601.1	615.9			
	50	-0.18	0.22			606.9	576.3			
	55	-0.26	0.28			568.7	577.5			
	60	-0.3	0.34			608.2	586.5			
	65	-0.37	0.43			606.3	564.2			
FM 2113		EB	WB	EB	WB	EB	WB	915.3	956.4	4.3
	50	0.14	-0.12	5.23	-4.78	866.7	993.2			
	55	0.18	-0.16			868.1	970.5			
	60	0.22	-0.21			881.4	931.0			
	65	0.27	-0.24			873.9	978.7			
	70	0.31	-0.32			901.6	888.2			

Table 30 Continued.

Curve/ Description	Speed (mph)	Average Lateral Acceleration (g)		Average Superelevation (%)		Radius Considering Superelevation (ft)		Average	RI Log Radius (ft)	% Diff
		EB	WB	EB	WB	EB	WB			
FM 487 (Curve 1)	35	0.16	-0.15	3.65	-5.93	415.6	390.2	401.6	409.9	2.0
	40	0.22	-0.2			415.9	411.4			
	45	0.31	-0.3			389.6	375.7			
	50	0.38	-0.35			400.2	407.2			
	55	0.45	-0.45			414.5	396.0			
		EB	WB	EB	WB	EB	WB			
FM 487 (Curve 2)	35	-0.14	0.15	-8.3	6.68	366.2	376.7	378.3	409.1	7.5
	40	-0.2	0.21			376.9	385.4			
	45	-0.28	0.29			371.9	378.4			
	50	-0.35	0.37			384.9	381.6			
	55	-0.45	0.46			378.4	382.8			
		EB	WB	EB	WB	EB	WB			
FM 935	35	0.15	-0.14	5.5	-8.58	398.4	361.7	379.5	409.6	7.4
	40	0.21	-0.19			402.5	386.8			
	45	0.33	-0.28			350.6	369.1			
	50	0.4	-0.34			366.3	391.4			
	55	0.48	-0.43			376.9	391.0			

The cumulative average percent difference between the calculated radius and the radius found in the RI log was 7.8 percent. This implies that the data collected with this device will provide better radius estimates than the data from any of the ball bank indicators. Table 31 shows how the average error compares between the three methods of calculating radius.

Table 31. Average Percent Difference between Radius Estimates Compared to RI Log Radius Estimates for Three Methods of Calculating Radius.

	Physics			Empirical			Lateral Acceleration VC 3000
	Slope-meter	Rieker Mech.	Rieker Digital	Slope-meter	Rieker Mech.	Rieker Digital	
Average Percent Difference	18.2	16.7	11.2	22.7	20.0	13.7	7.8

The delineator spacing that would be recommended by the Texas MUTCD was compared to the recommended spacing for the actual radius. The recommended spacing was calculated for both the actual and estimated radius using the equation listed in Table 3D-1 of the Texas MUTCD (Spacing = $3[\text{Radius}-50]^{1/2}$). Table 32 shows the percent error in spacing that would be incurred by using the radius estimates calculated from the lateral acceleration method.

Table 32. Summary of Spacing Percent Error for Lateral Acceleration Radius Estimates Compared with the Actual Radius.

Road/Description	Advisory Speed (mph)	Actual Radius (ft)	TxMUTCD Recommended Delineator Spacing (ft)	Estimated Radius (ft)	TxMUTCD Recommended Delineator Spacing (ft)	Percent Difference for Spacing
FM 3090 Curve 1	15	191	36	166	32	9.3
FM 974 Curve 2	30	316	49	292	47	4.6
FM 974 Curve 3	30	478	62	416	57	7.5
FM 1237	35	409	57	386	55	3.3
FM 1179 Curve 1	35	474	62	457	61	2.1
FM 3090 Curve 2	35	478	62	615	71	14.9
FM 1179 Curve 2	35	482	62	446	60	4.2
FM 487 Curve 2	40	409	57	378	54	4.4
FM 935	40	410	57	379	54	4.3
FM 487 Curve 1	40	410	57	402	56	1.2
FM 1860	40	567	68	564	68	0.3
FM 159	40	721	78	702	77	1.4
FM 2086	50	637	73	591	70	4.0
FM 2223	50	958	90	889	87	3.9
FM 2113	55	956	90	915	88	2.3

The lateral acceleration method was again found to be more accurate when compared to the ball bank indicator methods. The average percent difference between the Texas MUTCD recommended spacing for the estimated radius compared to the actual radius was 4.5 percent. Table 33 shows how the spacing using the lateral acceleration radius estimates compares with the spacing using the ball bank indicator radius estimates.

Table 33. Summary of Spacing Percent Error for Three Methods of Estimating Radius.

	Physics			Empirical			Lateral Accel. VC 3000
	Slope-meter	Rieker Mech.	Rieker Digital	Slope-meter	Rieker Mech.	Rieker Digital	
Average Percent Difference	12.0	11.2	8.1	14.8	13.0	9.8	4.5

The advantages of this method are that only one person is required to collect data and the error in this method is relatively low. Accept for measuring the superelevation, data collectors will be able to collect all the necessary information from the vehicle. The disadvantages of this method are that the device is expensive (almost $5,000) and like the ball bank indicator method several runs are required at different speeds to come up with a good average lateral acceleration. Also, a laptop computer would be required to download and analyze the data; therefore, this method is not ideal because of the significant cost.

YAW RATE TRANSDUCER METHOD

The lateral accelerometer also allowed the researchers to place one of the roll-rate sensors in an inverted position such that it would act as a pseudo yaw rate transducer and record the deflection of the curve while the lateral accelerometer simultaneously measured the distance traveled along the curve. Although the same data can be obtained by walking the curve with a handheld compass and a measuring wheel, the latter approach requires additional time and exposes the field crews to potential hazards on and along the road. The radius is then calculated using the simple equation:

Equation 9: $$R = (57.3 \times L) / \Delta$$

Where:

R = the curve radius, in ft

L = the roadway curve length in ft,

Δ = the change in roadway direction, in degrees

Figure 16 shows an example of the yaw rate data collected on one test section. The yaw rate was plotted versus time. There are four replicates of data, each collected while driving the same constant speed. Due to the amount of noise in the yaw rate data, this method was not pursued further.

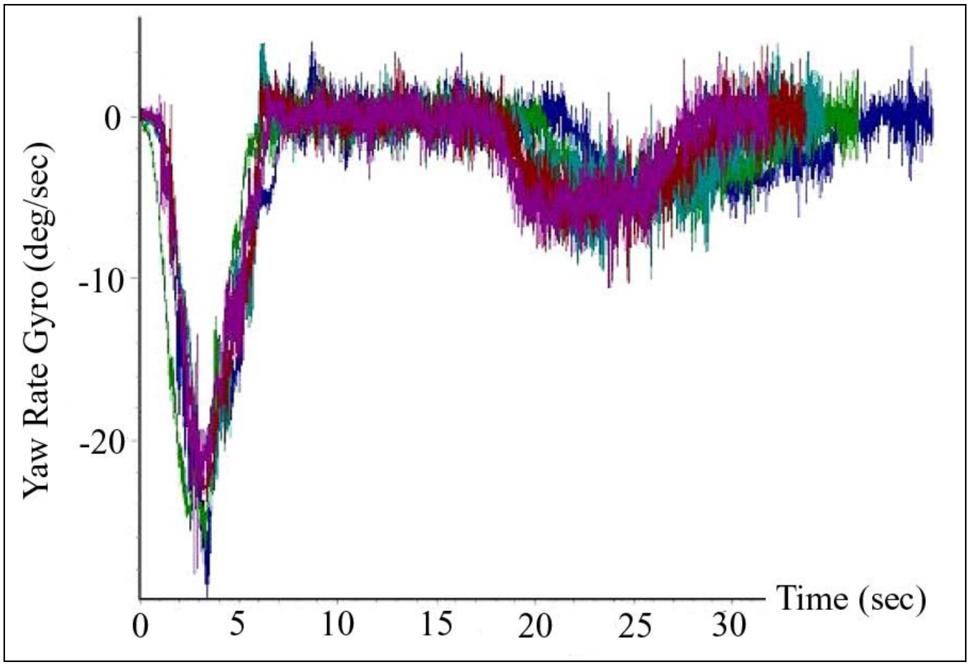

Figure 16. Example of Yaw Rate Data from One Curve.

RADIUSMETER – GPS DATA

Technology has advanced GPS technology to the point where it has become more reasonably priced and more accurate than ever before. Thus, the researchers investigated the feasibility of using GPS to estimate the radius. In concept, this method is much like the yaw rate transducer method. In other words, one method for estimating curve radius is to measure the deflection angle anywhere between the start of the curve and end of the curve and the corresponding circumferential distance between those two points along the curve. These measurements can be done with a GPS reporting velocity, bearing, and position. The absolute accuracy of a GPS fix is typically about 15 m in the non-differential mode but the second-to-second accuracy during a series of continuous measurements such as those made along a horizontal curve is much better because drift occurs over longer time intervals.

Researchers developed a system at the TTI Proving Ground to capture GPS data as a vehicle traverses a horizontal curve. The data are immediately processed by means of a microcontroller and used to solve for the radius of the curve. This system is able to operate from any vehicle at any speed allowing the measuring vehicle to travel with the normal traffic flow. Distance, which is derived from GPS speed, is measured each second and totaled at the end of the curve being measured. This distance along with the change in angle from start to end is used to calculate the radius. The start and end of the curve is defined by the operator operating a switch on the unit. Methods to automatically measure curve with no operator intervention have been investigated, but at this time, researchers feel that a human operator is best to determine what part of the roadway to measure under unusual geometrics.

Once the operator flips the switch to indicate the end of curve, the unit will display the curve radius on the liquid crystal display on the front of the unit. This number will remain until the reset button is pressed where the display will return to showing latitude and longitude should the operator wish to note the location of the test. The system consists of two components. The GPS antenna and receiver are in one unit that is the size and shape of a computer mouse. It has a magnetic base that will adhere to the roof of a vehicle. The processor/display is in a small box that could be placed on the dash or seat of the test vehicle where the operator can reach the measurement switch. Power is obtained from the 12-volt cigarette lighter plug. Figure 17 shows the Radiusmeter setup.

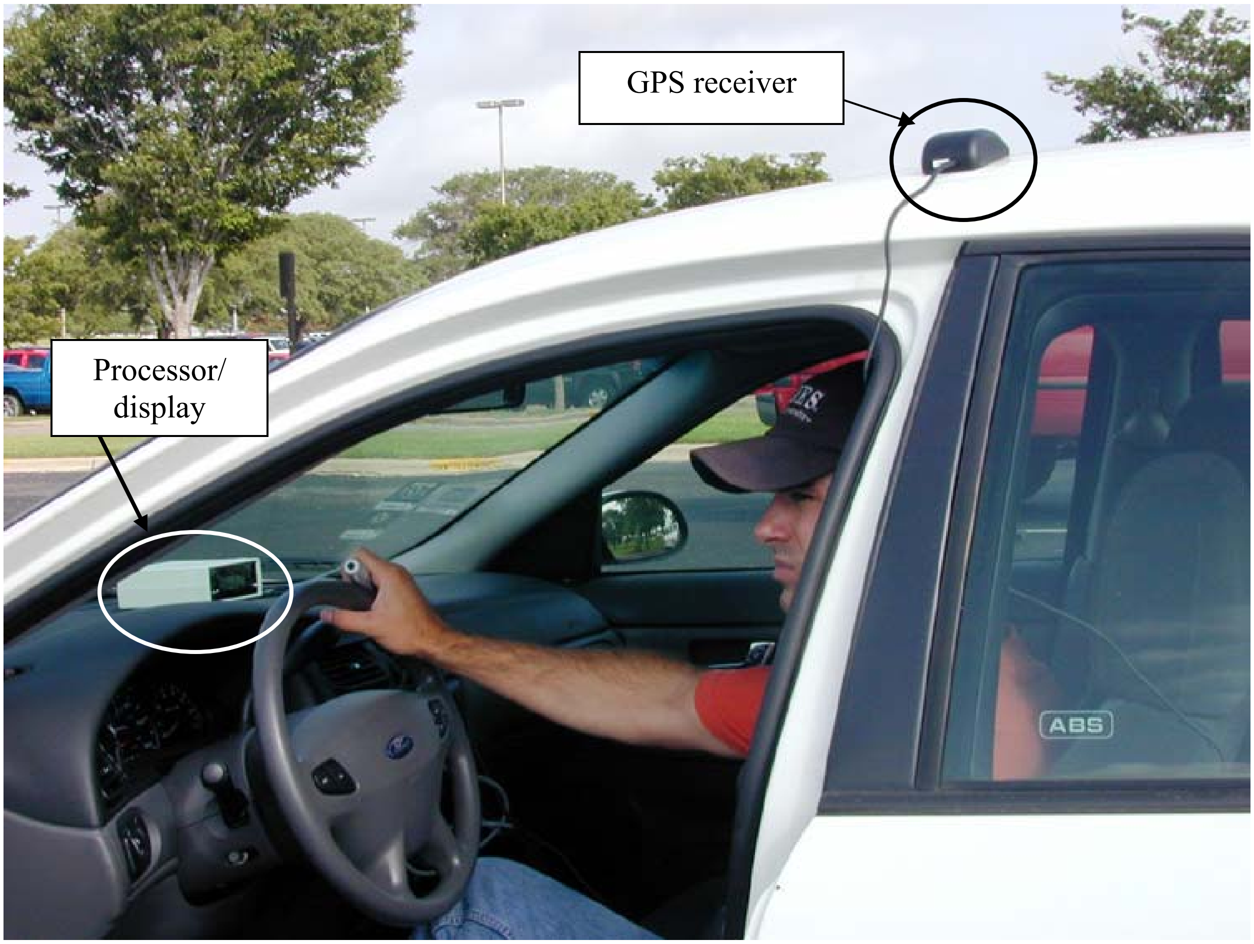

Figure 17. Radiusmeter Setup.

Thus far, the prototype Radiusmeter has produced good results. The data in Tables 34 and 35 show the results given by the Radiusmeter. The Radiusmeter was tested at several different speeds, and the radius output at those different speeds was averaged in the "Average GPS Radius" column. The percent difference was calculated using the data in the "Average GPS Radius" column.

Table 34. Average Radius and Percent Difference Data Using the Radiusmeter on Curves in the Waco District.

Road/Description	Speed	GPS Radius		Average GPS Radius	Radius Given on RI Log	Percent Difference
FM 487 (Curve 1)	35	402.4	427.3	410.2	409.9	0.1
	40	397.6	420.3			
	45	391.8	420.1			
	50	401	421.4			
FM 487 (Curve 2)	35	423.9	403.9	404.3	409.1	1.2
	40	408.3	396.3			
	45	398.8	395.8			
	50	403.5	403.7			
FM 1860 (Obstructing Trees)	35	600.7	543	629.2	567.4	10.9
	40	652.7	679.1			
	45	578.0	664.7			
	50	594.2	607.2			
	55	773.3	598.7			
FM 2086	45	639	658	636.1	637.1	0.2
	50	620	640			
	55	626	653			
	60	630	639			
	65	624	632			
FM 1237	30	423	388	412.0	409.1	0.7
	35	406	414			
	40	414	422			
	45	405	428			
	50	402	418			
FM 935	30	399	409	410.8	409.6	0.3
	35	430	406			
	40	436	398			
	45	420	389			
	50	423	398			

(Advisory speed is bold and italicized.)

Table 35. Average Radius and Percent Difference Data Using the Radiusmeter on Curves in the Bryan District.

Road/Description	Speed	GPS Radius		Average GPS Radius	Radius Given on RI Log	Percent Difference
		NB	SB			
FM 159	35	754	797	750.5	721.2	4.1
	40	713	769			
	45	785	779			
	50	692	715			
FM 3090 (Curve 1)	***15***	197	218	191.0	191	0.0
	20	185	191			
	25	188	197			
	30	184	168			
FM 3090 (Curve 2)	30	508	541	525.3	478.1	9.9
	35	531	530			
	40	534	525			
	45	501	532			
FM 2223	45	931	917.2	926.2	957.8	3.3
	50	938	903.6			
	55	924.5	934.8			
	60	919.1	941.3			
	65	923.7	915.5			
FM 974 (Curve 2)	25	323.6	316.1	319.0	315.8	1.0
	30	327.3	312.7			
	35	323.7	318.1			
	40	311.6	318.5			
FM 974 (Curve 3)	25	480.1	479.7	466.1	477.1	2.3
	30	451.4	500.9			
	35	452.5	458.2			
	40	443.6	462.6			
FM 46 (Obstructing Trees)	40	987.8	962.9	980.1	1027.4	4.6
	45	991.6	940.8			
	50	950	979.2			
	55	950.2	991.8			
	60	1046.5	1000.1			

(Advisory speed is bold and italicized.)

The data show that the radius calculated using the GPS device on most curves evaluated had less than a 5 percent difference between the average GPS radius and the RI log radius. Table 36 shows how the accuracy of the Radiusmeter compares with the accuracy of the other methods.

Table 36. Comparison of Four Methods of Estimating Radius.

	Physics			Empirical			Lateral Acceleration VC 3000	Radiusmeter
	Slopemeter	Rieker Mechanical	Rieker Digital	Slopemeter	Rieker Mechanical	Rieker Digital		
Average Percent Difference	19.9	18.3	13.7	24.4	21.6	16.5	7.8	3.7

Table 36 shows that the Radiusmeter has given radius estimates that are closer to the RI log radius than the other methods. The average percent error for the Radiusmeter was only 3.7 percent, which is better than any of the previously tested methods.

Again, the delineator spacing that would be recommended by the Texas MUTCD was compared to the recommended spacing for the actual radius. The recommended spacing was calculated for both the actual and estimated radius using the equation listed in Table 3D-1 of the Texas MUTCD (Spacing $=3[\text{Radius}-50]^{1/2}$). The purpose of Table 37 is to show the approximate error in delineator spacing that would be incurred using the Radiusmeter radius estimates.

Table 37. Spacing Percent Error for the GPS Method Using the Radiusmeter.

	Road/Description	Advisory Speed (mph)	Actual Radius (ft)	TxMUTCD Recommended Delineator Spacing	Expected Radius (ft)	TxMUTCD Recommended Delineator Spacing	Percent Difference for Spacing
1	FM 3090 Curve 1	15	191	36	191	36	0.0
2	FM 974 Curve 2	30	316	49	319	49	0.6
3	FM 487 Curve 2	40	409	57	404	56	0.7
4	FM 487 Curve 1	40	410	57	410	57	0.1
5	FM 974 Curve 3	30	478	62	466	61	1.4
6	FM 3090 Curve 2	35	478	62	525	65	5.4
7	FM 1860	40	567	68	629	72	5.8
8	FM 159	40	721	78	751	79	2.2
9	FM 2223	50	958	90	926	89	1.8
10	FM 46	45	1027	94	980	91	2.5

Table 38 summarizes the average percent error in delineator spacing for each method of estimating the radius.

Table 38. Summary of Spacing Percent Error for Four Methods of Estimating Radius.

	Physics			Empirical			Lateral Accel. VC 3000	Radius-meter
	Slope-meter	Rieker Mech.	Rieker Digital	Slope-meter	Rieker Mech.	Rieker Digital		
Average Percent Difference	12.0	11.2	8.1	14.8	13.0	9.8	4.5	2.0

Researchers again found the Radiusmeter to be more accurate when compared to the other methods. The average percent difference between the Texas MUTCD recommended spacing for the estimated radius compared to the actual radius was 2 percent. Two curves had heavy tree cover, and the researchers feel that the heavy tree cover probably affects the accuracy of the instrument. These two curves had percent errors for delineator spacing of about 5.5 percent. If these two curves were to be left out of the average percent error calculation for delineator spacing, the average would be cut in half.

The benefits of the Radiusmeter extend beyond its relatively high accuracy. The second prototype of this method is handheld and does not require a laptop; thus, only one person would be required to collect radius data. The device eliminates the need for personnel to be out of the vehicle on the road collecting data. It is easy to use and requires fewer calculations than the ball bank indicator method; thus, it would require minimal training. It is also much less expensive than the VC 3000 method. The main drawback of this method is that there is an initial investment. The Radiusmeter was designed using relatively low-end GPS technology, so the estimated cost to build the device is approximately $400.

ADVISORY SPEED PLAQUE

The theory behind the Advisory Speed Plaque method for placing Chevrons and delineators is to identify a relationship between advisory speed and radius, and use that relationship and the Texas MUTCD delineator spacing table to create a table that would provide a specific spacing for a specific advisory speed. This method indirectly uses ball bank indicator data since advisory speeds are set using a BBI. It simplifies chevron and delineator spacing by eliminating the need for maintenance personnel to know the radius of the curve in order to place these traffic control devices. It should also be noted that this procedure is already used by one of the TxDOT districts.

Figure 18 shows the advisory speed and the radius for each of the 18 curves to investigate their potential relationship. Several types of trendlines were generated for the advisory speed versus radius plot including a linear best-fit line, a power best-fit line, and an exponential best-fit line. Each trendline was plotted with the corresponding equation and coefficient of determination (R^2) for the trendline. The R^2 value is a measure of how good the data fit the trendline. The closer the R^2 value is to one, the better the data fit the trend. The R^2 value for the exponential trendline was closest to one, so a 95 percent confidence bandwidth was calculated for the exponential relationship. Figure 18 shows a graphical representation of the advisory speeds for the pilot study curves plotted against their respective radius. The data indicate that at specific advisory speeds the radius can be considerably different. A relatively low level of accuracy is indicated by the fact the bandwidth is so wide.

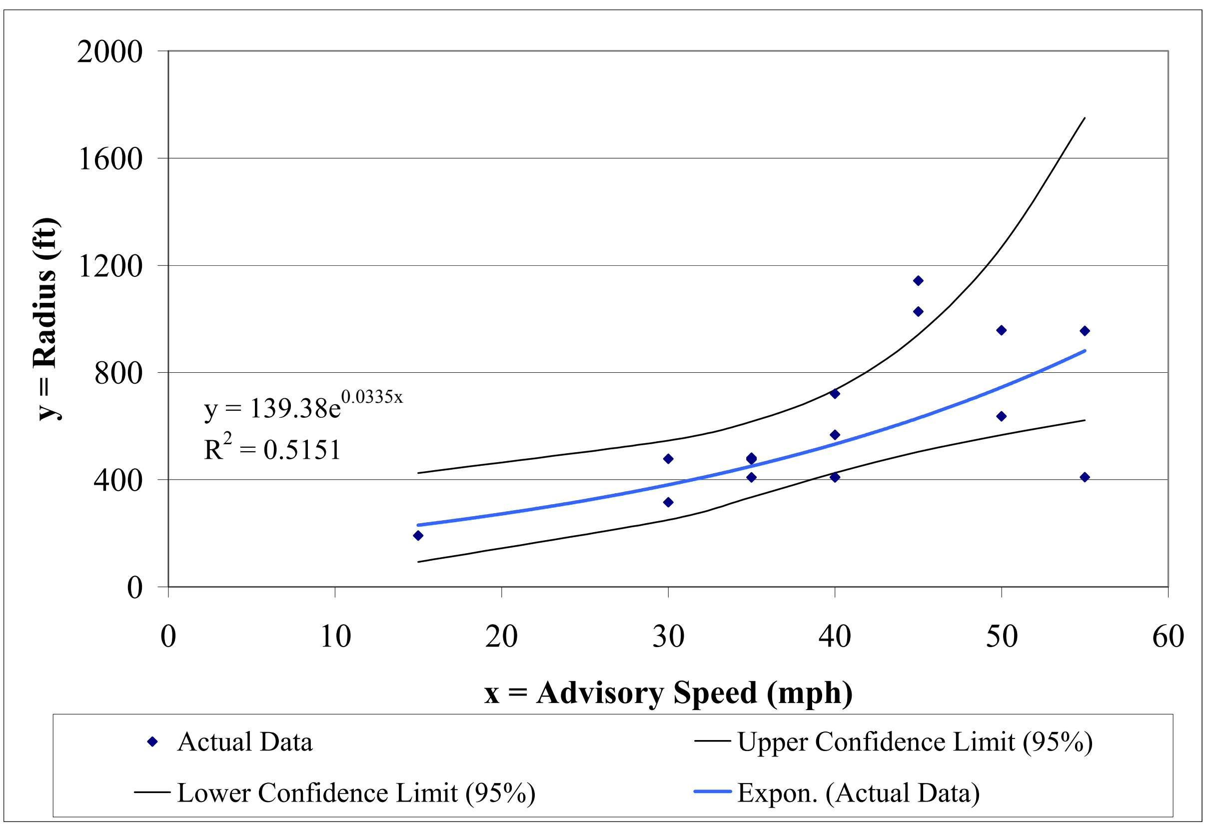

Figure 18. Preliminary Comparison between Advisory Speed and Radius of the Curve.

The expected radius was compared to the actual radius by calculating the percent difference between the values. Table 39 shows the percent difference calculated at each curve. The difference ranges from only 1.3 percent error to almost 40 percent error. The large variation in error is another indication of a low level of accuracy. Table 40 shows how the percent error for the advisory speed method compares with the other methods previously discussed.

Table 39. Comparison between Expected Radius and Actual Radius.

		Posted Speed (mph)	Advisory Speed (mph)	Expected Radius (ft)	Actual Radius (ft)	Percent Difference (%)
1	FM 3090 Curve 1	60	15	198.3	191	3.9
2	FM 974 Curve 2	60	30	369.6	316	17.0
3	FM 974 Curve 3	60	30	369.6	478	22.6
4	FM 1237	60	35	454.9	409	11.2
5	FM 1179 Curve 1	65	35	454.9	474	4.1
6	FM 3090 Curve 2	60	35	454.9	478	4.9
7	FM 1179 Curve 2	65	35	454.9	482	5.6
8	FM 487 Curve 2	55	40	559.8	409	36.8
9	FM 935	55	40	559.8	410	36.7
10	FM 487 Curve 1	55	40	559.8	410	36.6
11	FM 1860	60	40	559.8	567	1.3
12	FM 159	60	40	559.8	721	22.4
13	FM 46	60	45	688.8	1027	33.0
14	FM 2038	70	45	688.8	1142	39.7
15	FM 2086	60	50	847.7	637	33.0
16	FM 2223	70	50	847.7	958	11.5
17	FM 2311	60	55	1043.1	955	9.3
18	FM 2113	60	55	1043.1	956	9.1

Table 40. Comparison of Four Methods of Estimating Radius.

	Physics			Empirical			Lateral Accel. VC 3000	Radius-meter	Advisory Speed
	Slope-meter	Rieker Mech.	Rieker Digital	Slope-meter	Rieker Mech.	Rieker Digital			
Average Percent Difference	19.9	18.3	13.7	24.4	21.6	16.5	7.8	3.7	18.8

Table 40 shows that the average percent error for the advisory speed method is higher than the error for the lateral acceleration, Radiusmeter, and the physics ball bank indicator method with the Rieker instruments.

From a practical standpoint, the goal of this project is to develop an easier way to space delineators so that the spacing used conforms to the Texas MUTCD spacing recommendations. Researchers wanted to determine how close could one expect the spacing estimated by the advisory speed equation, shown in Figure 18, be to the recommended TxMUTCD spacing. Thus, the radius was calculated using the exponential trendline shown in Figure 18; and then, the equation given in Table 3D-1 of the Texas MUTCD: $3*(R-50)^{1/2}$ was used to calculate the recommended spacing for the actual radius and the recommended spacing for the expected radius. Table 41 shows the results of this analysis. Spacing calculated using the radius estimated with the advisory speed equation was compared to the spacing calculated at the actual radius. Researchers found the average percent difference to be 10.3 percent. There is still a lot of variability in the amount of error one could expect to incur from curve to curve; however, this method does provide a safe and fast way for field personnel to select an approximate spacing for delineators.

Table 41. Comparsion between the Spacing Recommended for the Expected Radius and the Spacing Recommended for the Actual Radius.

		x Advisory Speed (mph)	í Expected Radius (ft)	TxMUTCD Recommended Delineator Spacing for í	y Actual Radius (ft)	TxMUTCD Recommended Delineator Spacing for y	Percent Difference for Spacing
1	FM 3090 Curve 1	15	198	37	191	36	2.6
2	FM 974 Curve 2	30	370	54	316	49	9.7
3	FM 974 Curve 3	30	370	54	478	62	13.6
4	FM 1237	35	455	60	409	57	6.2
5	FM 1179 Curve 1	35	455	60	474	62	2.3
6	FM 3090 Curve 2	35	455	60	478	62	2.8
7	FM 1179 Curve 2	35	455	60	482	62	3.2
8	FM 487 Curve 2	40	560	68	409	57	19.1
9	FM 935	40	560	68	410	57	19.1
10	FM 487 Curve 1	40	560	68	410	57	19.0
11	FM 1860	40	560	68	567	68	0.7
12	FM 159	40	560	68	721	78	12.9
13	FM 46	45	689	76	1027	94	19.2
14	FM 2038	45	689	76	1142	99	23.5
15	FM 2086	50	848	85	637	73	16.6
16	FM 2223	50	848	85	958	90	6.3
17	FM 2311	55	1043	95	955	90	4.8
18	FM 2113	55	1043	95	956	90	4.7

Table 42 summarizes the average percent error in delineator spacing for each method of estimating the radius.

Table 42. Summary of Spacing Percent Error for Five Methods of Estimating Radius.

	Physics			Empirical			Lateral Accel. VC 3000	Radius-meter	Advisory Speed
	Slope-meter	Rieker Mech.	Rieker Digital	Slope-meter	Rieker Mech.	Rieker Digital			
Average Percent Difference	12.0	11.2	8.1	14.8	13.0	9.8	4.5	2.0	10.3

The data in Table 42 indicate the average delineator spacing using the advisory speed method was not as accurate as the lateral acceleration method, the Radiusmeter method, or either ball bank indicator method using the Rieker digital ball bank indicator. The average percent error for delineator spacing using the advisory speed method is better than or fairly close to the average percent error using any of the ball bank indicator methods. This indicates that the advisory speed method may be a good alternative to the ball bank indicator methods because there is not a large difference in percent error and the ball bank indicator method requires a substantial amount of additional effort.

The two benefits of this method are simplicity and economy. The only thing that is required for this method is the advisory speed plaque and a table. Since there is no new equipment required, there are no new costs. The drawbacks of this method are that it is more likely to have a relatively large error than the GPS or the lateral acceleration methods. The advisory speeds must be set appropriately or the spacing error could be substantially higher.

ASSESSMENT OF TESTED METHODS COMPARED TO CURRENT PRACTICE

This section provides a comparison between the spacing error that was measured in the field and the spacing error that would be incurred by using one of the methods discussed in this chapter to determine the radius. Because a table for delineator spacing currently exists, only the delineator field spacing was used for this comparison. Table 43 shows the average measured field spacing between delineators, the TxMUTCD recommended spacing, and the percent error between the actual and recommended spacing. The average percent error is 22 percent.

Table 43. Average Percent Error for Spacing Using Current Field Measurements.

Location	Actual Delineator Spacing			
	Average Spacing	Radius	TxMUTCD	Percent Difference
	(ft)	(ft)	(ft)	(%)
FM 935	114	637	73	36
FM 1860	96	567	68	29
FM 159	79	721	78	2
FM 46	117	1027	94	20

Table 44 shows the average percent error between the average estimated spacing and the actual spacing recommended by the TxMUTCD for the actual radius. It includes the average spacing from the field measurements.

Table 44. Cumulative Average Percent Difference between Spacing Using Radius Estimate and Spacing Using Actual Radius.

	Physics			Empirical			Lateral Accel. VC 3000	Radius-meter	Advisory Speed	Field Spacing
	Slope-meter	Rieker Mech.	Rieker Digital	Slope-meter	Rieker Mech.	Rieker Digital				
Average Percent Difference	12.0	11.2	8.1	14.8	13.0	9.8	4.5	2.0	10.3	22

Table 44 indicates that there is quite a bit to be gained by using any of the methods to estimate the radius. It is important to note, however, that only four curves were used in the estimate of the average percent difference for field spacing. For each of the other methods, all of the curves were used. This was a limitation in the initial data set, but nonetheless, the results still demonstrate the potential for improving curve delineation in terms of consistency.

CHAPTER 6: DEVELOPING DELINEATOR SPACING ALTERNATIVE

INTRODUCTION

After analyzing the results from the preliminary methods used to estimate radius, the researchers met with the TxDOT project advisors to discuss the results and formulate a plan for more intense evaluations. The panel chose two methods for more intense evaluation. The Advisory Speed method and the GPS method, were chosen for complete development based on their simplicity, safety, and low cost. The data up to this point were obtained from the Bryan and Waco Districts; however, the project advisors thought of two potential issues with these methods that could not be addressed in these districts. The first potential problem was determining whether heavy tree cover or desolate locations would affect the GPS unit's ability to lock in on a satellite, and thus, produce erroneous radius estimates or no estimate at all. The second potential issue was determining whether flatter superelevation, as would be seen in the snow regions, would negatively affect the accuracy of the Advisory Speed method. In order to address these two issues, curves were selected in the Atlanta District in East Texas, an area with more tree coverage, and Amarillo, an area that experiences a fair amount of wintry weather (i.e., snow, ice, and sleet) and has low population areas in the district. Researchers also desired a variety of advisory speeds from the evaluated curves, which also ensured a variety of curve sizes (i.e., some sharp, some medium, and some gentle curves).

Researchers visited a total of 58 curves. Thirty-five curves had delineators, 15 had Chevrons, and eight curves had only an advisory speed plaque. Table 45 shows the number of data collection sites organized by the advisory speed of the curves, and also organized by whether they were located in the Panhandle (i.e., Amarillo District) or not. The Amarillo District was split out because the curves from this area were expected to have flatter superelevation than those in the other districts.

Table 45. Summary of the Advisory Speeds for the Curves Evaluated.

Advisory Speed Value (mph)	Number of Data Collection Sites	
	Panhandle Region	All Other Regions
15	0	1
25	0	2
30	0	4
35	1	6
40	4	6
45	3	2
50	3	3
55	7	3
60	5	1
65	5	2
TOTAL	*28*	*30*

At least four curves were visited for each advisory speed between 30 mph and 65 mph. Sharper curves were generally more difficult to locate on state roads; thus, fewer sites were examined with advisory speeds less than 30 mph. For each curve, several site characteristics were collected including approximate length of the curve, spacing of the chevrons or delineators, posted speed limit and advisory speed, and RI log. The data were used to determine the quality of the two alternative spacing methods.

ADVISORY SPEED PLAQUE METHOD

Despite the error associated with the advisory speed plaque method, the method is appealing because it is easy for field crew to implement and no additional costs are associated with this method. After the pilot study, the average error for the advisory speed plaque method was 18.8 percent. To fully develop the Advisory Speed Plaque Method, researchers incorporated the data from all 58 sites, and again calculated the average error. For the fully developed method, the percent error dropped slightly to 16.3 percent. Figure 19 shows a 95 percent confidence band around the best-fit trendline. The equation for the trendline was Radius = $92.655e^{0.045\ (\text{Advisory Speed})}$. The radius at each advisory speed was then used to calculate the spacing in Table 46 using the MUTCD equation for delineator spacing: $S = 3(R\text{-}50)^{1/2}$.

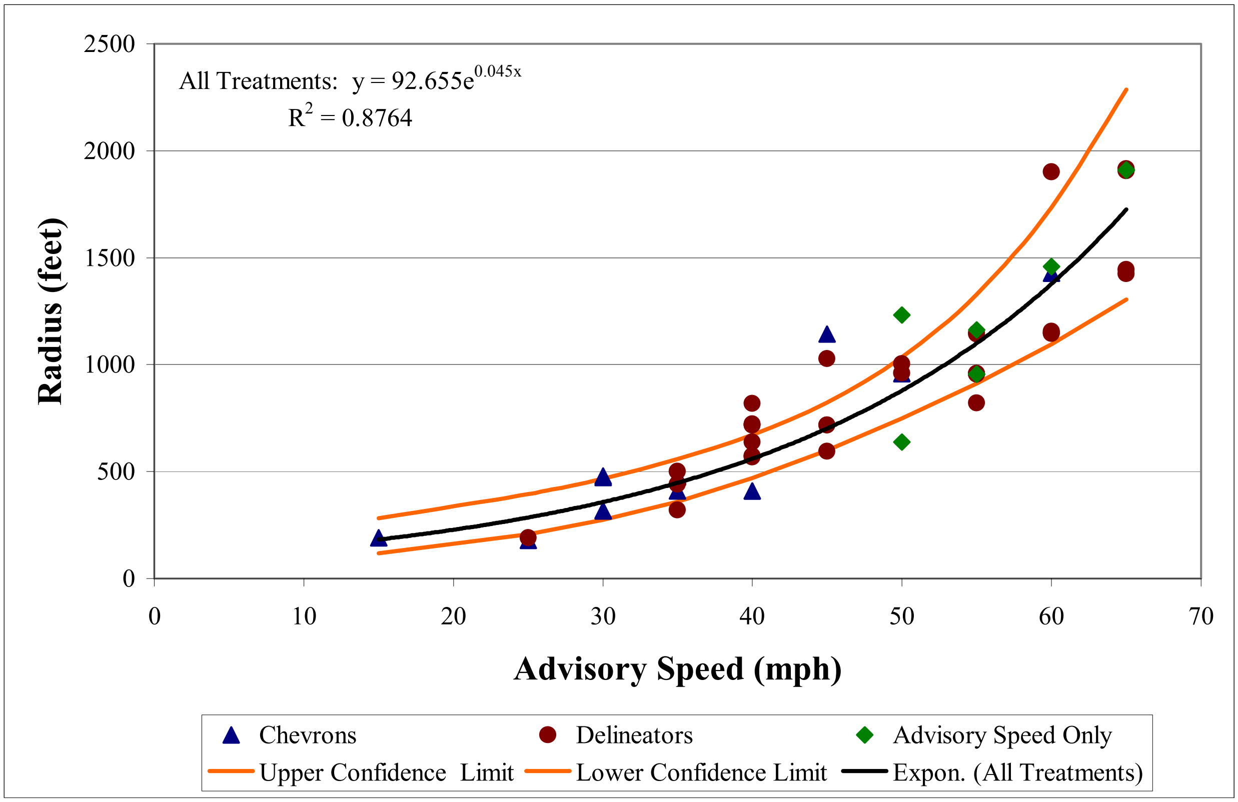

Figure 19. Comparison between Advisory Speed and Radius of the Curve.

Table 46. Delineator Spacing Table Based on Advisory Speed.

Advisory Speed (mph)	Suggested Spacing (ft)
15	35
20	40
25	50
30	55
35	60
40	70
45	75
50	85
55	100
60	110
65	130

Again, the major benefits of this method are that it is easy to use and requires no additional cost. To implement this method, all that a field crew worker must do is look at the advisory speed approaching the curve and select a spacing from the table above.

The error associated with this method can be related to many things. This method is dependent on the advisory speed plaque on a particular curve. The advisory speed on the curve is dependent on whether the ball bank indicator was used properly or whether the advisory speed was adjusted to a lower advisory speed due to high accident rates. Also, all curves that ball bank at, for example, 35 mph will not have the same radius. Variations in superelevation and smoothness of the road are some examples of factors that could influence the ball bank indicator reading. When using this method, it is a good idea to verify that the advisory speed was set appropriately to avoid any unnecessary error.

GPS RADIUSMETER METHOD

The Radiusmeter is a GPS device that was developed at TTI to estimate the radius as a driver traverses a curve. This method was further developed in the second phase of this project because of its high level of accuracy and its relative low cost. The unit cost around $400, and the percent error calculated in the pilot study was 3.7 percent. After the second phase of the project was completed and the data from all 58 curves were analyzed, the percent error was recalculated and found to be on average 3.5 percent (comparing the radius calculated by the Radiusmeter to the radius obtained from the RI logs). However, an average error of only 1.9 percent was calculated when comparing the MUTCD recommended spacing using the radius given by the Radiusmeter compared to the MUTCD recommended delineator spacing given by the radius obtained from the RI logs.

The results show that the Radiusmeter will provide accurate estimates of the radius of a horizontal curve. The drawbacks of this method are the initial cost (about $400) and the fact that it is not as simple as the advisory speed method. The instrument itself is easy to use, but the method is not as simple as observing an advisory speed and using it in a look-up table to select the appropriate spacing.

CONCLUSIONS

Both the GPS and the advisory speed methods were successfully developed in the second phase of this project. The GPS method provided a higher level of accuracy, but requires an initial financial investment and does not provide the same level of simplicity seen in the advisory speed method. The advisory speed method does not require additional costs and is simple to use but does not provide a high level of accuracy.

SPACING BASED ON ADVISORY SPEED VALUE

The findings of this chapter were used to generate alternative spacing criteria that could be used by field personnel to space delineators. Table 47 shows the findings.

Table 47. Spacing Based on Advisory Speed Value.

Advisory Speed Value (mph)	Delineator Spacing (ft)
15	35
20	40
25	50
30	55
35	60
40	70
45	75
50	85
55	100
60	110
65	130

CHAPTER 7:
CHEVRON FIELD STUDY

INTRODUCTION

Currently, the MUTCD suggests that two chevrons in view at any one time provide sufficient information to the driver about the change in alignment of the road. Literature findings, however, suggests four chevrons in view at any one time provides the driver with optimal information about the curve *(23)*. The MUTCD delineator spacing table provides delineator spacings that result in about four delineators in view at any one time. As described in Chapter 1, one of the issues within the scope of this project was to simplify the spacing of both delineators and Chevrons.

This chapter describes the efforts that the researchers completed in order to identify a more objective procedure for spacing Chevrons. Initially, the researchers determined the theoretical spacing needs as a function of typical curve geometrics and restrictive sight lines. This effort resulted in a preliminary spacing table dependent on the radius and how many Chevrons were desired to be in view at any one time. Then, researchers performed a field study to determine if there were any driver performance differences between having only two and up to four Chevrons in view at any one time. The procedures and results are described herein.

THEORETICAL CHEVRON SPACING CALCULATIONS

One objective of this project was to provide a way to for TxDOT personnel to quickly, safely, and inexpensively determine the radius of a curve so that delineators could be spaced in accordance with the Texas MUTCD. The Texas MUTCD *(2)* provides the following standard regarding Chevron placement: "Spacing of Chevron Alignment signs should be such that the road user always has at least two in view, until the change in alignment eliminates the need for the signs. Chevron Alignment signs should be visible for a sufficient distance to provide the road user with adequate time to react to the change in alignment." The standard is broad to account for geometric design features and other site obstructions such as steep vertical curvature or heavy vegetation. This allows flexibility based on site characteristics and available funds, and the verbiage also creates a lower liability risk than a spacing chart. However, it allows for inconsistencies in the roadway system and provides little guidance for maintenance personnel. A better way of spacing Chevrons was needed. In order to develop an initial spacing table, researchers conducted a desktop analysis. Researchers performed the analysis based on the assumption that the scenario curve had poor visibility conditions, but was not the worst possible case scenario. The assumptions about the curve were intended to represent a typical scenario where site distance may affect chevron spacing. Researchers made the following assumptions about for this analysis:

- The terrain was assumed to be flat (i.e., no vertical curvature).
- Maximum superelevation was assumed to be eight percent.
- Design speed around the curve was assumed to be between 25 mph and 65 mph, in 5 mph increments.
- Roads were assumed to be two lanes, lanes were assumed to be 12 ft wide, and shoulders were assumed to be 2 ft wide.
- Chevron placement was assumed to be 6 ft off the shoulder of the road, and the first chevron is placed at the Point of Curvature (PC) of the curve.
- Site obstructions were assumed to be continuous throughout the curve starting just over 6 ft off the edge of the travel way.

The goal was to provide a minimum spacing that enables the motorists to view two Chevrons when the vehicle reaches a position in advance of the point of curvature that affords the motorist enough distance to decrease the speed by 25 mph before he or she reaches the curve. The minimum distance was determined using the sight distance equation in the *AASHTO Green Book* (30), and assuming a deceleration rate of 11.2 ft/s^2 as suggested by the G*reen Book*. MicroStation drawings were made of curves with several different radii; then a site distance line from the center of the lane on the inside of the curve was drawn to a point where the line was tangent to the site obstruction line on the inside curve and intersected the site obstruction line on the outside curve. Figure 20 illustrates this procedure.

Table 48 shows the expected spacing for two, three, or four Chevrons in view based on the assumptions stated previously. The radius chosen represents curves with design speeds between 25 to 65 mph. Radii associated with design speeds between 25 to 40 mph were selected from Exhibit 3-23 in the *AASHTO Green Book* (*30*) and represent the minimum radius at that design speed. Radii associated with design speeds of 45 mph or higher represent the "usual minimum radius" from Table 2-3 in the TxDOT Roadway Design manual. The design speeds were assumed to be indicated by the advisory speed plaque and the curve was assumed to be on a road with a speed limit 25 mph higher than the design speed due to TxDOT guidelines for chevron placement (*28*).

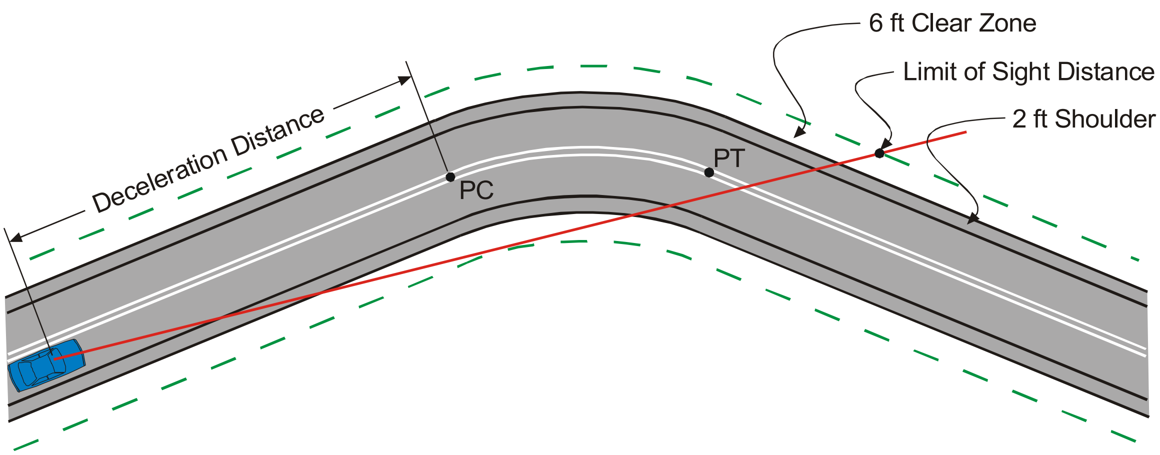

Figure 20. Limit of Sight Distance.

Table 48. Suggested Minimum Chevron Spacing for Curves with e_{max} = 8 percent.

Design Speed of Curve (mph)	Minimum Radius at Centerline (ft)	Deceleration Distance (ft)	Minimum Spacing: 2 in view (ft)	Minimum Spacing: 3 in view (ft)	Minimum Spacing: 4 in view (ft)
25	170	187	139	70	46
30	250	205	166	83	55
35	350	223	195	98	65
40	465	242	225	113	75
45	755	260	289	145	96
50	960	279	326	163	109
55	1490	297	375	188	125
60	1985	315	480	240	160
65	2445	334	536	268	179

Table 49 shows a simplified version of the Table 48. The minimum spacing in Table 49 has been rounded to the nearest 10 ft.

Table 49. Simplified Suggested Minimum Chevron Spacing.

Minimum Radius at centerline (ft)	Minimum Spacing: 2 in view (ft)	Minimum Spacing: 3 in view (ft)	Minimum Spacing: 4 in view (ft)
170	140	70	50
250	170	90	60
350	200	100	70
465	230	120	80
755	300	150	100
960	330	170	110
1490	380	190	130
1985	480	240	160
2445	540	270	180

Figure 21 shows how the suggested spacing from Table 49 compares with the average spacing measured in the field on the evaluated curves with Chevrons. The curve represents a polynomial trendline for the field data. This trendline is fairly close to the suggested minimum spacing for three Chevrons in view. All field measured average spacings are less than the suggested spacing for two Chevrons in view. Figure 21 also includes the TxMUTCD recommended delineator spacing.

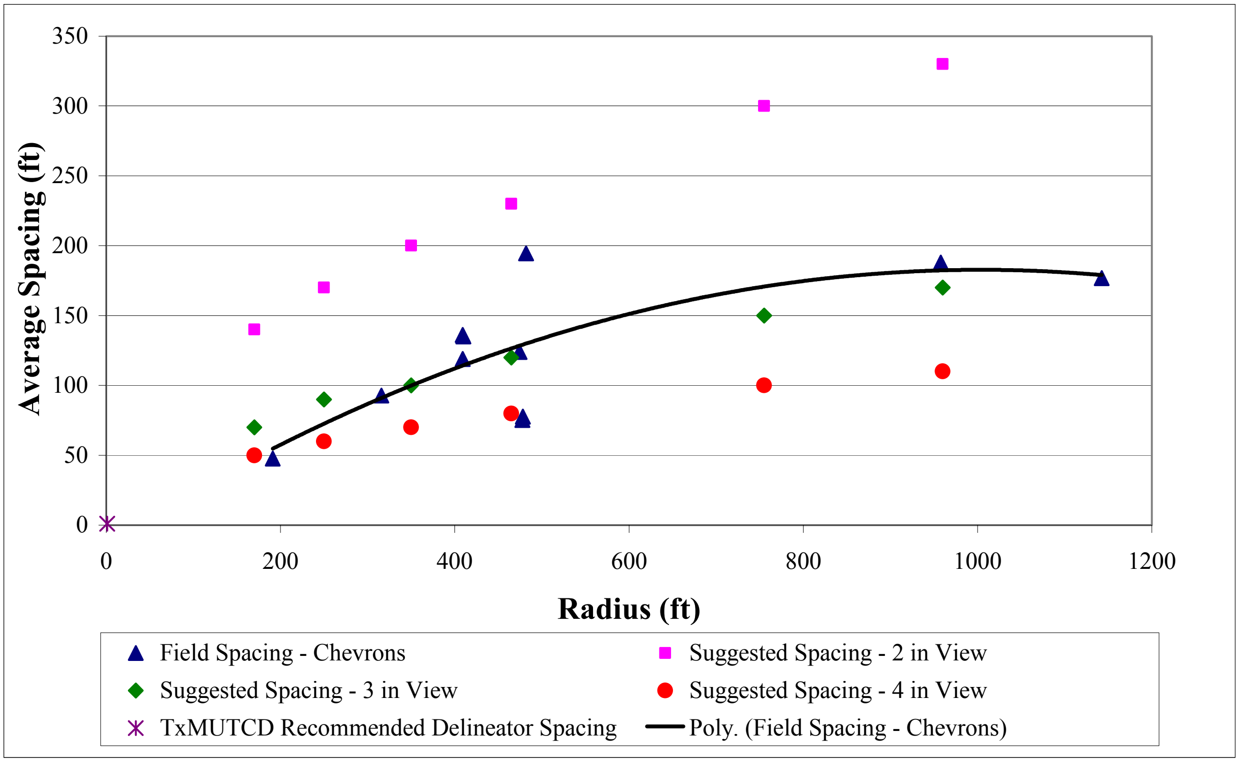

Figure 21. Suggested Chevron Spacing versus Field Chevron Spacing.

FIELD STUDIES

As described above, a theoretical Chevron spacing exercise was performed to develop a spacing table based on sight distance requirements. The results provide a spacing table for two, three, or four Chevrons in view at any time. In order to select the appropriate number of Chevrons to be visible to the driver, the researchers performed a field study to measure driver performance as a function of the number of Chevrons.

Researchers chose three curves that had previously been examined in this study to field test whether more than two Chevrons in view would provide additional information for a driver approaching and traveling around the curve. The following measures of effectiveness were analyzed to determine if more chevrons in view provided any benefits: approach speed, curve speed, and deceleration rates. Optimally, researchers would have performed a crash analysis; however, time constraints on the project prevented a crash analysis from being a viable option.

As mentioned previously, researchers selected three sites for this study. These sites were selected based on the current spacing of Chevrons and the severity of the three curves. Researchers selected one sharp, one medium, and one gentle curve (based on the advisory speed). The Chevron spacing on all three curves fell between two and three chevrons in view for the before condition based on the spacing shown in Table 49.

Table 50 shows several site characteristics of the selected curves. This table also shows the "before" average spacing and theoretical spacing from Table 49. According to theoretical calculations, all three curves would fall between two chevrons in view and three chevrons in view. However, at all three curves, the sight distance restrictions were less than the assumed sight restrictions for the theoretical calculations.

Table 50. Site Characteristics for Chevron Spacing Field Study.

Location	Advisory Speed	Radius	Average Superelevation	Average Spacing	Data from Table 49		
					2 in View	3 in View	4 in View
	(mph)	(ft)	(Percent)	(ft)	(ft)	(ft)	(ft)
FM 2223	50	958	+5.3	188	326	163	109
FM 2038	45	1142	+3.4	177	225	113	75
FM 1237	35	409	+5.0	119	195	98	65

FM 2223 was the gentle curve selected for this study. This curve had been repaved since researchers originally visited it during the pilot study. After it was repaved (i.e., for the Chevron field study), the curve ball banked at 50 mph, and the average superelevation was +5.3 percent for the side of the curve evaluated in this field study. FM 2038 was considered the moderate or average curve. The radius of this curve is actually larger than FM 2223; however, FM 2038 has only a very mild superelevation so the curve cannot be taken as fast as FM 2223. The advisory speed is set appropriately on this curve as well. FM 1237 was selected as the sharp curve. The advisory speed on this curve is actually set high. Using the TxDOT standard, the ball bank indicator should not exceed 10 degrees; the advisory speed on this curve should be set at 30 mph.

For ease of implementation, one Chevron was added halfway between each existing Chevron within the curve, essentially doubling the number of Chevrons on the curve. Single-sided Chevrons existed on the approach of FM 2038; however, additional Chevrons were not added in the approach of the curve.

Data Collection Procedures

Researchers obtained speed data at four locations on each curve using automated counters connected to pneumatic tubes. The first counter was placed upstream of the curve such that neither the curve nor any of the chevrons could be seen. Researchers placed another counter at the apparent PC on the curve, and a third counter at approximately the middle of the curve (MC). The distance along the curve between the classifier at the PC and the classifier at the MC was measured, and the final counter was placed the same distance upstream of the PC. Figure 22 illustrates the four locations where speed data were collected for each curve.

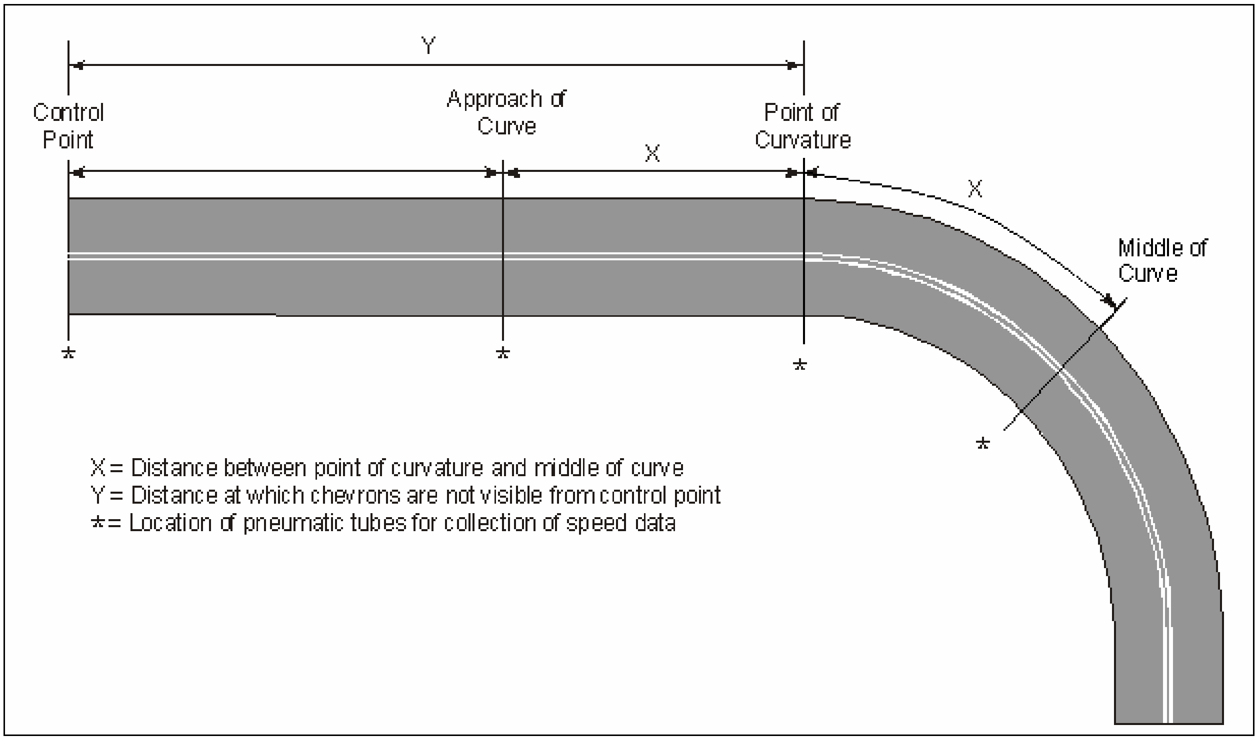

Figure 22. Illustration of Speed Data Collected.

Researchers collected both before and after data for each site only during the weekend in an attempt to capture more unfamiliar drivers (weekend data defined as: 12:01 a.m. Saturday – 11:59 p.m. Sunday). Unfamiliar drivers were desirable in this situation because they do not have a preexisting idea about the safe speed of a curve; thus, they rely more heavily on traffic control devices such as chevrons to provide them information about the alignment of the road.

Data Screening

The raw speed data measured at the project sites were screened to create a random and unbiased sample of speeds for free-flowing, uninhibited passenger vehicles. The objective of screening the data was to isolate the effect of additional chevrons on a curve by eliminating vehicles that might have adjusted their speed for some reason other than the curve treatment. Researchers attempted to identify and eliminate all anomalous vehicles such as vehicles slowing down to turn or vehicles that just turned onto the road and were not driving at a free-flow speed. The purpose of eliminating anomalous vehicles is to eliminate vehicles traveling at slower speeds for reasons unrelated to the additional chevrons on the curve. Researchers defined anomalous vehicles using the following criteria (all vehicles meeting these criteria were eliminated from the sample):

- vehicles with less than an eight second headway (criterion used to eliminate vehicles speeds that may have been influenced by the speed of the vehicle directly in front of it);
- vehicles with speeds lower than the speed limit minus 20 mph at the upstream control point (criterion used to eliminate vehicles that might have been slowing down to turn or vehicles that had just turned onto the road and were not yet at free-flow speed); and
- vehicles other than passenger vehicles (criterion used to eliminate heavy vehicles because they tend to have different speed patterns than passenger vehicles and researchers lacked control over the proportion of these vehicles during the before and after conditions. Thus, a higher proportion of heavy vehicles in the after study may cause the data to look as though all vehicles slowed down. There were too few present in the sample to perform an individual analysis for heavy vehicle speeds at each site.).

Data Formatting

Researchers collected spot speeds at each site in four different locations using classifiers and pneumatic tubes, and then downloaded the into either .txt files or .xls files. The data was then reduced to eliminate anomalous vehicles. Once in spreadsheet format, researchers compared timestamps at successive counters in an attempt to "track" vehicles through the site. By comparing the difference between the timestamps for two successive counters to the expected travel times based on speed and distance between the counters, researchers were able to track a vehicle's speed through the four counters in many instances.

Analysis

Researchers analyzed the data for this experiment using two different statistical tests. The first test was a multiple factor analysis of variance (ANOVA), and the second statistical test was a comparison of two binomial proportions (i.e., Z-test).

Analysis of Variance (ANOVA)

Researchers used ANOVA to test for significant differences between the mean speeds and decelerations for each site. ANOVA allows for testing of differences between mean values of multiple populations as a function of the independent variables (i.e., before study or after study, and day or night light conditions) and the interactions between the independent variables. Researchers ran two sets of ANOVA tests for each site. The first set of three tests were run to determine any significant differences in the mean speeds, and the second set of three ANOVA tests were run to determine any significant differences in deceleration between the before and after studies. The dependent variable for the first three ANOVA tests were one of the three different spot speeds: approach of curve (AC), point of curvature, and middle of curve. The dependent variable for the second three ANOVA tests were the difference between successive counters: control point speed – approach of curve speed (CP-AC), approach of curve speed – point of curvature speed (AC-PC), and point of curvature speed – middle of curve speed (PC - MC). As mentioned earlier, the data were reduced such that a vehicle's speed was tracked through the four classifiers using timestamp and expected speed data. The independent or fixed factors included light condition (day versus night as determined by sunrise and sunset times) and study (before versus after). The control point speed was entered into the analysis as a covariate. Researchers accounted for vehicles having different speeds prior to viewing the curve by adding the upstream speed as a covariate in this analysis. For example, vehicles traveling faster upstream of the site are also likely to travel faster through the curve; using the control point speed as a covariate accounts for these occurrences.

Z-Test for Comparing Two Binomial Proportions

The Z-test was used to compare the proportions of vehicles exceeding the speed limit and the advisory speed before the additional chevrons were placed to the proportions exceeding the speed limit and advisory speed after the additional chevrons were installed. These tests were useful for identifying any effect that the placement of additional chevrons had on the "upper extremities" of the speed data.

FIELD STUDY FINDINGS

This section describes the findings of the statistical analysis for the Chevron field study. Findings have been organized by the type of statistical analysis performed, which include:

- ANOVA analysis to compare mean speeds,
- ANOVA analysis to compare deceleration magnitudes between two spots speeds,
- 85th percentile speed comparisons, and
- Z-Test to compare proportion of vehicles exceeding the speed limit and advisory speed.

To keep this report as concise as possible, only summary statistics are given within the report. Appendix B presents detailed site-by-site results.

ANOVA Analysis

Researchers performed ANOVA analyses to compare the mean speeds at each of the three spot speed locations within the site (i.e., approach of curve, point of curvature , and middle of curve) with the upstream control point speeds coded in as the covariate for the analysis. ANOVA analyses were also performed to compare deceleration magnitudes between successive speed locations. The upstream control point speed was again used as a covariate. Researchers analyzed data for each site separately.

Comparing Mean Speeds

After running the ANOVA analysis, researchers examined the factors that significantly affected the mean speed at each spot speed location. Light condition (i.e., day versus night), study (before versus after), and the interaction between light condition and study were the factors in the analysis that could be shown to affect the mean speed. Table 51 shows which factors were shown to significantly affect the mean speeds at each point. When researchers found the interaction between light condition and study was found to be significant, they performed the ANOVA analysis again with the data file split by light condition. This means the ANOVA was performed with either the "day" data or the "night" data, and "Study" was the only independent factor. An interaction between "study" and "light condition" means that the additional chevrons may have had a different effect on the day and night data. In other words, there may have been a significant decrease in mean speeds at night but not during the day. Splitting the data, though not statistically necessary, helped researchers more clearly understand the effects of the additional signs.

Table 51. Summary of Significant Factors Found Comparing Mean Speeds.

Site	Significant Fixed Factors[1]				Curve Characteristics		Speed		Average	
	CP	AC	PC	MC	Radius (ft)	Δ[2] (°)	Limit[3] (mph)	Advis[4] (mph)	Space Before[5] (ft)	Space After[5] (ft)
FM 2223	S L	I	S I	S I	958	45.8	70	50	188	96
FM 2038	N	S L	S L	L	1142	47.1	70	45	177	86
FM 1237	L	S L	S L	S L	409	91.0	60	35	119	55

[1] S = Study (i.e., Before versus After); L = Light Condition (Day versus Night); I = Interaction (i.e., interaction between Study and Light Condition); N = No Significant Factors. Factors deemed significant based on ANOVA tests shown in Appendix B.
[2] Δ = External angle
[3] Limit = Speed limit
[4] Advis = Advisory speed for curve
[5] Average spacing reported

The factors that significantly affect control point (CP) speeds are the first important information to note from Table 51. At FM 2223, the gentle curve site, both the study period and the light condition significantly affected the mean speeds at this upstream location. This indicates that speeds were not only different between day and night conditions, but they were also different between the before and after study. Since the control point is located upstream of the site where the curve is not, in view this means that traffic at this location was generally either slower or faster for some unknown reason during the after study. The fact that traffic was different at the control point in the after study makes it difficult to draw any definitive conclusions at this site. However, study period was not a significant factor at the control point for either of the other sites. On FM 2038, there was no significant factors, indicating that mean speeds for traffic at the control point were about the same regardless of light conditions and the study period. On FM 1237, light condition was a significant factor, probably indicating that traffic drove slower at night. On FM 2223, as would be expected, since traffic was different at the control point, the interaction between study and light condition was found to be significant at all three locations. This result further complicates and weakens any conclusions drawn from the data at this site. On FM 2038 and FM 1237, however, there were no interactions. Study was a significant factor at two out of the three speed locations on FM 2038 and at all three of the speed locations on FM 1237.

Table 52 shows the mean speeds at the four locations for each curve. As shown in Table 51, the interaction between study and light condition is significant at all three spot speed locations within the site. It is possible for the interaction to mask significant differences between the before and after data that may only show up for one of the two light conditions. For this reason, researchers split the data file by light condition, and repeated the ANOVA analysis for the spot speed locations where the interaction was significant. Table 53 shows the results of this second analysis.

FM 2038 was the moderate or average curve site. The speed limit on this curve was 45 mph. There were no significant differences in speeds at the control point for the site on FM 2038. This indicates that traffic patterns were similar at the control point during both the before and after period. It also indicates that most vehicles did not drive any slower at night than during daylight at the control point. Table 52 also indicates that there was a significant difference in mean speeds between the before and after studies at the approach of the curve and at the point of curvature. Speeds were also significantly different between day and night conditions at these two locations. This result may seem a little confusing at the approach of the curve because the mean speeds for day are equal (60.6 mph). Remember, however, that the upstream control point speed was used as a covariate for each analysis. Upon closer examination, when vehicles reached the classifier at the approach of the curve, they had on average only reduced their speed by about 0.3 mph in the before study; whereas, the reduction was 1.9 mph in the after study. Another important detail to take note of is that the reduction in mean speeds at night is more obvious. Mean vehicle speeds for night data at the approach of the curve decreased from 60.1

mph to 58.9 mph after the additional Chevrons were installed, a decrease of 1.2 mph. At the point of curvature, again both study period and light condition were significant factors. Small reductions in mean speeds between the before and after study periods were seen during both day and night light conditions. Again, the reduction between before and after mean speeds was larger at night than during daylight. Mean speeds observed during daylight dropped from 55.6 mph to 54.9 mph (a reduction of 0.7 mph); whereas, the mean speeds at night fell from 55.4 mph to 52.8 mph after additional Chevrons were installed on the curve. This equates to a reduction of 2.6 mph in night mean speeds, which is more than three times the decrease observed at the same location during the day. There was no significant difference in mean speeds at the middle of the curve at this site between the before and after study. These results indicate that the additional chevrons did provide a benefit in the form of a small reduction in speeds approaching the curve and at the start of the curve. The benefits were more pronounced at night. Researchers observed a reduction of 1.2 mph at the approach of the curve and a reduction of 2.6 mph at the point of curvature at night after additional Chevrons were installed on the curve compared with no measurable reduction in the actual value of the mean speed at the approach of the curve and a 0.7 mph reduction at the point of curvature during daylight.

At FM 1237, researchers observed similar results to those seen on FM 2038. This site was considered the sharp curve. The advisory speed on the curve was 35 mph. At the control point, researchers found a significant difference between mean speeds with respect to the light condition (i.e., day versus night), but found no significant difference in the mean speeds between the before and after study. This result indicates that traffic speeds during the day in the before study were similar to traffic speeds during the day in the after study, and the same can also be said for the night data collected at the control point on FM 1237. There were also no significant interactions at this site so the data was not split by light condition. Both study and light condition were significant factors at all three locations within the site. At the approach of the curve, the installation of additional chevrons resulted in a subtle mean speed reduction from 52.1 mph to 51.8 mph for daylight data, a difference of only 0.3 mph. At night, mean speeds were reduced from 49.7 mph in the before study to 48.1 mph in the after study, a reduction in speed of 1.6 mph. At the point of curvature for daylight, data a reduction in speeds was again observed after the installation of additional chevrons. Daylight mean speeds at the point of curvature dropped from 42.9 mph in the before study to 40.2 mph after the installation of additional

Chevrons, a difference of 2.7 mph. Again, a more dramatic reduction in mean speeds was observed in the night data. Researchers observed a reduction in mean speeds, after the installation of additional Chevrons, from 41.0 mph to 37.2 mph at the point of curvature at night, a difference of 3.8 mph. At this site, mean speeds at the middle of the curve were also significantly different. During the day, mean speeds were reduced from 39.6 mph to 38.9 mph, (0.7 mph reduction), and night mean speeds were reduced from 38.7 mph to 37.3 mph after the installation of additional Chevrons, a reduction of 1.4 mph.

The results from FM 2038 and FM 1237 indicate that the additional chevrons had a greater effect on night speeds than day speeds. At both sites, the largest reduction in speeds were seen at the point of curvature; however, both sites experienced small reductions in mean speeds at the approach of the curve as well. The results also indicate that additional Chevrons in view affect speeds more dramatically on sharper curves.

Table 52. Effect of Additional Chevrons on Mean Vehicular Speeds.

Site	Time of Day[1]	Sample Size	Mean Speeds at Control Point (CP) (mph)			Mean Speeds Approaching Curve (AC) (mph)			Mean Speeds at Point of Curvature (PC) (mph)			Mean Speeds at Middle of Curve (MC) (mph)		
			Before	After	Total	Before	After	Total	Before	After	Total	Before	After	Total
FM 2223	D	1368	70.2[SL]	66.8[SL]	67.8	65.4[I]	63.8[I]	64.2[I]	61.0[SIU]	58.5[SIU]	59.2[SIU]	59.7[SI]	57.6[SI]	58.2[I]
	N	461	67.2[SL]	63.8[SL]	64.2	65.1[I]	61.3[I]	61.8[I]	60.7[SIU]	55.4[SIU]	56.1[SIU]	61.6[SI]	55.2[SI]	55.7[I]
	T		69.8	65.9		65.3[I]	63.0[I]		60.9[SIU]	57.6[SIU]		59.8[SI]	56.9[SI]	
FM 2038	D	355	60.9	62.5	61.8	60.6[SL]	60.6[SL]	60.6	55.6[SL]	54.9[SL]	55.3	53.8	54.3	54.0[L]
	N	122	61.5	61.6	61.6	60.1[SL]	58.9[SL]	59.6	55.4[SL]	52.8[SL]	54.2	52.5	51.7	52.2[L]
	T		61.1	62.3		60.5	60.2		55.6	54.4		53.4	53.6	
FM 1237	D	659	56.9	57.2	57.1[L]	52.1[SL]	51.8[SL]	52.0	42.9[SL]	40.2[SL]	42.8	39.6[SL]	38.9[SL]	39.2
	N	382	55.6	55.6	55.6[L]	49.7[SL]	48.1[SL]	49.1	41.0[SL]	37.2[SL]	40.5	38.7[SL]	37.3[SL]	38.0
	T		56.4	56.7		51.1	50.7		42.1	38.7		39.2	38.5	

[1] D = Day, N = Night, T = Total Average (i.e., Day + Night data)
[S] Difference in mean speeds between the before and after studies is statistically significant at a 95 percent confidence interval based on ANOVA analysis.
[L] Difference in mean speeds between the day and night light conditions is statistically significant at a 95 percent confidence interval based on ANOVA analysis.
[I] The interaction between the fixed factors (i.e., study and light condition) is statistically significant at a 95 percent confidence interval based on ANOVA analysis.
[U] Unequal variances
Gray highlighted cells indicate no significant difference.

As previously mentioned, researchers found significant interactions between study and light conditions in the original ANOVA analysis for the FM 2223 gentle curve site. In order to develop a better understanding of this data, researchers split the file by light condition, and the day and night data were analyzed separately. Table 53 shows a summary of the results from these analyses. After the data were split by light condition, the study period was found to be a significant factor at each spot speed location. However, because the mean speeds at the control point speeds were significantly slower after the additional Chevrons were installed, it is still difficult to draw any conclusions from the mean speed data. The difference in mean speeds at any spot speed location is influenced by the fact that traffic during the after study was driving slower in general. It is important to note that at the point of curvature unequal variances were only observed during the day data. Unequal variances indicate that the analysis is not valid. The deceleration analysis proved to be a better indicator of any benefits resulting from more Chevrons in view on the curve.

Table 53. Summary of ANOVA Analysis Split by Light Condition.

Site	Time of Day[1]	Sample Size	Mean Speeds at Control Point (CP) (mph)		Mean Speeds Approaching Curve (AC) (mph)		Mean Speeds at Point of Curvature (PC) (mph)		Mean Speeds at Middle of Curve (MC) (mph)	
			Before	After	Before	After	Before	After	Before	After
FM 2223	D	1368	70.2^SL	66.8^SL	65.4^S	63.8^S	61.0^SU	58.5^SU	59.7^S	57.6^S
FM 2223	N	461	67.2^SL	63.8^SL	65.1^S	61.3^S	60.7^S	55.4^S	61.6^S	55.2^S

[1] D = Day, N = Night
S = Study (i.e., Before versus After); L = Light Condition (Day versus Night); I = Interaction (i.e., interaction between Study and Light Condition); N = No Significant Factors. Factors deemed significant based on ANOVA tests shown in Appendix B.

Comparing Deceleration Magnitudes

ANOVA analysis was also used to compare the deceleration magnitudes for successive classifiers. The upstream control point was again used as the covariate in each analysis. Table 54 shows a summary of the factors that were statistically significant for each analysis.

Table 54. Summary of Significant Factors Found Comparing Deceleration Magnitudes.

Site	Significant Fixed Factors[1]			Curve Characteristics		Speed		Average	
	CP-AC	AC-PC	PC-MC	Radius (ft)	Δ[2] (°)	Limit[3] (mph)	Advis[4] (mph)	Space Before[5] (ft)	Space After[5] (ft)
FM 2223	I	S L	S L	958	45.8°	70	50	188	96
FM 2038	S L	S	S	1142	47.1°	70	45	177	86
FM 1237	S L	S	S L	409	91.0°	60	35	119	55

[1] S = Study (i.e., Before versus After); L = Light Condition (Day versus Night); I = Interaction (i.e., interaction between Study and Light Condition); N = No Significant Factors. Factors deemed significant based on ANOVA tests shown in Appendix B.
[2] Δ = External angle
[3] Limit = Speed limit
[4] Advis = Advisory speed for curve
[5] Average spacing reported

There was only one analysis with a significant interaction between light condition and study period. The significant interaction was again present on the FM 2223 gentle curve site. Study was a significant factor for all the other analyses performed. Table 55 gives the mean decelerations between each classifier for both before and after data.

On FM 2223, the interaction between study and light condition was significant for the deceleration between the control point and the approach of the curve. The data was split by light condition, and study was found to be a significant factor for both day and night data. In Table 55, it can be seen that vehicles actually decelerated less after the additional Chevrons were installed at this curve. A small but statistically significant difference in deceleration was observed for the night data after the additional Chevrons were installed. The deceleration between the approach of the curve and the point of curvature was found to be statistically lower after the installation of additional Chevrons on the curve. The difference between the before mean deceleration and the after mean deceleration was greater at night (difference = 1.5 mph) than during the day (difference = 0.8 mph), following the trend previously identified in the mean speed comparison for the other two curves. Between the point of curvature and the middle of the curve, vehicles actually decelerated less after additional Chevrons were installed during both daylight and night. This result could be a combination of the fact that traffic in the after study was generally slower than traffic in the before study and also traffic in the after study had already slowed down more by the time motorists had reached the point of curvature so they did not need to decelerate as much between the point of curvature and the middle of the curve.

Table 55. Effect of Additional Chevrons on the Magnitude of Deceleration.

Site	Time of Day[1]	Sample Size	Mean Deceleration between CP – AC (mph)			Mean Deceleration between AC – PC (mph)			Mean Deceleration between PC – MC (mph)		
			Before	After	Total	Before	After	Total	Before	After	Total
FM 2223	D	1368	4.8 I	3.0 I	3.5 LI	4.4 SL	5.2 SL	5.0	1.4 SL	0.9 SL	1.0
	N	461	2.1 I	2.5 I	2.4 LI	4.4 SL	5.9 SL	5.7	1.0 SL	0.2 SL	0.2
	T	1829	4.5 I	2.9 I		4.4	5.4		1.3	0.7	
FM 2038	D	355	0.3 SL	1.4 SL	1.1	4.9	4.9	5.3	1.7	2.8	1.3
	N	122	1.9 SL	2.8 SL	2.0	5.7	6.1	5.5	0.8	1.1	2.0
	T	477	0.6	2.09		4.9 S	5.8 S		2.0 S	0.9 S	
FM 1237	D	659	5.0 SL	5.6 SL	5.5	9.3	11.2	9.4	3.5 SL	2.4 SL	3.4
	N	382	6.0 SL	7.1 SL	6.5	9.3	11.4	9.5	2.0 SL	-0.7 SL	1.7
	T	1041	5.4	6.3		9.2 S	11.3 S	9.4	3.0	0.7	2.8

[1] D = Day, N = Night, T = Total Average (i.e., Day + Night data)
S Difference in mean speeds between the before and after studies is statistically significant at a 95 percent confidence interval based on ANOVA analysis.
L Difference in mean speeds between the day and night light conditions is statistically significant at a 95 percent confidence interval based on ANOVA analysis.
I The interaction between the fixed factors (i.e. study and light condition) is statistically significant at a 95 percent confidence interval based on ANOVA analysis.
U Unequal variances.
Gray highlighted cells indicate not significant data.

On FM 2038, the ANOVA analyses of the deceleration magnitudes confirm many of the conclusions previously drawn from the mean speed analyses. Deceleration magnitudes were greater in the after study for all three analyses. The average deceleration between the control point and the approach of the curve increased from only 0.3 mph during daylight to 1.4 mph after additional Chevrons were installed on the curve. Thus, on average, vehicles were slowing down 1.1 mph more after installing additional Chevrons on the curve between the control point and the approach of the curve. At night, the deceleration increased from 1.9 mph to 2.8 mph, a difference of 0.9 mph. So the average change in deceleration was actually slightly less at night than during the day between the upstream control point and the approach of the curve. Between the approach of the curve and the point of curvature the average deceleration increased from 4.9 mph in the before study to 5.8 mph in the after study for day and night data, a difference of 1.1 mph. Between the point of curvature and the middle of the curve, vehicles were actually decelerating less after additional chevrons were installed on the curve.

On FM 1237, the ANOVA analyses of the deceleration magnitudes show a similar trend to the results for FM 2038. Average deceleration magnitudes increased by 0.5 mph and 1.1 mph, respectively, for day and night data between the control point and the approach of the curve. Average deceleration between the approach of the curve and the point of curvature increased from 9.2 mph to 11.3 mph after additional chevrons were installed. Thus, traffic was slowing down on average 2.1 mph more after the curve treatment between the approach of the curve and the start of the curve. Between the point of curvature and the middle of the curve, vehicles actually decelerated less after additional Chevrons were installed for day time data; perhaps more interesting, at night vehicles actually sped up slightly between the point of curvature and the middle of the curve. This indicates that most vehicles at night had slowed down to a perceived safe speed by the point of curvature.

The largest changes in deceleration were seen between the approach of the curve and the point of curvature at all three locations. Also, at all three locations, vehicles actually slowed down less after the chevrons were installed when driving between the start of the curve and the middle of the curve. These results do continue to support the conclusion that the installation of additional Chevrons has provided some benefit.

Comparing 85th Percentile Speeds

Table 56 shows the 85th percentile speeds for each site. These data were not analyzed for statistical significance. As would be expected, the 85th percentile data at each site follows a similar trend to the mean speed data for each site. The largest differences between before and after data are seen at the start of the curve. Larger differences are seen on the sharper curve than the average curve. Again, it is hard to draw any conclusions about the data at FM 2223 since the after speeds at the control point are so much slower than the before speeds.

Table 56. Effect of Additional Chevrons on 85th Percentile Vehicular Speeds.

Site	Time of Day[1]	Sample Size	85th Percentile							
			Speeds Control Point (CP) (mph)		Approaching Curve (AC) (mph)		Point of Curvature (PC) (mph)		Middle of Curve (MC) (mph)	
			Before	After	Before	After	Before	After	Before	After
FM 2223	D	1368	76	72	71	69	67	64	66	63
	N	461	74	69	70	67	66	61	66	62
FM 2038	D	355	69	69	67	67	61	60	60	59
	N	122	68	68	67	66	61	59	58	58
FM 1237	D	659	65	65	58	57	48	44	44	43
	N	382	63	63	56	54	46	40	42	41

[1] D = Day, N = Night

Z-Test: Comparing Binomial Proportions

The percent of vehicles exceeding the speed limit and the advisory speed was also examined at the three curves. Appendix B contains the calculations for this test. Table 57 shows the results for the comparison of the percent exceeding the speed limit, and Table 58 shows the results for the comparison of the percent exceeding the advisory speed limit at each site.

On FM 2223, there was a significant difference between the percent of vehicles exceeding the speed limit in the before study and the percent of vehicles exceeding the speed limit in the after study, which was an expected result since the mean speed in the after study was significantly lower than the mean speed at the control point in the before study. There are significantly lower percentages of vehicles speeding at each point for daytime data at this site, but this could be attributed to the generally slower traffic. At the point of curvature and the middle of the curve, researchers found that the percent exceeding the speed limit was significantly lower; however, this too could be attributed to the generally slower traffic at this site in the after condition.

On FM 2038, there were no significant differences between the before and after percentages of vehicles exceeding the speed limit. The only significant difference between percentages of vehicles exceeding the advisory speed was seen at the point of curvature for the night data. Results were the same for FM 1237. Researchers detected no significant differences between the percentages of vehicles exceeding the speed limit between the before and after data, and the only difference detected between percentages of vehicles exceeding the advisory speed were at the point of curvature at night.

Table 57. Effect of Additional Chevrons on Percent Exceeding the Speed Limit.

Site	Time of Day[1]	Sample Size	Percent Exceeding Speed Limit: Control Point (CP) (Percent) Before	Control Point (CP) (Percent) After	Approaching Curve (AC) (Percent) Before	Approaching Curve (AC) (Percent) After	Point of Curvature (PC) (Percent) Before	Point of Curvature (PC) (Percent) After	Middle of Curve (MC) (Percent) Before	Middle of Curve (MC) (Percent) After
FM 2223	D	1368	45.9*	25.3*	16.0*	10.0*	4.8*	1.1*	3.9*	1.0*
	N	461	21.3	12.8	9.8	6.0	4.9*	0.5*	6.3*	0.5*
FM 2038	D	355	7.3	10.5	6.7	3.9	0.6	0.0	0.0	0.0
	N	122	10.6	8.9	4.5	0.0	0.0	0.0	0.0	0.0
FM 1237	D	659	33.5	34.5	8.2	8.1	0.0	0.0	0.0	0.0
	N	382	25.1	27.7	3.9	2.1	0.0	0.0	0.0	0.0

* Significantly Different at a 95 percent confidence interval based on Z-test.
[1] D = Day, N = Night.

Table 58. Effect of Additional Chevrons on Percent Exceeding the Advisory Speed.

Site	Time of Day[1]	Sample Size	Percent Exceeding Advisory Speed: Control Point (CP) (Percent) Before	After	Approaching Curve (AC) (Percent) Before	After	Point of Curvature (PC) (Percent) Before	After	Middle of Curve (MC) (Percent) Before	After
FM 2223	D	1368	100.0	99.7	98.7	97.7	96.2*	92.9*	95.0*	91.1*
	N	461	100.0	98.8	98.4	96.3	95.1*	80.0*	100.0*	79.8*
FM 2038	D	355	100.0	100.0	99.4	98.3	96.8	98.3	92.1	96.1
	N	122	100.0	100.0	100.0	100.0	100.0*	91.1*	88.1	85.7
FM 1237	D	659	100.0	100.0	99.3	99.3	95.8	89.5	84.1	84.7
	N	382	100.0	100.0	99.0	97.9	86.6*	60.0*	75.4	71.8

* Significantly Different at a 95 percent confidence interval based on Z-test.
[1] D = Day, N = Night.

SUMMARY OF RESULTS

The results of the Chevron field study indicate that having more than two Chevrons in view on a curve does provide the benefit of a small reduction in mean speeds. Additional Chevrons in view seem to provide a stronger effect at the point of curvature, a reduction in mean speeds of 2.6 to 2.8 mph. Also, the data indicates that additional Chevrons may provide more benefit on sharper curves than more moderate curves. Light condition was also a factor that often influenced the magnitude of reduction in speed. Researchers found that larger reductions in mean speeds were often seen in night data. The magnitude of deceleration followed the same trends. Little benefit was found when the percentages exceeding the speed limit and the advisory speed were compared. For both FM 2038 and FM 1237, a significant reduction of 8.9 and 16.6 percent, respectively, was observed in the percentage of vehicles exceeding the advisory speed. The data for FM 2038 and FM 1237 provide convincing evidence that increasing the number of Chevrons required to be in view on the curve will result in slower speeds around the curve.

CHEVRON SPACING TABLE

Using the findings presented above, the relationships shown in Figure 21, and the preliminary Chevron spacing computations summarized in Table 49, the researchers worked to refine the recommendations for Chevron spacing criteria. The process was designed so that at least Chevrons would be in view at any one time, but possibly four to five depending on the sight restrictions at specific curves. Furthermore, for ease of implementation, the Chevron spacing was rounded to 40-ft increments so that field crews could use the RRPM spacings along the curve centerline to determine the spacing of the Chevrons quickly and easily. The Chevron spacing table resulting from these assumptions and simplifications is shown in Table 59.

Table 59. Chevron Spacing.

Degree of Curve	Chevron Spacing (ft)
1	400
2	280
3 – 4	200
5 – 8	160
9 – 13	120
14 – 23	80
> 23	40

CHAPTER 8:
DELINEATOR VISIBILITY STUDIES

As mentioned in Chapter 1, one of the main objectives of this project was to determine if there was a need to distinguish between single and double delineators in the MUTCD. The current language of the MUTCD specifies the use of single delineators in certain applications and double delineators in other applications. If the visibility of single and double delineators is the same, and there is not difference between driver perception of roadway alignment or features as a function of delineator size, then there may not be a need to distinguish between single and double delineators.

Another issue was the viable spacing of delineators on the approach and departure to horizontal curves. The state-of-the-practice assessment demonstrated that this practice was rarely completed in full. Furthermore, the state survey showed that many states were modifying this MUTCD guideline to something much simpler.

The goals of this task were to:

- perform visibility studies to explore how drivers perceived delineated roadway features (such as curves, crossovers, and deceleration lanes) as a function of delineator size;
- perform visibility studies to explore how drivers perceived horizontal curves as a function of approach delineator spacing (using the MUTCD variable spacing technique and a fixed spacing technique); and
- evaluate drivers' understanding of delineator color.

Subjects

Twenty-four Texas drivers participated in the study. They were all recruited from the Bryan-College Station area. Each participants received $40 for participating. An equal number of men and women participated. The subjects were divided into two groups by age: Younger, ranging from 22 – 44 years old with a mean age of 32.3; and Older, ranging in age from 55 to 72 years old with a mean age of 64.3.

Vision Tests

The researcher administered three vision tests: a Snellen acuity "eye chart test", a Vistech contrast sensitivity screening test, and a Color Vision test with color plates. The researcher recorded the participant's performance in each of the tests on the demographic information forms.

The results of the vision test showed all participants to have acuity of 20/40 or better, with a median acuity of 20/20. None of the participants displayed color vision deficiencies. The contrast sensitivity scores were all in the normal range, except for the older group at the highest spatial frequency, which is typical of older individuals.

Experimental Session Procedure

Each experimental session began in a TTI office where the participant could easily read and fill out the appropriate paperwork and a researcher could administer the various vision tests. The participant first read and signed the informed consent form; then the researcher made sure the participant understood the study and answered any questions that arose. The researcher stressed that only an ID number would identify the participant during the data collection part of the study. The participants were informed that they could choose not to continue to participate in the research study at any time. They would then receive compensation based on the portion of time participated.

After signing the consent form, the participant was asked to fill out a form containing simple demographic and driving habit information.

The vision tests were administered, followed by the memory test for delineator color. After these tasks were completed in the office, the field test began. All testing was completed in 60 to 75 minutes.

Memory Test for Delineator Color

Before the participants were given any instructions concerning the actual field test, they were given a self-administered pre-test containing short questions concerning photographs of various pieces of roadway. All photographs were printed, in color, full size on 8 ½ x 11 inch paper with an identifying number printed in the corner. Each was placed in a page protector in a three-ring binder. Each subject received a separate piece of paper with the questions listed, each referring to a numbered photograph.

The questions assessed the participant's knowledge of the appropriate usage of yellow and white reflectors. The first question, shown below, was asked at the beginning of the survey to allow subjects to freely produce a color name. Then, the same photograph was shown later in the book, and the researcher asked the subjects to choose between only yellow and white. In addition to identifying the correct color, subjects were asked to rate their confidence in their answers. The roadways shown included one left-hand curve, a crossover without a deceleration lane, and a crossover with a deceleration lane with delineators that showed either yellow or white reflectors.

EXAMPLE OF PRODUCTION QUESTION. In this photo of a left curve, there are several posts on the right side of the road that would have reflectors on them. What color would the reflectors on these posts be ? ______________________

Please rate your confidence in the correctness of your answer (circle a number):

1	2	3	4	5
I am very unsure that I am right				I am very sure that I am right

EXAMPLE OF FORCED CHOICE QUESTION. In this photo of a left curve, there are several posts on the right side of the road that would have reflectors on them. Should the reflectors on these posts be:

a) White b) Yellow

(Circle a color)

Please rate your confidence in the correctness of your answer (circle a number):

1	2	3	4	5
I am very unsure that I am right				I am very sure that I am right

Field Setup

All field testing was conducted after dark. Each participant drove a 1999 Ford Taurus Sedan with low beam headlamps. The windshield and headlamps were cleaned each evening.

The researcher sat in the front passenger seat with a clipboard to record responses illuminated by a flashlight with a red lamp so night vision was not affected. A Numetrics ™ Distance Measuring Instrument was used to record distances, where appropriate. Participants were instructed to drive a maximum of 30 mph. Both occupants wore their safety belts. The complete instructions are provided in Appendix C.

The driving course consisted of four curves marked by delineators, and one straight-away marked by one right-hand and one left-hand delineator. Each participant would drive the course four times. Between each lap, additional researchers traveling in a separate vehicle altered two variables of the curves and one of the straight-away. At each curve, the subject provided a subjective assessment of the degree of curvature using a five-point rating scale, described in detail below. For the straight-away, the detection distance of each post was measured as well as the distance at which the subject could identify how many individual reflectors were present on the post.

When surveying the placement of each curve's delineator posts, marks were made on the ground to represent both a fixed spacing and a variable spacing of the posts along the curve's tangent. From point of curvature to point of curvature throughout the curve itself, the delineator spacing was constant regardless of the tangent spacing. Curves of two different actual radii were used in the study; 300 ft and 950 ft curve radius were used. Figure 23 illustrates the fixed and variable spacing. For example, Curves 1 and 3 were 300 ft radius curves and had the delineators placed within the curve spaced 50 ft apart. For the fixed spacing of the delineators along the tangent, the curve spacing was doubled, and the delineators were placed at 100 ft from each other. For the variable spacing along the tangent, the Sign Crew Field Manual Table 7-2 was followed for spacing of 180 ft, 270 ft, and 300 ft from each other. For each curve, only three delineators were used along the tangent. For Curves 2 and 4, the curve radius was 950 ft, so the delineators within the curve were spaced farther apart at 90 ft. For the fixed spacing along the tangent, the delineators were spaced at 180 ft apart, and for the variable spacing, the delineators were placed at 95 ft, 145 ft, and 285 ft from each other. Each delineator post was attached to a 2 x 4 base that allowed it to be easily moved between the fixed and variable spacing. The posts reached a height of 4 ft above the pavement. See the figure below as an example of the spacing for a 300 ft radius curve. Figure 24 shows an example of the posts used in Curve 1.

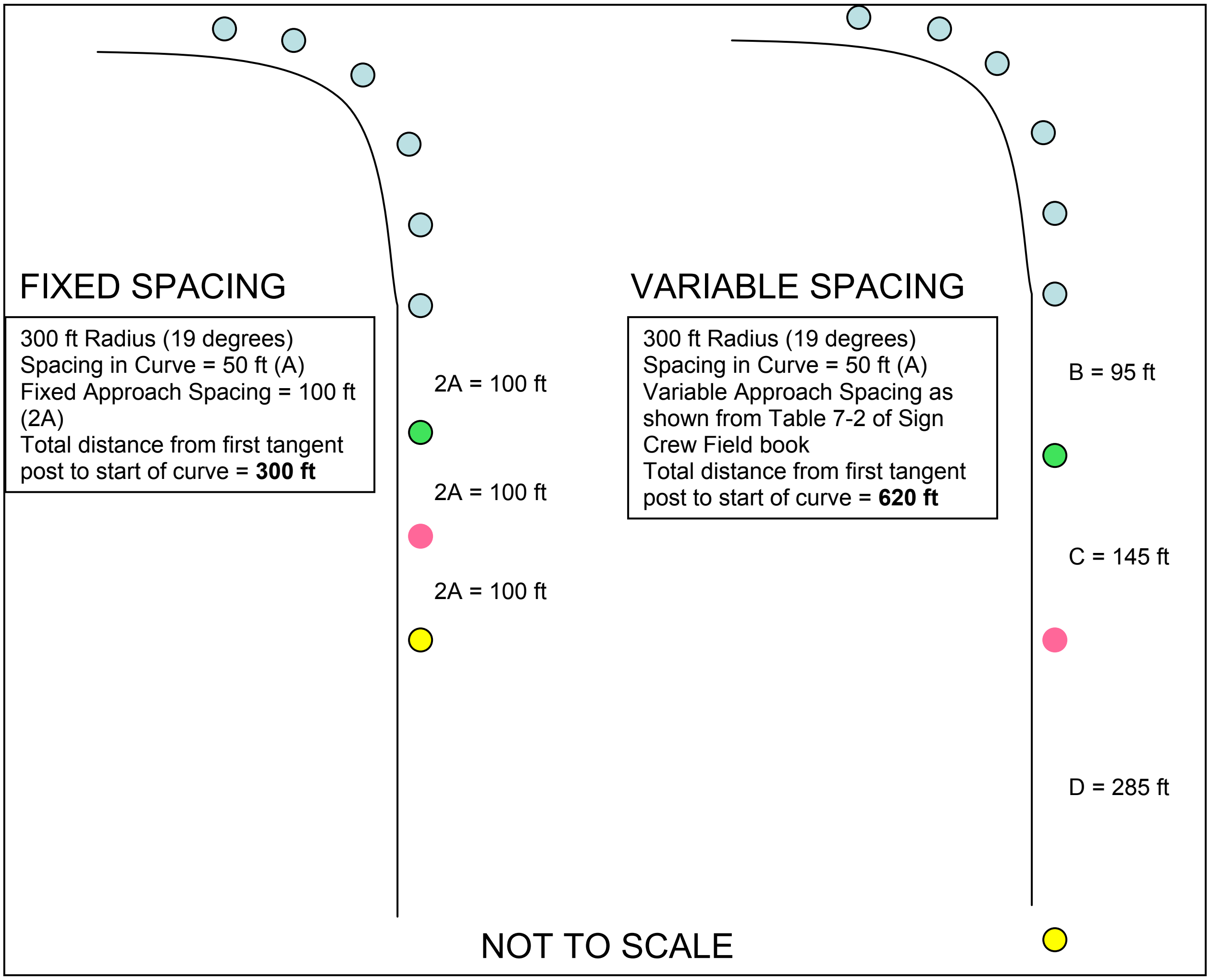

Figure 23. Post Positions with Fixed and Variable Spacing.

Figure 24. Example of Marked Curve.

Along with a change in spacing, the other variable altered was the number of reflectors on the delineator post. Although the reflectors were always white along the curves, the number of reflectors were altered between one or two. Extra reflective sheeting cut at the appropriate dimension and affixed to a card could easily be added by using a rubber band to attach the card to the post. This allowed for quick alterations of each post between laps.

Four total independent variables were used in the setup of the curves from lap to lap: curve radius, curve direction, delineator spacing, and the number of reflectors. Although the curve radius and curve direction could not be altered during the experiment runs, the delineator spacing and number of reflectors were. Table 60 shows the complete experimental design of the four curves for the duration of four laps.

Table 60. Experimental Design for the Degree of Curvature Rating Task.

	Lap 1	Lap 2	Lap 3	Lap 4
Curve 1 300 ft Radius Right Curve	Fixed Spacing 2 Reflectors	Variable Spacing 1 Reflector	Variable Spacing 2 Reflectors	Fixed Spacing 1 Reflector
Curve 2 950 ft Radius Right Curve	Fixed Spacing 1 Reflector	Variable Spacing 2 Reflectors	Variable Spacing 1 Reflector	Fixed Spacing 1 Reflectors
Curve 3 300 ft Radius Left Curve	Variable Spacing 2 Reflectors	Fixed Spacing 2 Reflectors	Fixed Spacing 1 Reflector	Variable Spacing 1 Reflector
Curve 4 950 ft Radius Left Curve	Variable Spacing 1 Reflector	Fixed Spacing 1 Reflector	Fixed Spacing 2 Reflectors	Variable Spacing 2 Reflectors

The straight-away section of the driving course was located between Laps 1 and 2. Only one variable was changed between laps for these two delineators: the number of reflectors on the post. This variable was altered in the same manner as the posts located on the curves, although the left post would always display yellow reflective sheeting, while the right post displayed white. The posts were positioned approximately 1500 ft apart, with the first post placed 2500 ft from the starting point. Table 61 shows the randomization of the posts' configurations for the four laps.

Table 61. Experimental Design for Detection Task.

	Lap 1	Lap 2	Lap 3	Lap 4
Post 1 Right-Hand Side	2 Reflectors	3 Reflectors	1 Reflector	Blank
Post 2 Left-Hand Side	2 Reflectors	1 Reflector	Blank	3 Reflectors

Field Study Procedure

For the field study, a TTI-owned passenger vehicle instrumented with a distance measuring instrument (DMI) was used. During data collection, the participant drove the vehicle while a researcher rode in the front passenger seat. The researcher also ensured that the vehicle's low beam headlights were on.

Before beginning, the participants were given a verbal description of the study and the tasks they would perform. The researcher explained that they would participate in two different types of tasks: a curve identification task and a reflector identification task.

For the curve identification task, the researcher would ask the participant to drive to a point marked by blue raised pavement markers (RPMs) and then stop there. They would then be asked what direction they believed the road was curving, and which illustrated curve best matched their perception of the curve ahead. Figure 25 shows the illustrated curves for a left curve that the researcher presented to the participant. An analogous card was presented for right curves (see Figure 26). On this card, curve 2 is a 950 ft radius curve, and curve 4 is a 300 ft radius curve. The curves were drawn in MicroStation and then reproduced on the cards. The range of curve radii were selected to bracket the actual curves. As will be discussed, subjects rarely selected the most extreme curve (Number 5).

The subject was asked to rate the curve at three stopping points at distances of 1500, 1000, and 500 ft from the point of curvature. The procedure would be repeated for the four separate curves, and the entire course was driven four times. The researcher would record the participant's responses on a data sheet.

For the detection task, the participants would be looking for a single delineator post on the right side of the road, and then one on the left. For each post, they were instructed to say "POST" as soon as they identified that they saw something there, and then, as they continued to approach the post, they would say the number of reflectors that were on the post when they felt they could correctly identify them. Before driving this segment, the participant was instructed to drive between two cones and the researcher would zero the DMI. For consistency, each participant was asked to drive the straight-away at 30 mph. The researcher would use the DMI to determine and record the distance from the starting points of each of the participant's responses. The participant would drive the straight-away once in each of the four laps.

Figure 25. Rating Scale for Left Curves.

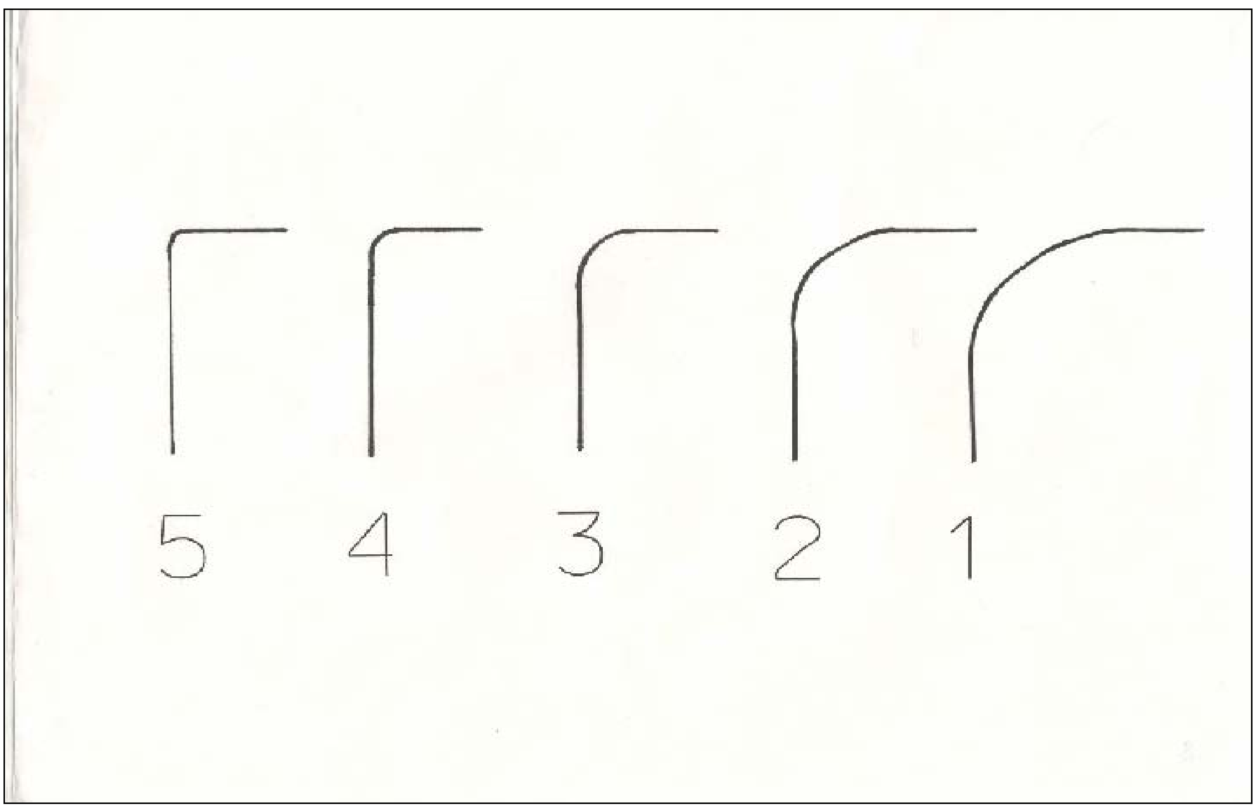

Figure 26. Rating Scale for Right Curves.

RESULTS

Memory for Delineator Color

Color of Delineators in Curves

Two questions focused on color of delineators in curves. The first question asked subjects to freely produce an answer; the second question asked subjects to choose between yellow and white reflectors. The correct answer is white. Figure 27 shows the photograph used for these questions. In the production version, no reflector was present. The results are shown in Table 62. In the forced choice version, two photographs were shown on the page, one with white reflectors and one with yellow reflectors. Table 63 shows these results. The posts in each photograph were white.

The majority of responses were incorrect. Nearly 80 percent of responses on the production question and 70 percent on the forced choice question were incorrect. Those who responded correctly (white) had slightly higher confidence ratings than those who responded incorrectly. For the forced choice, the confidence ratings were slightly higher for the incorrect answers.

Figure 27. Stimulus for Curve Delineator Question.

Table 62. Summary of Responses to Color Production Question for Curve Delineators.

Color	Percent	Number	Average Confidence Rating
Orange	20.83%	5	3.80
Red	12.50%	3	3.33
White	20.83%	5	4.00
Yellow	37.50%	10	3.50
Yellow Orange	4.17%	1	5.00
		SUMMARY	
	Percent	Number	Colors
Correct	20.83%	5	White
Incorrect	79.17%	19	Orange, Yellow, Yellow Orange, and Red
Total		24	

Table 63. Summary of Responses for Forced Choice for Curve Delineator Color.

Color	Percent	Number	Average Confidence Rating
White	29.17%	7	3.43
Yellow	70.83%	17	3.65

Crossover without Deceleration Lane

Two questions focused on color of delineators at crossovers without deceleration lanes. The first question asked subjects to freely produce an answer; the second question asked subjects to choose between yellow and white reflectors. The correct answer is yellow. Figure 26 shows the photograph used for these questions. In the production version, no reflector was present. Table 64 shows the results. In the forced choice version, two photographs were shown on the page, one with white reflectors and one with yellow reflectors. Table 65 shows these results. The posts in each photograph were white.

The results to these questions show more disagreement between the color production and the forced choice questions. When asked to produce a color freely, 54 percent of responses were correct as yellow or orange. Those who responded incorrectly (white) had slightly higher confidence ratings. When forced to choose, however, the percent correct jumped to 70 percent. There was little difference in the confidence ratings for the forced choice question.

Figure 28. Stimulus for Crossover without Deceleration Lane Question.

Table 64. Summary of Responses to Color Production Question for Crossover without Deceleration Lane.

Color	Percent	Number	Average Confidence Rating
Blue	4.17%	1	2.00
Orange	8.33%	2	3.00
Red	25.00%	6	2.50
White	16.67%	4	3.50
Yellow	45.83%	11	3.27
SUMMARY			
	Percent	Number	Colors
Correct	54.17%	13	Orange and Yellow
Incorrect	45.83%	11	Red, Blue, and White
Total		24	

Table 65. Summary of Responses for Forced Choice Question for Crossover without Deceleration Lane.

	Percent	Number	Average Confidence Rating
Correct	29.17%	7	3.20
Incorrect	70.83%	17	3.32
Total		24	

Crossover with Deceleration Lane

Two questions focused on color of delineators at crossovers, with deceleration lanes. The first question asked subjects to freely produce an answer, the second question asked subjects to choose between yellow and white reflectors. The correct answer is yellow. Figure 29 shows the photograph used for these questions. In the production version, no reflector was present. The results are shown in Table 66. In the forced choice version, two photographs were shown on the page, one with white reflectors and one with yellow reflectors. Table 67 shows these results. The posts in each photograph were white.

Figure 29. Stimulus for Crossover with Decleration Lane Question.

The results to these questions again show disagreement between the color production and the forced choice questions. When asked to produce a color freely, 59 percent of responses were correct as yellow or orange. Those who responded correctly (yellow) had slightly higher confidence ratings. When forced to choose, however, the percent correct jumped to nearly 80 percent. There was little difference in the confidence ratings for the forced choice question.

Table 66. Summary of Responses for Color Production Question on Crossover with Deceleration Lane.

Color	Percent	Number	Average Confidence Rating
Orange	25.00%	6	2.50
Red	16.67%	4	2.25
White	25.00%	6	3.17
Yellow	33.33%	8	3.25
		SUMMARY	
	Percent	Number	Colors
Correct	58.33%	14	Orange and Yellow
Incorrect	41.67%	10	Red and White
Total		24	

Table 67. Summary of Responses to Forced Choice Question on Crossover with Deceleration Lane.

Color	Percent	Number	Average Confidence Rating
White	20.83%	5	3.20
Yellow	79.17%	19	3.21

Degree of Curvature Ratings

The curve rating scale developed for the study was shown to be somewhat biased in that respondents only chose the most extreme curves three times. A total of 1152 ratings were obtained from 24 subjects rating four curves each three times across four laps (24 x 3 x 4 x 4 = 1152). Figure 30 shows the overall distribution of the ratings, illustrating this bias. Even with this bias in the scale, the differences between the fixed and variable spacing can be examined, as can the difference between one and two reflectors.

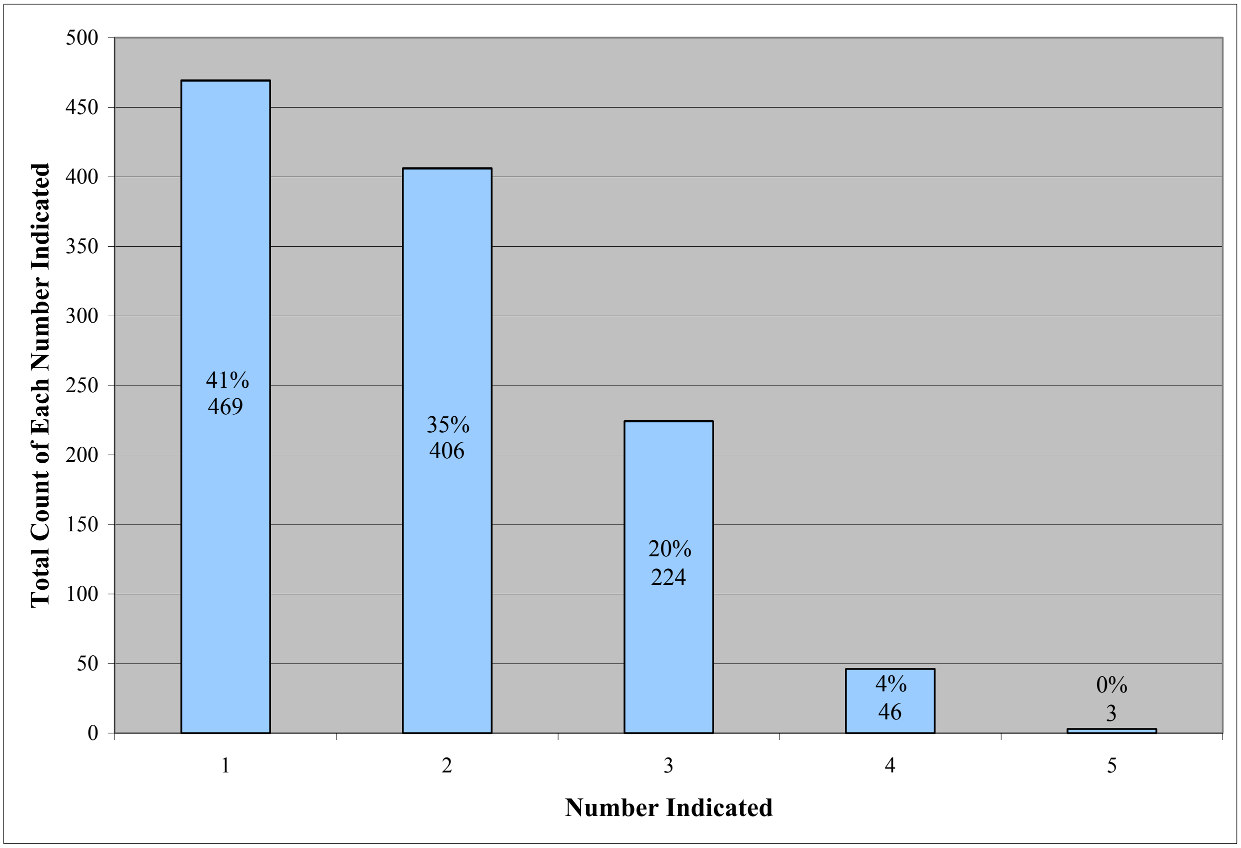

Figure 30. Overall Distribution of Curve Ratings.

Overall the viewing distance did not affect the ratings significantly as shown in Table 68.

Table 68. Distribution of Ratings as a Function of Viewing Distance.

Rating	500	1000	1500
1	14.4%	14.1%	12.2%
2	11.0%	11.9%	12.3%
3	6.7%	6.1%	6.7%
4	1.2%	1.1%	1.6%
5	0.0%	0.1%	0.2%

The actual radius of the curve did affect the ratings as shown in Table 69. The small radius curves had more ratings in category 3 than did the large radius curves.

Table 69. Distribution of Ratings as a Function of Actual Curve Radius.

Rating	Large Radius	Small Radius
1	24.0%	16.8%
2	17.9%	17.4%
3	6.1%	13.4%
4	2.0%	2.0%
5	0.0%	0.3%

The effects of spacing can be examined by comparing the distribution of ratings for fixed and variable spacing. These distributions are shown in Table 70. There are only slight differences between the two, with variable spacing resulting in more ratings in category 1, which indicates the perception of less curvature.

Table 70. Distribution of Ratings as a Function of Delineator Spacing.

Rating	Fixed	Variable
1	19.5%	21.2%
2	18.4%	16.8%
3	9.8%	9.6%
4	2.1%	1.9%
5	0.0%	0.3%

Likewise, Table 71 compares the ratings for curves with one reflector versus two reflectors on the delineator post. The results suggest a tendency to give more category 1 ratings to one reflector, which translates to a perception of less curvature. These results, taken along with those comparing fixed and variable spacing, suggest that variable spacing with one reflector results in a perception of slightly less curvature.

Table 71. Distribution of Ratings as a Function of Number of Reflectors.

Rating	One Reflector	Two Reflectors
1	21.4%	19.4%
2	16.9%	18.3%
3	9.3%	10.2%
4	2.2%	1.8%
5	0.1%	0.2%

Detection Distance

The configuration of the posts for the detection distance task did not allow sufficient viewing distance for some subjects. That is, at the starting point, 2500 ft from the first post, many subjects could immediately see the post. For that reason, the data are presented here in two ways. First, the average detection distances are given, followed by a presentation of the percentage of people who could see the post at the starting point. The data in Table 72 are the average detection distances for all subjects, given in ft, as a function of the number of reflectors present on the post. Table 73 gives the detection distances for the younger age group only. Note that for the three reflectors condition, all of the subjects detected the post at the starting point of 2500 ft. Table 74 shows the older subject's detection distances. For both groups, there was a pronounced increase in detection distance when moving from two to three reflectors. This observation is most clear when looking at the Post 2 data only where subjects had up to 4000 ft of viewing possibility for the post (2500 ft from the starting point to the first post, plus 1500 feet from the first post to the second).

The next set of tables show the percentage of detection responses that were made immediately at the starting point. Table 75 contains the data for all the subjects and illustrates that even at a distance of 4000 ft, 4 percent of the participants could detect the three reflector yellow post at position 2. The differences in age can be seen by comparing Tables 76 and 77, where roughly twice as many younger drivers could immediately detect each of the posts when compared to the older group.

Table 72. Average Detection Distances (All Subjects).

Number of Reflectors	Post 1 (White Delineators) (ft)	Post 2 (Yellow Delineators) (ft)
0	959.62	592.96
1	2070.50	1464.21
2	1897.82	1441.25
3	1985.67	2162.78

Table 73. Average Detection Distances (Younger Age Group Subjects).

Number of Reflectors	Post 1 (White Delineators) (ft)	Post 2 (Yellow Delineators) (ft)
0	975.50	765.75
1	2224.25	1600.67
2	2023.67	1778.75
3	At least 2500	2568.08

Table 74. Average Detection Distances (Older Age Group Subjects).

Number of Reflectors	Post 1 (White Delineators) (ft)	Post 2 (Yellow Delineators) (ft)
0	945.18	404.45
1	1993.63	1327.75
2	1850.63	1103.75
3	1985.67	1720.64

Table 75. Percentage of Detection Distances at Starting Point (All Subjects).

Number of Reflectors	Post 1 (White Delineators)	Post 2 (Yellow Delineators)
0	12.50%	0.00%
1	50.00%	0.00%
2	54.17%	0.00%
3	75.00%	4.17%

Table 76. Percent of Detection Distances at Starting Point (Younger Age Group Subjects).

Number of Reflectors	Post 1 (White Delineators)	Post 2 (Yellow Delineators)
0	16.67%	0.00%
1	66.67%	0.00%
2	75.00%	0.00%
3	100.00%	0.00%

Table 77. Percentage of Detection Distances at Starting Point (Older Age Group Subjects).

Number of Reflectors	Post 1 (White Delineators)	Post 2 (Yellow Delineators)
0	8.33%	0.00%
1	33.33%	0.00%
2	33.33%	0.00%
3	50.00%	8.33%

CHAPTER 9:
FINDINGS AND RECOMMENDATIONS

This chapter describes the findings of each of the research tasks that were completed in this project. Based on the research findings, the researchers have provided a number of recommendations that are meant to simplify delineator and Chevron applications without jeopardizing safety.

PROJECT FINDINGS

The project findings have been organized by each individual research task in order to demonstrate the broad range of activities that were completed within this effort. Each subheading below provides a summary of the findings from each specific research task.

Literature Review

The researchers determined that the FHWA has not maintained records that document the reason or justification for the current MUTCD language regarding the delineator and Chevron issues under investigation in this project. The researcher also learned that there has been very little research devoted to the issues at hand, and the little that exists provides inconsistent results. Finally, the researchers also collaborated with other researchers performing potentially related studies to avoid redundancy. In particular, the researchers have contacted and coordinated efforts with an NHCRP Research Project, 3-61, *Communicating Changes in Horizontal Alignment*.

State Survey

As described in Chapter 3, the researchers designed and administered a survey to the states to determine the state-of-the-practice regarding delineation and Chevron applications around the country. A total of 34 states responded to the survey. Of particular significance was the finding that 63 percent of the states delineate gentle curves on expressways and freeways as tangent sections. The cutoff curve radii criteria for this decision ranged from 2865 ft to 14,000 ft, with and average of 6400 ft. The survey also revealed that most states still use the radius-dependent delineator spacing in the MUTCD, but they simplify the approach and departure delineator spacing to the horizontal curves. Even though most states still use the radius-dependent spacing table for delineation, there were no innovative solutions suggested for determining radius in the field. Some states are still using the chord method.

State-of-the-Practice

The researchers visited a number of horizontal curves early in the project to assess the current state-of-the-practice regarding curve delineation treatments. On average, delineator spacing was about what was recommended by MUTCD but there are large variances indicating lack of consistency. Furthermore, there was no strong relationship found between radius and delineator spacing or radius and Chevron spacing. This effort also discovered that if delineators are used on the approach and departure tangents to horizontal curves (which is a rather uncommon event; only one is used, and it is typically spaced at S, or the same spacing as used in the curve).

The Chevron spacing varied significantly among districts. One consistent finding, however, was that the use of Chevrons in horizontal curves appeared to start and end at the transition point between the curve and the tangent (either the approach or departing tangent). The research also learned that curves are not delineated in accordance to TxDOT guidelines, but again, a large difference was found from district to district.

There were no systematic differences found in three different BBI devices. However, the use of the BBI devices was a concern. Overall, only 29 percent of advisory speed values were considered to be set appropriately (when using all three BBI devices). The score increased to approximately 47 percent when at least one BBI measurement agreed with the speed advisory plaque setting. There also appeared to be inconsistent setting of the advisory speed plaque from district to district. In other words, when the values that were set in the field did not match the researchers' values, some districts tended to be higher in nearly all the cases while other districts appeared to be lower in nearly all the cases.

Preliminary Spacing Procedures

A total of nine different spacing techniques were initially considered and investigated. The results of the initial investigations were presented to the project advisory panel and two methods were selected for complete development – the advisory speed method and the GPS method.

Final Spacing Procedures

Chapter 6 of the report describes the work that was completed in order to fully develop two methods for spacing delineators and/or Chevrons in horizontal curves. The advisory speed method is simple to use but has more error. The field personnel simply use the advisory speed value in a look-up table to determine the appropriate spacing. The accuracy of the technique relies on an accurate advisory speed value setting, and as discussed above, the advisory speed values across the state are not set consistently. The second method uses a GPS-based device (named the Radiusmeter in this project) developed by the research team. This device is highly accurate and easy to use, but requires an initial investment of $400 to $500. The Radiusmeter produces an immediate radius value after traversing a horizontal curve at highway speed in any type of vehicle.

Chevron Spacing Field Study

In this part of the project, the researchers tried to develop a more objective procedure for spacing Chevrons along horizontal curves. The first task that was completed was the development of a theoretical spacing table based on sight distance restrictions and assumed curve geometrics and vehicle dynamics. This effort resulted in a Chevron spacing table with two, three, or four Chevrons in view at any one time. The researchers then performed a field study to determine drivers' responses to an increased number of Chevrons. They found that having more than two Chevrons in view does provide small benefits in terms of decreased speeds entering and traversing horizontal curves. For instance, at the point of curvature, the researchers observed a decrease of about 3 mph in average speeds after the number of Chevrons in the curve was increased. They also found that the speeds at night were particularly lower after the Chevron numbers were increased.

Delineator Visibility Study

Several of the issues related to this research dealt with the visibility of delineators. For instance, the MUTCD distinguishes between single and double delineators, and the MUTCD also provides guidelines for spacing delineators at variable spacings entering and leaving horizontal curves. In order to address whether these guidelines provide any measurable benefits, the researchers performed a nighttime visibility study at Texas A&M University's Riverside Campus.

The researchers determined that drivers cannot distinguish between single and double delineators, and they cannot distinguish between variable spacing and fixed spacing on approaches to horizontal curves. The researchers also discovered that drivers do not understand the difference between yellow and white delineators.

RECOMMENDATIONS

Based on the findings summarized above, the researchers recommend the following procedures and practices.

For spacing delineators and Chevrons in curves, TxDOT's policies and standards should include Table 78 for field personnel. This table allows the field personnel to easily determine an appropriate spacing for delineators or Chevrons using the advisory speed. It recommends a simpler procedure for spacing delineators on the approach and departure to horizontal curves. A note of caution should be included with this table so that the advisory speed value is double-checked for accuracy. For ultimate accuracy, however, the researchers recommend that the Radiusmeter be used to determine the radius and select spacing using the MUTCD criteria or Table 79.

Table 78. Spacing Criteria for Field Personnel.

Advisory Speed Value (mph)	Delineator Spacing = S (ft)	Chevron Spacing = S (ft)
15	35	40
20	40	80
25	50	80
30	55	80
35	60	120
40	70	120
45	75	160
50	85	160
55	100	160
60	110	200
65	130	200
NOTE: Approach and departure delineation on horizontal curves should be spaced at 2S using three delineators or one Chevron.		

For spacing delineators and Chevrons in curves, TxDOT's policies and standards should include Table 79 for engineers. This table allows the engineers to easily determine set appropriate spacing for delineators or Chevrons based on the radii of the curves in the design plans. Like Table 78, it also recommends a simpler procedure for spacing delineators on the approach and departure to horizontal curves. Furthermore, it includes a cutoff for delineation of curves at one degree of curvature (based on the state survey). Table 79 could be used by field personnel if they knew the radius or had a device to measure the radius such as the Radiusmeter.

Table 79. Radius-Based Spacing Recommendations.

Degree of Curve	Radius (ft)	Delineator Spacing = S (ft)	Chevron Spacing = S (ft)
1	5730	225	400
2	2865	160	280
3	1910	130	200
4	1433	110	200
5	1146	100	160
6	955	90	160
7	819	85	160
8	716	75	160
9	637	75	120
10	573	70	120
11	521	65	120
12	478	60	120
13	441	60	120
14	409	55	80
15	382	55	80
16	358	55	80
19	302	50	80
23	249	40	80
29	198	35	40
38	151	30	40
57	101	20	40
NOTE: Approach and departure delineation on horizontal curves should be spaced at 2S using three delineators or one Chevron.			

The final recommendation is that TxDOT develop and send a letter to the FHWA requesting the MUTCD be modified to incorporate the research findings described in this report. The implementation of these findings will simplify horizontal curve delineation and, thereby, increase consistency while not compromising safety. Appendix D provides a draft of a letter requesting such a change.

REFERENCES

1. *Manual on Uniform Traffic Control Devices for Streets and Highways.* Federal Highway Administration, Washington, D.C., 2000.

2. Texas Manual on Uniform Traffic Control Devices. Texas Department of Transportation. Austin, TX.

3. Sign Crew Field Book, Texas Department of Transportation, Traffic Operations Division, Austin, TX.

4. Fildes, B.N., and T.J. Triggs, *Traffic Engineering: The Effects of Road Curve Geometry and Approach Distance on Judgments of Curve Exit Angle.* In Australian Road Research Board Proceedings from 11th ARRB Conference Vol. 11 Part 4. Melbourne, 1982, pp. 135-145.

5. Zador, P., H.S. Stein, P. Wright, and J. Hall. *Effects of Chevrons, Post-Mounted Delineators, and Raised Pavement Markers on Driver Behavior at Roadway Curves.* Transportation Research Record 1114.

6. Felipe, E., and F. Navin. *Automobiles on Horizontal Curves: Experiments and Observations*. Transportation Research Record 1628.

7. Nemeth, Z.A., T.H. Rockwell, and G.L. Smith. *Recommended Delineation Treatments at Selected Situations on Rural State Highways*. Report No. FHWA/OH86/009. Federal Highway Administration. September 1986.

8. *Manual on Uniform Traffic Control Devices for Streets and Highways.* Federal Highway Administration, Washington, D.C., 1948.

9. *Manual on Uniform Traffic Control Devices for Streets and Highways.* Federal Highway Administration, Washington, D.C., 1961.

10. Johnston, I.R., *Traffic Engineering: Modifying Driver Behavior on Rural Road Curves – A Review of Recent Research*. In Australian Road Research Board Proceedings from 11th ARRB Conference Vol. 11 Part 4. Melbourne, 1982, pp. 115-125.

11. David, R.E., *Appendix M: Comparison of Delineator Treatments on a Two-Lane Rural Horizontal Curve*. NCHRP Report No. 130: Roadway Delineation Systems. Highway Research Board, 1972, pp. 244-251.

12. Stimpson, W.A., H.W. McGee, W.K. Kittleson, and R.H. Ruddy. *Field Evaluation of Selected Delineation Treatments on Two-Lane Rural Highways.* Report No. FHWA-RD-77-118. FHWA, U.S. Department of Transportation, Washington, D.C., October 1977.

13. Agent, K. R. and Creasey, T. *Delineation of Horizontal Curves.* Report No. UKTRP-86-4. Kentucky Transportation Cabinet, March 1986.

14. Hall, R.R. *The Delineation of Rural Roads and Curve Negation at Night*. Australian Road Research Board. Research Report ARRB No. 103. Victoria, Australia, 1979.

15. Freedman, M., L.K. Staplin, D.P. Gilfillan, and A.M. Byrnes. Noticeability Requirements for Delineation on Nonilluminated Highways. FHWA-RD-88-028. Federal Highway Administration. July, 1998.

16. Zwahlen, H.T. *Optimization of Post Delineator Height and Spacing*. FHWA/OH-86/015. Federal Highway Administration. July, 1986.

17. Austroads. *Guide to Traffic Engineering Practice, Part 8 – Traffic Control Devices*. Sydney, Australia, 1988, pp. 28-33.

18. O'Flaherty, C.A. *Delineating the Edge of the Carriageway in Rural Areas*. Printerhall Limited, Holborn Viaduct, England, April 1972.

19. CTRE (http://www.ctre.iastate.edu/pubs/itcd/curves.pdf). Iowa Traffic Control Devices and Pavement Markings: A Manual for Cities and Counties. Iowa State University, 2001, pp. C5.1 – C5.6.

20. California Department of Transportation. Traffic Manual Chapter 6: Markings. CALTRANS, July 1996.

21. LTAP. Delineation of Turns and Curves. LTAP Technical Information Sheet #91. The Pennsylvania Local Roads Program, 2001.

22. Official Rulings on Requests for Interpretations, Changes, and Experimentations Volume III, December 1977, Sn-211, pp. 27-28.

23. Zwahlen, H.T., and J.Y. Park. *Curve Radius Perception Accuracy as a Function of Number of Delineation Devices (Chevrons)*. Transportation Research Record, 1495. pp. 99-106.

24. Jennings, B.E., and M.J. Demetsky. *Evaluation of Curve Delineation Signs on Rural Highways.* Report No. VHTRC 84-R16. Virginia Highway and Transportation Research Council in cooperation with the U.S. Department of Transportation. Charlottesville, VA, December 1983.

25. Niessner, C.W. *Post Mounted Delineators*. Report No. FHWA-TS-83-208. FHWA, U.S. Department of Transportation, Washington, D.C., July 1983.

26. U.S. Department of Transportation, Federal Highway Administration. Roadway Delineation Practices Handbook, August 1994.

27. Zwahlen, H.T. Optimal Application and Placement of Roadside Reflective Devices for Curves on Two-Lane Rural Highways. FHWA/OH-94/011. Federal Highway Administration. July 1993.

28. Texas Department of Transportation. Traffic Operations Manual: Signs and Markings Volume, Austin, TX, 1997.

29. Fitzpatrick, K., C.B. Shamburger, and D.B. Fambro. *Design Speed, Operation Speed, and Posted Speed Survey*, 1996.

30. *A Policy on Geometric Design of Highways and Streets.* AASHTO, Washington D.C., 1994.

31. Carlson, P.J. and J.M. Mason, Jr. *Relationships between Ball Bank Indicator Readings, Lateral Acceleration Rates, and Vehicular Body-Roll Rates*. In *Transportation Research Record 1658*, TRB, National Research Council, Washington, D.C., 1999, pp. 34-42.

32. Moyer, R.A., and D.S. Berry. *Marking Highway Curves with Safe Speed Indicators*. Proceedings from Highway Research Board, Volume 20, 1940.

APPENDIX A:
SPACING TABLES

This appendix contains the delineator and Chevron spacing table that other states submitted as a result of the request contained in the state survey (not all states submitted their practices). The state survey is shown in Chapter 3 along with a summary of the results. In this appendix, the specific state that submitted the response has been removed.

Table 80. Delineator Spacing Table from State #2.

Radius	Spacing on Curve	Spacing in Advance and Beyond Curve (ft)		
(ft)	(ft)	First	Second	Third
R	SC	D_1	D_2	D_3
1000	90	160	270	300
900	85	155	250	300
800	80	145	240	300
700	75	135	225	300
600	70	125	210	300
500	65	115	195	300
400	55	100	165	300
300	50	90	150	300
250	40	70	120	240
180	35	65	105	210
115	25	55	90	180
50	20	35	60	120

Table 81. Mainline Delineator Spacing Table from State #3.

Radius of Curve (ft)	Middle Ordinate at Inside of Pavement Edge (in)*	Spacing on Curve (ft)	Spacing in Advance and Beyond Curve (ft)		
			A	B	C
Less than 150	Greater than 90.55	25	45	75	150
150 – 300	46.85 – 90.55	50	90	150	300
300 – 500	27.95 – 46.85	75	135	250	450
500 – 1000	15.35 – 27.95	100	180	300	500
1000 – 2000	7.48 – 15.35	150	270	450	500
2000 – 3000	4.33 – 7.48	200	360	500	500
3000 – 4000	3.93 – 4.33	250	450	500	500
4000 – 5000	3.14 – 3.93	300	500	500	500
5000 – 6000	2.75 – 3.14	350	500	500	500
6000 – 8000	1.96 – 2.75	400	500	500	500
8000 – 10560	1.18 – 1.96	450	500	500	500
Greater than 10560	Less than 1.18	500	500	500	500

*Middle Ordinate based on 100 ft chord.

Table 82. Interchange Delineator Spacing Table from State #3.

Radius of Curve (ft)	Spacing on Curve (ft)	Spacing in Advance and Beyond Curve (ft)		
		A	B	C
Less than 150	25	45	75	150
150 – 300	50	90	150	200
300 – 500	75	135	200	200
500 – 1000	100	180	200	200
1000 – 2000	150	200	200	200
Greater than 2000	200	200	200	200

Table 83. Chevron Spacing Table from State #3.

Spacing Table	
Radius (ft)	**Spacing (ft)**
50	20
75	20
100	25
150	30
200	35
300	50
400	55
500	65
600	70
700	75
800	80
900	85
1000	90
1200	100
1400	110
1600	115
1800	125
2000	130
2500	150
3000	160

(Formula: Spacing = $3*(R-50)^{1/2}$)

Table 84. Delineator Spacing Table for Curves from State #5.

Radius "R" (m)	Spacing "S" (m)
15	6
23	8
30	9
46	11
61	12
91	15
122	18
152	20
183	22
213	23
244	25
274	26
305	28
366	31
427	33
488	35
548	37
610	40
762	44
914	48

$S=1.6(R)^{1/2}$ (Note equation is different from metric version of MUTCD spacing equation.)

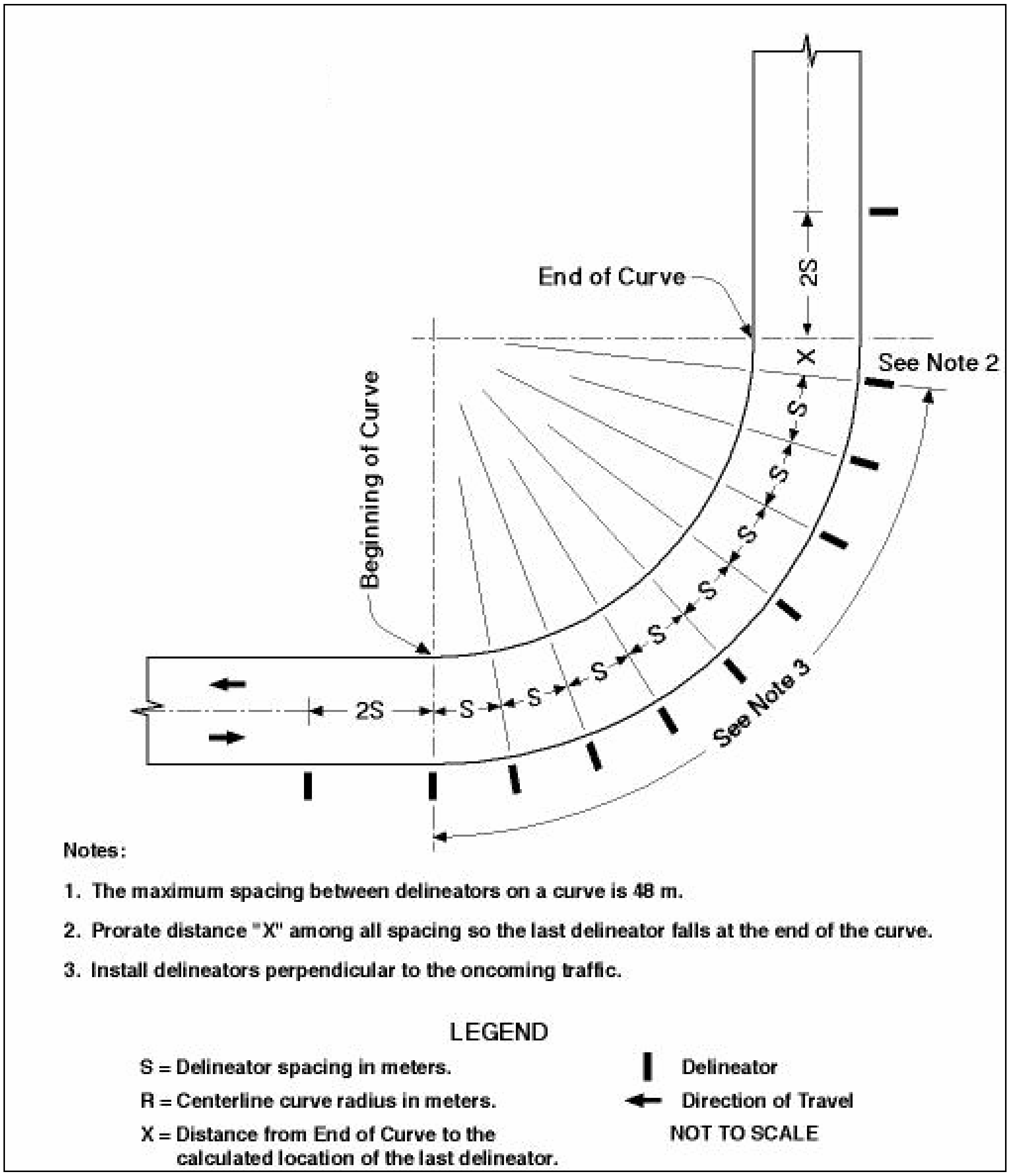

Figure 31. Diagram for Delineator Spacing on Curves from State #5.

Table 85. Spacing for Delineator Posts on Horizontal Curves from State #6.

'D' Degree of Curve	'R' Radius (ft)	*- • Spacing on Curve (ft)	*Spacing in Advance of and Beyond Curve (ft)		
			First Space	Second Space	Third Space
0°30'	11460	300	300	300	300
1°00'	5730	226	300	300	300
1°30'	3280	184	300	300	300
2°00'	2865	159	300	300	300
2°30'	2292.0	142	284	300	300
3°00'	1910.0	129	259	300	300
3°30'	1637.1	120	239	300	300
4°00'	1432.5	112	223	300	300
4°30'	1273.3	105	210	300	300
5°00'	1146.0	99	199	298	300
5°30'	1041.8	94	189	283	300
6°00'	955.0	90	181	271	300
6°30'	88.1	87	173	260	300
7°00'	818.6	83	166	250	300
7°30'	764.0	80	160	240	300
8°00'	716.3	77	155	232	300
8°30'	674.1	75	150	225	300
9°00'	636.7	73	145	218	300
9°30'	603.2	71	141	212	300
10°00'	573.0	69	137	206	300
10°30'	545.7	67	134	200	300
11°00'	520.9	65	130	195	300
11°30'	498.3	64	127	191	300
12°00'	477.5	62	124	186	300
15°00'	382.0	55	109	164	300
18°00'	318.3	49	98	147	295
21°00'	272.9	45	90	134	269
25°00'	229.2	40	80	120	241
30°00'	191.0	36	71	107	214
40°00'	143.2	29	58	87	174
50°00'	114.6	24	48	72	145
60°00'	95.0	20	40	61	121

*On conventional roadways, omit the "third space" and double the spacing "On the Curve" and "in advance of and beyond the curve" (300 ft max). R=5730/D

•Spacing for curves not shown may be computed from the formula: $3(R-50)^{1/2}$. Spacing in advance of and beyond curve is: First Space = 2S, Second Spaces = 3S, Third Space = 6S. Spaces should not be less than 20 ft nor more than 300 ft.

Table 86. Chevron Spacing Table from State #10.

Installation Spacing	
Degree of Curve	**Spacing (S) (*10)**
<6°	
6°	125
8°	112.5
10°	100
12°	87.5
14°	75

Table 87. Chevron Spacing Table Based on Advisory Speeds from State #11.

Posted Advisory Speed (mph)	Spacing (ft)
20	75
25	75
30	75
35	100
40	100
45	100
50	125

Table 88. Delineator Spacing Table Based on Radius or Advisory Speed from State #15.

Spacing Based on Curve Radius		Spacing Based on Advisory Speed	
Curve Radius (ft)	**Delineator Spacing (ft)**	**Advisory Speed (mph)**	**Delineator Spacing (ft)**
50	20	10	20
150	30	20	30
200	35	25	35
250	40	25	40
300	50	30	50
400	55	30	55
500	65	35	65
600	70	35	70
700	75	40	75
800	80	45	80
900	85	45	85
1000	90	50	90

Table 89. Delineator Spacing Table for Horizontal Curves from State #17.

Radius (ft) "R"	Spacing on Curve (ft) "S"	Spacing in Advance of and Beyond Curve (ft)		
		First Space (2 x "S")	Second Space (3 x "S")	Third Space (6 x "S")
3500	175	300	300	300
3000	160	300	300	300
2865	160	300	300	300
2500	150	300	300	300
2000	130	260	300	300
1910	130	260	300	300
1800	125	250	300	300
1600	120	240	300	300
1435	110	220	300	300
1400	110	220	300	300
1150	100	200	300	300
1000	90	180	270	300
820	80	160	240	300
800	80	160	240	300
640	75	150	225	300
600	70	140	210	300
500	65	130	195	300
480	60	120	180	300
385	55	110	165	300
300	50	100	150	300
275	45	90	135	270
230	40	80	120	240
195	35	70	105	210
145	30	60	90	180
100	20	40	60	120

Table 90. Delineator Spacing on Horizontal Curves from State #18.

Curve Radius		Delineator Spacing	
(m)	**(ft)**	**(m)**	**(ft)**
15	50	6	20
23	75	6	20
30	100	8	25
45	150	9	30
61	200	11	35
91	300	15	50
122	400	17	55
152	500	20	65
183	600	21	70
213	700	23	75
241	800	24	80
274	900	26	85
305	1000	27	90
366	1200	30	100
427	1400	34	110
488	1600	35	115
549	1800	38	125
610	2000	40	130
762	2500	46	150
914	3000	49	160

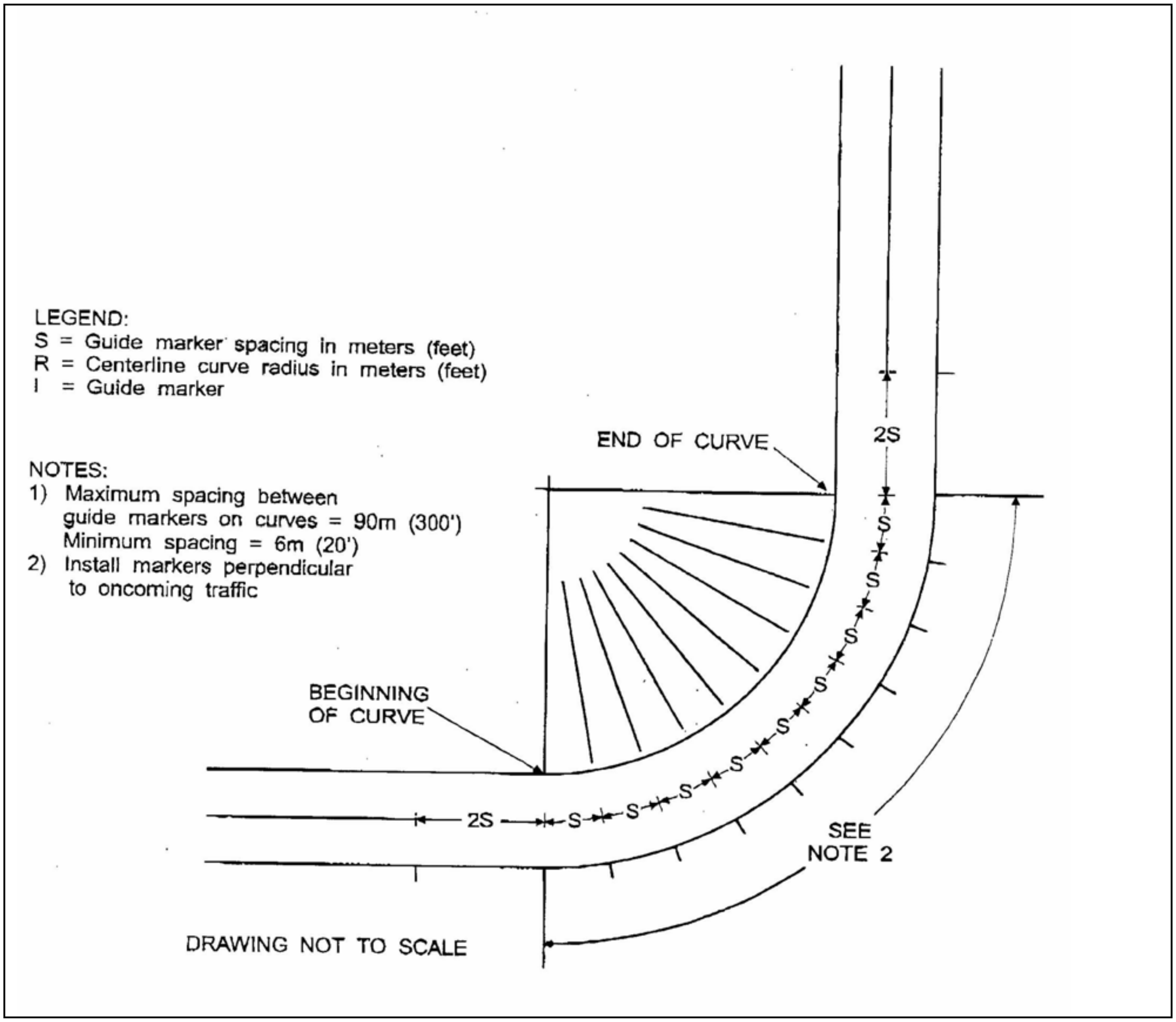

Figure 32. Delineator Spacing Diagram from State # 18.

Table 91. Chevron Spacing Table from State #18.

Radius of Curve		Degree of Curvature	Chevron Spacing	
(m)	**(ft)**	**(degrees)**	**(m)**	**(ft)**
45	150	38°15’	14-18	45-60
60	200	28°45’	16-21	53-70
80	250	23°00’	18-24	60-80
90	300	19°00’	23-30	75-100
120	400	14°15’	25-33	83-110
150	500	11°30’	30-40	98-130
180	600	9°30’	32-43	105-140
210	700	8°15’	34-46	112-150
240	800	7°15’	37-49	120-160
270	900	6°15’	39-52	127-170

Table 92. Draft Chevron Spacing Table from State #20.

Degree of Curve	Radius (ft)	Spacing on Curve (ft)	Spacing on Turn (ft)	Spacing on Tangent (feet)
	10,000	400	200	200
1		304	152	200
	5000	282	141	200
	3000	218	109	196
2		212	106	191
	2500	198	99	178
	2000	176	88	158
3		172	86	155
	1800	168	84	151
	1600	156	78	140
4		148	74	133
	1400	148	74	133
	1200	136	68	122
5		132	66	119
	1000	124	62	112
	900	116	58	104
7		110	55	99
	800	110	55	99
	700	102	51	92
9		96	48	86
	600	94	47	85
	500	84	42	76
12		82	41	74
	400	74	37	67
15		72	36	65
	350	70	35	63
18		66	33	59
	300	64	32	58
21		60	30	54
	250	56	28	50
25		56	28	50
	200	48	24	43
30		48	24	43
	150	40	20	36
40		38	19	34
	100	28	14	25

Table 93. Delineator Spacing Table for Horizontal Curves from State #21.

Radius of Curve (R) (ft)	Spacing on Curve (S) (ft)	Spacing in Advance of and Beyond Curve (ft)		
		1st	2nd	3rd
50	20	40	60	120
150	30	60	90	180
200	35	70	105	210
250	40	80	120	240
300	50	100	150	300
400	55	110	165	300
500	65	130	195	300
600	70	140	210	300
700	75	150	225	300
800	80	160	240	300
900	85	170	255	300
1000	90	180	270	300
1200	100	200	300	300
1400	110	220	300	300
1600	120	240	300	300
1800	125	250	300	300
2000	130	260	300	300
2500	150	300	300	300
3000	165	300	300	300
5000	210	300	300	300
10,000	300	300	300	300

Spacing for specific radii not shown may be interpolated from this table or computed from the formula $S=3(R-50)^{1/2}$. The minimum spacing should be 20 ft. The maximum spacing on curves should not exceed 300 ft.

Table 94. Delineator (Guide Post) Spacing Table from State #31.

Radius "R" (ft)	Spacing "S" (ft)
50	30
100	40
150	50
200	60
250	70
300	80
400	90
500	100
600	110
700	120
800	130
900	130
1000	140
1500	170
2000	200
2500	220
3000	240
3500	260
4000	280
4500	300

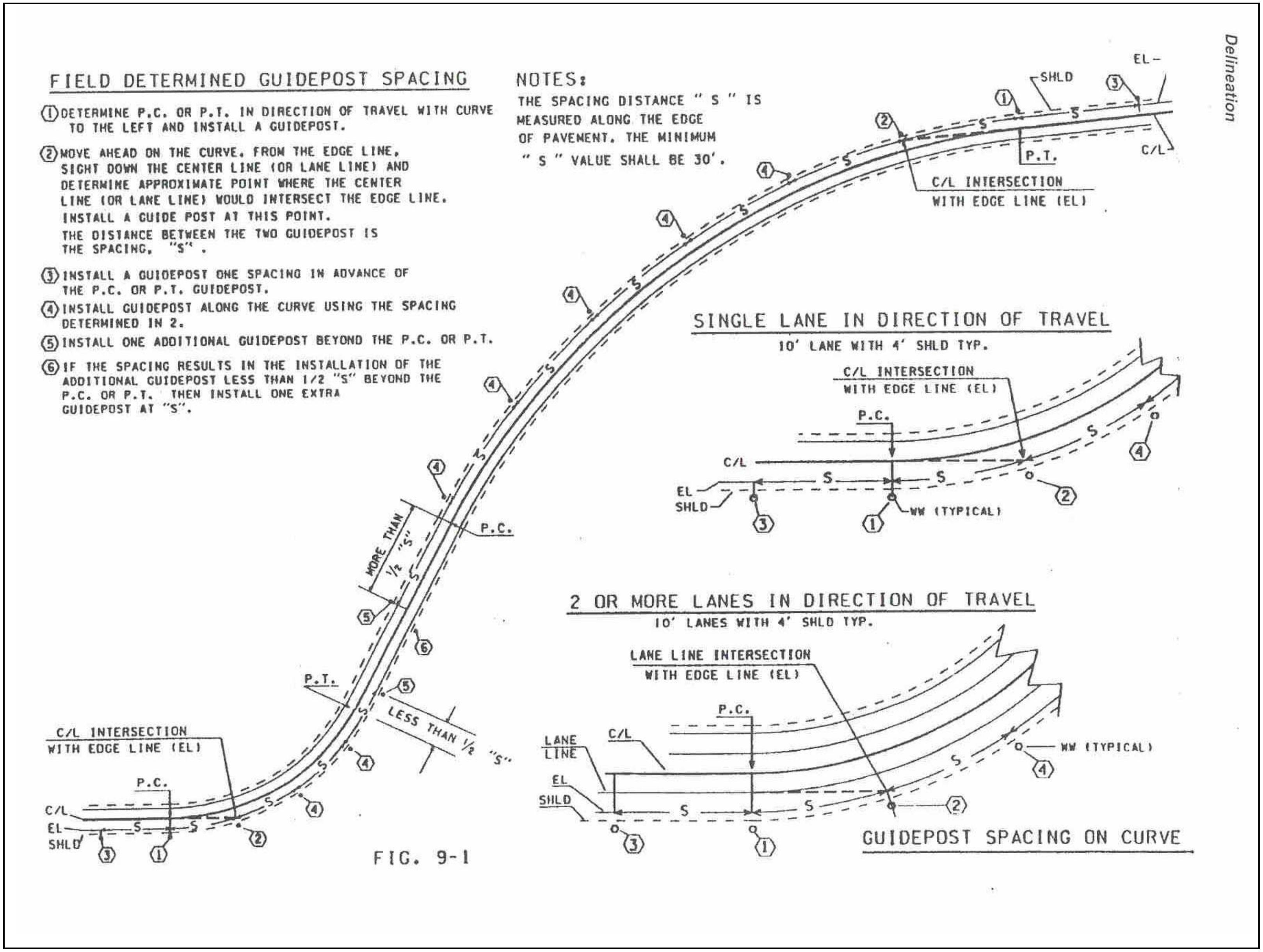

Figure 33. Diagram and Directions for Delineator Placement from State #31.

Table 95. Chevron Spacing Table Based on Advisory Speeds from State #33 .

Spacing (ft)	Typical Speed* (mph)
80	35
100	40
100	45
150	50
150	55

* Advisory Speed, ball bank, or computed.

APPENDIX B:
STATISICAL RESULTS FROM THE CHEVRON FIELD STUDY

FM 2223 STATISTICAL ANALYSIS RESULTS

Site Characteristics

FM 2223 was considered the gentle curve for the Chevron field study. The following table lists some of the site characteristics for this curve.

Table 96. FM 2223 Site Characteristics.

Speed Limit	Advisory Speed	Radius	Δ[1]	Length	Before Spacing[2]	Number of Chevrons Before	After Spacing[2]	Number of Chevrons After
(mph)	(mph)	(ft)	(degrees)	(ft)	(ft)	(#)	(ft)	(#)
70	50	958	45.8	765	188	5	96	9

[1] External Angle
[2] Average spacing reported

ANOVA Analysis

For each ANOVA analysis, the following variables were coded as fixed (i.e., independent) factors: Study (Before versus After) and Light Condition (Day versus Night).

SPSS ANOVA Results for Test 1: Comparing Mean Speeds at the Control Point

ANOVA FM 2223 Test 1 Factors

Dependent Factor:	Control Point (Cntrl Pt)
Covariate:	None
Fixed Factors:	Study Light Condition (Lightcond)

Between-Subjects Factors

		Value Label	N
Before or After	.00	Before	455
	1.00	After	1374
Lightcond	0	Day	1368
	1	Night	461

Descriptive Statistics

Dependent Variable: Control Point (mph)

Before or After	Lightcond	Mean	Std. Deviation	N
Before	Day	70.22	6.022	394
	Night	67.23	5.875	61
	Total	69.82	6.082	455
After	Day	66.77	6.202	974
	Night	63.79	6.418	400
	Total	65.90	6.408	1374
Total	Day	67.76	6.344	1368
	Night	64.24	6.450	461
	Total	66.88	6.550	1829

Levene's Test of Equality of Error Variances(a)

Dependent Variable: Control Point (mph)

F	df1	df2	Sig.
1.081	3	1825	.356

Tests the null hypothesis that the error variance of the dependent variable is equal across groups.
a Design: Intercept+Study+Lightcond+Study * Lightcond

Tests of Between-Subjects Effects

Dependent Variable: Control Point (mph)

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	8242.504(a)	3	2747.501	71.444	.000
Intercept	3198256.201	1	3198256.201	83165.601	.000
Study	2116.776	1	2116.776	55.043	.000
Lightcond	1587.929	1	1587.929	41.292	.000
Study * Lightcond	.005	1	.005	.000	.991
Error	70183.074	1825	38.456		
Total	8258283.000	1829			
Corrected Total	78425.578	1828			

a R Squared = .105 (Adjusted R Squared = .104)

SPSS ANOVA Results for Test 2: Comparing Mean Speeds at the Approach of the Curve

ANOVA FM 2223 Test 2 Factors

Dependent Factor:	Approach to Curve (AC)
Covariate:	Control Point (Cntrl Pt)
Fixed Factors:	Study Light Condition (Lightcond)

Between-Subjects Factors

		Value Label	N
Lightcond	0	Day	1368
	1	Night	461
Before or After	.00	Before	455
	1.00	After	1374

Descriptive Statistics

Dependent Variable: Approach of Curve (mph)

Lightcond	Before or After	Mean	Std. Deviation	N
Day	Before	65.3985	5.97928	394
	After	63.7526	6.13009	974
	Total	64.2266	6.13037	1368
Night	Before	65.1311	5.25191	61
	After	61.2875	6.19603	400
	Total	61.7961	6.21269	461
Total	Before	65.3626	5.88232	455
	After	63.0349	6.24834	1374
	Total	63.6140	6.23945	1829

Levene's Test of Equality of Error Variances [a]

Dependent Variable: Approach of Curve (mph)

F	df1	df2	Sig.
.447	3	1825	.720

Tests the null hypothesis that the error variance of the dependent variable is equal across groups.

a. Design: Intercept+Ctrl_ Pt+Lightcond+Study+Lightcond * Study

Tests of Between-Subjects Effects

Dependent Variable: Approach of Curve (mph)

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	34894.448[a]	4	8723.612	438.694	.000
Intercept	5602.346	1	5602.346	281.731	.000
Ctrl_Pt	31315.663	1	31315.663	1574.804	.000
Lightcond	68.759	1	68.759	3.458	.063
Study	33.771	1	33.771	1.698	.193
Lightcond * Study	216.487	1	216.487	10.887	.001
Error	36271.033	1824	19.885		
Total	7472654.000	1829			
Corrected Total	71165.482	1828			

a. R Squared = .490 (Adjusted R Squared = .489)

SPSS ANOVA Results for Test 3: Comparing Mean Speeds at the Point of Curvature

ANOVA FM 2223 Test 3 Factors

Dependent Factor:	Point of Curvature (PC)
Covariate:	Control Point (Cntrl Pt)
Fixed Factors:	Study Light Condition (Lightcond)

Between-Subjects Factors

		Value Label	N
Lightcond	0	Day	1368
	1	Night	461
Before or After	.00	Before	455
	1.00	After	1374

Descriptive Statistics

Dependent Variable: Point of Curvature (mph)

Lightcond	Before or After	Mean	Std. Deviation	N
Day	Before	60.9543	6.16631	394
	After	58.5123	5.42778	974
	Total	59.2156	5.75540	1368
Night	Before	60.7213	5.62178	61
	After	55.4200	5.89368	400
	Total	56.1215	6.12252	461
Total	Before	60.9231	6.09078	455
	After	57.6121	5.73995	1374
	Total	58.4358	6.00081	1829

Levene's Test of Equality of Error Variances[a]

Dependent Variable: Point of Curvature (mph)

F	df1	df2	Sig.
4.094	3	1825	.007

Tests the null hypothesis that the error variance of the dependent variable is equal across groups.

a. Design: Intercept+Ctrl_ Pt+Lightcond+Study+Lightcond * Study

Tests of Between-Subjects Effects

Dependent Variable: Point of Curvature (mph)

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	26872.351[a]	4	6718.088	314.576	.000
Intercept	7931.231	1	7931.231	371.382	.000
Ctrl_Pt	20410.881	1	20410.881	955.744	.000
Lightcond	.479	1	.479	.022	.881
Study	700.264	1	700.264	32.790	.000
Lightcond * Study	365.530	1	365.530	17.116	.000
Error	38953.351	1824	21.356		
Total	6311381.000	1829			
Corrected Total	65825.701	1828			

a. R Squared = .408 (Adjusted R Squared = .407)

SPSS ANOVA Results for Test 4: Comparing Mean Speeds at the Middle of the Curve

ANOVA FM 2223 Test 4 Factors

Dependent Factor:	Middle of the Curve (MC)
Covariate:	Control Point (Cntrl Pt)
Fixed Factors:	Study Light Condition (Lightcond)

Between-Subjects Factors

		Value Label	N
Lightcond	0	Day	1357
	1	Night	432
Before or After	.00	Before	415
	1.00	After	1374

Descriptive Statistics

Dependent Variable: Middle of Curve (mph)

Lightcond	Before or After	Mean	Std. Deviation	N
Day	Before	59.6997	5.86195	383
	After	57.6294	5.48765	974
	Total	58.2137	5.67079	1357
Night	Before	61.6250	4.83769	32
	After	55.2350	6.03829	400
	Total	55.7083	6.18419	432
Total	Before	59.8482	5.80717	415
	After	56.9323	5.75506	1374
	Total	57.6087	5.89553	1789

Levene's Test of Equality of Error Variances[a]

Dependent Variable: Middle of Curve (mph)

F	df1	df2	Sig.
1.020	3	1785	.383

Tests the null hypothesis that the error variance of the dependent variable is equal across groups.

a. Design: Intercept+Ctrl_ Pt+Lightcond+Study+Lightcond * Study

Tests of Between-Subjects Effects

Dependent Variable: Middle of Curve (mph)

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	21741.581[a]	4	5435.395	239.992	.000
Intercept	8903.653	1	8903.653	393.127	.000
Ctrl_Pt	17296.557	1	17296.557	763.703	.000
Lightcond	75.264	1	75.264	3.323	.068
Study	450.246	1	450.246	19.880	.000
Lightcond * Study	323.567	1	323.567	14.287	.000
Error	40404.523	1784	22.648		
Total	5999416.000	1789			
Corrected Total	62146.104	1788			

a. R Squared = .350 (Adjusted R Squared = .348)

SPSS ANOVA Results for Test 5: Comparing Deceleration Magnitude between the Control Point and the Approach of the Curve

ANOVA FM 2223 Test 5 Factors

Dependent Factor:	CP – AC
Covariate:	Control Point (Cntrl Pt)
Fixed Factors:	Study Light Condition (Lightcond)

Between-Subjects Factors

		Value Label	N
Lightcond	0	Day	1368
	1	Night	461
Before or After	.00	Before	455
	1.00	After	1374

Descriptive Statistics

Dependent Variable: Difference between Cntrl Pt and Approach of Curve

Lightcond	Before or After	Mean	Std. Deviation	N
Day	Before	4.8223	5.36257	394
	After	3.0154	4.83720	974
	Total	3.5358	5.05885	1368
Night	Before	2.0984	5.64419	61
	After	2.5000	4.48557	400
	Total	2.4469	4.65037	461
Total	Before	4.4571	5.47419	455
	After	2.8654	4.74170	1374
	Total	3.2613	4.98033	1829

Levene's Test of Equality of Error Variances[a]

Dependent Variable: Difference between Cntrl Pt and Approach of Curve

F	df1	df2	Sig.
.447	3	1825	.720

Tests the null hypothesis that the error variance of the dependent variable is equal across groups.

a. Design: Intercept+Ctrl_ Pt+Lightcond+Study+Lightcond * Study

Tests of Between-Subjects Effects

Dependent Variable: Difference between Cntrl Pt and Approach of Curve

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	9070.044[a]	4	2267.511	114.029	.000
Intercept	5602.346	1	5602.346	281.731	.000
Ctrl_Pt	7736.709	1	7736.709	389.064	.000
Lightcond	68.759	1	68.759	3.458	.063
Study	33.771	1	33.771	1.698	.193
Lightcond * Study	216.487	1	216.487	10.887	.001
Error	36271.033	1824	19.885		
Total	64795.000	1829			
Corrected Total	45341.077	1828			

a. R Squared = .200 (Adjusted R Squared = .198)

SPSS ANOVA Results for Test 6: Comparing Deceleration Magnitude between the Approach of the Curve and the Point of Curvature

ANOVA FM 2223 Test 6 Factors

Dependent Factor:	AC – PC
Covariate:	Control Point (Cntrl Pt)
Fixed Factors:	Study Light Condition (Lightcond)

Between-Subjects Factors

		Value Label	N
Lightcond	0	Day	1368
	1	Night	461
Before or After	.00	Before	455
	1.00	After	1374

Descriptive Statistics

Dependent Variable: Difference between Approach of Curve and PC

Lightcond	Before or After	Mean	Std. Deviation	N
Day	Before	4.4442	3.42468	394
	After	5.2402	2.41011	974
	Total	5.0110	2.76339	1368
Night	Before	4.4098	2.61647	61
	After	5.8675	2.48402	400
	Total	5.6746	2.54746	461
Total	Before	4.4396	3.32528	455
	After	5.4229	2.44760	1374
	Total	5.1782	2.72519	1829

Levene's Test of Equality of Error Variances[a]

Dependent Variable: Difference between Approach of Curve and PC

F	df1	df2	Sig.
2.403	3	1825	.066

Tests the null hypothesis that the error variance of the dependent variable is equal across groups.

a. Design: Intercept+Ctrl_Pt+Lightcond+Study+Lightcond * Study

Tests of Between-Subjects Effects

Dependent Variable: Difference between Approach of Curve and PC

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	1604.623[a]	4	401.156	61.122	.000
Intercept	201.885	1	201.885	30.760	.000
Ctrl_Pt	1162.514	1	1162.514	177.126	.000
Lightcond	80.713	1	80.713	12.298	.000
Study	426.472	1	426.472	64.979	.000
Lightcond * Study	19.407	1	19.407	2.957	.086
Error	11971.271	1824	6.563		
Total	62619.000	1829			
Corrected Total	13575.894	1828			

a. R Squared = .118 (Adjusted R Squared = .116)

SPSS ANOVA Results for Test 7: Comparing Deceleration Magnitude between the Point of Curvature and the Middle of the Curve

ANOVA FM 2223 Test 7 Factors

Dependent Factor:	PC – MC
Covariate:	Control Point (CP)
Fixed Factors:	Study Light Condition (Lightcond)

Between-Subjects Factors

		Value Label	N
Lightcond	0	Day	1357
	1	Night	432
Before or After	.00	Before	415
	1.00	After	1374

Descriptive Statistics

Dependent Variable: Difference between PC and Middle of Curve

Lightcond	Before or After	Mean	Std. Deviation	N
Day	Before	1.3629	2.26431	383
	After	.8830	1.95916	974
	Total	1.0184	2.06040	1357
Night	Before	1.0000	1.88372	32
	After	.1850	1.89069	400
	Total	.2454	1.90005	432
Total	Before	1.3349	2.23739	415
	After	.6798	1.96456	1374
	Total	.8317	2.04922	1789

Levene's Test of Equality of Error Variances[a]

Dependent Variable: Difference between PC and Middle of Curve

F	df1	df2	Sig.
.866	3	1785	.458

Tests the null hypothesis that the error variance of the dependent variable is equal across groups.

a. Design: Intercept+Ctrl_ Pt+Lightcond+Study+Lightcond * Study

Tests of Between-Subjects Effects

Dependent Variable: Difference between PC and Middle of Curve

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	394.397[a]	4	98.599	24.726	.000
Intercept	53.132	1	53.132	13.324	.000
Ctrl_Pt	115.561	1	115.561	28.980	.000
Lightcond	20.797	1	20.797	5.215	.023
Study	23.151	1	23.151	5.806	.016
Lightcond * Study	1.896	1	1.896	.476	.491
Error	7113.960	1784	3.988		
Total	8746.000	1789			
Corrected Total	7508.357	1788			

a. R Squared = .053 (Adjusted R Squared = .050)

FM 2223: Z-Test Comparing Two Binomial Proportions

FM 2223 - Day
Speed Lmt: 70 mph **Ad Speed:** 50 mph

Compare Before and After Proportions for Percent Exceeding the **Speed Limit**

	π	y	n	π	σπ1−π2	z	zα
Control Point (CP)							
Before	45.9%	181	394	0.3121345	0.0276655	***7.4758932***	***1.96***
After	25.3%	246	974				
Approach of Curve (AC)							
Before	16.0%	63	394	0.1169591	0.0191877	***3.1431161***	***1.96***
After	10.0%	97	974				
Point of Curvature (PC)							
Before	4.8%	19	394	0.0219298	0.0087442	***4.2233582***	***1.96***
After	1.1%	11	974				
Middle of Cuve (MC)							
Before	3.9%	15	383	0.018423	0.0081106	***3.5629334***	***1.96***
After	1.0%	10	974				

Compare Before and After Proportions for Percent Exceeding the **Advisory Speed**

	π	y	n	π	σπ1−π2	z	zα
Control Point (CP)							
Before	100.0%	394	394	0.997807	0.0027929	1.1028234	1.96
After	99.7%	971	974				
Approach of Curve (AC)							
Before	98.7%	389	394	0.9802632	0.0083047	1.1917198	1.96
After	97.7%	952	974				
Point of Curvature (PC)							
Before	96.2%	379	394	0.9385965	0.0143335	***2.2863138***	***1.96***
After	92.9%	905	974				
Middle of Cuve (MC)							
Before	95.0%	364	383	0.9218865	0.016185	***2.4537546***	***1.96***
After	91.1%	887	974				

y: yes the sample exceeded the speed limit n: sample size
Bold italicized numbers indicate significant difference at a 95 percent confidence interval

FM 2223 - Night
Speed Lmt: 70 mph **Ad Speed:** 50 mph

Compare Before and After Proportions for Percent Exceeding the **Speed Limit**

Control Point (CP)							
	π	y	n	π	σπ1−π2	z	zα
Before	21.3%	13	61	0.1388286	0.0475269	1.8013942	1.96
After	12.8%	51	400				
Approach of Curve (AC)							
	π	y	n	π	σπ1−π2	z	zα
Before	9.8%	6	61	0.0650759	0.0339042	1.1314416	1.96
After	6.0%	24	400				
Point of Curvature (PC)							
	π	y	n	π	σπ1−π2	z	zα
Before	4.9%	3	61	0.010846	0.0142371	***3.1031794***	***1.96***
After	0.5%	2	400				
Middle of Cuve (MC)							
	π	y	n	π	σπ1−π2	z	zα
Before	6.3%	2	32	0.0092593	0.0175956	***3.2678553***	***1.96***
After	0.5%	2	400				

Compare Before and After Proportions for Percent Exceeding the **Advisory Speed**

Control Point (CP)							
	π	y	n	π	σπ1−π2	z	zα
Before	100.0%	61	61	0.989154	0.0142371	0.8779868	1.96
After	98.8%	395	400				
Approach of Curve (AC)							
	π	y	n	π	σπ1−π2	z	zα
Before	98.4%	60	61	0.9652928	0.0251591	0.8389243	1.96
After	96.3%	385	400				
Point of Curvature (PC)							
	π	y	n	π	σπ1−π2	z	zα
Before	95.1%	58	61	0.8199566	0.0528128	***2.8557384***	***1.96***
After	80.0%	320	400				
Middle of Cuve (MC)							
	π	y	n	π	σπ1−π2	z	zα
Before	100.0%	32	32	0.8125	0.071705	***2.8240723***	***1.96***
After	79.8%	319	400				

y: yes the sample exceeded the speed limit n: sample size
Bold italicized numbers indicate significant difference at a 95 percent confidence interval

FM 2038 STATISTICAL ANALYSIS RESULTS

Site Characteristics

FM 2038 was considered the moderate or average curve for the Chevron field study. The following table lists some of the site characteristics for this curve.

Table 97. FM 2038 Site Characteristics.

Speed Limit	Advisory Speed	Radius	Δ^1	Length	Before Spacing[2]	Number of Chevrons Before[3]	After Spacing[2]	Number of Chevrons After[3]
(mph)	(mph)	(ft)	(degrees)	(ft)	(ft)	(#)	(ft)	(#)
70	45	1142	47.1	939.8	177	9	86	13

[1] External angle
[2] Average spacing reported
[3] Two-single sided chevrons were placed in advance of the curve in either direction. A new Chevron was placed between each of the existing Chevrons located on the curve.

ANOVA Analysis

For each ANOVA analysis, the following variables were coded as fixed (i.e., independent) factors: Study (Before versus After) and Light Condition (Day versus Night).

SPSS ANOVA Results for FM 2038 Test 1: Comparing Mean Speeds at the Control Point

ANOVA FM 2038 Test 1 Factors

Dependent Factor:	Control Point (Cntrl Pt)
Covariate:	None
Fixed Factors:	Study Light Condition (Lightcond)

Between-Subjects Factors

		Value Label	N
Before or After	0	Before	231
	1	After	246
Lightcond	0	Day	355
	1	Night	122

Descriptive Statistics

Dependent Variable: Control Point (mph)

Before or After	Lightcond	Mean	Std. Deviation	N
Before	Day	60.88	6.874	165
	Night	61.52	6.776	66
	Total	61.06	6.837	231
After	Day	62.55	6.457	190
	Night	61.64	6.403	56
	Total	62.34	6.443	246
Total	Day	61.77	6.696	355
	Night	61.57	6.581	122
	Total	61.72	6.661	477

Levene's Test of Equality of Error Variances [a]

Dependent Variable: Control Point (mph)

F	df1	df2	Sig.
.218	3	473	.884

Tests the null hypothesis that the error variance of the dependent variable is equal across groups.

a. Design: Intercept+Study+Lightcond+Study * Lightcond

Tests of Between-Subjects Effects

Dependent Variable: Control Point (mph)

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	248.244[a]	3	82.748	1.875	.133
Intercept	1371608.783	1	1371608.783	31087.444	.000
Study	72.293	1	72.293	1.639	.201
Lightcond	1.696	1	1.696	.038	.845
Study * Lightcond	53.136	1	53.136	1.204	.273
Error	20869.228	473	44.121		
Total	1838374.000	477			
Corrected Total	21117.472	476			

a. R Squared = .012 (Adjusted R Squared = .005)

SPSS ANOVA Results for FM 2038 Test 2: Comparing Mean Speeds at the Approach of the Curve

ANOVA FM 2038 Test 2 Factors

Dependent Factor:	Approach of Curve (AC)
Covariate:	Control Point (Cntrl Pt)
Fixed Factors:	Study Light Condition (Lightcond)

Between-Subjects Factors

		Value Label	N
Before or After	0	Before	231
	1	After	234
Lightcond	0	Day	343
	1	Night	122

Descriptive Statistics

Dependent Variable: Approach of Curve (mph)

Before or After	Lightcond	Mean	Std. Deviation	N
Before	Day	60.60	6.559	165
	Night	60.12	6.529	66
	Total	60.46	6.540	231
After	Day	60.61	6.275	178
	Night	58.89	6.332	56
	Total	60.20	6.318	234
Total	Day	60.60	6.404	343
	Night	59.56	6.442	122
	Total	60.33	6.424	465

Levene's Test of Equality of Error Variances[a]

Dependent Variable: Approach of Curve (mph)

F	df1	df2	Sig.
.797	3	461	.496

Tests the null hypothesis that the error variance of the dependent variable is equal across groups.

a. Design: Intercept+Ctrl_ Pt+Study+Lightcond+Study * Lightcond

Tests of Between-Subjects Effects

Dependent Variable: Approach of Curve (mph)

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	13378.332[a]	4	3344.583	266.717	.000
Intercept	609.417	1	609.417	48.598	.000
Ctrl_Pt	13234.133	1	13234.133	1055.367	.000
Study	151.306	1	151.306	12.066	.001
Lightcond	91.707	1	91.707	7.313	.007
Study * Lightcond	.072	1	.072	.006	.940
Error	5768.326	460	12.540		
Total	1711557.000	465			
Corrected Total	19146.658	464			

a. R Squared = .699 (Adjusted R Squared = .696)

SPSS ANOVA Results for FM 2038 Test 3: Comparing Mean Speeds at the Point of Curvature

ANOVA FM 2038 Test 3 Factors

Dependent Factor:	Point of Curvature (PC)
Covariate:	Control Point (Cntrl Pt)
Fixed Factors:	Study Light Condition (Lightcond)

Between-Subjects Factors

		Value Label	N
Before or After	0	Before	223
	1	After	229
Lightcond	0	Day	331
	1	Night	121

Descriptive Statistics

Dependent Variable: Point of Curvature (mph)

Before or After	Lightcond	Mean	Std. Deviation	N
Before	Day	55.62	5.465	158
	Night	55.43	4.851	65
	Total	55.57	5.283	223
After	Day	54.91	4.992	173
	Night	52.80	5.262	56
	Total	54.40	5.129	229
Total	Day	55.25	5.227	331
	Night	54.21	5.193	121
	Total	54.97	5.232	452

Levene's Test of Equality of Error Variances[a]

Dependent Variable: Point of Curvature (mph)

F	df1	df2	Sig.
.017	3	448	.997

Tests the null hypothesis that the error variance of the dependent variable is equal across groups.

a. Design: Intercept+Ctrl_ Pt+Study+Lightcond+Study * Lightcond

Tests of Between-Subjects Effects

Dependent Variable: Point of Curvature (mph)

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	6651.457[a]	4	1662.864	130.490	.000
Intercept	2101.114	1	2101.114	164.881	.000
Ctrl_Pt	6307.468	1	6307.468	494.966	.000
Study	403.665	1	403.665	31.677	.000
Lightcond	115.686	1	115.686	9.078	.003
Study * Lightcond	28.501	1	28.501	2.237	.135
Error	5696.224	447	12.743		
Total	1378328.000	452			
Corrected Total	12347.681	451			

a. R Squared = .539 (Adjusted R Squared = .535)

SPSS ANOVA Results for FM 2038 Test 4: Comparing Mean Speeds at the Middle of the Curve

ANOVA FM 2038 Test 4 Factors

Dependent Factor:	Middle of Curve (MC)
Covariate:	Control Point
Fixed Factors:	Study Light Condition

Between-Subjects Factors

		Value Label	N
Before or After	0	Before	210
	1	After	203
Lightcond	0	Day	305
	1	Night	108

Descriptive Statistics

Dependent Variable: Middle of Curve (mph)

Before or After	Lightcond	Mean	Std. Deviation	N
Before	Day	53.76	6.629	151
	Night	52.54	5.817	59
	Total	53.42	6.421	210
After	Day	54.26	5.569	154
	Night	51.67	5.921	49
	Total	53.64	5.749	203
Total	Day	54.01	6.112	305
	Night	52.15	5.853	108
	Total	53.53	6.094	413

Levene's Test of Equality of Error Variances[a]

Dependent Variable: Middle of Curve (mph)

F	df1	df2	Sig.
1.961	3	409	.119

Tests the null hypothesis that the error variance of the dependent variable is equal across groups.

a. Design: Intercept+Ctrl_Pt+Study+Lightcond+Study * Lightcond

Tests of Between-Subjects Effects

Dependent Variable: Middle of Curve (mph)

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	5763.713[a]	4	1440.928	61.655	.000
Intercept	1719.649	1	1719.649	73.581	.000
Ctrl_Pt	5447.177	1	5447.177	233.077	.000
Study	48.721	1	48.721	2.085	.150
Lightcond	250.937	1	250.937	10.737	.001
Study * Lightcond	2.422	1	2.422	.104	.748
Error	9535.270	408	23.371		
Total	1198532.000	413			
Corrected Total	15298.983	412			

a. R Squared = .377 (Adjusted R Squared = .371)

SPSS ANOVA Results for FM 2038 Test 5: Comparing Deceleration Magnitude between the Control Point and the Approach of the Curve

ANOVA FM 2038 Test 5 Factors

Dependent Factor:	CP – AC
Covariate:	Control Point (Cntrl Pt)
Fixed Factors:	Study Light Condition (Lightcond)

Between-Subjects Factors

		Value Label	N
Before or After	0	Before	231
	1	After	234
Lightcond	0	Day	343
	1	Night	122

Descriptive Statistics

Dependent Variable: Difference between Cntrl Pt and Approach of Curve

Before or After	Lightcond	Mean	Std. Deviation	N
Before	Day	.28	3.989	165
	Night	1.39	3.992	66
	Total	.60	4.013	231
After	Day	1.88	3.598	178
	Night	2.75	3.428	56
	Total	2.09	3.570	234
Total	Day	1.11	3.868	343
	Night	2.02	3.790	122
	Total	1.35	3.865	465

Levene's Test of Equality of Error Variances[a]

Dependent Variable: Difference between Cntrl Pt and Approach of Curve

F	df1	df2	Sig.
.797	3	461	.496

Tests the null hypothesis that the error variance of the dependent variable is equal across groups.

a. Design: Intercept+Ctrl_Pt+Study+Lightcond+Study * Lightcond

Tests of Between-Subjects Effects

Dependent Variable: Difference between Cntrl Pt and Approach of Curve

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	1161.235[a]	4	290.309	23.151	.000
Intercept	609.417	1	609.417	48.598	.000
Ctrl_Pt	814.824	1	814.824	64.979	.000
Study	151.306	1	151.306	12.066	.001
Lightcond	91.707	1	91.707	7.313	.007
Study * Lightcond	.072	1	.072	.006	.940
Error	5768.326	460	12.540		
Total	7775.000	465			
Corrected Total	6929.561	464			

a. R Squared = .168 (Adjusted R Squared = .160)

SPSS ANOVA Results for FM 2038 Test 6: Comparing Deceleration Magnitude between the Approach of the Curve and the Point of Curvature

ANOVA FM 2038 Test 6 Factors

Dependent Factor:	AC – PC
Covariate:	Control Point (Cntrl Pt)
Fixed Factors:	Study Light Condition (Lightcond)

Descriptive Statistics

Dependent Variable: Difference between Approach of Curve and PC

Before or After	Lightcond	Mean	Std. Deviation	N
Before	Day	4.94	3.022	158
	Night	4.92	3.193	65
	Total	4.93	3.065	223
After	Day	5.65	3.300	173
	Night	6.09	3.476	56
	Total	5.76	3.342	229
Total	Day	5.31	3.185	331
	Night	5.46	3.364	121
	Total	5.35	3.231	452

Levene's Test of Equality of Error Variances[a]

Dependent Variable: Difference between Approach of Curve and PC

F	df1	df2	Sig.
.996	3	448	.395

Tests the null hypothesis that the error variance of the dependent variable is equal across groups.

a. Design: Intercept+Ctrl_ Pt+Study+Lightcond+Study * Lightcond

Tests of Between-Subjects Effects

Dependent Variable: Difference between Approach of Curve and PC

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	1173.896[a]	4	293.474	37.111	.000
Intercept	418.247	1	418.247	52.889	.000
Ctrl_Pt	1089.153	1	1089.153	137.728	.000
Study	48.252	1	48.252	6.102	.014
Lightcond	4.112	1	4.112	.520	.471
Study * Lightcond	13.405	1	13.405	1.695	.194
Error	3534.874	447	7.908		
Total	17644.000	452			
Corrected Total	4708.770	451			

a. R Squared = .249 (Adjusted R Squared = .243)

SPSS ANOVA Results for FM 2038 Test 7: Comparing Deceleration Magnitude between the Point of Curvature and the Middle of the Curve

ANOVA FM 2038 Test 7 Factors

Dependent Factor:	PC – MC
Covariate:	Control Point (Cntrl Pt)
Fixed Factors:	Study Light Condition (Lightcond)

Between-Subjects Factors

		Value Label	N
Lightcond	0	Day	305
	1	Night	108
Before or After	0	Before	210
	1	After	203

Descriptive Statistics

Dependent Variable: Difference between PC and Middle of Curve

Lightcond	Before or After	Mean	Std. Deviation	N
Day	Before	1.72	3.347	151
	After	.84	2.563	154
	Total	1.27	3.005	305
Night	Before	2.78	3.567	59
	After	1.06	2.757	49
	Total	2.00	3.324	108
Total	Before	2.01	3.436	210
	After	.89	2.606	203
	Total	1.46	3.104	413

Levene's Test of Equality of Error Variances[a]

Dependent Variable: Difference between PC and Middle of Curve

F	df1	df2	Sig.
3.217	3	409	.023

Tests the null hypothesis that the error variance of the dependent variable is equal across groups.

a. Design: Intercept+Ctrl_Pt+Lightcond+Study+Lightcond * Study

Tests of Between-Subjects Effects

Dependent Variable: Difference between PC and Middle of Curve

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	184.212[a]	4	46.053	4.965	.001
Intercept	2.027	1	2.027	.219	.640
Ctrl_Pt	4.193	1	4.193	.452	.502
Lightcond	33.210	1	33.210	3.580	.059
Study	136.256	1	136.256	14.690	.000
Lightcond * Study	13.035	1	13.035	1.405	.237
Error	3784.456	408	9.276		
Total	4852.000	413			
Corrected Total	3968.668	412			

a. R Squared = .046 (Adjusted R Squared = .037)

FM 2038: Z-Test Comparing Two Binomial Proportions

FM 2038 - Day
Speed Lmt: 70 mph
Ad Speed: 45 mph

Compare Before and After Proportions for Percent Exceeding the **Speed Limit**

An Introduction to Statistical Methods (Ott) Stat 801

Section 8.5 pg 380 Z-Test to Compare Two Binomial Proportions

	π	y	n	π	$\sigma_{\pi1-\pi2}$	z	z_α
Point of Curvature (PC)							
Before	7.3%	12	165	0.0901408	0.030475	-1.067626	1.96
After	10.5%	20	190				
Approach of Curve (AC)							
Before	6.7%	11	165	0.0524781	0.0240979	1.1345737	1.96
After	3.9%	7	178				
Point of Curvature (PC)							
Before	0.6%	1	158	0.0030211	0.0060394	1.0479765	1.96
After	0.0%	0	173				
Middle of Cuve (MC)							
Before	0.0%	0	151	0	0	#DIV/0!	1.96
After	0.0%	0	154				

Compare Before and After Proportions for Percent Exceeding the **Advisory Speed**

	π	y	n	π	$\sigma_{\pi1-\pi2}$	z	z_α
Point of Curvature (PC)							
Before	100.0%	165	165	1	0	#DIV/0!	1.96
After	100.0%	190	190				
Approach of Curve (AC)							
Before	99.4%	164	165	0.9883382	0.0116019	0.9303032	1.96
After	98.3%	175	178				
Point of Curvature (PC)							
Before	96.8%	153	158	0.9758308	0.0168998	-0.846434	1.96
After	98.3%	170	173				
Middle of Cuve (MC)							
Before	92.1%	139	151	0.9409836	0.0269885	-1.50098	1.96
After	96.1%	148	154				

y: yes the sample exceeded the speed limit n: sample size
Bold italicized numbers indicate significant difference at a 95 percent confidence interval

FM 2038 - Night

Speed Lmt: 70 mph **Ad Speed:** 45 mph

Compare Before and After Proportions for Percent Exceeding the **Speed Limit**

	π	y	n	π	σπ1−π2	z	zα
Point of Curvature (PC)							
Before	10.6%	7	66	0.0983607	0.0541055	0.3100407	1.96
After	8.9%	5	56				
Approach of Curve (AC)							
Before	4.5%	3	66	0.0245902	0.0281377	1.6154336	1.96
After	0.0%	0	56				
Point of Curvature (PC)							
Before	0.0%	0	64	0	0	#DIV/0!	1.96
After	0.0%	0	56				
Middle of Cuve (MC)							
Before	0.0%	0	59	0	0	#DIV/0!	1.96
After	0.0%	0	56				

Compare Before and After Proportions for Percent Exceeding the **Advisory Speed**

	π	y	n	π	σπ1−π2	z	zα
Point of Curvature (PC)							
Before	100.0%	66	66	1	0	#DIV/0!	1.96
After	100.0%	56	56				
Approach of Curve (AC)							
Before	100.0%	66	66	1	0	#DIV/0!	1.96
After	100.0%	56	56				
Point of Curvature (PC)							
Before	100.0%	65	65	0.9586777	0.0362886	***2.4604319***	***1.96***
After	91.1%	51	56				
Middle of Cuve (MC)							
Before	88.1%	52	59	0.8703704	0.064922	0.3729563	1.96
After	85.7%	42	49				

y: yes the sample exceeded the speed limit n: sample size

Bold italicized numbers indicate significant difference at a 95 percent confidence interval

FM 1237 STATISTICAL ANALYSIS RESULTS

Site Characteristics

FM 1237 was considered the sharp curve for the Chevron field study. The following table lists some of the site characteristics for this curve.

Table 98. FM 1237 Site Characteristics.

Speed Limit	Advisory Speed	Radius	Δ^1	Length	Before Spacing[2]	Number of Chevrons Before	After Spacing[2]	Number of Chevrons After
(mph)	(mph)	(ft)	(degrees)	(ft)	(ft)	(#)	(ft)	(#)
60	35	409	91.0	649	119	7	55	14

[1] External Angle
[2] Average spacing reported

ANOVA Analysis

For each ANOVA analysis the following variables were coded as fixed (i.e. independent) factors: Study (Before versus After) and Light Condition (Day versus Night).

SPSS ANOVA Results for FM 1237 Test 1: Comparing Mean Speeds at the Control Point

ANOVA FM 1237 Test 1 Factors

Dependent Factor:	Control Point (Cntrl Pt)
Covariate:	None
Fixed Factors:	Study Light Condition (Lightcond)

Between-Subjects Factors

		Value Label	N
Before or After	0	Before	231
	1	After	246
Lightcond	0	Day	355
	1	Night	122

Descriptive Statistics

Dependent Variable: Control Point (mph)

Before or After	Lightcond	Mean	Std. Deviation	N
Before	Day	60.88	6.874	165
	Night	61.52	6.776	66
	Total	61.06	6.837	231
After	Day	62.55	6.457	190
	Night	61.64	6.403	56
	Total	62.34	6.443	246
Total	Day	61.77	6.696	355
	Night	61.57	6.581	122
	Total	61.72	6.661	477

Levene's Test of Equality of Error Variances[a]

Dependent Variable: Control Point (mph)

F	df1	df2	Sig.
.218	3	473	.884

Tests the null hypothesis that the error variance of the dependent variable is equal across groups.

a. Design: Intercept+Study+Lightcond+Study * Lightcond

Tests of Between-Subjects Effects

Dependent Variable: Control Point (mph)

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	248.244[a]	3	82.748	1.875	.133
Intercept	1371608.783	1	1371608.783	31087.444	.000
Study	72.293	1	72.293	1.639	.201
Lightcond	1.696	1	1.696	.038	.845
Study * Lightcond	53.136	1	53.136	1.204	.273
Error	20869.228	473	44.121		
Total	1838374.000	477			
Corrected Total	21117.472	476			

a. R Squared = .012 (Adjusted R Squared = .005)

SPSS ANOVA Results for FM 1237 Test 2: Comparing Mean Speeds at the Approach of the Curve

ANOVA FM 1237 Test 2 Factors

Dependent Factor:	Approach of Curve (AC)
Covariate:	Control Point (Cntrl Pt)
Fixed Factors:	Study Light Condition (Lightcond)

Between-Subjects Factors

		Value Label	N
Before or After	0	Before	231
	1	After	234
Lightcond	0	Day	343
	1	Night	122

Descriptive Statistics

Dependent Variable: Approach of Curve (mph)

Before or After	Lightcond	Mean	Std. Deviation	N
Before	Day	60.60	6.559	165
	Night	60.12	6.529	66
	Total	60.46	6.540	231
After	Day	60.61	6.275	178
	Night	58.89	6.332	56
	Total	60.20	6.318	234
Total	Day	60.60	6.404	343
	Night	59.56	6.442	122
	Total	60.33	6.424	465

Levene's Test of Equality of Error Variances[a]

Dependent Variable: Approach of Curve (mph)

F	df1	df2	Sig.
.797	3	461	.496

Tests the null hypothesis that the error variance of the dependent variable is equal across groups.

a. Design: Intercept+Ctrl_ Pt+Study+Lightcond+Study * Lightcond

Tests of Between-Subjects Effects

Dependent Variable: Approach of Curve (mph)

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	13378.332[a]	4	3344.583	266.717	.000
Intercept	609.417	1	609.417	48.598	.000
Ctrl_Pt	13234.133	1	13234.133	1055.367	.000
Study	151.306	1	151.306	12.066	.001
Lightcond	91.707	1	91.707	7.313	.007
Study * Lightcond	.072	1	.072	.006	.940
Error	5768.326	460	12.540		
Total	1711557.000	465			
Corrected Total	19146.658	464			

a. R Squared = .699 (Adjusted R Squared = .696)

SPSS ANOVA Results for FM 1237 Test 3: Comparing Mean Speeds at the Point of Curvature

ANOVA FM 1237 Test 3 Factors

Dependent Factor:	Point of Curvature (PC)
Covariate:	Control Point (Cntrl Pt)
Fixed Factors:	Study Light Condition (Lightcond)

Between-Subjects Factors

		Value Label	N
Before or After	0	Before	223
	1	After	229
Lightcond	0	Day	331
	1	Night	121

Descriptive Statistics

Dependent Variable: Point of Curvature (mph)

Before or After	Lightcond	Mean	Std. Deviation	N
Before	Day	55.62	5.465	158
	Night	55.43	4.851	65
	Total	55.57	5.283	223
After	Day	54.91	4.992	173
	Night	52.80	5.262	56
	Total	54.40	5.129	229
Total	Day	55.25	5.227	331
	Night	54.21	5.193	121
	Total	54.97	5.232	452

Levene's Test of Equality of Error Variances[a]

Dependent Variable: Point of Curvature (mph)

F	df1	df2	Sig.
.017	3	448	.997

Tests the null hypothesis that the error variance of the dependent variable is equal across groups.

a. Design: Intercept+Ctrl_ Pt+Study+Lightcond+Study * Lightcond

Tests of Between-Subjects Effects

Dependent Variable: Point of Curvature (mph)

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	6651.457[a]	4	1662.864	130.490	.000
Intercept	2101.114	1	2101.114	164.881	.000
Ctrl_Pt	6307.468	1	6307.468	494.966	.000
Study	403.665	1	403.665	31.677	.000
Lightcond	115.686	1	115.686	9.078	.003
Study * Lightcond	28.501	1	28.501	2.237	.135
Error	5696.224	447	12.743		
Total	1378328.000	452			
Corrected Total	12347.681	451			

a. R Squared = .539 (Adjusted R Squared = .535)

SPSS ANOVA Results for FM 1237 Test 4: Comparing Mean Speeds at the Point of Curvature

ANOVA FM 1237 Test 4 Factors

Dependent Factor:	Middle of Curve (MC)
Covariate:	Control Point
Fixed Factors:	Study Light Condition

Between-Subjects Factors

		Value Label	N
Before or After	0	Before	210
	1	After	203
Lightcond	0	Day	305
	1	Night	108

Descriptive Statistics

Dependent Variable: Middle of Curve (mph)

Before or After	Lightcond	Mean	Std. Deviation	N
Before	Day	53.76	6.629	151
	Night	52.54	5.817	59
	Total	53.42	6.421	210
After	Day	54.26	5.569	154
	Night	51.67	5.921	49
	Total	53.64	5.749	203
Total	Day	54.01	6.112	305
	Night	52.15	5.853	108
	Total	53.53	6.094	413

Levene's Test of Equality of Error Variances[a]

Dependent Variable: Middle of Curve (mph)

F	df1	df2	Sig.
1.961	3	409	.119

Tests the null hypothesis that the error variance of the dependent variable is equal across groups.

a. Design: Intercept+Ctrl_Pt+Study+Lightcond+Study * Lightcond

Tests of Between-Subjects Effects

Dependent Variable: Middle of Curve (mph)

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	5763.713[a]	4	1440.928	61.655	.000
Intercept	1719.649	1	1719.649	73.581	.000
Ctrl_Pt	5447.177	1	5447.177	233.077	.000
Study	48.721	1	48.721	2.085	.150
Lightcond	250.937	1	250.937	10.737	.001
Study * Lightcond	2.422	1	2.422	.104	.748
Error	9535.270	408	23.371		
Total	1198532.000	413			
Corrected Total	15298.983	412			

a. R Squared = .377 (Adjusted R Squared = .371)

FM 1237: Z-Test Comparing Two Binomial Proportions

FM 1237 - Day
Speed Lmt: 60 mph **Ad Speed:** 35 mph

Compare Before and After Proportions for Percent Exceeding the **Speed Limit**

	π	y	n	π	$\sigma_{\pi1-\pi2}$	z	z_α
Control Point (CP)							
Before	33.5%	111	331	0.339909	0.0369041	-0.24834	1.96
After	34.5%	113	328				
Approach of Curve (AC)							
Before	8.2%	24	292	0.0816327	0.0225835	0.0491819	1.96
After	8.1%	24	296				
Point of Curvature (PC)							
Before	0.0%	0	284	0	0	#DIV/0!	1.96
After	0.0%	0	19				
Middle of Cuve (MC)							
Before	0.0%	0	239	0	0	#DIV/0!	1.96
After	0.0%	0	274				

Compare Before and After Proportions for Percent Exceeding the **Advisory Speed**

	π	y	n	π	$\sigma_{\pi1-\pi2}$	z	z_α
Control Point (CP)							
Before	100.0%	331	331	1	0	#DIV/0!	1.96
After	100.0%	328	328				
Approach of Curve (AC)							
Before	99.3%	290	292	0.9931973	0.0067797	-0.013652	1.96
After	99.3%	294	296				
Point of Curvature (PC)							
Before	95.8%	272	284	0.9537954	0.0497457	1.2666345	1.96
After	89.5%	17	19				
Middle of Cuve (MC)							
Before	84.1%	201	239	0.8440546	0.0321112	-0.177855	1.96
After	84.7%	232	274				

y: yes the sample exceeded the speed limit n: sample size
Bold italicized numbers indicate significant difference at a 95 percent confidence interval

FM 1237 - Night

Speed Lmt: 60 mph **Ad Speed:** 35 mph

Compare Before and After Proportions for Percent Exceeding the **Speed Limit**

Control Point (CP)							
	π	y	n	π	$\sigma_{\pi1-\pi2}$	z	z_α
Before	25.1%	57	227	0.26178	0.045805	-0.574565	1.96
After	27.7%	43	155				
Approach of Curve (AC)							
	π	y	n	π	$\sigma_{\pi1-\pi2}$	z	z_α
Before	3.9%	8	207	0.031339	0.018907	0.942206	1.96
After	2.1%	3	144				
Point of Curvature (PC)							
	π	y	n	π	$\sigma_{\pi1-\pi2}$	z	z_α
Before	0.0%	0	157	0	0	#DIV/0!	1.96
After	0.0%	0	20				
Middle of Cuve (MC)							
	π	y	n	π	$\sigma_{\pi1-\pi2}$	z	z_α
Before	0.0%	0	118	0	0	#DIV/0!	1.96
After	0.0%	0	117				

Compare Before and After Proportions for Percent Exceeding the **Advisory Speed**

Control Point (CP)							
	π	y	n	π	$\sigma_{\pi1-\pi2}$	z	z_α
Before	100.0%	227	227	1	0	#DIV/0!	1.96
After	100.0%	155	155				
Approach of Curve (AC)							
	π	y	n	π	$\sigma_{\pi1-\pi2}$	z	z_α
Before	99.0%	205	207	0.985755	0.012859	0.868777	1.96
After	97.9%	141	144				
Point of Curvature (PC)							
	π	y	n	π	$\sigma_{\pi1-\pi2}$	z	z_α
Before	86.6%	136	157	0.836158	0.087878	***3.02969***	***1.96***
After	60.0%	12	20				
Middle of Cuve (MC)							
	π	y	n	π	$\sigma_{\pi1-\pi2}$	z	z_α
Before	75.4%	89	118	0.73617	0.057498	0.63113	1.96
After	71.8%	84	117				

y: yes the sample exceeded the speed limit n: sample size

Bold italicized numbers indicate significant difference at a 95 percent confidence interval

APPENDIX C: SUPPORT MATERIAL FOR THE DELINEATOR VISIBILITY STUDY

PRIOR TO STUDY –VERBAL INSTRUCTIONS TO SUBJECTS

My name is __________________________________; I work for the Texas Transportation Institute, which is part of the Texas A&M University System. I would first like to thank you for volunteering to participate in this study. The study is being sponsored by the Texas Department of Transportation. The purpose of this study is to determine how well drivers can see and read highway signs. Before I tell you about the study, I need to get a little information from you.

First, we need to confirm that you are between the ages of 18-45 or 55 or older, and you currently have a Texas driver's license.

NOTE: The above questions should have been asked when they were recruited. They are repeated at this time for added assurance.

Now, we're going to give you a simple visual screening test:

Snellen acuity "eye chart" (visual acuity screening test):

Binocular only. Record acuity (e.g., 20/20, 20/50) based on last line of which participant reads <u>all</u> letters correctly. If participant misses only one or two letters, have them try to read the next larger line. If they get all the letters correct, continue to the next line down. If they can't read it, go back to the previous line. If they still make errors, use the last all correct line to determine acuity.

Vistech (contrast sensitivity screening test):

Binocular only. First point, out the sample patches at the bottom of the chart with the three possible responses (left, right, or straight up). Start with Row A, and ask the participant to identify the last patch in which lines can be seen and tell you which direction they tilt. If a response is incorrect, have them describe the preceding patch. Once the participant has correctly identified a patch, have them guess which way the lines tilt in the next patch to the right. Record the last patch the patient correctly identifies in each row by marking the corresponding dot on the Evaluation Form. Record the lowest acuity (e.g., 20/20, 20/50 – highest number is lowest acuity) that the line falls through.

Do Color Vision test with color plates.

Before I tell you about the driving part of the test, I'd like you to answer these short questions about the photographs in this book.

Show binder with color identification questions in it. Don't let them page forward or back.

Now, let me tell you a little about your task tonight.

You will be driving a state-owned passenger vehicle on a closed course we've set up on the runway system here at the Riverside Campus. The vehicle is specially equipped to record and measure various driving characteristics, but drive just like normal vehicles. I will be in the car with you at all times, riding in the front passenger seat. The path you will drive is marked by reflective road markers.

We are interested in how the reflective delineator posts alongside the road influence driver's perceptions of how sharp a curve is. We are also interested in whether or not people can tell how many reflectors are on roadside delineator posts.

For the curve identification task, I will ask you to drive to a point marked by blue reflective road markers and stop there. I will then show you this sheet [show sheet] and ask you to say the number of the curve on the sheet that best matches your perception of the curve ahead. We will then proceed a little ways up the road to the next stopping point. For each curve, we will stop three times. There are four curves in all along the course. We will repeat the course four times altogether.

In between the first and second curve, we'll drive a straight section of road. After turning a corner and stopping at some blue markers, I'll ask you to speed up to 30 mph and maintain that speed. You will be looking for a single delineator post on the right side of the road, and then one on the left. For each post, you are to say out loud "POST" as soon as you can see that something is there. As you continue to approach the post, you are to say out loud the number of reflectors you think are on the post as soon as you feel you can correctly identify it. I will press a button in the car which will record the distance. This button makes a little beeping sound. It's alright to guess and then correct yourself. There's no penalty for being wrong. On some laps, we will have the post there with zero reflectors on it. In that case, we'd like you to say "blank" when you can tell that there's a post there with no reflector.

After you have completed the study course, a researcher will ask you a series of questions about what you have seen.

You will be driving through a number of different areas. Parts of the course will look very much like rural Texas roads you have driven on in the past. Other areas may not look much like roadways at all and may be confusing, but a researcher will always be in the car with you and will direct you where to drive. You are to drive 30 mph. It is important that you follow the researchers instructions very carefully when we're out on the test course.

An ID number will identify you during the data collection part of the study. The only information I will collect that identifies you by name is the Consent Form, and the disbursement log that I will ask you to sign. Nothing that identified you will be included in any data collected or reports written about this study.

There will be a cellular telephone and/or two-way radio available at all times during the study. *In case of an accident or medical emergency, appropriate emergency medical services will be called. However, neither TTI nor Texas A&M University will assume financial responsibility for any medical costs incurred due to your participation in this study. Continuing medical care and/or hospitalization for research-related injury will not be provided free of charge nor will financial compensation be available, or be provided by TAMU or the investigator.*

As you were told, the complete study will take about one hour. Upon completion of the study, you will be compensated $40.00 for your participation. If you are uncomfortable during any part of the study or have any questions, please let me know. I will try to answer any questions you have, except those that may affect the results of the study. If for any reason you choose not to continue to participate in the research study, you are free to quit at any time. If you do quit before the end of the study, you will receive compensation based on the portion of time you participated. Unforeseen circumstances such as equipment breakdown may cause the study to stop before it is completed. In that event, you will be compensated $10.00.

This study has been reviewed and approved by the Texas A&M's Institutional Review Board for the use of human subjects in research. Before we can begin you will need to read, understand, and sign this document (hand the subject the consent form). It's an informed consent document that confirms that you are volunteering to participate in this study and that you understand what is being asked of you. It summarizes the things that I've just gone over with you. Allow the participant to read the consent form, ask questions, sign form, and then give a copy of a signed form to the subject.

Now, unless you have some questions, we are ready to go. Once in the study vehicle, the researcher will give you more specific instructions on the study procedures.

(Offer restroom opportunity before leaving).

VERBAL INSTRUCTIONS TO PARTICIPANTS IN TEST VEHICLE

Make sure participants fasten their seat belt. Make sure the participant is wearing glasses if required on driver's license. Direct subject to the first study location.

NOTE: Make sure low beam headlights are on.

Okay, a few things we need to go over are:

- Drive 30 mph.
- There will be two blue markers on the road for you to line up with prior at each point we'd like you to stop to do the curve identification. Please try to come to a stop so that they are visible just beyond your hood.
- There will be road markers on your left to help guide you through the study area.
- For the reflector number task, I'll let you know when we get to that section.

At straight-away

- Please call out "POST" as soon as you can see that there is a post up ahead; it could be on the right or left side of the road.
- After you've spotted the post, please say the number of reflectors on each post, beginning with the one on the right side. I want to remind you that some of them may not have any reflector and on those please say "blank" as soon as you can tell that there's a post there. Just follow the red markers, keeping them on your left and drive straight. Please accelerate smoothly up to 30 mph and try to maintain that speed. I will be pressing a button when you say your response and this little device will make a beeping noise.

APPENDIX D: LETTER REQUESTING CHANGE TO THE MUTCD

Mr. Ernie Huckaby
MUTCD Team Leader
Office of Transportation Operations (HOTO)
Federal Highway Administration, Room 3408
400 Seventh Street SW
Washington, DC 20590

Mr. Huckaby:

Through this letter, the Texas Department of Transportation (TxDOT) is requesting that the Federal Highway Administration consider modifying Part 3 of the MUTCD to clarify and simplify delineation applications. A research project sponsored by the TxDOT and conducted at the Texas Transportation Institute was recently completed (research project 0-4052). This research was focused on the investigation of methods of simplify horizontal curve delineation treatments without jeopardizing safety. The specific objectives of the research were to simplify delineator and Chevron spacing along horizontal curves, determine a radius above which a horizontal curve on a freeway or expressway may be delineated as a tangent, and explore whether there is any new benefit in using double delineators. The findings and recommendations should be considered by the NUTCD and the FHWA when revising the current MUTCD. Specifically, based on the findings of the research project referenced above, the following modifications should be considered in the next rewrite of the MUTCD.

- Clarify the point at which a gentle curve on a freeway or expressway (already delineated with RRPMs) can be considered and delineated as a tangent section. Currently, the MUTCD language implies that all curves on freeways and expressways need post-mounted delineation, regardless of how gentle they may be. In snow country this may be an issue. A national survey found that 63 percent of the states delineate gentle curves on expressway and freeways as tangent sections. The cutoff curve radii criteria for this decision ranged from 2865 ft to 14000 ft, with and average of 6400 ft.
- Eliminate the suggested criteria that approach and departure delineation on horizontal curves be set at variable spacing. Research results have shown that drivers perceive curves the same regardless of whether the spacing is variable as currently suggesting in the MUTCD or fixed at twice the curve spacing (which depends on the radius).
- Eliminate the MUTCD's distinction between single and double delineators. The researchers showed that drivers cannot see double delineators farther than single delineators and drivers do not perceive curve radii any differently as a function of delineator size.

Thank you for your consideration. Please contact me with any questions.

Sincerely,

Branch Manager, Policy and Standards Sections, Traffic Operation Division