Procedure for Curve Warning Signing, Delineation, and Advisory Speeds for Horizontal Curves

by

Joseph E. Hummer, Ph.D. P.E.
William J. Rasdorf, Ph.D., P.E.
at
North Carolina State University
Department of Civil, Construction, and Environmental Engineering
Campus Box 7908
Raleigh, NC 27695

Daniel J. Findley, P.E.
at
Institute for Transportation Research and Education
Centennial Campus Box 8601
Raleigh, NC 27695

Charles V. Zegeer, P.E.
Carl A. Sundstrom, P.E.
at
UNC Highway Safety Research Center
730 Martin Luther King, Jr. Blvd.
Chapel Hill, NC 27599-3430

North Carolina Department of Transportation
Research and Development Group
Raleigh, NC 27699-1549

Final Report
Project: 2009-07

December 15, 2010

Technical Report Documentation Page

1. Report No. **FHWA/NC/2009-07**	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle **Procedure for Curve Warning Signing, Delineation, and Advisory Speeds for Horizontal Curves**		5. Report Date **September 30, 2010** 6. Performing Organization Code
7. Author(s) **Joseph E. Hummer, Ph.D. P.E., William J. Rasdorf, Ph.D., P.E., Daniel J. Findley, P.E., Charles V. Zegeer, P.E., and Carl A. Sundstrom, P.E.**		8. Performing Organization Report No.
9. Performing Organization Name and Address **North Carolina State University** **Department of Civil, Construction and Environmental Engineering** **Campus Box 7908** **Raleigh, NC**		10. Work Unit No. (TRAIS) 11. Contract or Grant No.
12. Sponsoring Agency Name and Address **North Carolina Department of Transportation** **Research and Analysis Group** **104 Fayetteville Street** **Raleigh, North Carolina 27601**		13. Type of Report and Period Covered **Draft Final Report** **August 2008 to August 2010** 14. Sponsoring Agency Code **2009-07**
Supplementary Notes:		

16. Abstract

Horizontal curves are relatively dangerous features, with collision rates at least 1.5 times that of comparable tangent sections on average. To help make these segments safer, this research developed consistent study methods with which field personnel could examine curves. This research included an examination of curve crash characteristics, the development of a manual field investigation procedure, the development of calibration factors for the relevant collision prediction equations in Highway Safety Manual, and GIS methods for finding key curve parameters. Based on this work, the research team recommends a systematic approach for identifying, investigating, analyzing, and evaluating horizontal curves. This systematic approach can lead to the selection and evaluation of promising curves, assessment of funding sources, and a recommendation of appropriate countermeasures. The approach should sometimes include a statistical analysis of horizontal curve collisions taking into account various road, crash, weather, and temporal attributes to help identify any unique circumstances that create an overrepresentation of certain types or characteristics of collisions. The research team found a calibration factor of 1.33 for the collision prediction equation for two-lane roads in the Highway Safety Manual. The research team also recommends several methodologies to identify and measure the key characteristics of horizontal curves using data already stored in GIS files.

17. Key Words **Horizontal curve, GIS, safety, data collection, study, radius**	18. Distribution Statement		
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 149	22. Price

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

DISCLAIMER

ACKNOWLEDGEMENTS

The research team acknowledges the North Carolina Department of Transportation for supporting and funding of this project. We extend our thanks to the project Steering and Implementation Committee members:

Brian Mayhew, Chair
Kevin Lacy
Jay Bennett
Joel Howerton
Daniel Keel
David Phipps
Larry Stallings
Brad Hibbs
Moy Biswas
Neal Galehouse

The authors especially thank those who were instrumental in assisting with the project. Mr. Brian Murphy, Mr. Shawn Troy, and Mr. Brian Mayhew were actively engaged in the field data collection and collision data collection which formed the basis for much of the analysis of this project. The organizers and attendees of the focus group sessions across the state were an excellent resource for sharing their experience. Mr. John Farley and Mr. Christopher Tilley were helpful with detailing and sharing GIS data. Ms. Carol Tan (FHWA Contract Manager), Mr. David Harkey (HSIS P.I.), Dr. Forrest Council, Mr. Yusuf Mohamedshah, and Mr. Behrang Hejazi provided the team with collision data from the HSIS. Mr. Kyungtae Ryoo supported the project as a research assistant in the Department of Civil, Construction, and Environmental Engineering.

Without the help of all the above individuals, the project could not have been completed in such a successful manner.

EXECUTIVE SUMMARY

Horizontal curves are relatively dangerous features, with collision rates at least 1.5 times that of comparable tangent sections on average. There is a wide variety of traffic control devices available for horizontal curves, but the available guidance on applying devices to curves is quite general. Much discretion is left to field personnel, as the factors that matter in optimum device choices are too complex to distill into simple formulas or tables. The lack of guidance has led to great inconsistencies in the application of traffic control devices for horizontal curves throughout the state. Some of this inconsistency causes real problems in at least three ways, including confused and surprised motorists who often get in collisions, vulnerability to lawsuits, and wasted time and money. To reduce some of this inconsistency, the purpose of this research was to develop better tools and a more uniform study procedure for field personnel to use when examining curves.

This research included a literature review, study of current NCDOT procedures, examination of curve crash characteristics, the development of a manual field investigation procedure, development of two-lane road calibration factors for the Highway Safety Manual, and development of methods for studying horizontal curves using available GIS data. The research team has several recommended actions in the areas studied for this project.

The research team recommends a statistical analysis of horizontal curve collisions taking into account various road, crash, weather, and temporal attributes to help identify any unique circumstances that create an overrepresentation of certain types or characteristics of collisions. The severity of two-lane curves, particularly in rural areas, drives the need for this type of analysis and the inclusion of curves as part of a hazardous site identification program. The analysis can identify specific hazardous locations as well as systematic deficiencies among regions, routes, geometric design factors, traffic control device consistency, shoulder width or type, maintenance practices, etc. This analysis should be part of a larger, planned approach for identifying, investigating, analyzing, and evaluating horizontal curves. This systematic approach can led to the selection and evaluation of promising curves, assessment of funding sources, and a recommendation of appropriate countermeasures.

The Highway Safety Manual is a useful new tool for highway agencies to predict the safety of a roadway. The research team recommends a random site selection to properly calibrate the predictive models. This results in the need for more data collection, but the sites can be used for many years until modifications are made to the roadway. A calibration factor or 1.33 was found to be appropriate to be applied to the HSM prediction method for two-lane roads to match North Carolina crash values. Data for AADT, curve radius, and curve length, are the most important factors in the model.

The research team recommends several possibilities to utilize a GIS data to help transportation professionals better identify and more efficiently study the characteristics of horizontal curves or to address other spatial data problems. The use of a GIS to determine horizontal curve radius and length is possible. A GIS-based approach can save time and resources compared to traditional field measurement techniques, as well as improve overall safety by eliminating the need to have personnel interact with the motoring public in potentially dangerous locations on

curves. The integration of one of the methods introduced and analyzed in this report into a comprehensive horizontal curve process would assist NCDOT in horizontal curve identification, investigation, and analysis. The available automated GIS program could likely be applied to the statewide system in less than an hour and the manual programs would likely require about a year to complete the entire system.

TABLE OF CONTENTS

DISCLAIMER .... **II**
ACKNOWLEDGEMENTS .... **III**
EXECUTIVE SUMMARY .... **IV**
TABLE OF CONTENTS .... **VI**
LIST OF FIGURES .... **IX**
LIST OF TABLES .... **X**
1.0 INTRODUCTION **1**
1.1 Research Objectives **1**
1.2 Outcomes and Benefits **2**
1.3 Report Organization **3**
2.0 LITERATURE REVIEW **4**
2.1 Introduction **4**
2.2 General Guides for TCDs for Horizontal Curves **4**
2.3 TCDs Effects on Horizontal curves **5**
2.3.1 TCD Application and Safety Effects for Horizontal Curves 5
2.4 Modeling for Determining Hazardous Curve Category **8**
2.5 Study Methods **9**
2.5.1 Ball-Bank Indicator Method 13
2.5.2 Compass Method 13
2.5.3 Direct Method 14
2.5.4 Lateral Acceleration Method 14
2.5.5 Yaw Rate Transducer Method 14
2.5.6 GPS Method 14
2.5.7 Study Method Comparison 15
2.6 Crash Modification Factor Clearinghouse **15**
3.0 CURRENT NCDOT PRACTICE ASSESSMENT **17**
4.0 CURVE CRASH CHARACTERISTICS **18**
4.1 INTRODUCTION **18**
4.2 Literature Review **19**
4.3 Methodology **20**
4.4 COLLISION DATA ANALYSIS **21**
4.4.1 Road Characteristics 22
4.4.2 Collision Characteristics 23
4.5 RESULTS **34**
4.6 Conclusions **37**

4.7 Recommendations **37**
5.0 MANUAL FIELD INVESTIGATION PROCEDURE **38**
6.0 HIGHWAY SAFETY MANUAL ANALYSIS **39**
6.1 Introduction **39**
6.1.1 Horizontal Curve Crash Data 40
6.2 Literature Review **40**
6.3 Methodology **41**
6.3.1 HSM predictive method calibration 41
6.3.2 Step 9: Select and apply SPF 41
6.3.3 Step 10: Apply CMFs 42
6.3.4 Step 11: Apply a calibration factor 42
6.4 Analysis **42**
6.4.1 Calibration factor analysis 42
6.4.2 Sensitivity analysis 45
6.5 Conclusions **46**
6.6 Recommendations **47**
7.0 INDIVIDUAL CURVE ANALYSIS GIS PROCESS **48**
7.1 Introduction **48**
7.1.1 Scope 48
7.1.2 Objective 49
7.2 Literature Review **49**
7.2.1 Roadway Alignments in GIS 49
7.2.2 Horizontal Curve Methods 50
7.2.3 Image Processing 51
7.2.4 Summary 51
7.3 Methodology **51**
7.3.1 Field Method 53
7.3.2 Curve Calculator 54
7.3.3 Curvature Extension 55
7.3.4 Curve Finder 56
7.4 Analysis **58**
7.4.1 GIS-Derived Curve Analysis 58
7.4.2 Field Measured Curve Analysis 60
7.4.3 Safety Analysis 66
7.5 RESULTS **67**
7.6 Conclusions **68**

7.7 Recommendations **70**
8.0 NETWORK CURVE ANALYSIS GIS PROCESS **72**
8.1 Introduction **72**
8.2 Literature Review **73**
8.3 Methodology **75**
8.3.1 Curve Identification 75
8.3.2 Geometric Characterization 76
8.3.3 Collision Data 76
8.4 Analysis **76**
8.4.1 Curve Finder Tolerance Sensitivity Analysis 77
8.4.2 Route Analysis 78
8.4.3 Hazardous Curve Analysis 84
8.4.4 Safety Analysis 85
8.5 RESULTS **87**
8.6 Conclusions **88**
8.7 Recommendations **89**
9.0 CONCLUSIONS **90**
9.1 Curve Crash Characteristics **90**
9.2 Highway Safety Manual Analysis **90**
9.3 Individual Curve Analysis GIS Process **91**
9.4 Network Curve Analysis GIS Process **93**
10.0 RECOMMENDATIONS **95**
10.1 Curve Crash Characteristics **95**
10.2 Highway Safety Manual Analysis **95**
10.3 Individual Curve Analysis GIS Process **95**
10.4 Network Curve Analysis GIS Process **96**
10.5 Horizontal Curve Procedure **97**
11.0 IMPLEMENTATION AND TECHNOLOGY TRANSFER PLAN **98**
11.1 Research Products **98**
12.0 CITED REFERENCES **99**
13.0 APPENDICES **104**
14.0 APPENDIX A: NCDOT DIVISION AND REGION MEETING SUMMARIES .. **105**
14.1 Meeting Script **120**
15.0 APPENDIX B: MANUAL FIELD INVESTIGATION PROCEDURE **123**

LIST OF FIGURES

Figure 1. Current NCDOT Practices 17
Figure 2. Horizontal Curve Collision Frequency Distribution 25
Figure 3. Horizontal Curve Collision Time of Day Characteristics 31
Figure 4. Horizontal Curve Collision Day of Week Characteristics 32
Figure 5. Horizontal Curve Collision Month of Year Characteristics 33
Figure 6. GIS Line Work – Horizontal Curve with 7 Points [ESRI 2009] 52
Figure 7. GIS Line Work – Horizontal Curve with 3 Points [ESRI 2009] 53
Figure 8. Horizontal Curve Layout [Findley and Foyle 2009] 54
Figure 9. Curve Calculator User Input Screen 55
Figure 10. Curvature Extension User Input Screen 56
Figure 11. Curve Finder User Input Screen 57
Figure 12. Tolerance Example 58
Figure 13. State Transportation Agencies Utilizing GIS to Identify Horizontal Curves 73
Figure 14. Horizontal Curve Study Methodology 74
Figure 15. Example of Manual Horizontal Curve Identification 75
Figure 16. Percentage of Curves Reported and Matched by Curve Finder Tolerance – NC96 & NC42 78
Figure 17. Percentage of Curves Reported and Matched by Curve Finder Tolerance – I40 78
Figure 18. Curve Finder Error Quotient Diagram 79
Figure 19. Radii Differences Between Curve Finder and Curvature Extension 82
Figure 20. Length Differences Between Curve Finder and Curvature Extension 84
Figure 21. Curve Influence Area (0.1, 0.2, and 0.5 miles) 87
Figure 22. Recommended Horizontal Curve Procedure 97
Figure 23. Division and Regional Meeting Locations. 106

LIST OF TABLES

Table 1. Study Methods for Curves. 10
Table 2. Horizontal Curve Collision Geometric Roadway Characteristics 22
Table 3. Horizontal Curve Collision Urban vs Rural Characteristics 23
Table 4. Horizontal Curve Collision Severity Characteristics 24
Table 5. Rural Horizontal Curve Collision Frequency Characteristics 26
Table 6. Horizontal Curve Collision Type Characteristics 27
Table 7. Horizontal Curve Collision Most Harmful Event Characteristics 28
Table 8. Horizontal Curve Collision Roadway Surface Characteristics 34
Table 9. Potential Countermeasures to Reduce the Frequency and/or Severity of Horizontal Curve Collisions 36
Table 10: HSM Calibration Factors Calculated 44
Table 11: Annual Calibration Factors 44
Table 12: Input Values for HSM (Minimum, Maximum, Average, and Median) 46
Table 13: Output Values from HSM (Predicted Collisions Per Year) 47
Table 14. Radius in Meters (feet) Comparison of GIS Methods 60
Table 15. Sensitivity Analysis for 304.8 Meter (1,000') Radius and 152.4 Meter (500') Length Curve 61
Table 16. Curve Radius: Field Measured vs GIS Calculated 63
Table 17. Curve Radius Differences from Field Measured Values 64
Table 18. Correlation Coefficients and P-values for Radius Values 64
Table 19. Curve Length: Field Measured vs GIS Calculated 66
Table 20. Curve Length Differences from Field Measured Length Values 67
Table 21. Correlation Coefficients and P-values for Length Values 67
Table 22. Safety Ranking of Top 10 Most Hazardous Field Measured vs GIS Calculated Curves 68
Table 23. Spearman Correlation Coefficients for Safety Rankings 68
Table 24. Radius Differences with Descriptive Parameters 82
Table 25. Length Differences with Descriptive Parameters 84
Table 26. Radius Differences with Descriptive Parameters 86
Table 27. Length Differences with Descriptive Parameters 86
Table 28: Collision Data (5 years – 2005 to 2009): Curve Related and All Crashes on NC42 and NC96 87
Table 29. Division and Region Meetings. 106
Table 30. Garner Meeting Attendance List 108
Table 31. Fayetteville Meeting Attendance List 111
Table 32. Greenville Meeting Attendance List 113
Table 33. Winston-Salem Meeting Attendance List 115
Table 34. Wilmington Meeting Attendance List 117
Table 35. Asheville Meeting Attendance List 119

1.0 INTRODUCTION

Great numbers of horizontal curves exist on NC roads. Unfortunately, horizontal curves are relatively dangerous features, with collision rates about 3 times that of comparable tangent sections on average (Lyles and Taylor, 2006).

There is a wide variety of traffic control devices available to keep motorists operating safely on horizontal curves, including pavement markings, normal warning signs, fluorescent signs, oversized signs, flashers, chevrons, advisory speeds, raised pavement markers, delineators, and others. The reference that provides the most important guidance for the application of those devices is the *Manual on Uniform Traffic Control Devices* (MUTCD). The guidance in the MUTCD for traffic control devices on curves is quite general, though. Much discretion is left to engineers and technicians in the field, as the factors that matter in optimum device choices are too complex to distill into simple formulas or tables. Other available manuals, including North Carolina's own version of the MUTCD, are not much more detailed.

The lack of specific guidance in the various manuals has led to inconsistencies in the application of traffic control devices for horizontal curves throughout the state. There are differences in treatment choices at curves between divisions and differences within divisions. Some of this inconsistency is fine, due to differences in terrain and other roadway features between different project sites. Some of this inconsistency causes real problems, however, in at least three ways. Most importantly, inconsistent application of traffic control devices for curves leads to confused and surprised motorists, which too often leads to collisions. It is an axiom in the design and operation of highways that we should meet driver expectations, and a surprising or inconsistently applied set of conditions leading into a horizontal curve is one of the worst offenders in this regard.

Inconsistent application of traffic control devices is also a recipe for liability problems. In the event of a lawsuit following a collision on a curve, (an event which will likely be more frequent with the recent increase in the state's liability cap), the NCDOT needs to be able to point to a policy and a process during the defense and say, "That is how we select curve-related safety treatments." A consistent process, with documentation in the files, is a great defense. Without a process and with an inconsistent result, the NCDOT is going to be more vulnerable.

Another problem resulting from inconsistent application of traffic control devices at curves is the likely cost to the NCDOT. There are situations where the NCDOT is undoubtedly spending excessive funds on unnecessary treatments. The Department may also be wasting staff time in needing to "reinvent the wheel" in many divisions and units during many different studies of curve warning devices each year.

1.1 Research Objectives

This project addressed the NCDOT's need for a consistent process in the application of traffic control devices on horizontal curves. We are not proposing a new set of standards or rigid guidelines. Indeed, we believe that standards and rigid guidelines in this case would be unnecessary and unsuccessful. Field personnel must have discretion in a problem this complex, and the NCDOT is not ready for a system-wide application. Instead, there is a need for a consistent study process that NCDOT field personnel should follow when deciding upon the right mix of devices for a horizontal curve or series of curves. If the study methods are identical, a reasonable amount of consistency will be achieved at similar sites, but appropriate variations will occur at different sites that deserve different treatments. A consistent study process will meet the NCDOTs needs and result in safer roads, with less vulnerability to lawsuits, and less wasted effort and resources by the NCDOT.

Note that the new method developed during this project dovetails nicely with the method developed during research project 2009-08, Procedure for Identification and Investigation of Horizontal Curves with Insufficient Superelevation Rates. That project was more narrowly focused, as it looked at field study techniques for curves that have already been identified as possibly deficient and on measuring radius and superelevation. This project was intended to be more proactive and comprehensive, in examining all relevant aspects of a curve or a set of curves, including sight distances, vertical alignments, roadsides, and other traffic and roadway features.

1.2 Outcomes and Benefits

The proposed project is important for NCDOT for several reasons. First of all, horizontal curves are relatively dangerous compared to tangent sections of roadway. Secondly, due to the terrain and historical factors, the NCDOT is charged with maintaining tens of thousands of miles of curvy road. Also, the decentralized nature of maintenance operations in the 14 Divisions means that there is the potential for a great degree of inconsistency across the state. In addition, the liability cap in NC has just risen to one million dollars per suit, so more lawsuits over allegedly inconsistent signing should be expected. It should also be mentioned that the MUTCD and other existing literature fall far short, to this point, of providing a consistent procedure the Divisions can use. Finally, new technology such as GPS and GIS increase the feasibility for implementing a new procedure for consistently determining proper curve warning devices feasible.

After the necessary training in the new study method, NCDOT engineers and technicians should be able to implement it consistently throughout the Department. The new method should result in more consistent warnings to motorists, which will reduce collisions, reduce NCDOT liability, and reduce wasted resources within the NCDOT. A new study method for deciding on curve devices will be applied in several places on NCDOT rural roads. The new method will be used as part of the spot safety process when the spots in question are horizontal curves. The NCDOT can also use the new method when citizen, media, politician, or Board inquiries are made. When the NCDOT constructs a new curve or reconstructs an old curve, the process will be useful as well.

Eventually, a new study method for curve warnings could be applied systematically to all curves on all state roads. The NCDOT is likely not ready for this yet, as it lacks the necessary curve inventory information or ongoing processes necessary to make this happen. However, some day such a comprehensive approach will be possible and will allow a proactive approach to safety—preventing collisions before they occur in addition to the current reactive approach of fixing places where collisions have occurred. A consistent new study method is the first step toward such a proactive system.

1.3 Report Organization

The remainder of the report is organized into chapters that present each of the major analyses performed during this project. Chapter 2 provides a literature review of traffic control devices, study methods, and crash modifications. Chapter 3 provides a summary of current NCDOT practices for horizontal curve investigations. Chapter 4 examines curve crash characteristics in North Carolina. Chapter 5 summarizes the manual field investigation procedure. Chapter 6 details the Highway Safety Manual analysis with two-lane road calibration factors. Chapter 7 presents an individual curve analysis process in GIS, while Chapter 8 provides network curve analysis in GIS. Chapters 9-11 present conclusions, recommendations, and technology transfer plans of the research project. Chapters 12 and 13 are references and appendices for the report.

2.0 LITERATURE REVIEW

2.1 Introduction

In North Carolina, there exist a great number of horizontal curves. As of 2006, the State of North Carolina had about 74,000 miles of two lane roads of a total of approximately 79,000 miles of roads (NCDOT 2007). The main function of horizontal curves is to provide a smooth transition between two tangent sections of roadway. Unfortunately, horizontal curves are relatively dangerous features, with collision rates about 3 times that of comparable tangent sections on average (Lyles and Taylor 2006). According to the statistics in the Fatality Analysis Reporting System (FARS) in 2002, about 42,800 people were killed in 38,300 fatal crashes on U.S. highways and 25 percent of the fatal crashes occurred on horizontal curves on two-lane rural highways.

The North Carolina Department of Transportation (NCDOT) has used several guidelines and handbooks for dealing with horizontal curve safety, including the Manual on Uniform Traffic Control Devices (USDOT 2003), AASHTO Green Book (AASHTO 2001), North Carolina Supplement to the Manual on Uniform Traffic Control Devices (NCDOT 2005), 3R Guide (NCDOT 2004), Traffic Control Devices Handbook (ITE 2001), and TEPPL (NCDOT 2010) for designing safe horizontal curves. These guidelines deal with various important horizontal design elements, such as selecting the adequate advisory speed, designing shoulder widths, and placing traffic control devices (TCDs).

There is a wide variety of traffic control devices available to assist motorists with operating safely on horizontal curves. Such measures include pavement markings, various types of warning signs (with and without flashers), chevron signs, advisory speed signs, raised pavement markers, pavement and post-mounted delineators, and others. The reference that provides the most commonly used guidance for the application of those devices is the Manual on Uniform Traffic Control Devices (MUTCD). The guidance in the MUTCD for traffic control devices on curves is quite general, however. Much discretion is left to transportation engineers and technicians in the field, as the factors that matter in optimum device choices are too complex to distill into simple formulas or tables. Other available manuals, including NC's own version of the MUTCD and the Traffic Engineering Policies, Practices and Legal Authority Resources (TEPPL), are also available but do not really provide much additional detail.

This literature review presented below is divided into four sections. The first section documents the general guides for traffic control devices for horizontal curves. The next section describes the known effects of traffic control devices for horizontal curves. The third section compares various study methods, and the final section summarizes the highlights of this review.

2.2 General Guides for TCDs for Horizontal Curves

This section covers the general guides for horizontal curves associated with traffic control devices or studies that are related to this research. The studies include literature that is commonly referred to by traffic engineers.

Traffic Control Devices (TCDs) including signs, signals, pavement markings and other devices play a role in moving vehicles safely and efficiently as providing important information on geometric design and traffic operation to drivers. The USDOT and ITE (USDOT and ITE 2004) briefly describe the function and characteristics of uniform TCDs. They provide resources to select proper TCDs and deal with several issues related to their installation and placement. As required resources for determining adequate TCDs on subject roads, they recommended the 2003 Edition of the MUTCD, the Traffic Engineering Handbook, and the Traffic Control Devices Handbook. They also mentioned six general issues relevant to TCD placement and installation. The reference provides general direction and information to correctly apply TCDs with consistency. The mentioned common issues are helpful to understand the weakness of currently used TCDs.

Lyles and Taylor (2006) developed guidelines for consistency and uniformity of traffic control devices to communicate changes in horizontal curves (concentrating on two-lane, two-way rural roads) to drivers. This study included a literature review, focus group exercises of practitioners and drivers, surveys of practitioners and drivers, and a limited field study of a drivers' behavior. The different types of TCDs available--including signs, advisory speeds, chevrons, edgelines, centerlines, delineators, and pavement markers--were summarized in the literature review. In addition, some problems were identified regarding communicating changes, such as changes in speeds and geometric design elements.

In that same study, focus group exercises, perceptions of drivers and practitioners were determined for the TCDs used for horizontal curves. Perceptions were determined to evaluate adequacy of devices, consistency of devices, and necessity to change devices. From these exercises, the authors concluded that there was inconsistency in use curve-related TCDs by different drivers and that the combinations of curves and TCD interpretation inconsistency can result in dangerous scenarios. A survey was conducted to obtain a wider point of view and assess responses to different curve-related issues. The survey provided similar results to the focus groups. Particularly, signing and marking were identified as issues for horizontal curves.

Finally, driver performance monitoring (DPM) techniques were used to observe randomly selected drivers' behaviors. DPM is a technique in which trained observers evaluate a driver's behavior including the driver's visual search, speed, and direction control on the curve. The authors suggested some changes such as the addition of winding road signs, advisory speed signs, and horizontal alignment signs in the MUTCD guidelines. (Lyles and Taylor, 2006)

2.3 TCDs Effects on Horizontal curves

This section describes the effects of traffic control devices on horizontal curves. The first sub-section describes studies to practically apply TCDs and their safety effects for horizontal curves. The second sub-section deals with modeling methods for determining hazardous curve categories.

2.3.1 TCD Application and Safety Effects for Horizontal Curves

In a 1991 study for FHWA, Zegeer et al. developed relationships between crashes and various geometric features of horizontal curves such as degree of curves, curve length, roadway width, spiral curve, superelevation, roadside condition, and average daily traffic. In the researchers' work, to meet the study objective, the horizontal curve features which affect traffic safety and operation were first identified. From the determined features, currently used countermeasures for enhancing safety and operations were determined. Finally cost-effective countermeasure guidelines and a methodology were developed to apply to particular curve sections. Analyses of a 10,900 horizontal curve data set from Washington State and a 3,277 curve data set from FHWA were performed with respect to curve features and crashes to estimate their relationships and to develop accident reduction factors (ARFs).

Through a variety of statistical methods, the Zegeer, et. al. study developed a crash prediction model consisting of six variables related to crashes and curve features was drawn. The variables found to be significantly related to the number of curve crashes included the degree of curve, roadway width, curve length, ADT, presence of a spiral, superelevation, and roadside condition. Based on the model, geometric improvements which were determined to reduce curve crashes included curve flattening, widening lanes and shoulders, adding spiral transitions, improving deficient superelevation, and making certain types of roadside improvements. Although that study did not specifically evaluate TCD's in terms of crash effects, the authors did discuss the relevance of such measures in the study recommendations:

…."Special attention to signing and markings is important along any highway, and particularly at critical locations such as sharp curves .It is clear, however, that the addition of signing, marking and delineation cannot be expected to solve a safety problem on a poorly designed curve. At the same time, proper signing, marking, and delineation in accordance with the Manual on Uniform Traffic Control Devices (MUTCD) is an essential ingredient to treating hazardous curves in conjunction with other improvements (e.g., clearing roadsides, widening the roadway, paving the shoulder, flattening the curve, and/or improving the superelevation). Even if construction or reconstruction of a poorly designed curve is not feasible, substandard signing, marking, and delineation should still be improved on hazardous curves."

During the past few years, there has been a variety of research on raised pavement markers (RPMs). In 2001, Hammond and Wegmann (2001) evaluated the effect of RPMs on motorists on horizontal curves. The RPMs are traffic control devices used to increase the visibility of changing roadway alignment. The authors derived relationships between RPM applications and driver behavior (the level of opposing-lane encroachment). Under dry weather and daylight conditions, a total of 600 data points of vehicle speed and encroachment were obtained from two horizontal curve segments located in Knoxville, TN. To quantify the effects of RPMs and verify the significance of the collected data, three types of statistical methods were utilized including F-test, Tukey test, and Chi-square test. From the statistical analysis, the results indicated that the level of encroachment decreased after installation of RPMs but the RPMs did not affect average operating speeds on horizontal curves. From this study, the authors recommended the 40 ft spacing of RPMs to prevent encroachment into the opposing lane. However, a shorter spacing than 40 ft is not cost-effective in daylight conditions.

Traffic engineers have continuously looked for the ways to increase the conspicuity of TCDs. Yellow warning signs, one of the important types of TCDs, play a role in notifying drivers of potentially dangerous conditions. Moreover, as fluorescent yellow sheeting method was recently introduced, the effectiveness has been evaluated in various ways. Eccles and Hummer (2000) assessed the safety effectiveness of fluorescent yellow warning signs at hazardous locations during daylight conditions. Based on collisions and traffic volume data, seven study sites were selected in Orange County, NC. As a study method for evaluating the effectiveness of fluorescent yellow warning signs, the authors conducted a simple before-and-after experiment using various indirect measures of effectiveness such as encroachments, stop sign observance, conflicts, and speed with respect to collisions. Collected data from all study sites were analyzed through statistical methods of t-test, Z-test, and F-test. The study results indicated that a fluorescent yellow warning sign enables its conspicuity and safety to improve on the road. Also, it is cost-effective compared to a normal yellow warning sign or especially to a flashing beacon. The paper identified the safety and economic effectiveness of fluorescent yellow warning signs. These signs can be applied to horizontal curves as well as to hazardous sites like those identified on the kick-off meeting slides. In addition, the cost-effectiveness of this sign closely corresponds with our project objective.

It was reported that about 25 percent of people who die every year on the Nation's highways are killed at horizontal curves. Also, about 75 percent of all fatal crashes occur on rural roads and 70 percent occur on two-lane highways. To reduce this danger, McGee and Hanscom (2006) provided practical, cost effective, safety information on the application of TCDs to horizontal curves. A variety of horizontal curve treatments was dealt in the reference, including basic traffic signs and markings as identified by the MUTCD; enhanced TCDs; other TCDs not mentioned in the MUTCD; rumble strips; minor roadway improvements; and innovative and experimental treatments. Finally, for all treatments, the authors concisely documented its description (what it is), application guidelines (when to install), design elements (what design elements to use), effectiveness (how the treatments can improve safety), cost (what it will cost), and additional sources.

Torbic et. al. (2004) suggested ways to improve the safety of horizontal curves. There were two primary purposes for their study. One was to reduce the possibility of a vehicle leaving its lane and either crossing the roadway centerline or leaving the roadway. The other was to minimize the adverse consequences of leaving the roadway at a horizontal curve. To accomplish these objectives, twenty detailed strategies were described as countermeasures for reducing curve-related crashes. Each strategy includes a general description, an estimate of the effectiveness of the treatment, and special issues pertaining to horizontal curves. Some of the strategies that cover signs, markings, sight distance, and horizontal alignment are related to this project.

Visually well designed TCDs in horizontal alignment enable drivers to rapidly and exactly respond to changes in potentially hazardous horizontal curves. On the other hand, the application of complicated TCDs makes some drivers confused and provides exposure to possible crash situations. One of the important goals of recent research at TTI was to simplify the delineator applications in the MUTCD. Chrysler et al. (2005) focused on comparing single and double delineators and providing appropriate delineator spacing depending on horizontal curve ratio. In order to examine the application of delineators in the current MUTCD for color, type, and spacing, vision tests and memory tests were conducted for twenty-four drivers. From the visibility study, the authors found that drivers approaching horizontal curves do not realize the difference between single and double delineators and discriminate between variable spacing and fixed spacing. Also, the drivers do not perceive the difference in delineator colors (yellow and white). The results of the study suggest ending the use of both single and double delineators and the use of variable spacing on horizontal curves.

Motor vehicle crashes are a significant and costly problem for two-lane horizontal curves. Various factors including driver factors, vehicle factors, and roadway factors contribute to vehicle collision on the curves. From previous studies, the vehicle speed approaching curves in those causal factors is apparently related to curve-related crashes especially on two-lane roadway with sharp horizontal curvatures. Retting and Farmer (1998) examined the effectiveness of pavement markings reducing curve speed based on vehicle speeds on rural and suburban two-lane horizontal curves. In their work, they compared vehicle speed before and after installation of the pavement marking. For the comparison, speed measurement was conducted using TimeMark™ Delta Traffic Counters connected to pneumatic road tubes on a two-lane sharp curve road (approximately 90 degrees) in Northern Virginia. The speed measurements data were collected for two weeks after marking installation. The equipment produced vehicle classification, gap, and speed data. Statistical analysis was performed using logistic regression models to measure the effect of the pavement marking. The results from this research have shown that the pavement marking in this study is associated with a decrease in vehicle speed of about 6 percent overall and 7 percent during daytime and late night periods.

2.4 Modeling for Determining Hazardous Curve Category

There are guidelines for signing and marking horizontal curves in some countries of Europe. In 2001, Herrstedt and Greibe (2001) developed a systematic signing and marking guideline to provide drivers with safe information about horizontal curves on two-lane rural roads. The authors regarded running speed before entering the curves as an important causal factor for safety and made the drivers adapt their approach speed to a suitable speed range in a determined category. Based on these design speed and approach speed on horizontal curves and kinetic energy considerations, they developed a model for determining the category of risk for curves and calibrated the model for both French and Danish conditions. Finally, using the developed model, the severity of expected dangerousness on horizontal curves was classified into one of five categories depending on the degree of risk. A combination of TCDs consisting of delineators, center and edge lines, pre-warning signs, speed signs, and chevron signs was suggested for each of the five categories.

Nielsen and Herrsted (1999) developed a systematic and uniform framework for signing and marking for substandard horizontal curves that have similar geographic design characteristics on rural roads. The objective of this study provides drivers on curves involved in particular danger category with the same information from signing and marking. This study consisted of three sections: models to define substandard horizontal curves and classify danger categories; basic signing and marking concepts depending on the danger categories; and detailed methods to apply in practice. The key point of the model is the approach speed and curve design speed. The larger the difference between speeds, the more serious the danger category.

Bonneson et. al. (2007b) developed a horizontal curve signing handbook to guide traffic engineers and technicians responsible for designing the traffic control devices for rural horizontal curves. The objective of the handbook is to identify when warning signs and advisory speed plaque should be installed for safe traffic operation on curves. Another important purpose was to determine the advisory speed for uniform and consistent driver expectation. In the guidelines, they first determined the curve's danger category based on tangent section speed and curve speed and applied combinations of several TCDs to the curve. They limited the number of TCDs used at a subject curve to improve the uniformity and consistency.

2.5 Study Methods

This section summarizes study methods used to estimate advisory speeds and curve radii for horizontal curves. Six methods were reviewed from the several references. The criteria for the evaluation of each method included precision, cost, utility (ease to use), and safety. Table 1 shows brief descriptions of the characteristics, drawbacks, and data produced from every method.

Table 1. Study Methods for Curves.

Method		Characteristic	Critical Feature	Data Produced								Resources			
				Speed	Radius	Superelevation	Lateral Acceleration	Deflection Angle	Curve Length	Volume Data	Yaw Rate	Device	Cost	Staff	Time
Ball-Bank Indicator (1,2)		-Easy to use -Vehicle mounted -More useful for variable advisory speed than compass method -Combination of lateral acceleration, superelevation, and vehicle body roll -Does not account for curve speed	-Requires several runs at different speeds to provide a good average lateral acceleration	✓	✓		✓					Ball-bank indicator, TYPE 10-10 M23	$90	1 person	1 hour
Compass	Automated (3,4,5)	-Easy to use -Based on curve geometry -Technicians needed on the roadside	-Calibration of devices is needed	✓	✓	✓		✓	✓			Ball-bank indicator, digital compass, distance-measuring instrument (DMI)	Low	2 people	1 hour
Compass	Manual (6)	-Easy to use -Based on curve geometry -Technician needed on the roadside	-Technician needed on the roadside		✓	✓						Tape measure, level, etc.	Low	1 person	Less than 30 minutes
Direct (4)		-Directly measure the speed preferences of driver population (car and truck) -Technicians needed on the roadside	-Sample size issue	✓						✓		Traffic classifier/radar gun	$800	1 person	1 to 2 hours

Method	Characteristic	Critical Feature	Data Produced								Resources			
			Speed	Radius	Superelevation	Lateral Acceleration	Deflection Angle	Curve Length	Volume Data	Yaw Rate	Device	Cost	Staff	Time
Lateral Acceleration (5)	-More accurate curve radius than BBI -Vehicle mounted	-Several runs are required at different speeds to provide a good average lateral acceleration		✓	✓	✓					Lateral accelerometer (VC3000)	$5,000	1 person	1 hour
Yaw Rate Transducer (2,5)	-Curve radius is calculated using equation -Upgraded (automated) version of compass method -Vehicle mounted	-Significant variance in the yaw rate data		✓			✓	✓		✓	Lateral accelerometer (VC3000)	$5,000	1 person	1 hour
GPS (2,7)	-Easy to use -Little training is needed -Similar to compass method -Good precision (accurate curve radius) -Vehicle mounted	-Easy to use	✓	✓			✓	✓			GeoXT	$100 to $20,000	1 person	1 hour
Accelerometer-based systems (8)	-Provide more accurate advisory speed than ball-bank indicator method -Vehicle mounted	-Expensive	✓					✓			GyroDMU-FOG			1 hour

Method		Characteristic	Critical Feature	Data Produced								Resources			
				Speed	Radius	Superelevation	Lateral Acceleration	Deflection Angle	Curve Length	Volume Data	Yaw Rate	Device	Cost	Staff	Time
HI-STAR (9)		-Installed in the center of a lane -Require no physical contact from vehicles	-Device might not capture every vehicle	✓						✓		HI-STAR (Model NC-97)	$1,000 per lane	2 to 3 people	1 to 2 hours
Vehicle-Based Systems	Gyroscope (10)	-Vehicle mounted -Vertical gyroscopes measures roll, pitch, and heading -Vertical and horizontal geometrics collected at 4 meter intervals	-Provides automated mapping capability		✓	✓	✓	✓	✓		✓	Smart Geometrics	Expensive	1 person	Highway Speeds
	Laser (11)	-Vehicle mounted -Dual scanning lasers measure transverse profile of road	-Over 1,200 points laterally per lane			✓						Laser XVP	Expensive	1 person	Highway Speeds

Table References	
1	Chowdhury et. al. ,1998, Are the Criteria for Setting Advisory Speeds on Curves Still Relevant?
2	Carlson et. al., 2004, Simplifying Delineator and Chevron Applications for Horizontal Curves
3	Bonneson, J., et al., 2007, Development of Guidelines for Establishing Effective Curve Advisory Speeds
4	Bonneson, J., et al., 2007, Horizontal Curve Signing Handbook
5	Carlson P. J., et al., 2005, Comparison of Radius-Estimating Techniques for Horizontal Curves
6	NCDOT Research Project 2009-09, Procedure for Identification and Investigation of Horizontal Curves with Insufficient Superelevation Rates
7	Inlander, E. et. al., 2007, Inventory and Sediment Modeling of Unpaved Roads for Stream Conservation
8	Koorey G. et al., 2002, Curve Advisory Speeds in New Zealand
9	Vest, A., et. al, 2005, Effect of Warning Signs on Curve Operating Speeds
10	Roadware Group Smart Geometrics
11	Roadware Group Laser XVP

2.5.1 Ball-Bank Indicator Method

Normally, advisory speeds for horizontal curve are determined through several direct runs of a test vehicle in the field. In general, the ball-bank indicator is the most commonly used method to select an advisory speed on horizontal curves (*18*). This method is initially based on experiments conducted in 1930s. Although the MUTCD provides general guidelines for several TCDs, there still exist a variety of difficulties in practical field implementation due to the subjectivity and variability in traffic engineer's opinions. Although there have been a lot of mechanical improvements in vehicle characteristics for the last 50 years, the criteria for setting advisory speeds on curves still use the old method.

Chowdhury et. al. (1998) assessed the validity in ball-bank indicator criteria for determining advisory speeds on horizontal curves. To accomplish the study objective, the authors collected the data on curve geometry, spot speeds, and ball-bank readings on 28 two-lane highways in Virginia, Maryland, and West Virginia. Data were analyzed to consider various factors including posted advisory speed, driver's compliance, and friction factors. The authors compared the existing posted speed with the speed recommended by ball-bank indicator, a standard formula, and the 85th percentile. The authors suggested that the existing criteria of ball-bank indicator reading (10°, 12°, and 14°) should be revised upward to 12°, 16°, and 20° to better reflect average curve speeds.

Carlson et. al. (2004) estimated the curve radius using ball-bank indicator method and curve speed. The curve radius was calculated by a point-mass equation from AASHTO Green Book (2001). Finally, the estimated radius was compared to true curve radius and the relative error was larger than other methods.

2.5.2 Compass Method

The compass method is based on an advisory speed equation for a curve of specified radius and superelevation rate. Basically, this method needs curve radius and superelevation rate information.

Bonneson et. al. (2007a, 2007b) provided traffic engineers with technical guidelines of TCDs application and procedure for rural horizontal curves in the "Horizontal Curve Signing Handbook" using a compass method. This reference described detailed processes and methods for establishing advisory speed on horizontal curves.

Currently, the ball-bank indicator method is a widely used method to establish various TCDs. As an alternative method for determining the advisory speed, compass method was developed in this project which is based on measurement of curve geometry. To evaluate the developed compass method, it was compared with traditional ball-bank indicator method with respect to speed variability. The result indicated that the compass method is more stable than the ball-bank indicator method for curves having similar geometries. This means that the compass method provides more uniform and consistent advisory speeds for horizontal curves. In addition, it was found that ball-bank indicator method does not consider tangent section speed although the speed affects the advisory speed. However, the compass method has safety problems since the field personnel leave their test vehicle to collect data on the roadside (Carlson et al., 2005).

2.5.3 Direct Method

The direct method is based on the measurement of vehicle speed at the curve mid-point using a radar gun, laser gun, or traffic classifier. The Horizontal Curve Signing Handbook (Bonneson et al., 2007b) describes the three steps of the direct method: 1) field measurements of speed, 2) Determination of advisory speed, and 3) confirmation of speed for conditions. The direct method has the advantage of being able to directly measure the speed preferences of driver population (car and truck) as they have an interaction with the subject curve. However, this method also has the disadvantage of taking more resources to determine adequate advisory speed comparing to ball-bank indicator method and compass method.

2.5.4 Lateral Acceleration Method

The lateral acceleration method is similar to the ball-bank indicator method except that the unbiased lateral acceleration rate is substituted in the point-mass equation of BBI to determine the curve radius. The data measured by a lateral acceleration device are stored with traveled distance and vehicle speed. The error of this method is relatively low compared to ball-bank indicator method and compass method (Carlson et al., 2005). Also, just one field technician is required to collect needed data. However, the measuring device is expensive and, like the ball-bank indicator method, it is essential to drive the curve several times to obtain a good lateral acceleration.

2.5.5 Yaw Rate Transducer Method

The yaw rate transducer method uses a lateral acceleration device. Additionally, it provides not only traveled curve distance and vehicle speed but also the deflection angle of the curve. Therefore, this method can calculate the final curve radius using a simple equation like the following:

$$\textbf{Curve Radius (ft)} = \frac{\textbf{57.3} \times \textbf{Curve Length (ft)}}{\textbf{The change degree in direction (degree)}} \quad \textbf{(Equation 1)}$$

However, this method is sometimes ignored in different study methods since significant noise exists in the collected yaw rate data.

2.5.6 GPS Method

As geographical information technology has developed for the last decades, its benefit was applied to the various areas in roadway geometric design. The GPS can be operated by a test vehicle running at particular speed allowing the measuring vehicle to travel with the normal traffic flow. The travel distance of the test vehicle is derived from GPS speed.

Carlson, et al. (2004) utilized a GPS method for determining delineator and chevron spacing, and a curve radius, on horizontal curves. The researchers performed surveys of a total of 34 states and visited 58 curve sites throughout the state of Texas to evaluate the current practices. During these visits, they obtained delineator and chevron spacing, curve radius, superelevation, driving speed, and other related curve characteristics. The results of the study show that a GPS provided a high level accuracy and cost-effectiveness. As a result, the authors suggested a simplified delineator and chevron spacing table using the GPS method.

2.5.7 Study Method Comparison

Carlson et. al. (2005) compared the various methods for estimating curve radius including basic ball bank indicator, advanced ball-bank indicator, chord length, compass, field survey, GPS, lateral acceleration, plan sheet, speed advisory plate, and vehicle yaw rate methods. Eight of these 10 techniques were conducted to measure 18 horizontal curves in Texas. The criteria to evaluate all techniques were accuracy, cost, ease of use, and safety. The results of this study show that the GPS method ranked the highest in all of the criteria. They recommended the GPS method as the best study method to estimate curve radius.

2.6 Crash Modification Factor Clearinghouse

The Federal Highway Administration (FHWA) has established a Crash Modification Factors (CMF) Clearinghouse (located at www.cmfclearinghouse.org) as a centralized location for CMFs. This tool allows for transportation professionals to search, identify, and evaluate which CMFs provide the most cost-effective roadway safety improvements given specific conditions. It is designed to be a user-friendly resource that presents and compares CMFs in a way that specific safety and research experience is not necessary. The clearinghouse is maintained by the UNC Highway Safety Research Center which will apply periodic content updates.

A CMF is a multiplicative factor used to estimate the change in the number of crashes after a given countermeasure is implemented under specific conditions. For example, a CMF for an intersection countermeasure of 0.80 indicates that if this countermeasure is implemented at an intersection experiencing 100 crashes, the expected number of crashes after implementation is 80 (100 x 0.80) for a crash reduction of 20%.

The clearinghouse has a comprehensive listing of all available CMFs categorized by a variety of parameters. These parameters allow users to easily locate CMFs using a search function that include the following categories:

- Keyword
- Countermeasure
- Crash type
- Crash severity
- Roadway type
- Intersection type
- Intersection geometry
- Traffic control
- Area type

The search creates a results list that provides a summary of each applicable CMF. This summary list allows users to compare applicable CMFs to determine which CMF may be best used for their specific situation. Included in the summary and details of each CMF is a star quality rating from 1-5 (with 5 indicating the highest quality). These star ratings are provided for the user to assess the quality of the CMF presented. Star ratings are developed through a review process that evaluates each study based on study design, sample size, standard error, potential bias, and data sources. The summary of each CMF also includes information on when and where these studies were done. This information is helpful for users to determine which studies were done recently and whether the locations are similar and applicable to their jurisdiction.

In an effort to keep the data current, the CMF Clearinghouse will be regularly updated with new research. This new research will be added through staff regularly examining published and presented material and through studies that are submitted through the website by users.

This tool is ideal for evaluating horizontal curve countermeasures given a specific curve. A February 2010 search for 'horizontal curves' yielded 177 results that could be further focused to a specific condition based on crash types and severity, roadway types, and area types. Categories included in the search results are advanced technology and ITS, alignment, roadside, roadway, roadway delineation, roadway signs and traffic control. Comparing two CMFs for rural conditions found a CMF of 0.741 for installing edgelines on curves and a CMF of 0.94 for installing raised pavement markers and transverse rumble strips on approaches to horizontal curves. These CMFs can then be evaluated for application at specific conditions in North Carolina based on further study details provided in the summary of each CMF.

3.0 CURRENT NCDOT PRACTICE ASSESSMENT

The research team visited the division and regional offices of the NCDOT and conducted interviews with traffic engineers and other staff to determine the current NCDOT practices that apply TCDs to horizontal curves. These visits and interviews provided the research team with valuable information about current NCDOT practices, which allowed the creation of Figure 1 which displays the current NCDOT practices. The appendix contains more details about the visits and interviews.

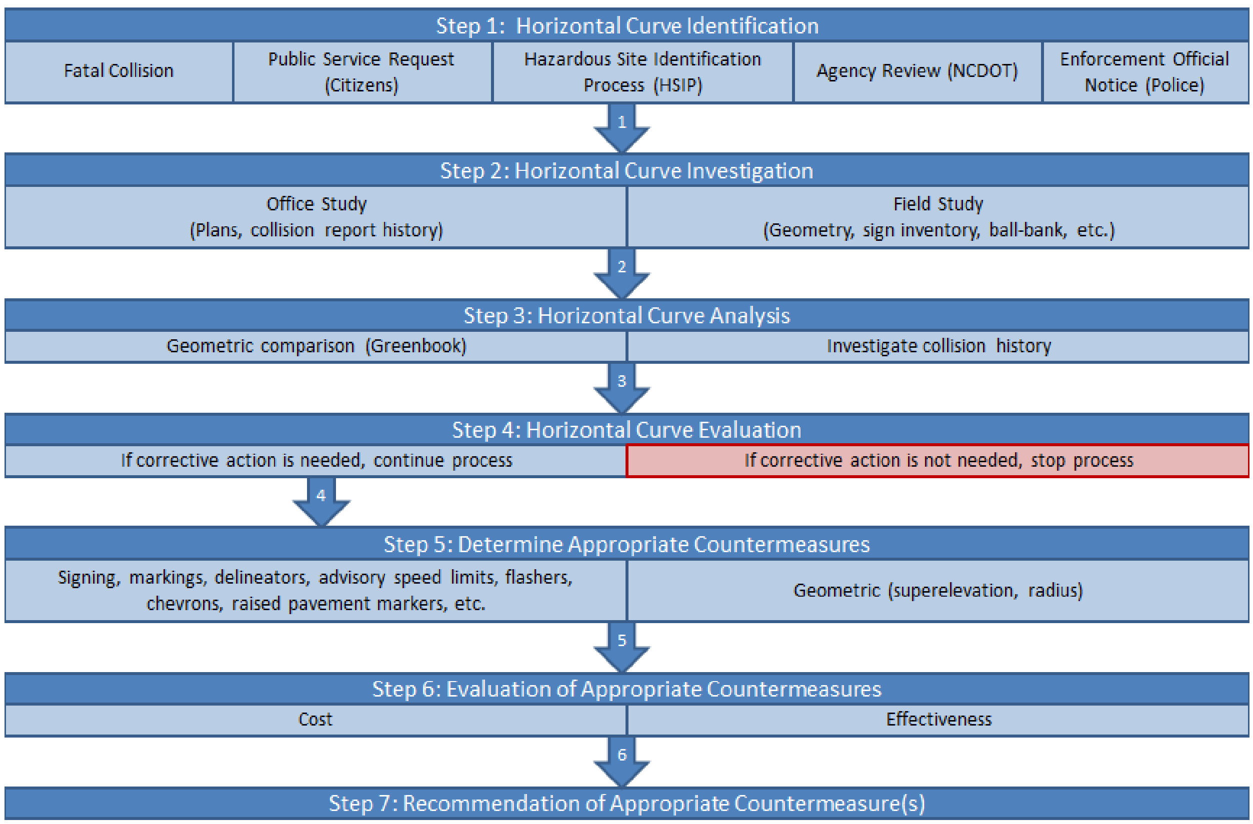


Figure 1. Current NCDOT Practices

4.0 CURVE CRASH CHARACTERISTICS

4.1 INTRODUCTION

Horizontal curves provide a transition from one tangent section of roadway to the next. These curves exert forces on a vehicle that vary significantly from a tangent section. Drivers must react appropriately to horizontal curves to safely traverse them or collisions will occur. A clear understanding of the scope and characteristics of horizontal curve collisions is critical for the informed design of roadways and the implementation of traffic control devices to provide adequate warning to drivers. This paper identifies and presents the most common collision characteristics among a large number of horizontal curves. The objective is to gain insight and understanding about collisions on curves. We do so by identifying and quantifying those characteristics that are found to contribute to the occurrence of collisions.

If we obtain a good understanding of the characteristics of previous collisions, we can then prioritize potential collision countermeasures (on two-lane roadways). The type of collisions, for example, particularly those with fixed roadside objects, play a significant role in collision severity. The same experience can assist in the deployment of traffic control devices (along with an understanding of the impact of the time of day, lighting, and roadway surface conditions) and can aid in designing effective enforcement, education, and other countermeasures. Which countermeasures have the most promise? What types of collisions should agencies target? Numerous other research efforts have examined specific curve collision countermeasures, generally on a project or corridor level basis. However, to this point, no one has published a characterization of curve collisions on a statewide scale. This paper seeks to do so.

The objective of this study is to characterize when, where, and how horizontal curve collisions occur on two-lane roads. Many states do not have a systematic, statewide method to identify horizontal curves which have high collision experience and/or a high potential for collisions. Thus, such a characterization could prove to be highly useful and is needed.

Understanding curve collision characteristics was the first step in developing a methodology to find and treat hazardous curve locations. The next step consisted of identifying countermeasures which can potentially reduce curve collisions associated with various collision factors. This requires a good understanding of the human, roadway, and environmental factors that contribute to the cause and the resulting severity of the collision. It also requires a thorough understanding of the different types of geometric and traffic control countermeasures which are available to address specific collision causes, as determined by available guidelines, by research, and by agency experiences. In conjunction with this analysis of curve collisions, the paper provides an initial matching of specific countermeasures to various collision characteristics.

The collision data analysis in this study focused on North Carolina (NC) roads. NC experiences a broad range of topographic conditions, climates, and rural and urban settings. This diversity of roadway exposures and conditions makes NC an appealing location for determining representative horizontal curve collision characteristics. The reporting threshold for data collection and reporting in NC is a collision that resulted in a fatality, non-fatal personal injury, property damage of $1,000 or more, or property damage of any amount to a vehicle seized (*NCDMV 2006*). The North Carolina Department of Transportation (NCDOT) controls almost 80,000 miles of roadways, which creates consistency across the state with roadway design, construction, and maintenance. These factors make findings based on NC collision data useful to many other jurisdictions.

4.2 Literature Review

There are many studies identifying collision characteristics and geometric design features that have an impact on collisions. The following studies all address horizontal curve collisions. They also identify horizontal curves as causal factors in highway collisions and indicate that curves have a significantly higher collision rate than tangent sections. Our purpose here is to see what curve characteristics and agency countermeasures have been identified and are most prevalent. Our literature review encompassed crash rates, roadway characteristics at curves, causal factors, and numerous potential treatments.

Garber and Kassebaum (2008) studied nearly 10,000 collisions on urban and rural two-lane highways in Virginia finding the predominate type of collision to be run-off-the-road collisions. The significant causal factors of these run-off-the-road collisions included roadway curvature and traffic volume as determined through a fault tree analysis. The countermeasures identified to mitigate run-off-the-road collisions include widening the roadway, adding advisory signs or chevrons to sharp curves, and adding or improving shoulders. However, this study did not specifically address curve collisions nor did it indicate how many of the collisions were on curves.

McGee and Hanscom (2006) provide a publication on low-cost countermeasures that can be applied to horizontal curves to address identified or potential safety problems. These countermeasures included: basic traffic signs and markings from the MUTCD, enhanced TCDs, other TCDs not mentioned in the MUTCD, rumble strips, minor roadway improvements, and innovative and experimental countermeasures. For every countermeasure, the authors concisely identified a description of the countermeasure, an application guideline, design elements, its effectiveness, cost, and maintenance, and additional sources of information.

In Volume 7 of NCHRP Report 500, Torbic et al. (2004) provided strategies to improve the safety of horizontal curves. This study had two primary purposes. The first was to reduce the likelihood of a vehicle leaving its lane and either crossing the roadway centerline or leaving the roadway at a horizontal curve. The other purpose was to minimize the adverse consequences of leaving the roadway at a horizontal curve. To accomplish these research objectives, twenty detailed strategies were described as countermeasures for reducing curve-related collisions. Each strategy included a general description, an estimate of the effectiveness of each countermeasure, and special issues pertaining to horizontal curves. These countermeasures addressed traffic control devices, markings, sight distances, and horizontal alignments.

Another study that investigated the relationship between roadway design attributes and collision activity was performed by Strathman et al (2001). This study investigated the statistical relationship between collision activity and roadway design attributes on Oregon highways. Using collision data from a two-year period (1997-1998), the highways were divided into variable length homogenous highway segments, yielding a set of over 11,000 segments. For non-freeway segments, maximum curve length and right shoulder width were found to be among the design attributes related to curves that were statistically related to collision activity. Maximum curve angle (a surrogate for degree of curvature) was not found to be related to collision activity in this study.

Souleyrette et al. (2001) evaluated roadway and collision characteristics for all highways in Iowa through integrating databases with digital imagery, roadway characteristics, and collision data. This project studied five collision types including collisions on horizontal curves and made use of the GIS technology to collect roadway characteristics that were not identified by collision records. Curves were found by using GIS to identify a 5º or more change in azimuth between tangents. The analysis of high collision locations on horizontal curves found that the degree of curvature had a direct impact on the collision rate. The model also indicated that the collision rate on shorter curve lengths was significantly higher than on longer curves. In addition, this study produced a curve database for Iowa with radii and length attributes and a procedure for identifying horizontal curves with high collision occurrences statewide.

Zegeer et al. (1991) analyzed over 13,000 horizontal curves, primarily in Washington, to evaluate the relationship between curve features and collisions. To meet the study objective, the horizontal curve features which affected traffic safety and operation were first identified. A collision prediction model (consisting of six variables relating to collisions and curve features) was developed through a variety of statistical methods. These six variables were: curve length, vehicles volume, degree of curve, presence of spiral transitions, and roadway width. From these identified variables, existing countermeasures for enhancing safety and operations at particular curve sections were determined and the model developed an effectiveness of collision reduction for each of these countermeasures. This study also provided general safety guidelines for curve design including signing, marking, and delineation as recommended cost-effective countermeasures.

Many other research efforts have examined specific curve collision countermeasures. However, to this point, as mentioned previously, no past study has characterized curve collisions on a large scale and matched the results of such a characterization with countermeasures directed at specific collision causes. Also, this paper provides recommendations on how an agency can conduct a comprehensive analysis of horizontal curve safety problems and deal with these problems in a systematic manner.

4.3 Methodology

The Highway Safety Information System (HSIS) collects and reports statewide collision data for participating states, which includes seven states with recent collision data (HSIS 2009). North Carolina was preselected as a data source by the Federal Highway Administration (FHWA) for inclusion in the HSIS program for its high quality collision, roadway inventory, and traffic volume databases. The NC database that the FHWA receives is derived from an Oracle database on the North Carolina Division of Motor Vehicles System. NC provides collision characteristics, data on vehicles and occupants in the collisions, and a roadway inventory (Council 2006).

To achieve the objective of characterizing curve collisions, horizontal curve collision data was requested from the NC HSIS. While NC does not have an individual curve database, a high number of curve collisions and corresponding roadway data are still available, making the database suitable for the curve collision analysis. The analysis (reported herein) was conducted on the dataset of curve collisions received from the HSIS and included curve and non-curve collisions on two-lane roads and on all road types. The two-lane road and all roads datasets were obtained from an internet application which contains collision data from 2001 to 2006 from the NCDOT collision database (HSRC 2009).

For the study described herein, NC collision data from 2003 to 2005 were analyzed in each database. The statewide data for all roads was compared to rural and urban roads which were the focus of our study. The collision data on all two-lane roads were an effective benchmark because two-lane curve collisions are a subset of the database consisting of all two-lane roads. It is understood that the design standard on two-lane curve segments and on all roads are very different. For example, for multi-lane highways, it is likely that a transition curve be installed between the tangent and curved segments, which may influence crash occurrence on curved segments. Moreover, sight distance requirement and other geometric features may also be different. Still, the comparisons made help explain the difference between collision characteristics.

Furthermore, most characteristics of the two datasets are somewhat similar on both tangents and curves in our study (for example, lane width, shoulder width, etc.). Thus, comparing these enables us to identify whether or not a curve has a tangent collision dependency. That is, we were able to separate the collisions based on their location on either a tangent or on a curve. We were then able to make comparisons based on both curves and tangents.

Traffic volumes would be a useful addition to the collision data to present the collisions in relation to collisions per million vehicle miles traveled, as a measure of the exposure or potential for collisions. However, volume data was not readily available for integration with the collision database. A potential area of concern with the data used for this study is the presence of qualitative data in the police reporting documents. Some data elements are qualitative which can be subjective, but are believed to be reasonable.

4.4 COLLISION DATA ANALYSIS

The three-year analysis period of collision data (2003 to 2005) resulted in 51,238 reported collisions on curves on two-lane roads in NC and 95,552 reported collisions on curves on all roads in NC. These collisions were identified based on their coding as "curve-related" by the reporting police officer on the collision report form. That is, police officers specified this set of collisions as being collisions on curves. It is the case that there could be a difference between collisions that actually occur on the curve and collisions that are related to the curve. This study did not investigate this difference.

In the data analysis tables presented in this paper, some column totals might not sum to 100% because of rounding. The data are presented as collision percentages rather than as collision frequencies for easier comparison. In the tables, “2-lane curve collisions” represent the collisions reported on two-lane curves, “all 2-lane collisions” represent the collisions reported on all two-lane roadways throughout NC, and “all roads collisions” represent the collisions reported on all roads throughout NC.

4.4.1 Road Characteristics

Aspects of the roadway itself significantly affect collisions. Table 2 reports on geometric roadway characteristics for two-lane and all-road collisions. The terms in Table 2 are, for the most part, well understood. However, their precise numerical definition does not exist on the collision data reporting form. Instead, their use by a police officer can vary. Thus, in Table 2 the term level grade is taken to mean a perceptively level roadway. The data obtained by the police officer and reported herein is thus qualitative, although likely reasonable.

Table 2. Horizontal Curve Collision Geometric Roadway Characteristics

Road Characteristic	Grade	All 2-Lane Collisions		All Roads Collisions	
Tangent	Level	68%	77%	80%	78%
	Hillcrest		4%		4%
	Grade		18%		17%
	Bottom		1%		1%
Curve	Level	21%	56%	14%	53%
	Hillcrest		4%		6%
	Grade		37%		38%
	Bottom		3%		3%
Other	N/A	10%	0%	6%	1%
Uncoded	N/A		100%		99%

Table 2 shows that 21% of all two-lane road reported collisions occur on horizontal curves, compared to 14% among all roads statewide. Curve collisions occur more often on roadways sections with a grade (37% for all two-lane roads, 38% for all roads) rather than on tangent sections on a grade (18% for all two-lane roads, 17% for all roads). The reported curve collisions primarily occur in rural locations (70%), compared to 62% of all two-lane collisions and 45% of all statewide collisions (Table 3). It appears that rural, horizontal curves are particularly susceptible to collisions.

Table 3. Horizontal Curve Collision Urban vs Rural Characteristics

Setting	Grade	2-Lane Curve Collisions		All 2-Lane Collisions	All Roads Collisions
Urban	Level	30%	54%	38%	55%
	Hillcrest		6%		
	Grade		37%		
	Bottom		3%		
Rural	Level	70%	57%	62%	45%
	Hillcrest		3%		
	Grade		37%		
	Bottom		2%		

4.4.2 Collision Characteristics

This section discusses how severity, frequency, type, alcohol involvement, time of day, day of week, month of year, lighting, and surface conditions affect collisions, as determined by our database.

Severity

Collision severity is an important component of collision analysis and countermeasure initiatives. Severity is measured on a five-point scale in NC: fatality (K), disabling injury (type A), evident injury (type B), possible injury (type C), and property damage only (PDO) (NCDMV, 2006). Two-lane curves, compared to three or more lines, typically have narrower lanes and shoulders, more sight distance concerns, and less frequent maintenance than other roadway types. By less frequent maintenance we refer to the fact that higher functional classification roads receive more attention with respect to maintenance practices (plowing, resurfacing, restriping, etc.). Table 4 shows that these factors indicate that two-lane curve collisions have twice the percentage of fatal and type A injury collisions when compared to collisions on all two-lane roads and all roads statewide. Fatal collisions comprise 1.9% of total reported two-lane curve collisions, compared to 0.9% of all two-lane road collisions and 0.6% of all statewide collisions. Disabling injury type A collisions have a similar trend, comprising 3.5% of the total reported number of two-lane curve collisions compared to 1.9% of all two-lane road collisions and 1.4% of all statewide collisions. Two-lane curve collisions are much more severe in urban areas than are all road collisions in those areas.

Table 4. Horizontal Curve Collision Severity Characteristics

Severity	2-Lane Curve Collisions			All 2-Lane Collisions	All Roads Collisions		
	Setting		Total	Total	Setting		Total
	Urban	Rural			Urban	Rural	
K	1.5%	2.1%	1.9%	0.9%	0.3%	1.0%	0.6%
A	3.0%	3.7%	3.5%	1.9%	0.8%	2.1%	1.4%
B	16.1%	18.3%	17.6%	11.9%	7.4%	11.7%	9.4%
C	24.4%	24.6%	24.5%	25.5%	26.2%	23.7%	25.1%
PDO	49.1%	44.1%	45.6%	54.7%	62.1%	58.0%	60.2%
Unknown	5.9%	7.2%	6.8%	5.1%	3.3%	3.5%	3.4%

Frequency

The frequency of collisions on curves on rural two-lane curved roads were examined with a sliding scale analysis using 0.1-, 0.2-, 0.3-, 0.5- and 1-mile segment lengths. A sliding scale analysis is useful for identifying concentrations of collisions without arbitrarily defining segments to analyze. A sliding scale of predetermined length moves along a roadway and is used to determine the number of collisions within the segment. Thus, the focus of our reporting is frequency of collisions (number) rather than collision rate (collisions/vehicle mile traveled). AADT is not taken into account in the data used in this study.

The results, presented in Table 5 show that only four segments experienced 10 or more collisions in 0.1-mile segment lengths during the three-year period of analysis. Note that we use 10 collisions in this segment length only as an example, recognizing that 10 is a commonly used number but not one that we are necessarily advocating. Figure 2 shows a graph of the 0.1-mile segment length collision frequency versus a theoretical Poisson distribution. Using a chi-square goodness of fit test, which is a stringent test to meet, the data do not fit a Poisson distribution function at the 95% confidence level. However, a visual inspection showed a close correlation between the data, perhaps reflecting a relationship at a lower confidence level. It should be pointed out that other distributions, such as the binomial and negative binomial distributions, might provide a better fit with the data. One of the recommendations is that additional study to improve the frequency analysis could be done.

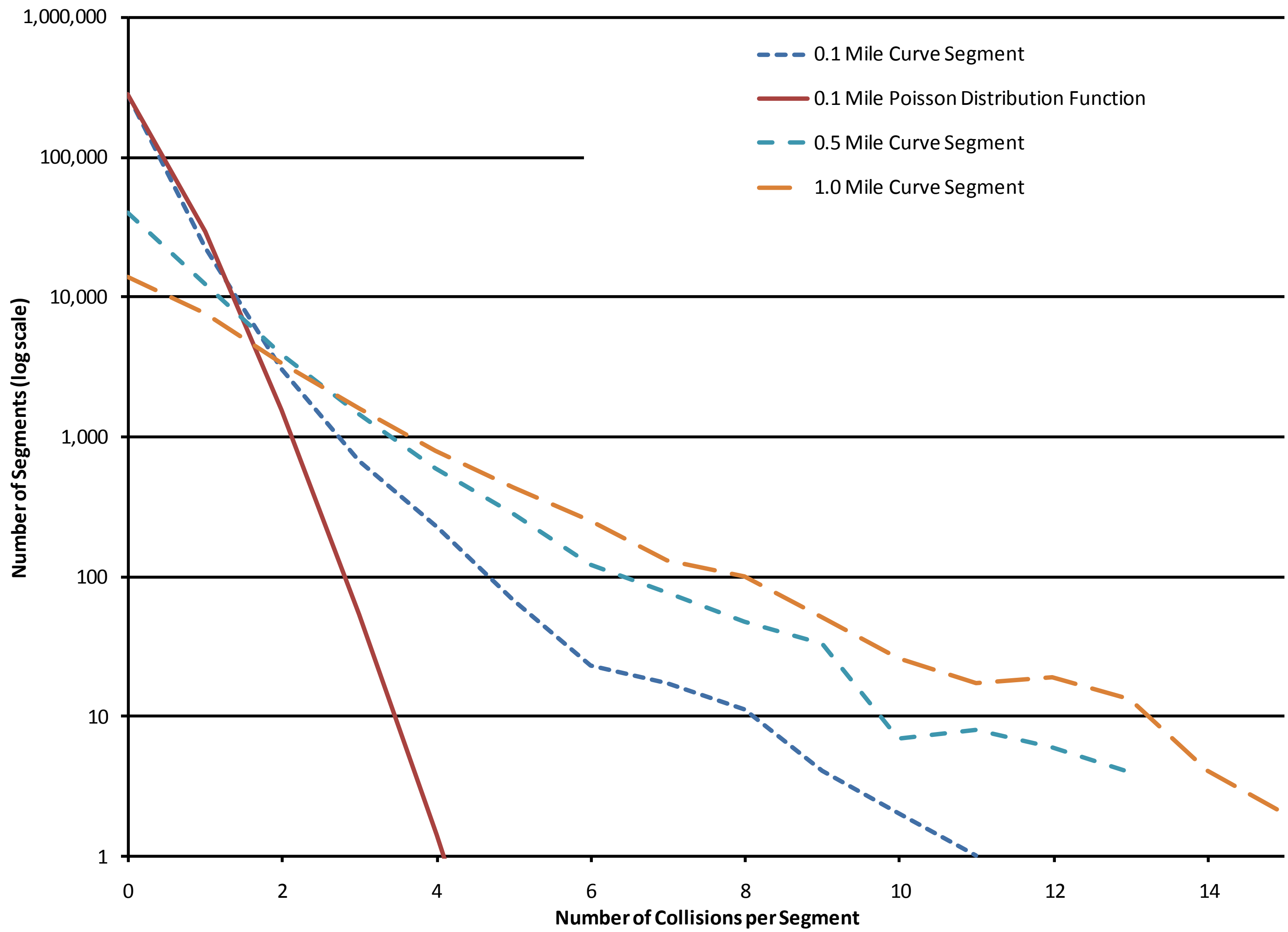


Figure 2. Horizontal Curve Collision Frequency Distribution

Table 5. Rural Horizontal Curve Collision Frequency Characteristics

Total Collisions	Frequency by Segment Length				
	0.1 Mile	0.2 Mile	0.3 Mile	0.5 Mile	1.0 Mile
0	282,960	129,260	78,966	40,206	13,755
1	22,767	18,721	16,176	12,497	7,496
2	3,037	3,690	3,857	3,910	3,327
3	668	959	1,175	1,467	1,563
4	224	353	455	601	786
5	67	144	181	285	435
6	23	60	101	122	247
7	17	25	39	77	129
8	11	18	26	48	100
9	4	7	19	33	50
10	2	6	8	7	26
11	1	2	2	8	17
12	-	3	3	6	19
13	-	-	1	4	13
14	-	-	1	-	4
15	-	-	1	1	2
16	-	-	-	-	1
17	-	1	-	-	3
18	-	-	-	-	1
19	1	-	-	-	-
20	-	1	1	1	-
21	-	-	-	-	-
22	-	-	-	-	-
23	-	-	-	-	1
24	-	-	-	-	2
25	-	-	-	-	-
26	-	-	-	-	-
27	-	-	-	1	-
28	-	-	-	-	-
29	-	-	-	-	1
Total	309,782	153,250	101,012	59,274	27,978

The key question related to this analysis is what is the most appropriate roadway segment length for use in identifying high-collision curves in a spot safety improvement analysis using this approach. The answer to this question must consider the accuracy of the locational aspect of the data by the reporting police agency, the geometric characteristics of the curves (e.g., spacing between curves, length of curves, etc.), and the nature of the collision file (e.g. relative number and distribution of curve collisions along routes). To serve the needs of their spot safety improvement program, many states use a floating fixed segment length, such as a 0.1 or 0.3-mile segment, and may also include a longer section (e.g., a 1-mile section) for "flagging" roadway sections for further analysis.

One way to approach determining an optimal segment length, for the purpose of a curve safety analysis, is to test different segment lengths for a sample of roadways and determine the segment length that yields the most useful results. For example, if roadway sections are located in rolling areas and have long gradual curves, a floating segment length of 0.3 to 0.5 miles may be appropriate. In mountainous areas with many sharp, short curves, a floating segment length of a shorter (e.g., 0.1 mile) length might be more meaningful to identify individual high-collision curves. Longer floating segment lengths (e.g., 1-mile) can be used to identify roadway sections which have either a higher frequency of collisions, or a higher than average, so the entire section can be addressed (and not each curve individually).

Type

Table 6 shows that collisions with fixed objects make up the majority (52%) of total reported two-lane curve collisions, compared to 23% of all two-lane road collisions and 15% of all statewide collisions. The differences are for more pronounced on urban two-lane curves, where collisions with fixed objects make up 43% of reported collisions, compared to 4% of all urban statewide collisions. Two-lane curve collisions experience a lower percentage of reported rear-end-stopped, angle, and animal collisions than all two-lane road and all road collisions.

Table 6. Horizontal Curve Collision Type Characteristics

Collision Type	2-Lane Curve Collisions			All 2-Lane Collisions	All Roads Collisions		
	Setting		Total		Setting		Total
	Urban	Rural			Urban	Rural	
Fixed Object	43%	56%	52%	23%	4%	28%	15%
Overturn/Roll	6%	10%	9%	3%	0%	4%	2%
Run Off Road - Right	8%	7%	7%	5%	4%	3%	4%
Rear End - Stopped	11%	4%	6%	20%	33%	17%	26%
Side Swipe - Opposite Direction	5%	5%	5%	3%	1%	2%	2%
Angle	5%	2%	3%	12%	21%	7%	15%
Left Turn - Different Road	4%	2%	3%	5%	4%	5%	5%
Run Off Road - Left	3%	3%	3%	2%	2%	2%	2%
Head On	2%	2%	2%	2%	1%	1%	1%
Left Turn - Same Road	3%	2%	2%	5%	6%	5%	5%
Animal	2%	2%	2%	4%	1%	13%	7%
Moveable Object	1%	1%	1%	1%	1%	1%	1%
Side Swipe - Same Direction	1%	1%	1%	3%	8%	3%	6%
Parked Motor Vehicle	1%	1%	1%	2%	2%	1%	1%
Other Non-Collision	1%	1%	1%	1%	1%	1%	1%
Rear End - Turning	1%	1%	1%	2%	1%	1%	1%
Other Collision	1%	0%	0%	1%	1%	1%	1%
Backing Up	1%	0%	0%	3%	3%	1%	2%
Right Turn - Different Road	1%	0%	0%	1%	1%	1%	1%
Right Turn - Same Road	0%	0%	0%	1%	1%	1%	1%
Pedestrian	0%	0%	0%	1%	1%	0%	1%

Table 7 shows the most harmful events and objects in single vehicle collisions. This table provides insight into which objects were struck by the vehicle. Overturn or rollover collisions (31%), collisions with trees (20%), and ditches (16%) constitute the majority of most harmful events in single vehicle collisions on two-lane curves. For all two-lane roads and all roads, the most harmful events are collisions with animals at 30% and 24%, respectively.

Table 7. Horizontal Curve Collision Most Harmful Event Characteristics

Event Type	2-Lane Curve Collisions			All 2-Lane Collisions	All Roads Collisions		
	Setting		Total	Total	Setting		Total
	Urban	Rural			Urban	Rural	
Overturn/Rollover	16%	32%	31%	18%	8%	18%	16%
Tree	14%	20%	20%	12%	6%	12%	11%
Ditch	7%	16%	16%	12%	3%	11%	10%
Embankment	3%	6%	5%	3%	1%	3%	3%
Utility Pole	8%	5%	5%	4%	7%	3%	3%
Other Fixed Object	5%	4%	4%	3%	5%	3%	3%
Fence or Fence Post	2%	3%	3%	2%	1%	2%	2%
Catch Basin or Culvert on Shoulder	2%	3%	3%	2%	1%	2%	2%
Animal	5%	2%	2%	30%	11%	27%	24%
Mailbox	1%	2%	2%	1%	0%	1%	1%
Guardrail Face on Shoulder	5%	1%	1%	1%	5%	2%	3%
Movable Object	4%	1%	1%	1%	6%	2%	2%
Official Highway Sign Non-Breakaway	1%	1%	1%	1%	1%	1%	1%
Ran Off Road Right	7%	0%	1%	1%	5%	0%	1%
Pedestrian	1%	1%	1%	2%	8%	2%	3%
Bridge Rail End	0%	1%	1%	0%	0%	0%	0%
Guardrail End on Shoulder	1%	0%	0%	0%	1%	1%	1%
Official Highway Sign Breakaway	1%	0%	0%	0%	1%	0%	1%
Bridge Rail Face	1%	0%	0%	0%	1%	1%	1%
Other Non-Collision	1%	0%	0%	1%	2%	1%	1%
Pedalcyclist	1%	0%	0%	1%	3%	1%	1%
Ran Off Road Left	4%	0%	0%	0%	2%	0%	1%
Fire/Explosion	0%	0%	0%	0%	0%	1%	1%
Other Collision With Vehicle	1%	0%	0%	0%	1%	0%	0%
Angle	1%	0%	0%	0%	2%	0%	0%
Shoulder Barrier Face	1%	0%	0%	0%	1%	0%	0%
Head On	1%	0%	0%	0%	1%	0%	0%
Sideswipe, Same Direction	0%	0%	0%	0%	1%	0%	0%
Read End, Slow or Stop	0%	0%	0%	0%	1%	0%	0%
Traffic Island Curb or Median	1%	0%	0%	0%	1%	0%	0%
Guardrail Face in Median	1%	0%	0%	0%	3%	2%	3%
Median Barrier Face	1%	0%	0%	0%	6%	2%	3%

Alcohol Involvement

Alcohol is involved in 11% of reported two-lane curve collisions, compared to 7% of all two-lane road collisions and 5% of all statewide collisions. Impaired drivers likely have a more difficult time keeping their vehicles on the road in curves than they do on tangents.

Time of Day

Two-lane road curve collisions tend to be more evenly dispersed throughout the day than do statewide road total collisions and two-lane road total collisions (Figure 3). During almost all hours, the point representing two-lane curve collisions during any given hour is closer to the average percentage of 4.2 per hour than it is for all statewide collisions and all two-lane collisions. Two-lane road curve collisions are more likely to be single vehicle collisions, primarily with fixed objects. Other roads experience more multi-vehicle collisions which are more likely a function of traffic volume fluctuations occurring during morning, afternoon, or other peak periods. Also, visibility at night is a more serious problem on curves than other road segments. Figure 3 shows a higher percentage of curve collisions at night than other types of collisions. Conversely, there is a lower percentage of crashed during daylight hours.

Day of Week

Two-lane road curve collisions tend to be more evenly dispersed throughout the week - and thus are more prominent during weekends - than statewide road total collisions and two-lane roads total collisions (Figure 4). This dispersion could again be because curve collisions are a function of a permanent roadway feature while the two-lane and all statewide road categories are subject to more pronounced traffic volume peaks. Two-lane statewide total collisions and statewide total collisions experience two peaks during the week: at the beginning of the work week (Monday) and at the end of the work week (Friday). Two-lane curve collisions experience a more gradual peak centered on the weekend.

Two-lane road curve collisions are also more likely to involve a single vehicle, while other roads experience more multi-vehicle collisions which generally occur during heavy traffic conditions. Alcohol could also play a role in increasing the weekend peak of two-lane curve collisions. Hourly volumes would be a useful addition to the collision data to present the collisions in relation to collisions per million vehicle miles traveled. However, hourly volume data was not readily available for integration with the collision database and we were unable to make such an analysis.

Month of Year

Two-lane road curve collisions tend to be less evenly dispersed by month throughout the year than statewide road total collisions and two-lane roads collisions (Figure 5). This uneven dispersion could be because curve collisions are impacted more heavily by more pronounced seasonal variations in volume. Each of the roadway types experiences peaks in percentage of collisions during the winter holiday months and at the beginning and ending of the summer months. Alcohol may also play a role near holidays. However, the peak in the winter is more likely due to weather conditions and a less frequent maintenance schedule (e.g., ice and snow removal priorities) given to two-lane roads than to other road classifications. Higher volumes in recreation areas on rural roads during the summer months could cause the increase in collisions for two-lane curves.

Lighting

Collisions during the day make up the majority of the total reported two-lane curve collisions (59%) compared to 67% of all two-lane road collisions and 68% of all statewide collisions. Collisions during the dark in unlighted conditions make up 31% of urban reported two-lane curve collisions, compared to 5% of all urban statewide collisions. Two-lane curve collisions experience a lower percentage of reported collisions at night in lighted conditions than all two-lane collisions or all road collisions. The collisions that occur at night in lighted and unlighted conditions are likely influenced by the percentage of statewide roads that have roadway lighting compared to 2-lane curve segments (particularly in urban locations).

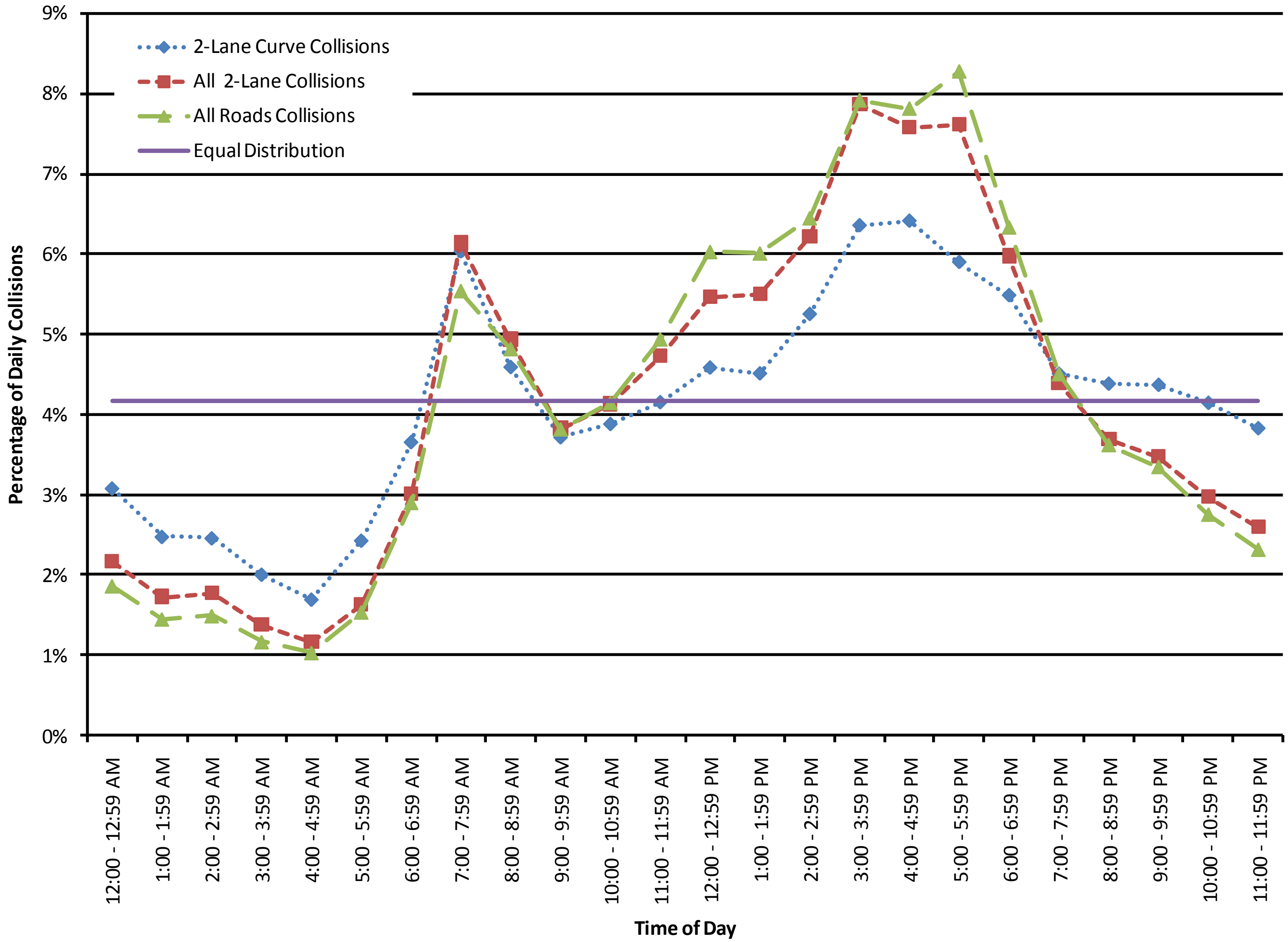


Figure 3. Horizontal Curve Collision Time of Day Characteristics

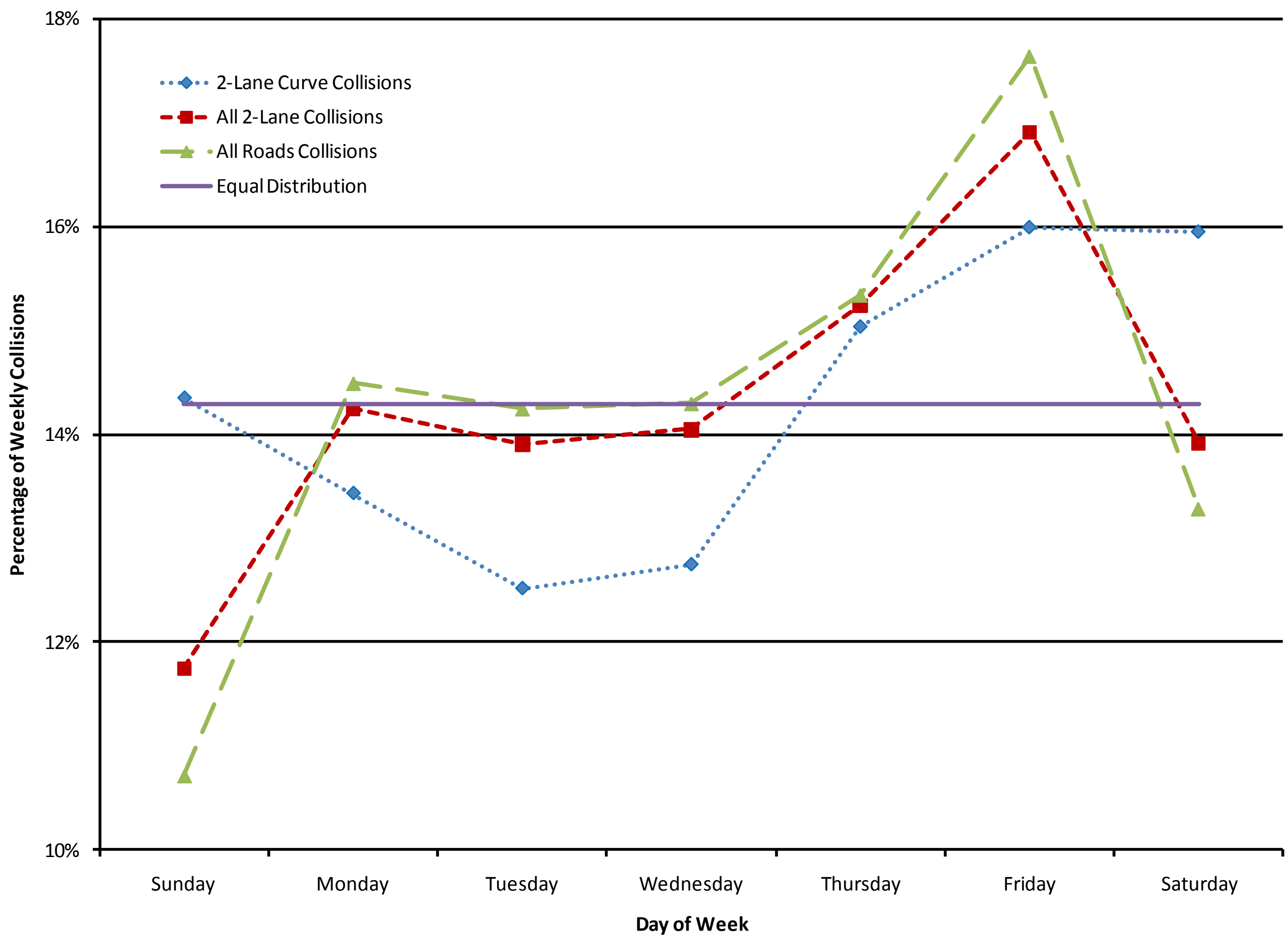


Figure 4. Horizontal Curve Collision Day of Week Characteristics

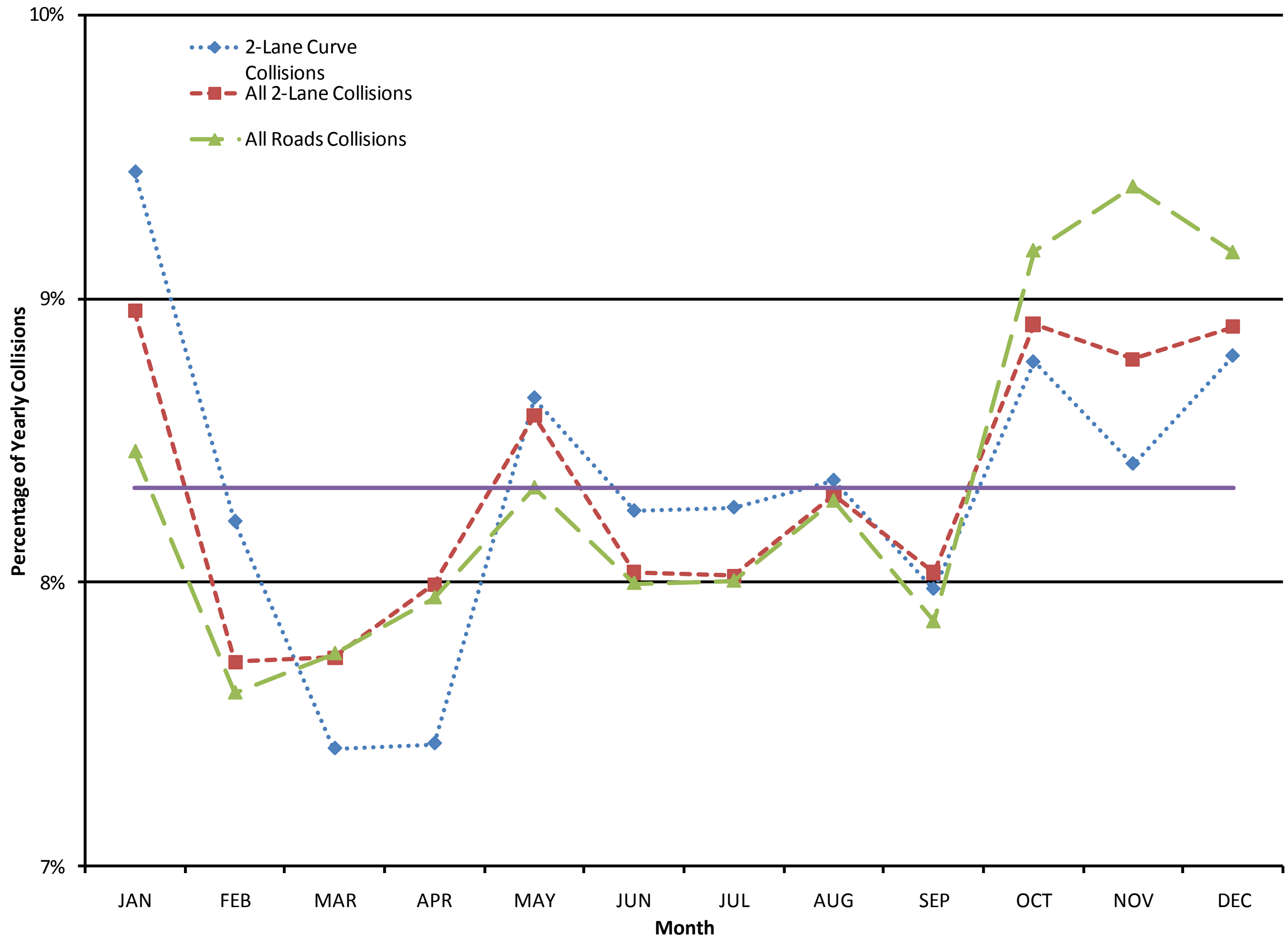


Figure 5. Horizontal Curve Collision Month of Year Characteristics

Surface

Collisions on a dry roadway surface make up 70% of the total reported two-lane curve collisions, compared to 77% of all two-lane road collisions and 77% of all statewide collisions (Table 8). Collisions on non-ideal roadway surface conditions (the combination of all conditions except dry) constitute a greater portion of total reported two-lane curve collisions (30%) than on all two-lane road collisions (23%) and all statewide collisions (23%). These findings tend to indicate that surface condition does influence collisions on curves where adverse surface conditions can lead to run-off-the-road collisions.

Table 8. Horizontal Curve Collision Roadway Surface Characteristics

Roadway Surface Condition	2-Lane Curve Collisions			All 2-Lane Collisions	All Roads Collisions		
	Setting		Total	Total	Setting		Total
	Urban	Rural			Urban	Rural	
Dry	71%	70%	70%	77%	79%	76%	77%
Wet	21%	21%	21%	17%	18%	18%	18%
Water	1%	1%	1%	1%	1%	1%	1%
Ice	4%	4%	4%	3%	2%	3%	2%
Snow	2%	2%	2%	2%	1%	2%	1%
Slush	1%	1%	1%	0%	0%	0%	0%

4.5 RESULTS

The collision analysis and characterization presented above led to the creation of Table 9 which presents 37 potential countermeasures (the rows of the table) that can be used to reduce the frequency and/or severity of horizontal curve collisions, particularly on two-lane roads. These countermeasures represent actions that can be taken to minimize the effects of one or more of the collision characteristics. The countermeasures were obtained from multiple sources in the literature, are based on NCHRPs guidance for potential countermeasures, and contain only curve collision countermeasures relevant to overrepresented curve characteristics in NC (the columns of the table). The list displays a degree of incompleteness, ambiguity, and redundancy, as a result. Still, Table 9 is useful in that it enables us to establish a relationship between the set of all countermeasures shown and the specific set of characteristics that are most troubling at curve collision locations. Such a comparison can be conducted by other states with a substitution of curve characteristics most applicable in that state. Furthermore, some studies have been conducted which validate the effectiveness of some of the countermeasures and collision modification factors (CMFs) have been found for them. The result of this paper is on determining the set of countermeasure that are related to curves. CMFs then enable us to quantify the individual members of that set.

For each of the countermeasures in Table 9, the check marks in the matrix indicate the type of collision factor the countermeasure is most likely to address. For example, collisions involving inadequate lighting are most likely to be reduced by such measures as countermeasure number 1 (provide advanced warning prior to curve), 2 (enhanced curve delineation), 3 (provide adequate sight distance, 9 (provide lighting on curve), etc., as indicated by the check marks in the corresponding matrix cells. If a curve has adverse surface conditions the countermeasures that can be used are 1, 7, 8, and 14.

The value of Table 9 is that it uses a set of collision characteristics from NC and a set of countermeasures from NCHRP and clearly illustrates the relationship between them. Thus, it is a useful tool in considering how to make changes and improvements once high curve collision locations are identified, inventoried, and analyzed.

Table 9. Potential Countermeasures to Reduce the Frequency and/or Severity of Horizontal Curve Collisions

Potential Countermeasures	Collision Characteristics							References
	Overturn/ Rollover/ Ditch Related	Adverse Surface Conditions	Inadequate Lighting	Tree	Utility Pole	Other Fixed Object	Curve/Grade Geometric	
1. Provide advance warning prior to curve	✓	✓	✓	✓	✓	✓	✓	a
2. Enhance curve delineation or pavement markings	✓		✓	✓	✓	✓		a,b
3. Provide adequate sight distance			✓				✓	a
4. Install shoulder rumble strips	✓			✓	✓	✓	✓	a,b
5. Install centerline rumble strips	✓			✓	✓	✓	✓	a
6. Prevent edge dropoffs	✓			✓	✓	✓		a,b
7. Provide skid-resistant pavement surfaces	✓	✓		✓	✓	✓		a,b
8. Provide grooved pavement	✓	✓		✓	✓	✓		a
9. Provide lighting of the curve			✓					a
10. Provide dynamic curve warning system	✓		✓	✓	✓	✓		a
11. Widen the roadway and/or shoulder	✓			✓	✓	✓	✓	a,b
12. Improve or restore superelevation	✓			✓	✓	✓	✓	a
13. Modify curve alignment/geometry	✓			✓	✓	✓	✓	a,b
14. Install automated anti-icing systems	✓	✓		✓	✓	✓		a
15. Prohibit/restrict long semi-trailers				✓	✓	✓	✓	a
16. Design safer slopes and ditches to prevent rollovers	✓						✓	a,b
17. Remove/relocate objects in hazardous locations				✓	✓	✓		a,b,c,d
18. Delineate roadside objects (trees, utility poles)			✓	✓	✓	✓		a,b,c,d
19. Add/improve roadside hardware	✓			✓	✓	✓	✓	a,b,d
20. Improve design/application of barrier systems	✓					✓	✓	a,d
21. Install edgeline profile marking or rumble strips	✓		✓	✓	✓	✓		b
22. Install midlane rumble strips	✓			✓	✓	✓	✓	b
23. Provide enhanced shoulder or in-lane delineation	✓		✓	✓	✓	✓		b
24. Develop and implement tree planting guidelines				✓				c
25. Develop mowing and vegetation control guidelines				✓				c
26. Remove trees in hazardous locations				✓				c
27. Shield motorists from striking trees/poles				✓	✓	✓		c,d
28. Modify roadside clear zone near trees				✓		✓		c
29. Remove utility poles in hazardous locations					✓			d
30. Relocate poles further from the roadway					✓			d
31. Use breakaway poles					✓			d
32. Shield drivers from poles in hazardous locations					✓			d
33. Improve driver's ability to see poles			✓		✓			d
34. Apply traffic calming measures					✓			d
35. Revise pole placement policies					✓			d
36. Place utilities underground					✓			d
37. Decrease number of utility poles along a corridor					✓			d

[a] Torbic et al 2004

[b] Neuman et al 2003b

[c] Neuman et al 2003a

[d] Lacy et al 2004

4.6 Conclusions

The purpose of this study was to conduct a detailed multi-year analysis of numerous horizontal curve collisions on a statewide basis to identifying common characteristics and key contributing factors associated with curve collisions. The results were used to match major collision characteristics and causes to potential countermeasures. The primary factors found to be associated with curve collisions on rural, two-lane roads include fixed objects (particularly trees and poles), overturn and ditch related factors, alcohol related, adverse light conditions (i.e., nighttime), adverse roadway surface conditions, curve and grade geometric issues, and time related factors (weekends), among others. However, two-lane curve collisions most often involve only a collision with roadway or roadside features, which means countermeasures can have a disproportionately positive impact on collisions.

In all of NC over a three-year period, only 4 segments out of almost 310,000 statewide (one tenth of a mile in length) experienced 10 or more curve collisions. Thus, the frequency of curve collisions per site are low compared to intersections, which could lead transportation agencies to overlook curves during hazard site identification processes. The selection of roadway segment length for identifying hazardous curve locations is critical. Length of segment as well as the acceptable collision threshold to use in the analysis should depend on the available budget for further inspection and investigation of the curves.

4.7 Recommendations

The research team recommends several actions to help transportation agencies better identify and understand the characteristics of horizontal curve collisions and identify the causes and problems involving horizontal curve collisions. First, a more integrated statistical analysis, taking into account various road, crash, weather, and temporal attributes could be conducted. Next, a statewide curve analysis similar to that presented herein can help identify any unique circumstances that create an overrepresentation of certain types or characteristics of collisions. The severity of two-lane curves, particularly in rural areas, should be considered as part of a hazardous site identification program. The curve collision analysis can identify specific hazardous locations as well as systematic deficiencies among regions, routes, geometric design factors, traffic control device consistency, shoulder width or type, maintenance practices, etc.

A comprehensive horizontal curve process would help guide agencies through horizontal curve identification, investigation, analysis, evaluation, countermeasure selection and evaluation, assessment of funding sources, and recommendation of countermeasures. The team also recommends the use of Table 9 as an initial guide to select potential countermeasures for horizontal curve collisions and, if possible, the eventual modification to Table 9 to suit each individual state’s needs.

5.0 MANUAL FIELD INVESTIGATION PROCEDURE

The manual field investigation procedure was developed to collect field data to better understand the safety problems and issues, it is important to determine characteristics of actual curves on rural, two-lane roadways across the state. The curve data was used to calibrate rural two-lane undivided segments in the Highway Safety Manual (HSM). The data also provided valuable information about the variation of curve characteristics within the state, both within each division and among the divisions. The proper calibration of the HSM provides NCDOT with a model that will provide a more complete representation of the safety impacts of horizontal curves and their treatments. Horizontal curve features and control device data were requested for each location which are detailed in the field investigation forms in the Appendices.

6.0 HIGHWAY SAFETY MANUAL ANALYSIS

6.1 Introduction

Horizontal curves are relatively dangerous portions of the highway system in the US and elsewhere. Crash prediction models typically show that curves have around 1.5 times the reported crashes per mile as comparable tangent sections of roadway. Fortunately, curves are also places where highway agencies have many options and opportunities for making safety improvements. Agencies can add signs, markings, beacons, guardrails, and superelevation or agencies can widen, straighten, and flatten sideslopes, just to name some prominent examples of potential improvements.

Typically, the analysis of a horizontal curve or set of curves for safety purposes by a highway agency is based on field visits and the judgment of experienced personnel. Many agencies seem to rely on a drive-through by an engineer or technician and a small set of countermeasures that seem to have proven themselves through the years. Analytical tools have existed for a number of years, such as the 1991 FHWA curve crash prediction model (Zegeer et al., 1991). However, such tools have not been widely implemented due to the large number of competing highway safety objectives, real or perceived difficulties in collecting the necessary data, and calibrating the model for local conditions, among other reasons.

The publication of the Highway Safety Manual (HSM) offers the chance to overcome this impasse and get a crash model in use in the field (AASHTO 2010). The HSM contains a crash prediction model for horizontal curves and estimates of crash modification factors (cmfs) for the most popular curve countermeasures. The model and cmfs have been approved by a committee of leading safety researchers and practitioners, which certainly provides credibility of the tools. The HSM also contains detailed instructions for applying the model and cmfs for the usual steps in a safety program, including:

- Finding hazardous sites,
- Finding countermeasures for hazardous sites, and
- Evaluating installed countermeasures.

Despite the promise of the HSM and the fact that draft versions circulated widely for several years before publication, it appears as though the HSM has not been widely applied during curve safety studies as of yet. Like many new tools, application of the HSM is expected to be an appropriate methodology to identify curves with higher than normal crash potential, to be used to complement crash-based methods for curve safety analysis. This HSM method will allow for identifying high-risk horizontal curves pro-actively before they experience high crash numbers and/or rates.

The objectives of this paper are to provide highway agencies with practical advice on how they can apply the new HSM to the analysis of horizontal curves as a supplement to the methods that identify curves with abnormally high crash experience. We want to answer the following questions:

- Can agencies use the new HSM to identify and analyze horizontal curves in need of safety improvements?
- If an HSM analysis is possible, how much effort should the agency expect to make?
- What steps should agencies take to make the HSM analysis more efficient to utilize and more cost-effective?

In satisfying these objectives for this paper, we hope to shorten the learning curve for agencies in using the HSM. We also hope to reduce the risk agencies and professionals will assume if they use this new tool. The results from this paper should also help agencies budget appropriately when employing the HSM.

The scope of the paper is limited in two important ways. First, the paper covers only the application of the HSM to two-lane rural horizontal curves (a portion of Chapter 10). Similar results might be expected when applying the HSM to other highway settings, but we would not know that for sure. We hope that others will undertake similar efforts and provide guidance on applying the HSM to other situations (e.g. multi-lane highways). Second, the paper only uses data from North Carolina. North Carolina is a large state with diverse terrain, climates, and driver demographics and should be representative of much of the US, but states with large differences in highway system design and operation, collision reporting, and other important factors should apply the recommendations in this paper cautiously and/or conduct their own calibration efforts

6.1.1 Horizontal Curve Crash Data

The crash data analysis in this study was focused on NC roads. NC experiences a broad range of topographic conditions, climates, and rural/urban settings. This diversity in conditions makes NC an appealing location for determining representative horizontal curve collision characteristics. The reporting threshold in NC is a collision that resulted in a fatality, non-fatal personal injury, property damage of $1,000 or more, or property damage of any amount to a vehicle seized. The NCDOT controls almost 80,000 miles of roadways, which creates consistency across the state with roadway design, construction, and maintenance. These factors make findings based on NC collision data useful to many other jurisdictions.

Horizontal curves are an important consideration because 21% of all 2-lane collisions occur on horizontal curves and collisions on two-lane curves are more than twice as likely to result in a fatality as all two-lane roadway segments in North Carolina (Hummer 2010).

6.2 Literature Review

Due to the recent release of the HSM, few studies have been completed on calibrating the crash prediction models in the HSM. However, two studies were reviewed that did evaluate the application of the HSM. The first study, by Sun et al. (Sun 2006), evaluated the applicability of the HSM safety prediction model to states from which crash data was not used in the original model development. The prediction model evaluated in this study was the method for 2-lane rural roads in the draft HSM. Data from state routes in

Louisiana was used. The authors did not follow the recommended HSM procedure for calibrating the predictive model due to the unavailability of data. However, the research team was able to create a database with the most important highway variables of ADT, segment length, lane width, shoulder width and type, horizontal curve, and driveway density. Since the average prediction model values were smaller than the observed values, a calibration parameter was computed as a function of ADT. The results of their analysis are presented in two groups; the first group consisted of 26 randomly selected control sections and the second group consisted of 16 control sections in the top 30 for crash frequencies for three years. The analysis indicates that the HSM model successfully predict crash frequencies, the level of effort required to obtain the data necessary to calibrate the model was a challenge.

The second study (Martinelli 2009), calibrates the HSM crash prediction model for the Italian Provence of Arezzo on 1,300 kilometers of rural, 2-lane highways. The authors evaluate the results of the HSM prediction model in a different country with differences in environment, road characteristics, driver behavior, and crash reporting than where the model was developed. The comparison between the observed crashes and four models with different calibration procedures are presented and each of the models strongly overestimates crashes. Additionally, it was found that the models overestimated crashes at low crash locations and an underestimation at the high crash locations. However, the authors conclude that calibration of the model is absolutely necessary to avoid the over prediction found in the base model.

6.3 Methodology

6.3.1 HSM predictive method calibration

The HSM predictive methods were developed such that they can be calibrated and adjusted based on local conditions. Examples of local conditions that may differ from the set predictive model include climate, driver population, and crash reporting thresholds. Calibration of these predictive models can be done to adjust for these local conditions.

The HSM predictive method for rural 2-lane, 2-way highways was applied in this evaluation to North Carolina highways. This application was applied following the steps provided in the HSM to estimate the expected average crash frequency of curve segments. The HSM predictive model contains 18 steps, with the focus of the paper on steps 9, 10, and 11, which are applied after segments have been identified and data collection including crash history and geometric conditions have been captured. These steps are repeated for each segment and are used to identify a safety performance function (SPF), crash modification factor, and calibration factor, that are used in the predictive model to calculate predicted crashes for each segment.

6.3.2 Step 9: Select and apply SPF

Once the crash history and geometric design features have been imputed for the selected segments (curves, for this analysis) the next step is to determine the appropriate SPFs for each site. The SPF determines the predicted crash frequency with base conditions and is later adjusted to local conditions using the calibration factor. Using the base conditions in the HSM, the SPF for each segment was found using the following equation:

$N_{spf\ rs} = AADT \times L \times 365 \times 10^{-6} \times e^{(-0.312)}$ (HSM equation 10-6)

Where:

$N_{spf\ rs}$ = predicted total crash frequency for roadway segment base conditions

AADT = average annual daily traffic volume (vehicles per day)

L = length of roadway segment (miles); in this analysis L = length of curve

6.3.3 Step 10: Apply CMFs

After a SPF is found for base conditions in each segment, they are multiplied by appropriate CMFs to adjust the estimated crash frequency to site specific conditions. The HSM identifies several appropriate CMFs for horizontal curves, which were evaluated for each segment in this analysis. Examples of the most common CMFs used to adjust for local conditions on the curves are the following:

- Lane width (HSM Table 10-8, Figure 10-7, Equation 10-11)
- Shoulder width and type (HSM Table 10-9, Figure 10-8, Table 10-10, Equation 10-12)
- Horizontal curves: length, radius, and presence or absence of spiral transitions (HSM Table 10-7)
- Horizontal curves: superelevation (HSM Equation 10-14, 10-15, 10-16)
- Grades (HSM Table 10-11)
- Driveway density (HSM Table 10-11)

Relating to CMFs, the Federal Highway Administration (FHWA) has established a CMF Clearinghouse (www.cmfclearinghouse.org) as a centralized location for CMFs, which are multiplicative factors used to estimate the change in the number of crashes after a given countermeasure is implemented under specific conditions. Included in this clearinghouse are the horizontal CMFs that have been developed. Of the 2,546 CMFs from 150 studies that are included in the clearinghouse, 221 CMFs and 18 studies relate to horizontal curves.

6.3.4 Step 11: Apply a calibration factor

Finally, once the estimated crash frequency for each segment is found and adjusted for site specific conditions, it is multiplied by an appropriate calibration factor developed for local conditions. This calibration factor is computed as a ratio of observed crashes to predicted crashes. For this analysis, several calibration factors were developed including an overall factor for all segments, a non-random selection curve segment factor, and a random selection curve segment factor.

6.4 Analysis

Applying an accurate crash prediction model for local conditions can be critical for identifying and prioritizing safety funding and projects. The following analysis includes an evaluation of calibration factor for HSM procedures and a sensitivity analysis of the differences when using default to site measured characteristic data for the HSM methods.

6.4.1 Calibration factor analysis

The calibration factor is a critical component of the HSM procedure to adjust the standardized factors presented in the manual to account for local differences. This analysis focuses on calculating a calibration factor for two-lane rural road segments, including curved segments, tangent segments, and the composite (including all curves and tangents) roadway. The HSM recommends that the calibration factors should be calculated every two or three years, which will likely be a significant burden on those who wish to regularly implement the procedures in the manual. Additionally, the manual specifies a desirable minimum sample size of 30 to 50 sites which experience a total of at least 100 collisions per year. This analysis included 51 sites which experienced 85 collisions per year on average, over a five-year period (Table 1). However, these 51 sites included 26 curve segments that were selected because of their abnormally high collision history or previous identification as a hazardous location. The other 25 sites were selected randomly by arbitrarily choosing a curve site while on the way to conduct other work commitments.

The HSM calibration factors are calculated by first applying the HSM method to calculate the predicted number of crashes. This method is applied using crash data and site characteristic data (e.g. lane width, shoulder width, roadside design) for specific sites. Once these predicted numbers of crashes are found, the calibration factor is computed as a ratio of observed crashes to predicted crashes. For example, in this analysis, the observed number of curve crashes for all 51 of the segments was 35.4 and the predicted number of crashes was 12.5, resulting in a calibration factor of 2.8.

The HSM does not specify how segments should be selected or if high crash location data should be used for this purpose. Table 10 shows that the inclusion of high crash locations significantly impacts the calibration factor. For instance, when considering the curved roadway segments, the calibration factor varies from 2.82 when including all 51 sites, to 1.33 when counting only those sites which were randomly selected, to 4.49 when incorporating only the high crash sites. To meet HSM recommendations for collisions, additional sites would be needed in each sample type. For instance, if a user decided to develop a two-lane curve calibration factor based on random selected curves to meet the criteria of 100 total crashes, a total of almost 300 sites would need to be included for the analysis. Collecting the detailed data needed to calibrate the HSM for 300 curve sites would be quite labor intensive.

A paired t-test was conducted to examine the importance or need for the calibration factors shown in Table 10. The test compared the reported and predicted collisions among each sample and roadway type, which are the underlying data for the calculation of the calibration factor. The assessment found a difference in reported and predicted collision in only four of the nine sample and roadway types. Therefore, only four of the calibration factor differed significant from a calibration factor of 1.

Table 10: HSM Calibration Factors Calculated

Sample Type (Sample Size)	Roadway Type	Calibration Factor	Reported Collisions (Collisions per Year)	Predicted Collisions (Collisions per Year)
All Segments (51)	Curve	2.82*	35.4	12.5
	Tangent	1.12	49.4	44.0
	Composite	1.50*	84.8	56.6
Random Selection (25)	Curve	1.33	8.8	6.6
	Tangent	1.00	20.4	20.4
	Composite	1.08	29.2	27.0
Non-random Selection (26)	Curve	4.49*	26.6	5.9
	Tangent	1.23	29.0	23.6
	Composite	1.88*	55.6	29.5

* Denotes a statistical difference from a calibration factor of 1.

Annual variations could exist when computing calibration factors. Table 11 shows five years of calibration factors from the same data set presented in Table 10. The calibration factor chosen in Table 11 for each year used only one year of data, so the samples of collisions were small. This table can provide users with an estimate of how much variation could exist when calculating annual calibration factors. The curve segments have the highest standard deviation for each sample type, while the tangent and composite sections have lower standard deviations. Overall, the randomly selected sites have the lowest standard deviation of the calibration factors.

Table 11: Annual Calibration Factors

Sample Type (Sample Size)	Roadway Type	2004 Calibration Factor	2005 Calibration Factor	2006 Calibration Factor	2007 Calibration Factor	2008 Calibration Factor	Standard Deviation
All Segments (51)	Curve	2.63	2.07	3.19	3.75	2.47	0.65
	Tangent	1.04	1.14	1.11	1.32	1.00	0.12
	Composite	1.40	1.34	1.57	1.86	1.33	0.22
Random Selection (25)	Curve	1.36	1.51	1.97	1.06	0.76	0.46
	Tangent	0.88	0.98	0.78	1.13	1.22	0.18
	Composite	1.00	1.11	1.07	1.11	1.11	0.05
Non-random Selection (26)	Curve	4.05	2.70	4.56	6.75	4.39	1.46
	Tangent	1.19	1.27	1.40	1.48	0.80	0.26
	Composite	1.76	1.56	2.03	2.54	1.52	0.42

Field investigations of the sites took approximately 30 minutes to complete (not including driving time to the site) the collection of necessary elements for HSM analysis. However, most of these elements do not change much or at all over time, so intensive data collection for HSM inputs can be used for many years. The effort required to obtain collision data varies depending on the way the data is stored and how efficiently it can be retrieved. The HSM analysis of the field data collection for predicted collisions and reported collisions allows for the determination of the calibration factors.

6.4.2 Sensitivity analysis

The sensitivity analysis focused on the effect of changing various HSM inputs on predicted collisions. The objective of this analysis is to understand which are the most critical HSM inputs and which are the inputs that might lend themselves more readily to default values thus saving data collection effort. Several HSM inputs were not included in this sensitivity analysis because no variation existed among the curves in our sample. These elements included spiral transition, passing lanes, roadway lighting, centerline rumble strips, two-way left-turn lanes, and automated speed enforcement. Table 12 shows the minimum, maximum, and mean values for HSM inputs from our sample (further analysis was only conducted on values for all sites).

Table 12: Input Values for HSM (Minimum, Maximum, and Mean)

HSM Input Factor	Minimum Value	Maximum Value	Mean Value
Input Values for All Sites (51 sites)			
AADT	240	21,000	3,885
Lane Width (ft)	9	12	10.4
Inside Shoulder Width (ft)	3	12	7.4
Outside Shoulder Width (ft)	3	12	8.0
Length of Horizontal Curve (ft)	200	1,550	579
Radius of Horizontal Curve (ft)	202	6,011	1,360
Superelevation (ft/ft)	0.010	0.102	0.056
Grade (%)	0.0	5.1	1.3
Driveway Density (driveways/mile)	0.0	54.6	9.6
Roadside Hazard Rating (1-7)	3.0	6.0	3.8
Input Values for Non-Random Sites (26 sites)			
AADT	240	17,000	3,451
Lane Width (ft)	9	12	10.3
Inside Shoulder Width (ft)	3	11	7.0
Outside Shoulder Width (ft)	4	12	8.2
Length of Horizontal Curve (ft)	200	1,550	599
Radius of Horizontal Curve (ft)	312	3,009	1,229
Superelevation (ft/ft)	0.010	0.074	0.032
Grade (%)	0.0	3.0	1.1
Driveway Density (driveways/mile)	0.0	54.6	9.4
Roadside Hazard Rating (1-7)	3.0	6.0	3.9
Input Values for Random Sites (25 sites)			
AADT	370	21,000	4,335
Lane Width (ft)	9	12	10.5
Inside Shoulder Width (ft)	4	12	7.8
Outside Shoulder Width (ft)	3	12	7.8
Length of Horizontal Curve (ft)	230	1,150	558
Radius of Horizontal Curve (ft)	202	6,011	1,495
Superelevation (ft/ft)	0.002	0.069	0.027
Grade (%)	0.0	5.1	1.6
Driveway Density (driveways/mile)	0.0	41.7	9.9
Roadside Hazard Rating (1-7)	3.0	5.0	3.7

Utilizing all of the field measured, individual curve data resulted in a predicted collision rate of 12.5 collisions per year for the set of all 51 curves. Table 13 shows the HSM outputs for the sensitivity analysis which tested the minimum, maximum, average, and median of each tested input value while holding all other tested inputs equal to the actual field condition of each curve. The table emphasizes the importance of collecting and using individualized data for AADT, curve radius, and curve length of the segment. The AADT had a range of 62.6 predicted collisions per year between using the minimum value and using the maximum value. There was also a 0.9 collisions per year (or 7%) difference between the collision prediction using the average input values and the collision prediction using the actual field values. The radius had a range of 18.9 predicted collisions per year between using the minimum value and using the maximum value. There was also a 0.8 collisions per year (or 6%) difference between the collision prediction using the average input values and the collision prediction using the actual field values. The length had a range of 19.5 predicted collisions per year between using the minimum value and using the maximum value. There was also a 0.5 collisions per year (or 4%) difference between the collision prediction using the average input values and the collision prediction using the actual field values.

Table 13: Output Values from HSM for All Sites (Predicted Collisions Per Year)

	HSM Predicted Collisions per Year for Set of 51 Curves				
Factor Input into HSM	**Using Minimum Value from Table 1**	**Using Maximum Value from Table 1**	**Difference Between Using Maximum Value and Minimum Value**	**Using Mean Value from Table 1**	**Difference Between Using Mean Value and Actual Field Measured Values**
AADT	0.8	63.4	62.6	13.4	0.9
Lane Width	14.7	11.5	3.2	13.4	0.9
Inside Shoulder Width	13.4	12.3	1.1	12.5	0.0
Outside Shoulder Width	13.4	12.3	1.1	12.2	0.3
Length of Horizontal Curve	6.6	26.1	19.5	12.1	0.5
Radius of Horizontal Curve	28.4	9.5	18.9	11.7	0.8
Superelevation	14.1	11.7	2.4	12.5	0.0
Grade	12.3	13.5	1.3	12.6	0.1
Driveway Density	11.5	21.5	10.0	12.4	0.1
Roadside Hazard Rating	11.9	14.6	2.6	12.6	0.0

6.5 Conclusions

The publication of the Highway Safety Manual (HSM) offers agencies an analytical tool to evaluate the safety of a horizontal curve or set of curves for safety purposes with fewer field visits from personnel. The HSM provides a crash prediction model for horizontal curves that can be applied to curves within any jurisdiction to identify the highest priority locations for safety treatments as well as common and effective countermeasures.

This paper evaluated horizontal two-lane rural roads in North Carolina to test the calibration of the HSM predictive method to local conditions. Based on the analysis it found that a large number of sites (approximately 300) are required to meet HSM recommendations for collisions. The large number of sites is partly due to the finding that the selection of random segments provided a more accurate outcome (in terms of matching the HSM prediction model) than the crash results from the high crash locations subset.

The challenge with requiring a large number of sites to develop an accurate model based on local conditions is the data collection aspect. For each of these sites, field investigations took approximately 30 minutes to complete (not including driving time to the site) for the collection of necessary elements for HSM analysis. However, most of these elements do not change much or at all over time, so intensive data collection for HSM inputs can be used for many years. To further lessen the data collection burden, an analysis of difference in results in the predicted collisions based on field data collection and using average or default values was performed. It was found that for AADT, curve radius, and curve length of the segment individualized data is necessary for model accuracy.

6.6 Recommendations

To properly calibrate the predictive models to HSM standards the research team found that a high number of segments are required to meet the HSM recommendations for collisions. In the case of this analysis for North Carolina, almost 300 sites are necessary; however this number will vary some for each location. Additionally, while it will require a greater number of sites, randomly selected segments are recommended for this process due to their lower calibration factor and standard deviation.

The field investigations are a time consuming part of this process. To minimize this data collection effort mean data for several parameters may be used in the model. However, data for AADT, curve radius, and curve length, it is important that individualized of the segment is used. These important parameters can be collected without a field visit, saving the agency time and resources. A calibration factor or 1.33 was found to be appropriate to be applied to the HSM prediction method in order for it to match the North Carolina crash values.

7.0 INDIVIDUAL CURVE ANALYSIS GIS PROCESS

7.1 Introduction

Horizontal curves provide a transition from one tangent segment of roadway to the next. These curves exert forces on a vehicle that vary considerably from a tangent section. Drivers must respond appropriately to horizontal curves to safely traverse them. Spatial knowledge of curve radius and arc length is critical for the informed allocation of scarce safety funding and the implementation of traffic control devices to provide warning to drivers. For instance, chevron signs, which are used to alert drivers of the change in direction they will experience through the curve, should target locations with a small radius to maximize the effectiveness of the signs. Also, knowledge of a curve's radius might alert a safety engineer that a safety improvement could be needed to mitigate a safety concern. Horizontal curves are an important consideration because collisions on two-lane curves have been found to be more than twice as likely to result in a fatality as all two-lane roadway segments in North Carolina (Hummer 2010).

Many rural roads are remnants of pathways used and constructed by preceding generations of people for use with modes of transportation in existence prior to the automobile. These pathways were eventually widened and paved as they were brought under the maintenance and supervision of transportation departments. These roads typically were not redesigned with contemporary design standards so curve radius and lengths are usually not known by the agency without a field visit. Because most roadways were designed and built decades ago, corresponding design plans are often not available. Thus, curve databases do not exist. The cost of creating and maintaining a horizontal curve database and undertaking the inventory necessary to populate it has traditionally been prohibitive, particularly for a state such as North Carolina, which has responsibility for about 80,000 miles of roadway. This paper explores the possibility of using a GIS method for determining curve characteristics which then can be helpful for an agency to conduct individual curve investigations, network analysis, or as a tool to help create a curve database.

7.1.1 Scope

Four methods were used to determine the curve radius: a field method (chord method) and three geographic information system (GIS) methods:

- Curve Calculator (by ESRI)
- Curve Finder (by NHDOT)
- Curvature Extension (by FDOT)

The field method is a comparatively labor intensive method which requires a site visit to each curve. Curve Calculator and Curvature Extension are designed for analyzing a single curve at a time, while Curve Finder can be applied to a network of roads. The choice between using an automated GIS curve analysis on a roadway network and conducting an individual GIS curve investigation depends on the needs of the agency and the purpose of the data. An individual manual curve investigation is well-suited to satisfying occasional data collection needs, while an automated method can be employed for inventory purposes, planning applications, or area-wide safety priority guidance. In either case GIS functionality can be invaluable due to the increased safety and efficiency which can result from the use of such tools to quickly determine field conditions of horizontal curves without actually going into the field.

7.1.2 Objective

The objective of this research is to determine the feasibility of utilizing available GIS computing technologies for horizontal curve data collection. Many transportation agencies do not have an inventory of the horizontal curves in their jurisdiction. Thus, a methodology for finding and measuring horizontal curves in a GIS could prove to be highly useful to many agencies and is needed. The purpose of using GIS is to automate the curve investigation process, utilize existing GIS line work, and reduce or eliminate the need for field curve investigations. Roads (and curves) are spatial linear entities that are represented as lines in a GIS. The GIS file that contains the representation of the state's roads is referred to as the line work file and the linear model of the roads is referred to as the line work.

7.2 Literature Review

GIS systems are commonly utilized in the field of transportation for planning, design, construction management, operations, safety, maintenance, and other purposes (ESRI 2010). In addition to the studies discussed below, the Methodology section presents further details of currently available applications that can be used with GIS software for the purpose of determining the radius of horizontal curves.

A current research need identified by the Transportation Research Board's Statewide Transportation Data and Information Systems Committee involves the desire for quantifiable benefits of GIS capabilities (TRB 2010). GIS applications are logical tools transportation departments could use as spatial analysis to gain operational efficiency improvements. However, the money available to invest in GIS applications is limited and their development should be examined by the need, importance, and benefits of these applications. This paper details the application of a set of GIS applications for horizontal curves and validates the ability of that application to identify and characterize curves. Doing so responds to the identified research need and contributes to more well founded GIS use, particularly for transportation applications.

7.2.1 Roadway Alignments in GIS

Rasdorf et al (2002) explored various algorithms for generating linear referencing system routes using a GIS. Route generation must consider both the needs of the transportation agency and the types of GIS analyses that the agency will need. The researchers recommended an algorithm that emphasized the importance of long, continuous routes by identifying and designating the longest routes first. This algorithm, the Longest Posted Route Algorithm, produced the longest routes and the fewest number of routes compared to the other alternatives considered during the research.

Khattak and Shamayleh (2005) utilized a GIS to obtain a 3-dimensional model of highways to conduct safety assessments regarding sight distances. The process included four steps: entering LiDAR data into a GIS, visually identifying potential problem areas, verifying sight obstructions, and validating the results with field observations. The visual identification process involved recognizing sight obstructions by exaggerating vertical factors. Doing so resulted in the isolation of ten problem spots which were then verified with contemporary design standards and a sight line analysis in a GIS. The field visit validated all ten locations which demonstrates the ability of a GIS to utilize and analyze data for sophisticated highway analysis conducted without a field visit.

Castro et al (2008) combined the mapping power of a GIS with horizontal and vertical alignment data to perform a safety evaluation of the highway alignment design based on estimated speeds. Using map information and alignment data, routes were generated to calculate speed profiles along the roadway. Finally, the consistency of the designs were evaluated and represented graphically. The methodology was applied to three two-lane rural highways in Spain with different radii, shoulder widths, lane widths, and design speeds. The methodology resulted in the identification of more problems areas than other contemporary methodologies.

7.2.2 Horizontal Curve Methods

Imran et al. [2006] studied vehicle paths on horizontal curve alignments in Ontario, Canada. The process involved the development of a method of incorporating global positioning system (GPS) information into a GIS for the calculation of the radius, length, spiral length, and vehicle position for nine curves. Each of the nine curves were investigated in both directions at three different speeds (80, 90, and 100 kilometers/hour). Curve radii ranged from 349 meters to 873.2 meters (1,145 to 2,865 feet) and the length of the curves ranged from 162.4 meters to 783.6 meters (532 to 2,571 feet). The method resulted in an average difference of 1.55% between observed and designed radius values, using an observation interval of 0.1 seconds of the GPS data. The length of each curve (arc length) was overestimated by approximately 4%, while the entry and exit spiral transition lengths were overestimated by 24% and 32%, respectively.

In the Arezzo province in Italy, Martinelli et al. [2009] used an automatic procedure to extract geometric curve data from a GIS model of all roads in the province. The geometric data was needed to conduct a safety analysis of the road network. The procedure identified curves based on the average angle between line segments. The automatic procedure is not publicly available and no other information is presented regarding how well the curves were identified or characterized.

Hans et al. [2009] used GPS data to develop a statewide curve database for crash analysis in Iowa. The data were manipulated in a GIS to identify sites with possible curvature by creating continuous linear features, simplifying the routes, and grouping consecutive points. The focus of this work was to detect the presence of a curve and not the specific values of curve characteristics. No other information is available regarding how well the curves were identified.

Another method of building and calculating curve radius values was developed by Price [2010]. The methodology includes 5 tasks (and 30 sub-tasks) which involve constructing chords, modeling the middle ordinate, separating the curves, and calculating the curve radius. The curve radius calculation is based on Equation 2**.** This methodology is similar to Curve Calculator by ESRI which can generate a curve radius based on its arc length and chord length. The methodology was presented along with a detailed exercise involving a 3.5 mile long, 16 feet wide roadway that climbs steeply up a mountain in Washington through many sharp curves. No other information is available regarding how well the curves were identified or characterized.

$$\text{Radius} = \frac{\text{Chord Length}^2}{8 \times \text{Middle Ordinate}} + \frac{\text{Middle Ordinate}}{2} \qquad \textbf{Equation 2}$$

7.2.3 Image Processing

Easa et al (2007) employed semi-automated image processing to estimate curve characteristics. A photographic satellite image of a curve or roadway goes through a process of refinement to isolate the roadway, including smoothing, differentiation, nonmaximal suppression, and thresholding. Subsequently, a technique known as the Hough transform is utilized to detect the curves and tangents. Twelve simple curves at a highway interchange were identified and characterized as part of the study ranging from 22 to 501 meters. The authors reported that each curve was accurately identified, but no quantitative measures were presented and the results were not compared to other methods or techniques.

7.2.4 Summary

Three of the four efforts discussed above have led to the development of programs or methods to extract horizontal curve data for a specific purpose [Imran 2006, Martinelli 2009, Price 2010]. Several other similar programs, the focus of this research, are publicly available [ESRI 2009, FDOT 2010, Harpring 2010]. However, to this point, no study has characterized the quality or optimal uses of the available programs. These previous efforts developed programs or methods specifically for the intended use of the study or for a specific locality, but with further analysis they might have the potential to be utilized by others. The focus of this research is to assess, compare, and benchmark the publicly available GIS methods for horizontal curve spatial data collection.

7.3 Methodology

This study involved two distinct evaluations: a GIS-derived comparison and a field measured comparison. These two evaluations provided especially useful results by allowing for a comparison of each method using two valuable data resources: precisely drawn curves (for a benchmark of the three GIS methods using 14 precisely drawn curves to benchmark the accuracy of the GIS methods) and actual field curve data (for a benchmark of the GIS line work using 51 field measured curves to benchmark the quality of the GIS line work).

The GIS-derived comparison examined how three different GIS-based methods (Curve Calculator, Curvature Extension, and Curve Finder) performed by comparing their output values to the values of precisely drawn GIS-derived curves that were created using ESRI's ArcMap GIS program [2009]. First, 14 curves were drawn in a GIS program with a range of radius values from 30.5 to 1524 meters (100 to 5,000 feet). Then, the three GIS methods were executed on the data to provide a benchmark of the methods when using precisely drawn curves. In other words we determined how well each of the three methods could determine curve spatial characteristics.

Field measurements of curve radius and length were obtained at 51 curve locations in 8 counties in central and eastern North Carolina. The three GIS applications were then executed on the NCDOT GIS model for these specific curves. The results obtained from the three applications were then compared to the actual field measurements of the curves. The result is that we assessed the GIS line work to determine its ability to deliver a good set of curves whose curve characteristics could be accurately determined. The benchmarking established that accuracy level. Curve Calculator and Curvature Extension are methods of studying individual curves with user defined curve limits and measurements. Curve Calculator is a straight line approximation while Curvature Extension derives its output from a circular arc. Curve Finder is deployed on a route or network of routes as selected by the user. This analysis provided a benchmarking of the GIS line work to assess its ability to provide a reliable set of curves.

In a GIS, curves are represented as a series of tangents. The quality of GIS line work is critical for obtaining an accurate representation of the location and geometric characteristics of roads and highways. Figure 6 and Figure 7 show a simple example illustrating the considerable variation of the number of vertices used to model two curves in the 51 curve dataset for this research. The deflection angle, delta (Δ), of the horizontal curve is the angle between successive tangents that form the ends of the curve. The curve shown in Figure 6 accomplishes the transition between the tangents with seven GIS points while the curve in Figure 7 makes the transition with only three GIS points. Therefore, each GIS point on average on the curve in Figure 6 realizes approximately 14% of Δ while each GIS point in Figure 7 must provide approximately 33% of Δ. The number of vertices represents the level of detail that portrays the field conditions of the roadway. Fewer vertices could cause a difference between field measured values and GIS calculated values.

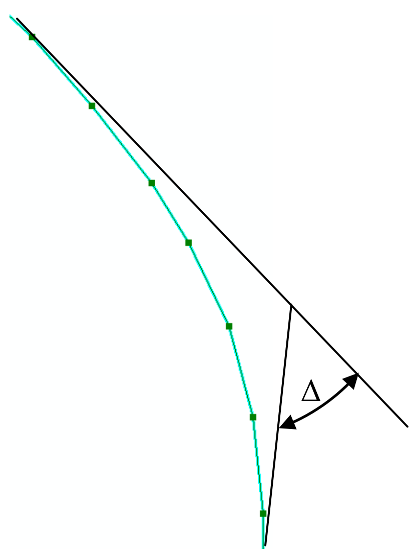


Figure 6. GIS Line Work – Horizontal Curve with 7 Points [ESRI 2009]

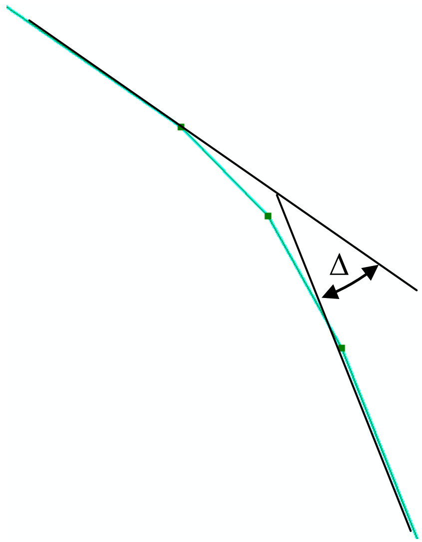


Figure 7. **GIS Line Work – Horizontal Curve with 3 Points [ESRI 2009]**

Two processes are required to obtain the horizontal curve data desired for this study: curve identification and geometric characterization (radius and arc length). Curve identification is a binary analysis that attempts to classify all road segments as either curve or non-curve segments. Geometric characterization is the process of defining the geometric characteristics of each curve in terms of radius and arc length. In two of the GIS methods, Curve Calculator and Curvature Extension, the curve identification process is conducted visually by the user who manually defines the beginning and ending of the curve to execute the geometric characterization process of the methods. Curve Finder automates both processes by executing identification and characterization on a route or network specified by the user.

7.3.1 Field Method

The Chord Method was used in the field to determine the radius of the horizontal curves. The Chord Method [Findley and Foyle 2009] eliminates the need for determining the deflection angle, delta (Δ), of the horizontal curve, which decreases the level of effort required from field personnel using this method. The method can be quickly and reliably executed in the field by one person. A chord of known length is placed between two points along the edge of the edge-line of the roadway as illustrated in Figure 8. Each end of the chord must be within the limits of the curve (between the point of curvature, PC, and point of tangency, PT, of a single radius horizontal curve). At the mid-point of the chord, a measurement of the middle ordinate is taken from the chord to the edge of the edge-line. The middle ordinate (M), the chord (LC), and the lane width (LW) measurements allow for the determination of the radius (R), in feet (Equation 3).

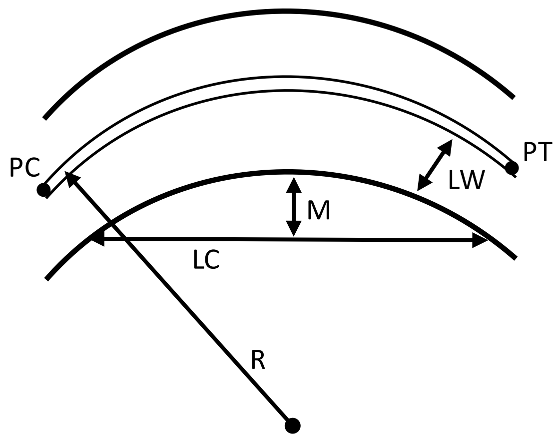


Figure 8. Horizontal Curve Layout [Findley and Foyle 2009]

The Chord Method and nine other curve radius estimating procedures were compared during an investigation in Texas [Carlson et al 2005]. That study compared each of the ten methods to a field survey and found that none of the methods were statistically inaccurate, meaning all of the methods produce sufficient results, which justifies the use of the Chord Method as an appropriate field measuring tool for curves.. The study found that the chord method had an average relative error of approximately -2% with a range of approximately 2% to -6%.

$$\text{Radius} = \frac{4 \times \text{Middle Ordinate}^2 + \text{Chord Length}^2}{8 \times \text{Middle Ordinate}} + \text{Lane Width} \quad \textbf{(Equation 3)}$$

7.3.2 Curve Calculator

Curve Calculator is a command within the coordinate geometry (COGO) toolbar in ArcGIS software developed by Environmental Systems Research Institute [ESRI 2009]. Curve Calculator entails manual curve identification which requires the user to define the PC, which is the point at which the roadway begins to curve, and the PT, which is the point at which the curve ends and the roadway returns to a tangent section. After identifying the PC and PT points, the user can then order the software to measure the chord and arc lengths. The arc length is a straight line approximation of the curve, which follows the vertices of the GIS line work as was illustrated in Figure 8. The user must input any two of four curve characteristics (chord length, angle, arc length, and radius) that are known to determine the remaining unknown characteristics and the chord height and tangent length. To determine the curve’s radius, the user should input the chord length (LC) and the arc length (distance along the curve from the point of curvature to the point of tangency on the horizontal curve), as shown in Figure 9.

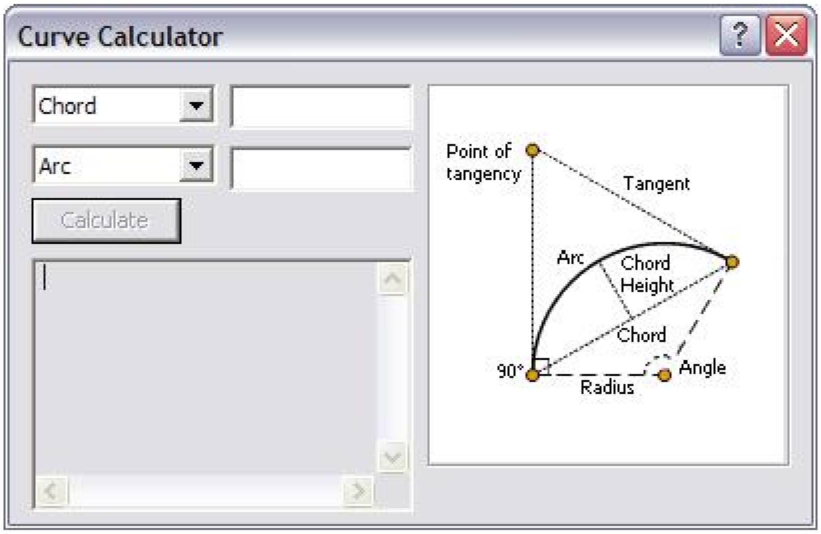


Figure 9. Curve Calculator User Input Screen

7.3.3 Curvature Extension

Curvature Extension is a program which can be added as a toolbar in ArcGIS software and was developed by the Florida Department of Transportation [FDOT 2010]. Curvature Extension, as with Curve Calculator, requires the users to manually identify a curve and to specify the limits of each curve. To execute the program for a curve, the user must select the appropriate data layers for the program to reference, an output file for the results, the direction of the curve (clockwise or counter-clockwise), and the PC and PT points, as shown in Figure 10. The radius is determined by creating a circular arc utilizing the chord length, chord angle, and length of the curve along the route. The curve length is calculated based on the end points. The calculated radius is displayed to the user on the existing GIS line work for visual confirmation of the suitability of the match.

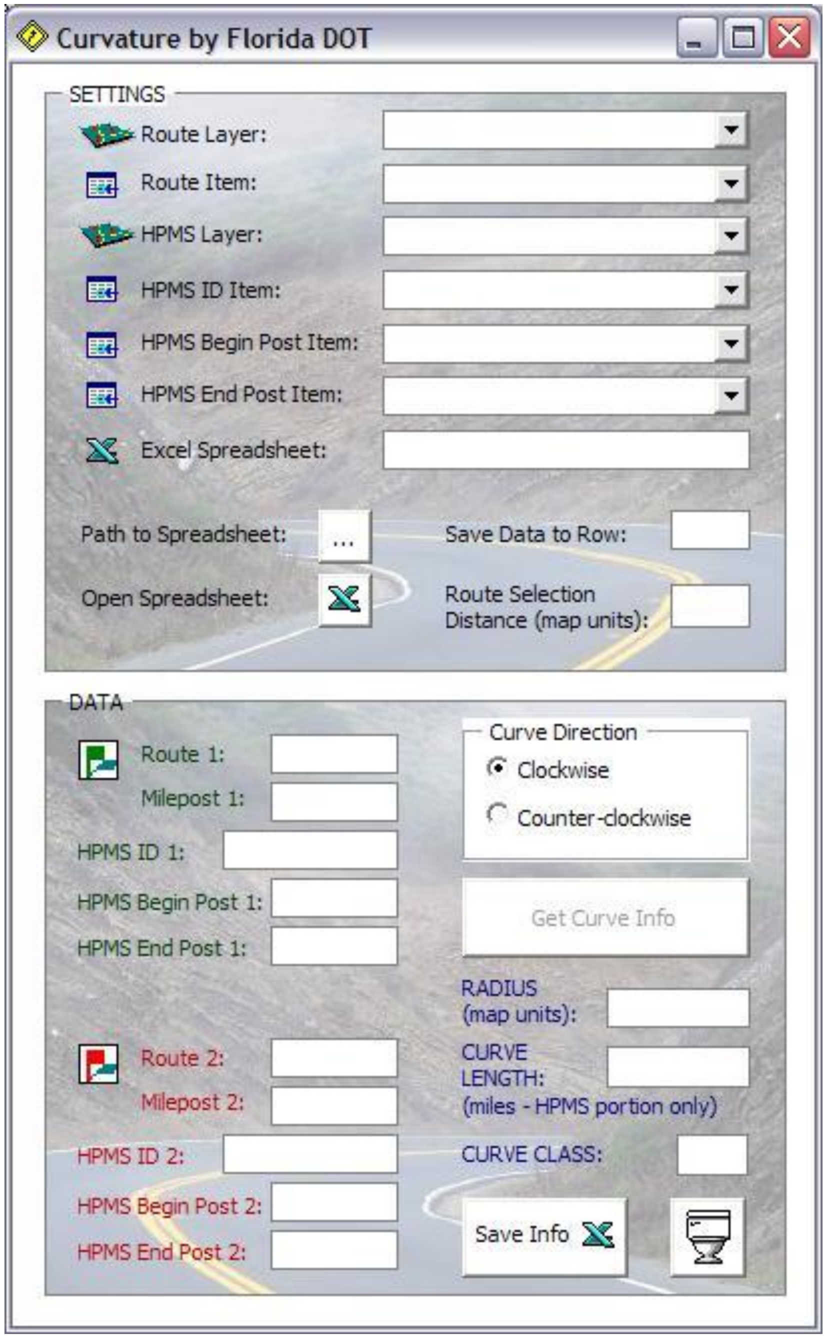


Figure 10. Curvature Extension User Input Screen

7.3.4 <u>Curve Finder</u>

Curve Finder is a program developed by the New Hampshire Department of Transportation. Curve Finder is an automated procedure that can be executed on a network of roadways whose user interface is shown in Figure 11. It is not limited to individual curves. The program operates using on a linear reference system with increasing mileposting of the distance along the routes. Curve Finder uses GIS polylines to determine curve length and radius through coordinate data. Curves are identified as the program moves through every series of three points (which together create a circle) and determines if the points meet the curve tolerance. The user opens the executable file which requires the inputs for the personal geodatabase containing the roadway of interest, the route name, the output location, and the tolerance. The output includes the starting and ending milepost, radius, number of segments, and an estimate of the error of the curve calculations.

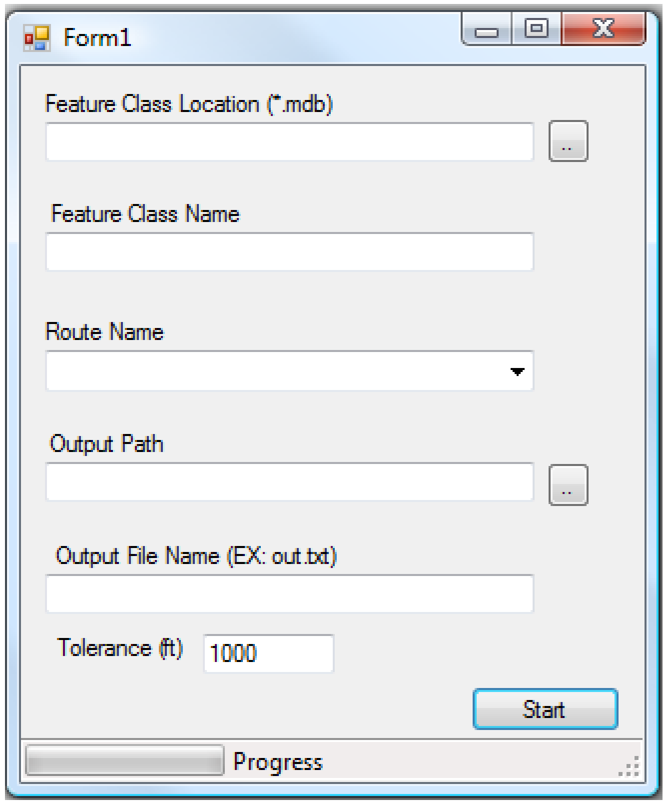


Figure 11. Curve Finder User Input Screen

The tolerance, as specified by the user, influences how precisely the program finds PC and PT of the curve. Figure 12 shows a visual representation of the tolerance. A curve will be detected if the distance between the centroid of a circle at a vertex and the centroid of the circle formed by the next vertex is less than the tolerance set by the user. Otherwise, the curve will not be detected by the program. A small tolerance setting can result in the splitting of a single curve into multiple smaller curves, while a high tolerance can result in multiple separate curves being combined into a single curve. The default tolerance for the program is 304.8 meters (1,000 feet). The resulting lines can be projected into the GIS program for a visual representation of the quality of the fit of the curve to GIS line work.

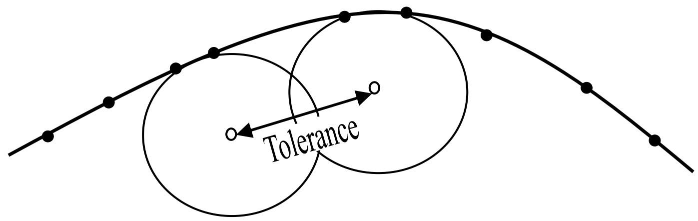


Figure 12. Tolerance Example

7.4 Analysis

Numerous factors can influence which type of study requires horizontal curve data: microscopic (individual location) studies or macroscopic (network) studies. These factors can include the level of detail required and the scope. With respect to the level of detail required, an agency that would request a long term plan for funding safety updates by realigning curves might want to know how many curves in their jurisdiction have a radius of less than 152.4 meters (500 feet). A database of curves (with each curve's location and characteristics) is ideal because relying on only crash data to identify curve-related crashes is subject to judgments of the presence and influence of a curve on a collision. Also, to precisely locate curves based only on mileposting is subject to inaccuracies in the reporting process. In this case, a jurisdiction-wide analysis would be most efficiently conducted by an automated method that can analyze a route or network of routes concurrently. An example of the influence of scope can occur if an agency desires a study because it observes an unusually high number of collisions at one particular curve compared to other curves, which would dictate an investigation of only this individual curve. In this instance, a small scope requires an analytical tool that does not have to be capable of numerous, rapid curve analyses.

The following analysis includes the two evaluations described earlier: a GIS-derived comparison and a field measured comparison. Figure 1 shows a visual display of the relationship of these two evaluations which provide a comparison of each method using two valuable data resources: precisely drawn curves (for a benchmark of the three GIS methods) and actual field curve data (for a benchmark of the GIS line work).

7.4.1 GIS-Derived Curve Analysis

The GIS-derived comparison examined how the three GIS-based methods performed by comparing their output to the accurately drawn curves that were created in a GIS program [ESRI 2009]. Each curve was drawn as a circular arc and subdivided into 10 equal segments (11 GIS points from the beginning of the curve to the end of the curve). Table 14 shows that each method performed well when determining the radius of the curve. The Curvature Extension method matched the true radius values exactly, while Curve Finder values were slightly different at the higher radius values. Curve Calculator accuracy degraded as the radius values increased because the number of segments remained constant and were unable to exactly estimate the larger radii.

Table 14. Radius in Meters (feet) Comparison of GIS Methods

True Radius	Curve Calculator	Curve Finder	Curvature Extension
30.5 (100)	30.5 (100)	30.5 (100)	30.5 (100)
61.0 (200)	61.0 (200)	60.9 (200)	61.0 (200)
91.4 (300)	91.7 (301)	91.4 (300)	91.4 (300)
121.9 (400)	122.2 (401)	121.9 (400)	121.9 (400)
152.4 (500)	153.0 (502)	152.4 (500)	152.4 (500)
182.9 (600)	183.8 (603)	182.9 (600)	182.9 (600)
213.4 (700)	214.3 (703)	213.4 (700)	213.4 (700)
243.8 (800)	245.1 (804)	243.8 (800)	243.8 (800)
274.3 (900)	275.5 (904)	274.3 (900)	274.3 (900)
304.8 (1,000)	306.3 (1,005)	305.1 (1,001)	304.8 (1,000)
457.2 (1,500)	459.3 (1,507)	457.2 (1,500)	457.2 (1,500)
609.6 (2,000)	612.7 (2,010)	609.3 (1,999)	609.6 (2,000)
762.0 (2,500)	765.7 (2,512)	762.6 (2,502)	762.0 (2,500)
1,524.0 (5,000)	1531.9 (5,026)	1,523.7 (4,999)	1,524.0 (5,000)

A sensitivity analysis was used to determine the effect that the number of GIS points has on the radius for each method (Table 15). Curve Calculator is the most heavily affected method, with an increase in accuracy as the number of GIS points increase. At 5 GIS points, Curve Calculator overestimated the radius by over 3%, while 8 GIS points resulted in a radius with an error of approximately 1% and 25 GIS points produced an error of less than 0.1%. Curve Finder fluctuated slightly (less than 0.03% on average) around the true radius of 1,000 feet, but not with a consistent trend. Curvature Extension exactly matched the true radius regardless of the number of GIS points.

Table 15. Sensitivity Analysis for 304.8 Meter (1,000') Radius and 152.4 Meter (500') Length Curve

Number of GIS Points	Radius in Meters (feet)		
	Curve Calculator	Curve Finder	Curvature Extension
5	314.5 (1,031.94)	304.8 (999.90)	304.8 (1,000)
6	310.9 (1,020.06)	304.8 (999.99)	304.8 (1,000)
7	309.0 (1,013.83)	304.6 (999.49)	304.8 (1,000)
8	307.9 (1,010.16)	304.8 (1,000.09)	304.8 (1,000)
9	307.2 (1,007.70)	304.8 (999.92)	304.8 (1,000)
10	306.7 (1,006.60)	304.8 (1,000.11)	304.8 (1,000)
11	306.3 (1,004.91)	304.8 (1,000.14)	304.8 (1,000)
12	306.0 (1,004.06)	304.8 (1,000.01)	304.8 (1,000)
15	305.6 (1,002.51)	304.8 (999.99)	304.8 (1,000)
20	305.2 (1,001.35)	304.9 (1,000.24)	304.8 (1,000)
25	305.1 (1,000.83)	304.9 (1,000.23)	304.8 (1,000)
30	305.1 (1,000.58)	304.7 (999.80)	304.8 (1,000)
40	304.9 (1,000.32)	304.8 (1,000.06)	304.8 (1,000)
50	304.9 (1,000.21)	305.5 (1,002.18)	304.8 (1,000)

7.4.2 Field Measured Curve Analysis

The field measured curve comparison examined how the GIS line work performed in the three GIS-based methods by comparing their output to field measured curves. GIS data for North Carolina roads were obtained from the North Carolina Department of Transportation (NCDOT). The most current Road Characteristics Arcs [NCDOT 2009] is a digital file of NCDOT's road inventory database which splits roadway segments each time a road characteristic changes from a previous segment. The file is updated quarterly to account for improvements in the line work based on photo-revisions of the existing network. Of the entire North Carolina network, 51 curves were individually studied using both the field procedure (described in this section) and the three GIS programs (described in the previous section). Often, the most time consuming portion of the analysis process is locating the curve of interest within the GIS, which can take several minutes. The processing of an individual curve in each of the methods takes approximately one minute to execute and complete.

Field Measured Curve Radius Analysis

Table 16 shows for each of the 51 curves the list of field measured radii in ascending order along with their values. The table also shows the predicted values (using the three GIS methods) and percent difference of the predicted values from the field measured results. The reader can see from Table 3 that there is no evident pattern of difference as the radii increase in value. However, statistical testing found that the errors produced by each of the methods had a negative correlation with the field measured radius, meaning that as the field measured radius increased, the error decreased. Curve Finder located 45 of the 51 curves, while Curve Calculator and Curvature Extension were able to locate every curve as the user specified each curve's PC and PT points.

The tolerance in Curve Finder is specified by the user and affects how precisely the program finds PC and PT of the curve. The default tolerance for Curve Finder is 304.8 meters (1,000 feet) and the practical limit for this analysis was set at 1524 meters (5,000 feet). Tolerances above 1524 meters (5,000 feet) produced unreasonable results. The 1524 meters (5,000 feet) limit excluded 6 of the curves, while the tolerances for the other 45 curves ranged from 30.5 to 1463 meters (100 to 4,800 feet). The default tolerance of 304.8 meters (1,000 feet) identified 26 of the curves, while tolerances between 1,100 and 4,800 identified the other 19 curves.

Table 16. Curve Radius: Field Measured vs GIS Calculated

Field Measured	Curve Calculator (ESRI)		Curve Finder (NHDOT)			Curvature Extension (FDOT)	
Radius in Meters (ft)	Radius in Meters (ft)	Difference (%)	Radius in Meters (ft)	Difference (%)	GIS Points	Radius in Meters (ft)	Difference (%)
61.6 (202)	48.2 (158)	-22	46.3 (152)	-25	6	47.5 (156)	-23
95.1 (312)	131.4 (431)	38	125.9 (413)	32	4	126.2 (414)	33
137.8 (452)	138.1 (453)	0	395.0 (1,296)	187	5	115.8 (380)	-16
150.9 (495)	128.3 (421)	-15	193.9 (636)	29	4	228.6 (750)	52
160.6 (527)	223.7 (734)	39	167.3 (549)	4	6	215.8 (708)	34
176.2 (578)	88.7 (291)	-50	252.1 (827)	43	4	112.2 (368)	-36
176.8 (580)	202.4 (664)	14	N/A	N/A	4	246.9 (810)	40
179.8 (590)	327.4 (1,074)	82	262.4 (861)	46	4	219.5 (720)	22
189.6 (622)	269.7 (885)	42	409.7 (1,344)	116	4	249.6 (819)	32
193.5 (635)	104.9 (344)	-46	93.3 (306)	-52	4	100.0 (328)	-48
206.7 (678)	154.5 (507)	-25	164.3 (539)	-20	4	145.4 (477)	-30
210.9 (692)	164.0 (538)	-22	157.0 (515)	-26	7	168.6 (553)	-20
221.0 (725)	267.3 (877)	21	248.7 (816)	12	4	231.3 (759)	5
221.0 (725)	252.4 (828)	14	208.8 (685)	-5	9	225.9 (741)	2
221.0 (725)	412.7 (1,354)	87	501.4 (1,645)	127	4	532.8 (1,748)	141
221.3 (726)	150.9 (495)	-32	232.9 (764)	5	5	217.9 (715)	-2
232.0 (761)	311.5 (1,022)	34	304.2 (998)	31	6	288.6 (947)	24
237.1 (778)	148.4 (487)	-37	655.3 (2,150)	176	5	145.4 (477)	-39
272.2 (893)	729.1 (2,392)	168	N/A	N/A	4	782.4 (2,567)	187
272.5 (894)	175.9 (577)	4	386.5 (1,268)	42	5	209.4 (687)	4
279.8 (918)	919.9 (3,018)	229	707.7 (2,322)	153	5	925.1 (3,035)	231
280.1 (919)	241.4 (792)	-14	283.8 (931)	1	7	252.4 (828)	-10
280.4 (920)	257.3 (844)	-8	274.3 (900)	-2	11	257.6 (845)	-8
289.3 (949)	391.7 (1,285)	35	329.2 (1,080)	14	5	379.2 (1,244)	31
307.5(1,009)	245.1 (804)	-20	N/A	N/A	4	346.3 (1,136)	13
341.7(1,121)	299.9 (984)	-12	260.6 (855)	-24	7	297.5 (976)	-13
354.5(1,163)	366.4 (1,202)	3	866.5 (2,843)	144	4	338.0 (1,109)	-5
368.5(1,209)	259.1 (850)	-30	241.4 (792)	-35	8	267.3 (877)	-27
369.1(1,211)	409.0 (1,342)	11	224.6 (737)	-39	4	404.8 (1,328)	10
369.1(1,211)	1,122.9 (3,684)	204	746.5 (2,449)	102	4	375.2 (1,231)	2
384.4(1,261)	307.5 (1,009)	-20	386.5 (1,268)	1	4	347.2 (1,139)	-10
400.8(1,315)	249.3 (818)	-38	343.5 (1,127)	-14	7	249.9 (820)	-38
457.2(1,500)	647.1 (2,123)	42	627.6 (2,059)	37	4	645.0 (2,116)	41
460.2(1,510)	454.2 (1,490)	-1	500.5 (1,642)	9	4	567.5 (1,862)	23
511.1(1,677)	311.5 (1,022)	-39	833.0 (2,733)	63	4	473.7 (1,554)	-7
511.1(1,677)	1,406.7 (4,615)	175	N/A	N/A	4	1,466.4 (4,811)	187
511.8(1.679)	310.0 (1,017)	-39	710.2 (2,330)	39	4	306.3 (1,005)	-40
541.3(1,776)	400.2 (1,313)	-26	496.8 (1,630)	-8	4	436.5 (1,432)	-19
541.3(1,776)	395.3 (1,297)	-27	394.7 (1,295)	-27	7	400.8 (1,315)	-26
574.5(1,885)	693.7 (2,276)	21	540.1 (1,772)	-6	4	713.2 (2,340)	24
574.9(1,886)	634.9 (2,083)	10	459.0 (1,506)	-20	4	472.1 (1,549)	-18
613.3(2,012)	771.4 (2,531)	26	691.0 (2,267)	13	4	804.4 (2,639)	31
655.9(2,152)	456.3 (1,497)	-30	316.1 (1,037)	-52	4	441.0 (1,447)	-33
656.2(2,153)	637.0 (2,090)	-3	1204.9 (3,953)	84	4	714.5 (2,344)	9
656.5(2,154)	954.6 (3,132)	45	848.9 (2,785)	29	4	1,000.4 (3,282)	52
706.5(2,318)	1,169.2 (3,836)	66	805.0 (2,641)	14	5	1,057.0 (3.468)	50
765.4(2,511)	299.6 (983)	-65	241.1 (791)	-68	5	300.8 (987)	-65
765.4(2,511)	1915.1 (6,283)	150	N/A	N/A	4	1,679.4 (5,510)	119
917.1(3,009)	196.0 (643)	-79	268.8 (882)	-71	4	157.9 (518)	-83
1,019.3(3,344)	573.9 (1,883)	-44	280.1 (919)	-73	4	680.9 (2.234)	-33
1,832.2(6,011)	792.8 (2,601)	-57	N/A	N/A	4	601.7 (1,974)	-67

Table 17 shows the number and percentage of curves identified by each method within 10%, 25%, and 50% of the field measured values. For the radius measurements, Curvature Extension identified the highest percentage of curves at all levels. For example, Curvature Extension determined that 41 curves (or 80% of the 51 curves) were within 50% of the field measured radius. Even still, the other two methods identified nearly the same percent of curves (69% for Curve Finder and 78% for Curve Calculator).

Table 17. Curve Radius Differences from Field Measured Values

Curves With Radius Within	Curve Calculator		Curve Finder		Curvature Extension	
	#	%	#	%[1]	#	%
10% of Field Value	6	12	9	20	12	24
25% of Field Value	19	37	18	40	23	45
50% of Field Value	40	78	31	69	41	80

[1] The percentage for Curve Finder is based on a total of 45 curves located by the method, while Curve Calculator and Curvature Extension are based on 51 curves.

There is significant linear correlation [SAS 2010] between all of the methods for determining the radius of the horizontal curves. That is, all p-values are significant to a level less than or equal to 0.005 (Table 18). Curve Calculator and Curvature Extension radius values are positively correlated with a correlation coefficient of 0.94 at a significant p-value of less than 0.0001.

Table 18. Correlation Coefficients and P-values for Radius Values

	Field Measured	Curve Calculator	Curve Finder	Curvature Extension
Field Measured	1			
Curve Calculator	0.47 *0.0005*	1		
Curve Finder	0.41 *0.005*	0.68 *< 0.0001*		
Curvature Extension	0.45 *0.0009*	0.94 *< 0.0001*	0.69 *< 0.0001*	1

Field Measured Curve Length Analysis

Curve lengths, otherwise known as the arc length or length along the roadway, were also examined in the field measured curve analysis. Table 19 shows the list of lengths for field measured curves in ascending order of length, the related GIS methods' calculated length values, and the percent difference of the GIS method results from the field measured results. Again, just as with radius, there is no evident pattern of differences as the lengths increase in value. However, statistical testing found that the errors produced by each of the methods had a negative correlation with the field measured length, meaning that as the field measured length increased, the error decreased. Curve Finder located 45 of the 51 curves, while Curve Calculator and Curvature Extension were able to locate every curve. Table 20 shows the number and percentage of curves identified by each method within 10%, 25%, and 50% of the field measured values. For example, Curve Calculator and Curvature Extension each determined that 39 curves (or 76% of the 51 curves) were within 50% of the field measured radius.

Table 19. Curve Length: Field Measured vs GIS Calculated

Field Measured	Curve Calculator (ESRI)		Curve Finder (NHDOT)		Curvature Extension (FDOT)	
Length in Meters (ft)	Length in Meters (ft)	Difference (%)	Length in Meters (ft)	Difference (%)	Length in Meters (ft)	Difference (%)
61.0 (200)	408.4 (1,340)	570	88.4 (290)	45	408.7 (1,341)	571
70.1 (230)	75.3 (247)	8	45.1 (148)	-35	75.6 (248)	8
70.1 (230)	152.7 (501)	118	70.1 (230)	0	153.0 (502)	118
79.2 (260)	201.8 (662)	155	96.3 (316)	22	201.2 (660)	154
82.3 (270)	73.2 (240)	-11	72.5 (238)	-12	72.5 (238)	-12
83.8 (275)	71.9 (236)	-14	N/A	N/A	70.7 (232)	-16
88.4 (290)	72.5 (238)	-18	37.2 (122)	-58	74.1 (243)	-16
91.4 (300)	128.0 (420)	40	76.5 (251)	-16	127.1 (417)	39
99.1 (325)	81.4 (267)	-18	30.8 (101)	-69	82.0 (269)	-17
99.1 (325)	53.6 (176)	-46	171.6 (563)	73	53.0 (174)	-46
106.7 (350)	150.6 (494)	41	50.6 (166)	-53	149.7 (491)	40
106.7 (350)	115.5 (379)	8	45.1 (148)	-58	114.3 (375)	7
106.7 (350)	103.6 (340)	-3	N/A	N/A	103.0 (338)	-3
106.7 (350)	178.3 (585)	67	118.9 (390)	11	178.6 (586)	67
115.8 (380)	153.0 (502)	32	68.3 (224)	-41	153.0 (502)	32
115.8 (380)	109.4 (359)	-5	40.2 (132)	-65	109.4 (359)	-6
121.9 (400)	130.8 (429)	7	52.1 (171)	-57	132.0 (433)	8
121.9 (400)	252.7 (829)	107	N/A	N/A	252.7 (829)	107
129.5 (425)	310.3 (1,018)	139	N/A	N/A	310.6 (1,019)	140
137.2 (450)	34.4 (113)	-75	34.7 (114)	-75	33.8 (111)	-75
137.2 (450)	349.6 (1,147)	155	118.0 (387)	-14	349.3 (1,146)	155
137.2 (450)	76.8 (252)	-44	76.8 (252)	-44	77.1 (253)	-44
141.7 (465)	139.0 (456)	-2	63.1 (207)	-55	138.4 (454)	-2
161.5 (530)	63.7 (209)	-61	64.0 (210)	-60	64.3 (211)	-60
164.6 (540)	136.6 (448)	-17	105.5 (346)	-36	136.9 (449)	-17
167.6 (550)	123.1 (404)	-26	44.5 (146)	-73	122.2 (401)	-27
175.3 (575)	129.2 (424)	-26	61.3 (201)	-65	128.6 (422)	-27
176.8 (580)	143.0 (469)	-19	90.2 (296)	-49	143.3 (470)	-19
182.9 (600)	230.4 (756)	26	122.8 (403)	-33	230.1 (755)	26
182.9 (600)	136. (447)	-25	66.1 (217)	-64	136.9 (449)	-25
190.2 (624)	648.0 (2,126)	241	N/A	N/A	647.1 (2,123)	240
190.5 (625)	48.8 (160)	-74	110.3 (362)	-42	48.2 (158)	-75
196.6 (645)	141.7 (465)	-28	77.7 (255)	-60	142.6 (468)	-27
198.1 (650)	174.0 (571)	-12	70.4 (231)	-65	173.7 (570)	-12
204.2 (670)	173.4(569)	-15	111.6 (366)	-45	173.7 (570)	-15
205.7 (675)	215.8(708)	5	89.0 (292)	-57	212.4 (697)	3
207.3 (680)	188.4 (618)	-9	79.2 (260)	-62	188.4 (618)	-9
213.4 (700)	210.6 (691)	-1	96.6 (317)	-55	209.1 (686)	-2
213.4 (700)	183.8 (603)	-14	40.2 (132)	-81	183.5 (602)	-14
216.4 (710)	152.1 (499)	-30	N/A	N/A	151.2 (496)	-30
219.5 (720)	167.0 (548)	-24	38.1 (125)	-83	167.3 (549)	-24
228.6 (750)	227.4 (746)	-1	75.0 (246)	-67	226.8 (744)	-1
240.8 (790)	132.3 (434)	-45	96.6 (317)	-60	132.0 (433)	-45
243.8 (800)	303.0 (994)	24	142.0 (466)	-42	302.7 (993)	24
259.1 (850)	200.3 (657)	-23	57.6 (189)	-78	199.6 (655)	-23
285.0 (935)	283.8 (931)	0	234.7 (770)	-18	283.2 (929)	-1
298.7 (980)	346.3 (1,136)	16	195.7 (642)	-34	344.4 (1,130)	15
304.8 (1,000)	232.9 (764)	-24	70.7 (232)	-77	231.6 (760)	-24
350.5 (1,150)	483.4 (1,586)	38	91.7 (301)	-74	482.8 (1,584)	38
438.9 (1,440)	399.3 (1,310)	-9	81.4 (267)	-81	399.0 (1,309)	-9
472.4 (1,550)	75.6 (248)	-84	166.1 (545)	-65	75.6 (248)	-84

Table 20. Curve Length Differences from Field Measured Length Values

Curves With Length Within	Curve Calculator		Curve Finder		Curvature Extension	
	#	%	#	%[1]	#	%
10% of Field Value	12	24	1	2	12	24
25% of Field Value	26	51	7	16	26	51
50% of Field Value	39	76	18	40	39	76

[1] The percentage for Curve Finder is based on a total of 45 curves located by the method, while Curve Calculator and Curvature Extension are based on 51 curves.

Again, there is significant linear correlation [SAS 2010] between all of the methods for determining the length of the horizontal curves (Table 21). Curve Calculator and Curvature Extension length values are highly correlated with a positive correlation coefficient of 0.99 and a p-value of less than 0.0001. The length measurements from Curvature Extension and Curve Calculator are almost perfectly correlated with each other (not perfectly correlated with the actual field measurements) because the user selected the beginning and end of each of curve for these two methods.

Table 21. Correlation Coefficients and P-values for Length Values

	Field Measured	**Curve Calculator**	**Curve Finder**	**Curvature Extension**
Field Measured	1			
Curve Calculator	0.35 *0.011*	1		
Curve Finder	0.40 *0.065*	0.35 *0.019*	1	
Curvature Extension	0.35 *0.011*	0.99 *< 0.0001*	0.35 *0.020*	1

7.4.3 Safety Analysis

The overall impact of differing results from the field measurements and GIS methods can be examined through the potential impact of decision making and project improvement funding. To estimate the impact of these results, the study team employed a nationally accepted model, the Highway Safety Manual, which relates radius and length (among other roadway and traffic factors) to highway safety [Hughes 2004]. Table 22 shows the amount of predicted collisions and the rank of those collisions within each method. The top ten most hazardous Field Measured curves experience 6.2 predicted collisions per year. Those same ten curves experience 3.9 collisions, 5.8 collisions and 5.9 collisions based on radius and length data from Curve Finder, Curve Calculator, and Curvature Extension, respectively. Curve Finder was not able to identify two of the curves located in the top ten of the Field Measured curves, however, the rank within Curve Finder of the collisions ranged from 1 to 20. The rankings within Curve Calculator ranged from 1 to 39 and from 1 to 38 in Curvature Extension.

Table 22. Safety Ranking of Top 10 Most Hazardous Field Measured vs GIS Calculated Curves

Field Measured Radius in Meters (feet)	Field Measured		Curve Calculator		Curve Finder		Curvature Extension	
	Predicted Collisions	Rank	Predicted Collisions	Rank	Predicted Collisions	Rank	Predicted Collisions	Rank
280.1 (919)	1.593	1	1.542	1	1.671	1	1.516	1
1019.3 (3,344)	0.867	2	0.847	4	0.817	2	0.82	4
369.1 (1,211)	0.661	3	0.247	14	0.388	5	0.379	8
280.4 (920)	0.634	4	0.596	6	0.282	9	0.596	6
656.5 (2,154)	0.516	5	0.677	5	0.135	20	0.674	5
511.1 (1,677)	0.49	6	0.898	3	Not Found		0.897	3
706.5 (2,318)	0.453	7	0.087	39	0.169	18	0.089	38
369.1 (1,211)	0.343	8	0.347	8	0.211	12	0.344	9
613.3 (2,012)	0.34	9	0.291	12	0.239	11	0.289	12
574.9 (1,886)	0.33	10	0.304	11	Not Found		0.322	10
Total	6.2 collisions		5.8 collisions		3.9 collisions		5.9 collisions	

The rankings of all 51 curves were examined using Spearman Correlation Coefficients, as shown in Table 23 [SAS 2010]. The Field Measured rankings were highly positively correlated with each method to a significant level (all p-values were less 0.0001).

Table 23. Spearman Correlation Coefficients for Safety Rankings

	Field Measured	Curve Calculator	Curve Finder	Curvature Extension
Field Measured	1			
Curve Calculator	0.90	1		
Curve Finder	0.88	0.86	1	
Curvature Extension	0.90	0.99	0.87	1

7.5 RESULTS

The initial curve analysis compared each of the three GIS methods to precisely drawn curves in a GIS whose geometric characteristics were precisely known. The comparison found that Curvature Extension was able to exactly determine the radius of each curve. Curve Finder correctly identified the radius of most of the curves and was within one or two feet difference at some of the larger radius values. Curve Calculator was capable of accurate identification of the curve radius at small radius values, but was progressively less accurate at larger radius values, although at 1524 meters (5,000 feet) it only differed from the true radius by approximately 0.5%.

A subsequent but separate sensitivity analysis of the radii's accuracy in relation to the number of GIS points that were used to define the curve itself found that the accuracy of Curve Calculator increased as the number of GIS points increased. The Curve Calculator error decreased from over 3% with 5 GIS points to approximately only 1% with 8 GIS points to less than 0.1% with 25 GIS points. The Curve Finder error was minor with an error of less than 0.03% on average, but not with a consistent trend in relation to the number of points. There was no error associated with Curvature Extension as it exactly matched the true radius regardless of the number of GIS points.

The field measured curve analysis compared each of the three GIS methods to 51 field measured curves in North Carolina. Curve Finder identified 45 of the 51 curves, while the other two methods identified every curve. Curvature Extension appears to be the most accurate evaluator of curve radius by measuring the radius within 50% of the field measured value on 80% of the curves. Curve Calculator was within 50% of the field measured value for 78% of the curves and Curve Finder measured 69% of the curves to within 50% of the field measurement. Curve Calculator and Curvature Extension were equally proficient in assessing length measurements with 76% of their measurements within 50% of the field measured values. Curve Finder reported only 40% of the curves to within 50% of the field measured length. A 1524 meters (5,000 feet) maximum tolerance was specified in Curve Finder which provided useful results for the curves examined in this study.

Curve safety rankings between the methods were tested using Spearman correlation coefficients. The Field Measured rankings share positive, statistically significant correlation with each method (from 0.88 to 0.90). When comparing the methods to each other, positive, statistically significant correlation is also observed, with the highest correlation between Curve Calculator and Curvature Extension of 0.99 representing a strong relationship between the rankings from the two programs.

A test of the linear correlation of both the radius and length between the methods was conducted to examine the similarity between the results for each method. Overall, many of the methods share positive, statistically significant correlation with each other which supports the reliability of the GIS methods while emphasizing the importance of quality line work for accurate results. The GIS line work showed considerable quality variation in this study ranging from some curves with minute errors to some errors larger than the radius itself. Still, Table 4 shows that even with the line work evaluated in this study, a considerable percentage of radius values were captured depending on the desired level of accuracy.

7.6 Conclusions

The need for horizontal curve information extends to numerous transportation purposes which range from individual curve safety investigations to long-range network planning and beyond to applications in other domains. This analysis found that each of the three GIS programs studied is well suited for specific applications, as discussed below, depending on the user's needs and the quality of the GIS line work. The level of accuracy that each of these programs can provide is high enough for most typical safety and planning applications. Many transportation agencies maintain GIS programs and roadway alignments; given these existing resources, the cost of running the three GIS programs is minimal. Each of the programs is available publicly for no additional cost above the expense of ArcGIS, but will require staff time to execute on the roadways of interest to the agency. The accuracy of the programs appears to be within the practical level of precision that can be achieved through the construction of the roadway and pavement paint stripping of the lanes. Design and engineering applications require a higher level of accuracy, but could employ one of these methods for initial planning or cost estimation to avoid field data collection or the cost of contracting of a mobile data collection vehicle.

Curve Calculator (by ESRI) performs well at characterizing curves when the GIS line work has a high concentration of points along the path of the curve, while low numbers of GIS points might still provide a radius of sufficient accuracy for other uses of the data. Since Curve Calculator is a built-in command in ArcMap, the user can quickly open the command and utilize the measurement tool to find the length and determine the radius of a given curve. While Curve Calculator computes a solution based on user defined lengths, it can only be used on one curve at a time.

Curvature Extension (by FDOT) produced the most accurate results in the GIS-derived analysis and in the field measured curve analysis. The circular approximation of the curve provides a more accurate representation of the curve than the straight-line approximation used by Curve Calculator. Still, Curvature Extension also operates on only a single curve.

Curve Finder (by NHDOT) produced accurate results in the GIS-derived analysis, but was less accurate than the other methods in the field measured curve analysis. However, the advantage of Curve Finder program is the ability to analyze entire roadways or networks of roadways in a single analysis. This ability provides the user with the opportunity to quickly acquire data on a large-scale in the same amount of time as a single curve. The results show that this automation can provide feasible results. However, Curve Finder was unable to locate 6 of the 51 curves of interest. The six curves that Curve Finder missed each had only four GIS points.

This paper demonstrated that there are GIS-based programs in existence that are capable of horizontal curve data collection and also provides a validation of their performance. The GIS programs demonstrated the ability to produce highly accurate results during a precise geometric GIS-derived analysis. However, the field measured analysis was much less accurate. The difference between the true highway geometry measured in the field and the GIS representation of that geometry is the cause of the differences between the two analyses. If the GIS road model (the line work) is not accurate, discrepancies will clearly arise from this difference.

The safety ranking of each method provides information about the accuracy of the GIS methods based on decision support for safety improvement funding. Although the differences from the output of the GIS methods produced slightly different values for the number of predicted curve collisions (Table 3), the correlation coefficients between the Field Measured rankings and the GIS methods' rankings showed high, positive correlation (Table 4). The correlation coefficients demonstrate that although some decisions could be altered (depending on which method is utilized) the overall rankings are similar to the Field Measured rankings which leads to consistent decision making.

The significant, positive correlation coefficients between many of the GIS program pairings indicate that the GIS line work results, while not as accurate, were comparable. For radius values, all of the methods were correlated to a significant level ($p \leq 0.005$) with a range of factors from 0.41 (Curve Finder and Field Measured) to 0.94 (Curvature Extension and Curve Calculator). For length values, Curve Calculator and Curvature Extension were highly correlated (coefficient of 0.99) with a p-value of less than 0.0001. The correlated results show a consensus of values among the GIS methods which are likely portraying an accurate representation of the GIS characteristics of the roadway. The GIS method benchmarking showed that each of the three methods perform well against precise measurements. On the other hand, the GIS line work benchmarking showed that the line work was unable to provide reliable spatial positioning to enable the methods to conduct calculations to produce highly accurate curve characteristics that match field measurements.

7.7 Recommendations

The research team recommends several possibilities to utilize a GIS methodology to help transportation professionals better identify and more efficiently study the characteristics of horizontal curves or to address other spatial data problems. The use of a GIS to determine horizontal curve radius and length is possible. Depending on available equipment, GPS (Imran 2006) and LiDAR (Khattak and Shamayleh 2005) can be used to generate feasible roadway alignments if the GIS line work does not exist or is not at a reasonable level of quality. A GIS-based approach can save time and resources compared to traditional field measurement techniques, as well as improve overall safety by eliminating the need to have personnel interact with the motoring public in potentially dangerous locations on curves. The integration of one of the methods introduced and analyzed here into a comprehensive horizontal curve process would assist agencies in horizontal curve identification, investigation, and analysis.

For individual curve analysis, Curvature Extension is recommended. However, Curve Calculator has been shown to be capable of producing reasonably accurate results with a large number of GIS points more quickly and efficiently than the other two methods. Curve Finder on the other hand, is recommended for network or route analysis. Curve Finder could be used to identify multiple locations with a small radius for safety applications or it could be used at the planning level to identify systematic deficiencies among regions or routes. Curve Finder can execute an analysis of one or many curves in only a couple of minutes, therefore, significant time efficiency can be obtained with large numbers of curves.

The tolerance in Curve Finder should be chosen carefully to capture as many curves as possible without unnecessarily splitting apart a single curve or combining together multiple curves. In this study, a 1524 meters (5,000 feet) maximum tolerance appears to be an appropriate level based on investigating multiple tolerances at each isolated individual curve. However, variations in the quality of the GIS line work impose the need for a detailed examination of the line work before beginning the analysis. The variations in quality could differ among jurisdictions and even among route classifications within a single jurisdiction (such as between interstate routes and local routes). Still, the line work quality in this study for rural, two-lane roads was good enough to enable the software to identify almost 90% of the curves (45 out of 51). If Curve Finder is utilized, a close assessment of the tolerance setting should be made by the user.

8.0 NETWORK CURVE ANALYSIS GIS PROCESS

8.1 Introduction

As a driver navigates a roadway, horizontal curves provide the necessary transition between straight roadway segments. A comprehensive knowledge of horizontal curves is important for transportation agencies to make well-informed decisions for possible roadway improvements that could enhance the safety of the roadway. However, many agencies do not know curve radii or lengths because drawings do not exist and inventories are not available. Horizontal curves have been identified as an element of interest on roadways because of their collision history (Hummer et al., 2010).

The objective of this research is to determine the feasibility of identifying and characterizing numerous horizontal curves along a route utilizing available GIS computing technologies. The functionality that these technologies can add to an agency through increased safety and efficiency can be invaluable by permitting the ability to assess field conditions without actually conducting a field investigation. This ability can assist agencies which do not have a horizontal curve inventory.

This study included two-lane roads and a multi-lane interstate highway. The two-lane roads were NC42 and NC96 which are predominately rural and run through central and eastern North Carolina. The analysis included all the sections of each route except where a higher order route (ie US route) ran concurrently with route. NC42 is 223 miles long with 246 curves and runs East and West through 11 counties; the analysis sections included 168 miles of the route. NC96 is 107 miles long with 174 curves and runs North and South through 5 counties; the analysis sections included 95 miles of the route. The interstate highway used in this study was I40 which is 416 miles long with 379 curves through North Carolina, running from the Tennessee border in the mountains of the western part of the state to the coast in the eastern part of the state.

Two GIS programs, Curve Calculator and Curvature Extension, were utilized that require curves to be identified manually before the program can determine geometric characteristics. Therefore, these two programs are designed to analyze a single curve at a time. Another GIS program we tested, Curve Finder, was able to automatically find curves and conduct geometric characterization, which makes the application more suitable for route or network applications. The selected methods used for these comparisons and evaluations are Curvature Extension (FDOT, 2010), Curve Calculator (ESRI, 2009), and Curve Finder (NHDOT, 2010). Curvature Extension and Curve Calculator are methods for analyzing individual curves, while Curve Finder is a method that can be deployed on a route or network of routes. All three methods include user-defined inputs and limits within their process. Shapefiles obtained from the North Carolina Department of Transportation (NCDOT) were used along with ArcGIS to create routes for the selected corridors of NC42, NC96, and I40. Crash data was obtained from NCDOT for safety analysis of NC42 and NC96, while I40 was examined only for curve characteristics.

8.2 Literature Review

This paper details the application of a set of GIS applications for horizontal curves and quantifies the ability of that application to identify and characterize curves along a route. The literature review involved an online search as well as contacting each state transportation agency to locate any available GIS methods for horizontal curves. Twenty-nine agencies responded to the request, with 6 agencies reporting current use of GIS to identify horizontal curves. Figure 13 shows the states that reported that they utilize GIS for horizontal curve identification. Three states said that they have developed GIS software or algorithms: California, Florida, and New Hampshire. The other three states that use GIS for horizontal curve identification employ the services of private asset inventory companies who utilize GIS for curve location.

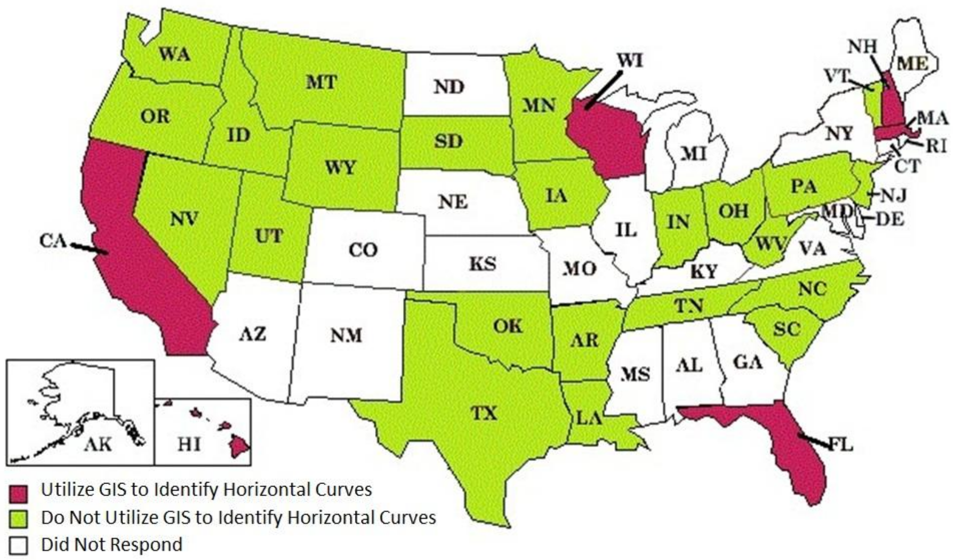


Figure 13. State Transportation Agencies Utilizing GIS to Identify Horizontal Curves

The alignments of the centerline of a road is an essential piece of information for transportation agencies for numerous purposes. A GIS is common platform for viewing and analyzing roadway centerlines. Previous research in GIS for roadway alignments has focused on creating algorithms for route generation (Rasdorf, et al., 2002) and using a GIS for safety assessments (Khattak and Shamayleh, 2005; Castro, et al., 2008). The extraction of horizontal curve data from a GIS includes processes that have examined the use of GPS data (Imran, et al., 2006), utilized automatic (Martinelli, et al., 2009; Harpring, 2010) or manual (ESRI, 2009; FDOT, 2010; Price, 2010) procedures for geometric data, and detected curve segments (Hans et al., 2009).

Prior research has quantifiably compared publicly-available GIS applications for horizontal curves and their ability to identify and characterize curves (Rasdorf, et al., 2010). That study used four methods to determine the curve radius: a field method (Findley and Foyle, 2009) and three geographic information system (GIS) methods: Curve Calculator, Curvature Extension, and Curve Finder. Curve Calculator is a command within the coordinate geometry (COGO) toolbar in ArcGIS software (ESRI, 2009). Curve Calculator requires manual identification of the curve limits and measurement of the chord length and the arc length to determine the radius. Curvature Extension (FDOT, 2010) is a program which can be added as a toolbar in ArcGIS software. Curvature Extension requires the users to manually identify a curve and to specify the limits of each curve which drives the radius and length measurements. Curve Finder (Harpring, 2010) is an automated procedure using geodatabase inputs that can be executed on a network of roadways, not just individual curves. Curve Finder uses GIS polylines to determine curve length and radius through coordinate data. The program identifies curves as it moves through every series of three points to determine where curves are located along the route along with their radii and length.

The study of horizontal curve GIS applications (Rasdorf, et al., 2010) involved two evaluations: a GIS-derived comparison and a field-measured comparison. Figure 14 shows the methodology used to assess the ability of the GIS methods for conducting route analysis and safety analysis. The GIS-derived comparison evaluated the GIS methods to precisely drawn curves in a GIS. The comparison found that all three GIS methods were able report the curve characteristics with little or no error with high-quality GIS line work. A sensitivity analysis of the accuracy of the radius prediction in relation to the number of GIS points showed that Curve Calculator’s accuracy increased as the number of GIS points increased, while Curve Finder and Curvature Extension were not impacted by the number of GIS points with precisely drawn curves. The field measured comparison examined each of the three GIS methods in relation to 51 field measured curves in North Carolina. As a measure of the accuracy provided by the methods, the percentage of curves within 50% of the field measured radius for Curve Calculator, Curvature Extension, and Curve Finder was 78%, 80%, and 69%, respectively.

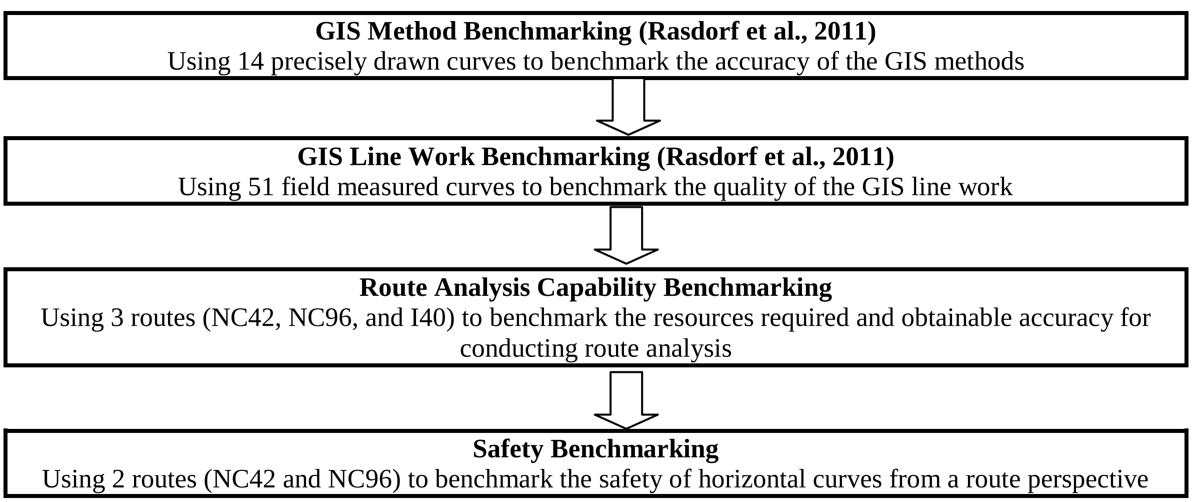


Figure 14. Horizontal Curve Study Methodology

However, to this point, no study has characterized the ability and resources required to conduct evaluation of entire routes using the available programs. These previous efforts developed programs or methods specifically for the intended purpose or only with individual curves. The focus of this research is to compare the publicly available GIS methods for horizontal curve data collection on a route or network basis.

8.3 Methodology

The scope of this work includes two steps agencies need to perform in safety and other analyses: curve identification and geometric characterization. The first step, curve identification, is to classify each road segment as either a curve or non-curve segment, which is a binary analysis. The second step, geometric characterization, is to describe each curve by its radius and arc length. Curve Calculator and Curvature Extension require the user to conduct the curve identification visually and then define the beginning and ending of the curve to execute the geometric characterization process. Each process is automated in Curve Finder which executes the identification and characterization processes on a route or network as specified by the user. The GIS data utilized for this project were Road Characteristics Arcs (NCDOT 2009a) acquired from the North Carolina Department of Transportation.

8.3.1 Curve Identification

To ensure that curve identification is consistently applied to Curve Calculator and Curvature Extension, the team manually labeled the PC (point of curvature, where the roadway begins to curve) and PT (point of tangency, where the curve ends). The PC and PT are important points as they provide the bounds of the curve for the limits of the arc and chord. Locating the PC and PT provides the ability to calculate the distance between each curve. Figure 15 shows an example of the curve labeling as part of the manual curve identification process. Outside of this research approach, the need to label each curve and its limits would be infrequent in typical applications. The manual curve identification process took approximately 30 seconds per curve. Curve Finder conducts the curve identification process automatically and simultaneously with the geometric characterization process. The visual curve identification relied on the recognition of tangents and curves; a curve was classified where two tangents with discernable differences in bearings meet (and transition to each other through a horizontal curve). This process of curve identification is more likely to lead to a Type I error (where the roadway segment is called a curve although it is not actually a curve) than a Type II error (where a roadway segment is called straight although it is actually a curve). The bias towards a Type I error is desirable because it is easier to disallow a curve classification through secondary measures (such as radius or length), than to locate curves that were inappropriately labeled as straight segments.

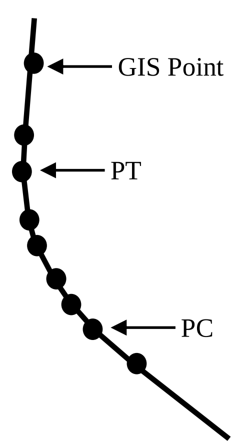


Figure 15. Example of Manual Horizontal Curve Identification

8.3.2 Geometric Characterization

After the curves are identified, each program can be executed to obtain geometric data. The geometric characterization process took approximately 25 seconds per curve with Curvature Extension and 30 seconds per curve with Curve Calculator. The majority of the time was derived from user selections, while the computer processing time was almost instantaneous (on computer with a Pentium IV 3.2 Ghz processor with 1 GB RAM). In Curve Finder, routes must have continuous and increasing mileposting along each route. The mileposting system implemented by NCDOT restarts at each county boundary, so an individual route through multiple counties must be merged to create one route or each county must be analyzed separately from other counties in Curve Finder. Curve Finder took approximately 30 seconds to execute for each of the route through all the counties included on the route.

8.3.3 Collision Data

Horizontal curve information can be obtained and utilized for various purposes, with curve safety investigations being one of the more significant applications. The crash data we analyzed consisted of detailed information including the milepost location of the crash, severity, and county along NC42 and NC96. The dataset included five years of collision data (January 1, 2005 to December 31, 2009) with 553 collisions listed (on the police collision report) as occurring on curves and 3,952 collisions occurring on straight segments. The classification was based on the roadway character type which designated which type of roadway alignment was present at the collision scene as reported by the responding police officer (NCDMV 2009). The essential effort related to the crash data was appropriately matching the reported crashes at their associated milepost location with the mileposting for the curves. This mileposting effort was necessary for this effort because sections of the route were omitted from the analysis when a higher order route ran concurrently with the route of interest to the team.

Curve-related collisions can be identified either through police officer coding on the collision report or through mileposting in relation to curves identified with a GIS. Some inaccuracies exist with the mileposting of collisions due to infrequent field markings of mileposts or post-processing errors. Collisions reported by the police as curve-related were examined to determine their relative location to the curves and collisions not explicitly labeled as curve-related were also examined for their relative location to the curves.

8.4 Analysis

Transportation agencies have to be able to find and measure their horizontal curves to manage their assets efficiently, distribute improvement funding appropriately, and examine roadways for potential safety issues. To properly assess the ability of Curve Finder to conduct the curve analysis, an appropriate tolerance value must be selected for the program. Consequently a sensitivity analysis was conducted to determine the optimal tolerance value. The following includes an analysis to benchmark the capability and resources required to find and measure curves on a route using three GIS methods. Subsequent to the route analysis, a safety analysis was conducted for horizontal curves based on collision data. The safety analysis considers different options to define horizontal curves and demonstrates the potential identification of horizontal curves with various collision data.

8.4.1 Curve Finder Tolerance Sensitivity Analysis

A key parameter setting for Curve Finder is the tolerance which effects whether or not a series of GIS points will be identified as a curve. Any three consecutive points in a GIS form a circle with a known centroid, unless the points are perfectly aligned which would create a straight line (or circle with an infinite radius). The distance between successive centroids (defined by two sets of three consecutive points: the first, second, and third points and the second, third, and fourth points) are compared to the tolerance value to determine if a curve is present on the road. A distance between centroids that is less than the tolerance value indicates that a curve is present on the road; otherwise, the program does not denote the presence of a curve. A perfect circle, with a constant radius, will have successive centroids in the same location with a distance between centroids of zero. The default tolerance is 1,000 feet, but can be modified by the user. The tolerance should be selected to carefully to avoid splitting a single curve into multiple smaller curves (with a small tolerance) and/or combining separate curves into a single curve (with a high tolerance).

The authors conducted a sensitivity analysis was used to determine the effect of Curve Finder tolerance values, ranging from 100 to 5,000 feet, on the percentages of curves matched and reported, as a percentage of the total number of curves on each route as found manually (Figure 16 and Figure 17). Larger tolerance settings resulted in a larger percentage of reported and matched curves, which increase rapidly until a tolerance of approximately 3,000 feet. However, the smaller tolerance settings exhibited a higher accuracy in matched curves, as displayed by the smaller gap between the reported and matched curves lines. A tolerance of 2,700 feet captures most of the increase in the percentage of reported and matched curves without the further decline in curves matched.

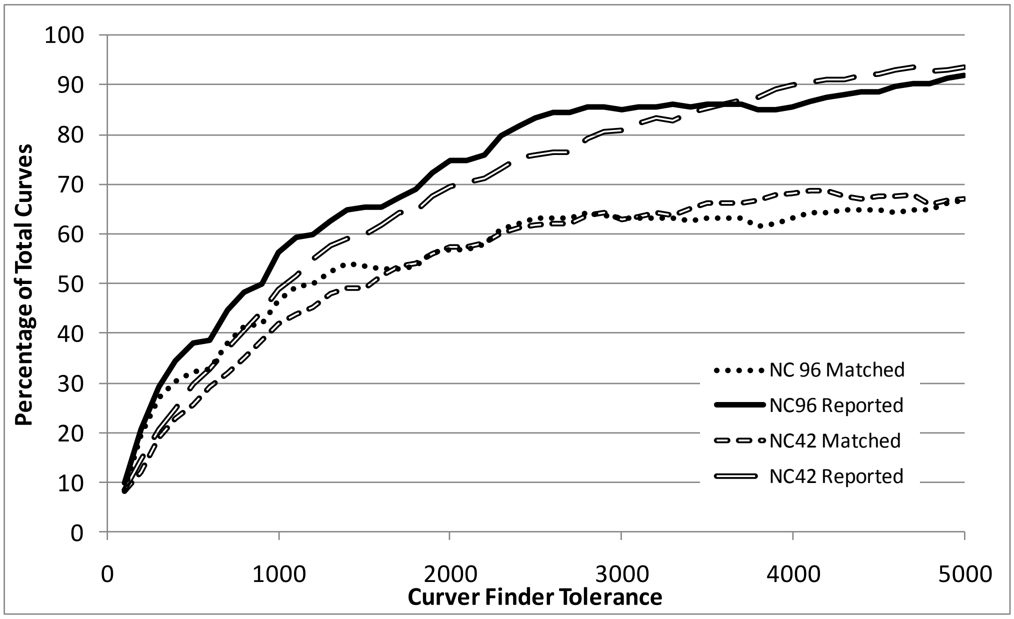


Figure 16. Percentage of Curves Reported and Matched by Curve Finder Tolerance – NC96 & NC42

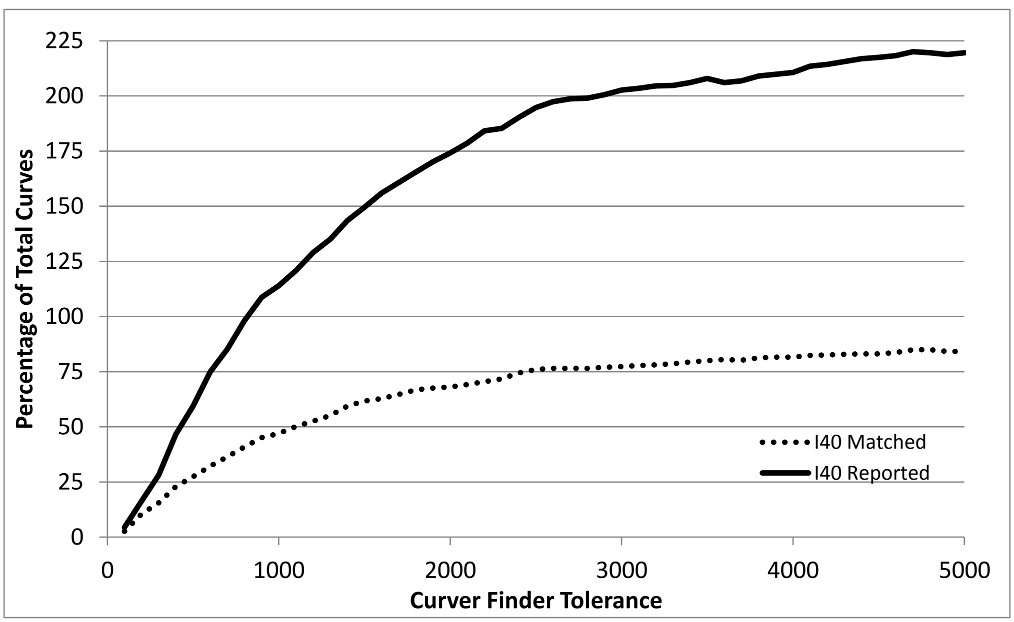


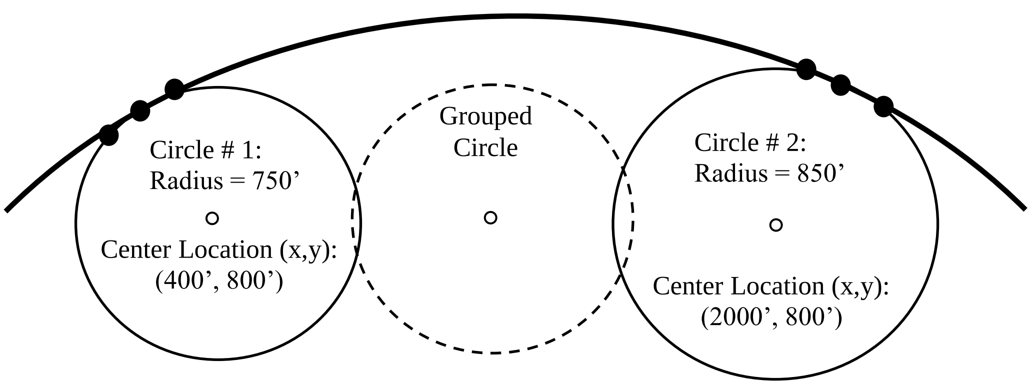
Figure 17. Percentage of Curves Reported and Matched by Curve Finder Tolerance – I40

8.4.2 Route Analysis

Only one program, Curve Finder, was able to automatically locate and characterize horizontal curves along a route. Therefore, a comparison was made between the results of Curve Finder and Curvature Extension. Curve Calculator was also executed on the routes, but Curvature Extension provides a slightly more accurate representation of field conditions, based on previous research by Rasdorf et al (2010). Although Curvature Extension was found to be more accurate, the average difference between Curve Calculator and Curvature Extension values for radius and length were approximately 0.5%.

Radius Analysis

The error quotient is a value calculated in Curve Finder that expresses how well a curve is defined. The quotient was designed to ensure that a particular curve was not combined with either of its neighboring curves. Every three GIS points have the potential to form a circle depending on the user's input for tolerance. A series of individual circles can be combined to form a larger system of circles which defines the curve. The parameters of the system of circles, the curve, are determined by averaging the parameters of the individual circles. The error quotient is calculated by determining the average of the distance from the center of each circle to the center of the overall grouped circle and dividing by the overall radius. Therefore, an ideal error quotient is zero, which implies an exact fit of individual and grouped circles. Equations shown with Figure 18 provide the basis for the error quotient calculations. Figure 18 provides an example diagram expressing the error quotient parameters. From this example, the grouped circle radius can be calculated by averaging the two radii from the individual circles for a radius of 800 feet. The location of the center of the grouped circle is determined by the average x and average y location for the individual circles. In this example, the grouped circle will have a location in the x-direction of 1200' and in the y-direction of 800'. The average distance from the center of each circle to the center of the grouped circle is 800 feet, so the corresponding error quotient for this example is 1 (800 feet divided by 800 feet).



So the Error Quotient =
Grouped Circle x-coordinate = $G_x = (\sum C_x)$ / Number of circles (Equation 4)
Grouped Circle y-coordinate = $G_y = (\sum C_y)$ / Number of circles (Equation 5)
Grouped Circle radius = $G_R = (\sum$ Individual Circle radii) / Number of circles (Equation 6)
Average x-coordinate error = $\text{Error}_x = (\sum | G_x - C_x |)$ / Number of circles (Equation 7)
Average y-coordinate error = $\text{Error}_y = (\sum | G_y - C_y |)$ / Number of circles (Equation 8)
Error Quotient = $(\text{Error}_{x} + \text{Error}_y) / G_R$ (Equation 9)

Where,
C_x = x-coordinate for each individual curve
C_y = y-coordinate for each individual curve

Figure 18. Curve Finder Error Quotient Diagram

The accuracy of the radius estimate for a horizontal curve is a critical component of a GIS tool. Table 24 shows useful descriptive parameters comparing radius values found with Curve Finder and Curvature Extension. The radii estimated by Curve Finder were compared to the estimate from Curvature Extension for each route. The number of curves matched, the percentage of curves matched in each range, the average error quotient, and average distance between GIS points are presented in the table. For instance, 63 curves (22% of the total curves matched) on I40 were matched with Curve Finder output between 0% and 5% of Curvature Extension with an average error quotient of 0.32 and an average distance between GIS points of 365 feet. A correlation and regression analysis was executed on the individual curve data for each route using SAS (2010) software which was inclusive and led to the categorization of data into increments of 5% with a minimum of 5 matched curves in each group. Figure 19 shows how the distance between GIS points relates to the difference between Curve Finder and Curvature Extension results, as well as how the error quotient relates to the difference between Curve Finder and Curvature Extension results.

Table 24. Radius Differences with Descriptive Parameters

I40 Curve Finder Curves				
Radii Difference Between Curve Finder and Curvature Extension	**# Matched**	**% of Matched**	**Average Error Quotient**	**Average Distance Between GIS Points (feet)**
0% to <5%	63	22	0.32	365
5% to <10%	48	17	0.43	398
10% to <15%	32	11	0.37	527
15% to <20%	23	8	0.48	368
20% to <30%	41	14	0.43	426
30% to <45%	22	8	0.31	383
45% to <60%	16	6	0.75	289
60% to <115%	25	9	0.78	356
≥115%	14	5	0.29	446
Total	284	100		

NC42 Curve Finder Curves				
Radii Difference Between Curve Finder and Curvature Extension	**# Matched**	**% of Matched**	**Average Error Quotient**	**Average Distance Between GIS Points (feet)**
0% to <5%	38	27	0.66	163
5% to <10%	27	19	0.57	202
10% to <15%	19	13	0.77	177
15% to <20%	7	5	0.51	152
20% to <30%	10	7	0.87	224
30% to <45%	21	15	0.83	159
45% to <60%	10	7	0.66	266
60% to <115%	5	3	0.57	193
≥115%	6	4	1.09	169
Total	143	100		

NC96 Curve Finder Curves				
Radii Difference Between Curve Finder and Curvature Extension	**# Matched**	**% of Matched**	**Average Error Quotient**	**Average Distance Between GIS Points (feet)**
0% to <5%	47	45	0.36	118
5% to <10%	14	13	0.60	176
10% to <15%	5	5	0.46	198
15% to <20%	12	11	0.70	172
20% to <30%	12	11	0.64	266
30% to <45%	5	5	0.72	172
45% to <60%	5	5	0.82	98
60% to <115%	5	5	0.78	101
≥115%	0	0	N/A	N/A
Total	105	100		

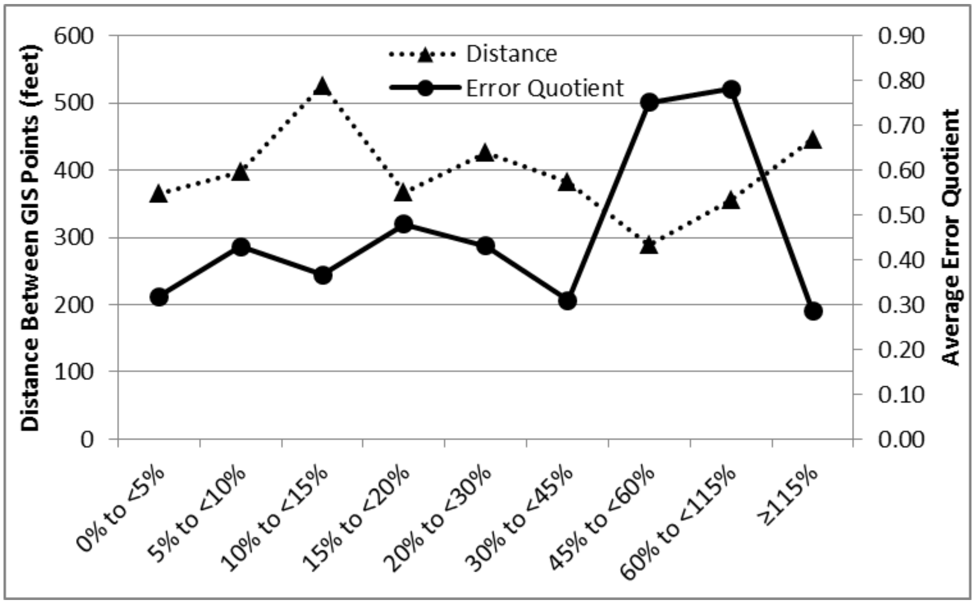


Figure 19. Radii Differences Between Curve Finder and Curvature Extension

Length Analysis

Along with radius information, the length of a horizontal curve is another important value to describe and examine curves. Table 25 shows useful descriptive parameters comparing lengths found with Curve Finder and Curvature Extension. The resulting lengths from Curve Finder were grouped in ranges of their difference from Curvature Extension for each route. The number of curves matched, the percentage of curves matched in each range, the average error quotient, and average distance between GIS points are presented in the table. For instance, 27 curves (10% of the total curves matched) on I40 were matched with Curve Finder output within 5% of their length as estimated by Curvature Extension with an average error quotient of 0.51 and an average distance between GIS points of 162 feet. A correlation and regression analysis was executed on the individual curve data for each route using SAS (2010) software which was inclusive and led to the data categorization. Figure 20 shows how the distance between GIS points relates to the difference between Curve Finder and Curvature Extension results and it also shows how the error quotient relates to the difference between Curve Finder and Curvature Extension results.

Table 25. Length Differences with Descriptive Parameters

I40 Curve Finder Curves				
Length Difference Between Curve Finder and Curvature Extension	**# Matched**	**% of Matched**	**Average Error Quotient**	**Average Distance Between GIS Points (feet)**
0% to <5%	27	10	0.51	162
5% to <15%	20	7	0.51	163
15% to <20%	9	3	0.44	162
20% to <25%	21	7	0.42	218
25% to <30%	16	6	0.49	214
30% to <35%	20	7	0.59	208
35% to <45%	26	9	0.36	319
45% to <60%	43	15	0.42	339
60% to <70%	43	15	0.34	507
70% to <85%	47	17	0.31	875
≥85%	12	4	0.84	500
Total	284	100		

NC42 Curve Finder Curves				
Length Difference Between Curve Finder and Curvature Extension	**# Matched**	**% of Matched**	**Average Error Quotient**	**Average Distance Between GIS Points (feet)**
0% to <5%	28	20	0.67	109
5% to <15%	13	9	0.61	127
15% to <20%	10	7	0.90	141
20% to <25%	16	11	0.52	161
25% to <30%	13	9	0.94	125
30% to <35%	9	6	0.45	184
35% to <45%	13	9	0.75	151
45% to <60%	19	13	0.56	277
60% to <70%	7	5	0.68	282
70% to <85%	8	6	0.59	407
≥85%	7	5	1.55	260
Total	143	100		

NC96 Curve Finder Curves				
Length Difference Between Curve Finder and Curvature Extension	**# Matched**	**% of Matched**	**Average Error Quotient**	**Average Distance Between GIS Points (feet)**
0% to <5%	23	22	0.39	102
5% to <15%	10	10	0.49	127
15% to <20%	7	7	0.38	137
20% to <25%	10	10	0.66	125
25% to <30%	7	7	0.69	125
30% to <35%	7	7	0.66	114
35% to <45%	15	14	0.71	144
45% to <60%	8	8	0.31	247
60% to <70%	8	8	0.49	281
70% to <85%	5	5	0.47	164
≥85%	5	5	0.69	279
Total	105	100		

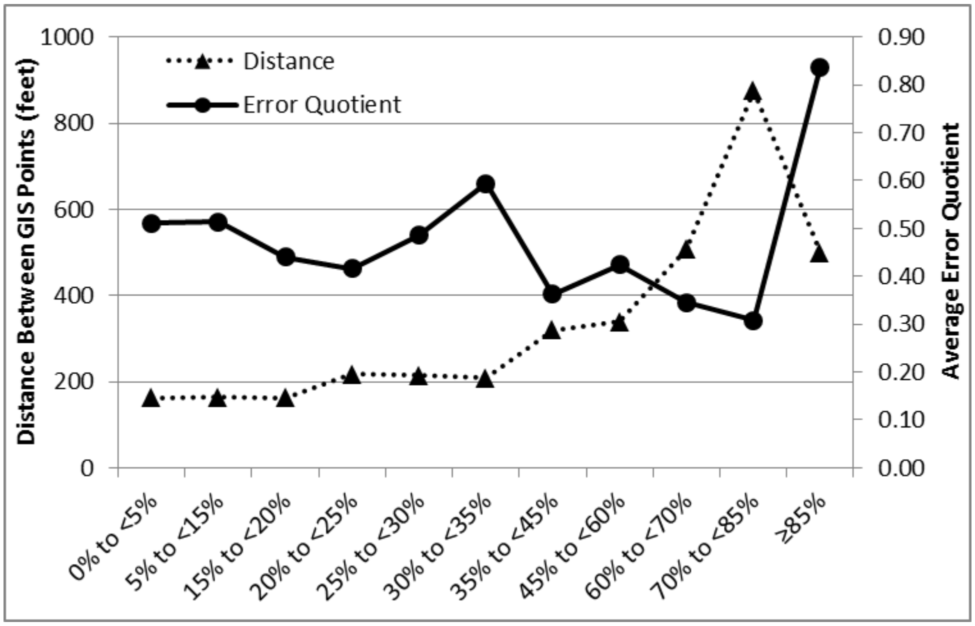


Figure 20. Length Differences Between Curve Finder and Curvature Extension

8.4.3 Hazardous Curve Analysis

In addition to analysis involving all curves, an analysis was conducted on the most hazardous curves to examine Curve Finder's performance with the most critical curves. Previous research by Zegeer et al (1991) studied the relationship between curvature and safety. The research found that there is a significant increase in collision rates for curves with a degree of curvature greater than four (which corresponds to a radius of 1,432 feet and less). Based on the results from Curvature Extension, I40 has 54 curves with a radius of less than or equal to 1,432 feet while NC42 has 91 curves and NC96 has 53 curves in the same category. Table 26 shows that Curve Finder identified 141 of the 198 curves on the three routes that met that criterion, with 88 of the located curves having a difference of less than 20% from the radius estimated by Curvature Extension. Table 27 shows that Curve Finder located 82 curves with a difference of less than 30% of the length estimated by Curvature Extension.

Table 26. Radius Differences with Descriptive Parameters

Range of Radius Differences Between Curve Finder and Curvature Extension	# Matched	% of Matched	Average Error Quotient	Average Distance Between GIS Points (feet)
0% to <10%	58	41	0.75	114
10% to <20%	30	21	0.76	141
20% to <30%	16	11	0.95	116
30% to <80%	23	16	1.50	119
≥80%	14	10	0.38	185
Total	141	100		

Table 27. Length Differences with Descriptive Parameters

Range of Length Differences Between Curve Finder and Curvature Extension	# Matched	% of Matched	Average Error Quotient	Average Distance Between GIS Points (feet)
0% to <15%	44	31	0.76	108
15% to <30%	38	27	0.75	168
30% to <45%	31	22	1.03	115
45% to <80%	18	13	0.92	169
≥80%	10	7	0.82	72
Total	141	100		

8.4.4 Safety Analysis

The safety analysis focused on two types of collisions: those that were identified as curve-related collisions by the collision report and those that were identified as being located on a curve from the GIS route analysis. A collision could be curve-related without actually occurring within the bounds of the curves, but should be within a reasonable distance of the curve.

Each collision is assigned a milepost along the route by the police, which was converted to a relative distance from the nearest curve by the study team. Collision report mileposting is reported in NC to the nearest 0.1-mile increment; therefore, tolerances for these data were crashes within 0.1, 0.2, and 0.5 miles of GIS located curves. Table 5 shows that NC42 had 318 reported collisions listed as occurring on a curve and 3,416 total reported collisions over the five-year period 2005 through 2009. NC96 experienced 258 reported curve collisions and 1,251 total reported collisions during the time period. Table 5 also shows the difficulties that can arise from defining curves based on collision history. Along NC42, of the reported collisions that occurred on the curves identified through the GIS procedures, 120 collisions were labeled as curve-related by the police and 513 (633 minus 120) collisions were on straight sections according to the police report. Similarly, along N96, of the reported collisions that occurred on the curves identified through the GIS procedures, 87 collisions were labeled as curve-related and 159 (246 minus 87) collisions were on straight sections.

Table 28 demonstrates the complexity with defining how collisions relate to curvature. By considering the curve influence area as an area more expansive (in this analysis, by 0.1, 0.2, and 0.5 miles as shown in Figure 21) than the limits of the curve itself, there is an increase in the number of curve collisions and curves with a collision. Curves comprise 15% and 23% of the roadway length on NC42 and NC96, respectively. The collisions reported by the police as curve-related are 9% and 21% of total collisions on NC42 and NC96, respectively, based on curves identified through a GIS by the study team. However, based on collision mileposting of all collisions by the study team, 19% and 20% of total collisions (regardless of roadway character) occurred on the curves on NC42 and NC96, respectively.

Table 28: Collision Data (5 years – 2005 to 2009): Curve Related and All Crashes on NC42 and NC96

Type of Collision Data	Distance to Nearest GIS Located Curve	NC42				NC96			
		Curve Collisions		Curve Length		Curve Collisions		Curve Length	
		Reported Collisions	Percentage of Total Reported Collisions	Length of Curves with at least one reported Collision[1] (miles)	% of Total Route	Reported Collisions	Percentage of Total Reported Collisions	Length of Curves with at least one reported Collision[1] (miles)	% of Total Route
Curve Related As Reported by Police	On Curve	120	4	14.91	9	87	7	6.18	7
	Within 0.1 miles	222	6	18.87	12	178	14	8.88	10
	Within 0.2 miles	248	7	20.02	12	201	16	9.95	11
	Within 0.5 miles	274	8	21.11	13	231	18	10.98	12
	Entire Route	318	9	24.04	15	258	21	20.89	23
All Reported Collisions	On Curve	633	19	27.53	17	246	20	12.62	14
	Within 0.1 miles	1,218	36	33.08	20	603	48	16.34	18
	Within 0.2 miles	1,610	47	35.20	22	785	63	17.00	19
	Within 0.5 miles	2,450	72	35.34	22	999	80	17.00	19
	Entire Route	3,416	100	24.04	15	1,251	100	20.89	23

[1] Lengths for "Entire Route" include total length of curves regardless of collision history

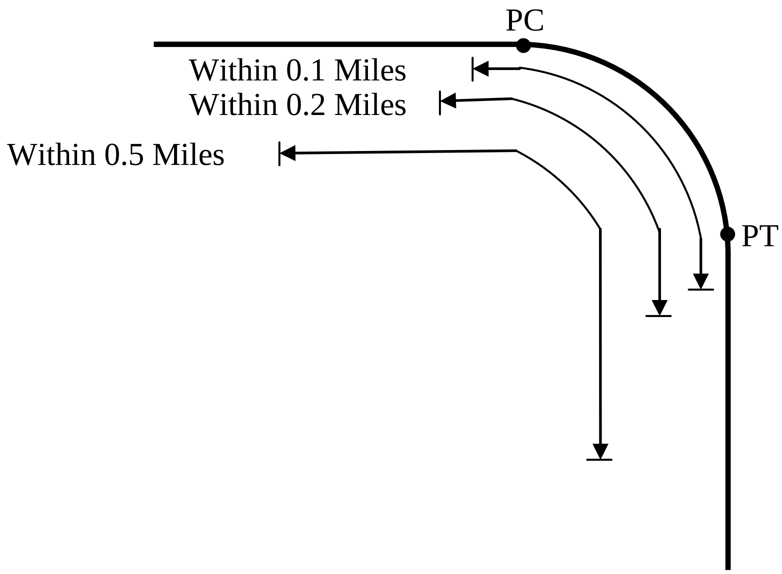


Figure 21. Curve Influence Area (0.1, 0.2, and 0.5 miles)

8.5 RESULTS

Curve Finder is an exciting new tool to automatically locate and characterize horizontal curves within a small or large network. The study team conducted three tests to determine whether Curve Finder could accurately locate and characterize a set of curves. These tests were to select an appropriate tolerance value in Curve Finder, compare Curve Finder results with Curvature Extension, and examine the safety of horizontal curves with regards to curve identification.

The user-defined tolerance is an essential setting in Curve Finder. A sensitivity analysis was implemented to determine an optimal tolerance value. Based on the examination of three routes, two mostly rural two-lane roads and one multi-lane interstate, a tolerance of 2,700 feet was most appropriate to balance the competing factors of total curves reported and total matched curves. Given the tolerance of 2,700 feet, Curve Finder found 532 of the 799 curves along the three routes that the study team identified manually. Among the 532 curves, Curve Finder estimated the radius within 20% of the Curvature Extension value for 65% of the curves and estimated the length within 20% of the Curvature Extension value for 31% of the curves. However, many of the 799 curves have large radii that do not pose as large of a safety risk to motorists as smaller radii curves.

Many users could require detailed and accurate data for all curves. However, some users, particularly those focused on safety, are most interested in hazardous locations. Smaller radius curves tend to have more collisions, and therefore, are of primary importance for safety investigation. In this analysis, curves with a radius less than or equal to 1,432 feet (4 degrees) were considered more hazardous. Curve Finder found 71% of the curves with a radius that met the criteria, which was a higher percentage than the complete set of curves.

Collision data were acquired for the two rural, two-lane routes, NC42 and NC96, from 2005 to 2009. A total of 3,416 collisions were reported on NC42 during the time period with 318 collisions listed by the police as occurring on a curve. A total of 1,291 reported collisions occurred on NC96 with 258 police-reported curve collisions. The analysis showed that majority of the collisions that occurred within the limits of the curve (as identified by the GIS methods) were not identified as curve-related collisions. On NC42, curves contribute 15% of the total length of the road while 9% of total collisions were identified as curve-related and 19% of total collisions were contained within the curves. On NC96, curves make up 23% of the total length of the road while 21% of total collisions were identified by the police as curve-related and 20% of total collisions were contained within the curves.

8.6 Conclusions

Some transportation agencies maintain detailed inventories on many roadway elements, including horizontal curves. For agencies without horizontal curve inventories, this research found that two programs, Curvature Extension and Curve Calculator, could be applied to each curve with a manual effort of about 60 seconds. Another program, Curve Finder, could be applied automatically to a road network in approximately 30 seconds total. These times only include the time execute each program, not the effort required to obtain the data and do any formatting that might be required. NCDOT maintains the second largest system of roadways in the United States, with 14,886 miles of primary highways and a total system of 79,439 miles (NCDOT 2009b). Assuming the average of approximately 0.9 curves per mile on I40 applies to other primary highways and that the approximately 1.6 curves per mile on NC42 and NC96 applies to other non-primary highways, time requirement estimates can be generated for the creation of curve inventories. Both of the manual programs could be executed statewide by one person in less than a year, or about 26 to 28 days for the primary highways and 200 days for the non-primary highways. Curve Finder, by contrast, could be applied to the statewide system in less than an hour.

Highway agencies must find and treat their hazardous horizontal curves. The safety analysis showed that the contribution of curvature to total collisions is influenced by the analysis or influence area surrounding the curve; if a curve-related collision can only occur within the bounds of a curve, the collisions attributable to a curve will be lower than if the influence area extends beyond the curve. For the routes studied in this research, the collisions identified as curve-related from the collision report show that curve collisions are underrepresented as a proportion of total roadway length. However, when considering all reported collisions that occur on the GIS identified curves, horizontal curves appear to be more dangerous than their proportion of length. Overall, this analysis demonstrates the importance of a multi-faceted approach to identify hazardous curves. Examining collision data can be helpful for agencies to identify current or previous hazardous locations, although the inherently random nature of collisions can create spikes in some locations one year and other locations another year. Therefore, an understanding of the underlying geometric roadway features can assist an agency in identifying truly hazardous locations and not just the locations that with high collisions due to random chance, high traffic volumes, unusual weather patterns, or other conditions.

The analysis showed a relationship between the results of Curve Finder and Curvature Extension with regards to the average distance between GIS points and the error quotient reported by Curve Finder. When Curve Finder made a large error in estimating the radius, it was most closely related to the error quotient, meaning that Curve Finder's output provides the user with information about how well the curve's radius was estimated. The differences of the length results were most closely related to the distance between GIS points, meaning that higher quality GIS line work with less distance between successive points provides better results.

This paper demonstrated the ability and resources required to quickly find and measure a large set of horizontal curves. This type of effort is important for agencies because many countermeasures can be applied to roads which contain numerous horizontal curves instead of just individual curves. The system based approach can provide an agency with the ability to make critical funding decisions for potential countermeasures.

8.7 Recommendations

The research team recommends the use of a GIS to find and measure curves on a large set of roadways of interest. Depending on the desired accuracy and the scope of the effort, one of the methods presented in this paper should provide an agency with the necessary information for numerous topics. Curve Finder provides an advantage over other comparable GIS tools in that it combines curve identification and geometric characterization. This combination of functions can significantly reduce the amount of time required to analyze the routes. Other methods studied required each curve to be visually identified manually.

The implementation of Curve Finder requires a tolerance value which commands how curves are found and reported. This research found that the optimal tolerance value was 2,700 feet for the GIS data used in the study. However, the optimal tolerance value could change among jurisdictions or roadway types, so the tolerance value should be studied to find an appropriate value for a particular agency. This paper can provide the framework for finding tolerance values in Curve Finder.

The automated processes in Curve Finder provide better results when the average distance between GIS points is 200 feet or less and the Curve Finder error quotient is less than 0.5. Therefore, a potential user can examine their existing line work to determine if the distance between GIS points is approximately 200 feet or less and Curve Finder output for the error quotient less than 0.5 to determine if the available data will provide the accuracy desired.

9.0 CONCLUSIONS

The organization of this report leads the reader through a literature review of traffic control devices, study methods, and crash modifications in Chapter 2. Next, a summary of current NCDOT practices for horizontal curve investigations in described in Chapter 3. Curve crash characteristics which could influence the procedure of safety investigations are presented in Chapter 4. The manual field investigation procedure which was developed for the collection of related data and for other uses within this report are described in Chapter 5. The Highway Safety Manual analysis with two-lane road calibration factors is presented in Chapter 6. Chapters 7 and 8 present potential GIS methods that can be utilized for horizontal curve data collection on an individual curve and network of curves basis. These chapters build upon themselves and relate to each other in a way that the reader can gain valuable insight from each analysis.

The following conclusions are compiled from the primary analysis chapters.

9.1 Curve Crash Characteristics

The purpose of this analysis was to conduct a detailed multi-year analysis of numerous horizontal curve collisions on a statewide basis to identifying common characteristics and key contributing factors associated with curve collisions. The results were used to match major collision characteristics and causes to potential countermeasures. The primary factors found to be associated with curve collisions on rural, two-lane roads include fixed objects (particularly trees and poles), overturn and ditch related factors, alcohol related, adverse light conditions (i.e., nighttime), adverse roadway surface conditions, curve and grade geometric issues, and time related factors (weekends), among others. However, two-lane curve collisions most often involve only a collision with roadway or roadside features, which means countermeasures can have a disproportionately positive impact on collisions.

In all of NC over a three-year period, only 4 segments out of almost 310,000 statewide (one tenth of a mile in length) experienced 10 or more curve collisions. Thus, the frequency of curve collisions per site are low compared to intersections, which could lead transportation agencies to overlook curves during hazard site identification processes. The selection of roadway segment length for identifying hazardous curve locations is critical. Length of segment as well as the acceptable collision threshold to use in the analysis should depend on the available budget for further inspection and investigation of the curves.

9.2 Highway Safety Manual Analysis

The publication of the Highway Safety Manual (HSM) offers agencies an analytical tool to evaluate the safety of a horizontal curve or set of curves for safety purposes with fewer field visits from personnel. The HSM provides a crash prediction model for horizontal curves that can be applied to curves within any jurisdiction to identify the highest priority locations for safety treatments as well as common and effective countermeasures.

This paper evaluated horizontal two-lane rural roads in North Carolina to test the calibration of the HSM predictive method to local conditions. Based on the analysis it found that a large number of sites (approximately 300) are required to meet HSM recommendations for collisions. The large number of sites is partly due to the finding that the selection of random segments provided a more accurate outcome (in terms of matching the HSM prediction model) than the crash results from the high crash locations subset.

The challenge with requiring a large number of sites to develop an accurate model based on local conditions is the data collection aspect. For each of these sites, field investigations took approximately 30 minutes to complete (not including driving time to the site) for the collection of necessary elements for HSM analysis. However, most of these elements do not change much or at all over time, so intensive data collection for HSM inputs can be used for many years. To further lessen the data collection burden, an analysis of difference in results in the predicted collisions based on field data collection and using average or default values was performed. It was found that for AADT, curve radius, and curve length of the segment individualized data is necessary for model accuracy.

9.3 Individual Curve Analysis GIS Process

The need for horizontal curve information extends to numerous transportation purposes which range from individual curve safety investigations to long-range network planning and beyond to applications in other domains. This analysis found that each of the three GIS programs studied is well suited for specific applications, as discussed below, depending on the user's needs and the quality of the GIS line work. The level of accuracy that each of these programs can provide is high enough for most typical safety and planning applications. Many transportation agencies maintain GIS programs and roadway alignments; given these existing resources, the cost of running the three GIS programs is minimal. Each of the programs is available publicly for no additional cost above the expense of ArcGIS, but will require staff time to execute on the roadways of interest to the agency. The accuracy of the programs appears to be within the practical level of precision that can be achieved through the construction of the roadway and pavement paint stripping of the lanes. Design and engineering applications require a higher level of accuracy, but could employ one of these methods for initial planning or cost estimation to avoid field data collection or the cost of contracting of a mobile data collection vehicle.

Curve Calculator (by ESRI) performs well at characterizing curves when the GIS line work has a high concentration of points along the path of the curve, while low numbers of GIS points might still provide a radius of sufficient accuracy for other uses of the data. Since Curve Calculator is a built-in command in ArcMap, the user can quickly open the command and utilize the measurement tool to find the length and determine the radius of a given curve. While Curve Calculator computes a solution based on user defined lengths, it can only be used on one curve at a time.

Curvature Extension (by FDOT) produced the most accurate results in the GIS-derived analysis and in the field measured curve analysis. The circular approximation of the curve provides a more accurate representation of the curve than the straight-line approximation used by Curve Calculator. Still, Curvature Extension also operates on only a single curve.

Curve Finder (by NHDOT) produced accurate results in the GIS-derived analysis, but was less accurate than the other methods in the field measured curve analysis. However, the advantage of Curve Finder program is the ability to analyze entire roadways or networks of roadways in a single analysis. This ability provides the user with the opportunity to quickly acquire data on a large-scale in the same amount of time as a single curve. The results show that this automation can provide feasible results. However, Curve Finder was unable to locate 6 of the 51 curves of interest. The six curves that Curve Finder missed each had only four GIS points.

This paper demonstrated that there are GIS-based programs in existence that are capable of horizontal curve data collection and also provides a validation of their performance. The GIS programs demonstrated the ability to produce highly accurate results during a precise geometric GIS-derived analysis. However, the field measured analysis was much less accurate. The difference between the true highway geometry measured in the field and the GIS representation of that geometry is the cause of the differences between the two analyses. If the GIS road model (the line work) is not accurate, discrepancies will clearly arise from this difference.

The safety ranking of each method provides information about the accuracy of the GIS methods based on decision support for safety improvement funding. Although the differences from the output of the GIS methods produced slightly different values for the number of predicted curve collisions (Table 3), the correlation coefficients between the Field Measured rankings and the GIS methods' rankings showed high, positive correlation (Table 4). The correlation coefficients demonstrate that although some decisions could be altered (depending on which method is utilized) the overall rankings are similar to the Field Measured rankings which leads to consistent decision making.

The significant, positive correlation coefficients between many of the GIS program pairings indicate that the GIS line work results, while not as accurate, were comparable. For radius values, all of the methods were correlated to a significant level ($p \leq 0.005$) with a range of factors from 0.41 (Curve Finder and Field Measured) to 0.94 (Curvature Extension and Curve Calculator). For length values, Curve Calculator and Curvature Extension were highly correlated (coefficient of 0.99) with a p-value of less than 0.0001. The correlated results show a consensus of values among the GIS methods which are likely portraying an accurate representation of the GIS characteristics of the roadway. The GIS method benchmarking showed that each of the three methods perform well against precise measurements. On the other hand, the GIS line work benchmarking showed that the line work was unable to provide reliable spatial positioning to enable the methods to conduct calculations to produce highly accurate curve characteristics that match field measurements.

9.4 Network Curve Analysis GIS Process

Some transportation agencies maintain detailed inventories on many roadway elements, including horizontal curves. For agencies without horizontal curve inventories, this research found that two programs, Curvature Extension and Curve Calculator, could be applied to each curve with a manual effort of about 60 seconds. Another program, Curve Finder, could be applied automatically to a road network in approximately 30 seconds total. These times only include the time execute each program, not the effort required to obtain the data and do any formatting that might be required. NCDOT maintains the second largest system of roadways in the United States, with 14,886 miles of primary highways and a total system of 79,439 miles (NCDOT 2009b). Assuming the average of approximately 0.9 curves per mile on I40 applies to other primary highways and that the approximately 1.6 curves per mile on NC42 and NC96 applies to other non-primary highways, time requirement estimates can be generated for the creation of curve inventories. Both of the manual programs could be executed statewide by one person in less than a year, or about 26 to 28 days for the primary highways and 200 days for the non-primary highways. Curve Finder, by contrast, could be applied to the statewide system in less than an hour.

Highway agencies must find and treat their hazardous horizontal curves. The safety analysis showed that the contribution of curvature to total collisions is influenced by the analysis or influence area surrounding the curve; if a curve-related collision can only occur within the bounds of a curve, the collisions attributable to a curve will be lower than if the influence area extends beyond the curve. For the routes studied in this research, the collisions identified as curve-related from the collision report show that curve collisions are underrepresented as a proportion of total roadway length. However, when considering all reported collisions that occur on the GIS identified curves, horizontal curves appear to be more dangerous than their proportion of length. Overall, this analysis demonstrates the importance of a multi-faceted approach to identify hazardous curves. Examining collision data can be helpful for agencies to identify current or previous hazardous locations, although the inherently random nature of collisions can create spikes in some locations one year and other locations another year. Therefore, an understanding of the underlying geometric roadway features can assist an agency in identifying truly hazardous locations and not just the locations that with high collisions due to random chance, high traffic volumes, unusual weather patterns, or other conditions.

The analysis showed a relationship between the results of Curve Finder and Curvature Extension with regards to the average distance between GIS points and the error quotient reported by Curve Finder. When Curve Finder made a large error in estimating the radius, it was most closely related to the error quotient, meaning that Curve Finder’s output provides the user with information about how well the curve’s radius was estimated. The differences of the length results were most closely related to the distance between GIS points, meaning that higher quality GIS line work with less distance between successive points provides better results.

This paper demonstrated the ability and resources required to quickly find and measure a large set of horizontal curves. This type of effort is important for agencies because many countermeasures can be applied to roads which contain numerous horizontal curves instead of just individual curves. The system based approach can provide an agency with the ability to make critical funding decisions for potential countermeasures.

10.0 RECOMMENDATIONS

The following recommendations are compiled from the primary analysis chapters.

10.1 Curve Crash Characteristics

The research team recommends several actions to help transportation agencies better identify and understand the characteristics of horizontal curve collisions and identify the causes and problems involving horizontal curve collisions. First, a more integrated statistical analysis, taking into account various road, crash, weather, and temporal attributes could be conducted. Next, a statewide curve analysis similar to that presented herein can help identify any unique circumstances that create an overrepresentation of certain types or characteristics of collisions. The severity of two-lane curves, particularly in rural areas, should be considered as part of a hazardous site identification program. The curve collision analysis can identify specific hazardous locations as well as systematic deficiencies among regions, routes, geometric design factors, traffic control device consistency, shoulder width or type, maintenance practices, etc.

A comprehensive horizontal curve process would help guide agencies through horizontal curve identification, investigation, analysis, evaluation, countermeasure selection and evaluation, assessment of funding sources, and recommendation of countermeasures. The team also recommends the use of Table 9 as an initial guide to select potential countermeasures for horizontal curve collisions and, if possible, the eventual modification to Table 9 to suit each individual state's needs.

10.2 Highway Safety Manual Analysis

To properly calibrate the predictive models to HSM standards the research team found that a high number of segments are required to meet the HSM recommendations for collisions. In the case of this analysis for North Carolina, almost 300 sites are necessary; however this number will vary some for each location. Additionally, while it will require a greater number of sites, randomly selected segments are recommended for this process due to their lower calibration factor and standard deviation.

The field investigations are a time consuming part of this process. To minimize this data collection effort mean data for several parameters may be used in the model. However, data for AADT, curve radius, and curve length, it is important that individualized of the segment is used. These important parameters can be collected without a field visit, saving the agency time and resources. A calibration factor or 1.33 was found to be appropriate to be applied to the HSM prediction method in order for it to match the North Carolina crash values.

10.3 Individual Curve Analysis GIS Process

The research team recommends several possibilities to utilize a GIS methodology to help transportation professionals better identify and more efficiently study the characteristics of horizontal curves or to address other spatial data problems. The use of a GIS to determine horizontal curve radius and length is possible. Depending on available equipment, GPS (Imran 2006) and LiDAR (Khattak and Shamayleh 2005) can be used to generate feasible roadway alignments if the GIS line work does not exist or is not at a reasonable level of quality. A GIS-based approach can save time and resources compared to traditional field measurement techniques, as well as improve overall safety by eliminating the need to have personnel interact with the motoring public in potentially dangerous locations on curves. The integration of one of the methods introduced and analyzed here into a comprehensive horizontal curve process would assist agencies in horizontal curve identification, investigation, and analysis.

For individual curve analysis, Curvature Extension is recommended. However, Curve Calculator has been shown to be capable of producing reasonably accurate results with a large number of GIS points more quickly and efficiently than the other two methods. Curve Finder on the other hand, is recommended for network or route analysis. Curve Finder could be used to identify multiple locations with a small radius for safety applications or it could be used at the planning level to identify systematic deficiencies among regions or routes. Curve Finder can execute an analysis of one or many curves in only a couple of minutes, therefore, significant time efficiency can be obtained with large numbers of curves.

The tolerance in Curve Finder should be chosen carefully to capture as many curves as possible without unnecessarily splitting apart a single curve or combining together multiple curves. In this study, a 1524 meters (5,000 feet) maximum tolerance appears to be an appropriate level based on investigating multiple tolerances at each isolated individual curve. However, variations in the quality of the GIS line work impose the need for a detailed examination of the line work before beginning the analysis. The variations in quality could differ among jurisdictions and even among route classifications within a single jurisdiction (such as between interstate routes and local routes). Still, the line work quality in this study for rural, two-lane roads was good enough to enable the software to identify almost 90% of the curves (45 out of 51). If Curve Finder is utilized, a close assessment of the tolerance setting should be made by the user.

10.4 Network Curve Analysis GIS Process

The research team recommends the use of a GIS to find and measure curves on a large set of roadways of interest. Depending on the desired accuracy and the scope of the effort, one of the methods presented in this paper should provide an agency with the necessary information for numerous topics. Curve Finder provides an advantage over other comparable GIS tools in that it combines curve identification and geometric characterization. This combination of functions can significantly reduce the amount of time required to analyze the routes. Other methods studied required each curve to be visually identified manually.

The implementation of Curve Finder requires a tolerance value which commands how curves are found and reported. This research found that the optimal tolerance value was 2,700 feet for the GIS data used in the study. However, the optimal tolerance value could change among jurisdictions or roadway types, so the tolerance value should be studied to find an appropriate value for a particular agency. This paper can provide the framework for finding tolerance values in Curve Finder.

The automated processes in Curve Finder provide better results when the average distance between GIS points is 200 feet or less and the Curve Finder error quotient is less than 0.5. Therefore, a potential user can examine their existing line work to determine if the distance between GIS points is approximately 200 feet or less and Curve Finder output for the error quotient less than 0.5 to determine if the available data will provide the accuracy desired.

10.5 Horizontal Curve Procedure

The research team recommends a systematic approach for identifying, investigating, analyzing, and evaluating horizontal curves. This systematic approach can lead to the selection and evaluation of appropriate countermeasures, assessment of funding sources, and a recommendation of appropriate countermeasures. Figure 22 shows the recommended horizontal curve procedure.

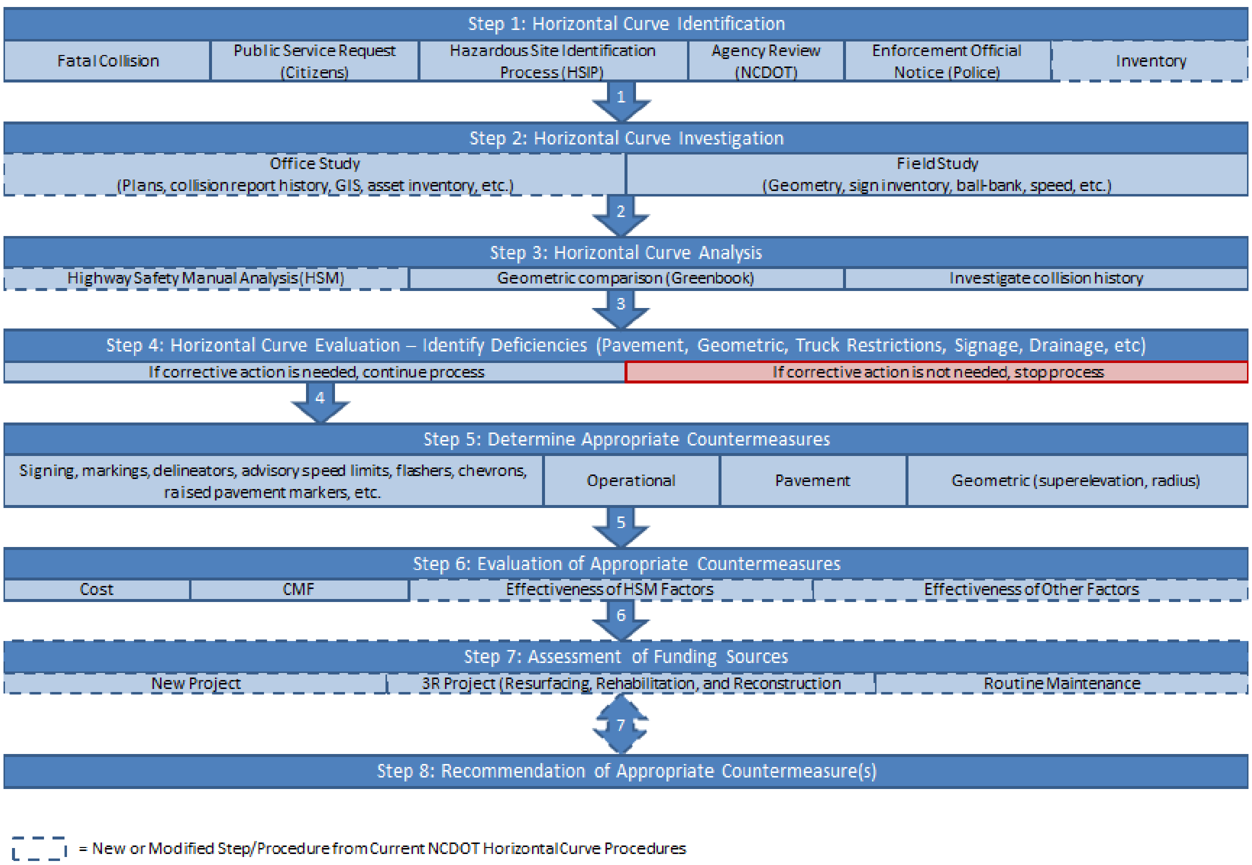


Figure 22. Recommended Horizontal Curve Procedure

11.0 Implementation and Technology Transfer Plan

Training the relevant NCDOT personnel in how to use the new methods from this research will be critical to its success. Without proper training, the methods are likely to languish and the benefits discussed earlier will not be achieved by the NCDOT and the motorists of North Carolina. The research team would like to present the research products at appropriate events and meetings as recommended by the steering and implementation committee. The Traffic Engineering and Safety Systems Branch is one of the key audiences for this material.

The most important personnel at the NCDOT who need to learn and practice the new methods described in this document are the Division Traffic Engineers and the Regional Traffic Safety Engineers. A meeting or seminar to give them this information could be productive. They, in turn, could teach the field personnel in the Divisions.

11.1 Research Products

The research products developed as a result of this research project include:

- Summary and comparison of horizontal curve study methods
- Manual field investigation procedure with instructions and data collection forms.
- Assessment of current NCDOT horizontal curve practices.
- Evaluation of GIS tools for horizontal curve investigations.
- Examination of curve crash characteristics in North Carolina.
- Calibration factors of two-lane curves, tangents, and general roadways for use in the Highway Safety Manual.
- The set of recommendations given in Chapter 10 of this report.
- Two peer reviewed journal papers:
    - Rasdorf, W., Findley, D. J., Zegeer, C. V., Sundstrom, C. A., and Hummer, J. E., "Evaluation of GIS Applications for Horizontal Curve Data Collection," Journal of Computing in Civil Engineering, American Society of Civil Engineers (Submitted 2010).
    - Hummer, J. E., Rasdorf, W., Findley, D. J., Zegeer, C. V., and Sundstrom, C. A., "Curve Crashes: Road and Collision Characteristics and Countermeasures," Journal of Transportation Safety and Security, Southeast Transportation Research Center (2010).
- Additional peer reviewed journal papers expected in at least the areas of HSM calibration and route analysis of horizontal curves.

12.0 CITED REFERENCES

AASHTO. (2001). A Policy on Geometric Design of Highways and Streets, Washington, D.C.

AASHTO (2010). *Highway Safety Manual*. American Association of State Highway Transportation Officials, Washington, D.C.

Bonneson, J., et al., (2007a). Development of Guidelines for Establishing Effective Curve Advisory Speeds, , TTI Technical Report, Texas Transportation Institute, College Station

Bonneson, J., et al., (2007b). Horizontal Curve Signing Handbook, , TTI Technical Report, Texas Transportation Institute, College Station

Carlson P. J., et al., (2004). Simplifying Delineator and Chevron Applications for Horizontal Curves, , TTI Technical Report, Texas Transportation Institute

Carlson, P., Burris, M., Black, K., and Rose, E. R. (2005). "Comparison of Radius-Estimating Techniques for Horizontal Curves." Transportation Research Record: Journal of the Transportation Research Board, Transportation Research Board of the National Academies, Washington, D.C. Pages 76-83.

Castro, M., Sánchez, J.A., Vaquero, C.M., Iglesias, L., and Rodríguez-Solano, R. (2008). "Automated GIS-Based System for Speed Estimation and Highway Safety Evaluation." Journal of Computing in Civil Engineering. American Society of Civil Engineers. Volume 22. Number 5. Pages 325-331.

Chowdhury, M. A., et al., (1998). Are the Criteria for Setting Advisory Speeds on Curves Still Relevant?, Journal of the ITE, Institute of Transportation Engineers

Chrysler, Susan T. et al., (2005). Simplifying Delineator Applications for Horizontal Curves. Transportation Research Record 1918, pp. 68–75, Washington D.C

Council, F. M., Patel, R., and Mohamedshah, Y. (2006). Highway Safety Information System Guidebook for the North Carolina State Data Files. FHWA, U.S. Department of Transportation, Washington, D.C.

Easa, S.M., Dong, H., and Li, J.(2007). "Use of Satellite Imagery for Establishing Road Horizontal Alignments." Journal of Surveying Engineering. American Society of Civil Engineers. Volume 133. Number 1. Pages 29-35.

Eccles, K. A. and Hummer, J. E, (2000). Safety Effects of Fluorescent Yellow Warning Signs at Hazardous Sites in Daylight Curves, , Transportation Research Board, Washington D.C.

Environmental Systems Research Institute (ESRI) Inc (2009). ArcGIS Desktop 9.3.1. Redlands, CA.

Environmental Systems Research Institute (ESRI) Inc (2010). GIS for Highways. URL: <http://www.esri.com/industries/highways/index.html> (Accessed April 30, 2010).

Findley, D. J. and Foyle, R. S. (2009). "Procedure for Identification and Investigation of Horizontal Curves with Insufficient Superelevation Rates." North Carolina

Department of Transportation. NCDOT Report No. FHWA/NC/2009-08. Raleigh, NC.

Florida Department of Transportation (FDOT) (2010). "Geographic Information System (GIS): Curvature Extension for ArcMap 9.x." Transportation Statistics Office, FDOT. Tallahassee, FL. URL: <http://www.dot.state.fl.us/planning/statistics/gis/> (Accessed April 30, 2010).

Garber, N. J. and Kassebaum, E. A. (2008). Evaluation of Crash Rates and Causal Factors for High-Risk Locations on Rural and Urban Two-Lane Highways in Virginia. Publication VTRC 09-R1. Virginia Transportation Research Council.

Hammond, J. and Wegmann, F (2001). Daytime Effects of Raised Pavement Markers on Horizontal Curves, , ITE Journal, August/01, 38-41, Institute of Transportation Engineers.

Hans, Z., Jantscher, T., Souleyrette, R., and Larkin, R. (2009). "Development of a Statewide Horizontal Curve Database for Crash Analysis." Proceedings, Mid-Continent Transportation Research Symposium. Iowa State University. Ames, IA.

Harpring, J. (2010). NHDOT "Curve Finder FAQ for Version 2." New Hampshire Department of Transportation. Concord, NH.

Herrstedt, L. and Greibe, P., (2001). Safer Signing and Marking of Horizontal Curves on Rural Roads, Traffic Engineering and Control Magazine, vol. 42, pp.82-87, Hemming Information Systems, London, England.

HSIS. (2009). Highway Safety Information System. Retrieved July 1, 2009, from Turner-Fairbank Highway Research Center: http://www.hsisinfo.org/.

HSRC. (2009). North Carolina Crash Data. Retrieved July 1, 2009, from Highway Safety Research Center at the University of North Carolina at Chapel Hill: http://www.hsrc.unc.edu/crash/

Hughes, W. E., Eccles K., Harwood, D., Potts I., and Hauer, E. (2004). "Development of a Highway Safety Manual", Appendix C: Prototype Chapter on Two-Lane Highways, NCHRP Project 17-18 (4) – Contractor Final Report. NCHRP Web Document 62. National Cooperative Highway Research Program. Transportation Research Board, National Research Council. Washington, DC.

Hummer, J. E., Rasdorf, W., Findley, D. J., Zegeer, C. V., and Sundstrom, C. A. (2010). "Curve Crashes: Road and Collision Characteristics and Countermeasures." Journal of Transportation Safety and Security, Southeast Transportation Research Center.

Imran, M., Hassan, Y., and Patterson, D. (2006). "GPS–GIS-Based Procedure for Tracking Vehicle Path on Horizontal Alignments." Computer-Aided Civil and Infrastructure Engineering. Blackwell Publishing. Malden, MA. Volume 21. Issue 5. Pages 383-394.

ITE (2001). Traffic Control Devices Handbook, Institute of Transportation Engineers, 2001

Khattak, A.J. and Shamayleh, H. (2005). "Highway Safety Assessment through Geographic Information System-Based Data Visualization." Journal of Computing in

Civil Engineering. American Society of Civil Engineers. Volume 19. Number 4. Pages 407-411.

Lacy, K., et al. (2004). Volume 8: A Guide for Reducing Collisions Involving Utility Poles, NCHRP Report 500. Transportation Research Board of the National Academies, Washington, D.C.

Lyles, R.L. and W. Taylor, (2006). Communicating Changes in Horizontal Alignment, NCHRP Report 559, Transportation Research Board, Washington D.C

Martinelli, F., La Torre, F., and Vadi, P. (2009). "Calibration of the Highway Safety Manual Accident Prediction Model for Italian Secondary Road Network." Proceedings of the Transportation Research Board 88th Annual Meeting, Transportation Research Board, National Research Council. Washington, DC.

McGee, H. W. and Hanscom, F. R. (2006). Low-Cost Treatments for Horizontal Curve Safety. Publication FHWA-SA-07-002. FHWA, U.S. Department of Transportation.

NCDMV. (2006). North Carolina Crash Report Instruction Manual. North Carolina Department of Transportation. Division of Motor Vehicles, Raleigh, NC.

NCDOT (2004). Guide for Resurfacing, Restoration and Rehabilitation (R-R-R) of Highways and Streets, North Carolina Department of Transportation. Raleigh, NC.

NCDOT (2005). 2004 North Carolina Supplement to the Manual on Uniform Traffic Control Devices, Traffic Engineering and Safety Systems Branch, Division of Highways, North Carolina Department of Transportation, 2005

NCDOT (2007). 2006 Highway and Road Mileage report, NCDOT Information, Mapping, and Graphics Unit, North Carolina Department of Transportation, Raleigh

NCDOT (2010). Traffic Engineering Policies, Practices, and Legal Authority Resource, North Carolina Department of Transportation

Neuman, T. R., et al. (2003a). Volume 3: A Guide for Addressing Collisions with Trees in Hazardous Locations, NCHRP Report 500. Transportation Research Board of the National Academies, Washington, D.C.

Neuman, T. R., et al. (2003b). Volume 6: A Guide for Addressing Run-Off-Road Collisions, NCHRP Report 500. Transportation Research Board of the National Academies, Washington, D.C.

Nielsen, M. A., Greibe, P., and Herrsted, L., (1999). Signing and Marking of Substandard Horizontal Curves on Rural Roads (Main Report), , Road Directorate Ministry of Transport Denmark Report 163, Traffic Management and Road Safety, Copenhagen, Denmark

North Carolina Department of Transportation (NCDOT) (2009). "NCDOT GIS Data Layers." Fourth Quarter 2009 Release Road Data. Road Characteristics Arcs. NCDOT. Raleigh, NC. URL: <http://www.ncdot.org/it/gis/DataDistribution/DOTData/default.html> (Downloaded November 1, 2009).

North Carolina Department of Transportation (NCDOT) (2009a). "NCDOT GIS Data Layers." Fourth Quarter 2009 Release Road Data. Road Characteristics Arcs.

NCDOT. Raleigh, NC. URL: <http://www.ncdot.org/it/gis/DataDistribution/DOTData/default.html> (Downloaded November 1, 2009).

North Carolina Department of Transportation (NCDOT) (2009b). "2008 Highway and Road Mileage." State Road Maintenance Unit. Road Inventory Information Section. NCDOT. Raleigh, NC.

North Carolina Division of Motor Vehicles (NCDMV) (2009). Crash Report Form DMV 349. North Carolina Department of Transportation. NCDOT. Raleigh, NC.

Price, M. (2010). "Under Construction: Building and Calculating Turn Radii." ArcUser Magazine. Winter 2010. Pages 50-56.

Rasdorf, W., Findley, D. J., Zegeer, C. V., Sundstrom, C. A., and Hummer, J. E. (2011). "Evaluation of GIS Applications for Horizontal Curve Data Collection." Journal of Computing in Civil Engineering. American Society of Civil Engineers. Submitted for Publication.

Rasdorf, W., Janisch, A., Robson, F., and Tilley, C.(2002). "Testing and Evaluating Alternative Algorithms for Location Referencing System Route Generation." Journal of Computing in Civil Engineering. American Society of Civil Engineers. Volume 16. Number 3. Pages 194–205.

Retting, R. A., and Farmer, C. M., (1998). Use of Pavement Markings to Reduce Excessive Traffic Speeds on Hazardous Curves, , ITE Journal, Vol. 68, No. 9, September 1998, pp. 30-36

SAS Institute Inc (2010). SAS 9.1.3. Cary, NC.

Souleyrette, R., et al. (2001). Systematic Identification of High Crash Locations. Publication TR-442. Iowa Department of Transportation.

Strathman, J. G., et al. (2001). Analysis of Design Attributes and Crashes on the Oregon Highway System. Publication FHWA-OR-RD-02-01. FHWA, U.S. Department of Transportation, Washington, D.C.

Sun, X., Li, Y., Magri, D., and Shirazi, H. H. (2006). "Application of the Highway Safety Manual Draft Chapter: Louisiana Experience." *Transportation Research Record: Journal of the Transportation Research Board*, No. 1950, Transportation Research Board of the National Academies, Washington, D.C., pp. 55-64.

Torbic, D. J. et al., (2004). Guidance for Implementation of the AASHTO Strategic Highway Safety Plan Volume 7: A Guide for Reducing Collisions on Horizontal Curves, Transportation Research Board, NCHRP Report 500, Washington D.C

Transportation Research Board (TRB) (2010). "Research Needs Statements." Geographic Information System Cost/Benefit Analysis Template. Transportation Research Board of the National Academies, Washington, D.C. URL: <http://rns.trb.org/dproject.asp?n=13581> (Accessed April 30, 2010).

USDOT (2003). Manual on Uniform Traffic Control Devices for Streets and Highways, FHWA, U.S. Department of Transportation. Washington, DC.

USDOT and ITE (2004). Traffic Control Devices: Uses and Misuses, USDOT and ITE, 2004, USDOT and ITE, http://www.ite.org/library/IntersectionSafety/TCD

Zegeer, C., et al. (1991). Cost-Effective Geometric Improvements for Safety Upgrading of Horizontal Curves. Publication FHWA-RD-90-074. FHWA, U.S. Department of Transportation, Washington, D.C.

13.0 APPENDICES

The appendices include the summary of NCDOT Division and Region meetings on horizontal curves and traffic control devices and the manual field investigation procedure.

14.0 APPENDIX A: NCDOT DIVISION AND REGION MEETING SUMMARIES

The research team visited personnel from all 14 NCDOT Divisions and all Traffic Engineering Regions to learn their current practices for finding hazardous horizontal curves and deciding on traffic control devices for those curves. Table 29 and Figure 23 summarize details of the meetings.

Table 29. Division and Region Meetings.

Meeting Location	Divisions	Regions	Date/ Time
1. Garner (Traffic Engineering headquarters)	5	Capital	11/3 (Mon), 10AM
2. Fayetteville (Sandhills Region Office)	6, 8	Sandhills	11/7 (Fri), 10AM
3. Greenville (Division 2 conference room)	1, 2, 4	Eastern & OBX	11/10 (Mon), 10AM
4. Winston Salem (Triad Region Office)	7, 9, 10, 11	Triad & Metrolina	11/21 (Fri), 10AM
5. Wilmington (Division 3 conference room)	3	Cape Fear	11/24 (Mon), 10AM
6. Asheville (Division 13 conference room)	12, 13, 14	Blue Ridge Mountains, High Country, & Foothills	12/01 (Mon), 1PM

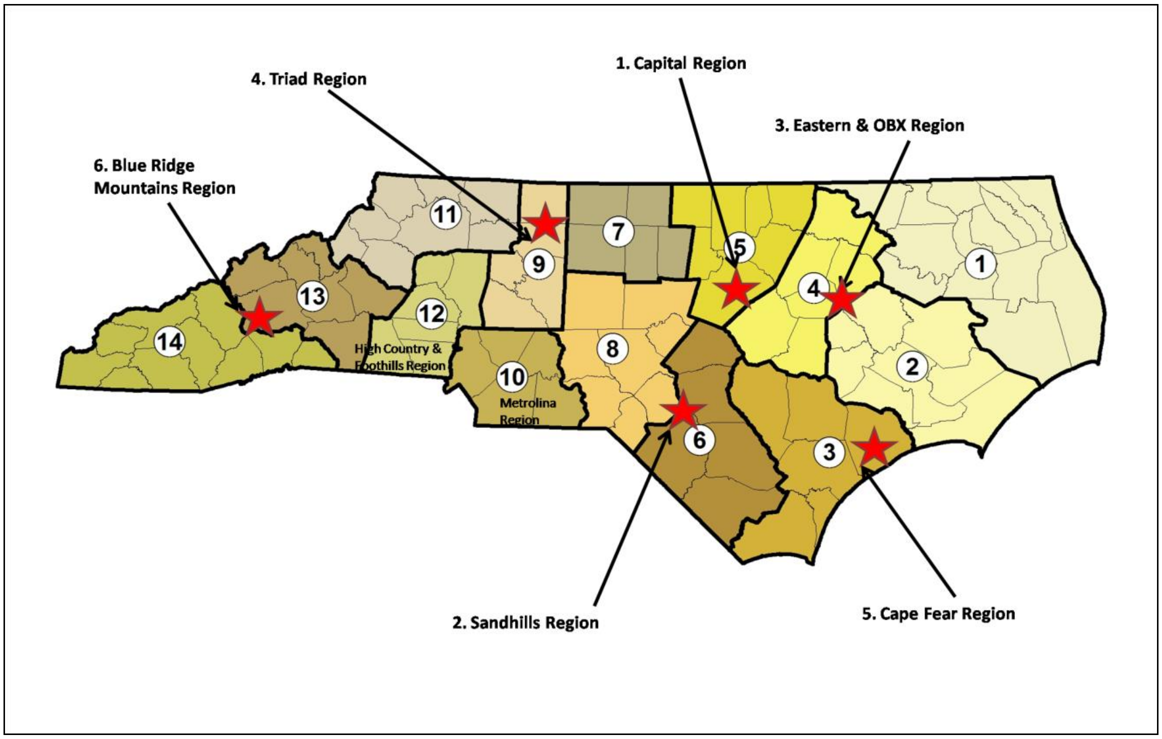


Figure 23. Division and Regional Meeting Locations.

The following pages present the most significant results from these meetings and identify the attendees.

Garner Meeting Summary

11/03/08

Table 30. Garner Meeting Attendance List

Name	Region or Division #	Email
Kyungtae Ryoo	NCSU	kryoo@ncsu.edu
Carl Sundstrom	UNC	sundstrom@hsrc.unc.edu
Charles Zegeer	UNC	Charlie_Zegeer@unc.edu
Chris Howard	Traffic Management Unit	cbhoward@ncdot.gov
Ron King	Signing Section	ronking@ncdot.gov
Kelly Becker	Capital Region	kbecker@ncdot.gov
Larry Stallings	Traffic Operations and Investigations Section	lstallings@ncdot.gov
James Speer	Roadway Design Unit	jspeer@ncdot.gov
Ron Garrett	Div 5	rjgarrett@ncdot.gov
Brian Mayhew (Host)	Traffic Safety Systems Management Section	bmayhew@ncdot.gov
Joe Hummer	NCSU	hummer@ncdot.gov
William Rasdorf	NCSU	rasdorf@ncsu.edu

1. Dr. Hummer served as moderator of the Garner meeting. He welcomed all participants and a sign-up sheet was circulated. A total of 7 engineers from Division 5, the region, and headquarters attended the meeting.

2. Dr. Hummer and other project team members introduced themselves and mentioned the main objectives of this meeting: focusing on the study techniques for collecting data. The NCDOT engineers introduced themselves and explained their roles in their areas.

3. The first question was who conducts studies, collects data, makes the decisions, on what signs and markings are used on certain curves. The regional traffic engineers investigate reported fatal crash locations as well as highway safety program locations. In other words, identifying hazardous curves is based mostly on crash data. Citizen requests supplement the reported crash data. There are several limitations to thoroughly investigating curves at the division level. The division level does not have enough staff with adequate training. No one regularly reviews all curves are in their area and there are no curve inventory data. Supervisors and technicians make many decisions on TCDs at curves. All staff rely on experience and on-the-job training more than formal training to make these decisions.

4. Field personnel use the ball-bank indicator method to measure for advisory speeds. They also check stopping sight distance.

5. In general, speed studies have not been performed at horizontal curves. However, speed studies are sometimes needed when requested for certain curves with high crash histories. The NCDOT uses lidar guns for speed studies and they are happy with that method. NCDOT engineers emphasized not to locate speed limit signs between advisory speed signs.

6. The group described several ways to improve existing raised pavement markers, 1) decreasing the pavement marker spacing at curve, 2) delineating the roadway edge line clearly, and 3) installing rumble strips.

7. Engineers at the meetings currently use the AASHTO Green Book, the MUTCD, the NC MUTCD, and the 3R (Resurfacing, Restoration and Rehabilitation) manual to decide on adequate TCDs on horizontal curves. The engineers thought that the commonly-used manuals need to be complemented to provide a set of consistent countermeasures for curves because the existing manuals handle things independently. Another problem is that the countermeasure suggestions available are limited for various situations so that field personnel have some trouble at actual curve sites.

8. When the traffic engineers apply TCDs on horizontal curves as decision makers, they basically assume that they have never experienced the road before. Then they drive back and forth on the road carefully watching for existing curve signs and sight distance. The engineers advocated driving the entire stretch of road, not just the curve in question. More specifically for potentially dangerous curves, they obtain current curve warning sign information, conduct studies using ball-bank indicators, and consider countermeasures like rebuilding shoulders, widening lanes, and adding chevrons in addition to warning signs.

9. There are some problematic cases of poor sight distance in horizontal curves because the curves are sometimes hidden by obstacles such as trees, structures, and so on. The group generally believed that good policies included : 1) Installing warning signs as little as possible on the curves, 2) If the sight distances were long enough, there is no need to add signs, 3) If there was no need to reduce vehicle speed (the existing posted speed is reasonable), it should be left alone.

10. The engineers used GIS to find curve geometry information to support decisions. Also the group felt it would be useful for saving traffic engineers' time and effort to have a curve inventory. Division 5 has their own county GIS maps, so they can measure curve geometry element that they want such as curve radii. However, although the GIS would be available, traffic engineers felt as though they should not make recommendations without exploring and seeing the curve in the field. Also, they thought Google Earth would be a very helpful GIS tool.
11. TCDs become deficient on some curves when unpaved roads are paved, changing the operating speeds, while the devices are not reviewed.

12. Some types of overlays change the superelevations on curves.

13. The Signing Unit is available to review devices. They mostly work on new designs.

14. Engineering judgment is critical when deciding on curve tcds because no two curves are alike. Guidelines cannot be too restrictive.

Fayetteville Meeting Summary

11/7/08

Table 31. Fayetteville Meeting Attendance List

Name	Region or Division #	Email
Kyungtae Ryoo	NCSU	kryoo@ncsu.edu
Joe Hummer	NCSU	hummer@ncsu.edu
Evan McKinnon	Div 8	emckinnon@ncdot.gov
Kent Langdon	Div 6	klangdon@dot.state.nc.us
Alfred Grandy (Host)	Sandhills Region	agrandy@ncdot.gov
David Willett	Div 8	dbwillett@ncdot.gov

1. Dr. Hummer served as moderator of the Fayetteville meeting. He welcomed all participants and a sign-up sheet was circulated. A total of 4 engineers from Division 6, Division 8 and the Sandhills region attended at the meeting.

2. Dr. Hummer introduced project team members and described the main objectives of this meeting: focusing on the study techniques for collecting data. The division and regional engineers introduced themselves and explained their roles in this area.

3. The first question was how the bad curves are located and who is finding them. The divisions have several ways to identify the bad curves. One is by the HSIP (highway safety improvement program) which is the method based on high crash rate. Another one is by investigating fatal collision locations. A third way is by citizen complaint and opinion. They also investigate secondary construction road and unpaved roads without curve signs. An assistant transportation supervisor or signal sign technician in the division often makes decisions to install and change signs.

4. The engineers were satisfied with ball-bank indicator method because it helps them save money. They were using the 16-degree ball-bank indicator.

5. When they drive on curves suggested by citizen complaints, they investigate curve design geometry elements like shoulder, crown, and superelevation.

6. Standard guide book include the AASHTO Green Book for defining sight distance on the curves. The MUTCD and TEPPL are mainly used to investigate advisory speed and decide on adequate curve signs. Additionally, Division 6 tried to establish its own standard for consistent speeds and signing. They were not familiar with FHWA's Traffic Control Devices Handbook

7. They normally follow the MUTCD to install chevron devices on some sharp curves. However, they thought there are inconsistent problems in height and shape among the divisions around the state in this aspect.

8. For another treatment on curves, they install rumble strips along the edges of high-speed roadways to reduce run-off-road crashes. The rumble strips normally have 18 inches of offset from the shoulder.

9. Divisions and regions do not perceive that they are consistent in TCD application procedures because there are different ways to identify dangerous curves, different study methods, and different countmeasures.

10. These divisions use basic Histar counters for speed studies. They count the vehicles for a certain time and calculate the vehicle percentile speed. However, they are sometimes questions on the accuracy from the counters. Additionally, they do not have the systematic database of speed limit history on their roads.

11. One division was using Google Earth and found it helpful. The Street View function within the Google Earth was useful to search for particular roads. Division and regional engineers strongly recommended that similar tools be included in our study, and that the tool could include sign and pavement marking information. In addition to finding horizontal curves, they wanted convenient methods to find horizontal curve design elements such as curve radius, center and edge lines, curve angles, superelevation, and so on.

12. Another tool that the group frequently uses is the county GIS systems. They are more satisfied with the county GIS system than general text map. However, the county GIS system has not been updated to newer version and sometimes not matched to the actual paper map. The county GIS systems are more helpful than the state GIS system.

13. The group thought that the current one-vehicle method to measure passing sight distance on horizontal curves was reasonable and scientific.

Greenville Meeting Summary
11/10/08

Table 32. Greenville Meeting Attendance List

Name	Region or Division #	Email
Kyungtae Ryoo	NCSU	kryoo@ncsu.edu
Carl Sundstrom	HSRC	sundstrom@hsrc.unc.edu
Earl Hoggard	Div 1	dehoggard@ncdot.gov
Mary Moore	Div 2	mmoore@ncdot.gov
Chad Edge	Div 1	dedge@ncdot.gov
Turnage Hill	Div 1	
Haywood Daughtry (Host)	ERMSFDE	hdaughtry@ncdot.gov
Steve Hamilton	Div 2	shamilton@ncdot.gov
Dwayne Alligood	Div 2	dalligood@ncdot.gov
Andy Brown	Div 4	ahbrown@ncdot.gov
Sid Tomlinson	Div 4	jstomlinson@ncdot.gov
Jay Mombaerts	Div 2	gemombaerts@ncdot.gov
Jim Evans	Div 2	jfevans@ncdot.gov
Chad T. Mills	Div 2	ctmills@ncdot.gov

1. Carl Sundstrom served as moderator of the Wilson meeting. He welcomed all participants and a sign sheet was circulated. A total of 12 staff members from Divisions 1, 2, 4 and the Eastern and Outer Banks regions attended the meeting.

2. Carl introduced project team members and described the main objective of this meeting as focusing on study techniques for collecting data. Division and regional staff members introduced themselves and explained their roles.

3. The first question was who is conducting the studies and identifying the horizontal curves. Typically, division traffic engineers receive curve location information based on high crash rates and complaints, then conduct speed study for determining an advisory speed using a ball bank indicator, then provide appropriate curve signs.

4. For the ball bank indicator, the division traffic engineers did not use the same degree of ball bank indicator among them for advisory speed. There was confusion that the NC MUTCD indicates 10 degrees although Federal MUTCD uses a 16-degree ball bank indicator.

5. For guidance on selecting signs, the divisions basically use the NC and Federal MUTCD.

6. To determine signs, after identifying the horizontal curves based on high crash rate, staff members directly experience the curves and investigate the signs that are currently at the location. As mentioned, investigators often conduct ball bank studies for speed. There are questions about whether the vehicle makes a difference in the ball bank readings. Also, some questioned whether to evaluate curves based on direction and provide different advisory speeds.

7. For the sign placement, they placed the signs based on the speed limit of the road (MUTCD indication). Basically, long distances are required on roads with high speed limits to provide drivers clear information.

8. For the raised paved markings, the spacing on curves is changed depending on the roadway speed limit. Most secondary roads have a lot of curve signs but don't have pavement markers.

9. Treatments like superelevation and shoulders are mostly associated with highway safety improvements. Attendees investigate the curve, consider shoulders and roadsides, and consider maintaining shoulders and fixing superelevation for potentially dangerous curves.

10. Chevrons are used to delineate the curves so that road drivers can have sufficient time to react to the change in curve alignment. The chevrons are mainly applied to the high crash rate curves with other curve warning signs.

11. Attendees stated that all of their dirt roads are driven and evaluated after becoming paved. When other roads are added to the system (such as neighborhoods) they are not always evaluated.

12. The group recommended a method to evaluate the implemented treatments, depending upon the priority each treatment has and the sources of the funding.

13. Attendees thought GIS tools would be helpful for obtaining the road elements and deciding the best position of TCDs on horizontal curves.

14. Further questions on study methods included the number of passes in each direction that should be performed, how one should drive the curve, and an evaluation of error between different ball bank technologies.

Winston-Salem Meeting Summary

11/21/08

Table 33. Winston-Salem Meeting Attendance List

Name	Region or Division #	Email
Kyungtae Ryoo	NCSU	kryoo@ncsu.edu
Rick Mason	Div 10	rmason@ncdot.gov
Trent Moody	NCDOT	tmmoody1@ncdot.gov
Vickie Embry (Host)	Regional Office	vembry@ncdot.gov
Brian Thomas	Regional Office	bthomas@ncdot.gov
Mark Aldridge	Div 7	maldridge@ncdot.gov
J.P. Couch	Div 9	jpcouch@ncdot.gov
Randy Ogburn	Div 9	rogburn@ncdot.gov
Dean Ledbetter	Div 11	dledbetter@ncdot.gov
William Rasdorf	NCSU	rasdorf@ncsu.edu

1. Dr. Rasdorf served as moderator of the Winston-Salem meeting. He welcomed all participants and a sign-up sheet was circulated. A total of 8 engineers from Division 7, Division 9, Division 10, Division 11 and the Triad region attended the meeting.

2. Dr. Rasdorf introduced project team members and described the main objectives of this meeting focusing on study techniques for collecting data. The division and regional engineers introduced themselves and explained their roles in this area.

3. The first question was who makes decisions about devices, who decides which devices are used, and who is involved in the process in the divisions and the region. They said mainly at the division and region engineer level they investigate fatal crash locations and record speed and geometry information (curvature) using the ball-bank indicator method. Crash reports are investigated more often at the regional level than the division level.

4. Subdivision roads in some divisions do not have enough curve warning signs or do not meet standards. However, other divisions have enough control of the design of subdivision roads. They use the tools such as MapQuest or GPS unit for identifying the location of new subdivision roads.

5. According to division and regional traffic engineers, dangerous curves are identified based on crashes and complaints. Are there ways to proactively identify curves?

They consider whether several curves in a sequence have the appropriate TCDs. Low volume mountain roads are a particular concern.

6. For study methods, the attendees recognize first whether the curve meets the traffic engineer's standard expectation or not. The engineer often drives the curve several times using a ball-bank indicator to judge this. Other factors considered in study process are weather and nighttime. Weather conditions, especially wet conditions, affect road surface and traffic engineers sometimes recommend additional signs or marking with that pattern.

7. For sign placement issues, basically they consider drivers' expectancy for the appropriate location of signs. They determine the location depending on approach driving speed. In case of multiple curves, they also make decisions on sign location considering spacing between curves.

8. Most attendees used the existing 10-degree ball-bank indicator method in the MUTCD.

9. Division 11 does not use the ball-bank indicator method. They post the advisory speeds based on the traffic engineers' judgment and opinion through driving the curve. They provided a chart related to sign selection and speed proposed for the MUTCD. The chart shows which signs are needed in case there is some difference between advisory speed and speed limit on the curves. It may be helpful when choosing TCDs.

10. The group was positive about new study methods like GIS and GPS techniques. They thought the new methods would be helpful in deciding what locations need a sign. Also, the techniques will be helpful for investigating curve speed and geometric elements such as superelevation and curvature.

11. For additional traffic devices, the attendees sometimes install chevrons to delineate hazardous horizontal curves.

Wilmington Meeting Summary

11/24/08

Table 34. Wilmington Meeting Attendance List

Name	Region or Division #	Email
Kyungtae Ryoo	NCSU	kryoo@ncsu.edu
Coke Gray	Regional Office	rcgray@ncdot.gov
Dan Cumbo	Div 3	dcumbo@ncdot.gov
Roger Hawkins	Regional Office	rdhawkins@ncdot.gov
Pate Butler (Host)	Regional Traffic Engineer	mpbutler@ncdot.gov
Joe Hummer	NCSU	hummer@ncsu.edu
Rod Wyatt	Div 3	rwyatt@ncdot.gov

1. Dr. Hummer served as moderator for the meeting. He welcomed the participants and circulated a sign-in sheet. A total of five staff members from Division 3 and the Cape Fear region participated.

2. Dr. Hummer emphasized that the main purpose of the meeting was to gather information on current practices for finding hazardous horizontal curves and deciding on appropriate traffic control devices. The emphasis was on improved and consistent study techniques rather than specifications for particular devices.

3. The discussion began with the question of who make decisions on devices. The group responded that all staff levels—regional engineers, division engineers, division supervisors, and division technicians—played key roles and made decisions sometimes. Regional engineers performed investigations of sites identified in the highway safety improvement program or of fatal collision sites. Division personnel often investigated sites where citizens complained. Traffic services supervisors were very important in conducting many investigations and making decisions. Supervisors typically had much experience. All staff levels consulted with each other as needed to get the decision correct.

4. The group cited the TEPPL as an important reference in making decisions on curve tcds. Other references cited included the MUTCD and the Green Book for checking appropriate superelevations.

5. Division 3 still has many unpaved roads needing paving. As those roads are paved, of course, the speeds become higher and the tcds on curves often need to be changed. A procedure to make sure those tcds are reviewed will be critical for some years to come.

6. Sometimes when subdivision streets are accepted into the state system, the curve-related tcds are insufficient and are not thoroughly reviewed. The attendees urged that a process be developed to insure that review. Revision of the Subdivision Manual would be one way to help.

7. Training of new staff members at all levels involved here tended to be experiential. The attendees thought that the training was adequate for the most part, but recognized that skills could erode as the very experienced staff members retired.

8. Attendees used the 10-degree ball-bank indicator to study curves and help set advisory speeds. They feel confident in the results the device provides.

9. A driver-through is a routine part of the study process for horizontal curves.

10. Speed studies are important in examining curves. The group emphasized that they tend to study speeds on the whole road corridor, not just a single curve. Attendees favored lidar guns for speed studies and considered the device effective.

11. Attendees noted inconsistent practices in signing curves between NCDOT divisions. Practices in the mountains tend to be much different than in the flatter terrain of Division 3.

12. Participants often use on-line aerial images during studies of curve sites. Google Earth would be a convenient resource because of its convenient user interface and clear images.

13. Attendees rarely use GIS now in studying horizontal curves. The group did see the potential for GIS to be helpful in the future.

14. The attendees do not use GPS to study curves. The group was aware that Division 9 uses GPS to assemble sign information.

15. Budget cuts had forced a suspension of the nighttime sign inspection program in Division 3 this year. Only critical signs are being replaced.

16. Participants were proud of some of the creative tcds they had employed in difficult situations as countermeasures. They felt that it was important to get drivers to recognize that a curve was ahead and to adjust to the appropriate speed.

Asheville Meeting Summary

12/01/08

Table 35. Asheville Meeting Attendance List

Name	Region or Division #	Email
Charlie Zegeer	UNC HSRC	Charlie_zegeer@unc.edu
Tim Barker	Div 14	tbarker@ncdot.gov
Scott Cook	Div 14	scook@ncdot.gov
Monty Ward	Div 14	dmward@ncdot.gov
Roger Ayers	Div 14	rayers@ncdot.gov
Mark Teague	Div 13	mteague@ncdot.gov
Byron Engle	Div 12	bengle@ncdot.gov
Steve Hefner	Div 12	shefner@ncdot.gov
Jimmy Hamrick	High Country & Foothills Region	jahamrick@ncdot.gov
Marshall Williams	Div 13	marshallwilliams@ncdot.gov
Anna Hendorson	Div 13	aghenderson@ncdot.gov
Haley Martin	Div 13	hmmartin@ncdot.gov
Bucky Galloway (Host)	Blue Ridge Region	dgalloway@ncdot.gov
Scott Collier	Blue Ridge Region	scollier@ncdot.gov
Kyungtae Ryoo	NCSU	kryoo@ncsu.edu

1. Charlie Zegeer served as moderator of the Asheville meeting. He welcomed all participants and a sign-up sheet was circulated. A total of 13 traffic engineers from Division 12, Division 13, Division 14, and the Blue Ridge region attended the meeting.

2. Charlie introduced project team members and mentioned that the main objective of this meeting was the study techniques for collecting data. The division and regional engineers introduced themselves and explained their roles in this area.

3. The first question was who conducts studies and what kinds of information are collected. They replied that the process is initiated by crash data (high crash listing) and speed data. For Division 12, mostly the traffic engineers and technicians investigate speed and crash data. First of all, they investigate the current speed limit on the road. Then they drive through at the post speed limit and check the ball-bank indicator around curve. Finally, they make a decision for an appropriate advisory

speed. In the speed study process using ball-bank indicator, they consider safe driving.

4. For other treatment options besides installing signs, they consider speed zones, superelevation, rumble strips, raised pavement markers. The more pronounced the crash problems, the more carefully they get looked at out at the site.

5. Most divisions are using 10-degree ball-bank indicators for appropriate curve speeds. They generally thought the 16-degree indicator was too conservative for current drivers.

6. For consistent treatments on the curve, many engineers use curve warning signs with advisory speeds. However, in case there is a problem crash history, they may give advisory speeds and chevrons.

7. For other treatments, some divisions use non-delineation curve treatments such as lane widening, shoulder improvement, friction treatment, and improving sight distance. In terms of treatment for night time, they mainly consider weather condition factors affecting speeds on curves.

8. For curves which are not clearly defined in guidelines but have not had complaints or crash problems, they follow their engineering judgment for advisory speed as mentioned in state policy.

9. For the other techniques, divisions are using different tools such as Google Earth, MapQuest, and so on to investigate their curves. They are overall happy with these tools. However, they recognize that there is no way to know vertical elements using aerial photos.

10. On unpaved roads, if a curve is very short, they apply curve warning signs and chevrons

11. Some divisions have databases including existing road conditions such as existing signs, shoulder widths, pavement widths, and so on.

12. Some divisions follow the TEPPL study procedure. Other divisions are not satisfied with the TEPPL and thought that it is impossible to apply, particularly using ball-bank indicators. They expect that a new document would include before-and-after photos on TCD installations and countermeasures for safety improvements.

13. The divisions requested technical trainings for new traffic engineers.

14. The attendees said that the public sometimes does not understand the difference between speed limit signs and speed advisory plates. The public is sometimes confused when there is short spacing between the devices, so the divisions adjust typical spacing.

14.1 Meeting Script

The meetings with NCDOT personnel were generally conducted in accordance with a script developed by the NCSU researchers. The purpose of the script was to ensure that appropriate scope of material was developed while providing a general framework for the meeting. The script is presented on the following pages.

First of all, we would like to thank you all for responding today. We are with North Carolina State University and University of North Carolina Highway Safety Research Center (Names of investigators present). We are conducting a study on Traffic Control Devices (TCDs) procedure for horizontal curves, and we are sponsored by the NCDOT.

We want to assure you that the responses you provide will be kept confidential. We will not record any personal information that may arise throughout the course of this session. We will also not attribute particular comments to any particular person. As a result we encourage you to respond in a candid manner.

Throughout this study, we will develop a standard new study method for finding the best set of TCDs for any particular horizontal curve. The objectives of this interview are as follow.

Objective 1: Who conducts studies and makes TCD decisions?
Objective 2: What are the current study methods?
Objective 3: What are the current processes for making decisions on TCDs?
Objective 4: What are the capabilities for new methods?

-Network level: looking for hazardous sites
-Unusual project level: identified as hazardous sites
-Typical project level: other sites

Objective 1: Who conducts studies and makes TCD decisions?

Who does studies for network level?

Who does studies for typical project level?

Who does studies for unusual project level?

Who makes decisions for network level?

Who makes decisions for typical project level?

Who makes decisions for unusual project level?

Objective 2: What are the current study methods?

What study methods do you use for the network level?

What equipment and/or software does each method require?

What data does this procedure collect?

What study methods do you use for the typical project level?

What equipment and/or software does each method require?

What data does this procedure collect?

What study methods do you use for the unusual project level?

What equipment and/or software does each method require?

What data does this procedure collect?

Do you have references or manuals for any novel methods? Please provide us the copies.

What kinds of curves and devices cause the most difficulty in data collection?

Are you happy with the current study methods? How can they be improved?

Objective 3: What are the current processes for making decisions on TCDs?

What factors do you consider at the network level?

Do you use rules of thumb or guidelines? Provide copies if written.

How much latitude does the decision maker have?

What factors do you consider at the typical project level?

Do you use rules of thumb or guidelines? Provide copies if written.

How much latitude does the decision maker have?

What factors do you consider at the unusual project level?

Do you use rules of thumb or guidelines? Provide copies if written.

How much latitude does the decision maker have?

What kinds of curves and devices cause the most difficulty in decision making?

Do you think that any of your procedures differ from those in other divisions?

Are you happy with the current decision making processes? How can they be improved?

Objective 4: What are the capabilities for new methods?

For each of the following, tell us the extent to which it is currently available, the quality if available, and the need for training for the people who would use it.

Roadway geometry via GIS

Roadway geometry via GPS

Speed and travel time via GPS

Speed via laser guns

Roadway geometry via as-built plans

Roadway geometry via inventory database

Roadway geometry via aerial image

Collision data

TCD evaluation using retroreflectometers

Sight distance using digital images

Any other new study methods or decision processes to relate?

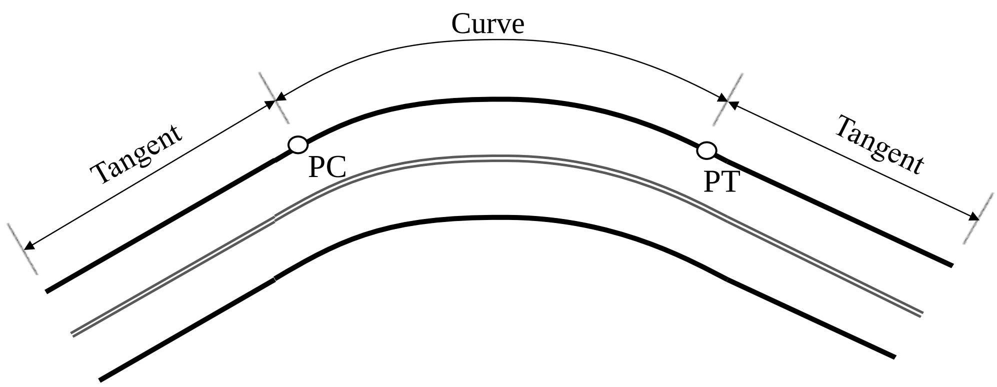
Any other comments?

We would like to thank you all for participating in this survey. If you have any questions or concerns please feel free to contact us. E-mail: hummer@ncsu.edu, Phone: (919)515-7733

15.0 APPENDIX B: MANUAL FIELD INVESTIGATION PROCEDURE

Field Data Collection for Horizontal Curves

The following data will be used collected from N.C. DOT research project titled: *Procedure for Curve Warning Signing, Delineation, and Advisory Speeds for Horizontal Curves.* Each curve should be isolated from other curves with tangent sections on each end, as shown in the figure below. The Roadside Hazard Ratings Definitions are attached which will be beneficial when determining the Roadside Hazard Rating of the roadway. The radius and superelevation should be determined based on the attached Field Investigation Procedure from N.C. DOT Research Project 2009-09, which is also attached to this document.



I. GENERAL INFORMATION	
Investigator Name:	
Phone Number:	
Email Address:	
County:	
Road Name:	
Closest Intersection:	
Other Site Description:	

II. ROADWAY FEATURES		
	Feature	**Curve**
1.	Posted Speed Limit (mph):	
2.	Lane Width (feet): *(Measure from center of the lane-line of the roadway to center of edgeline, round to the nearest foot)*	
3.	Inside Shoulder Width (feet): *(Measure from center of edgeline to edge of shoulder, round to the nearest foot)*	
4.	Inside Shoulder Type: *(Paved, Gravel, Turf, or Composite)*	
5.	Outside Shoulder Width (feet): *(Measure from center of edgeline to edge of shoulder, round to the nearest foot)*	
6.	Outside Shoulder Type: *(Paved, Gravel, Turf, or Composite)*	
7.	Length of Section (feet): *(Measure from beginning of the curve to the end of the curve along the edgeline, in feet, measure tangents from end of curve to the within 100' of the nearest intersection or next curve)*	
8.	Radius of Horizontal Curve (feet): *(Determine the radius using the attached Field Investigation Procedure and completed Field Investigation Form below)*	
9.	Roadside Hazard Rating (1-7): *(See the attached photos for examples)*	
10.	Inside Lane Superelevation (%): *(Determine the superelevation using the attached Field Investigation Procedure and completed Field Investigation Form below)*	
11.	Outside Lane Superelevation (%): *(Determine the superelevation using the attached Field Investigation Procedure and completed Field Investigation Form below)*	
12.	Grade (%): *(Determine the grade using the digital level to find the steepest grade)*	
13.	Number of Driveways: *(Record the total number of driveways along the length of the roadway from beginning to end of segment on both sides)*	
14.	Presence of Raised Pavement Markers (Yes/No):	
15.	Presence of Passing Lanes* (Yes/No):	
16.	Presence of Roadway Lighting* (Yes/No):	
17.	Presence of Centerline Rumble Strips* (Yes/No):	
18.	Presence of Two-Way Left-Turn Lanes* (Yes/No):	
19.	Presence of Shoulder Rumble Strips (Yes/No):	
20.	Presence of Skid Treatments (overlay) (Yes/No):	
21.	Presence of Skid Treatments (groove pavement) (Yes/No):	

Note: *These elements are typically not present on rural, two-lane roadways

III. ROADWAY FEATURES (Continued)	
Feature	**Curve**
22. Presence of Vertical Curve Sight Distance Issues (Yes/No):	
23. Presence of Sight Distance Obstructions (Yes/No): *(Describe the obstructions in the notes section)*	
24. Presence of Guardrail (Yes/No):	
25. Type of Guardrail (W-beam, etc.):	
26. Condition of Pavement Markings:	
27. Presence of Delineation on Guardrail (Yes/No):	

IV. FIELD INVESTIGATION FORM

The Field Investigation Procedure for determining the Middle Ordinate Measurements and Superelevation Measurements are detailed in the attached document

Middle Ordinate Measurements

Measurement 1:	Measurement 2:	Measurement 3:
inches	inches	inches

Circle the median value above, this should be used as the middle ordinate measurement in the Middle Ordinate Conversion Table to determine the radius. Record the radius value below.

Radius:

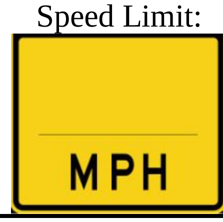
Inside Lane Superelevation Measurements

Measurement 1:	Measurement 2:	Measurement 3:	Measurement 4:	Measurement 5:
%	%	%	%	%

Outside Lane Superelevation Measurements

Measurement 1:	Measurement 2:	Measurement 3:	Measurement 4:	Measurement 5:
%	%	%	%	%

Circle the median value above for the inside and outside lanes. These should be used as the superelevation measurement.

V. SIGNS (on the curve or immediate approach to the curve)					
Sign	**Number in Inside Lane Direction**	**Number in Outside Lane Direction**	**Sign**	**Number in Inside Lane Direction**	**Number in Outside Lane Direction**
					
					
					
					
					
			Insert Advisory Speed Limit: 		

VI. CURVE DIAGRAM
Please draw the overall curve features including signs and relative locations with nearest intersections.

VII. Notes/Comments – Please describe/explain any unusual features or other notes

Roadside Hazard Rating Definitions[1]

Roadside Hazard Rating 1

Physical Characteristics:
- Wide clear zones greater than or equal to 9 m (30 ft) from the pavement edgeline.
- Sideslope flatter than 1:4.
- Recoverable.

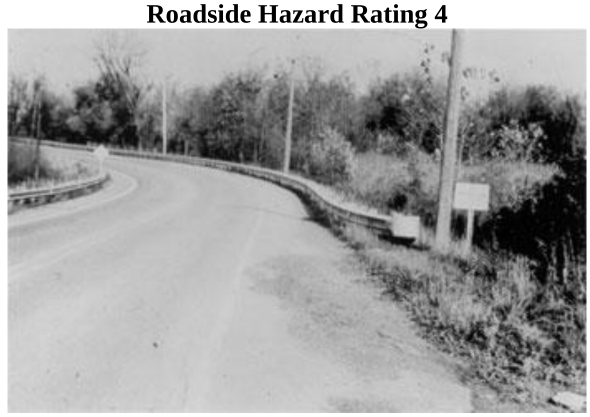
Roadside Hazard Rating 2

Physical Characteristics:
- Clear zone between 6 and 7.5 m (20 and 25 ft) from pavement edgeline.
- Sideslope about 1:4.
- Recoverable.

Roadside Hazard Rating 3

Physical Characteristics:
- Clear zone about 3 m (10 ft) from pavement edgeline.
- Sideslope about 1:3 or 1:4.
- Rough roadside surface.
- Marginally recoverable.

Roadside Hazard Rating 4



Physical Characteristics:
- Clear zone between 1.5 and 3 m (5 to 10 ft) from pavement edgeline.
- Sideslope about 1:3 or 1:4.
- May have guardrail (1.5 to 2 m [5 to 6.5 ft] from pavement edgeline).
- May have exposed trees, poles, or other objects (about 3 m or 10 ft from pavement edgeline).
- Marginally forgiving, but increased chance of a reportable roadside collision.

[1] Appendix D: Definitions of Roadside Hazard Ratings Used With the Accident Prediction Algorithm. Prediction of the Expected Safety Performance of Rural Two-Lane Highways. December 2000. Federal Highway Administration. Publication No. FHWA-RD-99-207.

Roadside Hazard Rating 5

Physical Characteristics:

- Clear zone between 1.5 and 3 m (5 to 10 ft) from pavement edgeline.
- Sideslope about 1:3.
- May have guardrail (0 to 1.5 m [0 to 5 ft] from pavement edgeline).
- May have rigid obstacles or embankment within 2 to 3 m (6.5 to 10 ft) of pavement edgeline.
- Virtually non-recoverable.

Roadside Hazard Rating 6

Physical Characteristics:

- Clear zone less than or equal to 1.5 m (5 ft).
- Sideslope about 1:2.
- No guardrail.
- Exposed rigid obstacles within 0 to 2 m (0 to 6.5 ft) of the pavement edgeline.
- Non-recoverable.

Roadside Hazard Rating 7

Physical Characteristics:

- Clear zone less than or equal to 1.5 m (5 ft).
- Sideslope 1:2 or steeper.
- Cliff or vertical rock cut.
- No guardrail.
- Non-recoverable with high likelihood of severe injuries from roadside collision.

Field Investigation Procedure

Simple Field Procedure for Determining Horizontal Curve Radius

Developed Under NCDOT Research Project 2009-09

by

Robert S. Foyle, P.E.

and

Daniel J. Findley, E.I.

at the:

Institute for Transportation Research and Education
North Carolina State University

Raleigh, North Carolina

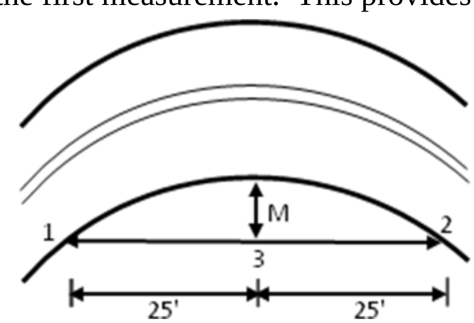
May 31, 2009

This document has been modified from its original content to reflect the needs of this field data collection to include only radius and superelevation information. Please refer to the original document for full instructions if a more detailed curve investigation is required.

1. Safety and Equipment – Before beginning any field investigation, check that all equipment is available and operable. Although this procedure was developed to minimize exposure to vehicles, some interaction is necessary, so follow NCDOT guidelines for personal safety while implementing this field procedure. Necessary equipment includes:
    a. Safety Vest (Class II or above as required)
    b. Digital Level (4’ long)
    c. Hammer
    d. Masonry Nails (e.g., Parker-Kalon 1½” by ¼”)
    e. Measuring Tape (50’ or 100’ Metal or Cloth, with metal preferred)
    f. Metal Tape Measure (25’)
    g. Clipboard, Field Investigation Form, and Pen
    h. Measuring Wheel

2. General Curve Investigation – Determine the limits (Point of Curvature, PC, and Point of Tangency, PT) of the curve through visual observations of the tangent sections leading into and out of the curve. All measurements should occur within these limits of the curve. Try to locate representative areas of the curve to conduct your measurements, avoiding any abnormalities. The first measurement should be about in the middle of the curve.

3. Measurement of Middle Ordinate – Determine the middle ordinate measurement through the following steps:
    a. Place nails in the pavement on the outside edge of the edgeline stripping 50’ apart (at points 1 and 2 in the figure). One nail can be used to hold the hook at the end of the 50’ measuring tape and the second nail can be used to pull the tape against or around (if cloth tape is used). The tape must be pulled taught and remain straight for step 3b.
    b. Measure the middle ordinate distance at the middle point of the tape (25’), using the smaller tape measure (at point 3 in the figure). The distance M should be read and recorded to the nearest 1/8”.
    c. Repeat this measurement by moving points 1 and 2 together about 10 feet left and then 10 feet right of the first measurement. This provides three measurements.



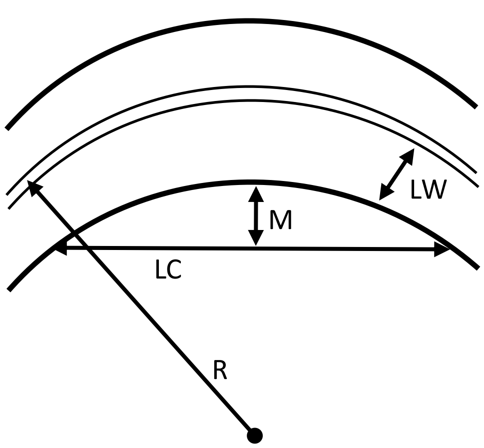
4. Measurement of Superelevation – Determine the superelevation of the curve by measuring the superelevation of the roadway perpendicular to the direction of travel by reading and recording five measurements that are representative of the superelevation of the middle section of the curve in each lane. Circle the median value, which will be used as the superelevation value. This value must be in increments of 0.2% as represented in the AASHTO Minimum Radius Tables. If necessary, round the field measured value up or down to the nearest 0.2% increment.

5. Radius Determination – Determine the radius of the curve by using the circled middle ordinate value from the Field Investigation Form and the Middle Ordinate Conversion Table. Add the inside lane width to the table value to determine the centerline radius of the curve. Record the value on the Field Investigation Form.

Middle Ordinate Conversion Table

Middle Ordinate, M (in)	Radius (ft) for a Long Chord of 50 ft	Middle Ordinate, M (in)	Radius (ft) for a Long Chord of 50 ft	Middle Ordinate, M (in)	Radius (ft) for a Long Chord of 50 ft	Middle Ordinate, M (in)	Radius (ft) for a Long Chord of 50 ft
0.125	30,000	2.625	1,429	5.25	715	10.25	366
0.250	15,000	2.750	1,364	5.50	682	10.50	358
0.375	10,000	2.875	1,304	5.75	652	10.75	349
0.500	7,500	3.000	1,250	6.00	625	11.00	341
0.625	6,000	3.125	1,200	6.25	600	11.25	334
0.750	5,000	3.250	1,154	6.50	577	11.50	327
0.875	4,286	3.375	1,111	6.75	556	11.75	320
1.000	3,750	3.500	1,072	7.00	536	12.00	313
1.125	3,333	3.625	1,035	7.25	518	12.25	307
1.250	3,000	3.750	1,000	7.50	500	12.50	301
1.375	2,727	3.875	968	7.75	484	12.75	295
1.500	2,500	4.000	938	8.00	469	13.00	289
1.625	2,308	4.125	909	8.25	455	13.25	284
1.750	2,143	4.250	883	8.50	442	13.50	278
1.875	2,000	4.375	857	8.75	429	13.75	273
2.000	1,875	4.500	834	9.00	417	14.00	268
2.125	1,765	4.625	811	9.25	406	14.25	264
2.250	1,667	4.750	790	9.50	395	14.50	259
2.375	1,579	4.875	769	9.75	385	14.75	255
2.500	1,500	5.000	750	10.00	375	15.00	251

Note: Add inside lane width to radius value from table to find centerline radius for a two-lane highway.



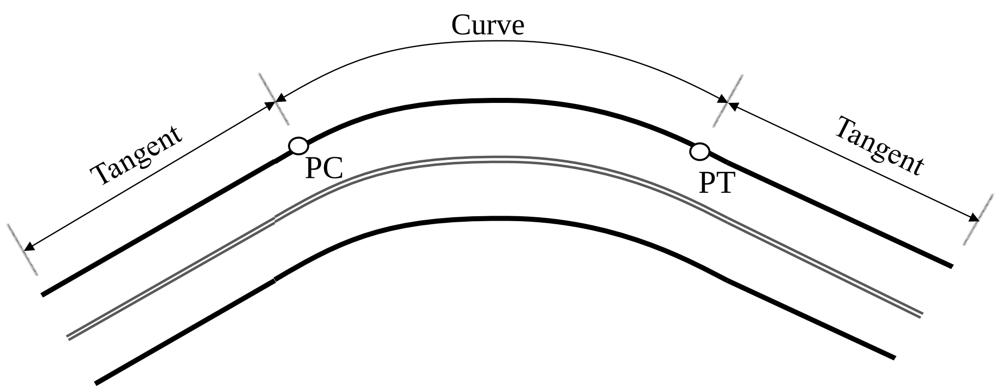
To find the radius of a curve with any chord length, the following equation can be used:

$$R = \frac{M^2 + 0.25LC^2}{2M} + LW$$

Where:
R = Radius (feet)
M = Middle Ordinate (feet)
LW = Lane Width (feet)
LC = Long Chord (feet)

Field Data Collection for Horizontal Curves Example

The following data will be used collected from N.C. DOT research project titled: *Procedure for Curve Warning Signing, Delineation, and Advisory Speeds for Horizontal Curves*. Each curve should be isolated from other curves with tangent sections on each end, as shown in the figure below. The Roadside Hazard Ratings Definitions are attached which will be beneficial when determining the Roadside Hazard Rating of the roadway. The radius and superelevation should be determined based on the attached Field Investigation Procedure from N.C. DOT Research Project 2009-09, which is also attached to this document.



I. GENERAL INFORMATION	
Investigator Name:	John Smith
Phone Number:	919-515-8564
Email Address:	John.Smith@ncdot.gov
County:	Wake
Road Name:	A Street
Closest Intersection:	0.2 miles West of B Street
Other Site Description:	0.3 miles East of C Street

II. ROADWAY FEATURES		
	Feature	**Curve**
1.	Posted Speed Limit (mph):	45 mph
2.	Lane Width (feet): *(Measure from center of the lane-line of the roadway to center of edgeline, round to the nearest foot)*	10 feet
3.	Inside Shoulder Width (feet): *(Measure from center of edgeline to edge of shoulder, round to the nearest foot)*	3 feet
4.	Inside Shoulder Type: *(Paved, Gravel, Turf, or Composite)*	Composite
5.	Outside Shoulder Width (feet): *(Measure from center of edgeline to edge of shoulder, round to the nearest foot)*	6 feet
6.	Outside Shoulder Type: *(Paved, Gravel, Turf, or Composite)*	Paved
7.	Length of Section (feet): *(Measure from beginning of the curve to the end of the curve along the edgeline, in feet, measure tangents from end of curve to the within 100' of the nearest intersection or next curve)*	400 feet
8.	Radius of Horizontal Curve (feet): *(Determine the radius using the attached Field Investigation Procedure and completed Field Investigation Form below)*	465 feet
9.	Roadside Hazard Rating (1-7): *(See the attached photos for examples)*	4
10.	Inside Lane Superelevation (%): *(Determine the superelevation using the attached Field Investigation Procedure and completed Field Investigation Form below)*	8.2%
11.	Outside Lane Superelevation (%): *(Determine the superelevation using the attached Field Investigation Procedure and completed Field Investigation Form below)*	7.8%
12.	Grade (%): *(Determine the grade using the digital level to find the steepest grade)*	6%
13.	Number of Driveways: *(Record the total number of driveways along the length of the roadway from beginning to end of segment on both sides)*	1
14.	Presence of Raised Pavement Markers (Yes/No):	Y
15.	Presence of Passing Lanes* (Yes/No):	N
16.	Presence of Roadway Lighting* (Yes/No):	N
17.	Presence of Centerline Rumble Strips* (Yes/No):	N
18.	Presence of Two-Way Left-Turn Lanes* (Yes/No):	N
19.	Presence of Shoulder Rumble Strips (Yes/No):	N
20.	Presence of Skid Treatments (overlay) (Yes/No):	N
21.	Presence of Skid Treatments (groove pavement) (Yes/No):	N

Note: *These elements are typically not present on rural, two-lane roadways

VIII. ROADWAY FEATURES (Continued)	
Feature	**Curve**
22. Presence of Vertical Curve Sight Distance Issues (Yes/No):	N
23. Presence of Sight Distance Obstructions (Yes/No): *(Describe the obstructions in the notes section)*	N
24. Presence of Guardrail (Yes/No):	Y
25. Type of Guardrail (W-beam, etc.):	W-Beam
26. Condition of Pavement Markings:	Good
27. Presence of Delineation on Guardrail (Yes/No):	Y

III. FIELD INVESTIGATION FORM

The Field Investigation Procedure for determining the Middle Ordinate Measurements and Superelevation Measurements are detailed in the attached document

Middle Ordinate Measurements

Measurement 1:	Measurement 2:	Measurement 3:
8 1/8 inches	8 1/4 inches	9 5/8 inches

Circle the median value above, this should be used as the middle ordinate measurement in the Middle Ordinate Conversion Table to determine the radius. Record the radius value below.

Radius: 455' + 10' (Lane Width) = 465'

Inside Lane Superelevation Measurements

Measurement 1:	Measurement 2:	Measurement 3:	Measurement 4:	Measurement 5:
8.2 %	8.0 %	8.4 %	8.4 %	8.0 %

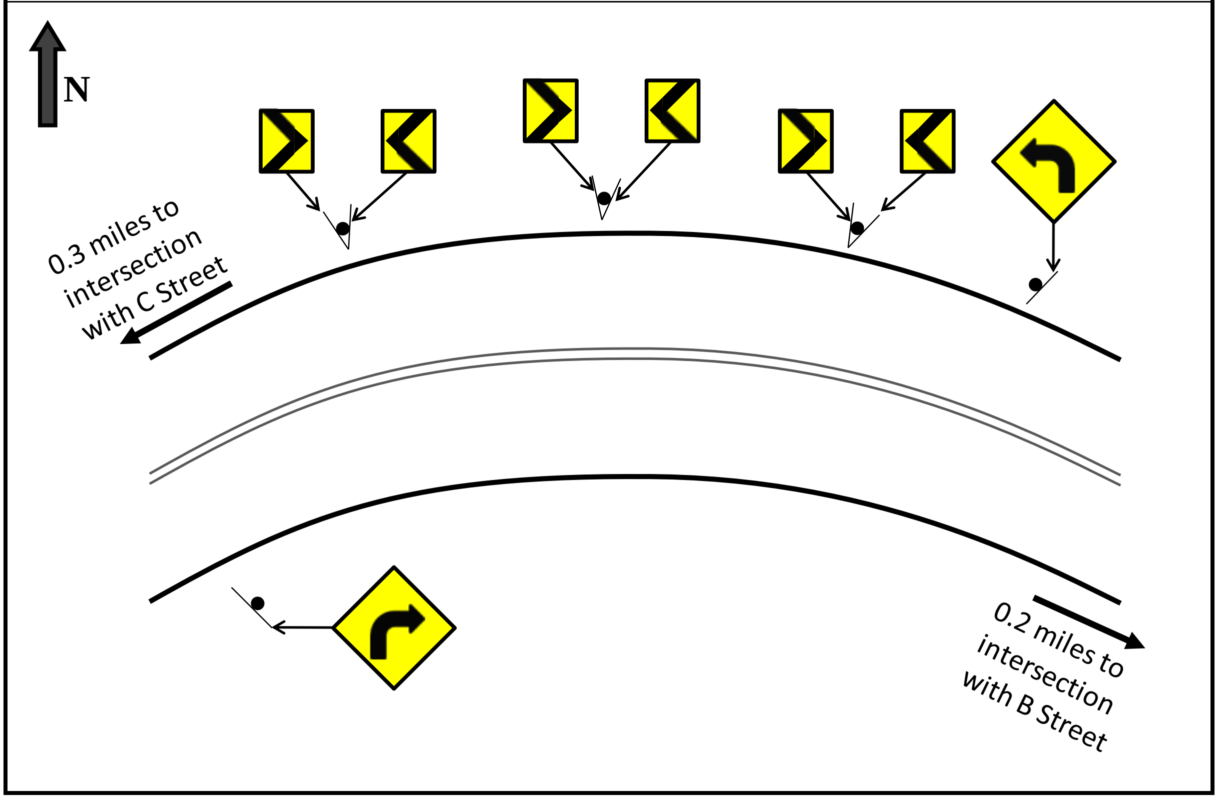
Outside Lane Superelevation Measurements

Measurement 1:	Measurement 2:	Measurement 3:	Measurement 4:	Measurement 5:
8.0 %	7.8 %	7.8 %	7.6 %	7.8 %

Circle the median value above for the inside and outside lanes. These should be used as the superelevation measurement.

IX. SIGNS (on the curve or immediate approach to the curve)					
Sign	**Number in Inside Lane Direction**	**Number in Outside Lane Direction**	**Sign**	**Number in Inside Lane Direction**	**Number in Outside Lane Direction**
	3	3			
				1	1
					
					
					
			Insert Advisory Speed Limit: 	1	1

IV. CURVE DIAGRAM
Please draw the overall curve features including signs and relative locations with nearest intersections.



V. Notes/Comments – Please describe/explain any unusual features or other notes