

TRAFFIC CONTROL DEVICE GUIDELINES FOR CURVES

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Paul Carlson, Bradford Brimley
Texas A&M Transportation Institute

H. Gene Hawkins, Jr.
Texas A&M University

Scott Himes, Hugh McGee, Frank Gross
Vanasse Hangen Brustlin, Inc.

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Paul J. Carlson, Ph.D., P.E.
Bradford K. Brimley, Ph.D.
Texas A&M Transportation Institute

Gene Hawkins, Ph.D., P.E.
Texas A&M University

Scott Himes, Ph.D.,
Hugh McGee, Ph.D., P.E.
Frank Gross, Ph.D., P.E.
Vanasse Hangen Brustlin, Inc.

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Executive Summary

Traffic control devices (TCDs) at curves serve the important function of communicating critical alignment information that can help drivers navigate the curve safely. Curves tend to be locations with high crash rates, and TCDs are one method of improving safety simply because of the information they communicate. There is a general consensus that curve-related TCDs are beneficial, though various reports are inconsistent in the specifics.

The objective of this research was to create guidelines for treating curves with TCDs, based on the needs of unfamiliar drivers and the potential for TCDs to improve safety at curves as determined by an examination of driver behavior and safety at curves. The research described in this report was designed to 1) characterize driver behavior at curves, 2) identify how TCDs at curves influence driver behavior, and 3) indicate the conditions under which TCDs at curves result in statistically significant reductions in crashes. The recommended guidelines for selecting TCDs in this report are supported mostly with new discoveries from the research, but also include a combination of material from previous studies, current *Manual on Uniform Traffic Control Devices* language, and engineering judgment. The recommended guidelines were designed so that the selection of curve-related TCDs fulfills unfamiliar driver needs and has a positive impact on safety.

While the recommendations for selecting TCDs at curves are primarily derived from results of the driver behavior and safety studies, there were other research activities whose findings were relevant in the development of recommended guidelines for treating curves, which are worth mentioning here. The following list describes the tasks of the research project and the main findings or result of that task.

- **Task 1: Review of Previous Research.** Several publications were reviewed to identify what is currently known about driver behavior at curves, the effects of curve-related TCDs on behavior, and how TCDs influence safety at curves. There are several inconsistencies regarding the specific effects of TCDs, but an overall agreement that TCDs communicate valuable information and, depending on the characteristics of the locations where they are used, can improve safety. Most of the information obtained from previous research is documented in Chapter 3 and Appendix D, with other important findings in other relevant places.
- **Task 2: Survey of State and International Practices.** Engineering documents from several states were reviewed to identify policies and guidelines for treating curves with TCDs to determine the “state of the practice” regarding curve-related TCDs. While reviewing the state documents, comparisons to information in the 2009 MUTCD were made to identify the extent to which states have adopted the federal guidelines or have developed their own procedures. The state policies tend to reflect the guidelines of the 2009 MUTCD, though there are some deviations that clarify policies or address specific practices in the state. The review of international practices identified some unique approaches to treating curves that influenced the formation of the recommended guidelines. Detailed results of Task 2 are provided in Appendix A and summarized in Chapter 2.
- **Task 3: Survey of State Driver Manuals.** The driver manuals of all 50 states were reviewed to identify what drivers are expected to know about curve TCDs and appropriate behavior at

curves. Though there are some states whose manuals provide detailed information about appropriate navigational behavior and the TCDs encountered at curves, most do not. It appears that drivers are expected to obtain this information through experience. Appendix B contains the detailed review of driver manuals; a summary is provided in Chapter 2.

- **Task 4: Conduct Driver Behavior Pilot Test.** The purpose of this task was to collect data from twelve unfamiliar drivers to solidify a procedure for collecting and analyzing data with a large number of participants in Task 7. The data and results of the pilot test are not reported here, but were used to make adjustments to the procedure and methodology used later.
- **Task 5: Determine Feasibility of Crash-Based Analysis.** This purpose of this task was to identify the data that were already available for a crash analysis and to determine the resources required to collect more data and improve the robustness of the analysis. The findings from Task 5 were applied in the work performed for Task 8.
- **Task 6: Prepare Phase I Deliverables and Meet with the Study Panel.** A report of the findings from Tasks 1–5 was produced and reviewed by the study panel. A meeting with the research team and the study panel helped direct the research that was conducted during the second phase of the study.
- **Task 7: Conduct Driver Behavior Study.** The driver behavior study involved having participants drive unfamiliar highways in three states using an instrumented vehicle that continuously collected performance data. A description of the study design is given in Appendix D. Appendix E documents how TCDs affect driver operational performance, and Appendix F contains findings of the analysis of eye-tracking data, showing how driver attention fluctuates throughout the process of negotiating curves. Findings presented in Chapter 4 document operational characteristics of drivers approaching and navigating curves, with brief references to Appendix E that state the effects TCDs have on behavior. The performance data indicate that the use of additional TCDs encourages drivers to start decelerating further from the curve and with reduced deceleration rates. The research team used these new discoveries to develop a curve TCD selection methodology based on the fulfillment of drivers' needs supported by research findings.
- **Task 8: Conduct Safety Analysis.** The crash-based study was conducted to identify how curve TCDs impact crash rates at curves. Analyses that produced crash modification factors indicate that TCDs used in advance of curves (e.g., Curve or Turn warning signs) and TCDs used within curves (e.g., chevrons or One-Direction Large Arrow signs) have the potential to substantially reduce curve crashes, especially as curve severity increases. In many instances, however, crash reductions are obtained only when traffic volumes reach specific thresholds (approximately 2,000 or 6,000 veh/day, depending on the level of significance). These volume thresholds are used in the recommended guidelines to suggest the level of regulation (either *recommended* or *required*) appropriate for a device under a specific scenario. A detailed description of the safety study is provided in Appendix G, with results documented in Appendix H. Chapter 5 summarizes the findings.
- **Task 9: Assess Findings from Tasks 7 and 8.** It was anticipated from the onset of the project that there would not be perfect harmony between the findings of the two primary research efforts (behavior and safety studies), although both studies would produce valuable information about driver behavior and safety. The purpose of Task 9 was to isolate the findings from the two studies that were the most meaningful and had potential for use in developing a methodology for selecting TCD treatments at curves.

- **Task 10: Determine Treatment Costs.** Any policy requiring the use of particular TCDs will financially impact the agencies responsible for their installation and maintenance. Each state has unique costs associated with these treatments. This task involved surveying state transportation agencies to identify the financial burdens associated with treating curves with TCDs. In addition to questions regarding the upfront costs and expected lifespan of the TCDs, the survey asked about the costs of performing the engineering work required to select an appropriate treatment. Results of the survey of treatment costs are documented in Appendix C and summarized in Chapter 2.
- **Task 11: Develop Methodology for Selecting TCD Treatments.** The assessment of findings performed in Task 9 identified the important pieces of information from the two primary research components to be used to develop treatment guidelines. In this task, the research team applied a combination of the critical findings of the present research, findings from previous research, and some additional judgment to identify the conditions at curves that are appropriate for TCDs. It is believed that the resulting methodology for selecting treatments is an approach that balances the expectations and needs of drivers at curves with the information provided by TCDs. Chapter 6 describes the approach to selecting TCD treatments; changes to the text of the 2009 MUTCD necessary to adopt the proposed guidelines are provided in Chapter 7.

Chapter 1: Introduction

BACKGROUND OF STUDY

Based on sampling from 2012 (1), crashes that occur at curves on two-lane roads are four times as likely to result in a fatality as crashes that occur elsewhere, and incapacitating injuries are twice as likely to occur. With a distribution of crash severity more treacherous for curves than for tangents, it is not surprising that highway curves have often been identified as locations with safety concerns (2, 3). Although highway curves are unavoidable, a number of enhancements can be used to make these locations safer. Such enhancements may include geometric changes (curve flattening) or increases in the pavement friction. These improvements, however, can be costly, and are thus only done in the most severe locations where agencies' resources are likely to provide the greatest benefit. In place of these more expensive solutions, traffic control devices (TCDs) are often used to address safety concerns associated with changes in horizontal alignment.

Warning signs (such as Turn, Curve, Winding Road, One-Direction Large Arrow, and Chevron signs) and a variety of delineation devices (such as post-mounted delineators and raised pavement markers [RPMs]) are the most common devices agencies place along or near curves to provide information to road users about the changing alignment. Prior to publication of the 2009 *Manual on Uniform Traffic Control Devices* (MUTCD), traffic engineers relied upon engineering judgment and engineering studies to determine the appropriate level of traffic control to apply at a curve; the 2003 MUTCD contained few requirements regarding the use of TCDs for changes in horizontal alignment. Past research has shown that such devices are used inconsistently from one jurisdiction to another and even from one location to another within a single jurisdiction. To address this inconsistency and to improve safety through applying the most appropriate TCDs at horizontal curves, the Federal Highway Administration (FHWA) introduced new material in the 2009 MUTCD. The new material is located in Section 2C.07 Horizontal Alignment Signs, which contains language pertaining to the application of signs on horizontal curves. One of the key elements of this section is Table 2C-5, which is shown in Table 1. Table 2C-5 calls for a hierarchical approach to select TCDs based on the speed change at a curve.

Table 1. Horizontal Alignment Sign Selection, adapted from MUTCD Table 2C-5

Type of Horizontal Alignment Sign	Difference Between Speed Limit and Advisory Speed			
	5 mph	10 mph	15 mph	20 mph or more
Turn (W1-1), Curve (W1-2), Reverse Turn (W1-3), Reverse Curve (W1-4), Winding Road (W1-5), and Combination Horizontal Alignment/Intersection (W10-1)	Recommended	Required	Required	Required
Advisory Speed Plaque (W13-1P)	Recommended	Required	Required	Required
Chevrons (W1-8) and/or One Direction Large Arrow (W1-6)	Optional	Recommended	Required	Required
Exit Speed (W13-2) and Ramp Speed (W13-3) on exit ramp	Optional	Optional	Recommended	Required

The introduction of the information in Table 1 initiated discussion among state departments of transportation (DOTs) and other agencies concerning the need for technical support before establishing a national policy. Many agencies had their own hierarchical approach, and those in southern states that do not have winter maintenance activities also noted that RPMs and delineation treatments, which can provide critical guidance information, were not included in the national policy. Other concerns have included the financial burden to treat curves in accordance with MUTCD Table 2C-5 and the apparent lack of flexibility in the current policy.

RESEARCH OBJECTIVES

The objective of this research was to develop guidelines for selecting TCDs at changes in horizontal alignment that can be incorporated into the MUTCD. The guidelines were to be based on a data-driven approach that documents driver behavior at curves, identifies the need for information provided by TCDs, and evaluates the impact TCDs may have on safety at curves. The issues faced by agencies and their concerns in applying TCDs at curves were to be considered in creating the guidelines.

RESEARCH APPROACH

In order to produce research-supported recommendations for treating curves with TCDs, the research plan involved multiple tasks that were aimed at studying driver behavior and safety at curves and the approaches and issues facing agencies as they work to improve safety and the

driving experience. Three separate tasks fall under the study of driver behavior and safety. The first was a review of driver handbooks, aimed at identifying what drivers are taught about TCDs and curve navigation when learning how to drive. The second study was a detailed investigation of how unfamiliar drivers approach and navigate curves on the open road, focusing on the effects of TCDs on driver operational performance and attention. The third was a crash analysis that documented the effects of curve TCDs on crash frequency and severity at curves.

Another issue of traffic control at curves is related to the perspectives of agencies responsible for treating curves in an effort to provide sufficient warning and guidance for navigation. This issue was addressed through two separate tasks. One was a survey of state, national, and international policies related to TCDs at horizontal curves. The other was a survey of state DOTs to identify the costs associated with providing TCDs at curves.

Of the five research tasks identified above, most resources were devoted to the open-road driver behavior study and the analysis of how TCDs influence crashes. The behavior and safety studies involved rich datasets and produced new results that propelled the research recommendations for selecting TCDs at curves. In order to complete the recommended guidelines for selecting curve-related TCDs, the research team supplemented their findings with key information from previous studies, current MUTCD language, and engineering judgment.

REPORT ORGANIZATION

Chapter 2 summarizes the current state of the practice of treating curves with TCDs, based on the review of state, national, and international policies. Additionally, the chapter includes a summary of the findings from the survey of driver manuals with respect to curve TCDs and how drivers are taught to navigate curves. Finally, Chapter 2 summarizes the findings from the investigation of costs for various TCDs.

Chapter 3 contains a summary of previous research on driver behavior, safety, and how TCDs at curves influence behavior and safety. While the primary research efforts described in this report involved obtaining an extensive amount of information about how TCDs influence driver behavior and safety at curves, it was understood from the project's beginning that the findings would not be exhaustive. In fact, it was always anticipated that there could be some contradictory findings when directly comparing the results of the safety and behavior studies. For these contradictions or areas lacking significant findings, there is value in identifying previous research that can be used in developing guidelines for TCDs at curves.

Chapters 4 and 5 focus on the results of the primary research activities, specifically the unfamiliar driver behavior study and the analysis of how TCDs impact crashes at curves. Chapter 4 describes the driver study and the critical findings of how drivers approach and navigate curves that contribute to the development of guidelines for TCDs at curves. Chapter 5 describes the safety analysis and also includes the findings that contribute to the guidelines for selecting TCDs. Chapter 6 contains the guidelines for selecting appropriate TCDs at curves based on the conducted research activities.

This report has several appendices that expand the methods and results of the studies described in the main body of the report. Appendix A is the review of state driver manuals. Appendix B is the review of state, national, and international practices for applying TCDs at curves. Appendix C is the survey of TCD costs based on data from several state agencies. Appendix D describes the procedures for conducting the open-road behavior study with

unfamiliar drivers and the methods used to analyze the data. Appendix E contains the findings from the open-road study regarding operational driver performance, and Appendix F contains the findings from the open-road study regarding driver attention. Appendix G describes the background and methods used in the safety analysis, and Appendix H contains the study results. Appendix I contains the specific language recommended for adoption in the national MUTCD.

Chapter 2: Background, Current Practices, and Financial Costs of TCDs

The horizontal components of a roadway are categorized into two types of segments: tangents and the changes in horizontal alignment (or curves) that connect them. While tangents provide the most direct connection between two locations, curves allow the tangents to be arranged so the road avoids crossing critical areas. Drivers thus expect to encounter curves. Regardless of such an expectation, curves historically have experienced disproportionately high crash rates (2).

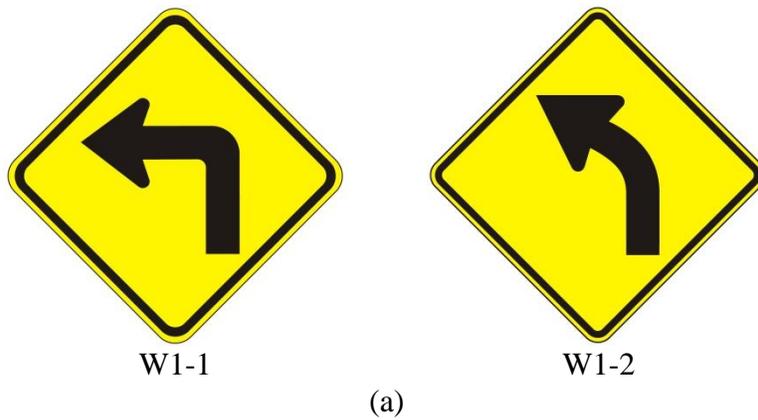
TCDs are used to provide drivers information relevant to the driving task. The MUTCD contains guidelines for the use of TCDs, defining when they must, should, or can be used. TCDs can be applied at curves—whether required by standards or otherwise optional—as a relatively low-cost treatment for reducing crashes, and their effectiveness at doing so has been shown multiple times (4, 5). Most previous research on TCDs has focused on showing that operational performance (traditionally measured as a vehicle’s speed, position, and acceleration) improves when TCDs are used.

One of the five requirements of an effective TCD, as stated in the MUTCD, is that the device should fulfill a need. For applying TCDs at a curve, this need is for the additional information that otherwise might not be provided to a driver but is necessary for the driver to prepare for and complete safe navigation. There are many TCDs that can be used at curves to provide drivers with important information. This chapter discusses the TCDs that are most commonly used: warning signs at or before curves, warning signs within curves, and delineation devices (specifically, RPMs and post-mounted delineators). After a discussion about the design and use of each device, a summary of the review of state driver manuals is provided, followed by a summary of the review of state, national, and international policies for curve TCDs. The final research presented in this chapter is the survey of costs state DOTs face in treating curves with TCDs.

TRAFFIC CONTROL DEVICES AT CURVES

Curve and Turn Horizontal Alignment Warning Signs

The most basic horizontal alignment warning signs used at curves are the Turn (W1-1) and Curve (W1-2) warning signs placed in advance of curves, shown in Figure 1. MUTCD Table 2C-5 requires that an advance warning sign be used when the speed on the approach tangent—defined as either the prevailing speed or the greater of the speed limit or 85th percentile speed—is 10 mph or greater than the curve advisory speed. A Turn sign is to be used instead of a Curve sign if the curve advisory speed is 30 mph or less. An Advisory Speed Plaque can be added to these warning signs to indicate to drivers the advisory speed. Such plaques are required by MUTCD Table 2C-5 when the speed change at the curve is 10 mph or greater.



(a)



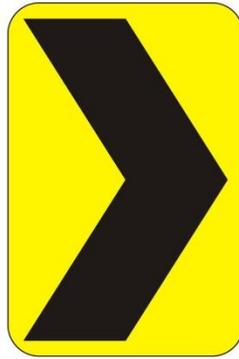
(b)

Figure 1. (a) Horizontal Alignment warning signs and (b) Curve sign with Advisory Speed Plaque.

There are several derivatives of the Turn and Curve signs that are not shown here. The Reverse Turn, Reverse Curve, and Winding Road signs are to be installed in advance of a series of curves when the curves are spaced less than 600 ft apart. Other derivatives include the Combination Horizontal Alignment/Intersection or Combination Horizontal Alignment/Advisory Speed signs, which also have an important role in communicating alignment information to drivers. The conditions investigated in this research specifically apply to curves in isolation or series with no other features that would require the use of a different warning sign.

Chevron Alignment Sign

The Chevron sign (W1-8) (Figure 2) was first included as an optional device in the 1978 MUTCD with guidelines describing how Chevron signs are to be used (with requirements for size, color, and spacing), rather than requirements stating where they are to be used. Later editions of the MUTCD clarified some of the guidelines, but not until the 2009 edition did chevrons become mandatory at some curves based on severity as defined by speed change at the curve. As indicated in MUTCD Table 2C-5, the use of chevrons and/or the One-Direction Large Arrow sign is required at curves when the difference between the approach and curve speeds is 15 mph or greater. Figure 2(b) shows chevrons with retroreflective sheeting applied to the posts, a common application in Texas.



W1-8
(a)



(b)

Figure 2. (a) Chevron Alignment sign and (b) chevrons installed at a curve.

The 2009 MUTCD indicates that “Chevron Alignment signs may be used [at curves] instead of or in addition to standard delineators,” implying that there are conditions that justify the use of delineators. The MUTCD currently does not require the use of delineators at curves. The use of chevrons specifically for curves is made clear by statements prohibiting their use on the far side of a T intersection (where a Two- or One-Direction Large Arrow sign would be appropriate) or as a device for marking obstructions (which is the function of an object marker). While previous editions of the MUTCD (and multiple best-practices documents) state that at least two chevrons should be in view to drivers on curves, the 2009 MUTCD provides spacing guidelines (shown in Table 2) based on curve radius or curve speed, which ensure that enough chevrons are in view for conventional applications.

Table 2. Spacing Guidelines for Chevrons from MUTCD Table 2C-6

Advisory Speed	Curve Radius	Sign Spacing
15 mph or less	Less than 200 ft	40 ft
20 to 30 mph	200 to 400 ft	80 ft
35 to 45 mph	401 to 700 ft	120 ft
50 to 60 mph	701 to 1,250 ft	160 ft
More than 60 mph	More than 1,250 ft	200 ft

Note: The relationship between the curve radius and the advisory speed shown in this table should not be used to determine the advisory speed.

One-Direction Large Arrow Sign

The MUTCD states that the One-Direction Large Arrow sign (W1-6) (Figure 3) may be used either as a supplement or alternative to Chevron Alignment signs. While there is no explicit statement that indicates only one One-Direction Large Arrow sign shall be used for a given curve, figures within the MUTCD imply that only one sign is necessary. When used at curves, the One-Direction Large Arrow sign is to be placed on the outside of the curve facing the direction of the approaching traffic.



W1-6
(a)



(b)

Figure 3. (a) One-Direction Large Arrow sign and (b) Large Arrow sign at a curve.

Raised Pavement Markers

Several agencies use RPMs, as shown in Figure 4, to supplement or replace traditional pavement markings. While the retroreflective elements of conventional pavement markings tend to be composed of glass beads, RPMs use prismatic sheeting, which tend to be more efficient at reflecting light and can be visible for much longer distances. The MUTCD does not require that RPMs be used for any specific circumstance, though southern states that do not have winter maintenance activities tend to use them more frequently than northern states.

The MUTCD states that “to improve the visibility of horizontal curves, center lines may be supplemented with [RPMs] for the entire curved section as well as for a distance in advance of the curve that approximates 5 seconds of travel time.” RPMs that supplement other markings should be spaced a distance equal to a broken line segment plus one gap of broken lines on the highway when the other markings are solid lines (which are often used at curves).



Figure 4. Raised pavement marker supplementing solid line markings.

Post-Mounted Delineators

Post-mounted delineators (Figure 5) have reflective elements mounted vertically approximately 4 ft above the edge of the roadway. The reflective elements of delineators tend to be 3 inches in width, which is considerably less than the minimum 18-in width of chevrons. To account for the overall small dimensions, the MUTCD states that the delineators “shall be capable of clearly retroreflecting light...from a distance of 1,000 feet when illuminated by the high beams of standard automobile lights.” Although they are small, and thus not very conspicuous during the daytime, delineators are considered to be effective devices at night and during adverse weather.



Figure 5. Delineators applied on the outside of a curve.

Guidance on delineator spacing in the 2009 MUTCD is based on curve radius. Similar to chevrons, multiple delineators should always be simultaneously visible in order for the road user to be able to identify the change in alignment. Table 3 identifies the appropriate spacing for delineators on curves from MUTCD Table 3F-1.

Table 3. Delineator Spacing from MUTCD Table 3F-1

Radius (ft)	Delineator Spacing (ft)
50	20
115	25
180	35
250	40
300	50
400	55
500	65
600	70
700	75
800	80
900	85
1,000	90

TCDs Illuminated at Night

TCDs are particularly important at night, when driver visibility is determined by the headlamp illumination that is reflected back to the driver. With the absence of natural light that makes fences, tree lines, or other boundaries associated with roadway alignment visible, drivers rely more on TCDs for specific information about the alignment. The retroreflective properties of TCDs make them particularly conspicuous at night, as shown in Figure 6. Because of the small size of each individual device, RPMs and delineators are primarily beneficial at night. The dimensions of curve warning signs, chevrons, and Large Arrow signs are quite large, which contributes to their visibility during both daytime and nighttime.

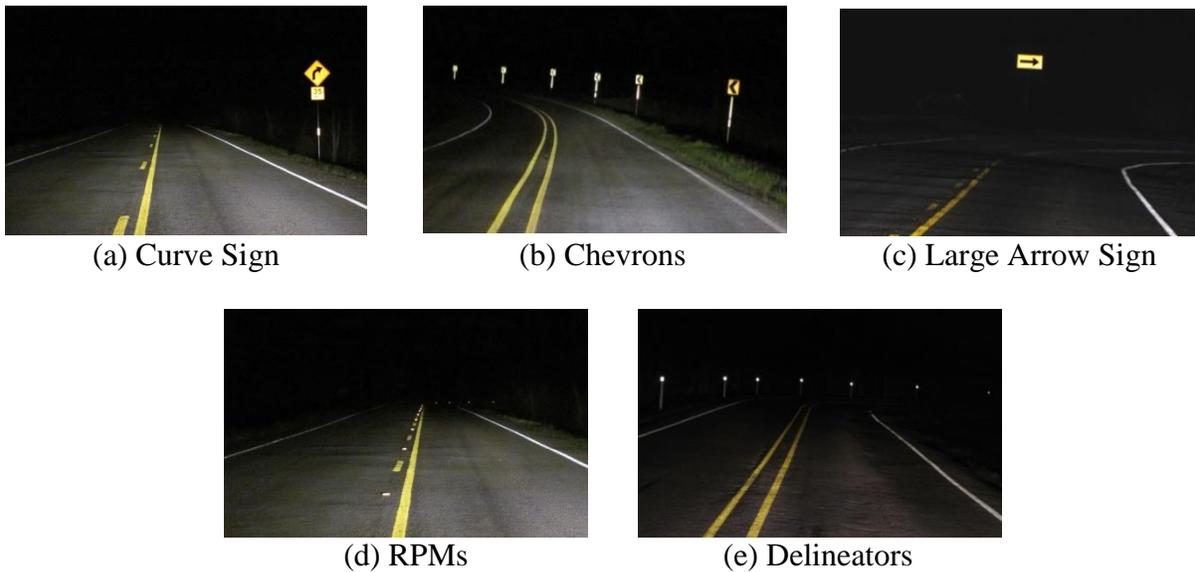


Figure 6. TCDs illuminated by headlamps at night.

STATE DRIVER MANUALS

Each state is responsible for the publication of a driver manual (or handbook) that includes information for the beginning driver to learn about safe vehicle operation. While most manuals are used in the education of new drivers, they can also serve as a resource for experienced drivers who may need to review some of the rules of the road or safe practices. This study included a review of the driver manuals of all 50 states and the District of Columbia to identify the extent to which states teach drivers about TCDs at curves and how to navigate curves safely. The review was based on manuals that were in use in 2012.

The full review of the driver manuals is contained in Appendix A. Overall, there is substantial variability in what drivers are taught about TCDs, including the proper way to respond to them and how to navigate curves. Of the 51 manuals, 13 do not contain any examples of signs or other information regarding TCDs at curves. The other 38 manuals contain at least one or more examples of curve TCDs in diagrams, usually with a short caption accompanying the image. Most manuals identify illegal maneuvers at curves, such as U-turns, passing, and

stopping. Apart from identifying such restrictions, 19 manuals do not provide any guidance on how to safely navigate curves.

There are some inconsistencies between the information about TCDs contained in the driver manuals and the MUTCD guidelines for curve TCDs. A certain level of inconsistency is understandable considering the audiences for each document, but it is advisable that the parties involved in drafting either the driver handbooks or the MUTCD be familiar with the policies and guidelines followed by the other party with respect to either the selection of TCDs or the information they are assumed to convey. It is important to have consistency between how drivers are taught to interpret TCDs and how decision makers intend for them to be interpreted.

STATE PRACTICES

MUTCD Table 2C-5 introduced a hierarchical approach to treating curves with the goal of ensuring uniformity in the application of TCDs. While states have the option to create their own guidelines, their practices must be in substantial conformance with the national MUTCD. To determine the extent to which states have either adopted the national policy or developed their own policies, the research team conducted a review of state practices based on state MUTCDs and engineering manuals. The review of state practices was based on a sample of 15 states with individual MUTCDs or a supplement to the national manual and 7 states with a traffic engineering manual.

Findings from the review of state MUTCDs and traffic engineering manuals (found in Appendix B) indicate that most states have adopted the guidelines of the 2009 MUTCD with only minor changes that clarify some of the text of the national manual. Information from the 2009 MUTCD and state practices suggests that multiple agencies use RPMs and delineators at curves. Although these two devices provide drivers with valuable alignment information, the current MUTCD does not include them in the hierarchy for treating curves. Based on current practices and information found in the reviewed manuals, it seems reasonable that some flexibility can be given to agencies when including RPMs and/or delineators in a proposed hierarchy for traffic control treatments. With the possibility of using alternative devices, there may be circumstances where agencies can meet driver needs without using multiple signs within curves, a practice that would expend fewer resources.

INTERNATIONAL PRACTICES

The policies regarding the use of TCDs at curves in five countries were reviewed to identify some of the ideas and approaches used by agencies outside the United States. Appendix B contains the complete review of the international practices. This section provides a summary of the findings. In comparison to how TCDs at curves are selected in the United States, there are three principal differences in the methods other countries use to select TCDs. They include consideration of the approach and curve speeds, the possible use of additional devices such as RPMs or delineators, and the size of the signs used.

Approach and Curve Speeds

Australia and Denmark are two countries whose policies reflect consideration for both the approach and curve speeds in the selection of TCDs. With such an approach, rather than using total speed change alone, decision makers can better account for the actual demands of the curve. For example, a 20-mph speed change at a higher initial speed is more demanding than a 20-mph speed change at a lower speed in terms of kinetic energy reduced and the distance over which the speed change occurs if the deceleration rate is constant for the two scenarios. Pratt and Bonneson (6) provide a discussion of using changes in energy in the assessment of curve severity, with a suggested application being the selection of TCDs. They discuss that, while previous research has shown that larger speed reductions at curves lead to higher crash rates, no consideration for the tangent speed before the curve will lead to an incorrect assessment of curve severity that is not consistent with driver expectations. A curve with a given speed reduction will be more severe if the approach tangent speed increases. Consideration of the operating speeds before and within curves, which is done in other countries, results in a better representation of the needs of drivers.

Delineators and RPMs

Although the 2009 MUTCD approves the use of delineators or RPMs at curves, the current guidelines indicating how agencies are expected to treat curves (Chapter 2C, “Warning Signs and Object Markers”) include only the use of signs. The review of international practices identified that delineators and RPMs are commonly used to treat curves in addition to signs. Denmark and Australia are two countries whose policies acknowledge that RPMs and delineators provide important alignment information to drivers and may be appropriate substitutes for signs placed within curves. By recognizing that alternative devices within curves (other than signs) may be appropriate in some circumstances where the current guidelines require the use of Chevron Alignment signs, agencies stand to benefit from the potential savings of reduced costs and the improvement of having the perceived messages of their devices better match the intended warning.

Sign Size

Policies in New Zealand and Australia include increases in sign size as curve severity increases. By increasing the sign size, the conspicuity and prominence of the sign reflects the importance of the message. Adjustments in sign size have a similar purpose to alternative devices in a treatment hierarchy: there are more options for communicating to drivers about the presence of a curve and its severity, so agencies have increased flexibility in providing the information necessary to warn drivers of upcoming curves and help them prepare to negotiate them.

SURVEY OF TCD COSTS

State DOTs were surveyed to identify the costs associated with installing TCDs at curves. They were asked to estimate the cost of performing an engineering study at a single curve (to

assess the need for a TCD treatment), the cost to install various TCDs, and the expected service life of each TCD. Each was also asked whether or not the agency uses any devices at curves that are not included in MUTCD Table 2C-5. Twenty-three states responded to the survey. A more complete description of the cost survey is provided in Appendix C.

There was substantial variability in the responses from the 23 state DOTs, reflecting the variety of options for each state to select a method to evaluate curves, obtain traffic control products, and install the devices. Additionally, the structure of each DOT and the number of curves in a jurisdiction may contribute to this variability. To limit the influence of extreme variability on each type of cost published here, the maximum and minimum in each category were excluded before calculating an average. Excluding the maximum and minimum values, the average cost of an engineering study for one curve is \$391.

Table 4 identifies the average material and installation costs and expected service life of each curve treatment investigated in the survey of state DOTs. Again, the averages were calculated after excluding the reported maximum and minimum values for each treatment. For consistency in estimating the cost to treat a single curve, the survey included a sample quantity of each TCD at one curve as given in the table. Specific conditions for a real curve will determine the actual quantity that should be used. None of the values in Table 4 account for maintenance costs.

Table 4. Average* TCD Treatment Costs

Treatment (Qty. per Curve)	Material Unit Cost	Installation	Total Cost per Curve	Service Life (Years)
Advance warning signs (2)	\$132	\$380	\$644	11.9
Advisory Speed plaques (2)	\$45	N/A	\$90	11.9
Chevrons (12; 6 per direction)	\$88	\$1,320	\$2,376	11.1
Large Arrow (2)	\$148	\$328	\$624	11.4
Delineators (8, applied on the outside)	\$27	\$383	\$599	9.1
RPM (snowplowable) (15)	\$9.67	\$499	\$644	5.8
RPM (non-snowplowable) (15)	\$1.83	\$101	\$128	2.2

* Based on responses of 23 state DOTs, excluding the maximum and minimum values

SUMMARY

This chapter discusses a variety of TCDs that communicate alignment information to drivers, how drivers are taught to navigate curves, the policies regarding how curves are treated across different agencies, and the costs for agencies to install TCDs at curves. While the 2009 MUTCD indicates that these devices may be used at curves, only the Turn or Curve warning sign (and their derivatives), Chevron Alignment sign, and One-Direction Large Arrow sign are included in actual guidelines for treating curves in Chapter 2C. Several agencies both within and outside of the United States use either delineators or RPMs to treat curves. Based on the reported costs to treat curves and the widespread use and likely benefit of delineators and RPMs, there appears to be great potential in identifying how those devices may fit within a policy for applying TCDs at curves.

Chapter 3: Previous Research

The design of horizontal curves is governed by the limitations of the system comprised of the driver, vehicle, and pavement. Guidelines for design (the most common ones are set by the American Association of State Highway and Transportation Officials and published in the “Green Book” (7)) are set conservatively so that the limitations of the driver, vehicle, and pavement should never be exceeded under normal operating conditions. These limitations can include the driver’s expectations and desire for comfortable navigation, the ability of the vehicle to respond to the driver’s maneuvers, and the ability of the pavement to supply the frictional forces that support the vehicle’s movements. Despite conservative guidelines, crashes continue to occur at curves in disproportionate numbers.

Three main geometric features that characterize curves are the radius, deflection angle, and superelevation. The radius defines the degree of curvature, or how quickly the direction of travel changes; the deflection angle is the total change in direction from the beginning to the end of the curve; and superelevation is the amount of banking or lateral incline. Lateral forces acting toward the center of the curve must be applied in order for a vehicle to travel in a circular path. Lateral acceleration has a quadratic relationship with the vehicle’s longitudinal speed and an inverse relationship with the curve radius. Superelevation reduces the lateral forces required to support the circular movement. The deflection angle alone does not directly affect the forces felt by the driver but may influence driver behavior because drivers tend to apply cornering techniques to “cut” the curve. Additionally, drivers may perceive curves with large deflection angles as more severe than those with small deflection angles. Superelevation does impact operational behavior, but a curve’s superelevation is more difficult to perceive at a distance than the radius or deflection angle. Its subtlety is evident by the absence of superelevation in numerous models of speed or acceleration. Other geometric elements also influence the behavior of drivers, such as the lane and shoulder widths, vertical curvature, and use of spiral transitions. The effects of these geometric elements were not specifically identified in the driver behavior analyses, though their influence was considered throughout in the study. The effects of lane and shoulder width were evaluated in the safety analyses, and were occasionally found to significantly influence safety.

In addition to the geometric components that must be considered in curve navigation, TCDs are an important element that contributes to the driving experience. Depending on the geometry, some curves may be severe enough that drivers need information provided from sources other than the roadway itself in order to properly prepare to navigate the curve. It is expected that, like the components of the curve’s geometry, TCDs impact how drivers approach and navigate curves, as measured both by driver behavior and observed crashes. The purpose of this chapter is to present previous research that has been conducted on driver behavior and safety at curves and the TCDs that are used at curves.

DRIVER BEHAVIOR WHILE NAVIGATING CURVES

Operational Performance

Many factors affect driver operational behavior at curves. The amount of lateral acceleration experienced by a driver navigating the curve has been identified as a controlling factor for the operating speed on the curve. Research shows that drivers do not adjust their speeds on curves to consistently accept the same amount of lateral acceleration. At higher speeds, for example, drivers are more cautious and accept less lateral acceleration (8-11). Since lateral acceleration is partly determined by the geometry of a curve, geometric elements will thus affect how much deceleration occurs as the driver approaches a curve. Depending on the speed at which drivers approach a curve, they may need to decelerate to a speed comfortable for navigation.

Driver speed throughout a single curve is usually not constant. Figueroa Medina and Tarko (12) observed that 66 percent of the total deceleration occurs on the tangent preceding the curve, with the remaining 34 percent of deceleration continuing after the point of curvature (PC). Generally, the minimum speed is assumed to be reached near the midpoint of the curve. Multiple speed prediction models (13-15) estimate a lower speed at the midpoint than at the PC. Speeds at the point of tangency (PT) are usually close to speeds at the entrance.

Early research on deceleration rates at curves identified constant rates of deceleration, based on observed averages. A rate of 2.79 ft/s^2 for both deceleration and the downstream acceleration was the first proposed value that was later validated by a separate study (16, 17). While Collins and Krammes (17) found the deceleration rate of 2.79 ft/s^2 to be an appropriate assumption, they observed that acceleration rates tend to be lower in magnitude. They noted that the assumption that deceleration and acceleration occur only on the upstream and downstream tangents is an oversimplification of true driver behavior, because deceleration and acceleration also occur within the confines of the curve. From the data evaluated by Figueroa Medina and Tarko (12), the average deceleration and acceleration rates were approximately 2.4 and 1.6 ft/s^2 , respectively. Fitzpatrick et al. (18) also showed that acceleration and deceleration rates are not equal, and are dependent on curve geometry. A step function based on curve radius was produced, with deceleration rates ranging from 0 to 3.3 ft/s^2 .

Drivers select a comfortable speed that is based on a number of factors associated with the design and operational characteristics of the facility. On a two-lane highway, for example, the *Highway Capacity Manual* identifies reductions in free-flow speed when the lane or shoulder width is less than 12 or 6 ft, respectively (19). Upon exiting a curve, drivers will want to accelerate to a comfortable operating speed, depending on the deceleration previous to the curve, the information they have, and their expectations about the upcoming curve. Hu and Donnell (20) showed that the acceleration rate after a curve is related to the deceleration rate immediately before the curve, and that the deceleration rate before a curve is related to the earlier acceleration rate exiting the upstream curve. This should not be surprising because there is a greater potential for drivers to increase their speed after exiting a severe curve that required substantial deceleration.

From past research (e.g., Figueroa Medina and Tarko (21)) there appear to be three principal phases of curve negotiation: 1) the acceleration that occurs when exiting a curve, 2) the deceleration that occurs when approaching a curve, and 3) the operational behavior that occurs within a curve. Models of operational metrics at curves have primarily focused on vehicle speeds

using radius (or degree of curvature) as the principal independent variable. Operational speeds on the approach tangent have also been found to significantly affect speeds within the curve (22-24). The models indicate that if there are two curves of identical geometry, the one that has a higher approach speed will have a higher operating speed. Bonneson (22) suggests that this happens because drivers are reluctant to decelerate at curves, even though they recognize there is a need to do so.

Visual Behavior and Attention

Most of the past research on driver behavior has focused on how drivers operate the vehicle, but eye-tracking technology has created an opportunity for more-closely evaluating the actual decision-making processes, rather than the output of operational performance. Early eye-tracking technology allowed researchers to identify where drivers look, but modern technology now has the capability to identify psychophysiological metrics that represent driver cognition.

One of the first evaluations of the visual behavior of drivers at curves was attributed to Shinar et al. (25). They investigated how eye movements differ when drivers are on a straight road with no approaching visible curve, on an approach immediately before a curve, and on the curve. The researchers found that lateral eye movements generally follow the direction of the curve beginning 2–3 s before entering the curve. In terms of vertical movements, the eyes exhibited patterns of fixations far ahead of the vehicle, followed by brief fixations near the vehicle, as if the driver needs verification of lane position. Based on the fixations on the road and scenery while the driver is on approach tangents compared to fixations when on curves alone, the researchers concluded that the process of curve negotiation starts before the curve, indicating the importance of the visual behavior on the approach.

Cohen and Studach (26) also evaluated visual behavior at curves but focused on the duration and location of fixations for inexperienced and experienced drivers. Fixations were different based on curve direction, and they found that the fixations of experienced drivers compared to those of inexperienced drivers were shorter and covered a greater horizontal distribution (which indicates more searching), which confirmed earlier findings of Mourant and Rockwell (27). As drivers approached a curve, the duration of the fixations decreased and the fixations were directed in the direction of the curve, similar to findings by Shinar et al. (25).

To reinforce the importance of previous findings regarding visual behavior on curve approaches, Lehtonen et al. (28) studied how eye movements on approaches change under different conditions of driver cognitive workload. They suggest that glances toward the occlusion point (the location where the curve becomes hidden from view) indicate that the driver is anticipating potential hazards and searching for additional roadway information. While other points along the road are used for steering and maintaining appropriate lane placement, such as locations near and far from the vehicle (29), thus focusing on the occlusion point is critical to judging curve severity and is different for each curve depending on the local conditions. In the study conducted by Lehtonen et al. (28), the researchers presented drivers with mathematical tasks during one of three runs with each participant. Each “loaded” run included cognitive loads placed on the drivers that required use of their working memory. During the two “free” runs, drivers made anticipatory eye movements more frequently than during the one loaded run. These studies indicate that anticipatory eye movements are an important part of the driving task, specifically as they relate to noticing potential hazards (such as curves) and determining a strategy for navigating them.

TRAFFIC CONTROL DEVICES AT CURVES

Chapter 2 identified a few of the several TCDs that agencies can use to warn drivers of an upcoming change in alignment and guide them through the curve. This section discusses some of the research on those devices.

Pavement Markings

The MUTCD requires that pavement markings be used on all highways with traffic volume greater than 6,000 vehicles per day (vpd). Because pavement markings are applied continuously, they are the first devices to provide drivers with information that guides them through alignment changes. Multiple studies have evaluated the distances at which drivers can view pavement markings or can identify changes in alignment based on pavement markings alone. They are summarized in this section.

Zwahlen and Schnell (30) used old and young participants to identify the visibility of pavement markings with medium ($R_L = 268 \text{ mcd/m}^2/\text{lx}$ for white markings) and high ($R_L = 706 \text{ mcd/m}^2/\text{lx}$ for white markings) retroreflectivity under low-beam and high-beam illumination. The average detection distance for older subjects with pavement markings of medium retroreflectivity illuminated by low-beam headlamps was approximately 400 ft. High beams and higher retroreflectivity slightly increased the detection distance. The young participants had longer average detection distances (an increase of 200 to 300 ft). An earlier study by Zwahlen and Schnell (31) found that 95 percent of young drivers detected a right curve at 265 ft and a left curve at 220 ft using a single right edge line alone (radius = 800 ft).

Several products are available for applying pavement markings, each with different properties to meet agencies' needs. The cited studies by Zwahlen and Schnell involved the raw detection distances of pavement markings. A study completed at the Texas A&M Transportation Institute (32) combined the detection distances of various pavement marking materials with vehicle speeds to determine the preview time provided to a driver traveling at a particular speed. The results of 18 pavement marking products and one RPM are shown in Table 5. Based on how the preview time is calculated, the preview time decreases as the speed increases. It appears that preview times of 3 or 4 s in dry conditions for speeds between 55 and 65 mph are not uncommon. No product under dry conditions has an average preview time less than 2.4 s.

The safety benefits of pavement markings over having no pavement markings (applicable to low-volume roads) have been shown multiple times (33-35). The MUTCD states that the width of "normal" pavement markings is 4 to 6 in, but agencies can use wider markings to provide greater conspicuity, especially at locations of complex environments. Use of wide markings has increased among state agencies (36, 37). Regarding safety, Park et al. (38) found that wider edge lines led to lower crash rates on rural roads in three states (Kansas, Michigan, and Illinois), though the reductions in crashes were not the same across all three states. Gates and Hawkins (36) found conflicting evidence of the safety benefits of wide pavement markings from a review of published studies (39-42) and unpublished internal documents. They conclude that the random and infrequent nature of crashes limits the ability to find a statistically valid relationship between small, subtle changes in line width and crashes.

The difficulty of linking marking width to safety, especially at curves, has led a number of researchers to study the effects of width on operational measures that may be surrogates for

safety. Lum and Hughes (43) found no link with safety but in a before-after field evaluation found wide pavement markings to reduce lane encroachments. Donnell et al. (44) studied the benefits of using wide (8-in) edge lines instead of standard edge lines on horizontal curves using measures of speed, frequency of line encroachments, lateral vehicle position, and deceleration distance at curves. The researchers were unable to identify a significant change in most operational measures but observed that drivers began decelerating on the approach to the curve at night earlier with the wide markings than with the standard markings.

The finding that wide markings lead to earlier responses at curves suggests that pavement markings play an unappreciated role in providing important alignment information to drivers. There are many situations at curves where pavement markings by themselves may be sufficient, but their utility as a TCD is often overshadowed by other devices (such as warning signs, chevrons, or delineators). Although the present study did not directly evaluate the performance of wide pavement markings, the review of potential safety and operational improvements due to wide markings emphasizes the important role markings (even traditional ones) have in providing drivers guidance information.

Table 5. Preview Times (seconds) of New Pavement Marking Materials at Night (Adapted from Carlson et al. (32))

Marking Material	Dry Conditions				Wet Conditions			
	30mph	45mph	55mph	65mph	30mph	45mph	55mph	65mph
Polyurea 4" Mixed Beads	8.43	5.62	4.60	3.89	3.73	2.48	2.03	1.72
Thermoplastic 4" Mixed Beads	7.00	4.67	3.82	3.23	3.55	2.36	1.93	1.64
Thermoplastic 6" Mixed Beads	6.98	4.65	3.81	3.22	3.93	2.62	2.14	1.81
Methyl methacrylate 6" Type I Bead	6.30	4.20	3.43	2.91	3.93	2.62	2.14	1.81
Methyl methacrylate 4" Type I Bead	5.91	3.94	3.22	2.73	3.98	2.65	2.17	1.84
Tape 4" High Index Bead	7.23	4.82	3.94	3.34	4.45	2.97	2.43	2.06
Thermoplastic 4" Mixed Beads	7.27	4.85	3.97	3.36	3.82	2.55	2.08	1.76
Thermoplastic 6" Mixed Beads	7.48	4.98	4.08	3.45	4.16	2.77	2.27	1.92
Tape 6"	7.57	5.05	4.13	3.49	4.80	3.20	2.62	2.21
Thermoplastic 4" Type II Bead	6.02	4.02	3.29	2.78	3.16	2.11	1.72	1.46
Thermoplastic 4" (rumble stripe) Type II Bead	5.39	3.59	2.94	2.49	3.66	2.44	2.00	1.69
Thermoplastic 6" Type II Bead	5.39	3.59	2.94	2.49	3.36	2.24	1.83	1.55
Thermoplastic 4" Type II Bead	5.20	3.47	2.84	2.40	3.41	2.27	1.86	1.57
Thermoplastic 4" Type III Bead	6.00	4.00	3.27	2.77	3.84	2.56	2.10	1.77
Thermoplastic 6" Type III Bead	5.70	3.80	3.11	2.63	3.45	2.30	1.88	1.59
Thermoplastic 4" (rumble stripe) Type III Bead	5.68	3.79	3.10	2.62	3.64	2.42	1.98	1.68
Thermoplastic 4" (rumble stripe) Type III Bead	5.43	3.62	2.96	2.51	3.64	2.42	1.98	1.68
Thermoplastic 4" (inverted profile) Mixed Beads	6.39	4.26	3.48	2.95	4.14	2.76	2.26	1.91
RPM Type II C-R	22.73	15.15	12.35	10.53	12.5	8.33	6.79	5.79

Note: Preview time color scale; ≥ 4 seconds, 3.00–3.99 seconds, 2.00–2.99 seconds, and < 2 seconds.

Curve and Turn Signs

Because they are required on all curves with speed changes of 10 mph or greater, advance warning signs (primarily Turn and Curve signs) are the most common TCDs used on curves, other than conventional pavement markings. The safety benefits of Turn and Curve warning signs have been recognized by multiple agencies. Montana and Florida use a crash reduction factor of 30 percent for all crashes from installing warning signs in advance of curves (45). The same publication cites a 20 percent reduction used in California when including an advisory speed. In New York, a reduction of 34 percent is assumed (46). These values are often based on internal notes and unpublished data that are not disseminated like most research. There are few published research reports showing the independent effect of Turn or Curve warning signs. A relatively old study by Hammer (47), published in 1968, found that Curve warning signs in California reduce crashes by 18 percent. Also in California, Bhullar et al. (48) identified a reduction in run-off-road (ROR) crashes from Curve warning signs.

As mentioned previously, warning signs are particularly noticeable when illuminated by headlamps at night and the background environment is dark. In a study where drivers were actively searching for Curve signs at night, all participants were able to recognize the sign at a distance of 600 ft, which corresponds to a legibility index of over 40 ft/in (49). This legibility index is greater than the index suggested by the MUTCD for word messages (30 ft/in), which is not surprising since symbolic signs tend to be easier to read. Other research has confirmed that drivers can recognize warning signs several hundred feet in advance of the sign (50, 51).

Overall, there appears to be no research that has been able to identify significant operational impacts of Turn and Curve warning signs. While there has been some research documenting the effects of alternative devices (such as a Combination Horizontal Alignment/Advisory Speed sign installed at the curve in addition to an advance warning sign, or the use of flashing lights or flags to increase conspicuity), multiple researchers have indicated that advance horizontal alignment warning signs are ignored because they are used frequently (52, 53).

Previous research suggests that advisory speed plaques used on horizontal alignment warning signs are also ignored. Literature reviews by Johnston (54) and Lyles and Taylor (3) conclude that advisory speed plaques have inconsistent or insignificant impacts on vehicle speeds. Ritchie (55) studied the effects of warning signs and advisory speed plaques in Ohio, finding a significant increase in vehicle speeds due to the signs, counter to what would normally be intended. As a possible explanation, he suggested that the increased speeds were due to increased driver confidence for the upcoming curve because of the sign. Zwahlen (56, 57) also found advisory speed plaques to generally be ignored, showing no significant change in speeds from their use. Chowdurry et al. (58) observed that drivers tend to be more compliant with higher advisory speeds than lower advisory speeds. The researchers found that decreases in observed speed were usually less than half of what was suggested.

Chevron Alignment Sign

Chevrons are not used for advance warning on curves in the same way a Turn or Curve sign is used. Spaced along the outside of the curve, chevrons provide additional information about the curvature that is visible in advance of the curve, and are especially helpful at night when the roadway environment is not clear and a severe change in alignment can go unnoticed.

A number of states apply crash reduction factors when evaluating the merits of chevrons at specific sites. Specific examples include 25 percent in New York (46), 35 percent in Indiana (59), and 35 percent in Florida (45). From earlier studies, Niessner (60) summarized several field studies evaluating the effect of chevrons on rural curves, showing that chevrons significantly reduced fatal crash rates. Internationally, Montella observed a reduction in crashes for treatments consisting of advance warning signs supplemented by Chevron signs together (61).

Operational studies of chevrons have been more numerous than safety studies. From a closed-course evaluation, Johnston (54) observed that chevrons encourage decreased speeds at night; however, increased speeds during the daytime were attributed to the enhanced driver confidence and comfort provided by the chevrons. In-field tests by Jennings and Demetsky (62) and Zador et al. (63) near the same time identified mixed or no significant changes in speed due to chevrons. In-field and open-road tests by Agent and Creasey (64), Chrysler et al. (65), Re et al. (66), and Bullough et al. (67) found chevrons effectively reduce driver speeds, at least during one period of the day, and usually by about 2 mph at the PC or midpoint of the curve. Using a simulator, Charlton (68) observed that chevrons encourage lower average speeds on curves than warning signs alone. Chevron boards (a series of chevrons on one sign), which are not used in the United States were also tested and produced similar results. Speed reductions have also been observed when increasing the number of chevrons or applying reflective sheeting to the Chevron sign posts (65, 69, 70).

One-Direction Large Arrow Sign

The One-Direction Large Arrow sign tends to be used less frequently than chevrons, though the hierarchy of signs for curves in the MUTCD considers a Large Arrow sign equal to a series of chevrons. Perhaps because it is used infrequently compared to other devices, the Large Arrow sign has received only limited attention in evaluations of driver performance. Vest et al. (53) obtained mixed findings regarding changes in average speed at one curve where a Large Arrow sign was tested, but it was very effective at reducing extreme speeds (above the 85th percentile).

Delineators

Studies of delineators have resulted in mixed findings. Vest et al. (53) observed increases in speed at two out of three locations, and Zador et al. (63) and Kallberg (71) also found that delineators led to an increase in speeds. Kallberg (71) found significant increases in speed at night (with insignificant increases during the daytime). In contrast to these findings, Chrysler et al. (65) observed some decreases in speed, approximately 2 mph or less, though the changes were not considered statistically significant.

Using a simulator, Molino et al. (72) showed that speeds are lower at curves with delineators. They compared the effects of three traffic control treatments at curves: edge lines alone, edge lines with delineators, and edge lines with delineators that have light-emitting diodes (LEDs). In the simulation, drivers reduced their speeds by an average of 2 mph when only edge lines provided delineation, 7–8 mph when edge lines and delineators were used, and 9 mph when edge lines and delineators with LEDs were used. The simulation clearly identified increases in

driver response with enhanced delineation. The LEDs also substantially increased the distance at which curves could be detected.

Raised Pavement Markers (RPMs)

Molino et al. (73) identified the detection distances for curves when combinations of pavement markings and RPMs, each with different luminance levels, are used. A factorial test of pavement marking luminance (high, medium, low, and none), RPM luminance (high, medium, low, and none), type of pavement markings (double yellow centerline only or double yellow center line with single white edge line), environmental lighting (dark overcast night or blackout), and speed (35 or 55 mph) was used to generate 128 different possible curve conditions for drivers to experience. As would be expected, the recognition distance increased as the luminance of the pavement markings and RPMs increased. When the pavement marking luminance was low and there were no RPMs on the center line, the drivers detected the curves at an average distance of 89 ft. For pavement markings with high luminance and no RPMs, the detection distance increased to 185 ft. When RPMs with high luminance were used with pavement markings of low and high luminance, the detection distances were 160 ft and 224 ft, respectively. RPMs of any level of luminance increased the detection distance under all conditions, but the greatest differences were observed when the pavement marking luminance was low.

Behavioral changes from RPMs on curves were studied by Krammes et al. (74), who evaluated the nighttime speed and lateral placement of vehicles after the placement of RPMs when delineators had been removed. They found that with the new RPMs, the mean speed at the midpoint of a curve could be 1–3 mph higher than with the delineators. The average lateral placement of the vehicles was also 1–2 ft further from the center of the roadway, and the variability in lateral placement decreased. However, there was a noticeable decrease in effectiveness after 11 months of use, likely a result of deterioration in the RPMs and their ability to provide advance warning of the curve. Krammes et al. recommended using RPMs as an alternative to delineators in cases where sight distance to the curve is adequate.

Smiley et al. (75) found that RPMs are an effective treatment at locations with a history of unusual crash frequencies. They found a decrease in total crashes, nighttime crashes, and wet weather crashes when the RPMs were installed at locations with high numbers of wet weather or nighttime crashes. In their study, the benefit of RPMs was not as clear at locations selected based on total crashes or without any selection criteria. Certain crash types increased in frequency after the application of RPMs, showing that selective implementation may prove effective but non-selective implementation ineffective.

SUMMARY

This chapter presents a summary of information about how drivers approach and navigate curves and how TCDs may influence some of the characteristics of that behavior. Agencies have several options for treating curves with TCDs to provide drivers more information that will help them properly prepare for and navigate the curve. The research discussed here shows that there is an overall consensus that TCDs at curves lead to both improved operational performance and reduced crash rates at curves. But based on these findings alone, it could seem sensible to require that all curves be treated with TCDs. What is missing from the literature is a solid scientific

understanding of *how* TCDs are effective based on an analysis of multiple aspects of curve negotiation. Much of what has been previously documented is only the end result of multiple processes and describes what is observed within the curve.

Details within the study performed by Chrysler et al. (65) start to address the idea that the influence of TCDs can be observed throughout the entire process of curve navigation, rather than just produce an end result of reduced speeds within curves. One part of their study involved a closed-course driving test during which drivers repeatedly approached and navigated through a series of curves that received various traffic control treatments with each repetition. The researchers recorded the distance from the curve at which the driver acknowledged being confident about the severity of the curve and the distance at which the driver stopped throttling the accelerator and first depressed the brake. When no treatment was used (pavement markings only) the drivers were, on average, approximately 220 ft from the midpoint of the curve when they expressed confidence in knowing the curve severity. When vertical delineation was used, the distance increased by 100–250 ft. The distances at which drivers stopped throttling the accelerator and began to depress the brake also increased, though not by much, suggesting that the drivers were reluctant to decelerate earlier even though they had more information about the upcoming curve. The approach used by Chrysler et al. was one of the first to produce evidence for how TCDs at curves work. When the amount of delineation increased, drivers recognized the curves earlier, making it possible for an earlier response if the conditions of the curve required it.

One of the five basic requirements of an effective TCD, as stated in the MUTCD, is that the device fulfills a need. There are some curves where drivers *need* to reduce their speed in order to safely navigate the curve, and that operational response must be carried out over some distance. Data showing where drivers begin obtaining information and operationally responding to curves can be used to determine how much distance drivers are provided with when encountering curves. Data that characterize natural driver behavior at curves (regardless of the TCDs used) can identify how much response distance a driver needs to properly prepare to navigate a curve with specific characteristics. By matching this demand for deceleration distance with the supply of response distance for a given TCD, reasonable guidelines can be created that ensure TCDs are used at curves where they fulfill a need.

The driver behavior and safety studies, independently conducted as main portions of this research, were designed to provide extensive information about driver behavior and crashes at curves and how TCDs influence driver behavior and crashes. It was understood from the beginning, however, that even two separate studies could not comprehensively identify every aspect of how drivers behave at curves and how TCDs influence behavior and crashes. Additionally, there could be conflicts when interpreting the findings of the two studies. These instances in which the findings of the present studies conflict or are insufficient for creating guidelines are opportunities to apply the results of previous research.

Chapter 4: Findings from the Driver Behavior Study

The research activities and findings described in this chapter include specific models of driver operational behavior, which are directly used in the research recommendations for selecting TCD treatments for curves. The findings include two components: models of driver behavior during the three phases of curve negotiation without factoring in the effects of TCDs, and the effects of TCDs on driver behavior as documented in Appendix E. While the driver study also included data collected by eye-tracking equipment to evaluate measures of driver visual attention, the specific findings of those analyses are not directly used to construct the research recommendations. However, the results of eye-tracking efforts are still reported in Appendix F. The findings reported in this chapter were the key operations findings used to support the research recommendations.

BACKGROUND

Study participants were recruited in Idaho, Oregon, and Texas to drive an instrumented vehicle on a rural and unfamiliar two-lane highway in their state. There were 103 total participants (approximately 34 in each state). Most of the participants were classified as young (18–35 years) to represent the demographic of drivers more often involved in fatal crashes on curves (76). Specific details about the study protocol are given in Appendix D.

The use of drivers who were unfamiliar with the highway was a fundamental part of this study. Many of the previous investigations of driver performance involved collecting data in the field after specific TCD changes were made (but without controlling for the user of the road, which can only be assumed to be familiar and regular drivers). The MUTCD states that an effective TCD should fulfill a need, and drivers who are familiar with a highway and its changes in alignment are generally not the ones in need of the information that curve TCDs provide. This need can be identified more clearly from an evaluation of drivers who are not familiar with the highway.

The data collected by the research team fit into two general categories: 1) operational performance, and 2) visual attention. The operational performance is defined by measures of speed and acceleration (i.e., longitudinal acceleration and deceleration and lateral acceleration). The visual attention is defined by where and for how long a driver fixates and various physiological measures of the drivers eyes obtained from eye-tracking cameras, specifically the pupil size, eye closure, and blink rate. While the operational performance describes characteristics of the vehicle, which reflect the outward responses of drivers at curves, the measures of visual attention reflect the cognitive processes of perceiving information about a curve. Both types of data were collected continuously along the study routes by equipment operating at relatively high frequency rates.

Throughout the driving study, researchers installed additional TCDs at selected curves so that each study condition at a curve was encountered by half of the participants. In Idaho and Oregon, RRPMs were installed. Delineators and Large Arrow signs were installed at curves in Texas that had already been treated with advance warning (Curve and Turn) signs. Chevrons had

already been installed at some curves in Texas. Statistical analyses were performed to identify how TCDs influence a driver's behavior along a segment starting on the tangent approach and continuing through the end of the curve.

METHODOLOGY

The analysis of the operations and eye-tracking data focused on developing multivariable linear regression models that illustrate one component of driver behavior and how it is affected by curve geometry and the TCDs used at the curve. The following dependent variables were obtained from evaluating the curves along each study highway:

- Radius (ft).
- Deflection (deg).
- Superelevation (percent).
- Curve direction.
- Curve length (ft).
- Approach tangent length (ft).

Superelevation, curve direction, and curve length do not appear as variables in any of the reported models because their effects were quite small in comparison to the other variables. The models thus only ever include the variables for radius, deflection, and tangent length. The following operations data were extracted from each study segment for use as dependent variables:

- Distance (ft) traveled downstream after exiting a curve until reaching a maximum tangent speed.
- Total increase in speed (mph) on a tangent.
- Speed reduction (mph) from the tangent to the curve entrance.
- Maximum deceleration rate (ft/s^2) on the tangent approach.
- Speed (mph) at the PC.
- Total speed reduction (mph), measured by the difference between the maximum tangent speed and minimum speed in the curve.
- Maximum deceleration rate (ft/s^2) in the curve.
- Maximum rate of lateral acceleration (g) experienced in the curve.

Some of the operations variables represent extremes (such as the maximum tangent speed), rather than features at defined points (such as the speed at 500 ft before the curve), because the extremes help define the boundaries that characterize an individual driver and the specific experience at that curve. It was desirable for the models to be simple, having been created using as few variables as possible. Although the addition of more variables can improve how well the model fits the data, the ability to visualize and interpret the significance of the model decreases as the complexity of the model increases. Where necessary, transformations were performed to account for non-constant variance within the data. There were approximately 4,800 entries in the complete dataset. Each model was based on a specific subset of the entire dataset to reduce the potential for bias from confounding factors. The effects of TCDs were

identified only from the nighttime data, representing the condition for which additional curve information is needed most.

FINDINGS

The two objectives in the analysis of the operations data were to:

- Identify characteristics of normal driver behavior as drivers approach and navigate curves.
- Identify how TCDs at curves impact these characteristics.

To fulfill these two objectives, the analyses are presented first with models and figures that illustrate the behavior when the factor for TCDs is not included. Then the effects of the TCDs are provided based on models using the TCDs as an indicator variable. Appendix E contains those complete models, which are not reprinted in this section because the focus is on normal driver behavior and the isolated effect of TCDs.

Previous research (21) divided the process of negotiating curves into three phases: acceleration after exiting a curve, deceleration upon approaching a curve, and navigating the curve. The models from the eight operations variables are divided into these three phases.

Acceleration after Exiting an Upstream Curve

The two metrics characterizing the acceleration phase are the distance traveled before the driver reaches a maximum speed on the tangent and the actual increase in speed observed on the tangent. Without factoring in the effects of TCDs, it was found that these two metrics are dependent upon the length of the tangent, the vehicle's initial speed at the end of the upstream curve, and the speed at which the driver desires to travel on the entire facility (which is likely to be near the speed limit, though unique to each driver). The desired speed of an individual driver is the maximum speed of that driver observed throughout the study. A new variable called the potential speed increase is used, which is the difference between the desired speed of the driver and the speed when exiting the upstream curve, representing how much the driver would accelerate if there were a sufficient distance before the next curve. It changes based on the severity of the previous curve (because low exit speeds are expected at severe curves) and the desired speed of the individual driver. If there is a long tangent between two curves and there is a greater potential to increase speed, then the distance traveled during the acceleration phase and the speed change experienced should be greater.

To capture a period of acceleration followed by deceleration, where a distinct maximum tangent speed is reached, only curves with approach tangents between 250 ft and 2,500 ft in length were used, resulting in applying only half of available data (2,300 total observations) in these models. Equations 1 and 2 are the corresponding formulas.

$$\sqrt{D_{Accel}} = -3.57 + 0.71\sqrt{L_{Tan}} + 0.27Potential \quad 1$$

$$\sqrt{\Delta_{Speed_{Accel}}} = -0.32 + \frac{9L_{Tan}}{10,000} + 0.091Potential \quad 2$$

where

- D_{Accel} = distance traveled (ft) before reaching the maximum tangent speed.
- $\Delta_{SpeedAccel}$ = increase in speed (mph) during the acceleration phase.
- L_{Tan} = tangent length (ft).
- $Potential$ = potential speed increase (mph) based on the difference between the driver's desired speed and the initial speed on the tangent.

Because the models include data for curves with preceding tangents up to 2,500 ft in length, which is a distance at which the curve geometry is not visible, the models in this phase do not account for the specific geometry of the downstream curve. It was found that the effects of curve geometry (i.e., radius and deflection angle) can be identified within the acceleration phase, but they are quite small in comparison to the effects of tangent length and potential speed increase. Graphical representations of the models are shown in Figures 7 and 8 and include fit lines representing sample tangent lengths. The graphs illustrate that drivers tend to accelerate more (in terms of both speed change and distance over which the acceleration is completed) as both the tangent length and the potential for speed change after a curve increase.

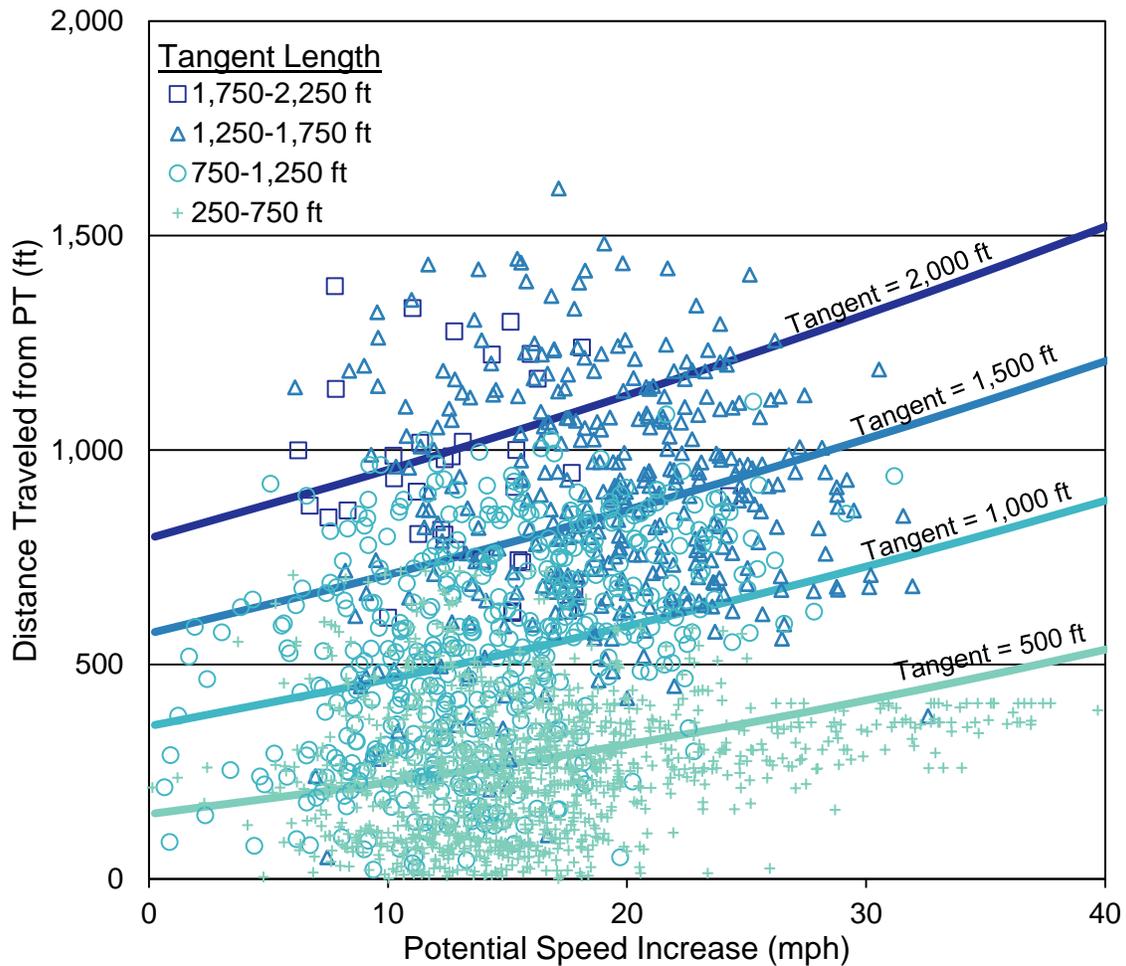


Figure 7. Distance (ft) traveled on a tangent before reaching maximum speed.

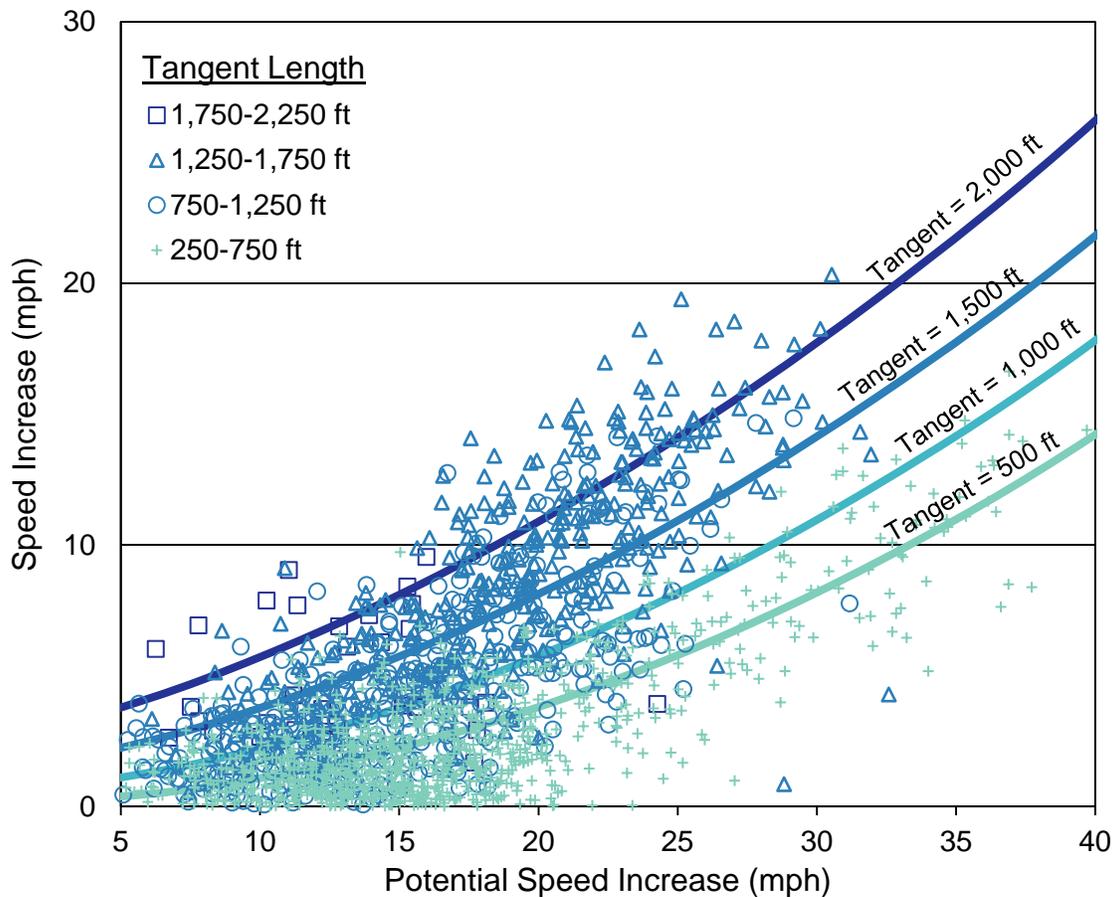


Figure 8. Increase in speed (mph) observed on a tangent after a curve.

The models for the acceleration phase provided in Equations 1 and 2 and shown in Figures 7 and 8 do not account for the TCDs that may be used at curves. Models with the same structure are shown in Appendix E but were created from a much smaller dataset to reduce the potential for introducing bias into the models. The effects of TCDs as an indicator variable are provided in Table 6. The values in Table 6 indicate that the advance warning signs and the vertical devices used within curves encourage drivers to stop accelerating on the tangent earlier than they otherwise would have and with a lower speed increase. For example, when a Curve sign is present, drivers stop accelerating on the tangent 140 ft earlier, having reached a maximum speed that is 3 mph lower.

Table 6. Effects of TCDs on Acceleration Models

Treatment	Effect on Acceleration Distance (ft)	Effect on Speed Increase (mph)
Curve sign	-140	-3
Delineators	-76	-0.7
Large Arrow	-81	-1.9
Chevrons	-137	-1.3
RPMs	Not significant	Not significant

Deceleration before Entering a Curve

The geometry of the downstream curve was not included in models for the acceleration phase because of the inability to detect the geometry so far from the curve. Geometry is included in models for deceleration because the driver is at a location where the appearance of the curve's severity can affect a response. The performance measures used in the deceleration phase are the speed reduction that occurs before the PC, the proportion of total speed change that occurs before the curve, and the maximum deceleration rate that is observed on the approach.

The first model, represented by Equation 3, identifies three independent variables that affect the total reduction in speed that occurs from the maximum tangent speed to the PC. As the maximum tangent speed increases, drivers are likely to experience more total deceleration; a greater deceleration distance also results in greater speed reduction; finally, the relationship with radius indicates that the speed reduction will increase as the curve becomes sharper.

$$\Delta_{Speed_{Decel}} = -11.5 + 0.22Speed_{Max} + \frac{51D}{10,000} + \frac{1287}{R} \quad 3$$

where

$$\begin{aligned} \Delta_{Speed_{Decel}} &= \text{change in speed (mph) before the curve.} \\ Speed_{Max} &= \text{maximum speed (mph) on the tangent.} \\ D &= \text{distance (ft) from the curve at maximum speed.} \\ R &= \text{radius (ft).} \end{aligned}$$

The proportion of total speed reduction that occurs before a curve was investigated as another performance measure associated with the pre-curve deceleration phase. Unfortunately, all potential models identified a very weak correlation, so no specific models are reported here. On average, 53 percent of the total speed reduction at each curve occurred before the curve.

The final model for this phase (shown by Equation 4 and represented by Figure 9) estimates the greatest deceleration rate (ft/s²) observed on the approach to a curve. While investigating the data, it was observed that the strongest predictor of acceleration rate is the total speed reduction that the driver executes at the curve. The relationship between total speed reduction and maximum observed deceleration rate is strongly correlated ($R^2 = 0.76$). Other variables were investigated in this model, specifically the effects of radius, deflection angle, and tangent length. It was found that the speed differential by itself accounts for such a large portion of the variance in the response that other measures such as geometry simply do not provide much benefit over the variable for total speed reduction. Additionally, the speed differential is by itself a function of those and other variables.

$$Decel_{Rate_{Tan}} = 0.89 + 0.22\Delta_{Speed} \quad 4$$

where

$$\begin{aligned} Decel_{Rate_{Tan}} &= \text{maximum deceleration rate (ft/s}^2\text{) on the tangent.} \\ \Delta_{Speed} &= \text{total speed differential at the curve.} \end{aligned}$$

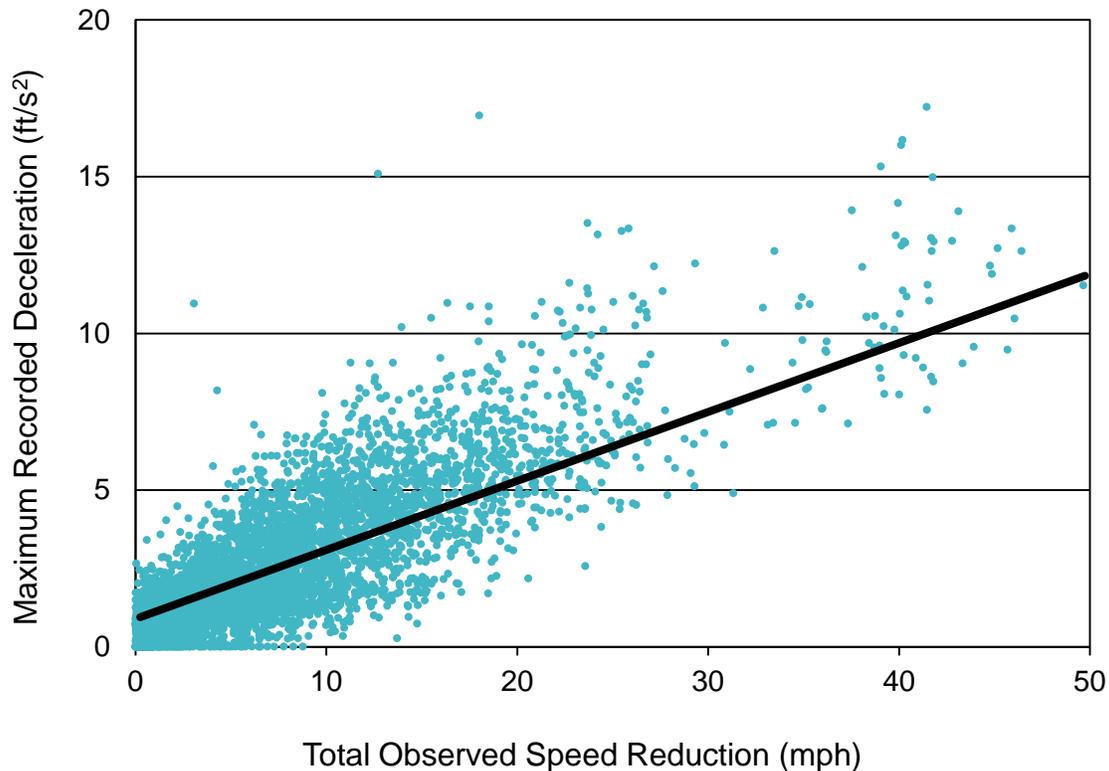


Figure 9. Maximum observed deceleration rate (ft/s^2) on an approach tangent estimated by the total speed change at the curve.

The deceleration rate for some of the observations in Figure 9 is equal to or near 0 although there was a small observed speed change at the curve. Those are instances when deceleration occurred only within the curve, whereas this model represents the maximum deceleration rate observed on the tangent. In order to execute a greater speed change for a curve, drivers can either accept a greater deceleration rate or begin decelerating earlier. The model for Equation 4 and shown in Figure 9 indicates that drivers are willing to accept increased deceleration rates. Though no model is shown here, it was found (unsurprisingly) that deceleration rates are lower when the deceleration phase begins earlier. The effect of the location where the deceleration phase begins is much weaker than the effect for the total speed change and is thus not incorporated into the model. This finding suggests that drivers are willing to sacrifice comfort (and potential safety) for the efficiency that comes from decelerating later.

The models for the deceleration phase provided in Equations 3 and 4 and shown in Figure 9 do not account for the TCDs that may be used at curves. Models with the same structure as those represented here are shown in Appendix E but were created from a much smaller dataset to reduce the potential for introducing bias into the models. The effects of TCDs as an indicator variable are provided in Table 7. Each type of device except RPMs results in a greater speed reduction (1–2.7 mph) in advance of the curve. Contrary to expectations, drivers responded to advance warning signs with an increased deceleration rate on the tangent. This was unexpected because the acceleration models showed that drivers stop accelerating earlier and have a reduced maximum speed when a Curve sign is used. All devices used within the curve have model indicator variables that support more-conservative deceleration rates.

Table 7. Effects of TCDs on Acceleration Models

Treatment	Effect on Pre-curve Speed Reduction (mph)	Effect on Deceleration Rate (ft/s ²)
Curve sign	1.0	0.50
Delineators	2.3	-0.46
Large Arrow	2.7	-0.13
Chevrons	2.5	-1.29
RPMs	Not significant	-0.18

Within-Curve Performance

Navigation within the curve is characterized in this study by three metrics: the speed at the PC, the maximum deceleration rate observed within the curve, and the maximum lateral acceleration rate observed within the curve. Models estimating these three metrics are provided by Equations 5–7, and two are illustrated in Figures 10 and 11. The speed at the PC is estimated by the curve radius and maximum approach speed. The relationships (unsurprisingly) indicate that a higher speed at the PC occurs with a higher tangent speed and larger radius. All parameters are significant and the correlation is strong ($R^2 = 0.88$). An initial model included the maximum approach speed and the reciprocal of the curve radius, but a log transformation of the radius, rather than the reciprocal, led to substantial improvements in the form of the residuals, indicating a better overall prediction.

$$Speed_{PC} = -14.5 + 5.49 \ln(R) + 0.50 Speed_{Max} \quad 5$$

$$Decel_{Rate_{Curve}} = 1.00 + 0.19 \Delta_{Speed} \quad 6$$

$$Accel_{Lat} = 0.30 + 0.046 \ln\left(\frac{I}{R}\right) \quad 7$$

where

- $Speed_{PC}$ = speed (mph) at the PC.
- $Decel_{Rate_{Curve}}$ = maximum longitudinal deceleration rate (ft/s²) in the curve.
- $Accel_{Lat}$ = maximum lateral acceleration (g) in the curve.
- R = radius (ft).
- $Speed_{Max}$ = maximum speed (mph) on the tangent.
- Δ_{Speed} = change in speed (mph) observed at the curve.
- I = curve deflection angle (deg).

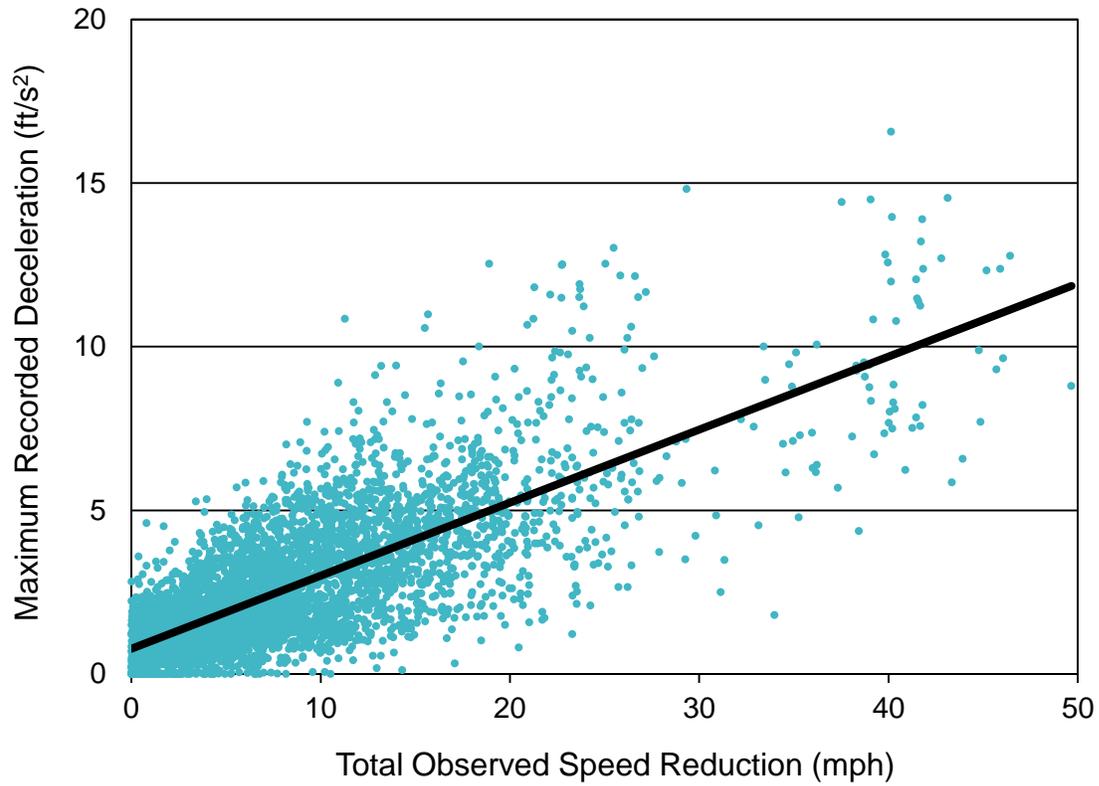


Figure 10. Maximum longitudinal deceleration (ft/s²) observed within a curve estimated by the total speed change at the curve.

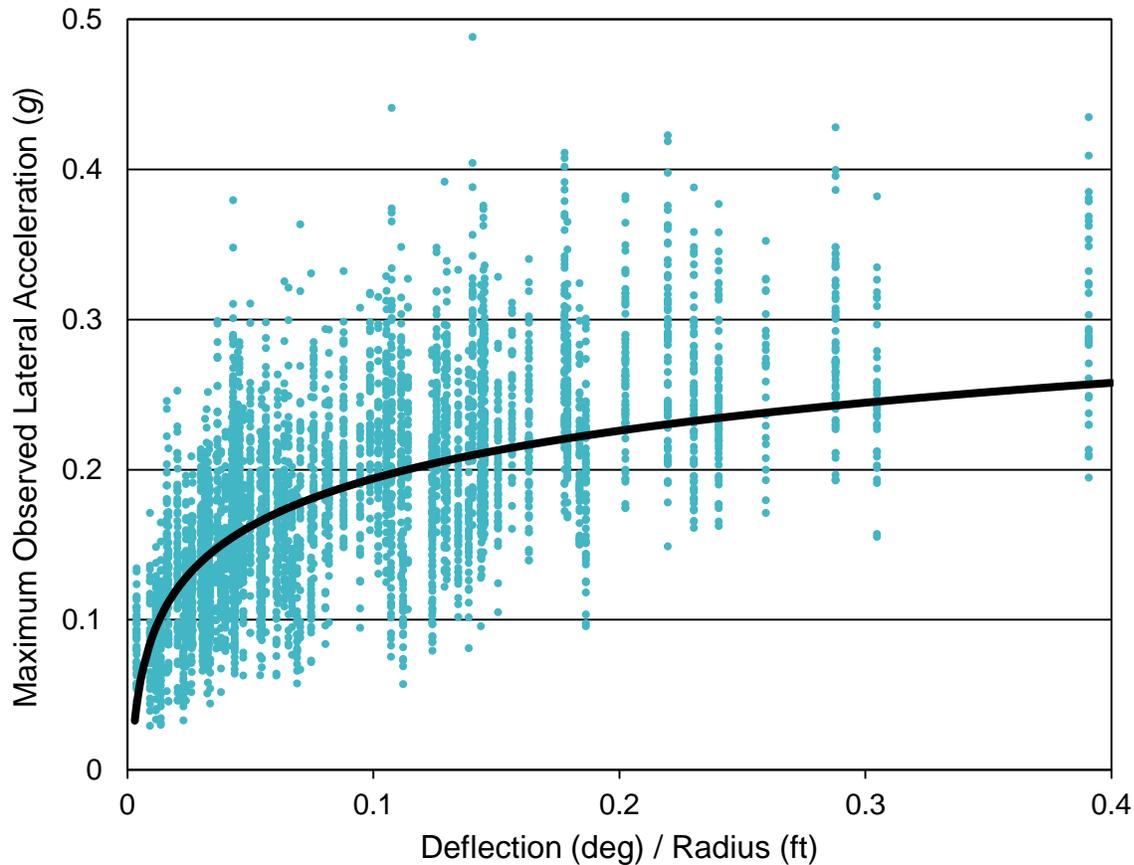


Figure 11. Maximum lateral acceleration (g) estimated by deflection/radius.

It has been discussed that not all deceleration occurs in advance of a curve, but continues after the PC. The previous models showed that the deceleration rate is easily relatable to the total observed speed change. The same variable is used here because it estimates the deceleration rate with the best accuracy. The correlation coefficient is 0.66, which is weaker than the model estimating the deceleration rate on the tangent.

It was found that one of the simplest relationships for estimating lateral acceleration is with a ratio of curve deflection (in degrees) to radius (in feet). The third model in Equation 7 identifies the relationship, which is best described by a log function of deflection/radius. It has been observed (77) that the ability of drivers to reduce lateral acceleration through cornering is limited by the deflection angle of the curve. The inclusion of deflection thus gives a novel perspective of severity that is not described by radius alone. The speed of the vehicle could have been included in the model, but it would have led to a near-perfect prediction of lateral acceleration. Other possible transformations of the dependent variable were investigated, but no other transformation proved as capable of illustrating the relationship.

Table 8 contains the indicator values for TCDs when they are included in models as identified in Appendix E. In all cases where the TCD has a significant effect, the impact is a reduced speed at the curve entrance, a lower deceleration rate within the curve, and a lower rate of lateral acceleration.

Table 8. Effects of TCDs on Curve Navigation Models

Treatment	Effect on Speed at PC (mph)	Effect on Deceleration Rate (ft/s ²)	Effect on Lateral Acceleration (g)
Curve sign	-0.88	Not significant	Not significant
Delineators	-2.3	-0.93	-0.018
Large Arrow	-2.7	-0.85	-0.0098
Chevrons	-2.5	-0.94	-0.026
RPMs	Not significant	-0.23	Not significant

Additional Illustrations

Many models of operational behavior developed in previous research, and some in this research, emphasize the influence of geometry by including geometric variables. But it is also important to recognize that the operating characteristics of one phase influence how drivers behave during another. For example, the speed at the PC is partly determined by the maximum speed on the tangent, which is consistent with previous research (22-24). Perhaps one of the most significant findings of these models is the dependency of deceleration rates on the total speed change at the curve. In other words, drivers do not decelerate at the same rate from one curve to another, but are willing to accept greater deceleration rates for sharper curves. Equation 4 and Figure 9 indicate a linear relationship between the deceleration rate and curve speed change. To illustrate the relationship in a different way, Figure 12 shows the cumulative distribution of the maximum deceleration rates accepted by drivers grouped into 5-mph speed change bins. The 50th percentile data indicate that the deceleration rate of the average driver ranges from 2.2 ft/s² to 7.2 ft/s² for speed differentials from 5 to 30 mph. This variation in deceleration rates indicates that drivers do not prepare for sharper curves by only starting to decelerate earlier; there is at least some adjustment in how strongly they decelerate by braking harder.

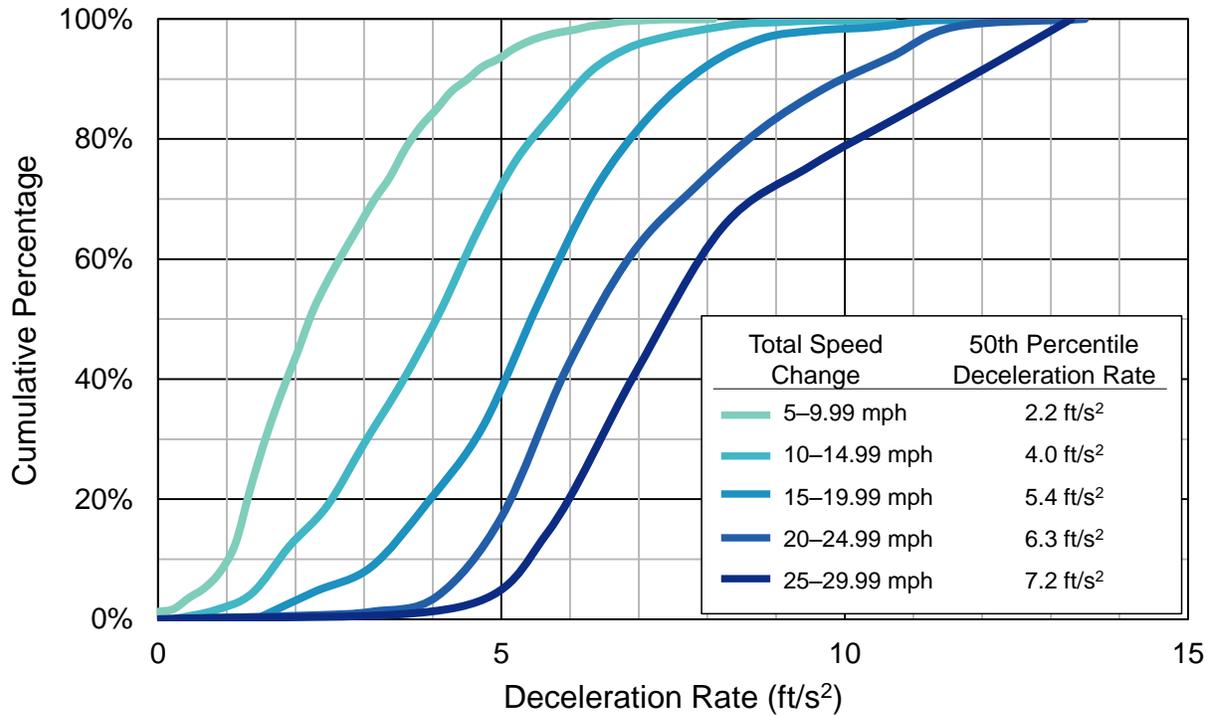


Figure 12. Cumulative distribution of deceleration rates separated by total speed change.

It was observed that, from all 4,800 observations of drivers navigating curves in this study, drivers on average would complete only 53 percent of the total speed change at curves in advance of the curve. Unfortunately, no useful models were developed that can predict the conditions that would result in a greater proportion of the speed reduction occurring before the curve. It is not surprising that the drivers in this study did not finish decelerating in advance of the curve because previous research has shown that speeds at the midpoint tend to be lower than at the PC (13-15). To illustrate the variability in the amount of deceleration drivers tend to accomplish before curves, as a proportion of the total observed speed reduction, Figure 13 contains cumulative distribution plots, again grouped by speed reduction. Figure 13 shows that the pre-curve speed change is not as dependent upon total speed differential as the deceleration rate is. The median value for how much speed change occurs before the curve increases from 51 percent for a 5-mph speed differential to 60 percent for a 25-mph speed differential. For curves with a 25-mph total speed differential, if a driver completes 60 percent of the deceleration before the curve, there is still a 10 mph deceleration expected within the curve (the pre-curve deceleration would be 15-mph).

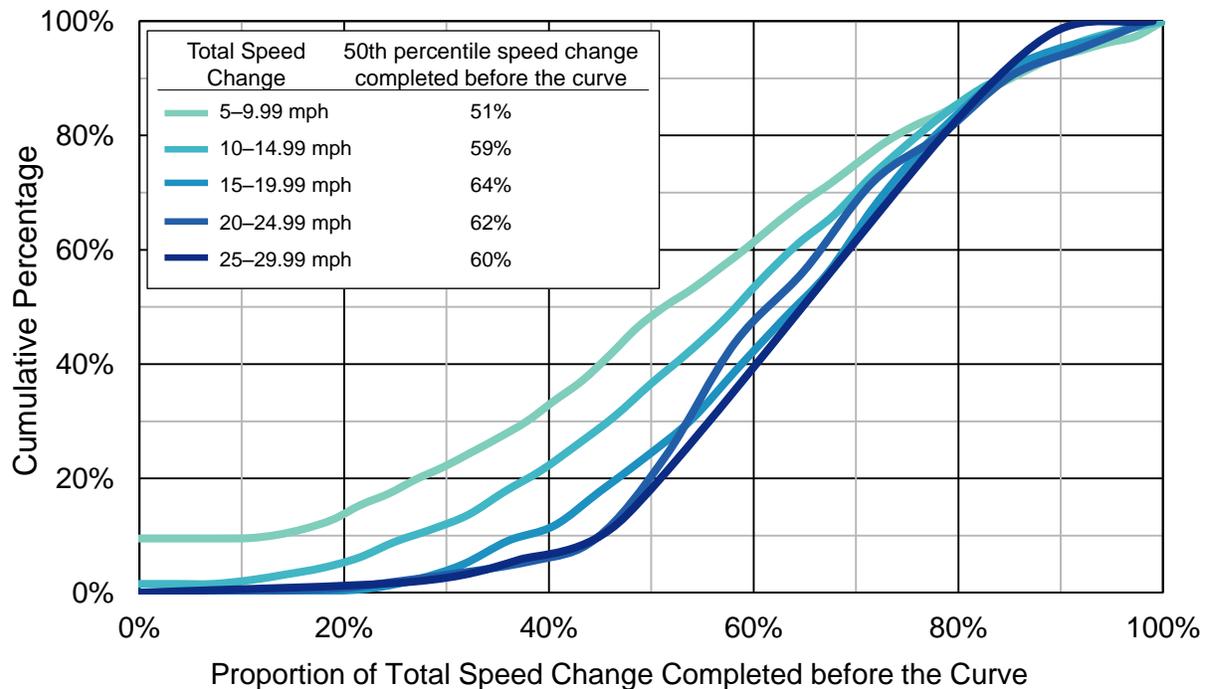


Figure 13. Cumulative distribution of the proportion of total speed change that occurs before the curve, separated by the total speed differential.

The information in Figures 12 and 13 is important because, when combined, the figures can be used to calculate the total distance over which a driver can be expected to decelerate in advance of a curve. Without this information, it might otherwise be assumed that drivers complete all deceleration in advance of curves, and that their deceleration rate is the same regardless of the conditions encountered. These figures illustrate that normal driver behavior is markedly different. With information about how much distance drivers use in executing a “normal” deceleration maneuver, the needs of drivers for information at curves can be better defined.

SUMMARY

The information in this chapter describing the operational behavior of drivers contains many insights into driver behavior that previously have not been reported. The phases of curve negotiation were investigated with several models that characterize the experience of drivers and the influence of TCDs at curves. By connecting the information related to all phases of curve negotiation, it can be said that TCDs help drivers prepare to navigate curves by providing drivers information about the curve at an earlier location (or time) than it otherwise would have been received. That earlier warning encourages drivers to stop accelerating earlier, not having reached as great a speed as would otherwise have been attained. By initiating the deceleration phase earlier, drivers also decelerate at a gentler rate and reach the curves at a reduced speed. Previous research has identified operational effects of TCDs within curves, but details of how those effects are achieved starting far from the curve have, until now, not been documented.

Chapter 5: Findings from the Safety Analysis

This chapter summarizes the findings from the analysis of crashes at curves designed to identify the influence curve TCDs have on crashes. Details of the study protocol and methodology are provided in Appendix G; details of the findings are provided in Appendix H. The findings, which contribute to the formation of the recommended guidelines for selecting TCDs at curves, include crash models for various crash types that estimate the number of crashes expected to occur at a given curve (or series of curves) in a given year under certain conditions. Crash modification functions (CMFunctions), which are a formula for calculating crash modification factors (CMFs), were isolated from the crash models to show how TCDs affect crash frequency and severity at curves. Because the CMFunctions vary based on other curve features, there are specific conditions for which TCDs influence safety.

BACKGROUND

The safety analysis was conducted to evaluate the effects of advance horizontal alignment warning signs and in-curve warning signs on safety at curves. The effects of these types of signs at both isolated curves and curve series were investigated. For advance warning signs, the Turn and Curve sign were investigated at isolated curves, and their corresponding Reverse Turn, Reverse Curve, and Winding Road warning signs were investigated at curve series. For in-curve warning signs, the effects of Chevron Alignment signs and One-Direction Large Arrow signs were investigated, also at isolated curves and curve series.

A preferred “before-after” study design was not feasible because installation dates for TCDs were unknown for a retrospective type analysis, and a request to change TCDs over a long period of time was not reasonable. Hence, a cross-sectional study design was chosen for estimating the safety effects of horizontal curve-related TCDs. The premise of a cross-sectional model is to estimate the safety effect of a feature (e.g., curve radius or chevrons) by considering sites with and without the feature or across its various levels. Through the use of multivariate regression models, the safety effects of horizontal alignment warning signs can be estimated while controlling for other characteristics that vary among sites. CMFs can be extracted from the modeling results, identifying the isolated effect on crashes of a treatment or feature. When the CMF is dependent upon another characteristic (such as curvature), a CMFunction is more appropriate. It was found that the effects of TCDs vary based on other features; therefore, CMFunctions were developed.

The study and data collection focused on rural two-lane highway curves, and crashes that occurred between 2009 and 2011. The data collection approach balanced the desire for plentiful and robust data with the constraints of time and resources available for such efforts. Data were collected in Florida (FL), Ohio (OH), Oregon (OR), and Tennessee (TN), for the reason that they could individually and collectively offer the following:

- Regional and terrain diversity.
- Completeness, quality, and availability of crash data.
- Availability of horizontal curve inventory.
- Availability of horizontal alignment warning sign inventory.

Data Elements

There were three categories of data (crash, roadway, and traffic/operations) with several variables in each category. The raw data collected are as follows:

For the

- Crash data:
 - Crash location.
 - Crash date.
 - Crash type.
 - Crash severity.
 - Light condition.
 - Sequence of events.
 - Roadway condition.
 - Vehicle type.
- Roadway data:
 - Area type (rural or urban).
 - Number of through lanes.
 - Degree of curve.
 - Curve length.
 - Curvature change rate (for curve series).
 - Proportion curve (for curve series).
 - Number of curves (for curve series).
 - Length of upstream tangent.
 - Roadside hazard rating.
 - Lighting presence.
 - Lane width.
 - Shoulder width.
 - Rumble strips presence.
 - Driveway presence.
 - Intersection presence.
- Traffic/Operations data:
 - Average annual daily traffic (AADT).
 - Horizontal alignment-related signs.
 - Posted speed limit.
 - RPM presence.
 - Delineator presence.
 - Center line pavement marking presence.
 - Edge line pavement marking presence.

The information about crash type allowed for several different models to be developed, in addition to models for total crashes, based on injury, single-vehicle run-off-road (SVROR), adverse pavement condition, and nighttime crashes. These specific crash types were determined to be important in the context of curve traffic control treatments. The presence of pavement markings (center and edge line), RPMs, and post-mounted delineators were documented in the data, but were not the primary focus of the analysis. For curves with advance warning signs, the presence of advisory speed plaques and the suggested speed reduction were also considered. If

there was no posted advisory speed, the speed reduction was considered to be zero. While it is accepted that these TCDs influence driver behavior and safety, the results of the research are geared toward horizontal alignment warning signs used in advance of and within curves.

Sample Size Estimates

The sample size required for multivariate regression models depends on a number of factors including the following:

- Average crash frequencies.
- The number of variables desired in the model.
- The level of statistical significance desired in the model.
- The amount of variation in each variable of interest between locations.

Data Collection Summary

The data collection resulted in 271 isolated curves and 270 curve series (minimum 2 curves) across the four states. Each isolated curve and separate curve series is considered to be a single site. Table 9 documents the number of sites that were identified in FL, OH, OR, and TN by horizontal alignment warning sign location (i.e., advance and/or in-curve). Three years of crash data (2009 to 2011) were collected for each site, resulting in a total of 813 site-years for isolated curves, and 810 site-years for series curves. The numbers of crashes counted in the database for each state and each year for the study are recorded in Table 10.

Table 9. Number of Sites by Region and Sign Location

Type of Sign	FL		OH		OR		TN		Combined	
	Isolated	Series								
No sign	2	0	17	19	22	14	15	11	56	44
Advance	15	19	29	39	29	48	34	45	107	151
In-Curve	0	0	1	0	1	0	1	1	3	1
Adv. & In-Curve	13	2	32	28	30	22	30	22	105	74
Total	30	21	79	86	82	84	80	79	271	270

Table 10. Total Yearly Crashes by State in Study Database

State	2009		2010		2011		Total	
	Isolated	Series	Isolated	Series	Isolated	Series	Isolated	Series
FL	16	17	25	16	11	9	52	42
OH	94	91	87	105	111	101	292	297
OR	27	49	27	43	49	48	103	140
TN	47	86	51	80	47	61	145	227
Total	184	243	190	244	218	219	592	706

METHODOLOGY

Multivariate regression was used to develop statistical relationships between the dependent variables (crash frequency for multiple crash types) and sets of predictor variables (such as traffic volume, curve characteristics, and TCDs). Coefficients for each of the predictor variables were estimated during the modeling process and represent the expected change in the dependent variable (crash frequency of a particular crash type) due to a unit change in the predictor variable, all else being equal.

Generalized linear modeling (GLM) techniques were applied to develop the crash prediction model, and a log-linear relationship was specified using a negative binomial error structure. Of particular concern was the possibility that a warning sign was installed to address safety concerns, which would introduce a site-selection bias. The assumption that treated sites are fundamentally different from untreated sites was tested by comparing summary statistics for site characteristics between the groups and performing propensity score analyses. The assumption was confirmed and required the use of specific methods to account for those differences. A propensity score-potential outcomes framework was used to overcome the dissimilarities of treated and untreated curves and to determine the safety effectiveness of advance and in-curve warning signs. The propensity score is the probability that a site will be treated with a warning sign given the characteristics of the site and outcomes of interest.

After developing a propensity score-based matched dataset, the following protocol was employed to develop the multivariate models:

- Step 1: Identify the base models with traffic volume only.
- Step 2: Explore other predictor variables.
- Step 3: Select final model.

Preliminary modeling indicated that Equation 8 was an appropriate functional form for all crash types. Therefore, $\log(\text{AADT})$ was considered in models for total, injury, SVROR, adverse pavement condition, and nighttime crashes.

$$\text{Crashes / year} = \text{AADT}^{\beta_1} \exp(\alpha) \tag{8}$$

where

- α and β_1 = parameters estimated in the model calibration process.
- AADT = annual average daily traffic (vpd).

Additional predictor variables were included in the crash prediction models to account for the differences among states, changes over time, curve length, and the presence of specific TCDs. States were represented as indicator variables FL, OH, and TN, and the base condition was that the study site is located in Oregon. If the state indicator was insignificant, it was not included in the model. Indicators for each year were tested to capture differences due to time, but were insignificant and excluded from the final models. A TCD variable was included in each model because horizontal alignment warning signs were the primary variables of interest. These variables were added to the base model as shown in Equation 9.

$$Total\ Crashes = AADT^{\beta_1} * HCL^{\beta_2} * \alpha * e^{\beta_3 * FL} * e^{\beta_4 * OH} * e^{\beta_5 * TN} * e^{\beta_4 * TCD} \quad 9$$

where

- α = constant.
- β_i = model coefficients.
- FL = 1 if site is in Florida; 0 otherwise.
- OH = 1 if site is in Ohio; 0 otherwise.
- TN = 1 if site is in Tennessee; 0 otherwise.
- AADT = average annual daily traffic (vpd).
- HCL = horizontal curve length (ft).
- TCD = traffic control device of interest.

Once the initial models were developed for each crash type, additional variables were considered using Variable Introduction Exploratory Data Analysis (VIEDA), as outlined by Hauer (78). VIEDA helps to answer the following two questions:

- Is the variable related to safety?
- What is the proper functional form the variable should take in the crash prediction model?

The final step was to consider correlations among predictor variables included in the model specifications. A set of prioritization rules for selecting a correlated predictor variable in a final model is provided in Appendix G. When multiple alternative models were identified, goodness-of-fit (GOF) measures were applied to determine the most suitable model. CMFunctions from the final best-fit models are presented for each crash type for isolated and series curves in the next section.

RESULTS

This section presents the final model results for the target crash types, including:

- Total crashes.
- Injury crashes.
- SVROR crashes.
- Adverse pavement crashes.
- Nighttime crashes.

Four matched databases were developed, including:

1. Chevrons and/or Large Arrows within isolated curves.

2. Chevrons and/or Large Arrows within series curves.
3. Turn or Curve warning signs in advance of isolated curves.
4. Reverse Turn, Reverse, or Winding Road warning signs in advance of series curves.

CMFunctions are presented for each crash type with a brief discussion highlighting the key results. It was found that the safety effect of in-curve warning signs interacted with AADT, while the safety effect of advance warning signs was best represented by interactions with curvature. The CMFunctions for in-curve and advance warning signs are thus dependent on AADT and curvature, respectively. A graphical representation of the CMFunctions are provided with 95 percent confidence intervals for total crashes in this section. The graphical representations help to illustrate the range for which results are statistically significant. Appendix H presents all final models and graphical representations of the CMFunctions for all crash types, as well as interpretations of the covariates in the model.

Chevrons and/or Large Arrows within Isolated Curves

The models for isolated curves consider the presence of Chevrons, a Large Arrow, or the combination of chevrons and Large Arrow. The effects of these in-curve warning signs were evaluated aggregately with a single variable representing all three possible treatments of a Large Arrow sign, chevrons, or a Large Arrow sign and chevrons combined.

Total Crashes

The CMFunction relating the effect of in-curve warning signs to total crashes by AADT is presented in Equation 10.

$$CMF_{total,isolated-within} = \exp(0.203 - 0.089 * AADT(thousands)) \quad 10$$

Figure 14 graphically represents the CMFunction for total crashes by AADT. The shaded region indicates where the value of the CMF is significantly less than 1.00 (indicating a significant reduction). For total crashes, chevrons and/or Large Arrows are significantly associated with fewer crashes when the AADT is more than 5,500 vpd. While the CMF is statistically insignificant for AADT less than 5,500 vpd, the mean CMF value is less than 1.00, indicating a potential safety benefit, when the AADT is greater than 2,500 vpd.

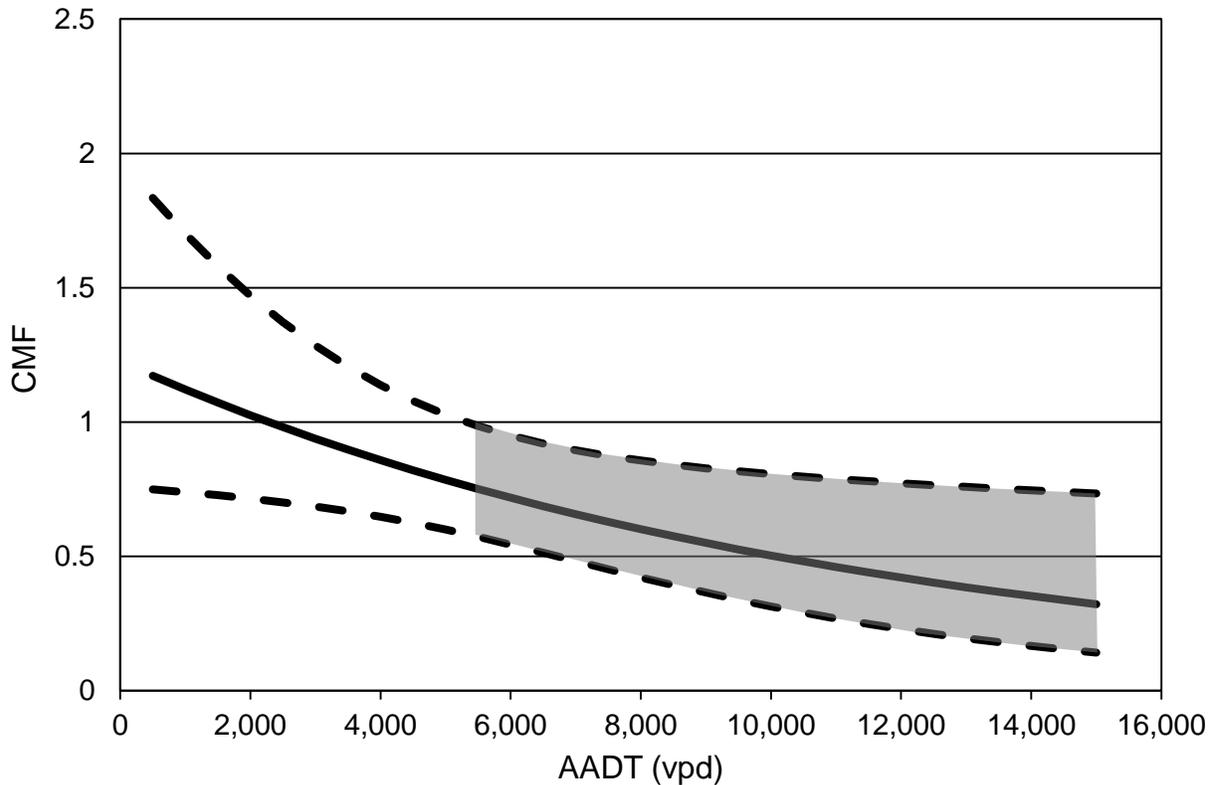


Figure 14. CMFunction for Total Crashes for In-Curve Warning Signs on Isolated Curves.

The results were further disaggregated by individual in-curve warning sign for total crashes. Figure 15 presents estimated CMFunctions for the applicable AADT range based on the data used to develop the crash prediction models. In Figure 15, Large Arrows tend to have a greater impact on crash reduction than chevrons, though the results are not statistically significant. Further analysis showed that Large Arrows are typically applied on roadways with lower traffic volumes and at curves that are more severe than where chevrons are applied. Large Arrow signs were also found to increase in effectiveness with increasing curve severity.

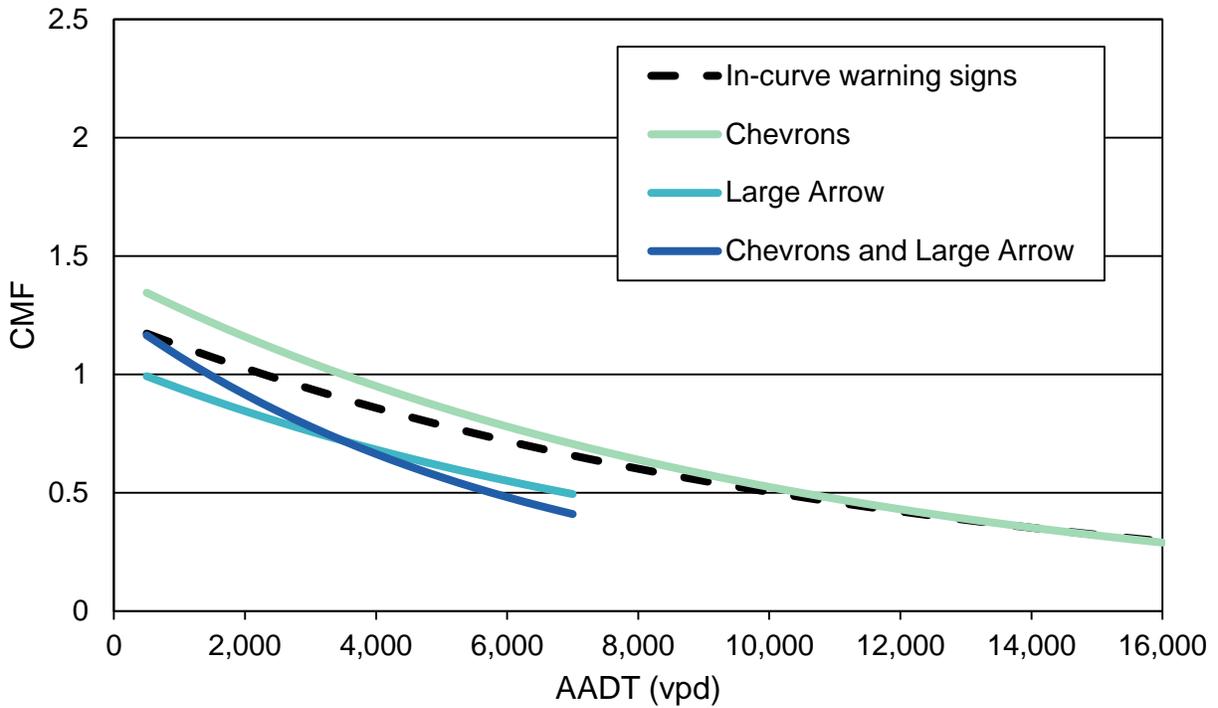


Figure 15. CMFunction for total Crashes for specific in-curve warning signs on isolated curves.

Injury Crashes

Equation 11 presents a CMFunction relating the effect of in-curve warning signs to injury crashes by AADT.

$$CMF_{injury,isolated-within} = \exp(0.564 - 0.157 * AADT(thousands)) \quad 11$$

Based on confidence intervals shown in Appendix H, chevrons and/or Large Arrows are significantly associated with fewer injury crashes when the AADT is more than 7,000 vpd. The mean CMF value is less than 1.00 (potential safety benefit) when the AADT is greater than 3,500 vpd.

Single-Vehicle Run-Off-Road Crashes

Equation 12 presents a CMFunction relating the effect of in-curve warning signs to SVROR crashes by AADT.

$$CMF_{SVROR,isolated-within} = \exp(0.179 - 0.079 * AADT(thousands)) \quad 12$$

Based on confidence intervals shown in Appendix H, chevrons and/or Large Arrows are significantly associated with fewer SVROR crashes when the AADT is between 7,000 and

11,500 vpd. While the CMF is statistically insignificant for AADT less than 7,000 vpd, the mean CMF value is less than 1.00 (potential safety benefit) when the AADT is greater than 2,000 vpd.

Adverse Pavement Condition Crashes

Equation 13 presents a CMFunction relating the effect of in-curve warning signs to adverse pavement condition crashes by AADT.

$$CMF_{adverse,isolated-within} = \exp(0.015 - 0.117 * AADT(thousands)) \quad 13$$

Based on confidence intervals shown in Appendix H, chevrons and/or Large Arrows are significantly associated with fewer adverse pavement condition crashes at isolated curves when the AADT is more than 4,000 vpd. The mean CMF value is less than 1.00 (potential safety benefit) for all values of AADT.

Nighttime Crashes

There were insufficient data to develop nighttime crash prediction models for in-curve warning signs on isolated curves.

Chevrons and/or Large Arrows within Curve Series

Crash models for in-curve signs within curve series also grouped treatments of chevrons, Large Arrow signs, and combinations of chevrons and Large Arrows into one variable, though a disaggregate analysis of the individual treatments was explored where possible. The results for each crash type are summarized in the following subsections.

Total Crashes

Equation 14 presents a CMFunction relating the effect of in-curve warning signs to total crashes by AADT.

$$CMF_{total,series-within} = \exp(0.401 - 0.065 * AADT(thousands)) \quad 14$$

Figure 16 graphically represents the CMFunction for total crashes by AADT. Surprisingly, chevrons and/or Large Arrows are significantly associated with more total crashes for AADT less than 2,500 vpd. The CMF is statistically insignificant when AADT is greater than 2,500 vpd, and there is a potential safety benefit (the mean CMF value is less than 1.00) when AADT exceeds 6,000 vpd.

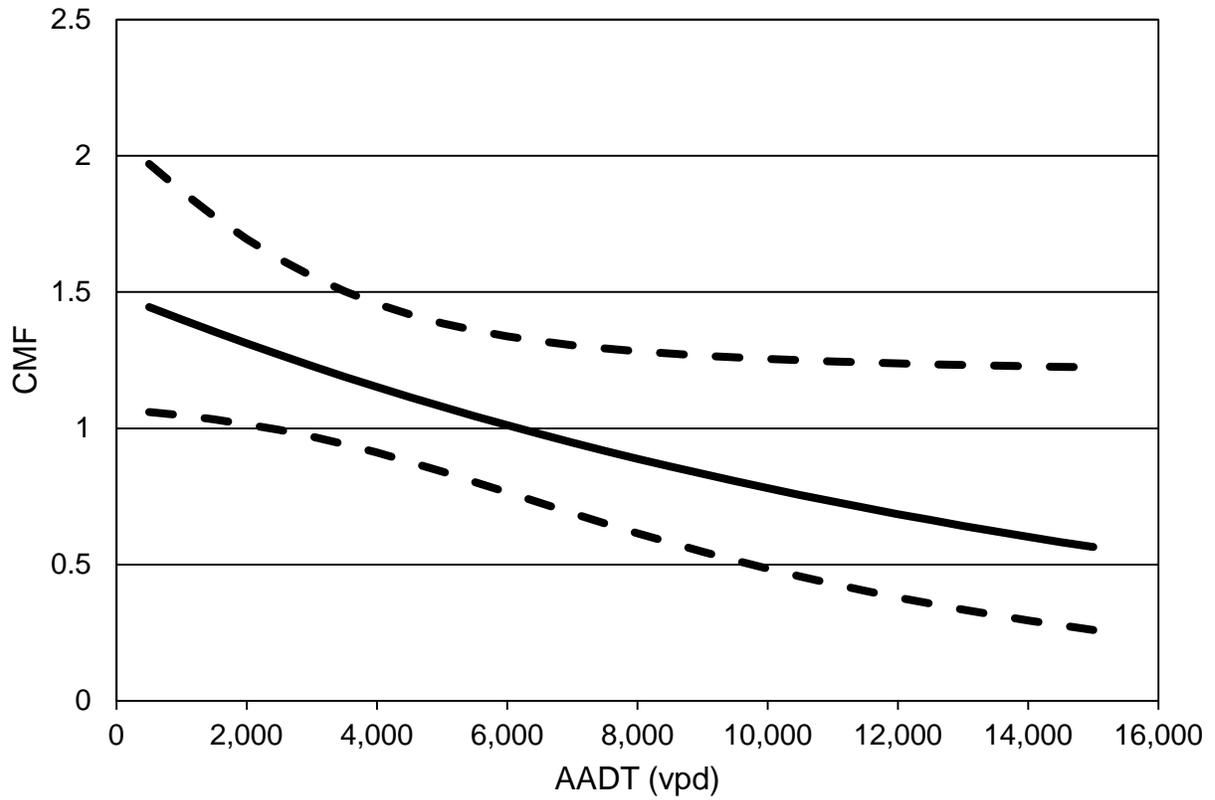


Figure 16. CMFunction for total crashes for in-curve warning signs on curve series.

A disaggregate analysis showing CMFunctions for chevrons and Large Arrow signs separately is illustrated in Figure 17. Data limitations restricted the inclusion of confidence intervals or a separate CMFunction for chevrons used in combination with Large Arrow signs.

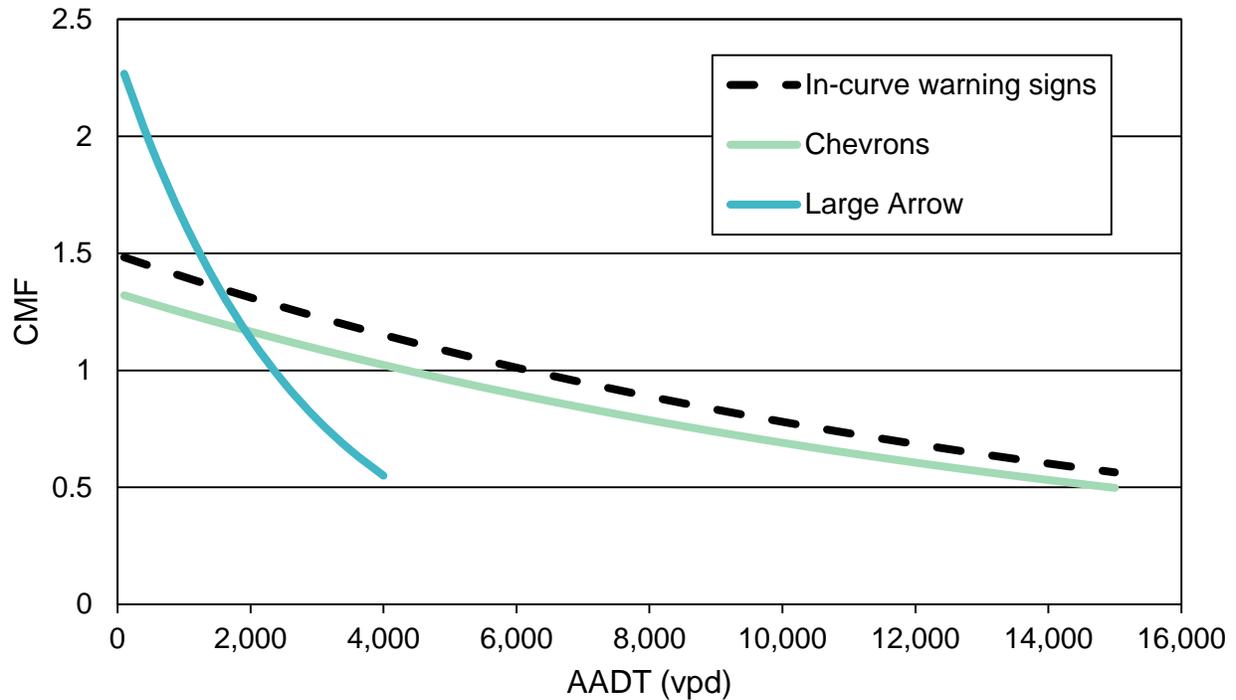


Figure 17. CMFunctions for total crashes for in-curve warning signs on curve series.

Injury Crashes

Equation 15 presents a CMFunction relating the effect of in-curve warning signs to injury crashes by AADT.

$$CMF_{injury,series-within} = \exp(0.860 - 0.150 * AADT(thousands)) \quad 15$$

Based on confidence intervals shown in Appendix H, chevrons and/or Large Arrows are significantly associated with more injury crashes when AADT is less than 3,500 vpd. There is a potential safety benefit (CMF less than 1.00) when AADT is greater than 6,000 vpd.

Single-Vehicle Run-Off-Road Crashes

Equation 16 presents a CMFunction relating the effect of in-curve warning signs to SVROR crashes by AADT.

$$CMF_{SVROR,series-within} = \exp(0.278 - 0.041 * AADT(thousands)) \quad 16$$

It was found that chevrons and/or Large Arrows are not significantly associated with fewer SVROR crashes for any value of AADT. While the CMF is statistically insignificant for all values of AADT, the mean CMF value is less than 1.00 (potential safety benefit) when AADT is greater than 7,000 vpd.

Adverse Pavement Condition Crashes

Equation 17 presents a CMFunction relating the effect of in-curve warning signs to adverse pavement condition crashes by AADT.

$$CMF_{adverse,series-within} = \exp(0.583 - 0.076 * AADT(thousands)) \quad 17$$

From confidence intervals shown in Appendix H, chevrons and/or Large Arrows are significantly associated with more adverse pavement condition crashes when AADT is less than 2,500 vpd. The mean CMF value suggests there is a potential safety benefit (CMF is less than 1.00) when AADT is greater than 7,500 vpd.

Nighttime Crashes

Equation 18 presents a CMFunction relating the effect of in-curve warning signs to nighttime crashes by AADT.

$$CMF_{nighttime,series-within} = \exp(0.455 - 0.136 * AADT(thousands)) \quad 18$$

It was found that chevrons and/or Large Arrows are significantly associated with fewer nighttime crashes when the AADT is greater than 7,000 vpd. While the CMF is statistically insignificant for AADTs less than 7,000, the mean CMF value is less than 1.00 (potential safety benefit) when the AADT is greater than 3,500 vpd.

Turn or Curve Warning Signs in Advance of Isolated Curves

The safety effect of advance warning signs was found to be a function of the degree of curvature. A relationship with speed reduction was not explored in this case, since speed reduction was defined as the difference between the posted speed limit and posted advisory speed. For untreated horizontal curves, no speed reduction value was calculated since there was no advisory speed plaque (and thus no advisory speed).

Total Crashes

Equation 19 presents a CMFunction relating the effect of advance warning signs to total crashes by degree of curvature.

$$CMF_{total,isolated-advance} = \exp(0.710 - 0.111 * degcrve) \quad 19$$

Figure 18 graphically represents the CMFunction from Equation 19. For total crashes, advance warning signs at isolated curves are significantly associated with fewer crashes when the degree of curvature is greater than 15 degrees (radius less than 400 ft). The mean CMF indicates a potential safety benefit when the degree of curvature is greater than approximately 6 degrees (radius less than 950 ft).

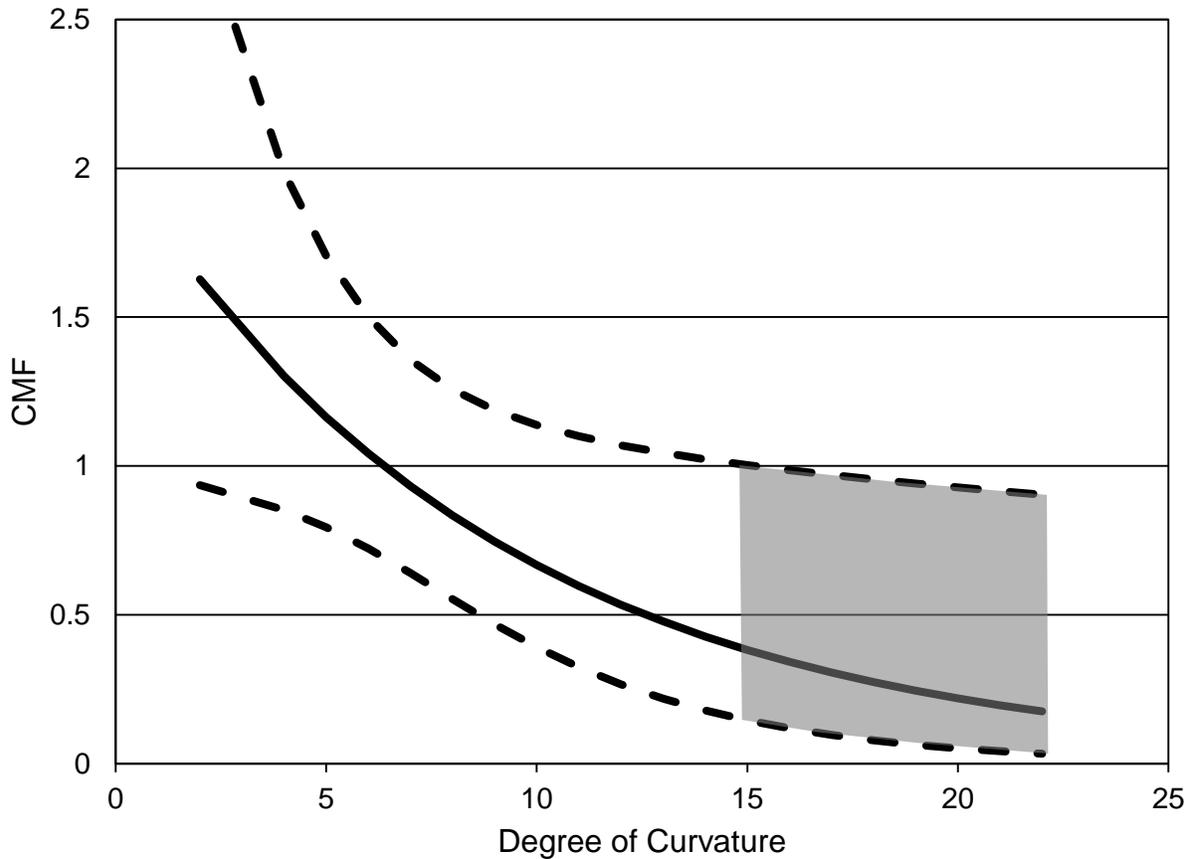


Figure 18. CMFunction for total crashes for advance warning signs on isolated curves.

A disaggregate analysis of the effects of the unique advance warning signs used at isolated curves resulted in the CMFunctions illustrated in Figure 19. Curve warning signs appear to be more effective when the degree of curvature is less than 10 degrees and Turn warning signs appear to be more effective when the degree of curvature is 10 degrees or more (radius less than approximately 600 ft). Confidence intervals could not be calculated.

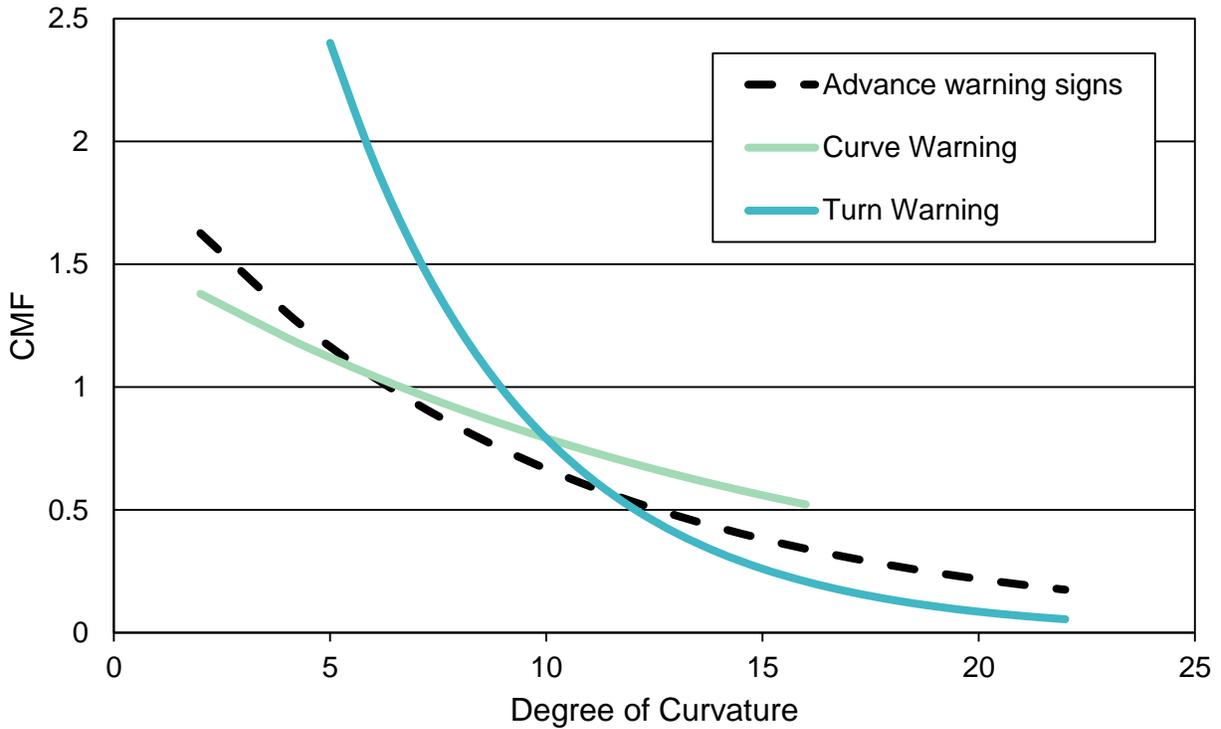


Figure 19. CMFunctions for total crashes for specific advance warning signs on isolated curves.

Injury Crashes

Equation 20 presents a CMFunction relating the effect of advance warning signs to injury crashes by degree of curvature.

$$CMF_{injury,isolated-advance} = \exp(0.729 - 0.096 * degcrve) \quad 20$$

Based on confidence intervals, advance warning signs are not significantly associated with fewer injury crashes at isolated curves for any curvature. The mean CMF is less than 1.00 (potential safety benefit) when the degree of curvature is greater than approximately 7 degrees (radius less than 800 ft).

SVROR Crashes

Equation 21 presents a CMFunction relating the effect of advance warning signs to SVROR crashes by degree of curvature.

$$CMF_{SVROR,isolated-advance} = \exp(0.623 - 0.094 * degcrve) \quad 21$$

Advance warning signs are not significantly associated with fewer SVROR at isolated curves crashes for any value of degree of curve. While the CMF is statistically insignificant for

all values of degree of curve, the mean CMF value is less than 1.00 (potential safety benefit) when the degree of curve is greater than approximately 6 degrees (radius less than 950 ft).

Adverse Pavement Condition Crashes

Equation 22 presents a CMFunction relating the effect of advance warning signs at isolated curves to adverse pavement condition crashes by degree of curvature.

$$CMF_{adverse,isolated-advance} = \exp(0.472 - 0.107 * degcrve) \quad 22$$

Based on confidence intervals, advance warning signs at isolated curves are not significantly associated with fewer adverse pavement condition crashes for any amount of curvature. While the CMF is statistically insignificant for all values of curvature, there is a potential safety benefit (CMF value is less than 1.00) when the degree of curvature is greater than approximately 4 degrees (radius less than 1,400 ft).

Nighttime Crashes

Equation 23 presents a CMFunction relating the effect of advance warning signs at isolated curves to nighttime crashes by degree of curvature.

$$CMF_{nighttime,isolated-advance} = \exp(0.749 - 0.144 * degcrve) \quad 23$$

Based on confidence intervals, advance warning signs are not significantly associated with fewer nighttime crashes for any degree of curvature. While the CMF is statistically insignificant, the mean CMF value is less than 1.00 (potential safety benefit) when the degree of curvature is greater than approximately 5 degrees (radius less than 1,150 ft).

Reverse Turn, Reverse Curve, or Winding Road Warning Signs in Advance of Curve Series

CMFunctions from the crash prediction models for advance warning signs at curve series are presented in this section. As with the other models for advance warning signs, the impact of the signs on safety was found to be a function of curvature. A relationship with speed reduction was not explored in this case, since no speed reduction could be calculated for untreated curves (because there is no posted advisory speed). The variable for curvature on a curve series was defined as an average of the degrees of curvature of the curves in the series, weighted based on the length of the curve.

Total Crashes

Equation 24 presents a CMFunction relating the effect of advance warning signs at curve series to total crashes by average degree of curvature.

$$CMF_{total,series-advance} = \exp(0.133 - 0.031 * degcrve) \quad 24$$

Figure 20 graphically represents the CMFunction of Equation 24. For total crashes, the advance warning signs are not significantly associated with fewer crashes for any amount of curvature. While the CMF is statistically insignificant for all values of average degree of curvature, the mean CMF value is less than 1.00 (potential safety benefit) when the average degree of curvature is greater than approximately 4 degrees (average radius less than 1,400 ft).

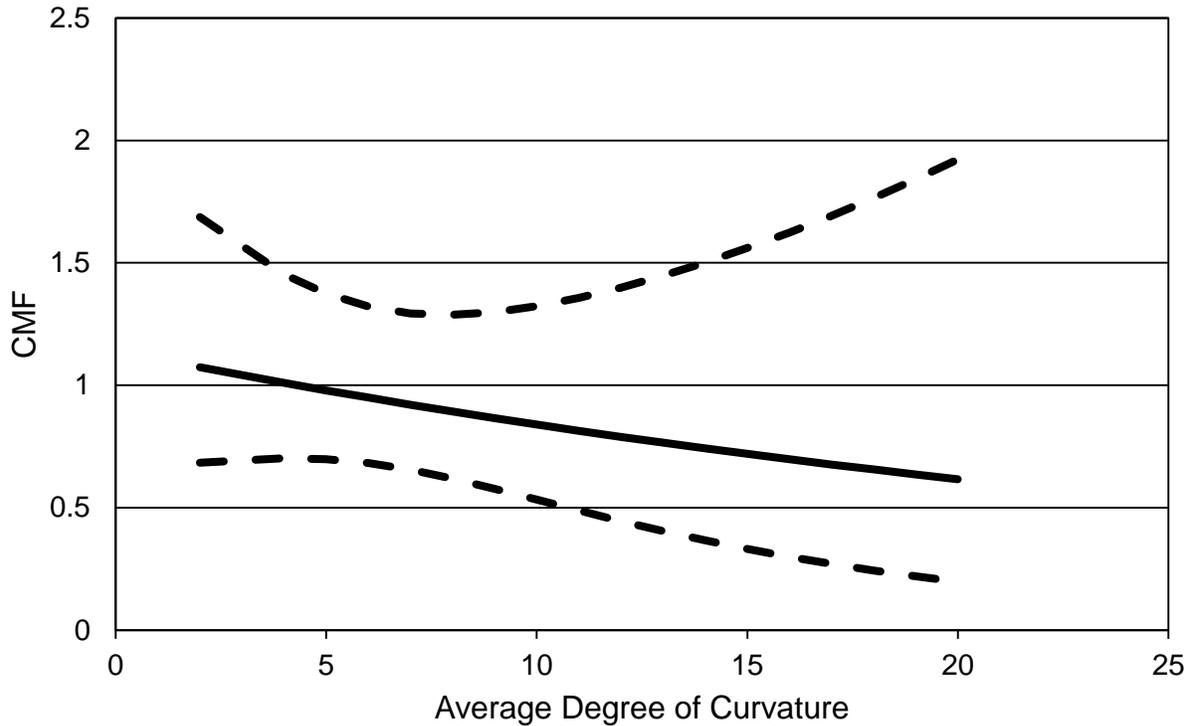


Figure 20. CMFunction for total crashes from advance warning signs on curve series.

CMFunctions from a disaggregate analysis of the effects of individual advance warning signs on total crashes at curve series is shown in Figure 21. Reverse Turn signs appear to be more effective when the average degree of curvature is 8 degrees or more (average radius less than 700 ft). The effectiveness of Reverse Curve signs appears to decrease as the average curvature increases, while other signs appear to be increase in effectiveness. The Winding Road sign appears to be the most effective advance warning sign when the average degree of curvature is 5 degrees or more (average radius less than 1,150 ft); however, Winding Road signs are applied differently than Reverse Turn and Reverse Curve signs. Confidence intervals could not be represented in Figure 21.

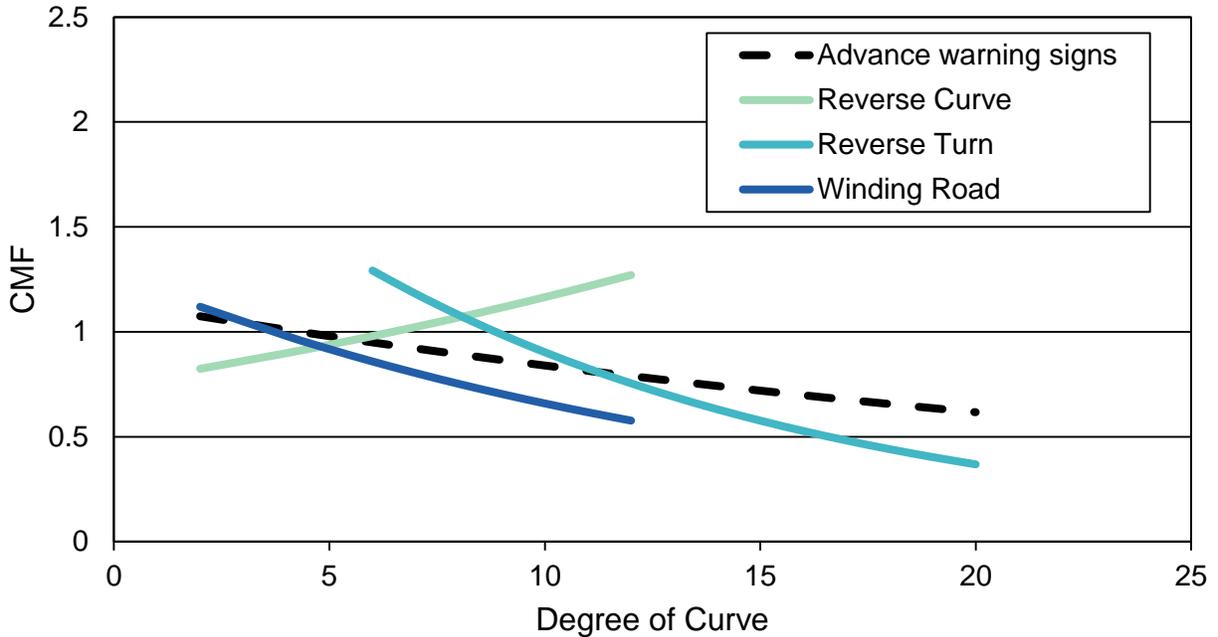


Figure 21. CMFunction for total crashes for individual advance warning signs on curve series.

Injury Crashes

Equation 25 presents a CMFunction relating the effect of advance warning signs at curve series to injury crashes by average degree of curvature.

$$CMF_{injury,series-advance} = \exp(-0.161 - 0.043 * degcrve) \quad 25$$

Based on confidence intervals, advance warning signs at curve series are not significantly associated with fewer injury crashes for any amount of curvature. While the CMF is statistically insignificant for all average curvatures, the mean CMF value indicates a potential safety benefit for all curvatures. Disaggregate analyses indicate that Reverse Turn signs have potential safety benefits (the mean CMF, but not the entire confidence interval, is less than 1.00) when the average degree of curvature is greater than approximately 13 degrees (average radius less than 450 ft). Winding Road signs were shown to significantly reduce crashes for an average degree of curvature greater than 5 degrees (average radius less than 1,150 ft).

SVROR Crashes

Equation 26 presents a CMFunction relating the effect of advance warning signs at curve series to SVROR crashes by average degree of curve.

$$CMF_{SVROR,series-advance} = \exp(-0.132 - 0.008 * degcrve) \quad 26$$

Based on confidence intervals, advance warning signs are not significantly associated with fewer SVROR crashes for any average curvature; however, the mean CMF value is less than 1.00 (potential safety benefit) for all average curvatures.

Adverse Pavement Condition Crashes

Equation 27 presents a CMFunction relating the effect of advance warning signs at curve series to adverse pavement condition crashes by average degree of curvature.

$$CMF_{adverse,series-advance} = \exp(0.775 - 0.059 * degcrve) \quad 27$$

Based on confidence intervals, advance warning signs at curve series do not significantly reduce adverse pavement condition crashes for any value of average curvature. While the CMF is statistically insignificant, the mean CMF value is less than 1.00 (potential safety benefit) when the average degree of curvature is greater than 13 degrees (average radius less than 450 ft).

Nighttime Crashes

Equation 28 presents a CMFunction relating the effect of advance warning signs at curve series to nighttime crashes by average degree of curvature.

$$CMF_{nighttime,series-advance} = \exp(0.524 - 0.079 * degcrve) \quad 28$$

Based on confidence intervals, advance warning signs at curve series are not significantly associated with fewer nighttime crashes for any value of average degree of curvature. The mean CMF value is less than 1.00 (potential safety benefit) when the average degree of curvature is greater than 6 degrees (average radius less than 950 ft).

SUMMARY

Crash prediction models were developed to estimate the effects of horizontal alignment warning signs on various crash types (total, injury, SVROR, adverse pavement, and nighttime crashes) at isolated curves and curve series. CMFunctions were created from the crash prediction models that show how the influence of the signs on crashes varies based on other curve features. It was found that the CMF for in-curve signs (treatments consisting of chevrons and/or Large Arrow signs) was best represented as a function dependent upon AADT. For advance warning signs (Turn and Curve signs at isolated curves and Reverse Turn, Reverse Curve, and Winding Road signs at curve series) the CMFs were found to be dependent upon degree of curvature, or average degree of curvature for curve series.

Several of the models were not able to show that the signs lead to statistically significant reductions in crashes. In fact, the only condition for which an advance warning sign results in a significant crash reduction is for isolated curves with curvature greater than 15 degrees (radius less than 400 ft). Each of the crash prediction models, however, did have certain conditions for which a calculated CMF is less than 1.00, indicating a probable reduction in crashes. Generally, a sign's influence on safety increases as the dependent variable increases (either AADT for in-

curve signs or curvature for advance warning signs). Table 11 indicates the conditions for which the investigated signs result in a statistically significant reduction in crashes and a probable reduction in crashes.

Table 11. Conditions (AADT or Degree of Curvature) for Significant and Probable Crash Reductions from Warning Signs

Crash Type	In-Curve Warning Signs (AADT)				Advance Warning Signs (curvature)			
	Isolated		Series		Isolated		Series	
	Significant Reduction	Probable Reduction	Significant Reduction	Probable Reduction	Significant Reduction	Probable Reduction	Significant Reduction	Probable Reduction
Total	>5,500 vpd	>2,500 vpd	Not Observed	>6,000 vpd	>15 deg	>6 deg	Not Observed	>4 deg
Injury	>7,000 vpd	>3,500 vpd	Not Observed	>6,000 vpd	Not Observed	>7 deg	Not Observed	All conditions
SVROR	7,000–11,500 vpd	>2,000 vpd	Not Observed	>7,000 vpd	Not Observed	>6 deg	Not Observed	All conditions
Adverse Pavement	>4,000 vpd	All conditions	Not Observed	>7,500 vpd	Not Observed	>4 deg	Not Observed	>13 deg
Nighttime	No Model	No Model	>7,000 vpd	>3,500 vpd	Not Observed	>5 deg	Not Observed	>6 deg

While the findings represented in Table 11 are based on aggregate data where the treatment could consist of any of the warning signs used in that group, several disaggregate analyses focused on the effects of individual types of signs on crashes. These disaggregate analyses were unable to identify the conditions for which a particular sign results in a statistically significant safety improvement over another sign, but the results of the averages suggest the following:

- A Turn signs is more effective than a Curve sign at isolated curves with a degree of curvature greater than 10 degrees (radius less than 600 ft).
- A Reverse Turn sign is more effective than a Reverse Curve sign at curve series where the average degree of curvature is greater than 8 degrees (average radius less than 700 ft).
- A Large Arrow sign is more effective than chevrons at all isolated curves. For curve series, the Large Arrow sign is more effective when the AADT exceeds 2,000 vpd.

Chapter 6: Guidelines for Traffic Control Devices at Curves

The objective of this research was to identify potential improvements to the MUTCD guidelines for the application of TCDs on curves. The research team used a two-pronged approach (unfamiliar driver behavior and crash-based safety studies) to produce new discoveries that were blended in a complimentary way to advance the understanding of driver behavior at curves and the effects of curve TCDs on behavior and safety. The focus of the research activities was on TCDs (other than traditional pavement markings) that are typically applied to curves on two-lane roads. These include advance warning signs used in advance of curves and multiple types of devices that can be used within curves, specifically chevrons, One-Direction Large Arrow signs, delineators, and RPMs. The guidelines recommended in this chapter are based on findings from the current research as well as other material which has been credited. The proposed guidelines for selecting TCDs is flexible and provides a methodology that can be adjusted based on future research findings. This flexibility includes opportunities to expand the guidelines to include other traffic control devices that were not evaluated in this research.

The driver behavior and the safety studies were coordinated in design and objectives but conducted and analyzed independently so the researchers could keep their analyses free of any bias introduced by knowing preliminary results of the other study. From the beginning of the research, it was understood that the findings of the separate studies might not always align with each other and that inconsistencies in the findings would need to be resolved. After the driver behavior and safety research efforts were conducted and analyzed, the research team worked together to use the new findings to develop the recommended guidelines and accompanying MUTCD language. The recommendations are thus supported by both driver behavior and safety study findings.

Both studies were designed and conducted in such a way that inherent bias was unavoidable due to current practices regarding the use of TCDs in curves. During the driver behavior study, the researchers were able to add TCDs to certain curves for the purpose of the study, but the liability associated with the removal of existing TCDs limited the study design. The safety study was also limited in a similar way because data were collected from sites that were treated based on current practices. The driver behavior study protocol is discussed in Appendix D, with the effects of TCDs on operational measures presented in Appendix E, and elements of driver attention discussed in Appendix F. Chapter 4 contains the operational findings from the driving study that are directly incorporated into the guidelines discussed in this chapter.

As documented in Appendix G, the crash data were analyzed using generalized linear modeling techniques with a log-linear relationship between crash frequency and site characteristics. A cross-sectional study of warning signs at isolated curves and curve series identified several ways these curve TCDs affect safety. Chapter 5 contains findings from the safety analysis that directly impacts the guidelines discussed in this chapter. Other substantial findings are documented in Appendix H.

With models of driver behavior, crash estimates, and data identifying how TCDs at curves influence both behavior and safety, the information produced by the analyses is quite extensive. However, there are still some specific areas where the data from the studies were not

sufficient for some of the details incorporated into the guidelines. It is important to recognize the value of previous research that may be used where the information produced from the present research is insufficient. Additionally, there is value in applying reasonable judgment where a particular element of the guidelines lacks the appropriate data, whether identified in previous research or discovered in this study. Where applicable, clarification is provided in the proposed guidelines stating whether justification is provided by data from the current research, relevant previous research, or judgment by the research team.

BACKGROUND

In review, the MUTCD states that a TCD should meet five basic requirements:

1. Fulfill a need.
2. Command attention.
3. Convey a clear, simple meaning.
4. Command respect from road users.
5. Give adequate time for proper response.

The MUTCD also states that “the proper use of traffic control devices should provide the reasonable and prudent road user with the information necessary to efficiently and lawfully use the streets, highways, [etc.]” In other words, the selection of a TCD should not be based on assumptions of unreasonable and imprudent behavior (for example, a distracted driver with reckless speed at night). Because the current research did not focus on the design and appearance of the devices, but rather on the determination of the conditions for which their use is appropriate, the guidelines developed in this study relate to the first, fourth, and fifth requirements above.

The current guidelines for curve TCDs in MUTCD Table 2C-5 essentially employ a hierarchy that increases the number of devices as the curve severity (as defined by the difference between the speed limit and the advisory speed) increases. Table 12 illustrates this hierarchy. Though perhaps forgotten as a device that aids in curve navigation, pavement markings provide critical delineation that is used for guidance both near to and far from the vehicle. Their use on most paved roads (required on rural roads when the AADT is greater than 6,000 vpd) justifies them to be considered as the lowest level of the curve TCD hierarchy, even though the MUTCD does not explicitly specify their use at curves. In the current hierarchy, an advance warning sign is required when the speed change at the curve is 10 mph or greater; chevrons and/or a Large Arrow sign must supplement the advance warning sign when the speed change is 15 mph or greater. A hierarchy in which the number and size of devices increases with curve severity is sensible because the urgency of the message matches how the message is delivered. The policies of international transportation agencies summarized in Chapter 2 reflect the same approach.

Table 12. Hierarchy of Required TCDs in Current MUTCD Guidelines

Severity	Curve TCDs
Level 1	Pavement markings (if AADT>6,000 vpd)
Level 2 ($\Delta v \geq 10$ mph)	Pavement markings, advance warning sign
Level 3 ($\Delta v \geq 15$ mph)	Pavement markings, advance warning sign, chevrons and/or Large Arrow

While the current guidelines reflect a rational desire for consistency in selecting curve treatments, there is no data-driven support for how the levels were defined, the thresholds for speed changes determined, and the guidelines structured. Despite the amount of previous research investigating the visibility of these devices and their effects on driver behavior and safety, the current guidelines were not created using a scientific approach that provides a systematic method for ensuring a selected TCD fulfills a need and is adequate for the proper response. Drivers may lose respect for TCDs when they are installed without fulfilling a need.

METHODOLOGY

The methodology used to develop the guidelines is a blended approach that builds from two main research efforts conducted under this project: the safety analysis and the driver behavior study. Regarding the safety analysis, TCDs used both within curves and in advance of curves were found to result in reductions in crashes. Statistical significance, however, was not observed for all conditions. The findings from the driving study were generally more consistent. Improvements in operational performance due to TCDs were observed under most, if not all, conditions encountered. By using the operational findings to determine the level of traffic control for specific curve conditions, and applying the findings of the safety study to determine the degree of regulation placed on each treatment and scenario, the guidelines satisfy the requirements of a TCD using a methodical, scientific approach that blends findings from both research efforts.

The methodology for selecting TCDs at curves is based on ensuring each device meets the requirements of an effective TCD as given in the MUTCD. Findings from the driver behavior study can be used to verify that the devices are needed to provide enough time for a proper response. Key findings of the driver behavior study include deceleration characteristics that can determine the distance a driver typically uses to decelerate before a curve. Also important are the observed effects of TCD treatments on the location in advance of a curve where drivers initiate the deceleration. By matching the distance traveled while decelerating with the distances from the curve at which a treatment is effective, it can be determined whether or not a TCD provides adequate time for a proper response (MUTCD's TCD requirement 5). If enough time for a proper response is given, the device is justified based on typical driver behavior (MUTCD's TCD requirement 1). Respect from the road users (MUTCD's TCD requirement 4) will be maintained as the devices are consistently used where they meet these other requirements and driver expectations.

Selecting an appropriate TCD based on the response distance supported by a particular curve treatment can be compared to finding an equivalence point where supply meets demand. In this example, the supply is the response distance supported by a particular TCD; the demand is how much distance a reasonable and prudent driver would use in responding to the curve. If a driver decelerates with a shorter distance, the curve is less demanding and a lower level of TCD is appropriate. It is expected that larger or more prominent devices result in increased supply. An appropriate TCD will provide a greater supply of response distance than a driver demands, but not so much as to lose respect (MUTCD's TCD requirement 4).

DATA USED TO SUPPORT THE PROPOSED GUIDELINES

While the results of the driver behavior and safety studies are documented in Chapters 4 and 5, respectively, some key findings of those studies are summarized here to support the methodology used in creating guidelines for curve-related TCDs. Additionally, some information from previous research is discussed because it plays a role in the development of the guidelines.

Driver Behavior Study

The driver behavior study was conducted to document elements of behavior at curves and how TCDs influence that behavior. The field study identified three important findings regarding driver behavior that are specifically used in developing guidelines for TCDs. The findings are derived from models that characterize deceleration rates, how much deceleration at a curve is completed in advance of the curve, and where drivers respond on the tangent approach. These characteristics, with the identified influences of TCDs, can be used to determine whether or not a device fulfills a need and provides enough time (or distance) for a proper response.

Deceleration Rate

It has been discussed that, depending on the characteristics of a curve, drivers may need to decelerate in order to navigate the curve at a comfortable (and safe) speed. Current design applications (e.g., placement of advance warning signs from MUTCD Table 2C-4) often assume a uniform deceleration rate of 10 ft/s^2 . Data collected in the driver behavior study reveal that typical deceleration rates approaching horizontal curves are much lower than the 10 ft/s^2 assumption. In fact, it was found that the deceleration rate a driver accepts is dependent upon the total speed change experienced at the curve. Cumulative distribution plots in Chapter 4 for the deceleration rates accepted by drivers indicate that with each 5-mph increase in total speed change, drivers tend to increase their rate of deceleration by 1 to 2 ft/s^2 . If it were assumed that drivers decelerate with a uniform rate for all conditions and curves, deceleration distances calculated for severe curves would be longer than drivers actually experience.

By recognizing that drivers accept a higher deceleration rate as the total speed differential increases, the needs of drivers at a curve can be better estimated. The guidelines that are presented in this chapter are based in part on the 50th percentile deceleration rate, which increases as the curve severity increases. .

Speed Change Completed before Curve

The second key finding of the driver behavior study is that drivers do not complete all of the speed change before entering the curve. In most cases, drivers continue to decelerate in the curve, reaching a minimum speed usually prior to or near the midpoint. Drivers in the driver behavior study on average completed 53 percent of the total speed change before the curve. The cumulative distribution plot of the proportion of the total speed reduction completed before the curve shown in Chapter 4 indicates that there is a small increase in the proportion of speed change completed before the curve as the total speed reduction experienced at the curve increases. For the average (50th percentile) driver, the proportion of total speed reduction that occurs before the curve increases from 51 percent for speed differentials of 5 to 9.99 mph up to

64 percent for speed differentials of 15 to 19.99 mph. There seems to be no consistent change as the speed differential increases beyond the 15-mph bin.

To assume that all deceleration is completed in advance of a curve would result in over-conservative guidelines that do not reflect observed driver behavior. By accepting that drivers continue decelerating within the curve, the guidelines can be structured in a way that better reflects a typical driving experience. Analyses indicate that TCDs do not affect the proportion of speed change occurring in advance of a curve.

Location of Driver Response

The first two key findings from the driver behavior study used to generate guidelines are characteristics of driver deceleration at curves. When combined, they can be used to identify the total distance needed for a driver to safely respond to the operational demands of the curve. The final key finding is the location where the drivers were observed to initially respond to the curve, based on the use of TCDs at the curve. Because the operational data were collected continuously throughout each drive, the data from each tangent can identify where drivers respond to curves even when they are located far from the curve.

With models that estimate the location of drivers when they reach maximum speed on a tangent—having accelerated after exiting a curve and then decelerating in advance of a curve—it was found that drivers initiate a deceleration response earlier when TCDs are used. Significant variables in the models indicate that, when delineators are used in the curve, drivers begin decelerating an average of 76 ft (Standard error [SE] = 35 ft) earlier than when nothing is used, other than pavement markings; for chevrons, the difference is an average of 137 ft (SE = 29 ft) earlier than when nothing is used except pavement markings. These distances of driver response are a key element of the guidelines. They represent when drivers react to these devices and not when they can see them.

Safety Study

For the driver behavior study, the primary and unique contribution is documentation that driver behavior is not uniform at curves with different characteristics, and that the total speed reduction can be used to estimate how drivers decelerate before a curve. The safety study similarly produced information that may change current assumptions regarding TCD effectiveness. These unique findings are emphasized in the proposed guidelines for TCDs.

Models detailing how TCDs at curves affect crashes are documented through the use of CMFunctions in Appendix H. Several scenarios are examined, including the use of TCDs in advance of or within curves, and the application of the devices at curves in series or in isolation. Overall, it was found that the effectiveness of advance warning signs increases as the curve becomes sharper, and that Turn signs are more effective than Curve signs at curves with a small radius. Large Arrow signs were found to be more effective at reducing crashes than chevrons, particularly for short curves with a small radius.

One of the most significant contributions of the safety study is the finding that the effectiveness of TCDs within curves increases as traffic volume increases, rather than with changes in curve severity. For total crashes on isolated curves, statistically significant crash reductions from chevrons and/or Large Arrow signs were observed when AADT was greater than 5,500 vpd. For specific crash types, reductions become significant starting at volumes

between 4,000 and 7,000 vpd. Probable reductions for total crashes from in-curve signs at isolated curves (meaning the CMF is less than 1, but the upper confidence limit is greater than 1) occur when the AADT is greater than 2,500 vpd. The models with advance warning signs were found to significantly reduce crashes in very limited applications, and the effect was dependent upon curve geometry. There are several instances of probable crash reductions due to advance warning signs, and the models suggest that the effect increases with increased severity. Table 13 summarizes the conditions for which there are significant and probable crash reductions from the warning signs tested in the safety study.

Table 13. Conditions (AADT or Degree of Curvature) for Significant and Probable Crash Reductions from Warning Signs

Crash Type	In-Curve Warning Signs (AADT)				Advance Warning Signs (curvature)			
	Isolated		Series		Isolated		Series	
	Significant Reduction	Probable Reduction	Significant Reduction	Probable Reduction	Significant Reduction	Probable Reduction	Significant Reduction	Probable Reduction
Total	>5,500 vpd	>2,500 vpd	Not Observed	>6,000 vpd	>15 deg	>6 deg	Not Observed	>4 deg
Injury	>7,000 vpd	>3,500 vpd	Not Observed	>6,000 vpd	Not Observed	>7 deg	Not Observed	All conditions
SVROR	7,000–11,500 vpd	>2,000 vpd	Not Observed	>7,000 vpd	Not Observed	>6 deg	Not Observed	All conditions
Adverse Pavement	>4,000 vpd	All conditions	Not Observed	>7,500 vpd	Not Observed	>4 deg	Not Observed	>13
Nighttime	No Model	No Model	>7,000 vpd	>3,500 vpd	Not Observed	>5 deg	Not Observed	>6

Based on the information in Table 13 that documents the traffic volumes for which in-curve warning devices effectively reduce crashes, AADT thresholds of 4,000 vpd and 2,000 vpd were used to determine the conditions for when a treatment is to be classified in the suggested MUTCD Language as required and recommended, respectively. These traffic volume thresholds were selected because agencies should not be compelled (by recommendation or requirement) to install devices without solid justification of a safety improvement.

Other Relevant Research Used in the Guidelines

For this study, pavement markings were used on all facilities where data were collected, whether for the driver behavior study or safety study. Consequently, an investigation of the impact of pavement markings at curves could not be completed as a part of the overall research. However, information from other sources can be used to determine when pavement markings alone are sufficient for drivers to navigate a curve. The requirements for minimum pavement marking retroreflectivity that are currently in the federal rule-making process (79) were developed based on a criterion that markings be visible for at least 2.2 s. Because 2.2 s of travel time results in a longer distance at faster speeds, the proposed minimum retroreflectivity level increases with the speed limit of the facility. Table 14 indicates the specific proposed requirements.

Table 14. Proposed Minimum Maintained Retroreflectivity Levels of Pavement Markings*

Road Type	Posted Speed (mph)		
	≤30	35–50	≥55
Two-lane roads with centerline markings only	N/A	100	250
All other roads	N/A	50	100
*Measured in units of mcd/m ² /lx (at 30-m geometry). Exceptions are provided when continuous roadway lighting or retroreflective RPMs are used.			

Since it is anticipated that agencies will be required to maintain the retroreflectivity of their pavement markings above a certain level (providing at least 2.2 s of preview time), it is reasonable to assume that, as the lowest level on the curve TCD hierarchy, pavement markings provide a preview distance equivalent to 2.2 s of travel time. If the deceleration maneuver at a curve can be completed in less distance than is traveled in 2.2 s, then no devices other than pavement markings should be required at the curve.

Retroreflectivity varies based on the types of materials used, and the actual visibility of a marking is dependent upon many other factors, such as headlamp configuration, contrast with the pavement, and precipitation (if any) collected on the marking. Previous visibility research identified the preview distances of various pavement marking treatments. Preview time was calculated by matching the preview distance with a given speed. The results shown in Chapter 3 indicate that preview times above 3 or 4 s are not uncommon, with very long preview times for low speeds and RPMs. No product under dry conditions had an average preview time less than 2.4 s (32). Preview times for wet conditions were also shown, but because wet conditions affect driver behavior in multiple ways, they were not included in the current field study nor considered in the guidelines for selecting TCDs. Based on the preview times shown in Chapter 3 and the forthcoming retroreflectivity requirement from FHWA, an assumption that pavement markings provide a preview time of 2.2 s was deemed reasonable for consideration in the guidelines for curve-related TCDs.

PROPOSED GUIDELINES FOR TCDs AT CURVES: MATCHING SUPPLY WITH DEMAND

The previous section summarizes the research relevant to understanding how much deceleration distance is demanded from drivers (based on the deceleration characteristics) and how much distance is supplied based on where drivers respond to the devices. Additional consideration for the traffic volume (from the safety study) is included. The guidelines are based on ensuring that more distance is supplied by a device than is demanded by a driver’s typical response at a curve.

TCD-Supported Response Distance (Supply)

The proposed guidelines are based on a hierarchy where each level of TCD extends the available response distance beyond what is provided by a previous, lower level. The guidelines are applicable to paved roads that have continuous pavement markings, since data collected for the field and safety studies came from such facilities. Identical to the current hierarchy shown in

Table 12, pavement markings are again used as the first level of traffic control. The next treatment level is defined by the addition of an advance warning sign, which also reflects current practice. From the field study, there is justification for having two levels of TCDs beyond the use of an advance warning sign. The third level in the hierarchy is the use of delineators; the fourth level is the use of chevrons. Delineators are not included in the current MUTCD hierarchy for curve TCDs (in Table 2C-5) even though they are suggested in the MUTCD as an effective guidance device at locations where the alignment might be confusing or unexpected, such as curves, and at night and during adverse weather (MUTCD Section 3F.01).

Table 15 illustrates the proposed hierarchy of TCDs at curves based on the findings from the field study. The primary difference between the current hierarchy of TCDs (Table 12) and the proposed hierarchy is the insertion of a level that includes delineators. The highest level still contains chevrons. Large Arrow signs are not shown in Table 15, but can still be used as discussed later. The following sections discuss the response distances supported by these devices.

Table 15. Proposed Hierarchy of TCDs Based on Study Findings

Severity	Curve TCDs
Level 1	Pavement markings
Level 2	Pavement markings, advance warning sign
Level 3	Pavement markings, advance warning sign, delineators
Level 4	Pavement markings, advance warning sign, chevrons

The relevant findings and data presented in the previous section identify that pavement markings provide a minimum of 2.2 s of preview time (based on proposed retroreflectivity guidelines). The findings and data also show that drivers respond earlier by approximately 76 or 137 ft (with standard errors of 35 or 29 ft, respectively) when approaching a curve treated with delineators or chevrons, respectively, than when no additional treatment is used beyond an advance warning sign and pavement markings. The total response distance supplied by a treatment is calculated based on the combination of distances supported by each device used in the treatment. Figure 22 illustrates how the assumed response distances provided by TCDs can be combined, starting with pavement markings that are visible for at least 2.2 s in front of the vehicle. Using a response time (2.2 s) for pavement markings results in an increase in available response distance as speed increases (which fits with the requirement for increased retroreflectivity). Although there are three groups of minimum retroreflectivity levels shown in Table 14, a continuous effect of 2.2 s is used here to maintain consistency with the original justification for the requirement. Figure 22 does not show advance warning signs as a level affecting the supplied response distance because the curves for which advance warning sign data were collected are not representative of the curves at which the proposed guidelines would suggest such a device be used. Though not shown as affecting the supplied deceleration distance (Figure 22), advance warning signs are included in the proposed guidelines discussed below. The supply provided by the use of delineators (in addition to the pavement markings) is illustrated by the orange band in Figure 22, with total supplied distance rounded to 75 ft. Since chevrons are the last level in the hierarchy, the end point of their supplied response distance is not defined in Figure 22.

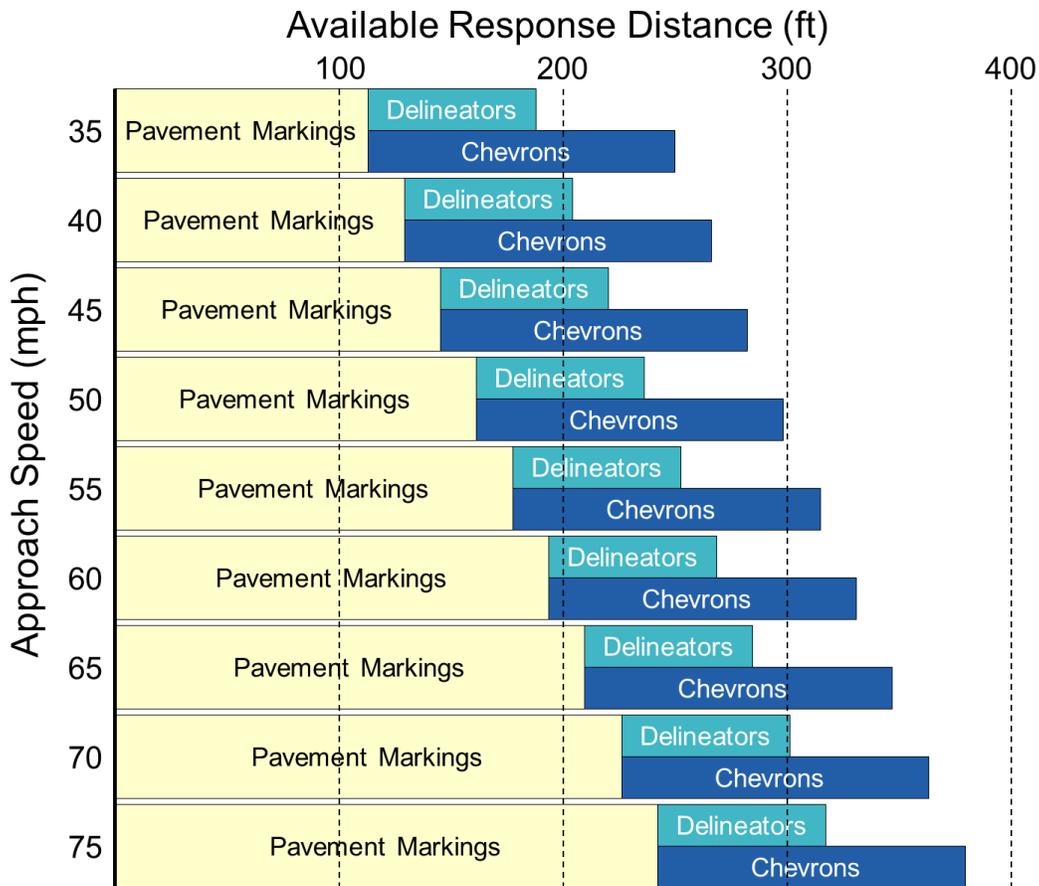


Figure 22. Total available response distance for TCDs using 2.2 s of travel time for pavement markings and adding 75 ft for delineators or more than 75 ft for chevrons.

Driver Response Distance (Demand)

After the response distance supplied by in-curve TCDs is identified, the next step is to identify a typical driver’s response, or the demand. The demand is the distance a driver needs to decelerate to an appropriate speed before the curve. The proposed guidelines use four components to calculate the deceleration distance. The first two components are the approach speed in advance of the curve and the curve speed. The approach speed may be identified as the speed limit of the facility or the prevailing or 85th percentile speed on the tangent preceding the curve. In the field study, the approach speed was identified as the driver’s maximum speed on the tangent. Many factors affect driver speeds, such as the functional class of the road or length of the tangent, so the proper application of engineering judgment in selecting an appropriate approach speed is crucial. The curve speed in the field study was identified as the driver’s minimum speed in the curve, which was highly correlated with the posted advisory speed (researchers did not evaluate the appropriateness of the advisory speeds on the curves studied).

The third and fourth variables are the deceleration characteristics (deceleration rate and proportion of total deceleration that occurs before the curve) that were discussed previously. Because it was observed that the speed change experienced at the curve primarily determines

how drivers decelerate, the first two inputs (approach and curve speeds) are actually used to define the values of deceleration rate and total deceleration completed before the curve.

Table 16 identifies the deceleration distances of a typical driver, based on the approach and curve speeds and using the 50th percentile deceleration characteristics identified in Figures 12 and 13. The 50th percentile observations represent a typical driver because half of the observations are expected to be greater and half are expected to be smaller. In other words, half of unfamiliar drivers will be more conservative and half will be less conservative. Since additional TCDs are likely to be used at curves with speed changes 15 mph and greater, the effects of TCDs on deceleration rates should be accounted for in those scenarios. The assumed 50th percentile deceleration rates are thus reduced by 0.5 ft/s² for speed changes of 15 and 20 mph and 1.3 ft/s² for speed changes 25 mph and greater. Additionally, the amount of deceleration completed before each curve is set to 50 percent for speed changes of 5 mph, 60 percent for 10-mph changes, and 65 percent for all speed changes 15 mph and greater. Finally, the 50th percentile characteristics for all speed changes greater than 25 mph used the values of the 25–29.99 mph bin.

Table 16. Deceleration Distances (ft) Using 50th Percentile Observations

Approach Speed (mph)	Curve Speed (mph)										
	20	25	30	35	40	45	50	55	60	65	70
25	60										
30	90	70									
35	130	105	85								
40	160	150	120	95							
45	220	185	175	135	105						
50	285	250	210	195	150	120					
55	365	325	280	235	215	170	130				
60	450	405	360	310	260	235	185	145			
65	540	495	445	395	340	285	260	200	155		
70	640	595	545	490	430	370	310	280	215	170	
75	750	700	645	590	530	465	400	330	300	235	180

Meeting Demand with Supply

Values representing the 50th percentile of driver behavior are used to determine whether or not a supplemental TCD, in addition to an advance warning sign, is appropriate for a curve. To meet the requirements of an effective TCD, the available response distance of the TCD level (illustrated in Figure 22) must be equal to or greater than the deceleration distance (calculated in Table 16). Figure 23 indicates the minimum level of supplemental TCD appropriate for each scenario of approach and curve speed.

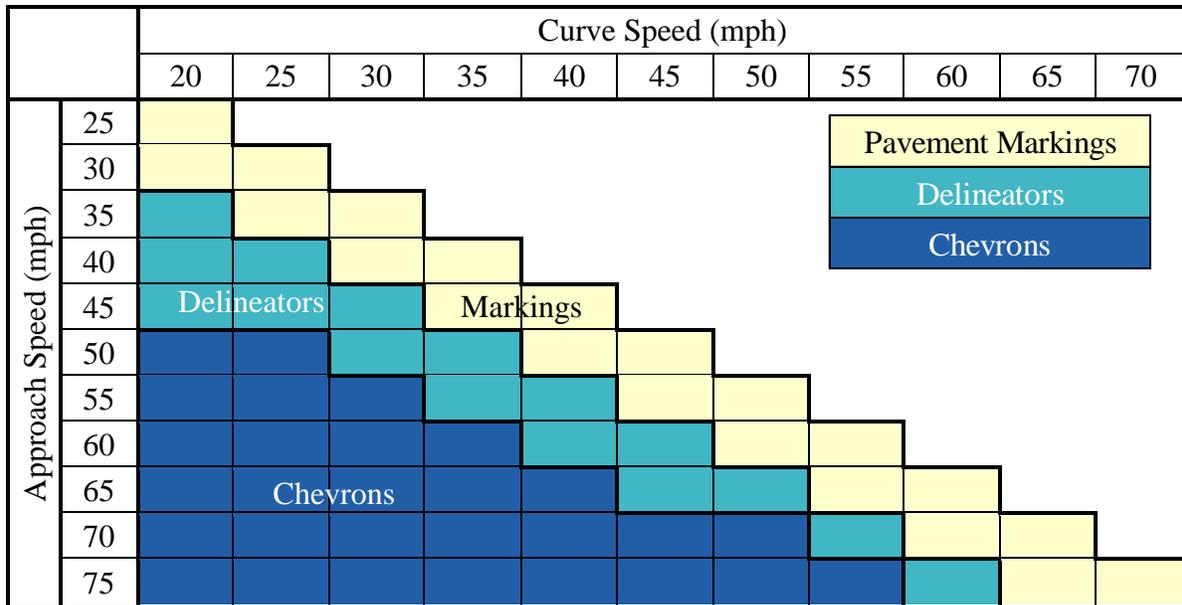


Figure 23. Appropriate in-curve TCDs based on typical deceleration characteristics.

Proposed Guidelines

Until now, there has been little discussion of where advance warning signs may fit in the guidelines. Unfortunately, findings regarding the influence of advance warning signs or advisory speed plaques on driver behavior simply were not robust enough to merit the inclusion of advance warning signs in the guidelines based on the approach used here. Data from the safety study provided some related findings but were not sufficient to identify the appropriate conditions (in terms of speed reduction) for an advance warning sign or advisory speed plaque. Regardless, advance warning signs (with or without advisory speed plaques) serve an important function in helping drivers prepare for curves, so there is still consideration for their use in the proposed guidelines.

In the current MUTCD guidelines, an advance warning sign is the level between having no traffic control (other than pavement markings, if they are used) and applying chevrons and/or the Large Arrow sign at the curve. An advance warning sign is therefore already in use when the supplemental in-curve devices *supplement* the sign. Figure 23 shows that delineators are appropriate for speed changes of 15 mph. Based on the research team’s judgment and current MUTCD practice, the use of a warning sign should come before a supplemental in-curve device, which would be for speed changes of 10 mph. The inclusion of warning signs starting at 10-mph speed differentials results in the enhanced guidelines in Figure 24. The suggested changes to the MUTCD language in Appendix I are primarily based on the information in Figure 24.

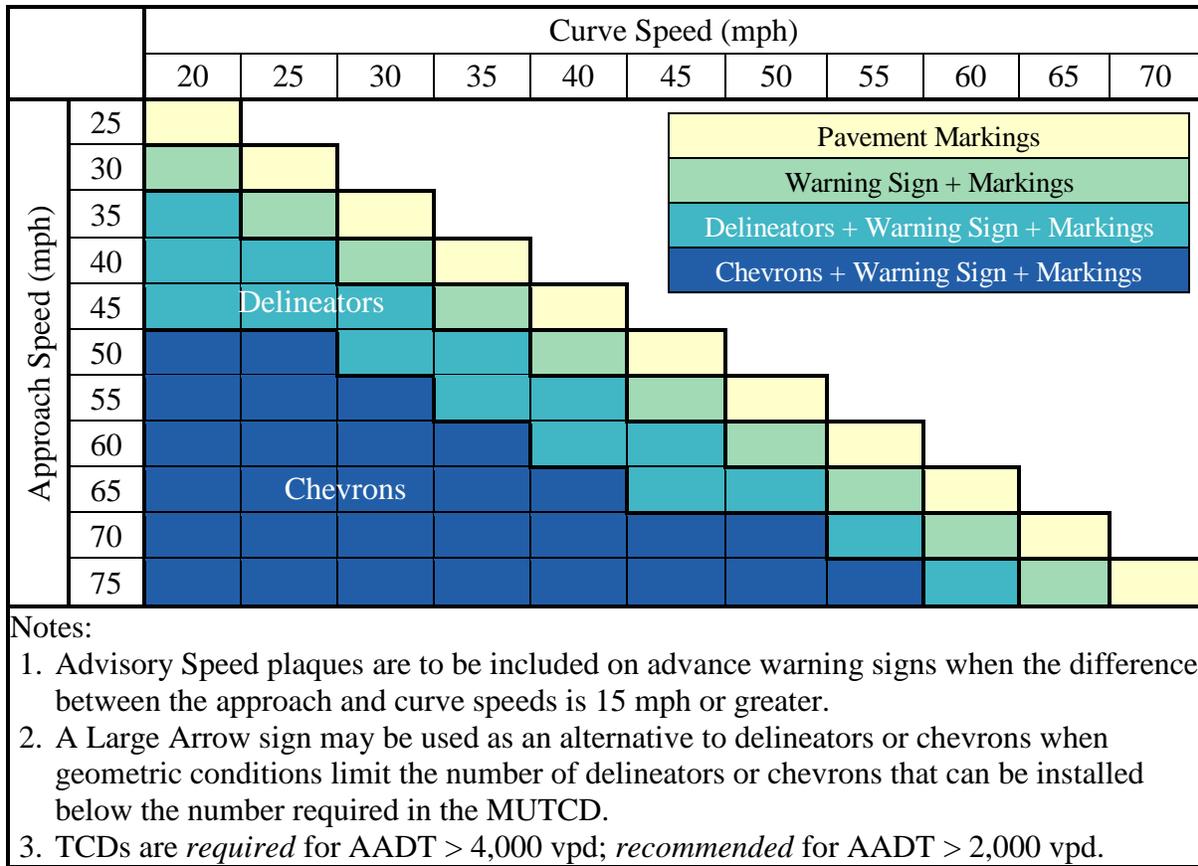


Figure 24. Proposed guidelines, representing the minimum level of appropriate curve TCDs.

The discussion so far has not fully addressed the use of advisory speed plaques with advance warning signs. Again, the data collected in the driver behavior and safety studies were insufficient to address the use of advisory speed plaques; however, it is understood that the value of the information advisory speed plaques convey likely increases with curve severity. In other words, advisory speed plaques serve an important function, particularly at severe curves. The research team proposes that an advisory speed plaque be used with an advance warning sign when the speed change of the curve is 15 mph or greater (Note 1 in Figure 24), which is the severity when a supplemental in-curve device is appropriate. It seems reasonable that if drivers need additional delineation within the curve, an advisory speed plaque should be used to provide more information about the appropriate speed to navigate the curve. The 5-mph increase in speed change at the curve for the use of an advisory speed plaque is similar to how the current guidelines are structured.

Another curve-related TCD that has yet to be addressed is the Large Arrow sign. The current MUTCD guidelines allow curves to be treated with a Large Arrow sign, giving it the same value as chevrons in the treatment hierarchy. Findings from the driver behavior study suggest that driver responses to Large Arrow signs are approximately equivalent to responses to delineators, but not quite on par with chevrons. The safety study, however, found that Large Arrow signs are likely more effective at reducing total crashes than chevrons. A complication in applying these findings is that a Large Arrow sign and chevrons are typically used exclusive of

one another. Chevrons are mostly used on long curves with large radii and Large Arrow signs are typically used on short curves with small radii, and on low-volume roads. After considering the study results and current practice, the research team's recommendation is that a Large Arrow sign be used as an alternative treatment in place of delineators or chevrons if the geometry of a curve and its roadside environment are so restrictive that there is not enough space to effectively use either of the delineator or chevron treatments (Note 2 in Figure 24). Because these treatments require that multiple (at least three) devices at a single curve be visible, they need adequate curve length without impedances such as driveways or sight obstructions. Additionally, the design and placement of a single Large Arrow sign is different from those of a treatment of delineators or chevrons. The sign does not delineate the entire curve, but does provide supplemental information that is not as directly conveyed by other treatments, especially delineators. This recommendation continues to allow the use of the Large Arrow sign as typically used, such as in curves with low posted speeds or large deflection angles and to supplement other devices at curves with an unusually high number of ROR crashes.

There are no recommended changes to how Turn or Curve (and Reverse Turn and Reverse Curve) signs are selected. Findings from the safety study suggest greater crash reductions occur when a Turn sign is used over a Curve sign if the curve radius is shorter than 600 ft. And the Reverse Turn sign appears more effective for average radii shorter than 700 ft. If an advance warning sign is required, the current guidelines state that a Turn sign is to be selected when the advisory speed is 30 mph or lower. Although curve speed alone is not dictated by radius, it was determined that the 30-mph speed used in current guideline is appropriate.

The proposed guidelines illustrated in Figure 24 are not intended to limit the extent to which a curve is treated with TCDs. They represent the *minimum* level of traffic control at curves that agencies should be expected to provide, based on the findings of the research discussed in this report. These guidelines do not remove the opportunity and obligation to apply engineering judgment where necessary. Increases beyond the minimum treatment level are a welcome method for addressing specific problems, such as limited sight distance or observed safety concerns. The specific findings related to behavior or safety documented in this report can help a practitioner decide whether or not a particular treatment is more appropriate based on actual field conditions.

CONCLUSION

A benefit of the proposed guidelines for curve TCDs developed from this research and the overall structure of the guidelines is that they are similar to material found in the current MUTCD. The proposed guidelines are based on selecting curve TCDs such that unfamiliar drivers will have sufficient distance to properly decelerate before a curve. By designating the level of regulation (recommended or required) for a particular device based on traffic volume thresholds identified from the safety study, agencies can be confident that the devices they install and maintain fulfill a need and have a measurable safety benefit.

There are several elements of driver behavior and safety that were selected from the research to develop the proposed guidelines. Additionally, some pieces of previous research and judgment were applied. The following list summarizes how each component contributed to the proposed guidelines:

- **Driver behavior study:** Researchers found that drivers vary their response at curves (including deceleration rates and how much deceleration is completed before entering the curve) based on the severity of the curve. Drivers begin reacting to curves farther from the curve as the level of traffic control treatment at the curve increases.
- **Safety study:** Researchers found that the safety effects of TCDs in curves (chevrons and Large Arrow signs) are dependent upon traffic volumes. Large Arrow signs may be more effective than chevrons, though agencies tend to use them more at severe curves on low-volume roads. Turn and Reverse Turn signs are more effective than Curve and Reverse Curve signs as curve severity increases.
- **Previous research:** Drivers are able to see pavement markings (and even detect curves) at a distance equivalent to several seconds of driving. It is anticipated that proposed MUTCD regulation will require that agencies maintain pavement markings at retroreflectivity levels that provide at least 2.2 s of preview time. Current pavement marking products provide more than 2.2 s of preview time in dry conditions.
- **Judgment:** Warning signs are appropriate at curves where the speed change is 10 mph. Advisory speed plaques are appropriate for curves where the speed change is 15 mph.

The methodology used to develop these guidelines allows for adaptation based on other research and improvements from future findings and even opens the possibility to include other TCDs that are not discussed here. While this research primarily focused on the devices that are considered *traditional* treatments, practitioners have myriad alternative treatments that can effectively warn drivers of an upcoming curve and provide the guidance necessary to successfully navigate it. Modification will be appropriate as other devices are studied and new data are generated.

Limitations of the Current Research

The driver behavior and safety studies completed as the primary tasks of the research were limited to two-lane rural roads. There are many conditions associated with curves that drivers can encounter that simply could not be accounted for given the resources used in this research. As with two-lane roads, each curve will have unique characteristics that produce unique responses from drivers. The proposed approach to treating curves by meeting a driver's need for information with the right TCDs at the right place and time is still valid.

Because there are already practices established for how curves are treated, the behavior and safety studies were not designed in a full-factorial type of experiment, where each possible curve characteristic could be matched with a potential traffic control treatment. Researchers applied various techniques to account for the influence of confounding variables and control the introduction of bias, but the inability to initiate these studies with a clean approach to how curves are treated by TCDs limits the applicability of the findings.

The posted advisory speeds at the curves were not verified in both the behavior and safety studies. Additionally, the placement locations of advance warning signs were not considered in the analyses. There are various methods for evaluating advisory speeds, and each may influence the selection of an appropriate device and its placement location. Although driver responses may be affected by how well an advisory speed matches his/her experience within a curve or by the distance from a curve at which a warning sign is placed, it was assumed that

these influences would be small in comparison to the findings that ultimately led to the proposed guidelines.

As identified, there were instances for which findings from previous research or judgment of the research team were applied in developing guidelines for TCDs at curves. One area is the use and benefit of pavement markings. The proposed first level of treatment for a curve is pavement markings, which is adequate for a 5-mph speed reduction. Not all highways have pavement markings. Guidance is provided in the suggested MUTCD text (Appendix I) for addressing curves on highways that do not have pavement markings.

Recommendations

The appropriate MUTCD text for incorporating the guidelines for selecting TCDs at curves based on the discussion of this chapter is contained in Appendix I. The key recommendation of the research is the adoption of the text in the MUTCD.

This research resulted in multiple discoveries about unfamiliar driver behavior and safety at curves that may have applications in other areas. For example, the observation that driver deceleration rates are not consistent from one curve to another suggests that design standards may benefit from changes that better reflect actual driver behavior, which varies for different scenarios. One application of this is the placement of advance warning signs, particularly at curves. Current guidelines for sign placement at curves include an assumption of a deceleration rate of 10 ft/s^2 , which is much greater than most drivers accept at most curves. However, to also reflect driver behavior, it would be appropriate to recognize that drivers tend to complete only a portion of the deceleration at a curve before the entrance.

While this research did not investigate the specific influence of device size or retroreflectivity, it is likely that these aspects of a device influence both driver responses and the resulting safety at the curve. The guidelines proposed in this research were developed from a framework that is flexible enough to consider changes in behavior and needs due to changed device visibility. Future research investigating these elements may lead to recommendations that are more comprehensive, providing agencies more flexibility in identifying appropriate traffic control treatments.

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Appendix A: Review of Driver Manuals

Each state is responsible for the publication of a driver manual (or handbook) that includes information for the beginning driver to learn about safe vehicle operation. While most manuals are used in the education of new drivers, they can also serve as a resource for experienced drivers who may need to review some of the rules of the road or safe practices. The driver manuals of all 50 states and the District of Columbia (2011 or 2012 editions) were reviewed to identify the current practice of how states teach drivers about TCDs used at curves and how to navigate curves safely. Overall, there is substantial variability in the information provided about TCDs used at curves and the proper way to respond to TCDs and navigate curves.

TCDS ON CURVES

Regarding TCDs, the manuals tend to put a strong emphasis on the colors and shapes associated with each type of sign, with the goal to teach drivers how to respond to a sign based on its type and to understand that certain types of signs are more important than others. Most manuals are limited to showing examples of regulatory and warning signs with only the highest importance because identifying all signs that can possibly be encountered would be impractical. The manuals are also limited in how much text can be used to describe a specific sign, especially for curve TCDs. This is where the manuals by each state are most distinctive. Specifically, each manual varies in the warning signs that are presented and the supporting text that is given to teach drivers the correct meaning and proper operational response.

Of the 51 manuals, 13 have no examples of signs or other information regarding TCDs for horizontal curves. The other 38 manuals contain one or more examples of signs that may be encountered on curves, usually with a short caption accompanying the image. The manuals for the following states provide at least five examples of warning signs associated with curves:

- Alabama: seven signs (Turn, Curve, Reverse Curve, Winding Road, Reverse Turn, Advisory Speed Plaque, and Chevron).
- The District of Columbia: five signs (Turn, Curve, Reverse Turn, Winding Road, and Advisory Speed Plaque).
- Florida: five signs (Curve, Reverse Curve, Winding Road, Turn, and Advisory Speed Plaque).
- Illinois: seven signs (Turn, Curve, Reverse Turn, Reverse Curve, Advisory Speed Plaque, Winding Road, and Chevron).
- Missouri: six signs (Curve, Turn, Reverse Turn, Advisory Speed Plaque, Large Arrow, and Chevron).
- Montana: six signs (Winding Road, Turn, Reverse Turn, Reverse Curve, Curve, and Advisory Speed Plaque).
- Nebraska: six signs (Turn, Reverse Turn, Reverse Curve, Curve, Winding Road, and Advisory Speed Plaque).
- Oklahoma: five signs (Reverse Curve, Curve, Turn, Winding Road, and Chevron).

- Oregon: six signs (Reverse Curve, Curve, Advisory Speed Plaque, Turn, Winding Road, and Chevron).
- Pennsylvania: 10 signs (Chevron, Right Curve, Left Curve, Right Turn, Left Turn, Winding Road, Large Arrow, Combination Horizontal Alignment/Intersection, Truck Rollover, and Advisory Speed Plaque).
- Tennessee: five signs (Turn, Curve, Reverse Turn, Advisory Speed Plaque, and Chevron).
- Texas: seven signs (Reverse Curve, Curve, Turn, Winding Road, Reverse Turn, Chevron, and Advisory Speed Plaque).
- Virginia: seven signs (Turn, Reverse Turn, Curve, Reverse Curve, Advisory Speed Plaque, Winding Road, and Combination Horizontal Alignment/Intersection).

The text in key sections of the manuals tends to be quite consistent from state to state, though each state is still responsible for the contents of its own manual. There are some unique approaches, however, to teaching drivers about these warning signs. The Pennsylvania manual provides the most examples of warning signs on curves of any manual and includes the Chevron Alignment, One-Direction Large Arrow, Truck Rollover, and Combination Horizontal Alignment/Intersection signs. While many manuals have simple two- or three-word text below each image, Pennsylvania’s manual has very descriptive text for each sign. Some examples from that manual are:

CHEVRON SIGNS—There is a sharp change in the direction of the road, such as a curve to the left or right. The road bends in the direction the chevron points. When used in a curve, there will be an advanced curve warning sign, and there may be several chevron signs placed throughout the curve.

SHARP LEFT TURN—The road ahead turns sharply to the left. You need to slow down substantially, stay in the center of your lane and prepare to navigate through the sharp left turn. Some sharp turn signs have an advisory speed located on the sign or posted below it.

One Direction Large Arrow—The road ahead changes direction at an extreme angle. Before you reach such an extreme curve, slow down as much as you would to make a turn at an intersection.

ROAD ENTERING CURVE—The main road curves to the left with a side road entering from the right. Approach the intersection with extra caution. A driver preparing to enter the main road may not be able to see you approaching from around the curve and may pull out in front of you, leaving you little room to avoid a crash, if you are traveling too fast.

The language used in the Pennsylvania manual also serves to illustrate the issue that text in driver manuals does not always agree with definitions provided in the MUTCD. For example, the Left Turn sign described above states that drivers “need to slow down substantially.” This characteristic is subjective and may not always be the case, depending on the actual road conditions. Also, the description for the One-Direction Large Arrow sign advises drivers to “slow down as much as you would to make a turn at an intersection.” Although such language

may present a more-conservative approach to navigating turns, the MUTCD requires either Chevron signs or the Large Arrow sign be used for speed reductions of 15 mph. At higher speeds, a 15-mph reduction may not be enough to result in a speed appropriate for turns at an intersection.

The description of Chevron signs in the Pennsylvania manual acknowledges that there are other warning signs in place at curves where Chevron signs are used, which is in conformance with MUTCD requirements. The Tennessee manual is the most consistent with definitions in the MUTCD, stating that Turn signs are used when the recommended speed is 30 mph or less, Curve signs are used for recommended speeds between 30 mph and 55 mph, Reverse Turn signs are used when two turns in opposite directions are separated by less than 600 ft, and Advisory Speed Plaques supplement warning signs and give the recommended maximum safe speed.

NAVIGATING CURVES SAFELY

Many manuals contain educational information about how to safely navigate curves. Some of the wording in these sections is repeated verbatim in several manuals. The following paragraph is the one encountered most often:

A vehicle can travel much faster in a straight line than it can in a curve. It is easy to go too fast in a curve. If you go too fast, then the tires will not be able to grip the road and the vehicle will skid. Always slow down before you enter the curve so you do not have to brake in the curve. Braking in a curve can cause the vehicle to skid.

A driver's awareness of the vehicle speed on a curve relates to more than just losing control and skidding. Regarding sight distance on curves (and hills), the following text is also printed in multiple manuals:

You may not know what is on the other side of a hill or just around a curve, even if you have driven the road many times. If a vehicle is stalled on the road just over a hill or around a curve, you must be able to stop. Whenever you come to a hill or curve where you cannot see over or around, adjust your speed so you can stop if necessary.

At least 12 manuals contain a copy of one or both of the above paragraphs related to driving on curves. But there are 19 that do not provide any guidance on navigating curves apart from restrictions on dangerous driving maneuvers at curves, such as U-turns, passing, and stopping. Although driver manuals are not able to provide drivers with information about every possible driving scenario, the abundance of curves on the nation's highways justifies the inclusion of this or similar information in all manuals. The review of the manuals found some exceptional examples that may serve as models for other states as they update their own manuals. The Pennsylvania manual thoroughly explains why driving too fast on curves is dangerous, gives supporting information to direct the reader to learning the signs presented earlier, and provides steps for successfully navigating curves. The North Carolina manual provides steps for safely negotiating both level curves and curves located on downgrades, and the New Hampshire manual

emphasizes the issues of sight distance and skidding due to centrifugal force. North Carolina also briefly describes different actions required by left- and right-hand curves. The specific text from these three manuals is reproduced here.

Pennsylvania Manual

The Pennsylvania manual states:

The most important thing to understand about curves is you cannot beat the laws of physics. Vehicles are heavy, and they have lots of inertia. This means if you are driving too fast on a curve, your vehicle is going to keep moving straight ahead instead of around the curve, no matter how much you try to steer it or slow it down to keep it in your lane. You will either run off of the road (on a left-bending curve) or go into the other lane of traffic (on a right-bending curve). You do not have to be traveling very fast for this to happen. If the curve is sharp and the road is wet or icy the most reduction in speed is needed.

TO MAINTAIN CONTROL ON CURVES, YOU MUST SLOW DOWN. DO IT BEFORE YOU ENTER THE CURVE.

As you approach a curve, you will usually see a yellow diamond warning sign showing how the road bends. If the road bends at a 90-degree angle, you may see a rectangular yellow sign with a large arrow pointing left or right. Some sharp curves also have chevron warning signs placed throughout the turn; these are very helpful at night or in poor visibility conditions. Review the various types of curve warning signs shown in Chapter 2.

HERE IS HOW YOU CAN SAFELY DRIVE THROUGH CURVES:

1. Keep slightly to the right of the lane center on right curves and in the middle of your lane on left curves.
2. The sharper the curve, the more you need to reduce your speed.
3. Look for traffic coming from the opposite direction. A speeder could easily stray into your lane.
4. For guidance about how to steer your vehicle, scan ahead and look at the inside edge of the curve. If there are multiple curves, look at the inside edge of each curve as far ahead as you can see.

The Pennsylvania manual also shows diagrams detailing the physical components of speeding on curves and contains a teen crash fact, which says that single-vehicle run-off-the-road crashes are the most frequent crash types for 16-year-old drivers in Pennsylvania (causing 2,969 crashes and 28 fatalities from 2007 to 2009).

North Carolina Manual

The North Carolina manual states:

The best way to handle a curve:

1. Slow down before you enter the curve so that you will not need to brake while you are in the curve;
2. Gradually increase your speed to maintain the traction necessary for good control of the vehicle as you round the curve;
3. If you must brake in the curve, apply the brakes gradually until you are sure it is safe to keep continuous pressure on the brake pedal;
4. Begin to turn the vehicle just prior to the point where the road begins to turn; and
5. Stay on your side of the road and drive as far to the right as you can.

If you encounter a curve while traveling downhill:

1. Consider the pull of gravity;
2. Shift to a lower gear before moving downhill; and
3. Begin to brake earlier and approach the curve more slowly than you would on a level roadway.

New Hampshire Manual

The New Hampshire manual states:

Curves call for special attention, therefore, it is a good idea to reduce your speed before entering any curve. Braking should be done before, NOT WHEN IN THE CURVE. Braking in a curve can cause a skid. Once you are in a curve at a proper speed you can speed up gradually through the rest of the curve.

At every curve assume that there may be something in your path. Be ready for a stopped vehicle or an oncoming vehicle on your side of the road.

Curves are dangerous at all times, especially when they are wet or slippery. Centrifugal force (the force that pushes you away from the center of the road) can cause the vehicle to go off the road on a curve. When entering a left-hand curve you should steer toward, but not over, the center of the road. On a right-hand curve steer toward the right side of the road.

SUMMARY

By determining the content of its driver manual, each state establishes the elements of the driving task that receive emphasis. On the cover of the Oklahoma manual, for example, are images of a suspected drunk driver, a person being arrested, and a wrecked car. Inside the Kentucky manual are letters from the governor and police commissioner that stress both the use

of seatbelts and the acceptance of driving as a privilege. And at the front of the California manual is information on new drunk driving and child restraining laws.

For some manuals, the information for curve TCDs is located in the second chapter, suggesting they are of utmost importance. For other manuals, that information may barely be covered in an appendix. Regarding the operational process of navigating curves, there is substantial variability in the amount of information given to drivers, with some manuals not providing any information and others being quite direct in what behavior to adopt. (Some even firmly warn drivers to fully decelerate in advance of the curve, which is not a reasonable expectation based on the findings of operational behavior. Drivers simply plan on executing some of their response within the curve.) Although each state regulates the content of its own manual, there may be value in ensuring the content from state to state is consistent and accurately portrays TCD meanings and the proper operational response.

Appendix B: State and International Practices for Treating Curves

This appendix identifies the policies, standards, or guidelines state DOTs and other countries follow in determining the TCDs used for treating horizontal curves. The information in this review illustrates the extent to which the state DOTs have adopted (as of 2013) the guidelines for TCDs on horizontal curves contained in the 2009 edition of the national MUTCD. This review also shows how states vary in the way they treat curves with devices, and provides information related to the approaches used outside of the United States. This information is valuable because it represents ideas used by several agencies (local, national, and international) to communicate with drivers the changes in horizontal alignment.

STATE PRACTICES

A survey was conducted to identify the policies and practices used to treat curves based on the 2009 (national) MUTCD and documents created by each DOT. States have the option to use their own manual, fully adopt the national manual, or supplement the national manual with additional guidance and policies. Table B-1 categorizes the states into groups based on these three levels of adoption. Nine states develop their own MUTCD, 19 adopt the national manual, and 24 have supplements. To survey the state of the practice throughout the nation, a random sample of 15 states was chosen from the 33 states whose policies may differ from the national manual—nine with individual MUTCDs and six that use supplements. Additionally, the project team reviewed the traffic engineering manuals of seven states, which were also randomly selected.

Table B-1. Adoption Status of the 2009 National MUTCD by States (in 2012)

State MUTCD	National MUTCD	National MUTCD with State Supplement
California	Arkansas	Alabama
Delaware	Connecticut	Alaska
Indiana	Florida	Arizona
Maryland	Georgia	Colorado
Michigan	Hawaii	Idaho
Minnesota	Kansas	Illinois
Missouri	Kentucky	Iowa
Ohio	Louisiana	Nebraska
Texas	Maine	Nevada
	Massachusetts	New York
	Mississippi	North Carolina
	Montana	North Dakota
	New Hampshire	Oklahoma
	New Jersey	Oregon
	New Mexico	Pennsylvania
	Rhode Island	South Carolina
	South Dakota	Tennessee
	Vermont	Utah
	District of Columbia	Virginia
		Washington
		West Virginia
		Wisconsin
		Wyoming
		Puerto Rico

The following state MUTCDs were reviewed in this study:

- Alaska (Supplement).
- Arizona (Supplement).
- California.
- Colorado (Supplement).
- Delaware.
- Illinois (Supplement).
- Indiana.
- Maryland.
- Michigan.
- Minnesota.
- Missouri.
- Nebraska (Supplement).
- Ohio.

- Oregon (Supplement).
- Texas.

The following state traffic engineering manuals were reviewed in this study:

- Arizona.
- Idaho.
- Minnesota.
- Ohio.
- Oregon.
- Pennsylvania.
- Washington.

One of the objectives of the review of state manuals was to identify the extent to which states have adopted the guidelines for treating curves as contained in the 2009 MUTCD. Tables B-2 and B-3 generalize the comparisons into three levels using the following criteria:

Accepted in entirety: the provisions regarding the TCDs on horizontal curves are replicated from the national MUTCD without any changes.

Minor revision: the provisions regarding the TCDs on horizontal curves are revised by adding detailed language, which conforms with the 2009 national MUTCD.

Major revision: the provisions regarding the TCDs on horizontal curves are altered and potentially contradictory to the 2009 national MUTCD.

From the information contained in Tables B-2 and B-3, there appears to be some deviation, though overall consistency, in adopting the guidelines of the national manual. The contents of the 2009 MUTCD and some of the changes in state manuals are discussed in the following sections. Emphasis is given to the devices that are more commonly used, specifically Curve and Turn warning signs (usually placed in advance of the curve and sometimes with an Advisory Speed Plaque), and traditional devices used within curves, including chevrons, One-Direction Large Arrow signs, RPMs, and delineators. Variations to the Curve and Turn signs, including the Reverse Curve, Turn, and Combination Horizontal Alignment/Intersection signs, are not discussed because the current study did not evaluate the additional conditions used to determine when their use is appropriate.

Table B-2. Summary of State MUTCDs

MUTCD Section		State MUTCD														
		AL	AZ	CA	CO	DE	IL	IN	MD	MI	MN	MO	NE	OH	OR	TX
Section 2C.06 Horizontal Alignment Warning Signs	Adjustment to Figure 2C-1	●	●	○	●	●	●	●	●	◐	●	●	●	●	●	◐
	Application of Warning Signs	◐	●	●	●	◐	●	●	●	●	●	●	●	●	●	●
Section 2C.07 Horizontal Alignment Signs	Adoption of Table 2C-5	○	●	●	●	◐	●	●	●	●	○	●	●	●	●	
	Turn vs. Curve Sign	●	●	◐	●	●	●	●	◐	●	●	◐	●	●	●	●
	Winding Road Sign	●	●	○	●	●	●	●	●	●	●	●	●	●	●	●
	Hairpin Curve Sign	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
Section 2C.08 Advisory Speed Plaque		○	●	◐	●	●	●	●	●	●	●	●	●	◐	●	●
Section 2C.09 Chevron Alignment Sign	Number of Chevron Signs	●	●	○	●	●	●	●	○	●	●	○	●	●	●	●
	Height of Chevron Signs	●	●	●	●	●	●	●	●	●	○	●	●	●	●	●
	Spacing of Chevron Signs	●	●	●	●	●	●	●	●	●	○	●	●	●	●	●
	Selection of Chevron Signs	●	●	●	●	●	●	●	●	●	●	◐	●	●	●	●
Section 2C.10 Combination Horizontal Alignment/Advisory Speed Sign		●	●	◐	●	●	●	●	●	●	●	●	●	●	●	●
Section 2C.11 Combination Horizontal Alignment/Intersection Signs		●	●	●	●	●	●	●	●	●	◐	●	●	●	●	●
Section 2C.12 One-Direction Large Arrow Sign		●	●	○	●	●	●	●	●	●	●	●	●	◐	●	●
Section 2C.14 Advisory Exit and Ramp Speed Signs		●	●	◐	●	●	●	●	●	●	◐	◐	●	●	●	●
Section 3B.01 Yellow Center Line Pavement Markings and Warrants		●	●	○	●	●	●	●	●	●	●	●	●	●	●	●
Section 3B.13 Raised Pavement Markers Supplementing Other Markings		●	●	●	●	○	●	●	●	●	●	●	●	●	●	●
Section 3F. 03 Delineator Application		●	●	○	●	●	●	●	◐	●	●	●	●	●	●	○
Section 3F.04 Delineator Placement and Spacing		●	●	●	●	●	●	●	●	●	●	●	●	●	●	●

●: accepts 2009 MUTCD in entirety, ◐: minor revision, ○: major revision

Table B-3. Summary of State Traffic Manuals

MUTCD Section		State Traffic Manual						
		AZ	ID	MN	OH	OR	PA	WA
Section 2C.06	Application of Warning Signs	--	--	--	●	◐	--	--
Section 2C.07 Horizontal Alignment Signs	Adoption of Table 2C-5	--	--	--	●	--	--	--
	Turn vs. Curve Sign	--	○	--	●	●	--	●
	Winding Road Sign	--	◐	--	●	--	--	--
	Hairpin Curve Sign	--	--	--	●	--	--	○
Section 2C.08 Advisory Speed Plaque		--	--	○	●	●	●	○
Section 2C.09 Chevron Alignment Sign	Number of Chevron Signs	--	○	--	●	--	○	○
	Height of Chevron Signs	--	--	--	●	--	--	●
	Spacing of Chevron Signs	--	--	○	●	--	●	●
	Selection of Chevron Signs	--	○	○	●	--	○	◐
Section 2C.10 Combination Horizontal Alignment/Advisory Speed Signs		--	--	--	●	--	--	--
Section 2C.11 Combination Horizontal Alignment/Intersection Sign		--	--	--	●	--	--	--
Section 2C.12 One-Direction Large Arrow Sign		--	--	--	◐	--	◐	--
Section 2C.14 Advisory Exit and Ramp Speed Signs		--	--	--	●	--	--	●
Section 3B.01 Yellow Center Line Pavement Markings and Warrants		--	--	--	●	--	--	--
Section 3B.13 Raised Pavement Markers Supplementing Other Markings		--	--	--	●	--	--	--
Section 3F.03 Delineator Application		--	--	--	●	--	--	--
Section 3F.04 Delineator Placement and Spacing		--	--	--	○	--	--	--

●: accepts 2009 national MUTCD in entirety, ◐: minor revision, ○: major revision, --: not mentioned

Horizontal Alignment Warning Signs

Figure 2C-1 in the national MUTCD, replicated in Figure B-1, contains a variety of horizontal alignment warning signs, which advise motorists of a change in the roadway alignment. From the review of state manuals, it was found that Texas, California, and Maryland created additional horizontal alignment warning signs to address scenarios not covered by the signs in the national manual or to convey information in a different way. These additional signs are shown in Figure B-2.

Figure 2C-1. Horizontal Alignment Signs and Plaques

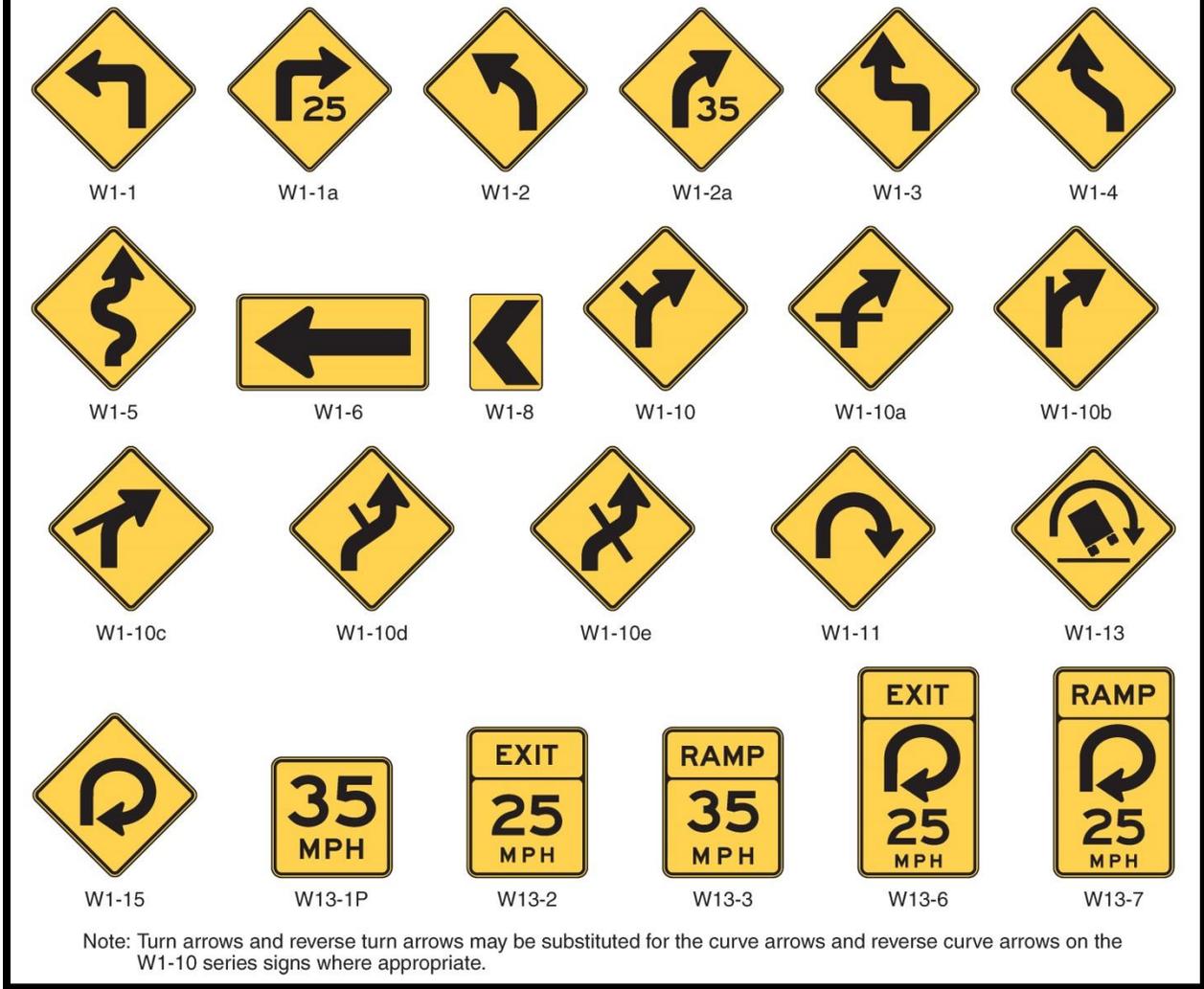


Figure B-1. Horizontal alignment signs from MUTCD Figure 2C-1.

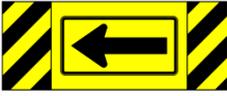
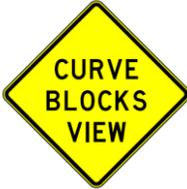
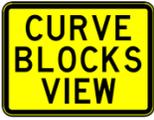
State	Additional Signs				
Texas					
	W1-9T	W1-11T	W1-11TP	W7-6TP	
California					
	W4-1 (CA)	W4-18 (CA)	W4-10 (CA)	W4-14 (CA)	SW22-1 (CA)
Maryland					
	W1-13(1)	W1-13(2)	W13-1(4)	W13-2(1)	

Figure B-2. Additional horizontal alignment warning signs from MUTCDs for Texas, California, and Maryland.

Table 2C-5 in the 2009 MUTCD (see Table B-4) identifies the appropriate horizontal alignment warning sign (from Figure B-1) to use at a curve based on the difference between the speed limit and curve advisory speed and on other alignment criteria, depending on the specific scenario. MUTCD Table 2C-5 is intended to enhance the consistency of how TCDs are applied at curves, and there is a hierarchy of requiring more signs as curve severity increases. Curve or Turn signs (and their derivatives) are at the bottom of the hierarchy, followed by the inclusion of an Advisory Speed Plaque, then chevrons and/or a Large Arrow sign, and then Exit Speed and Ramp Speed signs if appropriate. Section 2C.06 of the 2009 MUTCD states:

In advance of horizontal curves on freeways, on expressways, and on roadways with more than 1,000 AADT that are functionally classified as arterials or collectors, horizontal alignment warning signs shall be used in accordance with Table 2C-5 based on the speed differential between the roadway's posted or statutory speed limit or 85th-percentile speed, whichever is higher, or the prevailing speed on the approach to the curve, and the horizontal curve's advisory speed.

Table B-4. Horizontal Alignment Sign Selection, adapted from MUTCD Table 2C-5

Type of Horizontal Alignment Sign	Difference Between Speed Limit and Advisory Speed			
	5 mph	10 mph	15 mph	20 mph or more
Turn (W1-1), Curve (W1-2), Reverse Turn (W1-3), Reverse Curve (W1-4), Winding Road (W1-5), and Combination Horizontal Alignment/Intersection (W10-1)	Recommended	Required	Required	Required
Advisory Speed Plaque (W13-1P)	Recommended	Required	Required	Required
Chevrons (W1-8) and/or One Direction Large Arrow (W1-6)	Optional	Recommended	Required	Required
Exit Speed (W13-2) and Ramp Speed (W13-3) on exit ramp	Optional	Optional	Recommended	Required

The MUTCDs for Delaware and Alaska, as well as the *Oregon Traffic Manual*, contain some changes or clarifications to the statement in Section 2C.06. The Delaware MUTCD clarifies that the approach speed is on the tangent preceding the curve. Additionally, the Delaware MUTCD indicates that the provisions of Table 2C-5 in the 2009 national MUTCD are only applicable where the advisory speed is less than the posted or statutory speed limit; otherwise, engineering judgment is to be used. The Alaska MUTCD removes the language about functional classification and traffic volumes of the roadway, which means the provisions from Table 2C-5 should be applied not only on roadways with more than 1,000 AADT, but also on roadways with lower volumes. The *Oregon Traffic Manual* indicates that when applying Table 2C-5 to exit ramps, the speed in the parallel deceleration lane approaching the exit ramp curve should be used as the approach speed rather than the speed of the mainline freeway lanes. This clarification supports consideration of the actual conditions encountered by the drivers approaching the curve.

Among the 15 state MUTCDs and seven traffic manuals reviewed, only Missouri's did not introduce the same hierarchical approach to treating curves as found in MUTCD Table 2C-5. Delaware and Alaska, however, did make some minor adjustments. In the Missouri MUTCD, the table from the 2003 national MUTCD is used (as shown in Table B-5), which allows engineering judgment to determine whether or not a sign should be used at all. In comparison to MUTCD Table 2C-5, the table in the Delaware manual alters the text "Difference Between Speed Limit and Advisory Speed" to "Difference Between Approach Speed and Curve Advisory Speed." The approach speed is defined as the posted or statutory speed limit or 85th percentile speed on the tangent approach. More significant changes have been made by Alaska regarding the regulatory level of chevrons and/or a Large Arrow sign. The regulation for using chevrons or a Large Arrow sign is reduced from *recommended* to *optional* for speed differentials of 10 mph, and from *required* to *recommended* for speed differentials of 15 mph.

Table B-5. Horizontal Alignment Sign Usage in the Missouri MUTCD

Number of Alignment Changes	Advisory Speed	
	≤30 mph	>30 mph
1	Turn (W1-1) ^a	Curve (W1-2) ^a
2 ^b	Reverse Turn (W1-3) ^c	Reverse Curve (W1-4) ^c
3 or more ^b	Winding Road (W1-5) ^c	
Notes:		
^a Engineering judgment should be used to determine whether the Turn or Curve sign should be used.		
^b Alignment changes are in opposite directions and are separated by a tangent distance of 600 ft. or less.		
^c A Right Reverse Turn (W1-3R), Right Reverse Curve (W1-4R) or Right Winding (W1-5R) sign is used if the first change in alignment is to the right; a Left Reverse Turn (W1-3L), Left Reverse Curve (W1-4L) or Left Winding (W1-5L) sign is used if the first change in alignment is to the left.		

Advisory Speeds

Compared with the 2009 national MUTCD, all states whose policies were reviewed use the same method (a traditional ball-bank indicator) to determine the recommended advisory speed for a horizontal curve. However, three state MUTCDs or traffic manuals have alternative ball-bank criteria, shown in Table B-6.

Table B-6. Ball-Bank Indicator Criteria

Advisory Speed	2009 MUTCD	Washington <i>Traffic Manual</i>	Alaska MUTCD	Minnesota Traffic <i>Engineering Manual</i>
20 mph or less	16	14	15	14
25 to 30 mph	14	12	12.5	12
35 mph or greater	12	10	10	10

Selection of Turn or Curve Signs

With respect to the use of Turn and Curve signs, the 2009 MUTCD includes the following language:

A Turn (W1-1) sign shall be used instead of a Curve sign in advance of curves that have advisory speeds of 30 mph or less.

The *Idaho Traffic Manual* alters the 30-mph threshold of the 2009 MUTCD, stating that all single curves with a speed of 25 mph or less should be signed with a Turn sign. The California MUTCD provides further guidance for selecting Turn or Curve signs, suggesting that a Curve sign be considered in advance of any curve that produces a reading of 10 degrees on a ball-bank indicator at speeds lower than the approach speed, and that the sign should be supplemented with an advisory speed message.

Hairpin Curve Sign

The 2009 national MUTCD includes this statement pertaining to Hairpin Curve signs:

If the curve has a change in horizontal alignment of 135 degrees or more, the Hairpin Curve (W1-11) sign may be used instead of a Curve or Turn sign.

The *Washington Traffic Manual* includes additional requirements for using the Hairpin Curve sign, which are that the recommended curve speed is 30 mph or less and the recommended curve speed is equal to or less than the posted speed limit. Similarly, the *Idaho Traffic Manual* indicates that if the curve can be driven at a safe speed over 30 mph, a Curve sign should be used instead of a Hairpin Curve sign.

Chevrons

With respect to the visibility of Chevron Alignment signs, the 2009 national MUTCD states that “Chevron Alignment signs should be visible for a sufficient distance to provide the road user with adequate time to react to the change.” To ensure visibility, several state MUTCDs and traffic manuals specify that at least two (and, for some, three) Chevron Alignment signs must be in view to approaching drivers. The national MUTCD states that the minimum height of a chevron alignment sign is 4 ft; in the Missouri MUTCD, the height is amended to at least 5 ft.

In the 2009 national MUTCD, the spacing of Chevron Alignment Signs on horizontal curves is based on advisory speed or curve radius (as shown in Table B-7). Three of the reviewed manuals amend the criteria. The Missouri MUTCD (as shown in Table B-8) and the *Minnesota Traffic Engineering Manual* (as shown in Table B-9) use the radius or degree of curvature for spacing calculation. Also, the Missouri MUTCD (Table B-8) provides a larger range of sign spacing (from 80 to 400 ft) than the 2009 national version (from 40 ft to 200 ft) and adds the statement “engineering judgment may be used to modify the spacing.” The *Idaho Traffic Manual* suggests that the spacing should be one-fifth the radius of the curve.

Table B-7. Chevron spacing from MUTCD Table 2C-6

Advisory Speed	Curve Radius	Sign Spacing
15 mph or less	Less than 200 ft	40 ft
20 to 30 mph	200 to 400 ft	80 ft
35 to 45 mph	401 to 700 ft	120 ft
50 to 60 mph	701 to 1,250 ft	160 ft
More than 60 mph	More than 1,250 ft	200 ft

Note: The relationship between the curve radius and the advisory speed shown in this table should not be used to determine the advisory speed.

Table B-8. Chevron Spacing from the Missouri MUTCD

Radius (ft)	Chevron Spacing (ft)
500	84
600	94
700	102
800	110
900	116
1,000	124
1,200	136
1,400	148
1,600	156
1,800	198
3,000	218
5,000	282
10,000	400

Table B-9. Chevron Spacing from the *Minnesota Traffic Engineering Manual*

Radius(ft)	Chevron Spacing (ft)
150	45–60
200	53–70
250	60–80
300	75–100
400	83–110
500	98–130
600	105–140
700	112–150
800	120–160
900	127–170

The 2009 national MUTCD states that the use of Chevron Alignment signs shall be in accordance with the information shown in Table 2C-5, which is based on the difference between speed limit and advisory speed. It also indicates two situations where the Chevron Alignment signs shall not be used: one is on the far side of a T intersection facing traffic (where a Large

Arrow sign should be used instead); the other is to mark obstructions (where an object marker should be used). Five of the MUTCDs and traffic manuals reviewed provide more guidance on when the Chevron Alignment sign should and should not be used, summarized in Table B-10.

Table B-10. Additional Guidelines for Chevron Alignment Signs

Manual	Situations for Using Chevrons	Situations for Not Using Chevrons
2009 National MUTCD	According to Table 2C-5.	(1) On the far side of a T intersection facing traffic where a Large Arrow sign should be used. (2) To mark obstructions within or adjacent to the roadway, where an object marker should be used.
Missouri MUTCD	Chevrons shall be placed on all curves where there is a 15-mph difference between the posted speed limit and the advisory speed.	(1) Same provisions as in the 2009 national MUTCD. (2) Turns that have an advisory speed posted at or below 30 mph shall have an arrow board.
<i>Washington Traffic Manual</i>	Where run-off-the-road crashes have demonstrated an operational deficiency.	N/A.
<i>Idaho Traffic Manual</i>	Additional emphasis is needed with curve signing at curves with an advisory speed of 35 mph or higher.	(1) Use the Large Arrow signs for curves with 30 mph or lower advisory speeds. (2) The Large Arrow sign may be used instead if the Chevron Alignment signs cannot be spaced properly.
<i>Minnesota Traffic Engineering Manual</i>	Used only on curves of 6 degrees or greater.	Curves of less than 6 degrees are to be marked by standard delineation.
<i>Pennsylvania Traffic Engineering Manual</i>	(1) Curves or turns that are greater than 7 degrees. (2) Curves with excessive run-off-the-road crashes. (3) When standard delineation does not, or would not, show the roadway alignment.	(1) Do not use if a turn has inadequate length for proper spacing. (2) Consider flexible delineator posts for curves that are less than or equal to 7 degrees.

One-Direction Large Arrow Sign

Section 2C.12 of the 2009 national MUTCD includes the following statements:

A One-Direction Large Arrow (W1-6) sign (see Figure 2C-1) may be used either as a supplement or alternative to Chevron Alignment signs in order to delineate a change in horizontal alignment.

A One-Direction Large Arrow (W1-6) sign may be used to supplement a Turn or Reverse Turn sign to emphasize the abrupt curvature.

The *Pennsylvania Traffic Engineering Manual* states that the Large Arrow sign should be considered on curves and turns that are relatively short in length. It is also possible to sign longer curves with a single W1-6 sign, but engineering judgment based on field conditions must be used in making this decision.

Raised Pavement Markers

Of the documents reviewed in this study (including the 2009 MUTCD), the Delaware MUTCD is the only one that includes information about using RPMs on horizontal curves. The Delaware MUTCD suggests RPMs may be appropriate for locations with a history of roadway departure crashes, which tend to occur at curves. Figure B-3 comes from the Delaware MUTCD.

Delineators

Delineators are not included in the current curve TCD hierarchy because they are classified as guidance devices, and the hierarchy only includes warning signs, which are covered in Chapter 2C of the MUTCD. Even though delineators are not included in the current hierarchy for curve TCDs, Section 3F.01 of the 2009 MUTCD states that delineators are effective guidance devices at night and during adverse weather, and are beneficial at curves. There is no state practice that substantially alters the information provided in the MUTCD, other than the guidelines for spacing, which are adjusted in Texas and California.

Discussion of State and National Practices

MUTCD Table 2C-5 (Table B-4) introduced a hierarchical approach to treating curves with the goal of ensuring uniformity in the application of TCDs. Findings from the review of state MUTCDs and traffic engineering manuals indicate that states have generally adopted the guidelines of the 2009 MUTCD with only minor changes. The most significant change for a state was found in Missouri, whose guidelines reflect those of the 2003 MUTCD.

Information from the 2009 MUTCD and state practices suggests that RPMs and delineators are used at curves by multiple agencies. Although these two types of devices provide drivers with valuable alignment information, the current MUTCD does not include the devices in the hierarchy for treating curves. The objective of this project was to create guidelines for traffic control treatments at curves with consideration for alternative devices and conditions that would increase the flexibility given to agencies responsible for selecting TCDs at curves. It was thought that such flexibility may come in the form of determining whether or not RPMs and/or delineators should fit within a hierarchy for traffic control treatments. With the option to use alternative devices, agencies would be able to meet driver needs while perhaps expending fewer resources.

Figure 3B-15D. Example of Raised Pavement Marker (RPM) Application at Curves along Two-Lane Roads (Delaware Revision)

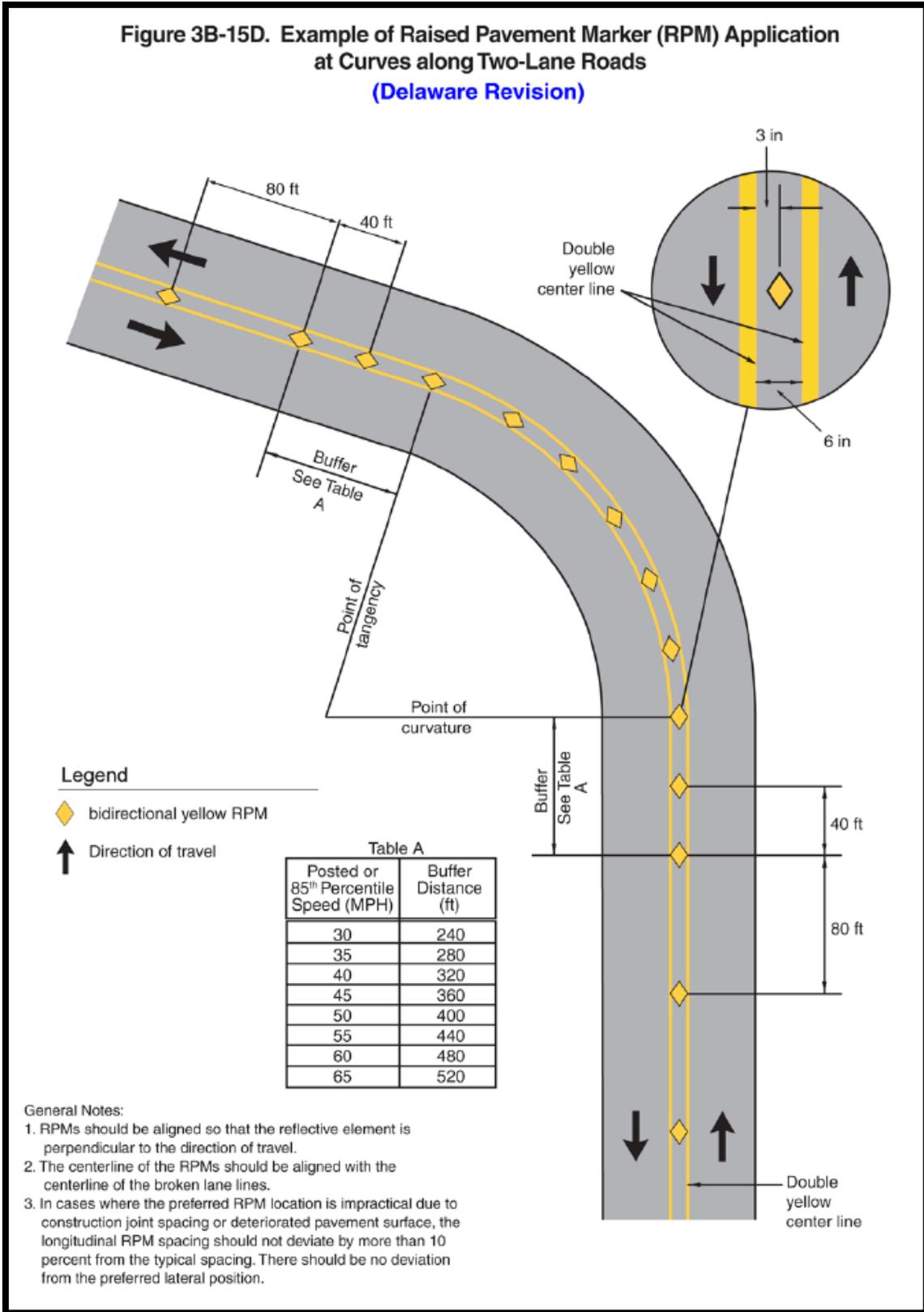


Figure B-3. RPM application at curves on two-lane roads (Delaware MUTCD).

INTERNATIONAL PRACTICES

Each country adopts a unique philosophy for addressing drivers' needs for warning and guidance on horizontal curves. Their approaches may provide useful insight in the search for the best practices for treating curves. The review of international practices includes primarily English-speaking countries (Australia, Canada, New Zealand, and the United Kingdom), with one non-English-speaking country (Denmark).

Australia

In Australia, a hierarchy based on speed differential is used to determine which warning signs should be used on curves. Unlike the current method used in the United States, the Australian standard includes the approach speed in the consideration of an appropriate device. Sign size requirements (sizes A–D) are another way the method differs. Also, the use of the Turn sign is not constrained to one advisory speed threshold (30 mph in the United States). Figure B-4 is a diagram from Figure 4.5 of Australian Standard 1742.2 (1) that shows the appropriate signs to use and identifies four sign sizes, by letters A–D, with higher speeds requiring larger signs.

The Australian standard requires warning signs when the speed differential is at least 10 km/h (6 mph). In the United States, warning signs are only required with a speed differential of 16 km/h (10 mph), and chevrons are required for a speed differential of 24 km/h (15 mph). The Australian standard states that chevrons should not be used “unless edge lines together with raised retroreflective pavement markers on lane or dividing lines are also in place,” indicating that the use of RPMs on curves is generally expected for severe curves.

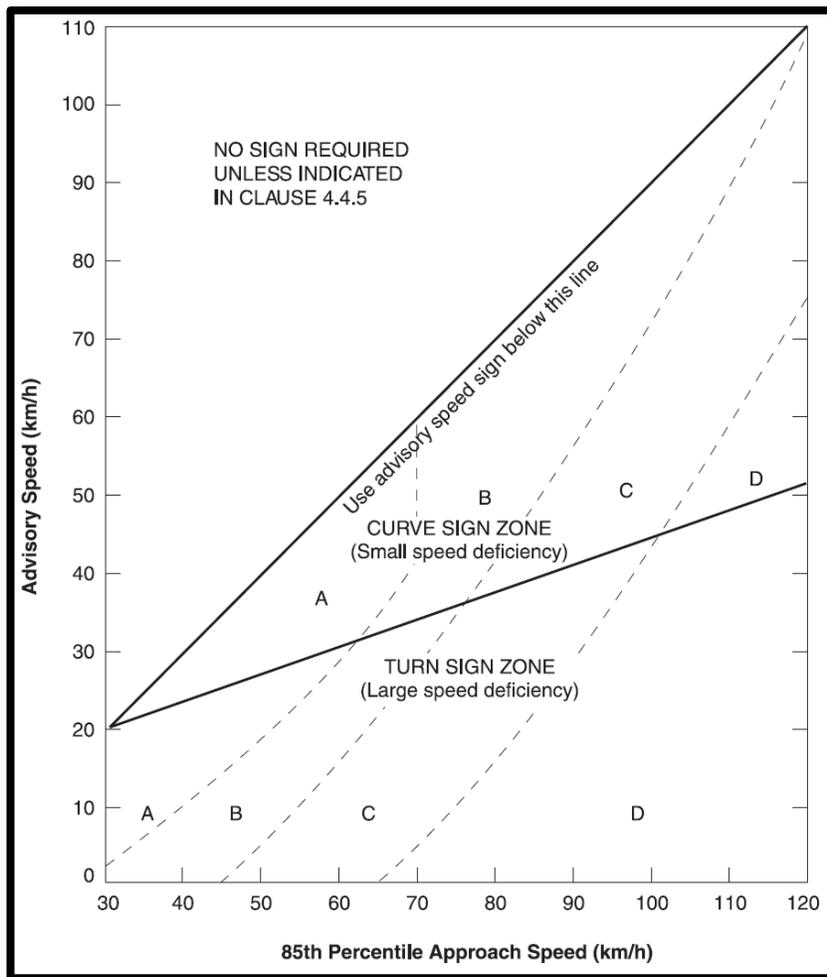


Figure B-4. Guide for curve warning signs in Australia¹.

Canada

The Canadian approach (2) for warning signs is similar to that of Australia, requiring a Turn sign when the recommended safe speed is less than two-thirds that of the approach design speed or speed limit, whichever is greater. The consideration for the design speed is unique and important, acknowledging that drivers may choose operating speeds with more attention to the road conditions than the posted limit. Advisory speed signs are used only when the advisory speed is 20 km/h (12 mph) lower than the speed limit and are mandatory for all advisory speeds less than 50 km/h (31 mph) regardless of speed limit.

¹ AS 1742.2-2009 Figure 4.5 – Reproduced with permission from SAI Global Ltd under License 1504-c066.

New Zealand

In New Zealand (3), the messages used on warning signs for curves are based more on geometry than the difference between approach speed and curve advisory speed. Four primary warning signs, shown in Figure B-5, are used based on the total deflection angle. With a geometric approach, rather than a speed differential criterion, drivers may have a better expectation of the curve geometry and thus be able to make the necessary decisions to properly navigate the curve. Advisory speed signs are recommended when the advised curve speed is approximately 25 or 30 percent less than the approaching 85th percentile speed. As in Australia, the size of warning signs in New Zealand is based on the difference in advisory and 85th percentile approach speeds. Chevrons are required only on curves that require the largest signs.

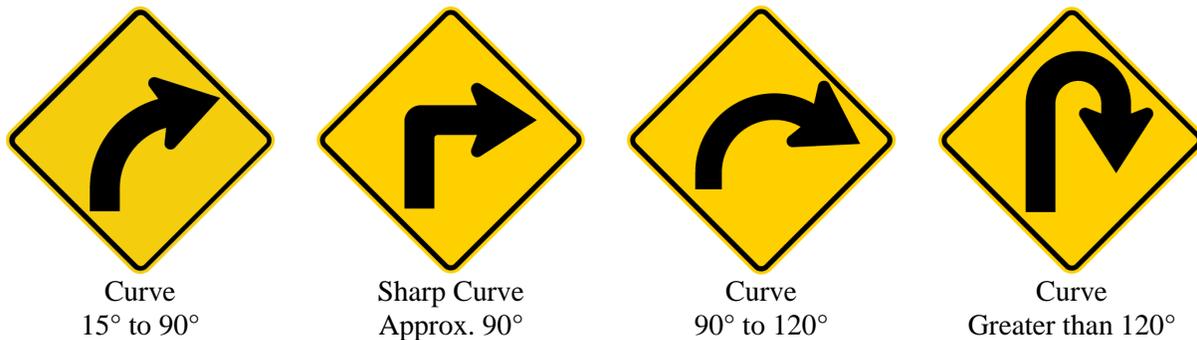


Figure B-5. Advance warning curve signs used in New Zealand.

United Kingdom

In the United Kingdom, the *Traffic Signs Manual* (4) stresses the use of engineering judgment in making a subjective assessment of the degree of danger on a curve based on four factors: the speed of the approach, the radius of curvature, the superelevation, and the skid resistance of the road surface. The manual recommends that bend (curve) signs be used sparingly and states that advisory speeds on curves should be used sparingly because “it should be for drivers to judge what speed to adopt.” This approach gives engineers more room to identify the treatments that best fit each curve and forces drivers to take more responsibility for judging curve severity.

Denmark

Curve treatments in Denmark are based on changes in kinetic energy required to navigate the curve properly (5). Because kinetic energy is dependent on the square of the initial and final speeds, a deceleration of 10 mph at a high initial speed presents a higher level of danger than the same deceleration at a low initial speed. There are five levels of curve treatments in the hierarchy used in Denmark, shown in Figure B-6. The lowest level is the use of delineator posts with ordinary pavement markings; the highest level is the use of a chevron board, curve warning sign, advisory speed sign, and profiled markings.

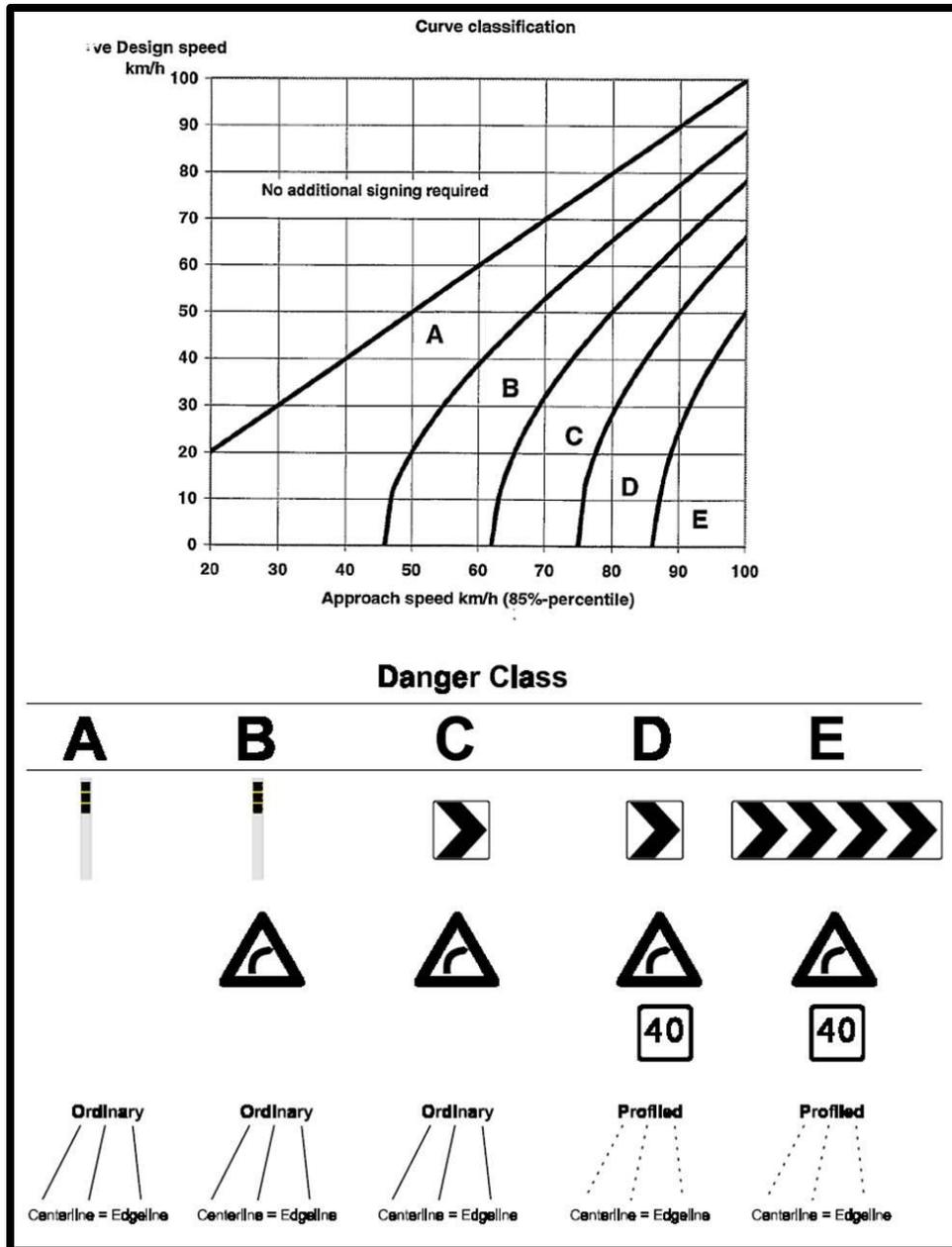


Figure B-6. Hierarchy of curve treatments used in Denmark.

Discussion of International Practices

In both Denmark and Australia, the approach speed directly affects the device installed, showing that those countries recognize that the reduction in kinetic energy for a single speed change increases as approach speed increases. In New Zealand, warning signs reflect the true geometric conditions. Providing drivers that information allows them to more actively react to the warning sign, deciding for themselves the appropriate response given their speed and the road's geometry. In the United Kingdom, a similar approach is used that allows drivers to take

responsibility instead of relying on messages for every unexpected situation. The regulation for the use of advisory speed signs in Canada is similar to the hierarchical approach of curve TCDs in the United States, where the advisory speed sign is required for certain speed changes. A requirement for posting an advisory speed sign on all curves with advisory speed below 50 km/h (regardless of speed limit) may be useful because drivers may exceed the speed limit on tangents and assume that their speed is also safe for an upcoming curve. The advisory speed limit thus serves as a warning or reminder of the safe speed.

In comparison to the policies in the United States, the notable differences with those countries reviewed here are the inclusion of the tangent approach speed in determining an appropriate device, additional TCDs (such as RPMs or delineators) included in a hierarchy of treatments, and consideration of sign size. Because each country has unique needs and conditions encountered on its roads, each has a unique approach to warning drivers of alignment changes and then guiding them through curves. The value of this survey of international policies is in the exploration of different methods that are currently used to address the same problem. Some of the ideas found in this survey are reflected in the guidelines proposed in this study.

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Appendix C: Survey of TCD Costs

This appendix documents the findings of a survey of state DOTs aimed at identifying the costs to install TCD treatments at curves.

SURVEY OF CURVE TREATMENT COSTS

All state DOTs were surveyed to identify the costs associated with installing and maintaining TCDs at curves. The purpose of the survey was to determine the financial burden placed on an agency to treat a single curve with conventional TCDs. In the event of a proposed change in policy, the data would be available for an analysis of the financial impact of such a policy. The DOTs were asked to estimate the cost of performing an engineering study at a single curve (to assess the need for a TCD treatment), the cost to install various TCDs, and the expected service life of each TCD. In addition to questions regarding the capital costs and expected service lives, the DOTs were asked whether or not they maintain records of previous engineering studies (i.e., a database with information about each curve) that would potentially reduce the costs to assess the needs of individual curves should there be any changes to the current guidelines. Each DOT was also asked whether or not the agency uses any devices at curves that are not included in MUTCD Table 2C-5, and whether or not the agency is responsible for monitoring and maintaining the devices after installation (some agencies may have that responsibility contracted to private companies).

The following specific questions were distributed by email to the American Association of State Highway and Transportation Officials Subcommittee on Traffic Engineering:

- Table 2C-5 of the MUTCD provides guidance for traffic control devices used at curves. What is the approximate cost (labor/equipment) to perform an engineering study to assess compliance with Table 2C-5 at one curve?
- Does your agency maintain records from engineering studies performed at curves in your jurisdiction? (In other words, if changes are made to the current guidelines for traffic control at horizontal curves, would your agency not need to [re]evaluate every curve in your jurisdiction?)
- Does your agency use any traffic control treatments that are not included in Table 2C-5 of the MUTCD? If so, which devices, and does your agency have guidelines for such devices?
- What is an estimate of the unit material cost for one of each of the following devices:
 - Advance warning horizontal alignment sign (W1-1, W1-2, W1-3, W1-4, W1-5, and W10-1).
 - Advisory Speed Plaque (W13-1P).
 - Chevron (W1-8).
 - One-Direction Large Arrow sign (W1-6).
 - Retroreflective RPM.
 - Delineator (post-mounted).
 - Pavement markings (per linear ft).

- What is the cost of labor and equipment to install the following devices at an “average” curve? (Sample quantities have been provided, considering two-directional traffic; assume traffic control has been contracted out.)
 - Advance warning signs (quantity 2).
 - Chevrons (quantity 12 [6 per direction]).
 - Arrow signs (quantity 2).
 - RPMs (quantity 15).
 - Delineators (quantity 8–10).
 - Pavement markings (per linear ft).
- Who is responsible for monitoring and maintaining devices after installation? (Maintenance may include cleaning, straightening, trimming trees and shrubbery, daytime and nighttime inspections, etc.)
- What is the approximate service life of the following devices in your jurisdiction:
 - Advance warning signs.
 - Chevron signs.
 - Arrow signs.
 - RPMs.
 - Delineators.
 - Pavement markings.

SURVEY RESPONSES

Twenty-three states responded to the survey. The following are some simple summary statistics:

Regarding records of previous engineering studies, 41 percent of agencies maintain a database that can be used to assess the needs of individual curves. (Approximately one-fourth of those positive responses, however, stated that their records need to be updated.)

Regarding alternative treatments, 64 percent of agencies responded that they use TCDs not specified in Table 2C-5. The most common treatment is post-mounted delineators.

Only one agency of the 23 respondents (4.5 percent) contracts the maintenance responsibilities to private companies; all other DOTs have personnel, either at an agency level or within their districts, responsible for device maintenance.

There was substantial variability in the responses regarding the cost to perform an engineering study and the material and installation costs of TCDs. This variability reflects the variety of options to select a method to evaluate curves, purchase traffic control products, and install the devices. Additionally, the structure of the DOTs, their priorities, and the economies of scale that may reduce overall costs when working with large quantities affect this variability. For example, the reported cost to perform an engineering study at one curve ranged from \$10 to \$1,500. When excluding the maximum and minimum reported costs, the average cost of an engineering study is \$391. The average cost to install each treatment and its average expected service life are reported in Table C-1. These averages were also identified after excluding the maximum and minimum values for each treatment. For consistency in estimating the cost to treat a single curve, a sample quantity of each TCD at one curve is given in the table. Specific conditions for a real curve will determine the actual quantity that should be used.

Table C-1. TCD Treatment Costs per Curve

Treatment (Qty. per Curve)	Material Unit Cost		Installation Cost		Total Avg. Cost	Service Life (Years)
	Avg.	Range	Avg.	Range		
Advance warning sign (2)	\$132	\$43–289	\$380	\$122–800	\$644	11.9
Advisory Speed Plaque (2)	\$45	\$11–100	N/A	N/A	\$90	11.9
Chevrons (12 [6 per direction])	\$88	\$28–154	\$1,320	\$230–4,000	\$2,376	11.1
Large Arrow sign (2)	\$148	\$46–287	\$328	\$134–670	\$624	11.4
Delineators (8)	\$27	\$9–50	\$383	\$100–750	\$599	9.1
RPM (snowplowable) (15)	\$9.67	\$4.00–17.00	\$499	\$180–1,043	\$644	5.8
RPM (non-snowplowable) (15)	\$1.83	\$0.62–4.00	\$101	\$12–230	\$128	2.2

Averages and ranges are reported after excluding the maximum and minimum values from the raw data. The unit material cost represents the capital cost of one (unit) device; the installation costs are the labor and equipment to install the assumed quantity for the whole curve. There were not enough responses to exclude maximum and minimum values from the RPM treatments.

None of the values in Table C-1 account for maintenance costs. Maintenance requires regularly monitoring the TCD to ensure it is functioning properly, and may include daytime and nighttime inspections, straightening, cleaning, and clearing of vegetation. Replacement should occur (on average) only as often as the service life indicates.

Appendix D: Open-Road Driving Study

This appendix documents the study protocol of the open-road driving study conducted in three states: Idaho, Oregon, and Texas. The data were collected to analyze driver operational performance and visual attention of drivers while they approach and navigate curves. Appendix E contains the results of the analyses specific to operational performance; Appendix F contains the results of the analysis of visual attention.

BACKGROUND

The open-road driving study was designed to provide detailed information about natural driver behavior when negotiating curves on an unfamiliar highway. It was determined that driver behavior can be divided into two primary components: operational performance and visual attention, or cognition.

Driver Operational Performance

Based on previous research as discussed in Chapter 3, there are three general phases of curve negotiation: deceleration before entering a curve; the process of navigating the curve, including the deceleration and lateral acceleration that occur within the curve; and acceleration after exiting the curve. The operational characteristics of drivers negotiating curves are documented in Chapter 3, including a discussion of how TCDs have been observed to influence performance. Most studies identified improvements in operational metrics when TCDs were used, though the findings were sometimes inconsistent. The inadequacies of much of the previous research seem to be a result of insufficient data: in many cases, the researchers simply did not have enough resources to obtain conclusive results.

One source of the shortfalls of some of the previous research is the method of data collection. Many of the previous studies involved data collection from speed measurements at fixed locations within curves or on the approach tangents. Driver behavior at curves, which may involve deceleration over long distances or sudden reactions in response to an unexpected alignment change, is much too complex to adequately characterize with single measurements of speed. Point-to-point speed measurements can mask the instantaneous changes that may occur at locations that do not have sensors, resulting in somewhat uninformative metrics.

The operational data for the driver behavior study documented in this report came from a global positioning system (GPS) receiver that tracked the vehicle's speed and position and a biaxial accelerometer that measured the longitudinal and lateral acceleration. The instruments operated continuously at a high sampling rate to overcome the limitation of only having data for a select number of locations. Although there is value in obtaining single-point measurements of vehicle speed (for example, to observe the characteristics of regular, daily traffic), the use of continuous data to measure operational characteristics while subjects drive a defined route is becoming more common (1, 2).

Driver Visual Attention

Drivers tend to fixate on the objects they consider to provide the most important information at that moment. Notable research on the visual attention of drivers has included studies of where drivers look (3, 4), how drivers adjust their fixations for different driving situations (5), how distractions or other cognitive loads affect these behavioral patterns (6-8), and the influence of driving experience (9-13). It has been shown that, as drivers approach curves, they concentrate on the occlusion point (where the curve becomes hidden from view), anticipating potential hazards and searching for additional roadway information at the earliest possible time (5, 8, 10). While the visual attention of drivers approaching and navigating curves has been documented multiple times by evaluating fixations, current eye-tracking technology allows other measures to be investigated that may provide insight into the driving experience. Such measures include the size of the pupils, the amount of closure of the eyes, and the blink rate.

The pupil is the part of the eye through which light enters before being processed as visual information. Pupils dilate and contract as a reflex to the amount of light entering the eye: contractions occur when encountering bright conditions, dilations with dim conditions. The reflex can be as great as 2 or 3 mm in diameter, depending on the lighting and the size of the person's pupil. Wang's (14) review of studies on pupil dilation discusses how pupils may dilate as one of a number of cognitive or emotional responses. Cognitively demanding processes lead to a peak dilation about 1–2 s after the stimulus (15), followed by a contraction back to a relaxed size after the task (15, 16). The involuntary contractions and dilations that occur in response to an individual's cognition tend to be smaller than the response to lighting and are often less than 0.5 mm. These small movements have been used as a metric called the task-evoked pupillary response (17).

A number of measures can be extracted from the raw pupil data to obtain a task-evoked pupillary response. Two of the metrics suggested by Beatty and Lucero-Wagoner (17) applied in this research are the dilation and the latency to dilation. The dilation is calculated as the difference between the maximum diameter observed during the period of interest and a baseline value. It provides a measure of magnitude that may reflect the level of workload for a specific situation. The latency to peak is the amount of time that occurs from the start of the period of interest to the maximum value (peak). In this study, the dilation and latency to dilation relate to the location of the driver when the pupils are fully contracted and begin dilating (indicating that the driver is actively obtaining information), the location when the pupils are fully dilated (representing the location when the driver is under maximum workload), and the magnitudes of the contraction and dilation during these processes (which represent the amount of relaxation or workload).

The percentage of the eye covered by the eyelid is another physiological measure indicative of a driver's cognitive state. As drivers become more alert, the proportion of the eye covered by the eyelid decreases, or in other words, the eye becomes wider. Similar to changes in pupil size, changes in how much the eyelid covers the eye signifies a change in the subject's cognition. The use of eye closure as a metric for evaluating the cognition of drivers is relatively new compared to pupil size. Most of the previous analyses of eye closure have used it to identify drowsy driving (18-20). Recent work (21) has identified changes in eye closure under normal driving scenarios, such as when executing a passing maneuver or waiting for a signal indication to change. This study uses metrics for eye closure that are similar to those of pupil size in that they identify when (or where) changes in attention occur and the magnitude of the changes.

Drew (22) observed that the rate at which a subject blinks tends to be approximately constant under constant conditions, but that an individual's blink rate is inversely related with the difficulty of a task (fewer blinks under higher workload). Drew comments that while blinking occurs just before and after a period of maximum difficulty, sometimes no blinking occurs during that time. Other researchers have observed decreases in blink rate with more cognitively-demanding tasks (23, 24), and it has been suggested that people suppress the urge to blink to avoid gaps during the continuous flow of visual information (25). The period of time that a blink affects information acquisition has been estimated to be near 400 ms (26, 27). Like metrics of pupil size and eye closure, changes in a driver's blink rate while on a curve approach may indicate a cognitive response associated with navigating curves.

The purpose of TCDs at curves is to provide drivers with the information necessary for safe and efficient curve navigation. Tracking the visual attention of drivers as they drive on a tangent and approach a curve may help identify when drivers perceive curves and the factors (such as TCDs) that affect the temporal aspects of driver cognition. The use of psychophysiological data from eye-tracking technology to evaluate drivers is a novel approach to understanding their behavior. Whether or not the metrics discussed here would prove useful in the context of curve negotiation was unknown before the research began, but it was hoped that some interesting insight would be gained that could support a scientific approach to selecting TCDs at curves.

STUDY DESIGN

The driving study involved having participants navigate an unfamiliar, rural two-lane highway in an instrumented vehicle. The vehicle contained equipment that collected data characterizing operational performance and parameters associated with the participant's visual attention. Data were collected in multiple states—Idaho, Oregon, and Texas—as shown in Figure D-1. On the highways where data were collected, some curves were selected to receive an additional traffic control treatment for part of the study.

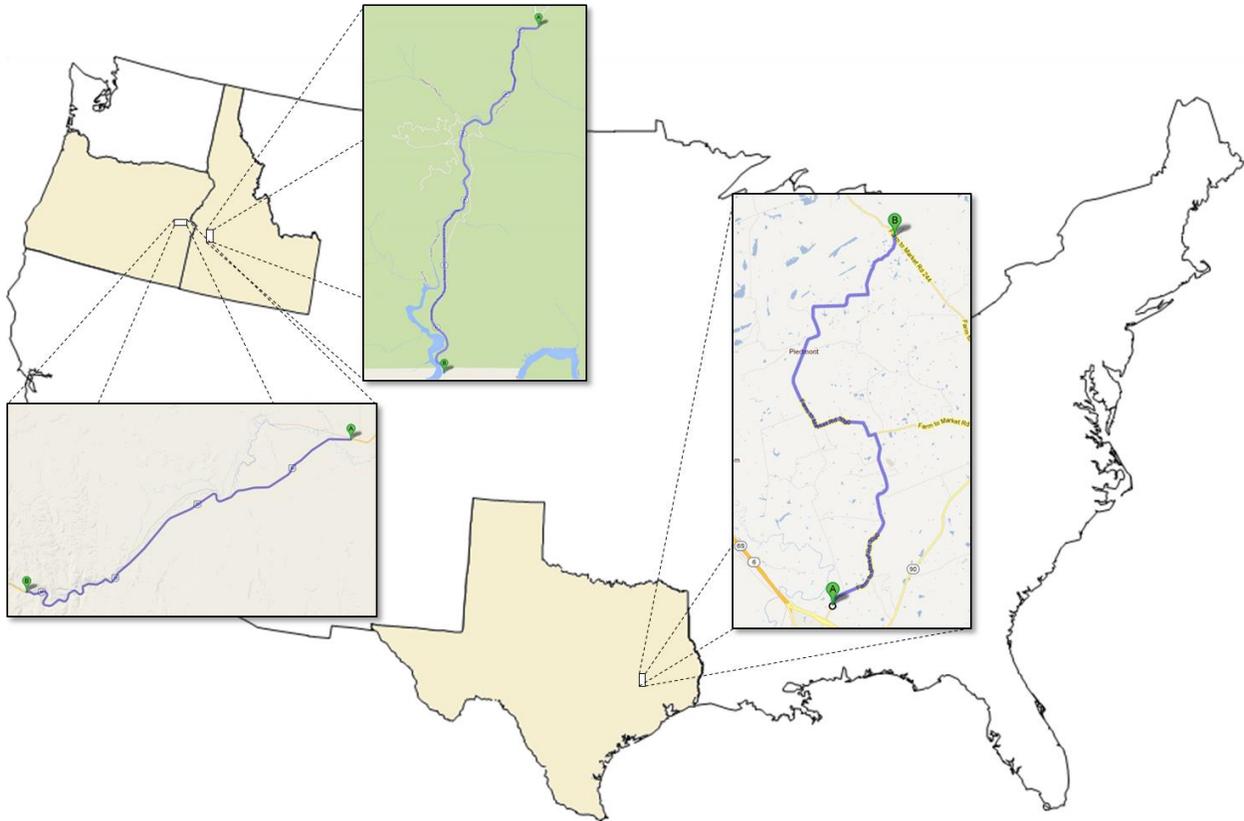


Figure D-1. Study routes used in the driving study (maps of study sites: Google).

Study Participants

There were 103 total participants (approximately 34 in each state) with an age distribution that roughly represents the demographics of drivers involved in fatal crashes on curves. Because there are more “young” than “old” drivers involved in fatal crashes, there were more young than old study participants (approximately a 2:1 ratio). The median age of all participants was 23 years, the mean was 30.4 years, and all were younger than 71. Tests were conducted during both day and night, but more participants drove at night. Nighttime driving was emphasized because the need for TCDs as a source of information is greater at night, and the effects of TCDs were determined based only on the nighttime data. In order to replicate a driving experience that is as normal as possible, the participants were not required to complete any tasks other than driving on the highway. Drivers were paid \$50 for their participation.

The selection of unfamiliar drivers was a fundamental component of this study. Many of the previous investigations of driver performance at curves involved collecting data in the field from drivers that can be assumed are familiar, regular drivers. Drivers who are familiar with a highway and its changes in alignment are generally not the ones in need of the information curve TCDs provide. The effectiveness of TCDs should be determined based on the drivers who rely on them the most. That information can best be produced by monitoring the behavior of drivers who are unfamiliar with a highway.

Equipment

The vehicle was a 2005 Dodge Caravan equipped with various instruments to record data relevant to the driving task. Two infrared cameras mounted to the dashboard were used to track the drivers' eyes using faceLAB software produced by Seeing Machines. Eye movements were recorded at 60 Hz. A GPS receiver operating at 10 Hz was used to track the position and speed of the vehicle, and a bi-axial accelerometer also operating at 10 Hz collected measurements of longitudinal and lateral acceleration. Data collected by the eye-tracking cameras, GPS receiver, and accelerometer were stored in separate files on a laptop computer operating in the rear of the vehicle. A computer time stamp recorded with each entry was used to synchronize the data sources, thus identifying the simultaneous visual attention and operational performance. Images of the equipment used in the vehicle for collecting data are shown in Figure D-2.



(a)



(b)



(c)



(d)

Figure D-2. Data collection equipment—(a) eye-tracking cameras, (b) GPS receiver, (c) accelerometer, and (d) laptop.

Experiment Protocol

Weather conditions during data collection were optimal for driving (good visibility and no precipitation). The participants were greeted in the lobby of a nearby hotel where they were given instructions regarding the driving study. A vision test was administered, and 75 percent of all participants had a measured acuity of 20/20 or better. They were allowed to wear corrective lenses if necessary. The participants were then placed in the study vehicle and allowed to adjust basic driver comfort settings before being guided through a procedure to calibrate fixations with the infrared cameras. Following the eye-tracking calibration, the participants were directed to drive to the study site, allowing them to become accustomed to the new vehicle. The participants were instructed to follow all traffic laws as they drove to the end of the highway. They were given little information about the purpose of the study.

When the participants reached the end of the designated study route, they were instructed to return to the hotel where the study began. During the return trip, the drivers were led to believe the instrumentation in the vehicle was no longer collecting data, while all devices were actually still running and data being stored on the computer. This element of deception for the return trip was incorporated into the study to further encourage the participants to drive as naturally and comfortably as possible. The analyses do not differentiate between when drivers were aware they were being monitored and when they believed the instrumentation was not operating. There are other factors that may influence the return drive; therefore, such a differentiation is not meaningful for this report.

Throughout the drive, the participants were discouraged from using the vehicle's cruise control, and the frequency and severity of some of the curves encountered generally made it impractical to do so anyway. Because traffic was very light, the participants were usually able to drive under free-flow conditions. There were occasions, however, when a participant encroached upon another vehicle traveling in the same direction. When that occurred, the participant was instructed to stop at the first reasonable location and wait to generate a substantial distance between the vehicles. During post-processing, any data collected when a participant driver was following another vehicle were discarded.

Study Sites

From the three study corridors, 167 total changes in alignment were identified as study curves. The corridors were divided into segments that each begin where an upstream curve ends at a tangent and continue until the PT of the downstream study curve. Because data were collected in both directions on the highway, each study curve can potentially appear in the analysis twice as two different curves; the alternative direction of the curve and operational characteristics of the two different approaches produce two unique experiences for the unfamiliar driver. Not every change in alignment was identified as a curve suitable for inclusion in the analysis. Vertical curvature was one characteristic that warranted a curve's exclusion from analysis. This applied more to the Texas site, which had gently rolling hills, than the Idaho and Oregon sites, which were relatively flat and adjacent to rivers. Vertical curvature data were not collected, though subjective decisions were made regarding an acceptable amount of elevation change.

The following geometric data were collected for each curve/segment:

- Radius (ft)

- Deflection (deg)
- Superelevation (percent)
- Curve direction
- Curve length (ft)
- Approach tangent length (ft)

Table D-1 contains a descriptive summary of the study curves identified in the three states.

Table D-1. Characteristics of Study Sites

	Oregon		Idaho		Texas	
	<u>Min.</u>	<u>Max.</u>	<u>Min.</u>	<u>Max.</u>	<u>Min.</u>	<u>Max.</u>
Number of curves	39		70		58	
Posted speed limit (mph)	55		45–55		60	
Radius (ft)	690	5,670	420	2,150	55	1,250
Deflection angle (deg)	22	151	14	123	7	90
Tangent length (ft)	490	10,400	140	6,300	140	5,900
Posted advisory speed (mph)*	40	45	35	45	15	50

*Represents only the curves treated with a warning sign and posted advisory speed. The posted advisory speeds were not validated.

Curve TCD Treatments

During the study, some of the curves along the study routes were treated with additional TCDs that were not originally installed by the governing agency. The TCDs used were post-mounted delineators and Large Arrow signs in Texas, and RPMs in Idaho and Oregon. The devices were installed so that each treatment at one curve was encountered by half of the participants. Eight locations in Texas were treated with either delineators or Large Arrow signs and 10 total locations in Idaho and Oregon were treated with RPMs. The delineators were visible from both approaches, and the delineators were spaced based on radius and according to MUTCD Table 3F-1, except that the three delineators installed in advance of and beyond each curve were spaced at constant distances of twice the in-curve spacing (consistent with Texas guidelines), rather than progressing from two times to six times the in-curve spacing as done in the national MUTCD. Two of the curves treated with Large Arrow signs only had one sign installed and facing one direction. In Texas, where delineators and Large Arrow signs were tested, approximately half of the curves received the treatment during the first half of data collection; the other half of the curves received the treatment during the second part of data collection. This ensured that all participants in Texas navigated some curves with a treatment. Additionally, a few curves in Texas had already been treated with chevrons, and no changes were made at those curves. All RPMs used in Idaho and Oregon were placed on the road during the second half of the study, meaning the first half of participants navigated the highway without any additional RPMs.

DATA REDUCTION

The data that were collected continuously along the study routes needed to be organized in a way that facilitated attributing characteristics of driver behavior to specific curve characteristics. To do this, the data from each source needed to be divided into segments for each study curve. Additionally, novel measures of effectiveness were created for finding unique relationships that physically extend beyond the traditional curve limits.

Data Sources

The GPS receiver and accelerometer operated at 10 Hz, each providing one data entry per 0.1 s. The eye-tracker operated at 60 Hz, providing one entry per 0.0167 s. Each trip with the study participants lasted at least 1 hour. Over the course of an hour, the GPS receiver and accelerometer each log 36,000 entries and the eye-tracker logs 216,000 entries. There are several extraneous data values logged by each data source. The critical values of raw data used in the study are as follows:

- For the GPS receiver:
 - Computer time stamp.
 - Longitude and latitude.
 - Speed (mph).
- For the Accelerometer:
 - Computer time stamp.
 - Longitudinal acceleration (ft/s²).
 - Lateral acceleration (g).
- For the eye-tracker:
 - Computer time stamp.
 - Video frame (for reference to the forward-facing camera).
 - For each eye:
 - Horizontal angle of fixation displacement (radians).
 - Vertical angle of fixation displacement (radians).
 - Pupil diameter (mm).
 - Eye closure percentage.
 - Blinking state (0 [not blinking] or 1 [blinking]).
 - Gaze quality (1 [low], 2 [medium], or 3 [high]).

Measures of Effectiveness

Since TCDs tend to be visible at several hundred feet, it was determined that the effects of TCDs on operational performance and visual attention may be observed not only within the curve, but far in advance of the curve. The measures of effectiveness were selected to capture characteristics of driver behavior beginning when the drivers are far from the curve in order to investigate where TCDs become influential or drivers begin responding to the curve. Some of these measures could be extracted from the data only because the speed, acceleration, and eye-tracking data were collected continuously.

The following metrics characterizing operational performance were used:

- Distance (ft) traveled downstream after exiting a curve until reaching a maximum tangent speed.
- Total increase in speed (mph) on a tangent.
- Speed reduction (mph) from the tangent to the curve entrance.
- Maximum deceleration rate (ft/s²) on the tangent approach.
- Speed (mph) at the PC.
- Total speed reduction (mph), measured by the difference between the maximum tangent speed and minimum speed in the curve.
- Maximum deceleration rate (ft/s²) in the curve.
- Maximum rate of lateral acceleration (g) experienced in the curve.

With the exception of the fixation location, the measures of visual attention from the eye-tracking data characterize the location of the driver when changes in attention occur and the magnitude of those changes. The following metrics of visual attention were used:

- Average fixation location (horizontal and vertical components of fixations).
- Distance traveled downstream from a curve until the pupil is contracted.
- Magnitude of pupil contraction.
- Distance before the downstream curve when the pupil is dilated.
- Magnitude of pupil dilation.
- Distance traveled downstream from a curve until the eyes reach maximum closure.
- Magnitude of eye closure.
- Distance before the downstream curve when eyes reach minimum closure.
- Average blink rate.

Data Extraction and Reduction

The extraction and reduction of the data centered on identifying the behavior of a driver while approaching and navigating a curve. With the curves previously identified, including their beginning and end (the PC and PT), the data continuously collected for each participant were parsed into segments that each begin after the exit of a curve (the start of a tangent) and continue to the end of a downstream curve. Because the data were collected at a high frequency (10–60 data points per second, depending on the instrument), a single segment could contain hundreds or even thousands of data entries.

The data associated with operational performance on each segment were reduced first. The following data were extracted from the GPS and accelerometer files: the maximum speed on the tangent, the location of the maximum speed, the maximum deceleration rate on the tangent, the speed at the PC, the minimum speed within the curve, the maximum deceleration rate within the curve, and the maximum lateral acceleration within the curve.

The eye-tracking data for each segment were then reduced. Of interest were the fixation location (recorded as horizontal and vertical rotation angles), pupil size, eye closure, and blinks. It was observed that the eye-tracking data were quite noisy, with quick fluctuations in these parameters that result from quick eye movements and blinks. To address the noise in the data, earlier work on fixations (28) combined 6 s of eye-tracking data; a separate pupillometry study used an average of 3 s (29). For this study, it was determined that an average over an interval of 4 s would sufficiently represent the cognitive state of the driver at a relatively small moment in

time, striking a balance between the need for a robust measure of visual attention while preventing short-lived deviations that create a noisy dataset. For 4 s, each parameter for each eye would be measured 240 times (60 frames per second across 4 s), for a total of 480 measurements.

The eye-tracking data for each participant contained over 100,000 entries. To limit the number of calculations that would need to be performed (which would have involved averaging 240 values for each parameter of each eye per data entry), the eye-tracking data were extracted and averaged only for 4-s intervals starting when the vehicle was at locations spaced at 100-ft increments along each segment. After each average parameter was extracted for each eye at an identified point of interest, the average of the two eyes was reported. Entries when the recorded gaze quality was poor (lower than a 3 for each eye as determined by the software) were excluded.

The final step involved cleaning the data. As previously discussed, despite driving on low-volume highways, there were occasions when the participant encroached upon a vehicle traveling in the same direction, which affected both the operational and visual behavior. When this occurred the participant was instructed to pull over at the nearest reasonable location and create a sufficient amount of distance between the two vehicles. Data collected during these occasions were removed from the dataset. It was also observed that the eye-tracking measures were significantly affected by encounters with opposing vehicles. Participants tended to fixate on the opposing vehicle until it passed, as if to ensure no conflict occurred with the other vehicle. At night, the pupils would also substantially contract due to the opposing vehicle's headlamps. There appeared to be no significant effects on operational behavior; therefore, the eye-tracking data during these encounters with opposing vehicles were eliminated, but the operational data were preserved.

Organization of Reduced Data

The data were recorded continuously from the time the participant exited the hotel parking lot to the time the participant returned, resulting in thousands of entries from each data source for each participant. The previous discussion presents how the process of data reduction involved extracting the data from the three sources in a way that identifies various complex parts of a driver's behavior while on an individual segment. The reduced dataset contains one entry for each study curve. Each entry contains information about the curve (radius, deflection angle, approach tangent length, TCDs, etc.) and information about the operational and visual behavior on the approach and within the curve (maximum tangent speed, maximum deceleration rate, initial pupil diameter, maximum pupil diameter, blink rate at the PC, etc.).

SUMMARY

The driving study was designed to obtain a large sample of data collected continuously while study participants navigated an unfamiliar, rural two-lane highway in one of three states. Speed and acceleration data were collected by a GPS receiver and bi-axial accelerometer, and visual attention data were collected by eye-tracking cameras. The data were collected at a high frequency with many participants over prolonged periods, resulting in an extensive dataset. The data were reduced in a way that facilitates analysis in statistical models to show the effects and

interactions of multiple independent variables. Appendix E contains the results of the analysis of operational performance; Appendix F contains the results of the analysis of visual attention.

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Appendix E: Effects of Traffic Control Devices on Driver Operational Performance

This appendix is the first of two that presents findings from the analysis of the driver behavior study and emphasizes driver operational performance with respect to curves and TCDs. As explained in Appendix D, the study included an evaluation of drivers in an instrumented vehicle on an unfamiliar highway in one of three states (Idaho, Oregon, and Texas). The operational performance as documented in this appendix relates specifically to measurements of speed and acceleration of the drivers on the highways.

The analyses indicate that the geometry of the highway alignment is the primary factor that influences operational behavior. In comparison, the effects of TCDs are noticeably subtle. Multivariable models that include the effects of geometry, operational characteristics, and the presence of a TCD are provided. The TCDs discussed in this appendix are Curve signs, Chevron Alignment signs, One-Direction Large Arrow signs, post-mounted delineators, and retroreflective RPMs.

BACKGROUND

The study was carried out and the data reduced as documented in Appendix D. A total of 103 study participants navigated one of three unfamiliar highways in the three states while a GPS receiver and accelerometer took operational measurements of speed and acceleration with high frequency. The following independent variables associated with the highway alignment and curves are used in models to identify the effects on the operational measures of interest:

- Radius (ft)
- Deflection (deg)
- Approach tangent length (ft)
- TCDs present at the curve

The following are the operational measures that are dependent variables in the models:

- Distance (ft) traveled downstream after exiting a curve until reaching a maximum tangent speed;
- Total increase in speed (mph) on a tangent;
- Speed reduction (mph) from the tangent to the curve entrance;
- Maximum deceleration rate (ft/s^2) on the tangent approach;
- Speed (mph) at PC;
- Total speed reduction (mph), measured by the difference between the maximum tangent speed and minimum speed in the curve;
- Maximum deceleration rate (ft/s^2) in the curve; and
- Maximum rate of lateral acceleration (g) experienced in the curve.

By evaluating the novel metrics that are based on continuous data, the models can provide a perspective of the behavior of drivers negotiating curves that has never before been shown. While the results specific to TCDs are valuable, what may be even more important is the characterization of drivers on the segments that can help identify the driver needs at curves.

METHODOLOGY

The dependent variables of operational performance were analyzed in multivariable linear mixed models. The fixed effects of the models were the geometric characteristics of curves, other relevant operational characteristics of the drivers, and the TCDs (if any) used at the curve. The drivers were included in the models as random effects to account for the variation across the participants. In most cases, the variables were transformed or weighted least squares regression was used to make appropriate adjustments for when the variance of the error terms was not constant. The models were created with JMP statistical software.

The original dataset included 167 study curves and approximately 4,800 unique observations representing a single driver approaching and navigating one curve. The study curves have a wide range of characteristics, including the various levels of traffic control. To isolate the effects of TCDs in models that also include other influences (such as curve geometry) and limit the possibility for introducing biases, subsets of the original 167 study curves were created using narrower ranges of characteristics. Multiple restrictions were applied to the dataset to ensure the applicability of the results. Descriptive statistics of the data subsets are provided in Table E-1. Only data collected at night are used in the analyses that evaluate the effects of TCDs, because TCDs are assumed to have the greatest influence at night due to the lack of other visible information.

Table E-1. Characteristics of Curves in Driver Behavior Analyses

General Statistics	Analysis Group		
	Curve Signs	Chevrons, Large Arrow Sign, Delineators	RPMs
Number of Curves	61	40	22
Total Observations	1,498	555	547
Radius (ft)	420-1,985	55-860	515-1,430
Deflection (deg)	22-99	27-90	23-150
Tangent Length (ft)	190-1,535	209-2,820	192-1,530
Observed Speed Change (mph)	0-9.6	5.8-41	0.8-9.4

RESULTS

The effects of TCDs at curves are identified in multivariable regression models that include indicators for the presence of a particular TCD. The results are divided by type of device, and the models within each group are ordered chronologically starting with the acceleration phase and finishing with the driver navigating the curve. In selecting a model, preference was given to the model with the simplest form (fewest variables) that still maintains a reasonable level of accuracy and significance. Often this meant rejecting a model that would improve (though marginally) the common model selection values of Akaike's information criterion (AIC), Bayes' information criterion (BIC), or R-squared correlation coefficient. Also for simplicity, the TCD variables are included as indicators with no interactions with the other main effects. The analyses of advance warning signs are presented first, followed by analyses of the vertical in-curve devices (chevrons, large arrows, and delineators), and then the effects of RPMs.

Advance Warning Signs

No advance warning signs were installed as part of the study, so the effects of Curve signs are determined by modeling data collected at curves not treated with warning signs and similar curves with warning signs. The resulting dataset consists of curves that are relatively gentle and at the threshold of being treated with a warning sign. Although there was not consistency in placement location, most warning signs were placed approximately 300 ft in advance of the curve.

Equation 1 estimates the distance the drivers traveled after exiting a curve while accelerating to the maximum approach tangent speed. Equation 2 estimates the increase in speed that occurs during that acceleration. In addition to an indicator for advance warning signs, the main effects of the models are the tangent length and the driver's potential speed increase. The potential speed increase is defined as the difference between the vehicle's speed at the beginning of the tangent and the maximum speed the driver ever reached on the highway. The R^2 value of Equation 1 is 0.74; the R^2 value for Equation 2 is 0.85.

$$D_{Accel} = 265 + \frac{952L_{Tan}}{10,000} - 10.0Potential + \frac{315(L_{Tan})(Potential)}{10,000} - 140I_{warning} \quad 1$$

$$\Delta_{Speed_{Accel}} = -1.21 + \frac{6.0L_{Tan}}{10,000} + 0.24Potential + \frac{2.7(L_{Tan})(Potential)}{10,000} - 3.0I_{warning} \quad 2$$

where

- D_{Accel} = distance traveled (ft) before reaching the maximum tangent speed.
- $\Delta_{Speed_{Accel}}$ = increase in speed (mph) during the acceleration phase.
- L_{Tan} = tangent length (ft).
- $Potential$ = potential speed increase (mph) based on the difference between the driver's desired speed and the initial speed on the tangent.
- $I_{warning}$ = indicator for a curve warning sign (1 if present; 0 if none).

Based on the models in Equations 1 and 2, curve advance warning signs lead drivers to stop accelerating earlier by about 140 ft and not reach as high a speed, by about 3 mph. It is interesting that the model indicates that drivers (overall) begin responding to the curve approximately 140 ft earlier when an advance warning sign is used, despite it being placed usually 200–400 ft in advance of the curve. When including the sign’s visibility distance, this comparison suggests that drivers substantially delay responding to the information provided by the sign. It is thought that the drivers wait for information from the curve itself that confirms the message of the warning sign before actually responding.

Equations 1 and 2 show that drivers respond to advance warning signs by limiting how much they accelerate on a tangent. With a lower maximum tangent speed and an earlier initiation of the deceleration when an advance warning sign is used, it is expected that the change in speed in advance of the curve and the maximum observed deceleration will be reduced. Equation 3 estimates how much the driver decelerates (as a change in speed) before reaching the curve, and Equation 4 estimates the maximum deceleration rate. The R^2 value for Equation 3 is 0.39, which is generally considered weak, although the variables are all significant. The weak correlation suggests that there are other variables (whether isolated in the data or completely unidentifiable) that may better relate to the change in speed. The R^2 value for Equation 4 is 0.55. The models in Equations 3 and 4 indicate that drivers respond to Curve signs by reducing their speed more in advance of a curve (about 1 mph) and accepting a greater rate of deceleration (by about 0.5 ft/s²) than they otherwise would without a Curve sign. It was expected that the Curve sign would lead to reduced deceleration rates, especially because drivers stopped accelerating earlier and reached a lower maximum speed on the tangents. Because the model was based on data collected at relatively gentle curves, the unexpected finding may suggest that these signs were installed at curves where they are not needed, and that drivers are needlessly responding to the signs.

$$\Delta_{Speed_{Tan}} = -1.1 + \frac{47D_{Decel}}{10,000} + \frac{1182}{R} + 1.0I_{Warning} \quad 3$$

$$Decel_{Rate_{Tan}} = 0.67 + 0.19\Delta_{Speed} + 0.50I_{Warning} \quad 4$$

where

- $\Delta_{Speed_{Tan}}$ = decrease in speed (mph) in advance of the curve.
- $Decel_{Rate_{Tan}}$ = maximum observed deceleration rate (ft/s²) on the tangent.
- D_{Decel} = distance (ft) from the curve when deceleration begins.
- R = curve radius (ft).
- $I_{warning}$ = indicator for a curve warning sign (1 if present; 0 if none).
- Δ_{Speed} = total speed differential (mph) observed at the curve.

The model for the speed at the PC is shown by Equation 5. The R^2 value for Equation 5 is 0.95.

$$Speed_{PC} = 5.1 + 0.89Speed_{Max} - \frac{1161}{R} - 0.88I_{Warning} \quad 5$$

where

- $Speed_{PC}$ = speed (mph) at the PC.

- $Speed_{Max}$ = maximum tangential speed (mph).
 R = curve radius (ft).
 $I_{warning}$ = indicator for a curve warning sign (1 if present; 0 if none).

The estimate for the effect of a curve warning sign suggests a decrease of almost 0.9 mph at the PC of the curve when an advance warning sign is used. It should not be surprising that the effect of a warning sign in Equation 5 is quite close to the effect in the model of pre-curve speed reduction in Equation 3. The slight difference in the estimated effects is due to the inclusion of a different main effect (either the distance from the curve when deceleration begins or the maximum speed on the tangent). Note that the estimates for the effect of radius in Equations 3 and 5 are also similar. The measures of driver responses within the curve (maximum in-curve deceleration rate and maximum lateral acceleration rate) were not significantly influenced by Curve signs.

Chevrons, Large Arrow Signs, and Delineators

Select curves in Texas were treated with Large Arrow signs or delineators to be tested during half of the participant runs. Chevrons were already present at some curves and were not changed from their original condition. The dataset used to model the effects of these vertical, in-curve TCDs on the measures of driver behavior is comprised of observations from curves only in Texas that are relatively similar in geometry. All the curves were already treated with advance warning signs, so the purpose of these models is to identify the effect of installing devices within the curve to supplement the advance warning. The models again were generated using only data collected at night and are presented in a type of chronological order with respect to the process of approaching and then navigating curves.

Models of the acceleration phase are given by Equations 6 and 7. The R^2 value for Equation 6 (the distance traveled while accelerating) is 0.91. The R^2 value for Equation 7 (the increase in speed during the acceleration) is 0.96. The effects for the TCD indicator in Equations 6 and 7 are given in Table E-2.

$$D_{Accel} = -174 + 0.64L_{Tan} + 8.6Potential + TCD \quad 6$$

$$\Delta_{Speed_{Accel}} = -8.04 + \frac{22L_{Tan}}{10,000} + 0.56Potential + \frac{1.3(L_{Tan})(Potential)}{10,000} + TCD \quad 7$$

where

- D_{Accel} = distance traveled (ft) before reaching the maximum tangent speed.
 $\Delta_{Speed_{Accel}}$ = increase in speed (mph) during the acceleration phase.
 L_{Tan} = tangent length (ft).
 $Potential$ = potential speed increase (mph) based on the difference between the driver's desired speed and the initial speed on the tangent.
 TCD = influence of a supplementary device (from Table E-2).

Table E-2. TCD Effects for Equations 6 and 7

TCD	Effect for Equation 6 (ft)	Effect for Equation 7 (mph)
Delineators	-76	-0.7
Large Arrow sign	-81	-1.9
Chevrons	-137	-1.3

The models represented by Equations 6 and 7 indicate that, like the warning signs, the vertical TCDs placed within the curve encourage drivers to end the acceleration phase earlier, not having reached as high a speed as they likely would have if no devices were present. The effect ranges from approximately 75 to 140 ft of distance and 0.7 to 1.3 mph of acceleration. It was mentioned that the placement of a warning sign hundreds of feet in advance of a curve may actually lead to a difference of only 140 ft when the deceleration phase begins. The devices at the curve that supplement the warning sign are also visible at a great distance, and the overall effect on the operational response (when compared to curves with only advance warning signs) ranges from approximately 75 to 140 ft.

Equations representing measures of the deceleration phase are provided in Equations 8 (the total change in tangential speed) and 9 (the maximum deceleration rate on the tangent). The R² value for Equation 8 is 0.80. The R² value for the model in Equation 9 is 0.70. The effects for the use of a supplementary TCD in the curve are provided in Table E-3.

$$\Delta_{Speed_{Tan}} = -17.1 + 0.42Speed_{Max} + \frac{1187}{R} + TCD \quad 8$$

$$Decel_{Rate_{Tan}} = 2.0 + 0.24\Delta_{Speed} + TCD \quad 9$$

where

- $\Delta_{Speed_{Tan}}$ = decrease in speed (mph) in advance of the curve.
- $Decel_{Rate_{Tan}}$ = maximum observed deceleration rate (ft/s²) on the tangent.
- $Speed_{Max}$ = distance (ft) from the curve when deceleration begins.
- R = curve radius (ft).
- TCD = influence of a supplementary device (from Table E-3).
- Δ_{Speed} = total speed differential (mph) observed at the curve.

Table E-3. TCD Effects for Equations 8 and 9

TCD	Effect for Equation 8 (mph)	Effect for Equation 9 (ft/s ²)
Delineators	2.3	-0.46
Large Arrow sign	2.7	-0.13
Chevrons	2.5	-1.29

The estimates for the effects of TCDs in Equations 8 and 9 suggest that drivers tend to respond to delineators, Large Arrow signs, and chevrons with greater changes in speed (approximately 2.3–2.7 mph) in advance of the curve. Of particular note is that the maximum

observed deceleration rate is reduced (approximately 0.5–1.3 mph) when the TCDs are used. Greater total deceleration and a reduced maximum deceleration rate are possible because drivers begin decelerating earlier (as suggested by Equation 6, which indicates where the acceleration phase ends). Additionally, it is possible that when the TCDs are not used, the maximum deceleration rate is greater because drivers are more likely to make a last-minute maneuver to decelerate to an appropriate speed for navigating the curve.

The measures of driver behavior within the curve are modeled in Equations 10 through 12. The speed at the PC (Equation 10), the maximum observed deceleration rate (Equation 11), and the maximum observed lateral acceleration rate (Equation 12) include indicator effects for the supplementary TCDs used in the curve. The R^2 values for the models in Equations 10–12 are 0.81, 0.54, and 0.49, respectively.

$$Speed_{PC} = 17.1 + 0.58Speed_{Max} - \frac{1187}{R} + TCD \quad 10$$

$$Decel_{Rate_{Curve}} = 2.29 + 0.19\Delta_{Speed} + TCD \quad 11$$

$$Accel_{Lat} = 0.31 + 0.038 \ln \frac{I}{R} + TCD \quad 12$$

where

- $Speed_{PC}$ = speed (mph) at the PC.
- $Decel_{Rate_{Curve}}$ = maximum observed deceleration rate (ft/s²) in the curve.
- $Accel_{Lat}$ = maximum observed lateral acceleration (g) in the curve.
- $Speed_{Max}$ = maximum tangential speed (mph).
- R = curve radius (ft).
- TCD = influence of a supplementary device (from Table E-4).
- Δ_{Speed} = total speed differential (mph) observed at the curve.
- I = deflection angle (deg).

Table E-4. TCD Effects for Equations 10–12

TCD	Effect for Equation 10 (mph)	Effect for Equation 11 (ft/s ²)	Effect for Equation 12 (g)
Delineators	-2.3	-0.93	-0.018
Large Arrow sign	-2.7	-0.85	-0.0098
Chevrons	-2.5	-0.94	-0.026

There is a notable connection between the models in Equations 8 and 10. The change in speed from the maximum approach speed to the curve entrance and the speed at the curve entrance are modeled with the same parameters and the same data, so the parameters have the same estimated effects. TCDs support an additional 2.3- to 2.7-mph deceleration. The model of the maximum observed deceleration rate within the curve suggests that the use of TCDs can decrease the deceleration rate by almost 1 ft/s². Also, there are noticeable reductions in lateral acceleration attributed to the use of TCDs. The consistency in the effects of TCDs at reducing the rates of deceleration or lateral acceleration should not be surprising considering the lower

overall speed estimated at the PC, especially considering the direct connection between speed and lateral acceleration.

Raised Pavement Markers

RPMs were installed at select curves in Idaho and Oregon for the second half of the participants in the study. RPMs were not found to significantly affect driver behavior in almost all tested models. The two cases for which the effects of RPMs are significant are the models of the maximum deceleration rate on the tangent and the maximum deceleration rate in the curve. The models are provided in Equations 13 and 14.

$$Decel_{Rate_{Tan}} = 0.45 + 0.23\Delta_{Speed} - 0.18I_{RRPMs} \quad 13$$

$$Decel_{Rate_{Curve}} = 0.72 + 0.19\Delta_{Speed} - 0.23I_{RRPMs} \quad 14$$

where

- $Decel_{Rate_{Tan}}$ = maximum observed deceleration rate (ft/s²) on the tangent,
- $Decel_{Rate_{Curve}}$ = maximum observed deceleration rate (ft/s²) in the curve,
- Δ_{Speed} = total speed differential (mph) observed at the curve, and
- I_{RPMs} = indicator for RPMs (1 = present, 0 = not used).

The effects of RPMs on the deceleration rates are quite small, but the data used to generate the models were collected at curves that are quite gentle in comparison with the curves used in the analyses of the other supplementary devices. When considering the deceleration experienced at these gentle curves, the small effects of the RPMs are worth noting. It is interesting that, even though the RPMs were found to significantly affect deceleration rates, there were no significant effects on some of the related measures, such as the characteristics of the acceleration phase or the speed at the PC.

SUMMARY AND DISCUSSION

The operational effects of warning signs and supplementary in-curve devices were tested in multivariable mixed models whose main effects are geometric and operational factors and the TCDs used at the curves. The analyses were conducted using datasets of observations at curves with characteristics within defined ranges that reduce the potential for bias from other conditions. The models were constructed in a way that identifies in terms as simple as possible the strong influence geometry has on operational behavior, as well as the smaller effects of TCDs. Even though the dependent variables were operational characteristics, most models included as an independent variable some other operational statistic, showing that driver behavior at one moment is strongly influenced by the driver's previous or future actions.

Drivers were found to respond to curve warning signs by ending the acceleration phase earlier (by approximately 140 ft), which results in reduced approach speeds (approximately 3 mph). Based on the data modeled, drivers tend to have a greater deceleration rate in advance of

the curve when a warning sign is used (approximately 0.5 ft/s^2) and enter curves 1 mph slower. The curves used in the analysis of warning signs were relatively gentle—none of them experienced total speed changes greater than 10 mph on average. From the analyses of the vertical in-curve devices (which were tested at more-severe curves), drivers tend to complete the acceleration phase earlier (75–140 ft) and with reduced approach speed (1–2 mph) when delineators, Large Arrow signs, or chevrons are used. With these TCDs, the drivers enter the curves at a slower speed (approximately 2.5 mph) despite having a reduced deceleration rate that is attributed to the devices. The resulting behavior within the curve is more conservative. The effects of RPMs were generally small and not observed in all stages of curve negotiation. The only observable responses to RPMs were slightly reduced deceleration rates.

To interpret the effects of the TCDs, it is important to understand the context under which they were evaluated. The current guidelines in the MUTCD require advance warning signs when the speed differential at a curve is 10 mph or greater; chevrons or a Large Arrow sign are required for speed differentials of 15 mph or greater. There is no guideline specifying the conditions for which delineators or RPMs should be used. Delineators were applied in this study at curves that were comparable to those treated with chevrons or Large Arrow signs; RPMs were applied at curves of lesser severity; and warning signs were evaluated at curves that seem to be on the threshold of being treated with a warning sign. Judging by a treatment's size and overall conspicuity, there may be a logical ordering of the expected magnitude of the responses to the TCDs evaluated. The effects of RPMs would be expected to be relatively small, followed by increased responses for delineators, Large Arrow signs, and chevrons. The models shown in this chapter seem to indicate that this progression of device effectiveness is reasonable, though with minor inconsistency.

By investigating the operational effects of TCDs on the tangent approach, rather than only within the curve, the models in this appendix show *how* TCDs influence driver behavior throughout the entire process of curve negotiation. The models indicate that what happens on the tangent (where drivers are receiving information about the downstream curve) affects the behavior within the curve. For example, Equation 10 indicates that vertical in-curve TCDs help reduce driver speeds by about 2.5 mph by the time the driver reaches the PC. That effect is useful information, but what may be more important is the finding that the TCDs encourage drivers to adopt slightly reduced speeds on the tangent approach and begin decelerating earlier. This observed behavior results in reduced vehicle speeds at the PC. These findings support the conclusion that curve TCDs are effective by providing drivers with information at an earlier location, which encourages them to respond to the curve earlier, thus leading to reduced speeds and more-conservative behavior near the curve.

Even though the effects of the TCDs are generally small, their influence observed on the tangent suggests that the primary benefit of TCDs at curves is not in the operational change at the curve, but in the earlier perception of information that results from their use. With information indicating where drivers begin responding to TCDs, the additional insight about driver deceleration rates and how much deceleration naturally occurs before entering the curve can be used to then determine whether or not a TCD is needed at the curve. Many of the models presented in this appendix show that TCDs are effective because they result in a desirable change in driver behavior. Effectiveness alone, however, should not be what determines policy that requires the use of a TCD. The recommended guidelines for selecting TCDs, presented in Chapter 6, discuss how the characteristics of driver behavior and the effects of TCDs can be combined to determine whether or not a curve has a need for TCDs. That need should be based

on whether or not drivers are given the right information at the right place and time, ensuring that they are able to make a natural and comfortable maneuver leading up to the curve.

Appendix F: Visual Behavior and Attention of Drivers Negotiating Curves

This appendix details the analysis of eye-tracking data collected during the unfamiliar driver behavior study. The results include patterns that show how visual attention changes while drivers approach curves and models indicating how TCDs may influence these changes. Driver visual attention in this appendix is characterized not only by how the driver views the forward scene, but also by physiological measures obtained through eye-tracking technology. These changes are indicative of the driver's workload. The analysis of operational data in Appendix E suggests that TCDs overall have a subtle influence on driver behavior, but that they begin affecting drivers several hundred feet in advance of the curve. The effects on driver attention should also be noticeable far from the curve because drivers must first perceive information before responding to it.

BACKGROUND

Since drivers tend to fixate on the objects they consider to provide the most important information at that moment, it was determined that eye-tracking cameras would provide useful data about the attention of drivers throughout the tasks associated with navigating curves. Modern technology provides the researcher with more information than just the driver's fixation location. Multiple physiological measurements, including the pupil size, eye closure, and blink rate, can be used to provide more insight into the driver's cognitive state than the fixation location alone. While metrics associated with these data have been used in previous research, their applicability in understanding driver behavior at curves was not realized until the data were analyzed.

The study was carried out and the data reduced as documented in Appendix D. A total of 103 study participants navigated one of three unfamiliar highways in the three states while eye-tracking cameras collected continuous data on where drivers were fixated and physiological measures of pupil size, eye closure, and blink rate. The following independent variables associated with the highway alignment and curves are used in models to identify the effects on visual attention:

- Radius (ft).
- Deflection (deg).
- Approach tangent length (ft).
- TCDs present at the curve.

To make full use of the eye-tracking data, several performance measures were developed from the raw data, which have the potential to provide better insight into the processes associated with perceiving and responding to information while navigating curves. The following are the measures of visual attention that were used as dependent variables:

- Average fixation location (horizontal and vertical components of fixations).
- Distance traveled downstream from a curve until the pupil is contracted.
- Magnitude of pupil contraction.

- Distance before the downstream curve when the pupil is dilated.
- Magnitude of pupil dilation.
- Distance traveled downstream from a curve until the eyes reach maximum closure.
- Magnitude of eye closure.
- Distance before the downstream curve when eyes reach minimum closure.
- Average blink rate.

By showing changes in cognition throughout the process of navigating curves, the findings discussed in this appendix suggest that drivers rely on the information provided in a timely manner to make correct decisions regarding their operational behavior at curves.

METHODOLOGY

The measures of visual attention were compiled over 4-s intervals at 100-ft increments along the approach tangent to the study curves. Like the analyses of operational performance, the analyses of visual attention employ multivariable mixed linear models that estimate the fixed effects of geometric factors and the TCDs (if any) used at the curves. Participant drivers are incorporated as random effects. The data in the analyses of each TCD were from the same subsets of segments and curves that were used in Appendix E, with descriptive statistics repeated in Table F-1.

Table F-1. Characteristics of Curves in Driver Behavior Analyses

General Statistics	Analysis Group		
	Curve Signs	Chevrons, Large Arrow Sign, and Delineators	RPMs
Number of curves	61	40	22
Total observations	1,498	555	547
Radius (ft)	420-1,985	55-860	515-1,430
Deflection (deg)	22-99	27-90	23-150
Tangent length (ft)	190-1,535	209-2,820	192-1,530
Observed speed change (mph)	0-9.6	5.8-41	0.8-9.4

Several models investigating relationships between the listed independent and dependent variables were developed. It was found that the raw magnitudes of the physiological measures (pupil size, eye closure, or blink rate) could not be modeled with variables of geometry or the use of TCDs. It was hoped that models investigating where the driver is located on the tangent at the time of an observed attentional change would indicate when drivers cognitively process the information obtained from TCDs. Unfortunately, the data were too noisy to identify some of those specifics as well. One statistical model was developed that predicts with reasonable accuracy the location of the driver's fixation while approaching a curve of a given radius. There were no significant effects of TCDs.

Despite the difficulty developing suitable models that identify how TCDs influence driver cognition, there is still value in understanding some of the patterns observed in the eye-

tracking data, even if the investigated relationships lack significance. Although the data are noisy, the patterns help illustrate the cognitive and visual processes of negotiating curves and the role TCDs may play in those processes. Preliminary investigations found that the patterns were very dependent upon the length of the tangent, likely because drivers are able to relax cognitively on long tangents while there are no apparent hazards. The illustration of the data was thus limited to curves with approach tangents longer than 1,000 ft. Of the 36 curves with tangents longer than 1,000 ft, 22 are directed to the left and 14 to the right.

There were 519 total observations of drivers approaching and navigating these curves. The patterns are presented in the following “Results” section, with the single model for the location fixation.

RESULTS

The operational analyses presented in Appendix E detail driver behavior in each of the three phases of negotiating curves: the acceleration after exiting a curve, the deceleration before a curve, and the actual navigation within the curve. The patterns shown in this section are not split into such phases but show the observed metric along the entire approach and through the curve. Each subsection focuses on a single measure of visual attention. The patterns in each figure are based on averages

Fixation Location

It is expected that the location where drivers fixate will change as they approach and navigate curves because the information obtained during that process will come from different sources. The horizontal and vertical components of the fixation location are analyzed separately.

Horizontal Displacement

Figure F-1 shows the average horizontal displacement of driver fixations as drivers approach and navigate curves in different directions. The average was based on all drivers at each 100-ft increment for the curves in either the left or right direction. The angular displacement shows that driver fixations tend to be slightly off-center to the right when far away from curves, but then begin moving more in the direction of the curve as the driver gets closer to the curve. The X axis of the figure represents where the driver is at the start of a 4-s interval over which the displacement data were averaged. The shaded areas in Figure F-1 represent one standard deviation of the data.

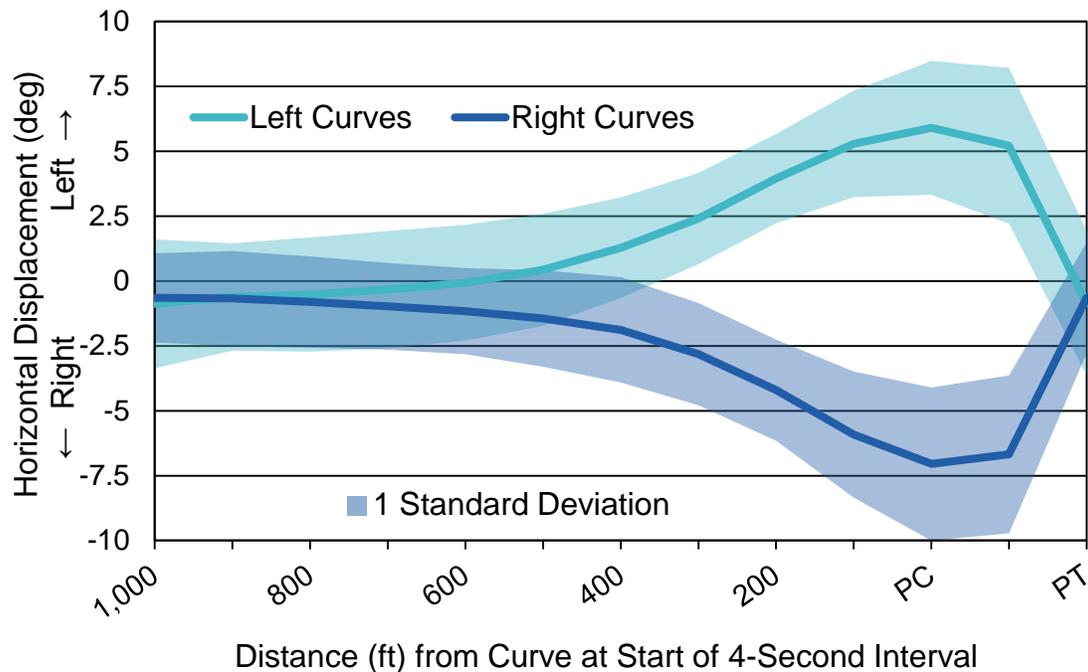


Figure F-1. Average horizontal gaze displacement by distance from curve.

Even though TCDs were not found to significantly impact the horizontal displacement of fixations, models of the effects of geometry are useful because they can indicate the location where drivers begin to respond visually to the curves. From Figure F-1, it appears that the visual response begins around 600 or 700 ft from the curve, based on the split of the average fixation location by direction. In order to declare that the driver is visually responding to the curve, there must at least be a noticeable effect of curve *direction* on the fixation displacement; additional influence from the specific geometry is desirable. The structure of a model that accounts for curve direction and geometry is shown by Equation 1. The model is a piecewise function, estimating the average horizontal displacement for the data at each 100-ft interval up to the curve, rather than using a continuous variable for distance, which may have been impossible considering the shape of the displacement in Figure F-1.

$$Hort. Displacement = \beta_0 + Direction \times \left(\beta_1 \times I_R + \frac{\beta_2}{R} \right) \quad 1$$

where

- Hort. Displacement* = horizontal fixation displacement (deg).
- β_0 = intercept.
- Direction* = indicator for direction {Right = +1; Left = -1}.
- β_1 = estimate for right curve indicator.
- I_R = indicator for right curve {Right = +1; Left = 0}.
- β_2 = estimate for effect of geometry.
- R = radius (ft).

Estimates for the parameters of Equation 1 are given in Table F-2. The parameters in the table are in bold text when significant, indicating that they affect the horizontal fixation displacement when the driver is at that location.

Table F-2. Multivariate Model of Horizontal Gaze Displacement (Curves without Supplementary TCDs)

Distance (ft) from Curve	β_0 (Intercept)	β_1 (for Right Curves)			β_2 (Geometric Effect)		
		Effect	t-Ratio	Prob> t	Effect	t-Ratio	Prob> t
1,000	-0.01	1.82	1.59	0.11	-332	-1.23	0.22
900	0.40	1.63	1.22	0.22	-296	-0.94	0.35
800	0.99	0.008	0.02	0.99	132	2.35	0.020
700	0.80	-0.13	-0.23	0.82	103	1.46	0.145
600	0.39	0.78	1.65	0.10	71.9	1.13	0.26
500	-0.27	2.0	5.15	<0.0001	8.01	0.15	0.88
400	-1.24	3.63	11.4	<0.0001	-54.6	-1.22	0.22
300	-2.48	5.52	19.2	<0.0001	-33.7	-0.80	0.42
200	-4.04	8.62	28.7	<0.0001	89.3	2.09	0.038
100	-4.83	10.8	29.4	<0.0001	550	10.7	<0.0001
0	-4.93	11.4	27.7	<0.0001	845	14.6	<0.0001

Note: Values in **Bold** indicate the parameter is significant at that location.

The value of the models with parameters provided in Table F-2 is not in the actual effects of the parameters but in identifying where the driver is when the effect becomes significant. As the driver gets closer to the curve, the ability to estimate the horizontal gaze displacement improves. The direction of the curve (with estimate β_1) becomes significant at 500 ft before the curve, and the geometry (1/radius, with estimate β_2) becomes significant at 200 ft before the curve. Figure F-1 suggests that the direction of average fixation splits near 700 ft in advance of the curve. Because of the variability in the data, however, direction is not a significant factor until 500 ft.

When interpreting these results, it must be recognized that the location data represents where the vehicle was at the start of the 4 s over which the data were averaged. It was found that driver gazes are influenced by the direction of the curve for the 4 s of data that begins 500 ft from the curve. Depending on the individual speed of the driver, those data may more likely represent an average location of 350 ft from the curve (factoring in approximately 50 mph for 2 s). A distance of 350 ft is not substantially different from other studies of where drivers look that involved curve detection.

Vertical Displacement

The vertical displacement of fixations is indicative of how far in front of the vehicle the drivers are viewing the forward scene. The viewing distance increases as vertical displacement increases. Without analyzing the exact position and orientation of the eye-tracking cameras and drivers, it is impossible to translate the vertical displacement angle to actual viewing distance. The general trends are still valuable. Figure F-2 shows the average vertical displacement of fixations for drivers approaching and navigating the same curves used in Figure F-1. One clear

observation about Figure F-2 is the variability in the vertical displacement, indicated with the shaded standard deviations. The average value is quite small compared to the standard deviation. It appears that the average preview distance begins to increase around 800 ft before each curve, likely indicating a change in visual behavior while approaching the upcoming curve, but it is difficult to definitively state so simply from visual inspection. No statistical analyses identified useful patterns in the vertical displacement data.

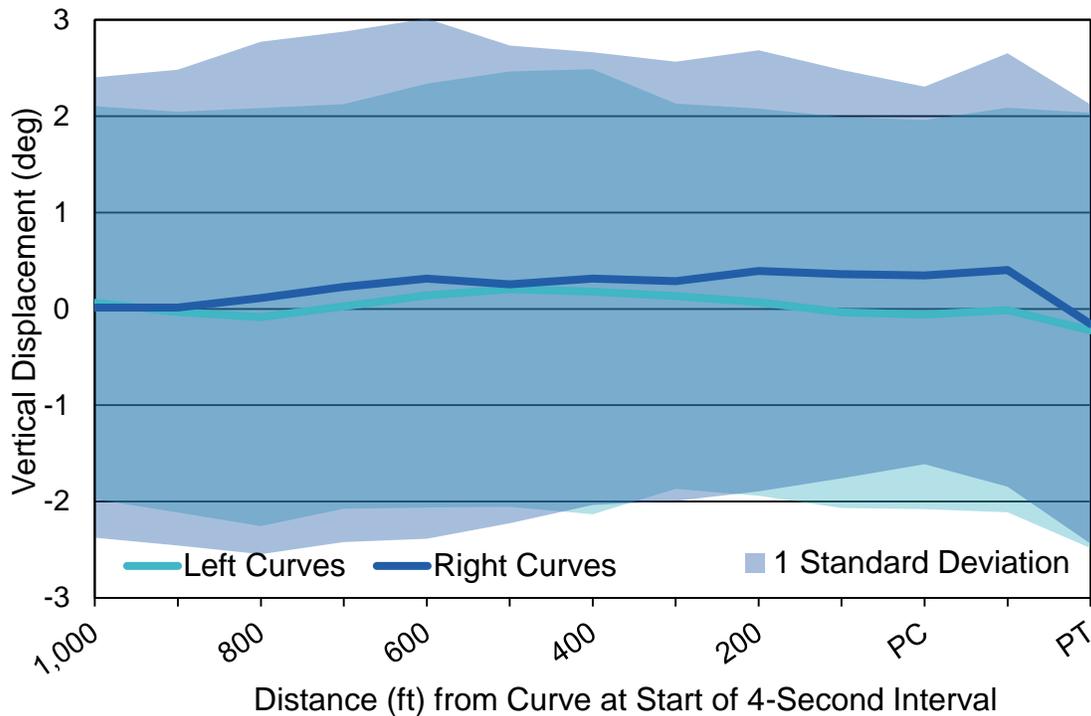


Figure F-2. Average vertical gaze displacement by distance from curve.

The horizontal fixation component in Figure F-1 is primarily controlled by the direction of the curve, and it would be expected that drivers do not allow their gazes to vary much outside of the roadway alignment. Regarding vertical displacement, previous research has shown that drivers alternate between near- and far-field fixations, even at curves (1). Patterns of drivers alternating between different preview distances were evaluated by Zwahlen (2) who found no consistent or preferred pattern. This may explain why the average vertical fixation displacement shown in Figure F-2 is more difficult to characterize than the horizontal displacement. Ultimately, there is a limit to how much can be interpreted from an average of fixations.

Another contribution to the difficulty in examining the fixation location is that drivers tend to scan an entire area with overall quick fixations, rather than concentrating on an isolated point. Figures F-1 and F-2 show averages of the fixations of drivers compiled over 4 s, but a reader may incorrectly interpret that the figures identify the actual fixation location. Once a driver obtains the relevant information (and, if necessary, makes additional fixations), there is no need to continue fixating on it. Research by Zwahlen (3–5) found this to be true for signs, showing that drivers do not fixate on signs for long periods of time. Repeated fixations along the alignment, however, are necessary because the driver is anticipating changes.

Pupil Diameter

As a physiological and involuntary response, changes in pupil size reflect cognitive processes of a driver. The task-evoked pupillary response is a measure of cognitive load. For drivers, pupil dilations are indicative of the workload associated with performing search tasks and anticipating and carrying out driving maneuvers. There are multiple ways to characterize the response, such as the latency to peak dilation or the magnitude of the dilation. One of the complexities of the pupillary response in this study is that the stimulus (the information about the curve from the TCDs) is not presented to the drivers at a uniform time. Drivers have unique visual abilities and priorities regarding the objects that are the targets of their fixations. Rather than suddenly being presented with a stimulus or task, TCDs gradually come into view as the drivers approach the curve.

Figure F-3 shows the difference between the drivers' measured pupil and their respective average diameters, averaged over the 36 curves which were also used in Figures F-1 and F-2. There is no differentiation for curve direction. The shaded area represents one standard deviation of the data for that location. There is a substantial amount of variability, and the overall average change seems small, but that is expected with so many curves and drivers. In Figure F-3, the eyes begin to dilate several hundred feet in advance of the curve in preparation to navigate it, which is near the location where the fixations started to change in Figures F-1 and F-2. The average pupil diameter reaches a peak near the entrance of the curve and then contracts toward the end.

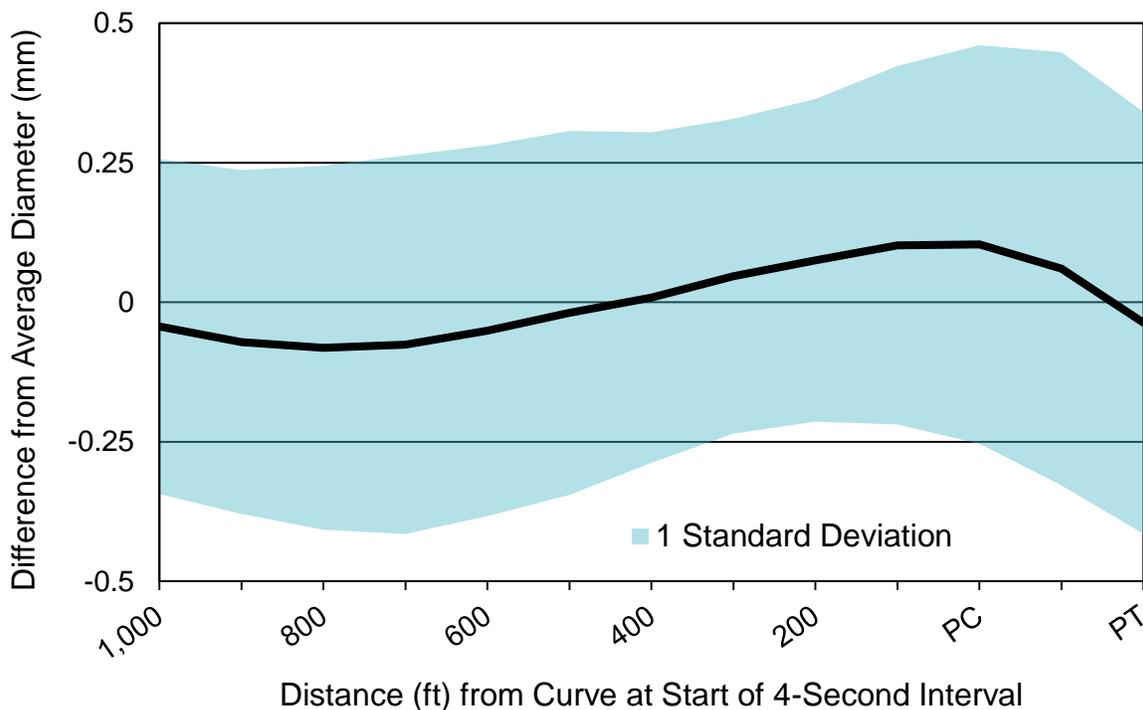


Figure F-3. Average difference between the participants' measured and average pupil diameters (mm).

Like the previous figures, Figure F-3 represents an average of multiple participants at multiple curves (a total of 321 observations, which is fewer observations than those evaluated for the fixation location due to difficulty measuring some participants' pupils). While Figure F-3 shows a quasi-sinusoidal pattern with total average change in diameter near 0.2 mm, the experience of an individual driver at a single curve may be quite different. The pupils of each participant at each curve may dilate earlier or later than what is shown here and with a different magnitude. The experience of an individual driver is thus overshadowed by the average for many participants. Individual changes were often between 0.2 and 1.0 mm, which are consistent for the task-evoked pupil response in previous work. Models testing relationships among curve geometry, TCDs, and changes in pupil size were quite weak.

Eye Closure

Eye closure is a measure of the amount of the eye covered by the eyelid, given as a percentage, and is investigated in this research as a measure of alertness. Figure F-4 shows the pattern of the difference between a driver's actual eye closure on a segment and average eye closure throughout the experiment. The trend in Figure F-4 shows the eyes becoming wider (less closed) as the driver approaches the curve. Although there is substantial variability shown in the figure, the eyes are (on average) closed the most in the 4-s interval that starts 800 ft before the curves. Similar to pupil size, the change in eye closure shows a period of increasing attention as the driver approaches the curve; the fastest changes occur starting at 400 ft from the curve, and the eyes are widest at the PC. There is a period of relaxation upon exiting the curve, when the eye becomes more closed. As with the pupil size, models investigating the relationship between geometry, TCDs, and measures associated with eye closure proved to be very weak.

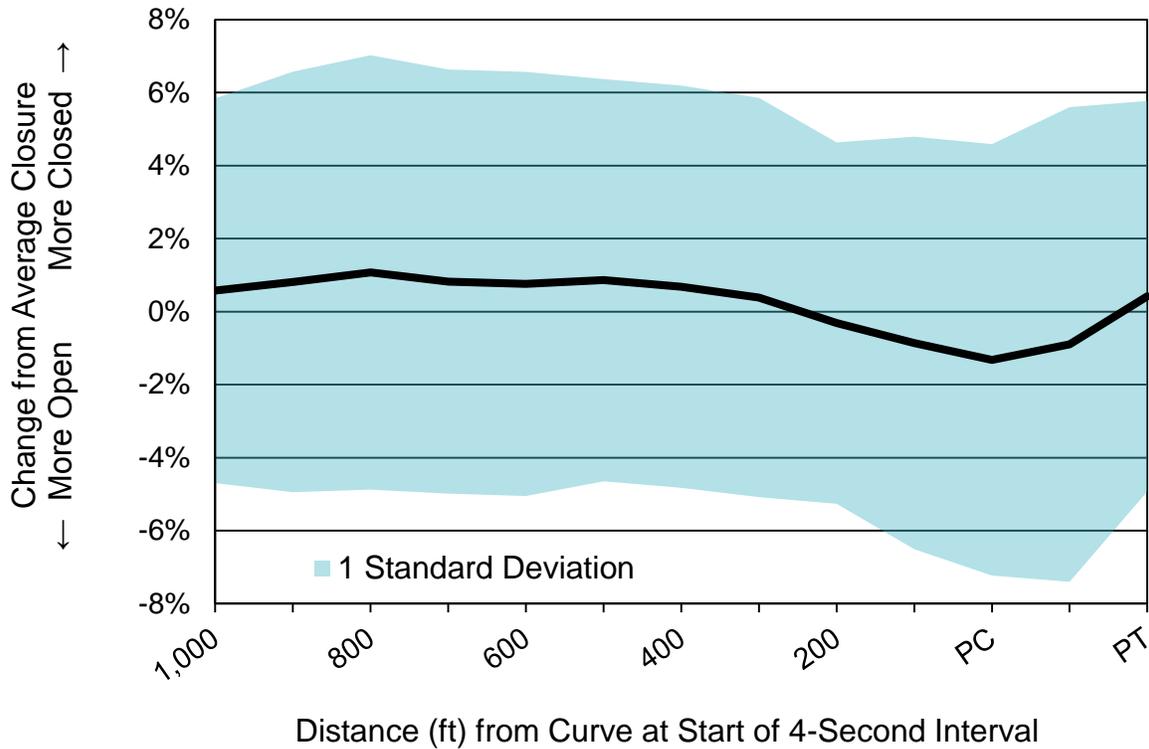


Figure F-4. Difference between measured eye closure and average eye closure by distance from curve.

Blink Rate

Blinks are recorded by the eye-tracker as binary occurrences through time, either as a 1 or a 0 to indicate that a subject is blinking or not blinking. By totaling the number of blinks over a 4-s interval, the blink rate (over 4 s) becomes more like a continuous metric. The variable is still difficult to use because it is not normally distributed within a reasonable range for each participant like the pupil size (3–7 mm) or eye closure (20–80 percent). Some drivers may go several seconds without blinking (blink rate = 0) or may blink quite frequently.

Like the pupil size and percent eye closure, each person has a unique blink rate when under normal and relaxed conditions. Previous research has shown that blink rate decreases when a person is under additional workload. A decrease in blink rate is thus expected as the driver approaches the curve. Figure F-5 shows the average blink rate observed for the participants as they approached curves starting at an approach distance of 1,000 ft, using an average of 434 observations for each data point. One standard deviation is also shown as shaded. Due to the variability of the blink data, no further analyses were investigated; however, the average pattern is still useful as an illustration of the overall changes in attention.

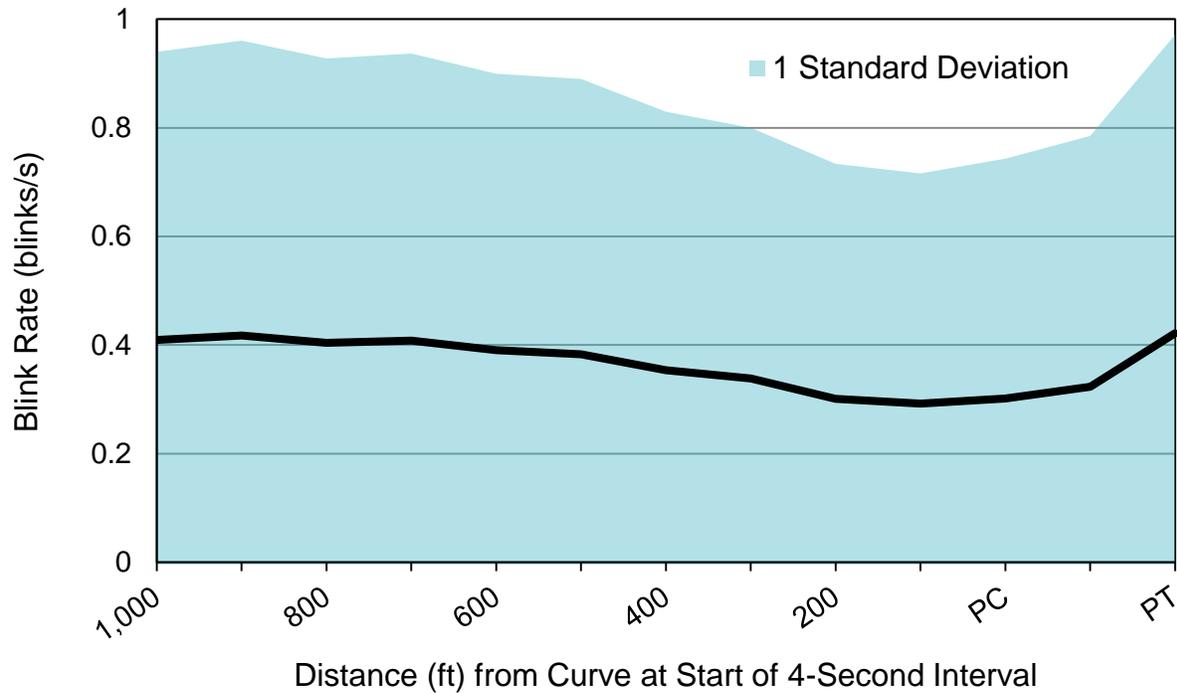


Figure F-5. Average blink rate by distance from curve.

SUMMARY AND DISCUSSION

The patterns shown in Figures F-1 through F-5 indicate that there are visual and cognitive changes that occur several hundred feet in advance of a curve. Under natural driving conditions, such changes are initiated only because drivers perceive information about an upcoming curve, whether or not from a certain device. Although several models were investigated, it was difficult to identify any substantial effects of TCDs on the metrics of visual attention used in this study. Based on the single model of horizontal fixation displacement, it can be said that curve geometry alone influences visual behavior beginning approximately 350 ft in advance of the curve. The average fixation location is determined mostly from the guidance provided by pavement markings, and the value of 350 ft is reasonable considering the research identifying where drivers are able to detect changes in alignment by using pavement markings alone.

The results of the visual attention analyses were less robust than those of operational performance, simply due to variability in the data. Even though the specific effects of TCDs are difficult to identify in this effort, the patterns show that drivers cognitively begin preparing to navigate a curve several hundred feet before reaching it. The operational side of this preparation is documented in Appendix E, and those results were able to include substantial effects of TCDs. Despite the unexpected lack of significance in some of the measures derived from the eye-tracking data due to the level of noise, it can be emphasized that a cognitive response to TCDs exists, simply by asserting that an operational response cannot happen without an initial cognitive stimulus. While this study was unable to identify how much quicker drivers can acknowledge and cognitively respond to curves when TCDs are used, the findings that show

earlier operational responses indicate that such an impact on cognition exists. It just may not be found with the current technologies or methodologies used in this study.

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Appendix G: Description of the Safety Analysis

This Appendix documents the study protocol of the crash-based analyses using data collected in four states: Florida, Ohio, Oregon, and Tennessee. The data were collected to identify the effect of TCDs on crashes at curves. The results of the analyses are presented in Appendix H.

OVERVIEW

A crash-based study was undertaken to identify the effects of various curve-related TCDs on crash frequency and severity. Warning signs in advance of horizontal curves and in-curve signs were considered in the analyses. Separate analyses were undertaken for isolated and series curves. Isolated and series curves were defined by the status of their existing horizontal alignment signs and the distance separating successive curves. Separate analyses were also undertaken for advance and in-curve warning signs. The following warning signs were directly considered in the crash-bases analyses:

- Advance Isolated Horizontal Alignment signs:
 - W1-1: Turn sign.
 - W1-2: Curve sign.
- Advance Series Horizontal Alignment signs:
 - W1-3: Reverse Turn sign.
 - W1-4: Reverse Curve sign.
 - W1-5: Winding Road sign.
- In-curve Horizontal Alignment signs:
 - W1-6: One-Direction Large Arrow sign.
 - W1-8: Chevron Alignment sign.

The presence of pavement markings (center and edge line), RPMs, and post-mounted delineators were noted and considered in the analyses, but were not the primary focus of the analyses. For curves with advance warning signs, the presence of advisory speed plaques and the suggested speed reduction (i.e., difference between posted speed limit and posted advisory speed) were also considered.

Prior to 2009, the MUTCD allowed “engineering judgment” to determine the need for a horizontal alignment warning sign and a posted advisory speed. Specific guidance was provided for the use of Curve versus Turn signs and isolated versus curve series warning signs, but there was limited guidance on when to consider the use of these signs. Additionally, no direct guidance was provided for the installation of chevrons and/or Large Arrows. This implies that a standard procedure for applying these warning signs both in advance and within curves was not used prior to 2009.

Due to the limited guidance, there is a strong chance that horizontal alignment warning signs were employed to address safety concerns such as crash frequency and/or crash severity. If this assumption holds true, then it can introduce selection bias and would need to be properly

addressed in the analysis. The assumption that treated sites are fundamentally different from untreated sites was tested by comparing summary statistics for site characteristics between the groups and performing propensity score analyses. This was done separately for isolated curves and for series curves. The assumption was confirmed and required the use of specific methods to account for those differences.

A cross-sectional study design was employed to analyze the safety effect of horizontal alignment warning signs. Data were collected in four states (Florida, Ohio, Oregon, and Tennessee) at sites with varying levels of warning sign treatments, including no signs present. Propensity score matching was used to match sites with and without horizontal alignment warning signs to mimic a randomized design experiment. Multivariate regression models were used to estimate the safety effects of signs while controlling for other characteristics that vary among sites. The safety effects were established through the development of crash modification functions (CMFunctions). A CMFunction is a formula used to estimate the crash modification factor (CMF) for a site (e.g., a horizontal curve) based on its characteristics (*I*). Safety effects were not found to be uniform for sites with different characteristics. CMFunctions allow the CMF to change over the range of a variable (e.g., traffic volumes or degree of curvature).

STUDY DESIGN

Study Questions

The primary question to be answered by the crash-based analysis was “what is the effect of various horizontal alignment warning signs on crash frequency and severity?” The specific crash types that were analyzed included the following:

- Total crashes: A non-intersection crash occurring within the influence area of a curve. The influence area includes crashes that occur between the PC and point of tangency (PT) as well as crashes within 0.1 miles upstream of the PC and downstream from the PT.
- Injury + fatality crashes (Injury): A subset of total crashes where the crash results in one or more fatalities or injuries within the influence area.
- Run-off-road crashes (ROR): A subset of total crashes where the crash involves a single vehicle leaving the roadway within the influence area.
- Adverse pavement condition crashes: A subset of total crashes where the pavement condition was anything other than dry (e.g., wet pavement) within the influence area.
- Night-time crashes: A subset of total crashes where the crash occurs at night within the influence area.

In answering the primary question, it was desirable to determine how the safety effect was dependent upon several roadway design and operation factors, including traffic volume, posted speed limit, curve radius or degree, lane and shoulder width, and roadside hazard rating.

Study Considerations

The following issues were explicitly addressed during the design and conduct of the safety evaluation to ensure the analysis was of sufficient quality and provided a reliable estimate of the potential safety effects:

- Measure of effectiveness: It is preferred to use direct measures of safety effectiveness, including crash frequency and severity. This study employed a crash-based analysis to evaluate the safety impacts of horizontal alignment warning signs on curves.
- Exposure: Crash frequency alone does not provide adequate information to determine the effectiveness of a particular treatment. Exposure must be considered as well. In this study, the exposure at each location was the traffic volume and the length of the curve.
- Sample size: The total number of crashes was the primary measure of sample size (not sites or years). However, it was necessary to include a sufficient number of sites and/or years in the study to identify an adequate sample of crashes for each analysis. Sample size was considered explicitly as described in the Sample Size Estimates section.
- Confounding factors: There are several roadway characteristics (e.g., geometry and traffic operations) as well as external factors (e.g., land use and weather) that can influence driver behavior and ultimately safety. A list of potential confounding factors was developed based on previous research related to geometric design, traffic operations, and curve safety (see Data Collection for further details).
- Site selection bias: In highway safety, sites are often selected for treatment based on need (i.e., those sites with the greatest crash frequency, crash severity, or potential for improvement are addressed first). If these are the only sites selected for analysis, then the results will only apply to sites with similar issues or “need.” Similarly, sites could be included in a study based on the perceived risk (e.g., sites with severe curvature); however, this would also limit the applicability of the results to sites with similar issues. The sampling methods employed in this study included a range of curve radii, curve length, and horizontal alignment warning signs to maximize the applicability of the results. Additionally, the propensity for curves to receive horizontal alignment warning signs based on site characteristics and crash history was considered through statistical modeling techniques.
- Regression-to-the-mean (RTM): RTM is the tendency of sites with abnormally high or low crash counts to return (regress) to the usual mean frequency of crashes during the following years. In some cases, it may be desirable to include sites with relatively high annual average crash frequency to increase the sample size, but RTM bias will arise if sites are selected for study based on crash history (i.e., a randomly high short-term crash count). The sampling method used for this study was based on the applicability (i.e., presence or absence of horizontal alignment warning signs) of the sites, and not on crash history. Multiple years of data were included for each site, helping to account for the random variation in annual crash frequency.
- Crash data quality: The lack of uniformity, timeliness, and general quality in crash data among jurisdictions was considered in the study design and analysis. The study team worked with the participating state and local agencies to identify crash reporting criteria and any limitations or changes in their crash data. The reporting thresholds for each state are as follows:
 - Florida: personal injury or \$500 property damage (in some cases crashes are reported for less than \$500 property damage).
 - Ohio: personal injury or \$400 property damage (in some cases crashes are reported for less than \$400 property damage).
 - Oregon: personal injury or \$1,500 property damage.
 - Tennessee: personal injury or \$400 property damage.

The use of data from Oregon adds an additional complexity regarding differences in crash data quality. Unlike other states, Oregon relies on citizen reports for data on the majority of crashes occurring on Oregon public roadways (2). This can have an impact on data quality, timeliness, and accuracy. Data quality can suffer because location information may be difficult to discern, often relying on text-based descriptions of crash locations. Additionally, citizen reports may be incomplete or have inconsistencies within a report or across reports if multiple drivers were involved in the same crash. Since the Oregon DOT relies on citizen reporting of crashes, lower severity crashes may be underreported compared to other states. This is more likely for crashes involving a single-vehicle since license restrictions can be enforced if there is only one driver reporting a multi-vehicle crash. However, higher severity crashes (especially fatal and severe injury crashes) are less likely to suffer from underreporting because they are more likely to have police reports filed in conjunction with the official crash report.

Differences in reporting thresholds and reporting practices were accounted for by including indicators for each state in multivariate regression models. For example, it was expected that Oregon would observe fewer crashes than other states due to its higher reporting threshold; the Oregon indicator would therefore have a negative value when compared to other states.

General Analytical Method

Gross et al. (1) discuss several study designs available for developing CMFs, which are shown in Figure G-1. While the current state-of-the-practice for developing CMFs is to employ an Empirical Bayes (EB) or Full Bayes (FB) before-after study design, one factor that can preclude their use is the availability of before and after data. Specifically, there may be insufficient instances where a treatment is implemented or a design feature is changed, in which case there would be few sites with “before” and “after” data, and too few observations to conduct a rigorous before-after evaluation. From the flow chart in Figure G-1, a cross-sectional study was deemed appropriate for meeting the objectives of this study. Since installation dates for horizontal alignment warning signs were unknown, a before-after study was not appropriate in this case. For this reason, a cross-sectional study design was chosen.

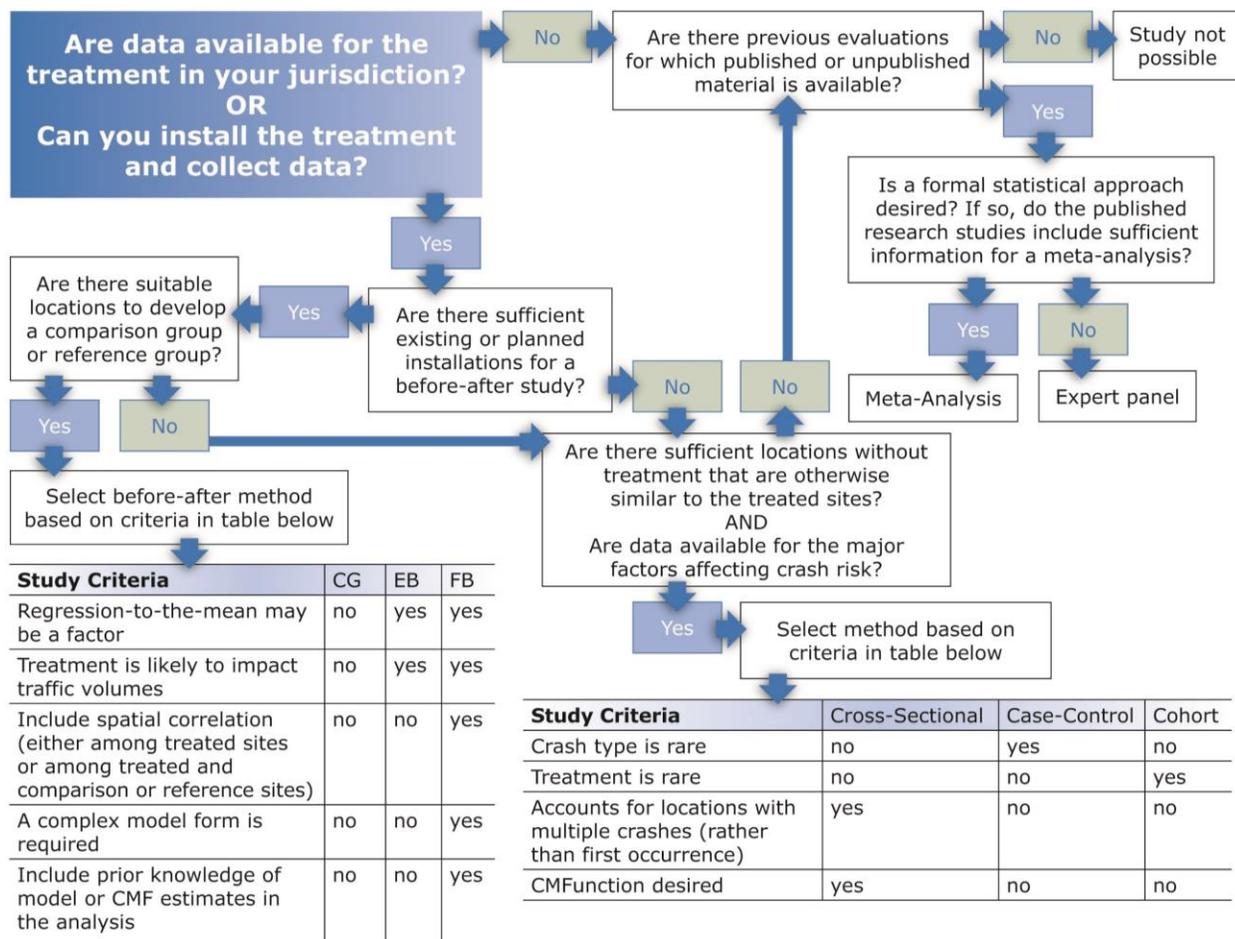


Figure G-1. Flowchart to identify applicable study design in developing CMFs (I).

The cross-sectional method is a technique in highway safety that can account for changes in traffic volume and other covariates related to crash frequency. The premise of a cross-sectional model is to estimate the safety effectiveness of a characteristic (e.g., chevrons) by considering sites with and without the characteristic or across various levels of a characteristic. This is accomplished through the use of crash prediction models. In these models, the relationship between the dependent variable (e.g., total crashes) and traffic and geometric characteristics is generally determined using count regression models.

While the cross-sectional method provides a means to estimate reliable CMFs, there are potential issues that need to be addressed. Based on the *Recommended Protocols for Developing CMFs (3)*, the following potential biases were identified in this study. The potential sources of bias are explained below with an explanation of why they were dismissed or how they were addressed.

- **Regression-to-the-mean (RTM):** RTM is the tendency of sites with abnormally high or low crash counts to return (regress) to the usual mean frequency of crashes during the following years. RTM bias arises if sites are selected for study based on crash history. The sampling method for the treated sites was not based on crash history and was instead based on applicability of the sites.

- Changes in traffic volume: Crash prediction models were developed using multiple years of data. The crash prediction models provide a means to predict crashes based on exposure (i.e., major and minor approach traffic volumes) and were used to account for changes in traffic volume over time.
- Temporal trends: Annual adjustment factors were considered to account for time trends.
- Accounting for regional differences: Data from four states were used to estimate the safety effects of horizontal alignment warning signs. As such, there is the potential for regional differences. Dummy variables were created to represent the various states and included in the analysis to account for regional differences.

Additional limitations to using cross-sectional models include the potential for site selection bias, lack of control for confounding variables, and unexplored interactions among explanatory variables included in the model (4). These limitations are further described below with an explanation of how they were addressed.

- Site selection bias: Site selection bias was identified as a concern for this study, as the Florida Department of Transportation (FDOT) noted to the research team that chevrons have historically been used as a mitigation measure for sites with a history of high crash counts. Site-selection bias can be shown through dissimilarities in curve features between the treated group and untreated group. If treated curves have different characteristics than untreated curves, the treatment effect is confounded by the differences between the curves (5). For this study, summary statistics were used to explore the traits of horizontal curves with and without specific warning signs (i.e., advance warning signs and in-curve warning signs). As the summary statistics in the next section show, there were substantial differences for treated and untreated curves in terms of degree of curve, total deflection angle, shoulder width, and speed reduction. Treated curves tend to have more severe values of these characteristics compared to untreated curves. This finding shows that one of the major requirements for cross-sectional analysis, that the two groups should be similar in all regards except for the feature of interest, is violated. The propensity score-potential outcomes framework developed by Sasidharan and Donnell (6) was used to overcome the dissimilarities of treated and untreated curves, and to determine the safety effectiveness of advance and in-curve warning signs.

The propensity score is the probability that a site will receive the warning sign given the characteristics of the site and outcomes of interest. In this case, the outcome of interest (crash frequency) cannot directly be used, since the crash frequency prior to treatment application is unknown. However, covariates related to crash frequency can be used in the propensity score model instead. Propensity scores are used to balance the covariates in the treated and untreated groups by reducing the bias due to differences in observed covariates. Propensity scores model the relationship between warning sign status and site characteristics. Since warning sign status is a binary outcome (treated or untreated), the logit model is used to estimate the propensity score. Propensity scores are used to identify homogenous treated and untreated curves to mitigate sample selection bias. The safety effect is then estimated using the count regression model (crash prediction model).

- Confounding variables: As noted in the *Study Considerations* section, there are several roadway characteristics (e.g., geometry and traffic operations) as well as external factors (e.g., land use and weather) that can influence safety. A list of potential confounding factors

was developed based on previous research related to geometric design, traffic operations, and curve safety (see *Data Collection* for further details). Confounding variables were balanced between treated and untreated groups to remove bias associated with their differences between groups. Confounding variables were included in the final model specifications to account for their safety impacts, reducing omitted variable bias.

- Unexplored interactions: Interaction effects occur when the effects of the predictor variables on the dependent variable are not additive—the effect of one predictor variable depends on another predictor variable. If the interaction effect is not accounted for in the model, then omitted variable bias occurs. However, introducing interaction terms results in models with higher correlation between predictor terms, and therefore the number of interaction terms should be limited. Interaction terms involving horizontal alignment warning sign variables were given priority for inclusion in models to determine if the effect of horizontal alignment warning signs differs across site characteristics.

DATA COLLECTION

This section presents a summary of the data collection effort in the four states. The study and data collection focused on rural two-lane highway horizontal curves.

Criteria for Inclusion

The data collection approach balanced the desire for plentiful and robust data with the constraints of time and resources available for such efforts. Data were collected in Florida (FL), Ohio (OH), Oregon (OR), and Tennessee (TN), for the reason that they could individually and collectively offer the following:

- Regional and terrain diversity. As this research effort is meant to provide guidance to practitioners across the nation, it is important that the states selected to contribute data are not exclusive to one particular part of the country and to one particular terrain type. Representing the Pacific Northwest, Midwest, and Southeast, the four selected states offer diversity to the study. In addition, data were collected across different regions within the states to better account for terrain diversity.
- Completeness, quality, and availability of crash data. There were three criteria that needed to be met in order to use a state's crash data. The state must collect most, if not all, of the required crash elements; must have a reputation for maintaining quality crash data; and must have data that can be made available to the research team upon request.
- Availability of horizontal curve inventory. It was also critical that each selected state have collected and maintained a horizontal curve inventory that can be made available to the research team upon request. Statewide curve data were made available by the selected states.
- Availability of TCD inventory. While not critical, preference was given to states that maintained a statewide inventory of sign type and location. Statewide sign data were available from Oregon and Tennessee.

Site Selection

State sign and curve inventories were used to identify potential study corridors, which were defined by routes with multiple curves. Corridors were useful for two primary reasons:

- They provide sites with some similarities (e.g., driver population, weather conditions, and temporal trends), which helps to account for unobserved effects.
- Their use expedited the data collection process, allowing the research team to identify multiple sites quickly.

Corridors included curves with varying combinations of horizontal alignment warning signs and geometric characteristics. For states with a sign inventory, a preliminary list of corridors was identified based on the number and type of horizontal alignment warning signs of interest along the corridor. Potential sites without horizontal alignment warning signs were also considered within the corridors. Once the potential sites were identified, a series of factors was checked to see if the sites were eligible for data collection. The following precluded a horizontal curve from being used in the analysis:

- A site had undergone recent and significant physical change (e.g., curve-flattening), as determined by a review of historical aerial imagery in Google Earth.
- A roadway was relatively new, having been opened since 2006. Since the crash analysis period includes data from 2009-2011, any road opened on January 1, 2007 or later would not have had a two-year acclimation period prior to the study period.
- The presence of construction activity within the study period.
- A change in TCD level within the study period. Historic video logs were used when possible to identify changes in TCDs.
- The presence of a nearby signalized or stop-controlled intersection. It was critical that vehicle speed on study curves not be influenced by the presence of other TCDs.
- A site was not in the horizontal curve inventory file or crash database.

Sample Size Estimates

The sample size required for multivariate regression models depends on a number of factors, including the following:

- Average crash frequencies.
- The number of variables desired in the model.
- The level of statistical significance desired in the model.
- The amount of variation in each variable of interest between locations.

Estimation of required sample size is an iterative process, although through experience and familiarity with specific databases it is possible to develop an educated guess. The *Highway Safety Manual* (HSM) presents a method for calibrating national crash prediction models to local conditions (7). Based on this method, 30 to 50 sites are recommended to calibrate a crash prediction model for a given facility type. These sites should not be selected on the basis of crash history, but should represent at least 100 crashes per year as a whole.

The data collection focus was for two lane roadways. Initially, assuming that each site experienced on average at least one crash per year, the minimum sample size recommended was

25 sites in each of four regions. The term “site” here refers to a single curve or curve series. The crash rate assumption was verified through initial data collection. Table G-1 presents the crash rates and estimated minimum sample size to achieve 100 crashes per year based on the initial data collection.

Table G-1. Crash Rates and Minimum Sample Size

Region	Isolated		Series	
	Rate <i>(Crashes/year)</i>	Sites	Rate <i>(Crashes/year)</i>	Sites
FL	0.58	43	0.67	37
OH	1.18	21	1.62	16
OR	0.48	52	0.64	39
TN	0.59	42	1.19	21
Total		158		113

The totals presented in Table G-1 reflect the minimum number of sites required for developing a crash prediction model. However, the data collection was expanded, based on available funds, to include more sites. In addition to the extra sites, multiple years of data were collected to further increase the sample size.

The data collection focused on horizontal curves for rural two-lane highways. The sites for each facility type and state should be reasonably representative of the range of site characteristics to which the predictive model will be applied. While no formal stratification by traffic volume or other site characteristics was employed during site selection, the team strove to identify a range of characteristics among the sites to meet the study objectives.

Data Elements

Table G-2 provides the specific data elements, with a description, for crash, roadway, and traffic/operations categories that were collected for each study location. They were either collected from databases provided by the state DOT or through video logs and Google Earth.

Table G-2. Data Elements of Interest

Data Type	Data Element	Description/Comment
Crash	Crash location	Typically consists of county, route, and milepost
	Crash date	Date of crash
	Crash type	Manner of collision
	Crash severity	Worst injury sustained during crash
	Light condition	Defined as light or dark based on police report
	Sequence of events	Events of crash listed in chronological order
	Roadway condition	Defined as dry or wet based on police report
	Vehicle type	Identifies the type of vehicle based on police report
Roadway	Area type	E.g., rural, urban
	Number of through lanes	Both directions of the major road
	Degree of curve	Degree of curve in degrees
	Curve length	Length of horizontal curve in feet
	Curvature change rate	Computed as the total deflection angle of curves in a series divided by the length of curve series section
	Proportion curve	Computed as the total length of curves in a series divided by the total length of the series
	Number of curves	Number of curves in a series of curves
	Length of upstream tangent	Measured as the average distance from PC of subject curve to PT of nearest upstream curve from both approaches
	Roadside hazard rating	Defined by categories in the Highway Safety Manual
	Lighting presence	Presence of highway lighting on the curve
	Lane width	Lane width in feet at the midpoint of the curve
	Shoulder width	Shoulder width in feet on average for the curve
	Rumble strips presence	Presence of longitudinal shoulder rumble strips
	Driveway presence	Presence of driveway within curve influence area
Intersection presence	Presence of intersection within curve influence area	
Traffic / Operation	AADT	Traffic volume including year that volume was determined in vehicles per day
	Horizontal alignment-related signs	The presence, type, and location of curve related signs
	Posted speed limit	Nearest upstream posted speed on approach of curve
	RRPM Presence	The presence of raised reflective pavement markings
	PMD Presence	The presence of post-mounted delineators
	CPM Presence	The presence of center line pavement markings
	EPM Presence	The presence of edge line pavement markings

Florida Data Collection

The Florida Department of Transportation (FDOT) provided known horizontal curve data and traffic volumes for the state highway system and crash records from 2009 to 2011. Since FDOT has relatively limited terrain, and no available sign inventory, the FDOT Horizontal Curve Database was used to identify potential corridors for data collection. There were only 46

total curves in the entire database with a degree of curve greater than 10. Once a curve was identified as being rural, Google Earth and Street View were used to obtain and verify geometric conditions and determine the level of traffic control at a site. Other sites within the corridor were then considered.

Ohio Data Collection

The Ohio Department of Transportation (ODOT) was unable to provide a sign inventory for signs in the field. However, Ohio is a participating state in the Highway Safety Information System (HSIS). The HSIS database provided crash, horizontal curve, geometric, and AADT data in a single source. Additionally, ODOT maintains an updated and historical statewide video-log inventory. Since Ohio had no available sign inventory, the HSIS curve and roadway files were used to identify potential corridors for data collection. ODOT video logs were used to identify the TCDs present in advance of and within curves. Historical and current video logs were used to determine if the TCD level had changed within the study period. No sites were found to have changed.

Oregon Data Collection

The Oregon Department of Transportation (ODOT) provided a complete set of resources for data collection, including a sign inventory, horizontal curve database, crash database, AADT data, and access to online video-logs.

Tennessee Data Collection

The Tennessee Department of Transportation (TDOT) provided a sign inventory, horizontal curve database, crash database, and AADT data. The sign inventory was used to identify a list of corridors for data collection. As with Oregon, corridors included curves with varying combinations of horizontal alignment warning signs and other characteristics. Sign presence and location, as well as roadway geometry, were verified using Google Earth and Street View.

Data Collection Summary

The data collection resulted in 271 isolated horizontal curves and 270 curve series (minimum 2 curves) across the four states. Each curve series was considered to be a site as was each isolated horizontal curve. Table G-3 displays the sites that were identified in FL, OH, OR, and TN by sign location (i.e., advance and/or in-curve warning sign). Three years of crash data (2009 to 2011) were collected for each site, resulting in a total of 813 site-years for isolated curves, and 810 site-years for series curves.

Table G-3. Number of Sites by Region and Sign Location

Type of Sign	FL		OH		OR		TN		Combined	
	Isolated	Series								
No sign	2	0	17	19	22	14	15	11	56	44
Advance	15	19	29	39	29	48	34	45	107	151
In-curve	0	0	1	0	1	0	1	1	3	1
Adv. & in-curve	13	2	32	28	30	22	30	22	105	74
Total	30	21	79	86	82	84	80	79	271	270

Consideration was also given to speed reduction, defined as the difference between the posted speed limit and the posted advisory speed, since vehicle operating speeds were unknown. If no posted advisory speed was present, then speed reduction was considered to be zero. Tables G-4 and G-5 present the number of sites by speed reduction and horizontal alignment warning sign location for isolated curves and series curves, respectively.

For both isolated and series curves, it appears from Tables G-4 and G-5 that the average speed reduction is greater for sites with both advance and in-curve warning signs, compared to curves with only an advance warning sign. There was not enough information to discern if an advisory speed plaque should be present, and it was assumed that posted advisory speeds were correct, since the advisory speed could not be checked with the available data. Table G-6 presents the number of total crashes for each State, stratified by year.

Table G-4. Sites by Speed Reduction and Warning Sign Location for Isolated Curves

Type of Sign	Speed Reduction (mph)								
	0	5	10	15	20	25	30	35	40
No sign	56	0	0	0	0	0	0	0	0
Advance	54	2	16	12	9	10	1	3	0
In-Curve	3	0	0	0	0	0	0	0	0
Advance & in-curve	18	1	16	12	18	16	9	12	3
Total	131	3	32	24	27	26	10	15	3

Table G-5. Sites by Speed Reduction and Warning Sign Location for Curve Series

Type of Sign	Speed Reduction (mph)								
	0	5	10	15	20	25	30	35	40
No sign	44	0	0	0	0	0	0	0	0
Advance	52	4	23	24	12	20	9	5	2
In-Curve	1	0	0	0	0	0	0	0	0
Advance & in-curve	12	0	3	11	14	11	11	9	3
Total	109	4	26	35	26	31	20	14	5

Table G-6. Total Yearly Crashes by State in Study Database

State	2009		2010		2011		Total	
	Isolated	Series	Isolated	Series	Isolated	Series	Isolated	Series
FL	16	17	25	16	11	9	52	42
OH	94	91	87	105	111	101	292	297
OR	27	49	27	43	49	48	103	140
TN	47	86	51	80	47	61	145	227
Total	184	243	190	244	218	219	592	706

In Florida, data were collected for 30 isolated curves and 21 curve series. From three years of crash data for each site, there were 90 available site-years of data for isolated curves and 63 site-years of data for curve series. For isolated curve sites in Florida, 33 percent had rumble strips; 13 percent had post-mounted delineators; no sites had a grade of three percent or more; and all sites had center line pavement markings, edge line pavement markings, and RPMs. For curve series, 29 percent of the sites had rumble strips; 5 percent had a grade of three percent or more; no sites had post-mounted delineators; and all sites had center line pavement markings, edge line pavement markings, and RPMs.

In Ohio, data were collected for 79 isolated curves and 86 curve series. The three years of crash data resulted in a possible 237 site-years of data for isolated curves and 258 site-years of data for curve series. For isolated curve sites in Ohio, 8 percent had rumble strips; 4 percent had post-mounted delineators; 33 percent had a grade of three percent or more; 78 percent had RPMs; and all sites had center line and edge line pavement markings. For curve series, 4 percent had rumble strips, 47 percent had a grade of three percent or more, 3 percent had post-mounted delineators, 99 percent had RPMs, and all sites had center line and edge line pavement markings.

In Oregon, data were collected for 82 isolated curves and 84 curve series. The three years of crash data for each site resulted in a possible 246 site-years of data for isolated curves and 252 site-years of data. For isolated curve sites in Oregon, 1 percent had rumble strips, 35 percent had post-mounted delineators, 32 percent had a grade of three percent or more, 27 percent had RPMs, 82 percent had edge line pavement markings, and all sites had center line pavement markings. For curve series, no sites had rumble strips, 58 percent had post-mounted delineators, 43 percent had a grade of three percent or more, 31 percent had RPMs, 75 percent had edge line pavement markings, and all sites had center line pavement markings.

In Tennessee, data were collected for 80 isolated curves and 79 curve series. The three years of crash data for each site resulted in a possible 240 site-years of data for isolated curves and 237 site-years of data for curve series. For isolated curve sites in Tennessee, 23 percent had rumble strips, 1 percent had post-mounted delineators, 26 percent had a grade of three percent or more, 38 percent had RPMs, and all sites had center line and edge line pavement markings. For curve series, 26 percent had rumble strips, 5 percent had post-mounted delineators, 39 percent had a grade of three percent or more, 35 percent had RPMs, 99 percent had edge line pavement markings, and 99 percent had center line pavement markings.

Tables G-7 through G-10 present summary statistics for all continuous data variables collected in Florida, Ohio, Oregon, and Tennessee, respectively. One observation consistent across the data collected in the four states is that the number of mean total crashes for curve series is only slightly greater (or even less) than the mean total crashes for curve series, suggesting that the presence of multiple curves does not contribute multiplicatively to total crash

frequency (i.e., a series of two curves does not experience twice as many crashes as an isolated curve).

Table G-7. Summary Statistics for Florida Curves

Variable	Isolated Curves				Curve Series			
	Min	Mean	Max	St Dev	Min	Mean	Max	St Dev
Dependent Variables								
Average Annual Daily Traffic (aadt) (veh/day)	500	6,007	15,700	3,846	600	4,944	15,300	3,297
Horizontal Curve Length (hclen) (ft)	185	892	1,795	407				
Degree of Curve (degcrveang) (degrees)	2.00	6.12	22.50	4.13				
Total Deflection Angle (hctotang) (degrees)	5.50	48.66	91.50	26.44				
Series Length (serieslen) (miles)					0.14	0.52	1.37	0.30
Weighted Degree of Curve (weightedavedeg) (degrees)					1.68	4.26	9.50	2.03
Curvature Change Rate (ccr) (degrees/mile)					76.9	190.5	454.6	103.0
Proportion Curve (propcurve)					0.61	0.81	0.95	0.10
Number of Curves (ncurves)					2	2.29	6	0.89
Posted Speed Limit (posted) (mph)	40	55.50	60	4.74	25	51.90	60	8.44
Lane Width (lw) (ft)	10.0	11.36	12.0	0.67	11.0	11.69	12.0	0.33
Shoulder Width (sw) (ft)	1.0	3.27	6.0	1.32	0.0	2.76	4.0	0.87
Speed Reduction (speedreduc) (mph)	0	7.33	25	8.18	0	1.90	15	4.25
Roadside Hazard Rating (rhr)	1	2.17	4	0.82	2	2.81	4	0.67
Upstream Tangent Length (uptan) (ft)	1,641	5,832	10,560	3,443				
Independent Variables (crashes/year)								
Total Crashes (totcrash)	0	0.58	8	1.11	0	0.67	5	1.05
Fatal and Injury Crashes (fi)	0	0.34	5	0.75	0	0.33	3	0.70
Single-Vehicle Run-Off-Road Crashes (svror)	0	0.22	3	0.51	0	0.32	3	0.67
Adverse Pavement Condition Crashes (adversepave)	0	0.10	1	0.30	0	0.13	2	0.38
Night Crashes (night)	0	0.28	2	0.54	0	0.33	2	0.57

Table G-8. Summary Statistics for Ohio Curves

Variable	Isolated Curves				Curve Series			
	Min	Mean	Max	St Dev	Min	Mean	Max	St Dev
Independent Variables								
Average Annual Daily Traffic (aadt) (veh/day)	330	4,263	12,870	3,844	160	2,802	15,140	2,946
Horizontal Curve Length (hclen) (ft)	106	330	1,162	220				
Degree of Curve (degcrveang) (degrees)	4.00	13.68	55.00	10.66				
Total Deflection Angle (hctotang) (degrees)	9.50	36.02	87.12	19.71				
Series Length (serieslen) (miles)					0.07	0.24	0.84	0.18
Weighted Degree of Curve (weightedavedeg) (degrees)					3.0	12.0	39.6	6.52
Curvature Change Rate (ccr) (degrees/mile)					129	421	1,860	246
Proportion Curve (propcurve)					0.33	0.68	1.00	0.15
Number of Curves (ncurves)					2	2.53	9	1.21
Posted Speed Limit (posted) (mph)	35	53.42	55	4.33	35	54.42	55	2.80
Lane Width (lw) (ft)	10.0	11.11	15.0	0.96	9.0	11.04	13.0	0.92
Shoulder Width (sw) (ft)	0.0	2.41	10.0	1.99	0.0	2.69	10.0	1.72
Speed Reduction (speedreduc) (mph)	0	11.84	40	12.81	0	14.36	40	12.3
Roadside Hazard Rating (rhr)	1	3.59	6	1.17	1	3.64	6	1.01
Upstream Tangent Length (uptan) (ft)	185	1,991	12,038	2,119				
Dependent Variables (crashes/year)								
Total Crashes (totcrash)	0	1.23	9	1.72	0	1.15	10	1.40
Fatal and Injury Crashes (fi)	0	0.36	6	0.73	0	0.48	5	0.85
Single-Vehicle Run-Off-Road Crashes (svror)	0	0.68	5	1.02	0	0.73	9	1.05
Adverse Pavement Condition Crashes (adversepave)	0	0.48	6	0.93	0	0.49	8	0.86
Night Crashes (night)	0	0.53	4	0.88	0	0.48	4	0.79

Table G-9. Summary Statistics for Oregon Curves

Variable	Isolated Curves				Curve Series			
	Min	Mean	Max	St Dev	Min	Mean	Max	St Dev
Dependent Variables								
Average Annual Daily Traffic (aadt) (veh/day)	120	1,864	10,700	1,860	230	2,124	10,700	2,143
Horizontal Curve Length (hclen) (ft)	81	543	1,849	395				
Degree of Curve (degcrveang) (degrees)	2.00	13.80	90.00	14.61				
Total Deflection Angle (hctotang) (degrees)	12.50	61.70	210.3	44.87				
Series Length (serieslen) (miles)					0.08	0.29	1.19	0.22
Weighted Degree of Curve (weightedavedeg) (degrees)					3.48	15.6	65.8	10.16
Curvature Change Rate (ccr) (degrees/mile)					123	656	2,068	424
Proportion Curve (propcurve)					0.27	0.76	1.00	0.19
Number of Curves (ncurves)					2	3.32	16	2.52
Posted Speed Limit (posted) (mph)	40	54.45	55	2.48	40	54.23	55	2.84
Lane Width (lw) (ft)	10.0	11.87	13.0	0.45	10.0	11.55	14.0	0.64
Shoulder Width (sw) (ft)	0.0	2.70	12.0	2.83	0.0	1.18	8.0	1.56
Speed Reduction (speedreduc) (mph)	0	12.01	40	12.66	0	18.69	40	12.1
Roadside Hazard Rating (rhr)	2	3.99	6	1.14	2	4.46	6	1.03
Upstream Tangent Length (uptan) (ft)	16.0	1,435	11,268	1,737				
Independent Variables (crashes/year)								
Total Crashes (totcrash)	0	0.42	3	0.72	0	0.56	4	0.86
Fatal and Injury Crashes (fi)	0	0.27	3	0.57	0	0.36	4	0.70
Single-Vehicle Run-Off-Road Crashes (svror)	0	0.30	3	0.62	0	0.36	3	0.66
Adverse Pavement Condition Crashes (adversepave)	0	0.17	3	0.46	0	0.23	3	0.50
Night Crashes (night)	0	0.08	2	0.30	0	0.12	2	0.34

Table G-10. Summary Statistics for Tennessee Curves

Variable	Isolated Curves				Curve Series			
	Min	Mean	Max	St Dev	Min	Mean	Max	St Dev
Independent Variables								
Average Annual Daily Traffic (aadt) (veh/day)	138	2,929	14,893	2,977	351	2,782	8,562	2,096
Horizontal Curve Length (hclen) (ft)	307	722	2,270	307				
Degree of Curve (degcrveang) (degrees)	2.40	9.89	41.10	7.13				
Total Deflection Angle (hctotang) (degrees)	9.24	66.33	196.9	43.23				
Series Length (serieslen) (miles)					0.09	0.41	1.15	0.25
Weighted Degree of Curve (weightedavedeg) (degrees)					2.60	8.72	33.20	5.78
Curvature Change Rate (ccr) (degrees/mile)					123.46	403.26	1,255	260.60
Proportion Curve (propcurve)					0.63	0.87	0.98	0.08
Number of Curves (ncurves)					2	3.20	10	1.95
Posted Speed Limit (posted) (mph)	35	48.19	55	5.27	35	46.90	55	5.42
Lane Width (lw) (ft)	9.0	10.84	13.0	1.05	9.0	10.98	13.0	0.94
Shoulder Width (sw) (ft)	0.0	1.64	10.0	1.86	0.0	1.59	12.0	2.32
Speed Reduction (speedreduc) (mph)	0	8.63	40	10.89	0	6.77	35	8.95
Roadside Hazard Rating (rhr)	2	3.78	6	1.07	2	4.20	6	0.92
Upstream Tangent Length (uptan) (ft)	75.0	1,664	12,122	1,936				
Dependent Variables (crashes/year)								
Total Crashes (totcrash)	0	0.60	5	0.94	0	0.96	7	1.21
Fatal and Injury Crashes (fi)	0	0.22	3	0.48	0	0.34	3	0.64
Single-Vehicle Run-Off-Road Crashes (svror)	0	0.38	5	0.75	0	0.59	5	0.84
Adverse Pavement Condition Crashes (adversepave)	0	0.21	4	0.57	0	0.21	3	0.50
Night Crashes (night)	0	0.27	3	0.63	0	0.36	4	0.66

SUMMARY

The analysis of crashes at curves involved collecting data related to crashes at curves and curve features from four states in different geographic regions. Data in each state were collected in different regions to ensure the final dataset represented a broad range of conditions drivers encounter at curves. Both isolated curves and curve series were investigated with attention to the use of in-curve and advance warning signs. The methods used to analyze the data and the final best-fit models are presented in Appendix H.

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Appendix H: Findings from the Safety Analysis

This Appendix documents the results of the safety analysis described in Appendix G. The objective was to identify how TCDs at curves (specifically, advance warning signs and in-curve warning signs) impact safety. Data were collected in four states (Florida, Ohio, Oregon, and Tennessee). Crash models were developed for different types of curves (isolated or series) and types of crashes (total, injury, SVROR, adverse pavement, and nighttime crashes) and include CMFunctions for the TCDs used at the curves.

METHODOLOGY

Multivariate regression was used to develop a statistical relationship between the dependent variable (i.e., crash frequency) and a set of predictor variables (e.g., traffic volume, type and placement of warning signs, roadway characteristics). Coefficients were estimated during the modeling process for each of the predictor variables. The coefficients represent the expected change in the dependent variable due to a unit change in the predictor variable, all else being equal.

The current state-of-the-practice for developing crash prediction models is to assume a log-linear relationship between crash frequency and site characteristics. Generalized linear modeling (GLM) techniques were applied to develop the crash prediction model, and a log-linear relationship was specified using a negative binomial error structure. The negative binomial error structure is now recognized as being more appropriate for crash counts than the normal distribution that is assumed in conventional regression modeling. The negative binomial error structure also has advantages over the Poisson distribution in that it allows for over-dispersion that is often present in crash data. The appropriate model form was determined after exploratory data analysis.

There are several potential sources of bias in the development of crash prediction models. These are described in the following list with an explanation of why they were dismissed or how they were addressed.

- Selection of appropriate functional form: Functional form relates to both the overall form of the model and the form of each independent variable. The current state-of-the-practice was used for the overall form of the model (i.e., log-linear relationship), and exploratory data analysis techniques were used to identify an appropriate form for each predictor.
- Correlation among independent variables: Correlation refers to the degree of association among variables. A high degree of correlation among the predictor variables makes it difficult to determine a reliable estimate of the effects of specific predictor variables. The correlation matrix was examined to determine the extent of correlation among independent variables, and used to prioritize variables for inclusion in the crash prediction model.
- Low sample mean and sample size: Low sample mean was mitigated by expansion of the number of sites where data were collected. Sample size was not an issue with respect to *total* crashes, but is a potential concern for evaluating individual crash types (e.g., adverse pavement condition crashes). This is a specific concern when indicator variables are included

in the model. Each binary indicator is composed of two bins, one for those sites with the characteristic of interest and one for those sites without the characteristic. Further subdivisions are created with each indicator variable added to the model. This limits the number of observations per bin.

- Over-fitting of prediction models: Over-fitting is related to the law of diminishing returns. At some point, it is not worth adding any more independent variables to the model because they do not significantly improve the model fit. Over-fitting also increases the opportunity to introduce correlation in the model, and the opportunity for small sample issues when considering indicator variables. Several combinations of predictor variables were considered, and relative goodness-of-fit measures were employed to penalize models with more estimated parameters.
- Selection Bias of Treatment Sites: Since horizontal alignment related warning signs are used to reduce crash frequency and severity, it is likely that these signs are implemented based on the crash history of the site. If this is the case, then using the cross-sectional approach (comparison of sites with and without treatment) will yield misleading results. The crash prediction model may report an increase in crash frequency in association with application, when in fact the association is because horizontal alignment warning signs are put in place due to a high crash history.

Selection bias was addressed before the development of crash prediction models. Selection bias was initially explored by comparing the traits of curves with and without various combinations of horizontal alignment warning signs. If the traits between the two groups are not similar, then it is not clear whether the outcome is a function of the treatment or the differences between the groups. Additionally, Rubin (1) indicates that treatment effects estimated from cross-sectional regression models are not trustworthy if the means of logit-propensity scores for treated and untreated groups exceed one half of the pooled within group standard deviation of propensity scores.

In this case, the propensity score is the conditional probability of a horizontal curve receiving a TCD treatment given the covariates and outcomes (i.e. crash frequency and severity). Propensity scores are used to balance the covariates in the treated and untreated groups by reducing the bias due to differences in observed covariates. The most frequently used method to estimate propensity scores include the logit model, robit model, and classification trees or neural networks. The logit model was considered in this study.

The logit model estimates the conditional probability that treatment will occur given X_i , where X_i is a covariate in Equation 1.

$$L_i = \ln \frac{P_i}{1 - P_i} = \beta_1 + \beta_2 X_i + u_i \tag{1}$$

P_i equals 1 if the curve has a treatment and equals 0 if the curve does not have the treatment in place. Estimated coefficients for covariates indicate if the curve is more or less likely to receive the treatment (i.e., if the coefficient is positive, the curve is more likely to receive the treatment). Covariates for the propensity score model should include all curve characteristics that are related to application. Additionally, if crash frequency is considered in application, and crash history is unknown, then variables related to crash frequency should be considered in the propensity score model. All treatment related variables should be included in the model, regardless of

significance. Table H-1 provides an example of summary statistics for isolated curves with and without chevrons and/or Large Arrows. There are key differences in the characteristics between the treated and untreated groups for in-curve warning signs. The average degree of curve for treated curves is 17.4 degrees, while the average for untreated curves is 8.05 degrees. This implies curves with a higher degree receive in-curve warning signs and those with lower degree do not. Similar differences between treated and untreated curves are shown for total curve angle and speed reduction. Additionally, untreated curves appear to have wider shoulders than treated curves.

Table H-2 provides a logit model for propensity scores for the isolated curve data for in-curve warning signs. Predictors with positive coefficients indicate an increase in treatment probability given an increase in the predictor variable. Predictors with negative coefficients indicate a decrease in treatment probability given an increase in the predictor variable. The propensity score model in Table H-2 reflects the differences apparent in Table H-1. For example, it shows a positive association between degree of curve and probability of treatment. Similarly, total angle is positively associated with probability of treatment; and shoulder width is negatively associated with probability of treatment.

Table H-1. Summary Statistics for Isolated Curves by Presence of In-Curve Warning Signs

Variable	With In-Curve Warning Signs				No In-Curve Warning Signs			
	Min	Mean	Max	St Dev	Min	Mean	Max	St Dev
Average Annual Daily Traffic (aadt) (vpd)	120	3,247	15,700	3,311	138	3,396	15,600	3,400
Horizontal Curve Length (hclen) (ft)	101.15	523.50	1,500	323.97	81.10	604.67	2,270	405.84
Degree of Curve (degcrveang) (degrees)	3.00	17.36	90.00	14.45	2.00	8.05	34.00	5.36
Total Deflection Angle (hctotang) (degrees)	14.26	71.83	210.28	45.40	5.50	42.42	144.88	28.26
Posted Speed Limit (posted) (mph)	35	52.08	60	5.24	35	52.64	60	4.97
Lane Width (lw) (ft)	9.00	11.29	15.00	0.87	9.00	11.28	13.5	0.97
Shoulder Width (sw) (ft)	0	1.61	8	1.58	0	2.86	12	2.48
Speed Reduction (speedreduc) (mph)	0	17.73	40	11.87	0	5.61	35	9.16
Roadside Hazard Rating (rhr)	1	3.94	6	1.13	1	3.39	6	1.23
Upstream Tangent Length (uptan) (ft)	75	1,954	12,122	2,589	16	2,282	12,038	2,468
Grade Indicator (gradeind)	0	0.42	1	0.49	0	0.20	1	0.40
Total Crashes (totcrash)	0	0.78	8	1.27	0	0.69	9	1.21
Fatal and Injury Crashes (fi)	0	0.32	5	0.63	0	0.27	6	0.62
Single-Vehicle Run-Off-Road Crashes (svror)	0	0.44	5	0.83	0	0.41	5	0.78
Adverse Pavement Condition Crashes (adversepave)	0	0.28	6	0.69	0	0.25	5	0.65
Night Crashes (night)	0	0.27	4	0.62	0	0.30	4	0.68

Table H-2. Propensity Score Model for Isolated Curve In-Curve Warning Signs

Variable	Coefficient	Standard Error	Z Score	P-Value
Constant	-7.045	1.917	-3.67	< 0.001
Log-AADT	0.425	0.126	3.38	0.001
Log-Curve Length	0.142	0.282	0.50	0.615
Florida Indicator	0.405	0.447	0.91	0.364
Tennessee Indicator	-0.082	0.326	-0.25	0.801
Ohio Indicator	-0.006	0.330	-0.02	0.986
Rumble Strips Indicator	-0.047	0.299	-0.16	0.876
Lane Width Less than 12 FT	-0.058	0.237	-0.24	0.808
Speed Reduction	0.040	0.012	3.33	0.001
Degree of Curve	0.063	0.026	2.43	0.015
Total Angle	0.012	0.006	1.96	0.050
Shoulder Width	-0.262	0.063	-4.16	< 0.001
RRPM Indicator	0.398	0.258	1.54	0.123
No Advance Warning	-2.017	0.405	-4.98	< 0.001
Roadside Hazard Rating	0.258	0.101	2.55	0.011
Upstream Tangent Length Thousands	0.100	0.044	2.18	0.029
Grade Indicator	0.570	0.226	2.52	0.012
N = 813; Log-likelihood = -365.48; Pseudo R ² = 0.331				

Once propensity scores are estimated, a comparison between treated and untreated groups should be made. The comparison can be made by plotting histograms of propensity scores, or linear predictions for both treated and untreated groups. Sasidharan and Donnell (2) note that the distributions will be different, but the ranges should be comparable. The data in the region with no overlap between the two groups should be discarded, as statistical inference for this region will be based entirely on extrapolation. Therefore, comparisons are limited to subgroups whose propensities lie in the region of overlap. Figure H-1 provides a plot of the histograms of linear predictions of propensity scores estimated from Table H-2 for isolated curves by in-curve warning sign status. The histogram shows that curves with a linear propensity score greater than 2.8 should not be considered, nor should curves with a linear propensity score less than -2.8. The average propensity score for treated curves was 0.626, while the average propensity score for untreated curves was 0.247. These results show that treated and untreated curves do not have an equal chance of treatment, and therefore matching is necessary.

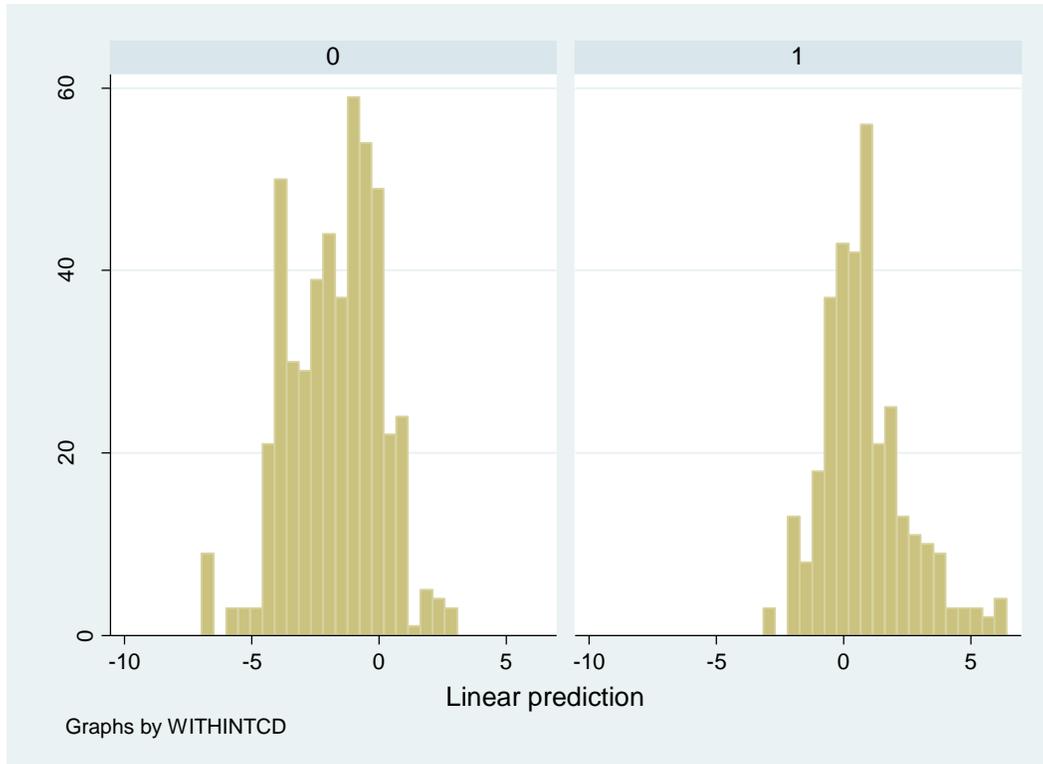


Figure H-1. Linear prediction of propensity scores for in-curve warning signs.

Since the data show that isolated curves with and without in-curve warning signs are dissimilar, matching sites based on propensity score is used to produce covariate balance. One of the most common sampling schemes is to use pair-wise matching of the propensity scores to pair each treated entity to an untreated entity with the closest propensity score. The matched pairs have the property that the distribution of observed variables for the treated and untreated groups is approximately the same (2). Matching on propensity scores mimics the results of a randomized block experiment in which entities having the same propensity scores are randomly assigned to treated or untreated groups (3). Schafer and Kang note that while matching seems wasteful for removing data, unmatched observations are noise in the data that may produce misleading conclusions.

Nearest neighbor (NN) matching is used to match treated and untreated sites, removing matched entities from the sample while not using the same site more than once. Matching took place using NN matching for all treated sites, since there were fewer treated than untreated sites, and by using a caliper. When a caliper is used, matches are restricted to a maximum distance equal to the caliper specified. If there is no caliper, then nearest neighbors are used regardless of the distance between the propensity scores. Previous studies have shown an optimal caliper is 0.25 times the within group standard deviation of propensity scores (2). For isolated curves, if no caliper was specified, there were 324 treated sites and 324 untreated sites matched. The mean propensity score for NN curves without a caliper was 0.626 for treated curves and 0.357 for untreated curves. However, when the caliper was specified, only 174 treated sites and 174 untreated sites were matched. The mean propensity score for NN curves with a caliper was 0.484 for treated curves and 0.467 for untreated curves.

After matching treated and untreated curves, the balance of the covariates for the matched sample must be checked. The percentage standardized bias is used to compare the matched and unmatched samples since t-statistics are not directly comparable. The standardized bias (or standardized difference in means) is estimated as the difference in sample means in the treated and untreated samples as a percentage of the square root of the average variance, as shown in Equation 2.

$$\text{Standardized Bias} = \frac{100 * (\bar{x}_t - \bar{x}_{ut})}{\sqrt{(s_t^2 + s_{ut}^2)/2}} \quad 2$$

where

- \bar{x}_t = the sample mean in the treated group.
- \bar{x}_{ut} = the sample mean in the untreated group.
- s_t^2 = the sample variance in the treated group.
- s_{ut}^2 = the sample variance in the untreated group.

Figure H-2 shows the standardized bias for different covariates included in the propensity score model for isolated curves with in-curve warning signs. In Figure H-2 the NN matched data has less bias than the original observed data, while the NN with caliper matched data consistently has substantially reduced bias. The final set of observations in Figure H-2 is average bias for all covariates in the model. For isolated curves with in-curve warning signs, the caliper-based match resulted in the most unbiased dataset.

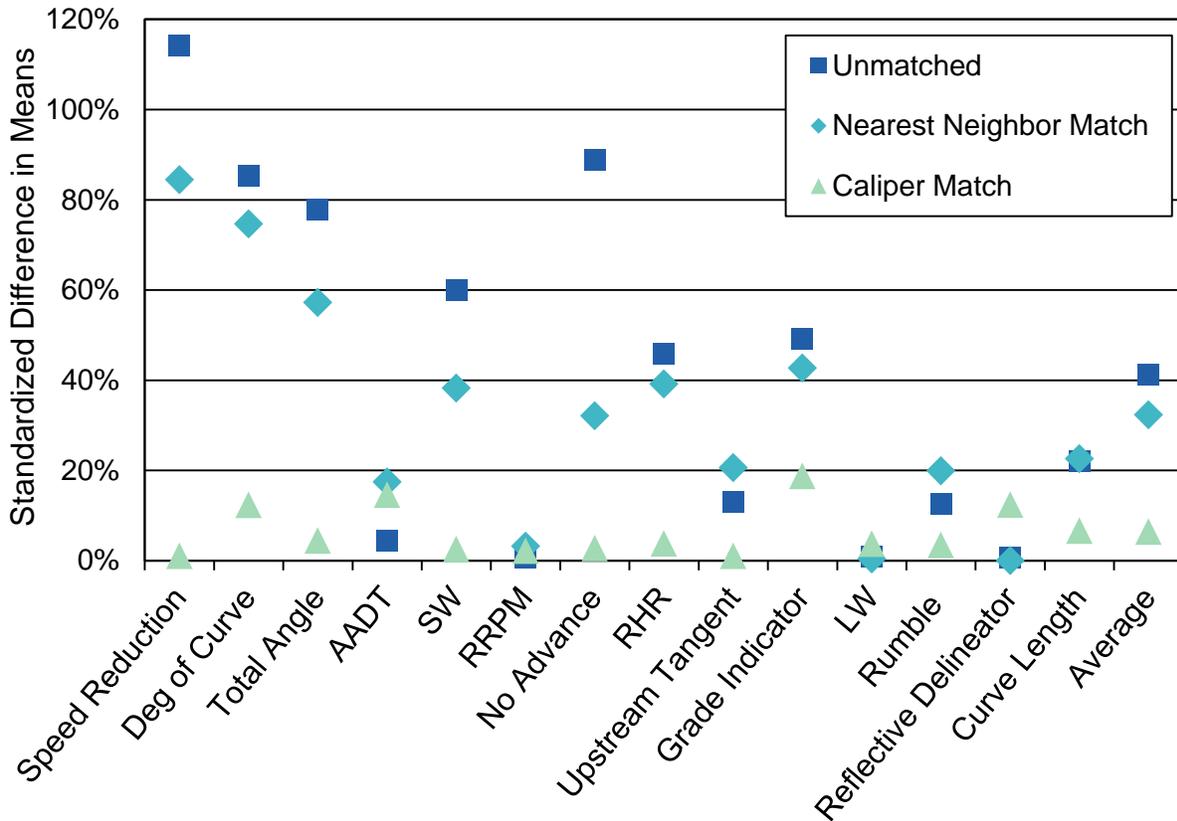


Figure H-2. Absolute standardized difference in means for in-curve warning signs on isolated curves.

Once the propensity score-based matched dataset was developed, the following protocol was employed to develop the multivariate models:

- Step 1: Identify the base models with traffic volume only.
- Step 2: Explore other predictor variables.
- Step 3: Select final model.

Base Models with Traffic Volume Only

The first step of the modeling process was to identify the proper functional form for the exposure term in the crash prediction model. Models were developed using average annual daily traffic (AADT), or log-AADT as the only predictor variable. The general form of this model is given by Equations 3 and 4. The decision on which form to use was based on an evaluation of parameter estimates and other goodness-of-fit measures.

$$\text{Crashes/year} = \exp(\alpha + \beta_1 * \text{AADT}) \tag{3}$$

$$\text{Crashes/year} = \text{AADT}^{\beta_1} \exp(\alpha) \tag{4}$$

where

- α = parameter estimated in the model calibration process.
- β_1 = parameter estimated in the model calibration process.
- AADT = annual average daily traffic of the horizontal curve.

Preliminary modeling identified that Equation 4 best fit the data for all crash types. Therefore, log-AADT was considered in models for total crashes, injury crashes, SVROR crashes, adverse pavement condition crashes, and nighttime crashes.

Exploration of Additional Predictors

Correlation matrices were used to identify potential additional predictors for inclusion in the crash prediction models. Correlation refers to the degree of association among variables. A positive value of 1.00 means that perfect positive correlation exists (as one variable increases, the other increases as well). A negative value of 1.00 means that perfect negative correlation exists (as one variable increases, the other decreases). For example, Tables H-3 and H-4 present the correlation between crash types and individual predictor variables for isolated curves and curve series, respectively. It appears that several potential predictor variables may be associated with the number of crashes on horizontal curves; however, the degree of correlation is low for all variables (less than 0.5). Potential predictor variables were evaluated for consistency of association with all crash types (i.e., the direction of association does not change) and whether or not the direction of association was intuitive. Only AADT appeared to have a consistent, strong relationship with each of the crash types across the curve types.

Counterintuitive variables were carefully considered in the statistical modeling to understand if there was correlation with other predictor variables or if interactions exist across variables. Alone, the correlation between the predictors and dependent variable is not completely informative because it does not account for the confounding effects of other variables. It does, however, provide an indication of the relative importance of predictors and the potential direction of effect. This information helped to frame the remaining analyses and to identify potential confounding effects that should be investigated further (i.e., when a predictor shows an effect that is opposite of expectations). For example, as seen in Table H-4, shoulder width has a positive association with all crash types for curve series. If counterintuitive effects remained for predictor variables after the modeling process, the variables were retained in the models.

A high degree of correlation among the predictor variables makes it difficult to determine a reliable estimate for the effects of those variables if they are included in the same model. Tables H-5 and H-6 show the correlation among potential predictor variables, highlighting those variables with a correlation greater than 0.5. Due to the high degree of correlation between predictor variables, use of both variables in the same crash prediction model should be avoided.

Table H-3. Correlation Matrix for Dependent Variables and Predictors for Isolated Curves

Predictors	Total	Injury	SVROR	Adverse	Night
AADT	0.42	0.30	0.25	0.24	0.38
Degree of Curve (D)	-0.09	-0.07	-0.06	-0.07	-0.08
Curve Length (HCL)	-0.02	0.03	-0.05	-0.02	-0.02
Total Curve Angle (TCA)	-0.12	-0.06	-0.08	-0.06	-0.14
Posted Speed Limit (PSL)	-0.02	0.04	-0.06	0.01	0.00
Rumble Strip Presence (RU)	-0.04	-0.05	-0.05	0.00	0.00
Edge line Presence (EPM)	0.09	0.09	0.09	0.08	0.09
Post-Mounted Delineator Presence (PMD)	-0.06	0.00	-0.02	-0.02	-0.11
RRPM Presence (RPM)	0.13	0.05	0.10	0.13	0.10
Lane Width (LW)	0.05	0.07	0.01	0.04	-0.01
Shoulder Width (SW)	0.02	0.03	-0.03	-0.01	0.05
Advisory Speed (ASP)	0.00	0.02	-0.02	-0.02	0.05
Speed Reduction (SR)	-0.01	0.00	-0.01	0.03	-0.05
Roadside Hazard Rating (RHR)	0.13	0.05	0.16	0.13	0.05
Upstream Tangent Length (UT)	0.02	0.04	-0.04	-0.02	0.05
Florida Indicator (FL)	-0.04	0.03	-0.09	-0.09	-0.01
Ohio Indicator (OH)	0.26	0.08	0.20	0.21	0.24
Oregon Indicator (OR)	-0.17	-0.02	-0.11	-0.10	-0.21
Tennessee Indicator (TN)	-0.07	-0.07	-0.03	-0.05	-0.02

Table H-4. Correlation Matrix for Dependent Variables and Predictors for Series Curves

Predictors	Total	Injury	SVROR	Adverse	Night
AADT	0.32	0.25	0.17	0.15	0.22
Average Degree of Curve (D)	-0.10	-0.05	-0.05	-0.02	-0.09
Series Length (LEN)	0.14	0.05	0.07	-0.02	0.08
Curvature Change Rate (CCR)	-0.07	-0.02	-0.03	0.00	-0.09
Proportion Curve (PC)	0.01	-0.03	0.01	-0.07	-0.04
Number of Curves (NC)	0.03	0.00	0.03	-0.03	-0.01
Posted Speed Limit (PSL)	-0.04	0.01	-0.03	0.05	-0.03
Rumble Strip Presence (RU)	0.02	-0.06	-0.07	-0.04	-0.01
Edge line Presence (EPM)	0.15	0.10	0.14	0.09	0.13
Post-Mounted Delineator Presence (PMD)	-0.08	0.02	-0.05	-0.03	-0.12
RRPM Presence (RPM)	0.12	0.06	0.06	0.12	0.10
Lane Width (LW)	-0.05	-0.01	-0.09	-0.09	-0.06
Shoulder Width (SW)	0.15	0.13	0.13	0.08	0.13
Advisory Speed (ASP)	-0.01	-0.01	-0.01	-0.02	0.03
Speed Reduction (SR)	-0.01	0.01	-0.01	0.04	-0.04
Roadside Hazard Rating (RHR)	0.06	0.05	0.06	0.04	-0.03
Florida Indicator (FL)	-0.05	-0.02	-0.08	-0.08	0.01
Ohio Indicator (OH)	0.16	0.08	0.15	0.21	0.17
Oregon Indicator (OR)	-0.18	-0.03	-0.14	-0.08	-0.21
Tennessee Indicator (TN)	0.05	-0.04	0.04	-0.09	0.04

Table H-5. Correlation Coefficients for Predictor Variables for Isolated Curves

Predictors	AADT	D	HCL	TCA	PSL	RU	EPM	PMD	RPM	LW	SW	ASP	SR	RHR	UT	FL	OH	OR	TN
AADT	1.00																		
D	-0.28	1.00																	
HCL	0.07	-0.36	1.00																
TCA	-0.28	0.56	0.31	1.00															
PSL	0.01	-0.07	0.01	-0.19	1.00														
RU	0.21	-0.21	0.10	-0.16	0.08	1.00													
EPM	0.19	-0.20	0.15	-0.18	-0.12	0.09	1.00												
PMD	-0.14	-0.03	0.06	0.09	0.20	0.01	-0.14	1.00											
RPM	0.31	-0.08	-0.13	-0.29	0.08	0.29	0.23	-0.10	1.00										
LW	0.22	-0.01	-0.03	-0.01	0.16	0.16	-0.22	0.24	-0.10	1.00									
SW	0.26	-0.28	0.11	-0.24	0.19	0.11	0.20	0.02	0.06	0.25	1.00								
ASP	0.24	-0.65	0.25	-0.54	0.35	0.19	0.18	0.10	0.16	0.14	0.36	1.00							
SR	-0.25	0.67	-0.26	0.49	0.05	-0.17	-0.24	-0.02	-0.14	-0.08	-0.31	-0.92	1.00						
RHR	-0.07	0.30	-0.19	0.25	-0.18	-0.20	-0.17	0.05	-0.13	0.08	-0.30	-0.30	0.24	1.00					
UT	0.27	-0.30	0.31	-0.21	0.26	0.20	0.14	0.07	0.23	-0.05	0.22	0.35	-0.26	-0.47	1.00				
FL	0.28	-0.18	0.30	-0.05	0.21	0.22	0.09	0.00	0.32	0.03	0.14	0.17	-0.09	-0.42	0.52	1.00			
OH	0.18	0.11	-0.41	-0.30	0.13	-0.12	0.16	-0.20	0.37	-0.12	0.01	-0.02	0.08	-0.01	-0.04	-0.23	1.00		
OR	-0.29	0.12	-0.05	0.13	0.26	-0.23	-0.37	0.42	-0.37	0.41	0.10	0.02	0.09	0.20	-0.19	-0.23	-0.42	1.00	
TN	-0.08	-0.11	0.26	0.20	-0.54	0.20	0.16	-0.23	-0.21	-0.31	-0.21	-0.12	-0.10	0.09	-0.13	-0.23	-0.42	-0.43	1.00

Table H-6. Correlation Coefficients for Predictor Variables for Series Curves

Predictors	AADT	D	LEN	CCR	PC	NC	PSL	RU	EPM	PMD	RPM	LW	SW	ASP	SR	RHR	FL	OH	OR	TN
AADT	1.00																			
D	-0.33	1.00																		
LEN	0.02	-0.30	1.00																	
CCR	-0.29	-0.89	-0.31	1.00																
PC	0.09	-0.16	0.04	0.13	1.00															
NC	-0.19	0.12	0.66	0.06	-0.14	1.00														
PSL	-0.21	0.14	-0.13	0.07	-0.26	-0.10	1.00													
RU	0.36	-0.24	0.12	-0.19	0.23	-0.10	-0.17	1.00												
EPM	0.24	-0.44	0.10	-0.42	-0.01	-0.01	-0.14	0.11	1.00											
PMD	-0.06	0.21	-0.15	0.31	0.05	-0.03	0.13	-0.10	-0.15	1.00										
RPM	0.23	-0.11	0.00	-0.15	-0.16	-0.07	0.09	0.18	0.30	-0.15	1.00									
LW	0.27	-0.09	-0.04	0.02	0.12	-0.17	0.11	0.26	-0.18	0.20	-0.02	1.00								
SW	0.33	-0.37	0.05	-0.39	-0.04	-0.19	0.16	0.22	0.23	-0.21	0.24	0.14	1.00							
ASP	0.17	-0.67	0.21	-0.69	-0.05	-0.07	0.17	0.18	0.33	-0.25	0.08	0.09	0.30	1.00						
SR	-0.26	-0.72	-0.26	0.70	-0.07	0.03	0.28	-0.25	-0.38	0.30	-0.04	-0.04	-0.22	-0.90	1.00					
RHR	-0.14	0.23	0.10	0.28	0.14	0.27	-0.10	-0.13	-0.13	0.20	-0.22	-0.05	-0.32	-0.16	0.11	1.00				
FL	0.24	-0.26	0.23	-0.24	0.08	-0.10	0.00	0.16	0.09	-0.15	0.24	0.15	0.13	0.26	-0.25	-0.32	1.00			
OH	0.01	0.03	-0.25	-0.10	-0.37	-0.15	0.31	-0.15	0.20	-0.29	0.55	-0.15	0.28	0.04	0.10	-0.23	-0.20	1.00		
OR	-0.16	0.33	-0.11	0.37	-0.07	0.13	0.28	-0.24	-0.41	0.62	-0.39	0.25	-0.25	-0.22	0.34	0.29	-0.20	-0.46	1.00	
TN	0.01	-0.22	0.23	-0.13	0.41	0.08	-0.59	0.30	0.16	-0.25	-0.32	-0.19	-0.10	0.04	-0.30	0.12	-0.19	-0.44	-0.43	1.00

Effects of Individual Predictors

In this step, additional predictors were considered for inclusion in the crash prediction models. Initial models were specified considering the correlation between dependent variables and potential predictors. The initial models included the variables shown in Equation 5.

$$\text{Total Crashes} = \text{AADT}^{\beta_1} * \text{HCL}^{\beta_2} * \alpha * e^{\beta_3 * \text{FL}} * e^{\beta_4 * \text{OH}} * e^{\beta_5 * \text{TN}} * e^{\beta_4 * \text{TCD}} \quad 5$$

where

α	=	constant.
β_i	=	model coefficients.
FL	=	1 if site is in Florida; 0 otherwise.
OH	=	1 if site is in Ohio; 0 otherwise.
TN	=	1 if site is in Tennessee; 0 otherwise.
AADT	=	average annual daily traffic on the horizontal curve.
HCL	=	horizontal curve length.
TCD	=	traffic control device of interest (i.e., in-curve or advance).

Indicator variables for each state were considered in each model to account for unobserved differences between each state. The base condition was Oregon. If the state indicator was insignificant, it was not included in the model. Indicators for each year were considered to capture differences due to time; however, these indicators were insignificant and excluded from the final models. Note that a TCD variable was included in each model as horizontal alignment warning signs were the primary variables of interest. The specific TCD variable coincided with the propensity score analysis matching for the data. For example, if the propensity score matching was for chevrons and/or Large Arrow signs on isolated curves, then an indicator for in-curve warning signs was the predictor of interest for the dataset.

Once the base models were developed for each crash type, additional variables were considered using Variable Introduction Exploratory Data Analysis (VIEDA), as outlined by Hauer (4). This approach differs from the typical approach, which is to identify whether or not a parameter is statistically significant, and if so, add the variable to the model. Instead, VIEDA helps to answer the following two questions:

- Is the variable related to safety?
- What is the proper functional form the variable should take in the crash prediction model?

VIEDA was used to identify whether the ratio of observed crashes to predicted crashes exhibits a regular relationship with the variable considered for addition to the model, and if so, it was used to identify the proper functional form for the added variable. The base model was used for each crash type to predict crash frequency. Pivot tables were then used to identify if the ratio of observed to predicted crashes exhibited a relationship with potential predictor variables. For example, if the ratio of observed to predicted crashes was 1.00 for curves with post-mounted reflective delineators and for curves without post-mounted reflective delineators, then post-mounted reflective delineators are found not to be related to crash frequency.

For continuous variables (e.g., lane width), the variable of interest was grouped into bins of various sizes to determine if a relationship exists with crash frequency and if the variable

should be considered as a continuous variable or introduced as an indicator variable. As an example, the base model was found to consistently under predict crashes for sites that had lane widths less than 12 feet. The relationship fit better as an indicator variable than a continuous variable (a similar ratio was found for sites with an 11 foot lane width and sites with a 10 foot lane width). Therefore, lane width was considered in models as an indicator variable for narrow lane width (i.e., 1 for narrow lane widths less than 12 feet, and 0 for wide lane widths).

Once a variable was included in the model, the estimated parameters and associated standard errors were examined to answer the following questions:

- Is the direction of effect (i.e., expected decrease or increase in crashes) consistent with expectations?
- Does the magnitude of the effect seem reasonable?
- Are the parameters of the model estimated with statistical significance?
- Does the estimated over-dispersion parameter improve significantly?

The final step was to consider correlations among predictor variables included in the model specifications. When highly correlated predictor variables are both included in the crash prediction model, it is more difficult to associate the change in the dependent variable (i.e., crashes) to one or the other correlated predictor variables. This can lead to large standard errors and insignificant regression coefficients even though a definite relationship exists between the predictor variables and crashes. Additionally, interpreting marginal effects of highly correlated variables may be impractical since one predictor variable cannot feasibly be held constant when considering a unit change in the other correlated predictor variable. Correlated predictor variables were prioritized for inclusion in the final models. The following prioritizations were considered:

- Speed reduction was chosen over degree of curve for in-curve warning sign datasets. Correlation existed between speed reduction and degree of curve, but speed reduction was found to have a stronger relationship with most crash types for the in-curve warning sign dataset. For the advance warning sign matched datasets, priority was given to degree of curve, since sites without advance warning signs all have a speed reduction of zero.
- Average degree of curve was chosen over curvature change rate for series curves. The two variables were quite similar, and average degree of curve is more intuitive for engineers, based on curve design.
- Series length was chosen over number of curves for curve series to be consistent with isolated curves.
- Speed reduction was chosen over advisory speed for all datasets. Speed reduction was directly calculated from advisory speed and was more consistent with Table 2C-5 from the MUTCD.

With an extensive dataset of predictor variables, several different models can be created to estimate a single dependent variable. When multiple alternatives were identified, goodness-of-fit (GOF) measures were applied to determine the most suitable model.

RESULTS

This section presents the final model results. Four matched databases were developed, including:

1. Chevrons and/or Large Arrows within isolated curves.
2. Chevrons and/or Large Arrows within series curves.
3. Curve or Turn warning signs in advance of isolated curves.
4. Reverse Curve, Reverse Turn, or Winding Road warning signs in advance of series curves.

The final model, including interaction terms among predictor variables, is presented along with interpretations of the covariates in the model. The interaction term model shows how the relationship between horizontal alignment warning sign application and crash outcomes varies across other predictor variables (e.g., AADT). Crash modification functions (CMFunctions) are presented for each crash type with figures that include confidence intervals.

Chevrons and/or Large Arrows within Isolated Curves

The final matched dataset for isolated curves considers the presence of chevrons, a Large Arrow sign, or the combination of chevrons and Large Arrow. Due to the smaller sample of sites with Large Arrows or a combination of chevrons and Large Arrows, the effects of individual sign types/combinations were analyzed aggregately. This definition of in-curve warning signs is consistent with MUTCD Table 2C-5, which specifies the use of chevrons and/or a Large Arrow. The dataset used for the analysis of in-curve warning signs for isolated curves was selected using NN matching with the caliper. The caliper based match was used due to the reduction in bias, as shown previously in Figure H-2. While the original isolated curve dataset consisted of 324 treated curves and 489 untreated curves, the final matched dataset consisted of 174 site-years of treated curves and 174 site years of untreated curves. For sites treated with chevrons and/or Large Arrows, 95 percent had a Curve or Turn warning sign. For untreated sites, 95 percent also had a Curve or Turn warning sign. Only 5 percent of sites in the matched dataset had no advance warning sign.

The final crash prediction models are presented below, along with interpretations of the variables included in the models. The results of the models focus on the CMFunctions for the presence of in-curve warning signs. CMFunctions were developed because the safety effect of in-curve warning signs was found to be a function of the traffic volume (AADT). Additional interactions were explored between in-curve warning signs and speed reduction. The resulting interaction terms were counterintuitive, finding that chevrons and/or Large Arrows are less effective, or are even associated with more crashes, as speed reduction increases. Upon further exploration, the data showed a negative correlation between AADT and speed reduction (see Table H-7). It is quite clear that mean and maximum AADT values generally decrease as observed speed reduction increases. This finding is intuitive since roadways with higher AADT are more likely to be designed to higher standards.

Table H-7. AADT Summary Statistics by Speed Reduction

Speed Reduction (mph)	Minimum AADT (vpd)	Mean AADT (vpd)	Maximum AADT (vpd)
0	524	4,737	15,700
5	3,600	8,211	12,500
10	130	5,124	15,600
15	500	3,434	15,600
20	370	2,813	12,870
25	138	1,670	7,160
30	1,360	2,100	2,840
35	330	732	1,310
All	130	3,758	15,700

The subsections below present the final model developed for each crash type and include a CMFunction. A corresponding figure is presented for each CMFunction, with the 95 percent confidence interval for the safety effect. Shaded regions in the figures indicate regions where the safety effect is a statistically significant reduction.

Total Crashes

The functional form of the crash prediction model for total crashes considering in-curve warning signs is given by Equation 6 and the coefficients and related statistics are provided in Table H-8. The presence of chevrons, Large Arrows, or a combination of chevrons and Large Arrows is indicated with a single variable for in-curve warning signs (withintcd). This format is consistent with the 2009 MUTCD and was also necessary due to the small sample of sites with only a Large Arrow or a combination of chevrons and Large Arrow.

$$Total\ Crashes = AADT^{\beta_1} * HCLen^{\beta_2} * exp(Constant + C_1X_1 + \dots + C_nX_n) \quad 6$$

Table H-8. Crash Prediction Model Coefficients for Total Crashes

Variables	Coefficient	St. Error	Z-Score	P-Value	L95 CI	U95 CI
Constant	-10.082	1.198	-8.42	< 0.001	-12.429	-7.735
β1 (log-aadt)	0.955	0.102	9.34	< 0.001	0.755	1.155
β2 (log-hclen)	0.350	0.125	2.79	0.005	0.104	0.595
C1 (Florida)	-0.961	0.268	-3.58	< 0.001	-1.486	-0.435
C2 (Tennessee)	-0.420	0.207	-2.03	0.043	-0.826	-0.014
C3 (rumble)	-0.463	0.245	-1.89	0.059	-0.943	0.017
C4 (lwl12)	0.378	0.150	2.53	0.012	0.085	0.672
C5 (speedreduc)	0.020	0.008	2.51	0.012	0.004	0.036
C6 (rhr3l)	-0.231	0.151	-1.53	0.127	-0.528	0.065
C7 (withintcd)	0.203	0.245	0.83	0.406	-0.276	0.683
C8 (withinaadtint)	-0.089	0.040	-2.26	0.024	-0.166	-0.012
Overdispersion	0.124	0.095				

N = 348; Log-likelihood = -366.73; Pseudo R² = 0.150

Interpretations for the covariates include:

- AADT (log-AADT): A positive association was found between the natural logarithm of AADT and total crashes. An increase in AADT results in an increase in total crashes. However, the AADT variable is also included in the interaction with in-curve warning signs (withinaadtint).
- Horizontal Curve Length (log-hclen): A positive association was found between the natural logarithm of horizontal curve length and total crashes. An increase in curve length results in an increase in total crashes.
- Florida and Tennessee Indicators (Florida, Tennessee): A negative association was found between total crashes and the site location being in Florida or Tennessee. The base condition is that the site location is in Ohio or Oregon. Sites in Florida and Tennessee experience fewer total crashes than those in Ohio and Oregon.
- Rumble Strips Indicator (rumble): A negative association was found between the indicator for the presence of rumble strips and total crashes. The base condition is no rumble strips present. Sites with rumble strips experience fewer total crashes than those without rumble strips.
- Lane Width Less than 12 feet Indicator (lwl12): A positive association was found between the narrow lane width and total crashes. The base condition is a lane width that is 12 feet or greater. Sites with a narrow lane (i.e., less than 12 feet) experience more total crashes than sites with wide lanes.
- Speed Reduction (speedreduc): A positive association was found between speed reduction and total crashes. An increase in speed reduction is associated with an increase in total crashes.
- Roadside Hazard Rating Three or Less (rhr3l): A negative association was found between a curve having a roadside hazard rating of three or less and total crashes. The base condition is a roadside hazard rating greater than 3 (more severe). A less severe roadside hazard rating is associated with fewer total crashes.
- Presence of In-Curve Warning Signs (withintcd): A positive association was found between having an in-curve warning sign and total crashes. The finding is not even marginally significant, and is part of an interaction with AADT.
- Interaction term for In-Curve Warning Sign and AADT (withinaadtint): A negative relationship was found between the interaction term and total crashes. This implies that in-curve warning signs on roadways with higher AADT are associated with fewer total crashes. AADT in the interaction term is entered in thousands of vehicles.

A CMFunction relating the effect of in-curve warning signs to total crashes by AADT is presented in Equation 7.

$$CMF_{total,isolated-within} = \exp(0.203 - 0.089 * AADT(thousands)) \quad 7$$

Figure H-3 graphically represents the CMFunction for total crashes by AADT. The shaded region indicates where the value of the CMF is significantly less than 1.00 (indicating a significant reduction). For total crashes, Chevrons and/or Large Arrows are significantly associated with fewer crashes when the AADT is greater than approximately 5,500. While the CMF is statistically insignificant for AADTs less than 5,500, the mean CMF value is less than 1.00 (potential safety benefit) when the AADT is greater than approximately 2,500.

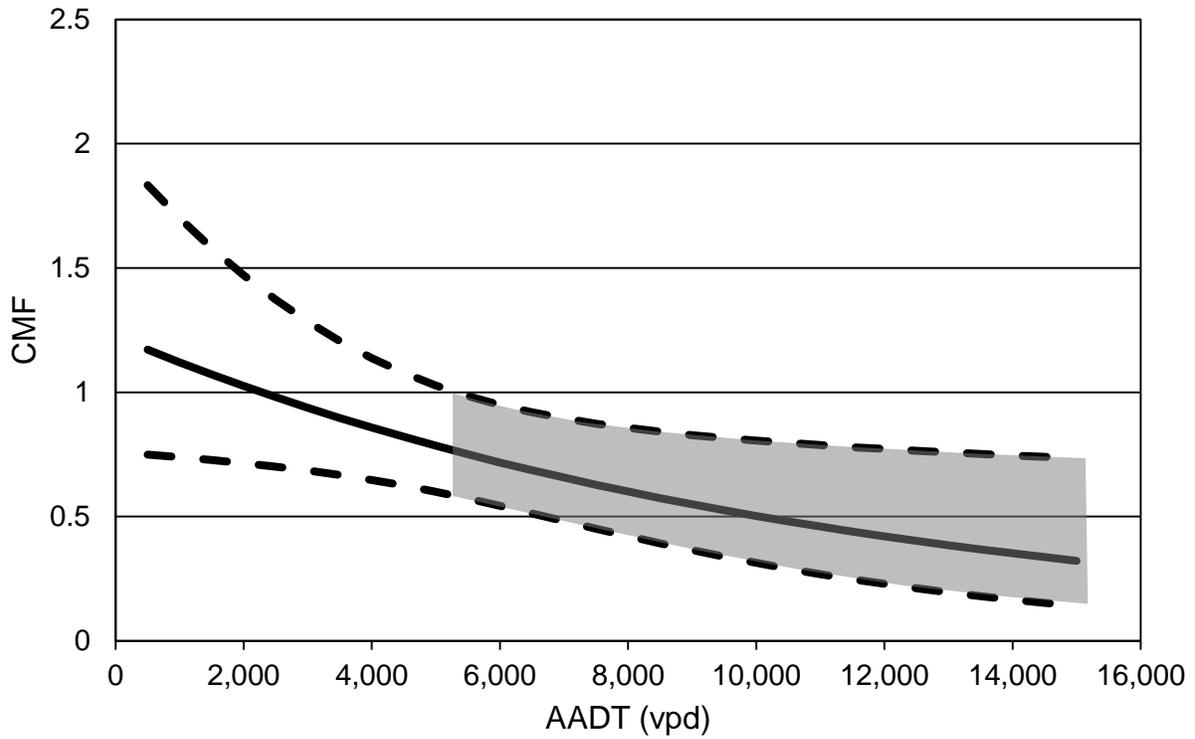


Figure H-3. CMFunction for total crashes for in-curve warning signs on isolated curves.

The results were further disaggregated by individual in-curve warning sign for total crashes. Figure H-4 presents estimated CMFunctions for the AADT range applicable based on the data used to develop the crash prediction models.

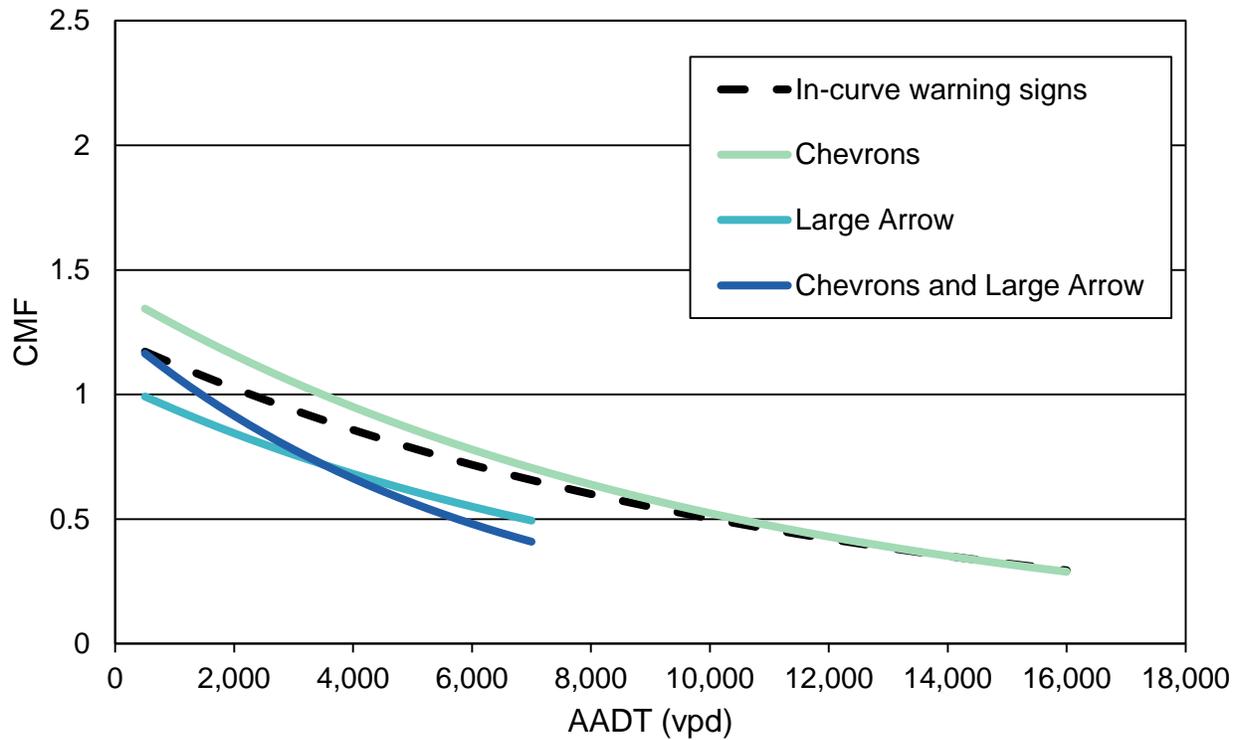


Figure H-4. CMFunction for total crashes for specific in-curve warning signs on isolated curves.

It appears from Figure H-4 that, where applied, Large Arrow signs have a greater impact on crash reduction than chevrons. Further analysis showed that Large Arrows are typically applied on roadways with lower traffic volumes and more severe horizontal curves. Figure H-5 presents the CMFunction for Large Arrows against degree of curve. The CMFunction for Large Arrows was found to have minimal correlation with AADT, unlike chevrons and chevrons plus Large Arrows. This allowed for development of the CMFunction by degree of curvature for Large Arrows. Figures H-4 and H-5 illustrate the mean estimate of CMFunctions and do not include confidence intervals because they could not be calculated. Due to small sample sizes, similar disaggregate analyses were not possible for other crash types for in-curve warning signs on isolated curves.

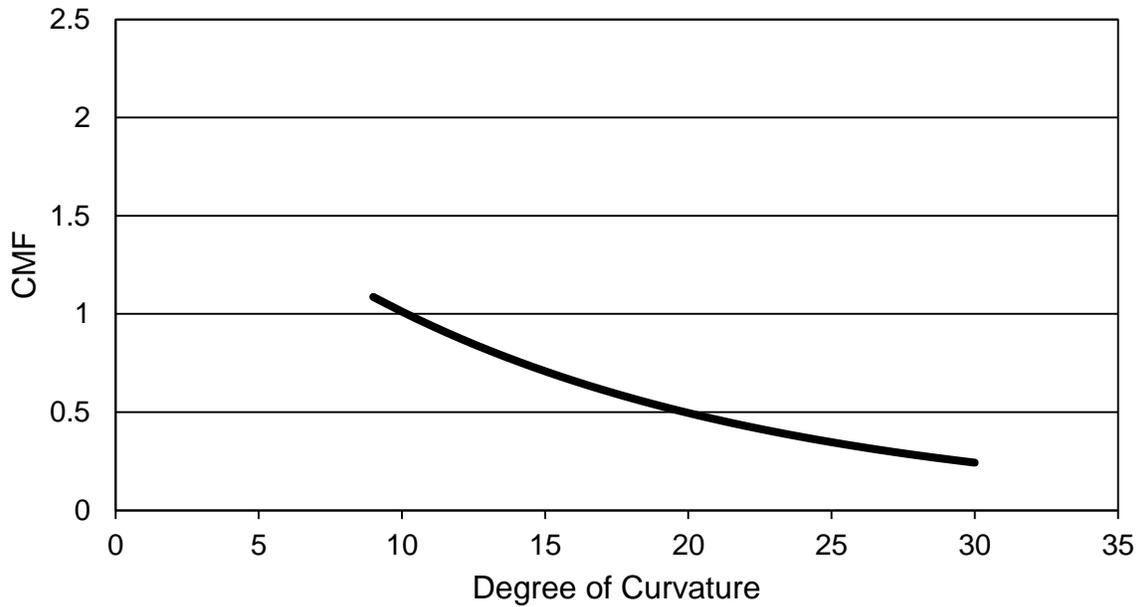


Figure H-5. CMFunction for total crashes for Large Arrow signs on isolated curves.

Injury Crashes

The functional form of the crash prediction model for injury crashes is given by Equation 8 and the coefficients and related statistics are provided in Table H-9. The presence of chevrons, Large Arrows, or a combination of chevrons and Large Arrows is indicated with a single variable for in-curve warning signs (withintcd).

$$Injury\ Crashes = AADT^{\beta_1} * HCLLEN^{\beta_2} * exp(Constant + C_1X_1 + \dots + C_nX_n) \quad 8$$

Table H-9. Crash Prediction Model Coefficients for Injury Crashes

Variables	Coefficient	St. Error	Z-Score	P-Value	L95 CI	U95 CI
Constant	-10.090	1.845	-5.47	< 0.001	-13.707	-6.474
β1 (log-aadt)	0.955	0.164	5.81	< 0.001	0.633	1.277
β2 (log-hclen)	0.247	0.185	1.34	0.181	-0.115	0.609
C1 (Florida)	-1.106	0.430	-2.57	0.010	-1.949	-0.263
C2 (Tennessee)	-0.905	0.389	-2.33	0.020	-1.667	-0.142
C3 (Ohio)	-0.716	0.341	-2.10	0.036	-1.384	-0.048
C4 (rumble)	-1.023	0.450	-2.27	0.023	-1.904	-0.141
C5 (lwl12)	0.612	0.268	2.28	0.022	0.087	1.138
C6 (speedreduc)	0.017	0.012	1.44	0.150	-0.006	0.039
C7 (withintcd)	0.564	0.356	1.59	0.113	-0.133	1.261
C8 (withinaadtint)	-0.157	0.063	-2.50	0.012	-0.281	-0.034
Overdispersion	0.110	0.184				

N = 348; Log-likelihood = -231.25; Pseudo R² = 0.108

Interpretations for the covariates include:

- AADT (log-AADT): A positive association was found between the natural logarithm of AADT and injury crashes. An increase in AADT results in an increase in injury crashes.

However, the AADT variable is also included in the interaction with in-curve warning signs (withinaadtint).

- Horizontal Curve Length (log-hclen): A positive association was found between the natural logarithm of horizontal curve length and injury crashes. An increase in curve length results in an increase in injury crashes.
- Florida, Tennessee, and Ohio Indicators (Florida, Tennessee, Ohio): A negative association was found between the indicators for the sites located in Florida, Tennessee, or Ohio and injury crashes. The base condition is that the site location is in Oregon. Sites in Florida, Tennessee, and Ohio experience fewer injury crashes than those in Oregon.
- Rumble Strips Indicator (rumble): A negative association was found between the indicator for the presence of rumble strips and injury crashes. The base condition is no rumble strips present. Sites with rumble strips experience fewer injury crashes than those without rumble strips.
- Lane Width Less than 12 feet Indicator (lwl12): A positive association was found between the narrow lane width and injury crashes. The base condition is a lane width that is 12 feet or greater. Sites with a narrow lane (i.e., less than 12 feet) experience more injury crashes than sites with wide lanes.
- Speed Reduction (speedreduc): A positive association was found between speed reduction and injury crashes. An increase in speed reduction is associated with an increase in injury crashes.
- Presence of In-Curve Warning Signs (withintcd): A positive association was found between having an in-curve warning sign and injury crashes. The finding is part of an interaction with AADT.
- Interaction term for In-Curve Warning Signs and AADT (withinaadtint): A negative relationship was found between the interaction term and injury crashes. This implies that in-curve warning signs on roadways with higher AADT are associated with fewer injury crashes. AADT in the interaction term is entered in thousands of vehicles.

A CMFunction relating the effect of in-curve warning signs to injury crashes by AADT is presented in Equation 9.

$$CMF_{injury,isolated-within} = \exp(0.564 - 0.157 * AADT(thousands)) \quad 9$$

Figure H-6 graphically represents the CMFunction for injury crashes by AADT. For injury crashes, Chevrons and/or Large Arrows are significantly associated with fewer crashes when the AADT is more than 7,000. While the CMF is statistically insignificant for AADTs less than 7,000, the mean CMF value is less than 1.00 (potential safety benefit) when the AADT is greater than 3,500.

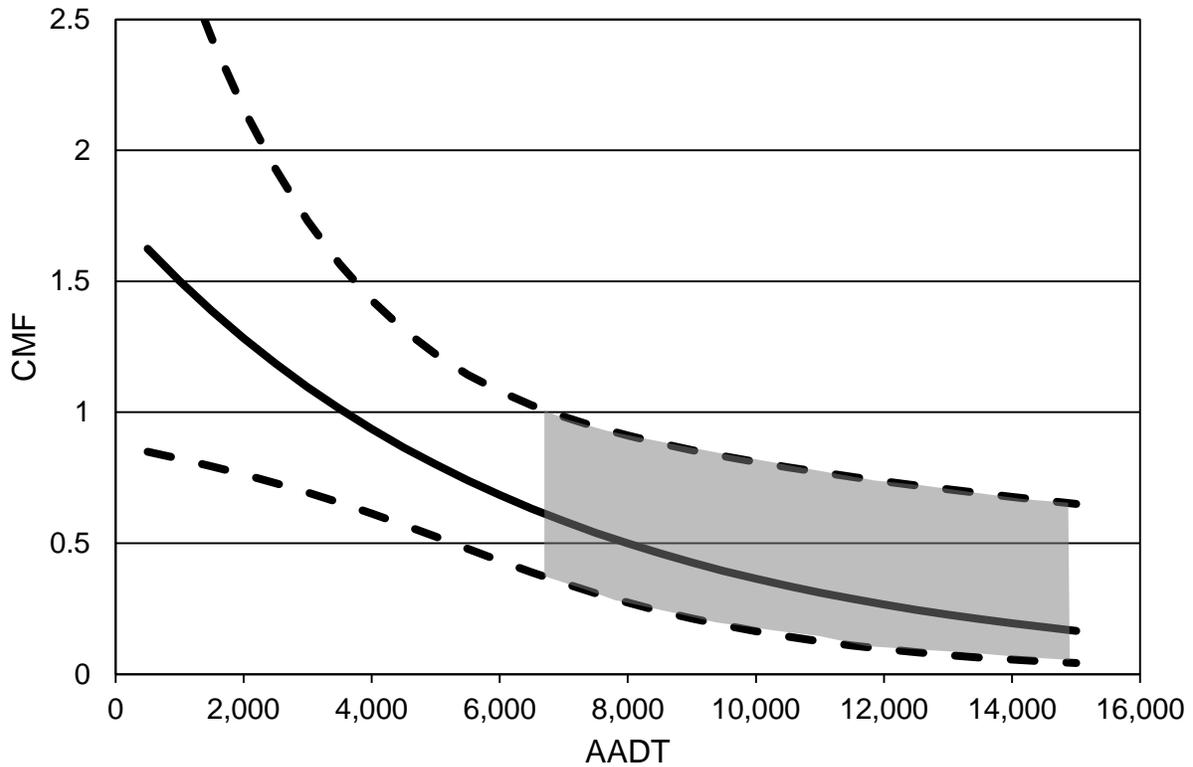


Figure H-6. CMFunction for injury crashes for in-curve warning signs on isolated curves.

SVROR Crashes

The functional form of the crash prediction model for SVROR crashes is given by Equation 10 and the coefficients and related statistics are provided in Table H-10. The presence of chevrons, Large Arrow signs, or a combination of chevrons and Large Arrows is indicated with a single variable for in-curve warning signs (withintcd).

$$SVROR\ Crashes = AADT^{\beta_1} * HCLLEN^{\beta_2} * exp(Constant + C_1X_1 + \dots + C_nX_n) \quad 10$$

Table H-10. Crash Prediction Model Coefficients for SVROR Crashes

Variables	Coefficient	St. Error	Z-Score	P-Value	L95 CI	U95 CI
Constant	-8.961	1.533	-5.85	< 0.001	-11.965	-5.957
β_1 (log-aadt)	0.884	0.127	6.94	< 0.001	0.634	1.133
β_2 (log-hclen)	0.209	0.145	1.44	0.150	-0.076	0.494
C1 (Florida)	-1.072	0.374	-2.87	0.004	-1.806	-0.339
C2 (rumble)	-1.023	0.305	-2.28	0.022	-1.296	-0.099
C3 (rhr3l)	-0.374	0.196	-1.91	0.056	-0.758	0.009
C4 (speedreduc)	0.019	0.010	1.86	0.063	-0.001	0.039
C5 (withintcd)	0.179	0.302	0.59	0.552	-0.412	0.770
C6 (withinaadtint)	-0.079	0.051	-1.53	0.127	-0.179	0.022
Overdispersion	0.224	0.166				
N = 348; Log-likelihood = -283.24; Pseudo R ² = 0.115						

Interpretations for the covariates include:

- AADT (log-AADT): A positive association was found between the natural logarithm of AADT and SVROR crashes. An increase in AADT results in an increase in SVROR crashes. However, the AADT variable is also included in the interaction with in-curve warning signs (withinaadtint).
- Horizontal Curve Length (log-hclen): A positive association was found between the natural logarithm of horizontal curve length and SVROR crashes. An increase in curve length results in an increase in SVROR crashes.
- Florida Indicator (Florida): A negative association was found between SVROR crashes and the site location being in Florida. The base condition is that the site location is in Ohio, Oregon, or Tennessee. Sites in Florida experience fewer SVROR crashes than those in Ohio, Oregon, and Tennessee.
- Rumble Strips Indicator (rumble): A negative association was found between the indicator for the presence of rumble strips and SVROR crashes. The base condition is no rumble strips present. Sites with rumble strips experience fewer SVROR crashes than those without rumble strips.
- Roadside Hazard Rating Three or Less (rhr3l): A negative association was found between a curve having a roadside hazard rating of three or less and SVROR crashes. The base condition is a roadside hazard rating greater than 3 (more severe). A less severe roadside hazard rating is associated with fewer SVROR crashes.
- Speed Reduction (speedreduc): A positive association was found between speed reduction and SVROR crashes. An increase in speed reduction is associated with an increase in SVROR crashes.
- Presence of In-Curve Warning Signs (withintcd): A positive association was found between having an in-curve warning sign and SVROR crashes. The finding is part of an interaction with AADT, and the main effect was not significant.
- Interaction term for In-Curve Warning Signs and AADT (withinaadtint): A negative relationship was found between the interaction term and SVROR crashes. This implies that in-curve warning signs on roadways with higher AADT are associated with fewer SVROR crashes. AADT in the interaction term is entered in thousands of vehicles.

A CMFunction relating the effect of in-curve warning signs to SVROR crashes by AADT is presented in Equation 11.

$$CMF_{SVROR,isolated-within} = \exp(0.179 - 0.079 * AADT(thousands)) \quad 11$$

Figure H-7 graphically represents the CMFunction for SVROR crashes by AADT. For SVROR crashes, Chevrons and/or Large Arrows are significantly associated with fewer crashes when the AADT is more than 7,000 and less than 11,500. While the CMF is statistically insignificant for AADTs less than 7,000 and greater than 11,500, the mean CMF value is less than 1.00 (potential safety benefit) when the AADT is greater than 2,000.

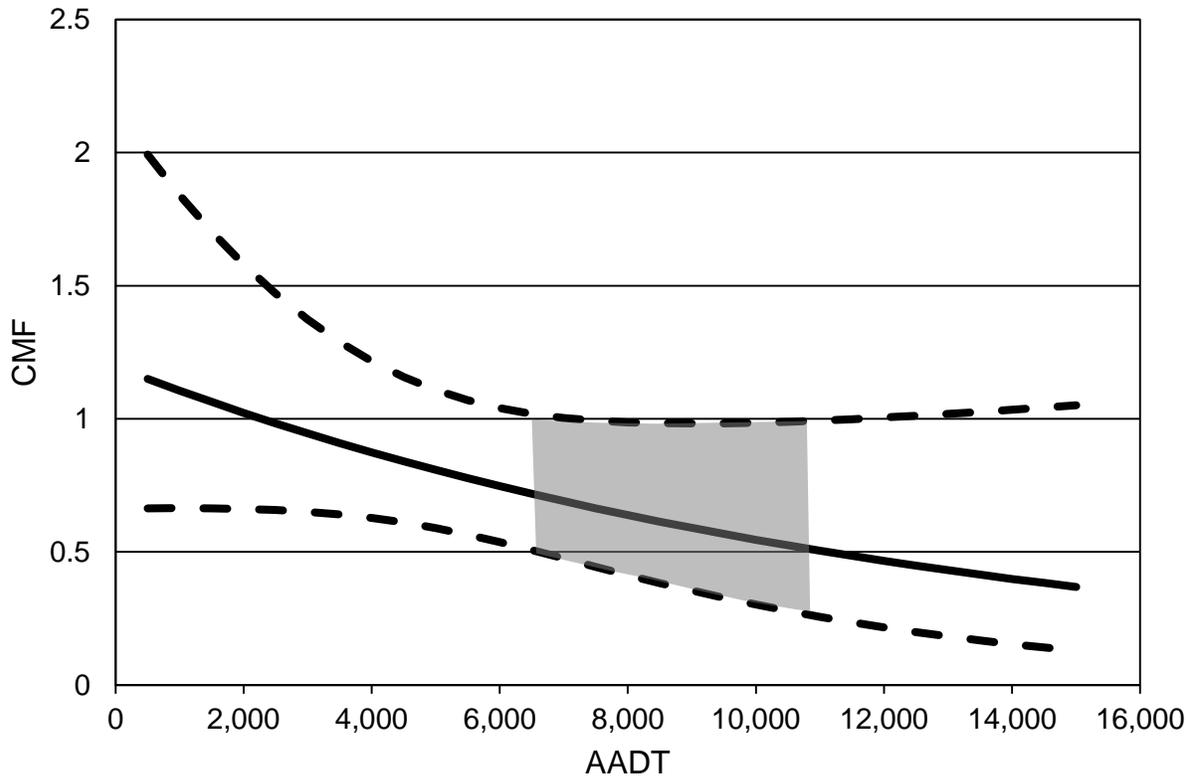


Figure H-7. CMFunction for SVROR crashes for in-curve warning signs on isolated curves.

Adverse Pavement Condition Crashes

The functional form of the crash prediction model for adverse pavement condition crashes is given by Equation 12 and the coefficients and related statistics are provided in Table H-11. The presence of chevrons, Large Arrows, or a combination of chevrons and Large Arrows is indicated with a single variable for in-curve warning signs (withintcd).

$$Adv. Pvmnt. Crashes = AADT^{\beta_1} * HCLEN^{\beta_2} * exp(Constant + C_1X_1 + \dots + C_nX_n) \quad 12$$

Table H-11. Crash Prediction Model Coefficients for Adverse Pavement Condition Crashes

Variables	Coefficient	St. Error	Z-Score	P-Value	L95 CI	U95 CI
Constant	-16.343	2.018	-8.10	< 0.001	-20.298	-12.388
β1 (log-aadt)	1.095	0.161	6.80	< 0.001	0.780	1.411
β2 (log-hclen)	0.601	0.182	3.30	0.001	0.244	0.958
C1 (Florida)	-2.724	0.654	-4.17	< 0.001	-4.006	-1.443
C2 (rumble)	-0.733	0.403	-1.82	0.069	-1.523	0.058
C3 (lwl12)	0.689	0.239	2.88	0.004	0.220	1.158
C4 (speedreduc)	0.040	0.013	3.15	0.002	0.015	0.065
C5 (rrpm)	0.541	0.256	2.11	0.035	0.039	1.043
C6 (pmd)	0.766	0.406	1.89	0.059	-0.030	1.562
C7 (posted)	0.036	0.025	1.47	0.141	-0.012	0.084
C8 (rhr3l)	-0.349	0.239	-1.46	0.144	-0.818	0.120
C9 (withintcd)	0.015	0.406	0.04	0.970	-0.780	0.811
C10 (withinaadtint)	-0.117	0.066	-1.77	0.078	-0.247	0.013
Overdispersion	< 0.001	< 0.001				
N = 348; Log-likelihood = -191.46; Pseudo R ² = 0.211						

Interpretations for the covariates include:

- **AADT (log-AADT):** A positive association was found between the natural logarithm of AADT and adverse pavement condition crashes. An increase in AADT results in an increase in adverse pavement condition crashes. However, the AADT variable is also included in the interaction with in-curve warning signs (withinaadtint).
- **Horizontal Curve Length (log-hclen):** A positive association was found between the natural logarithm of horizontal curve length and adverse pavement condition crashes. An increase in curve length results in an increase in adverse pavement condition crashes.
- **Florida Indicator (Florida):** A negative association was found between the indicator for the site location being in Florida and adverse pavement condition crashes. The base condition is that the site is located in Ohio, Oregon, or Tennessee. Sites in Florida experience fewer adverse pavement condition crashes than those in Ohio, Oregon, and Tennessee.
- **Rumble Strips Indicator (rumble):** A negative association was found between the indicator for the presence of rumble strips and adverse pavement condition crashes. The base condition is no rumble strips present. Sites with rumble strips experience fewer adverse pavement condition crashes than those without rumble strips.
- **Lane Width Less than 12 feet Indicator (lwl12):** A positive association was found between the narrow lane width and adverse pavement condition crashes. The base condition is a lane width that is 12 feet or greater. Sites with a narrow lane (i.e., less than 12 feet) experience more adverse pavement condition crashes than sites with wide lanes.
- **Speed Reduction (speedreduc):** A positive association was found between speed reduction and adverse pavement condition crashes. An increase in speed reduction is associated with an increase in adverse pavement condition crashes.
- **Raised Reflective Pavement Markings (rrpm):** A positive association was found between RRPMs and adverse pavement condition crashes. The base condition is no RRPMs present. Sites with RRPMs experience more adverse pavement condition crashes than sites without RRPMs.
- **Post-Mounted Delineators (pmd):** A positive association was found between PMDs and adverse pavement condition crashes. The base condition is no PMDs present. Sites with PMDs experience more adverse pavement condition crashes than sites without PMDs.

- Posted Speed Limit (posted): A positive association was found between posted speed limit and adverse pavement condition crashes. An increase in posted speed limit is associated with an increase in adverse pavement condition crashes.
- Roadside Hazard Rating Three or Less (rhr3l): A negative association was found between a curve having a roadside hazard rating of three or less and adverse pavement condition crashes. The base condition is a roadside hazard rating greater than three (more severe). A less severe roadside hazard rating is associated with fewer adverse pavement condition crashes.
- Presence of in-curve warning signs (withintcd): A positive association was found between having an in-curve warning sign and adverse pavement condition crashes. The finding is part of an interaction with AADT, and the main effect was not even marginally significant.
- Interaction term for In-Curve Warning Signs and AADT (withinaadtint): A negative relationship was found between the interaction term and adverse pavement condition crashes. This implies that in-curve warning signs on roadways with higher AADT are associated with fewer adverse pavement condition crashes. AADT in the interaction term is entered in thousands of vehicles.

A CMFunction relating the effect of in-curve warning signs to adverse pavement condition crashes by AADT is presented in Equation 13.

$$CMF_{adverse,isolated-within} = \exp(0.015 - 0.117 * AADT(thousands)) \quad 13$$

Figure H-8 graphically represents the CMFunction for adverse pavement condition crashes by AADT. For adverse pavement condition crashes, Chevrons and/or Large Arrows are significantly associated with fewer crashes when the AADT is more than 4,000. While the CMF is statistically insignificant for AADTs less than 4,000, the mean CMF value is less than 1.00 (potential safety benefit) for all values of AADT.

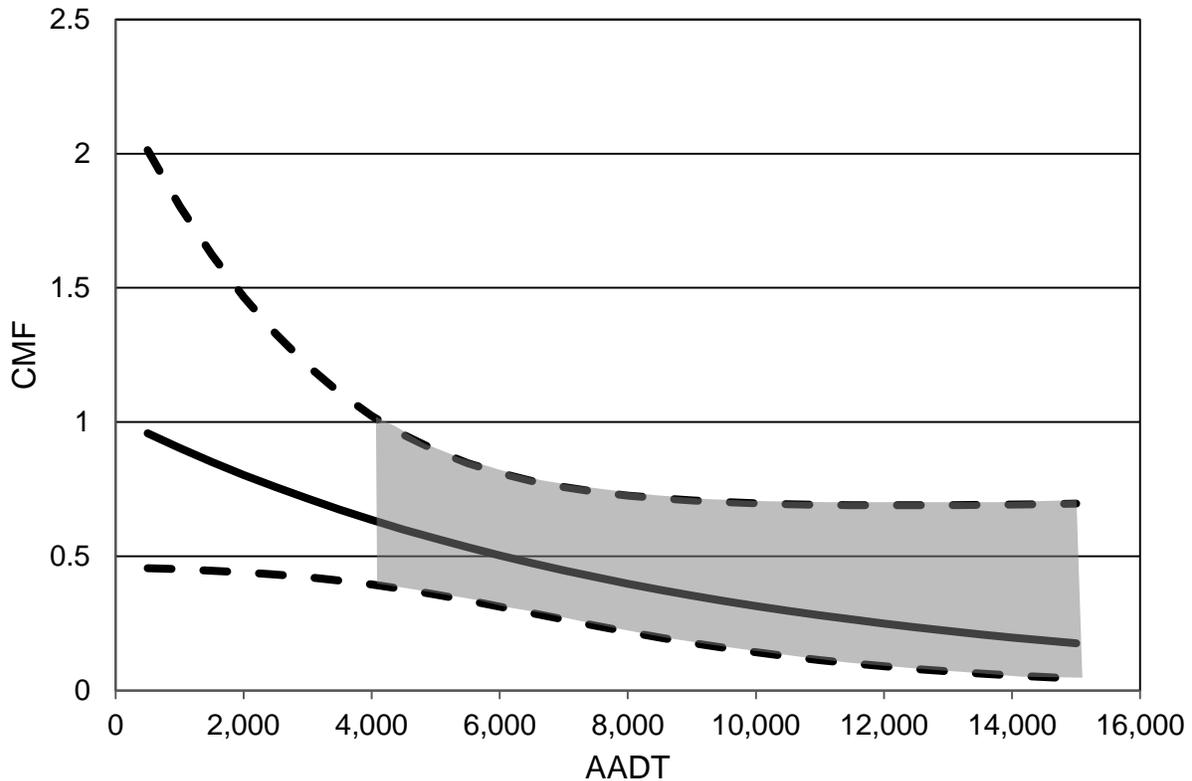


Figure H-8. CMFunction for adverse pavement condition crashes for in-curve warning signs on isolated curves.

Nighttime Crashes

There was an insufficient amount of data to develop nighttime crash prediction models for in-curve warning signs on isolated curves.

Chevrons and/or Large Arrows within Series Curves

The final matched dataset for series curves considers the presence of chevrons, Large Arrow signs, or the combination of chevrons and Large Arrows. Due to the smaller sample of sites with a Large Arrows or a combination of Chevrons and Large Arrows, the effects of individual sign types/combinations were analyzed aggregately. The dataset used for the analysis of in-curve warning signs for series curves was selected using NN matching without a caliper, because the caliper based match did not result in a reduction in bias compared to NN matching. While the original series curve dataset consisted of 225 treated curves and 585 untreated curves, the final matched dataset consisted of 225 site-years of treated curves and 225 site years of untreated curves. For sites treated with chevrons and/or Large Arrows, 99 percent had a Reverse Curve, Reverse Turn, or Winding Road warning sign. For untreated sites, 94 percent also had a Reverse Curve, Reverse Turn, or Winding Road warning sign. Only 4 percent of sites in the matched dataset had no advance warning sign.

The final crash prediction models are presented in the subsections below, along with interpretations of the variables included in the models. The results of the models focus on the CMFunctions for the presence of in-curve warning signs. CMFunctions were developed because the safety effect of in-curve warning signs was found to be a function of the traffic volume (AADT). The figures corresponding for each CMFunction identify with shaded regions the ranges over which the treatment results in a statistically significant reduction in crashes. Additional interactions were explored between in-curve warning signs and speed reduction. The resulting interaction terms were counterintuitive, finding that chevrons and/or Large Arrows are less effective, or are even associated with more crashes, as speed reduction increases. As with isolated curves, upon further exploration, the data showed a negative correlation between AADT and speed reduction. Therefore, the final CMFunctions consider the interaction between in-curve warning sign application and traffic volume.

Total Crashes

The functional form of the crash prediction model for total crashes considering in-curve warning signs is given by Equation 14, with the coefficients and related statistics provided in Table H-12. A single variable (withintcd) indicates the presence of chevrons, Large Arrows, or a combination of chevrons and Large Arrows.

$$\text{Total Crashes} = \text{AADT}^{\beta_1} * \text{Length}^{\beta_2} * \exp(\text{Constant} + C_1X_1 + \dots + C_nX_n) \quad 14$$

Table H-12. Crash Prediction Model Coefficients for Total Crashes

Variables	Coefficient	St. Error	Z-Score	P-Value	L95 CI	U95 CI
Constant	-7.523	0.872	-8.62	< 0.001	-9.233	-5.813
β1 (log-aadt)	0.854	0.097	8.82	< 0.001	0.664	1.044
β2 (log-length)	0.342	0.091	3.77	< 0.001	0.164	0.520
C1 (Tennessee)	0.410	0.211	1.95	0.052	-0.003	0.823
C2 (Ohio)	1.140	0.220	5.18	< 0.001	0.708	1.571
C3 (Iw112)	0.295	0.136	2.17	0.030	0.028	0.562
C4 (rhr)	0.086	0.056	1.54	0.124	-0.024	0.196
C5 (speedreduc)	0.013	0.007	2.01	0.045	0.001	0.027
C6 (propcurvel60)	-0.364	0.180	-2.02	0.044	-0.717	-0.011
C7 (rrpm)	-0.295	0.160	-1.85	0.064	-0.608	0.018
C8 (pmd)	0.449	0.207	2.17	0.030	0.044	0.855
C9 (withintcd)	0.401	0.170	2.36	0.018	0.069	0.733
C10 (withinaadtint)	-0.065	0.033	-1.95	0.052	-0.130	0.001
Overdispersion	0.224	0.086				

N = 450; Log-likelihood = -536.86; Pseudo R² = 0.112

Interpretations for the covariates include:

- AADT (log-AADT): A positive association was found between the natural logarithm of AADT and total crashes. An increase in log-AADT results in an increase in total crashes. However, the AADT variable is also included in the interaction with in-curve warning signs (withinaadtint).
- Series Length (log-length): A positive association was found between the natural logarithm of series length and total crashes. An increase in length results in an increase in total crashes.

- Tennessee and Ohio Indicators (Tennessee, Ohio): A positive association was found between total crashes and the site location being in Tennessee or Ohio. The base condition is that the site is located in Florida or Oregon. Sites in Tennessee and Ohio experience more total crashes than those in Florida and Oregon.
- Lane Width Less than 12 feet Indicator (lw12): A positive association was found between the narrow lane width and total crashes. The base condition is a lane width that is 12 feet or greater. Sites with a narrow lane (i.e., less than 12 feet) experience more total crashes than sites with wide lanes.
- Roadside Hazard Rating (rhr): A positive association was found between roadside hazard rating and total crashes. An increase in roadside hazard rating is associated with more total crashes.
- Speed Reduction (speedreduc): A positive association was found between speed reduction and total crashes. An increase in speed reduction is associated with an increase in total crashes.
- Proportion Curve Less than 60 Percent (propcurvel60): A negative association was found between the proportion of the curve series being less than 60 percent curvature and total crashes. The base condition is that more than 60 percent of the series is curvature. Sites with less than 60 percent curvature are associated with fewer crashes than sites with more curvature.
- Raised Reflective Pavement Markings (rrpm): A negative association was found between RRPMs and total crashes. The base condition is no RRPMs present. Sites with RRPMs experience fewer total crashes than sites without RRPMs.
- Post-Mounted Delineators (pmd): A positive association was found between PMDs and total crashes. The base condition is no PMDs present. Sites with PMDs experience more total crashes than sites without PMDs.
- Presence of In-Curve Warning Signs (withintcd): A positive association was found between having an in-curve warning sign and total crashes. The finding is part of an interaction with AADT.
- Interaction term for In-Curve Warning Signs and AADT (withinaadtint): A negative relationship was found between the interaction term and total crashes. This implies that in-curve warning signs on roadways with higher AADT are associated with fewer total crashes. AADT in the interaction term is entered in thousands of vehicles.

A CMFunction relating the effect of in-curve warning signs to total crashes by AADT is presented in Equation 15.

$$CMF_{total,series-within} = \exp(0.401 - 0.065 * AADT(thousands)) \quad 15$$

Figure H-9 graphically represents the CMFunction for total crashes by AADT. For total crashes, chevrons and/or Large Arrows are significantly associated with more crashes for AADT less than 2,500. While the CMF is statistically insignificant for AADT greater than 2,500, the mean CMF value is less than 1.00 (potential safety benefit) for AADT greater than 6,000.

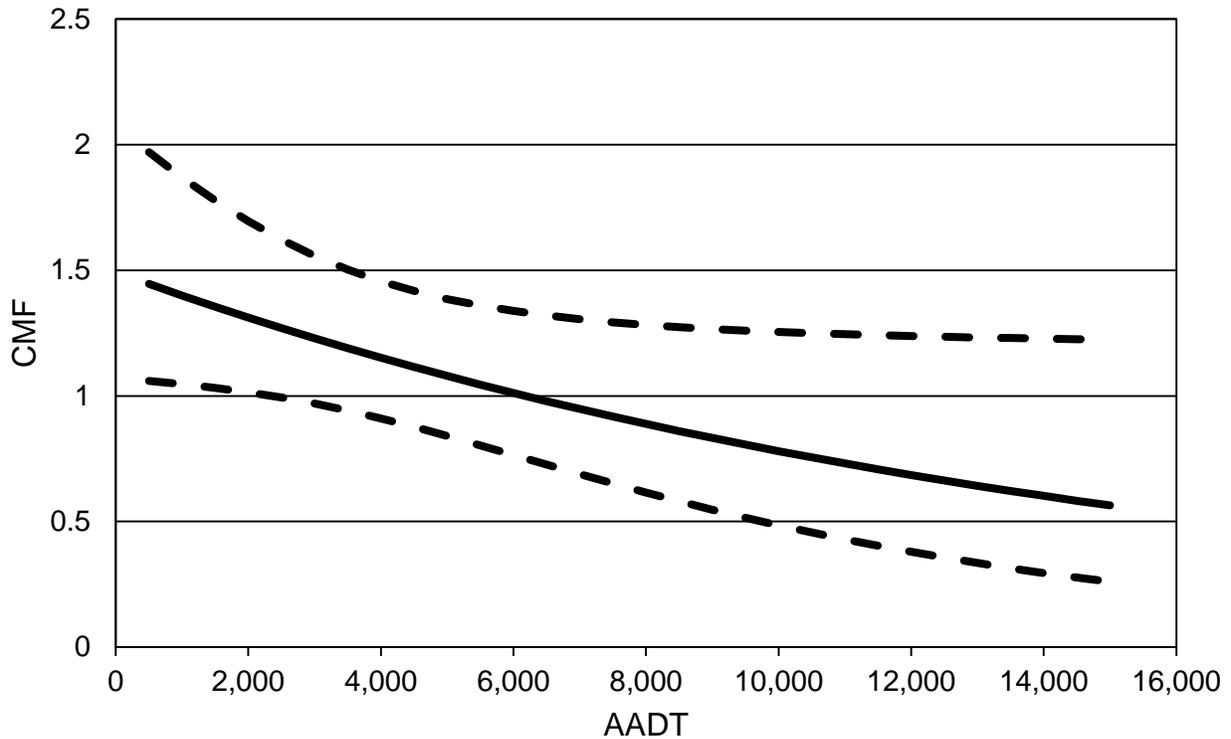


Figure H-9. CMFunction for total crashes for in-curve warning signs on series curves.

The results were further disaggregated by individual in-curve warning signs for total crashes. Figure H-10 presents estimated CMFunctions for the AADT range applicable based on the data used to develop the crash prediction models. There were too few observations to include the combination of chevrons and Large Arrows; however, there was no trend indicating an increased benefit from including in-curve warning signs in combination. It appears from Figure H-10 that, where applied, Large Arrows have a greater impact on crash reduction than Chevrons for AADT greater than 2,000. Further analysis showed that Large Arrows are typically applied on roadways with lower traffic volumes and more severe horizontal curves. Figure H-10 illustrates the mean estimate of CMFunctions; confidence intervals could not be calculated. Due to small sample sizes, similar disaggregate analyses were not possible for other crash types for in-curve warning signs on series curves.

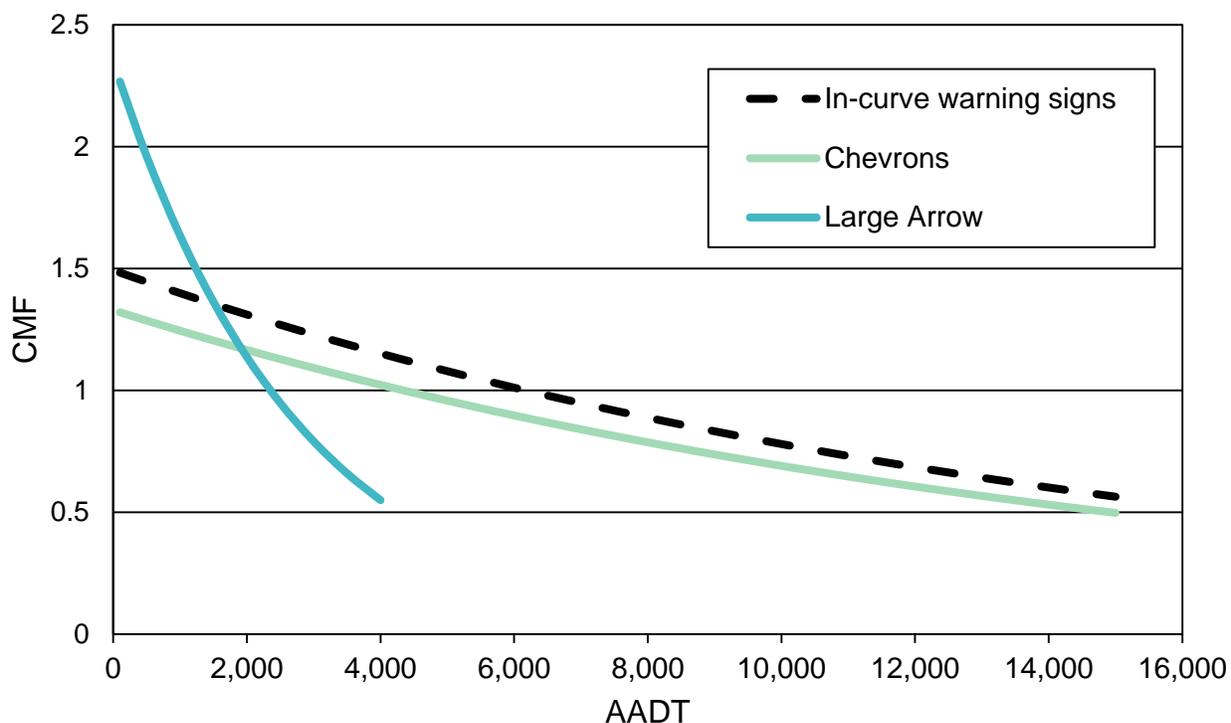


Figure H-10. CMFunction for Total Crashes for Specific In-Curve Warning Signs on Series Curves.

Injury Crashes

The functional form of the crash prediction model for injury crashes considering in-curve warning signs is given by Equation 16 and the coefficients and related statistics are provided in Table H-13. A single variable (withintcd) indicates the presence of chevrons, Large Arrows, or a combination of chevrons and Large Arrows.

$$\text{Injury Crashes} = \text{AADT}^{\beta_1} * \text{Length}^{\beta_2} * \exp(\text{Constant} + C_1X_1 + \dots + C_nX_n) \quad 16$$

Table H-13. Crash Prediction Model Coefficients for Injury Crashes

Variables	Coefficient	St. Error	Z-Score	P-Value	L95 CI	U95 CI
Constant	-8.920	1.313	-6.79	< 0.001	-11.493	-6.346
β_1 (log-aadt)	0.976	0.152	6.41	< 0.001	0.678	1.275
β_2 (log-length)	0.035	0.134	0.27	0.790	-0.226	0.297
C1 (Florida)	-0.442	0.440	-1.01	0.315	-1.305	0.420
C2 (lwl12)	0.245	0.194	1.27	0.206	-0.134	0.624
C3 (rhr3l)	-0.290	0.225	-1.29	0.197	-0.730	0.150
C4 (rumble)	-0.968	0.517	-1.87	0.061	-1.981	0.045
C5 (speedreduc)	0.015	0.009	1.59	0.111	-0.003	0.032
C6 (withintcd)	0.860	0.291	2.95	0.003	0.289	1.431
C7 (withinaadtint)	-0.150	0.069	-2.18	0.029	-0.285	-0.015
Overdispersion	0.495	0.217				
N = 450; Log-likelihood = -352.90; Pseudo R ² = 0.084						

Interpretations for the covariates include:

- AADT (log-AADT): A positive association was found between the natural logarithm of AADT and injury crashes. An increase in AADT results in an increase in injury crashes. However, the AADT variable is also included in the interaction with in-curve warning signs (withinaadtint).
- Series Length (log-length): A positive association was found between the natural logarithm of series length and injury crashes. An increase in length results in an increase in injury crashes. This finding was not even marginally significant, but was retained in the base model for consistency.
- Florida Indicator (Florida): A negative association was found between the indicator for the site location being in Florida and injury crashes. The base condition is that the site location is in Ohio, Oregon, or Tennessee. Sites in Florida experience fewer injury crashes than those in Ohio, Oregon, and Tennessee.
- Lane Width Less than 12 feet Indicator (lwl12): A positive association was found between the narrow lane width and injury crashes. The base condition is a lane width that is 12 feet or greater. Sites with a narrow lane (i.e., less than 12 feet) experience more injury crashes than sites with wide lanes.
- Roadside Hazard Rating Three or Less (rhr3l): A negative association was found between having a roadside hazard rating of three or less and injury crashes. The base condition is a roadside hazard rating greater than three. Sites with a roadside hazard rating of three or less are associated with fewer injury crashes.
- Rumble Strips Indicator (rumble): A negative association was found between the indicator for the presence of rumble strips and injury crashes. The base condition is no rumble strips present. Sites with rumble strips experience fewer injury crashes than those without rumble strips.
- Speed Reduction (speedreduc): A positive association was found between speed reduction and injury crashes. An increase in speed reduction is associated with an increase in injury crashes.
- Presence of In-Curve Warning Signs (withintcd): A positive association was found between having an in-curve warning sign and injury crashes. The finding is part of an interaction with AADT.
- Interaction term for In-Curve Warning Signs and AADT (withinaadtint): A negative relationship was found between the interaction term and injury crashes. This implies that in-curve warning signs on roadways with higher AADT are associated with fewer injury crashes. AADT in the interaction term is entered in thousands of vehicles.

A CMFunction relating the effect of in-curve warning signs to injury crashes by AADT is presented in Equation 17.

$$CMF_{injury,series-within} = \exp(0.860 - 0.150 * AADT(thousands)) \quad 17$$

Figure H-11 graphically represents the CMFunction for injury crashes by AADT. For injury crashes, Chevrons and/or Large Arrows are significantly associated with more crashes for AADT less than 3,500. While the CMF is statistically insignificant for AADTs more than 3,500, the mean CMF value is less than 1.00 (potential safety benefit) for AADT greater than 6,000.

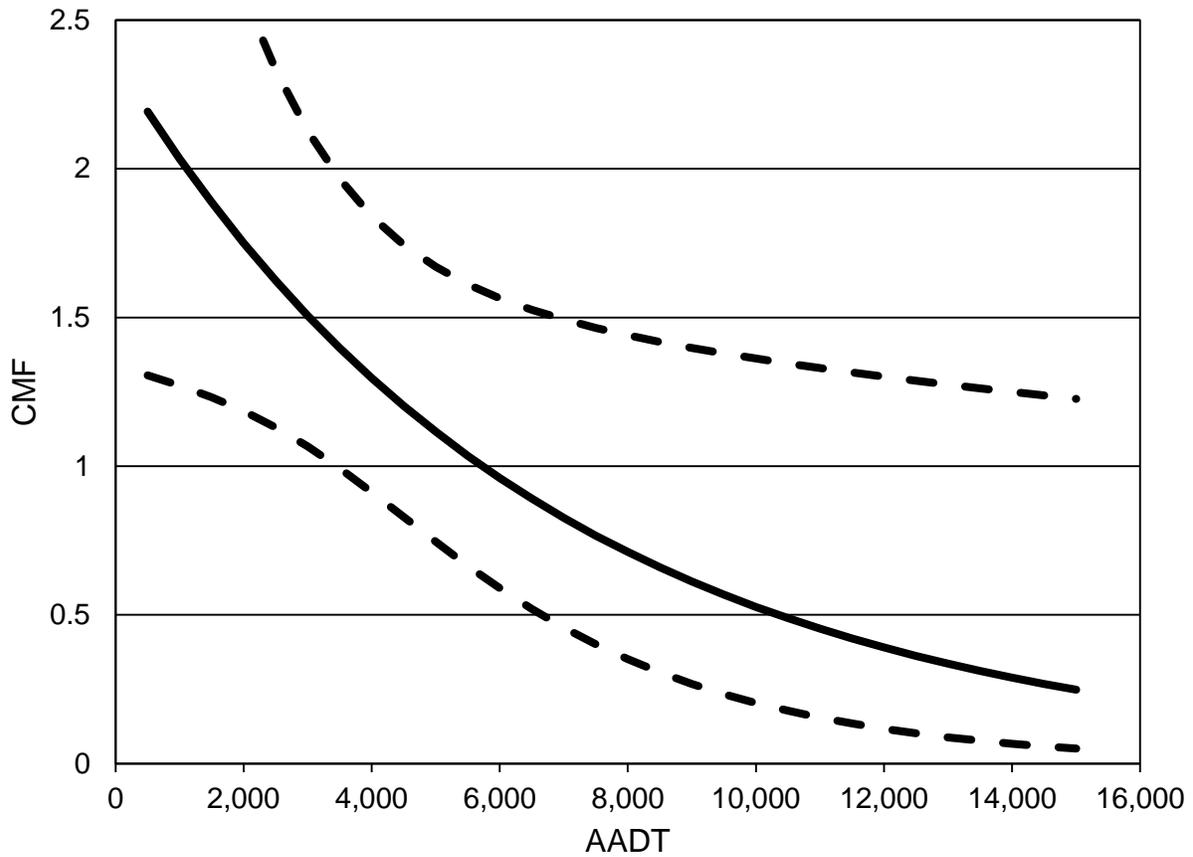


Figure H-11. CMFunction for injury crashes for in-curve warning signs on series curves.

SVROR Crashes

The functional form of the crash prediction model for SVROR crashes considering in-curve warning signs on curve series is given by Equation 18 and the coefficients and related statistics are provided in Table H-14. The presence of chevrons, Large Arrows, or a combination of chevrons and Large Arrows is indicated with a single variable for in-curve warning signs (withintcd).

$$SVROR\ Crashes = AADT^{\beta_1} * Length^{\beta_2} * exp(Constant + C_1X_1 + \dots + C_nX_n) \quad 18$$

Table H-14. Crash Prediction Model Coefficients for SVROR Crashes

Variables	Coefficient	St. Error	Z-Score	P-Value	L95 CI	U95 CI
Constant	-6.508	1.025	-6.35	< 0.001	-8.517	-4.500
β_1 (log-aadt)	0.689	0.119	5.79	< 0.001	0.456	0.923
β_2 (log-length)	0.261	0.123	2.13	0.033	0.021	0.502
C1 (Tennessee)	0.729	0.283	2.57	0.010	0.174	1.285
C2 (Ohio)	1.437	0.293	4.90	< 0.001	0.862	2.012
C3 (lwl12)	0.215	0.177	1.22	0.224	-0.131	0.561
C4 (rhr3l)	-0.313	0.177	-1.77	0.077	-0.659	0.033
C5 (rumble)	-0.572	0.386	-1.48	0.138	-1.328	0.184
C6 (propcurvel60)	-0.294	0.222	-1.32	0.187	-0.730	0.143
C7 (pmd)	0.646	0.260	2.49	0.013	0.137	1.156
C8 (rrpm)	-0.266	0.212	-1.26	0.208	-0.681	0.148
C9 (ccr)	0.040	0.026	1.55	0.120	-0.010	0.090
C10 (withintcd)	0.278	0.217	1.28	0.200	-0.147	0.703
C11 (withinaadtint)	-0.041	0.049	-0.84	0.399	-0.138	0.055
Overdispersion	0.321	0.135				
N = 450; Log-likelihood = -433.23; Pseudo R ² = 0.084						

Interpretations for the covariates include:

- **AADT (log-AADT):** A positive association was found between the natural logarithm of AADT and SVROR crashes. An increase in AADT results in an increase in SVROR crashes. However, the AADT variable is also included in the interaction with in-curve warning signs (withinaadtint).
- **Series Length (log-length):** A positive association was found between the natural logarithm of series length and SVROR crashes. An increase in length results in an increase in SVROR crashes.
- **Tennessee and Ohio Indicators (Tennessee, Ohio):** A positive association was found between SVROR crashes and sites located in Tennessee or Ohio. The base condition is that the site location is in Florida or Oregon. Sites in Tennessee and Ohio experience more SVROR crashes than those in Florida and Oregon.
- **Lane Width Less than 12 feet Indicator (lwl12):** A positive association was found between the narrow lane width and SVROR crashes. The base condition is a lane width that is 12 feet or greater. Sites with a narrow lane (i.e., less than 12 feet) experience more SVROR crashes than sites with wide lanes.
- **Roadside Hazard Rating Three or Less (rhr3l):** A negative association was found between having a roadside hazard rating of three or less and SVROR crashes. The base condition is a roadside hazard rating greater than three. Sites with a roadside hazard rating of three or less are associated with fewer SVROR crashes.
- **Rumble Strips Indicator (rumble):** A negative association was found between the indicator for the presence of rumble strips and SVROR crashes. The base condition is no rumble strips present. Sites with rumble strips experience fewer SVROR crashes than those without rumble strips.
- **Proportion Curve Less than 60 Percent (propcurvel60):** A negative association was found between the proportion of the curve series being less than 60 percent curvature and SVROR crashes. The base condition is that more than 60 percent of the series is curvature. Sites with less than 60 percent curvature are associated with fewer SVROR crashes than sites with more curvature.

- Post-Mounted Delineators (pmd): A positive association was found between PMDs and SVROR crashes. The base condition is no PMDs present. Sites with PMDs experience more SVROR crashes than sites without PMDs.
- Raised Reflective Pavement Markings (rrpm): A negative association was found between RRPMs and SVROR crashes. The base condition is no RRPMs present. Sites with RRPMs experience fewer SVROR crashes than sites without RRPMs.
- Curvature Change Rate (CCR): A positive association was found between CCR and SVROR crashes. CCR is entered in hundreds. An increase in CCR is associated with an increase in SVROR crashes.
- Presence of In-Curve Warning Signs (withintcd): A positive association was found between having an in-curve warning sign and SVROR crashes. The finding is part of an interaction with AADT and was marginally significant.
- Interaction term for In-Curve Warning Signs and AADT (withinaadtint): A negative relationship was found between the interaction term and SVROR crashes. This implies that in-curve warning signs on roadways with higher AADT are associated with fewer SVROR crashes. AADT in the interaction term is entered in thousands of vehicles. The interaction term was insignificant.

A CMFunction relating the effect of in-curve warning signs to SVROR crashes by AADT is presented in Equation 19.

$$CMF_{SVROR,series-within} = \exp(0.278 - 0.041 * AADT(thousands)) \quad 19$$

Figure H-12 graphically represents the CMFunction for SVROR crashes by AADT. For SVROR crashes, chevrons and/or Large Arrows are not significantly associated with fewer crashes for any value of AADT. While the CMF is statistically insignificant for all values of AADT, the mean CMF value is less than 1.00 (potential safety benefit) for AADT greater than 7,000.

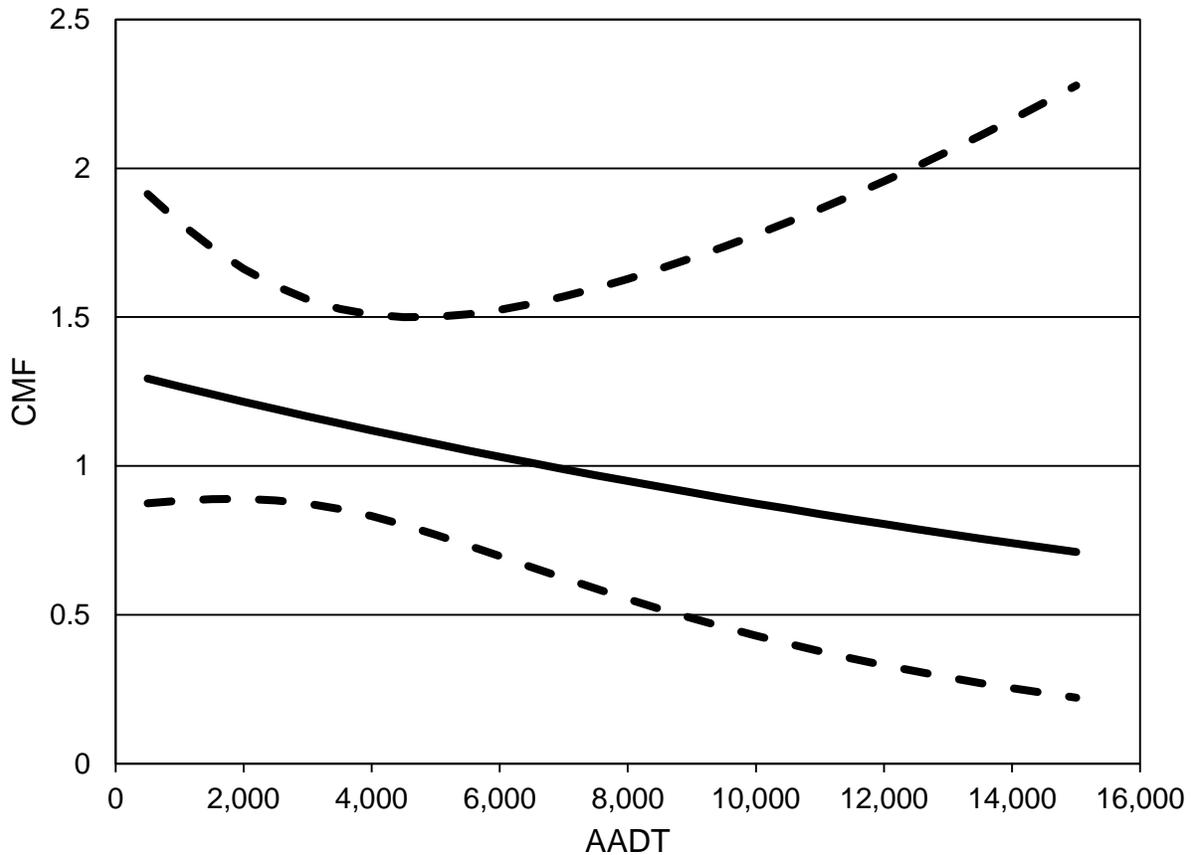


Figure H-12. CMFunction for SVROR Crashes for In-Curve Warning Signs on Series Curves

Adverse Pavement Condition Crashes

The functional form of the crash prediction model for adverse pavement condition crashes considering in-curve warning signs is given by Equation 20 and the coefficients and related statistics are provided in Table H-15. The presence of chevrons, Large Arrows, or a combination of chevrons and Large Arrows is indicated with a single variable for in-curve warning signs (withintcd).

$$Adv. Pvmnt. Crashes = AADT^{\beta_1} * Length^{\beta_2} * exp(Constant + C_1X_1 + \dots + C_nX_n) \quad 20$$

Table H-15. Crash Prediction Model Coefficients for Adverse Pavement Condition Crashes

Variables	Coefficient	St. Error	Z-Score	P-Value	L95 CI	U95 CI
Constant	-8.076	1.308	-6.17	< 0.001	-10.640	-5.512
β1 (log-aadt)	0.815	0.159	5.13	< 0.001	0.503	1.126
β2 (log-length)	0.176	0.145	1.22	0.223	-0.107	0.460
C1 (Ohio)	1.515	0.317	4.78	< 0.001	0.894	2.135
C2 (lwl12)	0.518	0.233	2.22	0.026	0.061	0.976
C3 (rhr3l)	-0.426	0.226	-1.88	0.060	-0.868	0.017
C4 (propcurvel60)	-0.551	0.279	-1.98	0.048	-1.098	-0.005
C5 (pmd)	0.829	0.273	3.04	0.002	0.294	1.363
C6 (rrpm)	-0.477	0.264	-1.81	0.070	-0.994	0.040
C7 (withintcd)	0.583	0.271	2.15	0.032	0.051	1.114
C8 (withinaadtint)	-0.076	0.054	-1.41	0.159	-0.182	0.030
Overdispersion	0.355	0.202				
N = 450; Log-likelihood = -294.69; Pseudo R ² = 0.108						

Interpretations for the covariates include:

- **AADT (log-AADT):** A positive association was found between the natural logarithm of AADT and adverse pavement condition crashes. An increase in AADT results in an increase in adverse pavement condition crashes. However, the AADT variable is also included in the interaction with in-curve warning signs (withinaadtint).
- **Series Length (log-length):** A positive association was found between the natural logarithm of series length and adverse pavement condition crashes. An increase in length results in an increase in adverse pavement condition crashes.
- **Ohio Indicator (Ohio):** A positive association was found between the indicator for the site location being in Ohio and adverse pavement condition crashes. The base condition is that the site location is in Florida, Oregon, or Tennessee. Sites in Ohio experience more adverse pavement condition crashes than those in Florida, Oregon, and Tennessee.
- **Lane Width Less than 12 feet Indicator (lwl12):** A positive association was found between the narrow lane width and adverse pavement condition crashes. The base condition is a lane width that is 12 feet or greater. Sites with a narrow lane (i.e., less than 12 feet) experience more adverse pavement condition crashes than sites with wide lanes.
- **Roadside Hazard Rating Three or Less (rhr3l):** A negative association was found between having a roadside hazard rating of three or less and adverse pavement condition crashes. The base condition is a roadside hazard rating greater than three. Sites with a roadside hazard rating of three or less are associated with fewer adverse pavement condition crashes.
- **Proportion Curve Less than 60 Percent (propcurvel60):** A negative association was found between the proportion of the curve series being less than 60 percent curvature and adverse pavement condition crashes. The base condition is that more than 60 percent of the series is curvature. Sites with less than 60 percent curvature are associated with fewer adverse pavement condition crashes than sites with more curvature.
- **Post-Mounted Delineators (pmd):** A positive association was found between PMDs and adverse pavement condition crashes. The base condition is no PMDs present. Sites with PMDs experience more adverse pavement condition crashes than sites without PMDs.
- **Raised Reflective Pavement Markings (rrpm):** A negative association was found between RRPMs and adverse pavement condition crashes. The base condition is no RRPMs

present. Sites with RRPMs experience fewer adverse pavement condition crashes than sites without RRPMs.

- Presence of In-Curve Warning Signs (withintcd): A positive association was found between having an in-curve warning sign and adverse pavement condition crashes. The finding is part of an interaction with AADT.
- Interaction term for In-Curve Warning Sign and AADT (withinaadtint): A negative relationship was found between the interaction term and adverse pavement condition crashes. This implies that in-curve warning signs on roadways with higher AADT are associated with fewer adverse pavement condition crashes. AADT in the interaction term is entered in thousands of vehicles. The interaction term was marginally significant.

A CMFunction relating the effect of in-curve warning signs to adverse pavement condition crashes by AADT is presented in Equation 21.

$$CMF_{adverse,series-within} = \exp(0.583 - 0.076 * AADT(thousands)) \quad 21$$

Figure H-13 graphically represents the CMFunction for adverse pavement condition crashes by AADT. For adverse pavement condition crashes, Chevrons and/or Large Arrows are significantly associated with more crashes for AADT less than 2,500. While the CMF is statistically insignificant for AADTs more than 2,500, the mean CMF value is less than 1.00 (potential safety benefit) for AADT greater than 7,500.

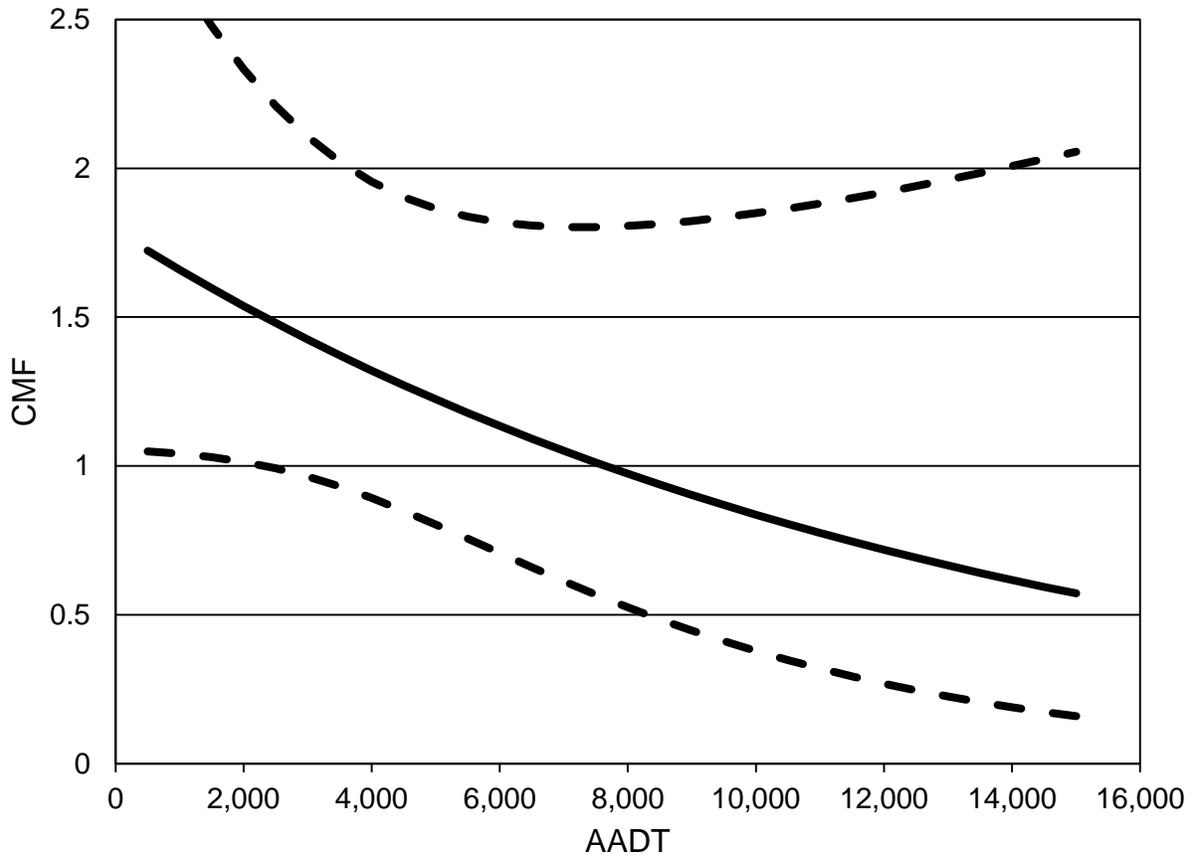


Figure H-13. CMF for adverse pavement condition crashes for in-curve warning signs on series curves.

Nighttime Crashes

The functional form of the crash prediction model for nighttime crashes considering in-curve warning signs is given by Equation 22 and the coefficients and related statistics are provided in Table H-16. The presence of chevrons, Large Arrows, or a combination of chevrons and Large Arrows is indicated with a single variable for in-curve warning signs (withintcd).

$$\text{Nighttime Crashes} = \text{AADT}^{\beta_1} * \text{Length}^{\beta_2} * \exp(\text{Constant} + C_1X_1 + \dots + C_nX_n) \quad 22$$

Table H-16. Crash Prediction Model Coefficients for Nighttime Crashes

Variables	Coefficient	St. Error	Z-Score	P-Value	L95 CI	U95 CI
Constant	-9.701	1.304	-7.44	< 0.001	-12.257	-7.145
β_1 (log-aadt)	0.970	0.145	6.70	< 0.001	0.686	1.254
β_2 (log-length)	0.407	0.146	2.78	0.005	0.120	0.694
C1 (Florida)	0.807	0.567	1.42	0.155	-0.304	1.918
C2 (Tennessee)	0.963	0.444	2.17	0.030	0.092	1.834
C3 (Ohio)	1.886	0.494	3.82	< 0.001	0.918	2.855
C4 (lwl12)	0.482	0.219	2.20	0.028	0.053	0.911
C5 (pmd)	0.460	0.433	1.06	0.288	-0.389	1.309
C6 (rrpm)	-0.316	0.275	-1.15	0.249	-0.855	0.222
C7 (ccr)	0.053	0.035	1.51	0.132	-0.016	0.122
C8 (withintcd)	0.455	0.272	1.67	0.095	-0.079	0.988
C9 (withinaadtint)	-0.136	0.055	-2.47	0.014	-0.244	-0.028
Overdispersion	0.004	0.156				
N = 450; Log-likelihood = -293.62; Pseudo R ² = 0.136						

Interpretations for the covariates include:

- **AADT (log-AADT):** A positive association was found between the natural logarithm of AADT and nighttime crashes. An increase in AADT results in an increase in nighttime crashes. However, the AADT variable is also included in the interaction with in-curve warning signs (withinaadtint).
- **Series Length (log-length):** A positive association was found between the natural logarithm of series length and nighttime crashes. An increase in length results in an increase in nighttime crashes.
- **Florida, Tennessee, and Ohio Indicators (Florida, Tennessee, Ohio):** A positive association was found between the indicator for the site location being in Florida, Tennessee, or Ohio and nighttime crashes. The base condition is that the site location is in Oregon. Sites in Florida, Tennessee, and Ohio experience more nighttime crashes than those in Oregon.
- **Lane Width Less than 12 feet Indicator (lwl12):** A positive association was found between the narrow lane width and nighttime crashes. The base condition is a lane width that is 12 feet or greater. Sites with a narrow lane (i.e., less than 12 feet) experience more nighttime crashes than sites with wide lanes.
- **Post-Mounted Delineators (pmd):** A positive association was found between PMDs and nighttime crashes. The base condition is no PMDs present. Sites with PMDs experience more nighttime crashes than sites without PMDs.
- **Raised Reflective Pavement Markings (rrpm):** A negative association was found between RRPMs and nighttime crashes. The base condition is no RRPMs present. Sites with RRPMs experience fewer nighttime crashes than sites without RRPMs.
- **Curvature Change Rate (CCR):** A positive association was found between CCR and nighttime crashes. CCR is entered in hundreds. An increase in CCR is associated with an increase in nighttime crashes. The finding was marginally significant.
- **Presence of In-Curve Warning Signs (withintcd):** A positive association was found between having an in-curve warning sign and nighttime crashes. The finding is part of an interaction with AADT and was marginally significant.
- **Interaction term for In-Curve Warning Signs and AADT (withinaadtint):** A negative relationship was found between the interaction term and nighttime crashes. This implies that in-curve warning signs on roadways with higher AADT are associated with fewer

nighttime crashes. AADT in the interaction term is entered in thousands of vehicles. The interaction term was insignificant.

A CMFunction relating the effect of in-curve warning signs to nighttime crashes by AADT is presented in Equation 23.

$$CMF_{nighttime,series-within} = \exp(0.455 - 0.136 * AADT(thousands)) \quad 23$$

Figure H-14 graphically represents the CMFunction for nighttime crashes by AADT. For nighttime crashes, Chevrons and/or Large Arrows are significantly associated with fewer crashes when the AADT is more than 7,000. While the CMF is statistically insignificant for AADTs less than 7,000, the mean CMF value is less than 1.00 (potential safety benefit) when the AADT is greater than approximately 3,500.

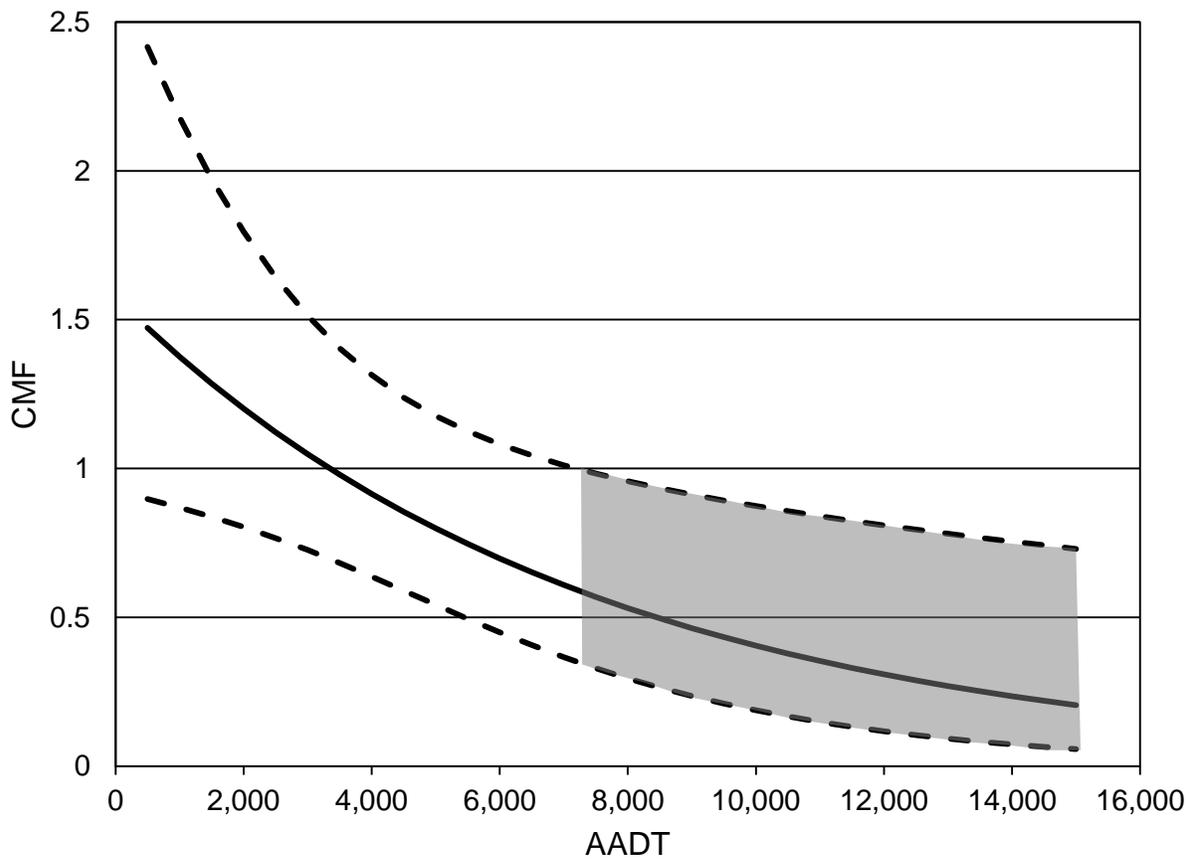


Figure H-14. CMFunction for nighttime crashes for in-curve warning signs on series curves.

Curve or Turn Warning Signs in Advance of Isolated Curves

The final matched dataset for advance warning signs for isolated curves considers the presence or absence of a Curve or Turn warning sign. The dataset used for the analysis of advance warning signs for isolated curves was selected using NN matching without a caliper, because the caliper based match did not result in a reduction in bias compared to NN matching. While the original series curve dataset consisted of 636 treated curve site-years and 177 untreated curve site-years, the final matched dataset consisted of 177 site-years of treated curves and 177 site-years of untreated curves.

The final crash prediction models are presented below, along with interpretations of the variables included in the models. The results of the models focus on the CMFunctions for the presence of advance warning signs. CMFunctions were developed because the safety effect of advance warning signs was found to be a function of the degree of curve. Figures are included to show how the effect of warning sign on crash type changes with degree of curve. A relationship with speed reduction was not explored in this case, since speed reduction was defined as the difference between the posted speed limit and posted advisory speed. For untreated horizontal curves, no speed reduction value was calculated since there was no advisory speed, and the appropriate advisory speed could not be established with the data at hand. Therefore, the final CMFunctions consider the interaction between advance warning sign application and degree of curvature.

Total Crashes

The functional form of the crash prediction model for total crashes considering advance warning signs is given by Equation 24 and the coefficients and related statistics are provided in Table H-17. The presence of a Curve Warning or Turn Warning sign is indicated with a single variable for advance warning sign (advancetcd).

$$\text{Total Crashes} = AADT^{\beta_1} * HCLen^{\beta_2} * \exp(\text{Constant} + C_1X_1 + \dots + C_nX_n) \quad 24$$

Table H-17. Crash Prediction Model Coefficients for Total Crashes

Variables	Coefficient	St. Error	Z-Score	P-Value	L95 CI	U95 CI
Constant	-8.766	1.106	-7.93	< 0.001	-10.933	-6.598
β1 (log-aadt)	0.664	0.089	7.48	< 0.001	0.490	0.838
β2 (log-hclen)	0.226	0.123	1.84	0.065	-0.014	0.467
C1 (Tennessee)	0.627	0.241	2.61	0.009	0.155	1.098
C2 (Ohio)	0.587	0.216	2.72	0.007	0.164	1.009
C3 (uptan)	-0.105	0.061	-1.71	0.088	-0.225	0.016
C4 (swl2)	0.212	0.166	1.28	0.202	-0.113	0.537
C5 (pmd)	0.655	0.249	2.63	0.009	0.167	1.142
C6 (rumble)	-0.498	0.316	-1.58	0.115	-1.117	0.122
C7 (trrpm)	0.369	0.194	1.91	0.057	-0.010	0.749
C8 (rhr)	0.228	0.079	2.87	0.004	0.072	0.383
C9 (withintcd)	-0.282	0.198	-1.43	0.154	-0.670	0.106
C10 (degerve)	0.015	0.028	0.55	0.585	-0.040	0.070
C11 (speedreduc)	0.053	0.012	4.30	< 0.001	0.029	0.078
C12 (advancetcd)	0.710	0.366	1.94	0.053	-0.008	1.427
C13 (advancedegint)	-0.111	0.051	-2.17	0.030	-0.212	-0.011
Overdispersion	0.089	0.095				

N = 354; Log-likelihood = -348.26; Pseudo R² = 0.159

Interpretations for the covariates include:

- AADT (log-AADT): A positive association was found between the natural logarithm of AADT and total crashes. An increase in AADT results in an increase in total crashes.
- Horizontal Curve Length (log-hclen): A positive association was found between the natural logarithm of horizontal curve length and total crashes. An increase in curve length results in an increase in total crashes.
- Tennessee and Ohio Indicators (Tennessee, Ohio): A positive association was found between total crashes and the indicators for the site being located in Tennessee or Ohio. The base condition is that the site location is in Florida or Oregon. Sites in Tennessee and Ohio experience more total crashes than those in Florida and Oregon.
- Average Upstream Tangent Length (uptan): A negative association was found between upstream tangent length and total crashes, suggesting that longer tangents tend to experience fewer total crashes. Upstream tangent length is expressed in thousands of feet.
- Shoulder Width Less than Two Feet Indicator (swl2): A positive association was found between the narrow shoulder width and total crashes. The base condition is a shoulder width that is two feet or greater. Sites with a narrow shoulder (i.e., less than two feet) experience more total crashes than sites with wide shoulders.
- Post-Mounted Delineators (pmd): A positive association was found between PMDs and total crashes. The base condition is no PMDs present. Sites with PMDs experience more total crashes than sites without PMDs.
- Rumble Strips Indicator (rumble): A negative association was found between the indicator for the presence of rumble strips and total crashes. The base condition is no rumble strips present. Sites with rumble strips experience fewer total crashes than those without rumble strips.
- Raised Reflective Pavement Markings (rrpm): A positive association was found between RRPMs and total crashes. The base condition is no RRPMs present. Sites with RRPMs experience more total crashes than sites without RRPMs.
- Roadside Hazard Rating (rhr): A positive association was found between roadside hazard rating and total crashes. An increase in roadside hazard rating is associated with an increase in total crashes.
- Presence of In-Curve Warning Signs (withintcd): A negative association was found between having an in-curve warning sign and total crashes. The base condition is no in-curve warning sign. Sites with in-curve warning signs experience fewer crashes than those without in-curve warning signs.
- Degree of Curve (degrcurve): A positive association was found between degree of curve angle and total crashes. This characteristic was the main effect for an interaction with advance warning signs, and was insignificant.
- Speed Reduction (speedreduc): A positive association was found between speed reduction and total crashes. An increase in speed reduction is associated with an increase in total crashes.
- Advance Warning Sign (advancetcd): A positive association was found between the presence of an advance warning sign and total crashes. The parameter estimate is the main effect for an interaction with degree of curve.
- Advance Warning Sign and Degree of Curve Interaction (advancedegint): A negative association was found between the interaction term and total crashes. The interaction

term indicates that advance warning signs become more effective as the degree of curve increases.

A CMFunction relating the effect of advance warning signs to total crashes by degree of curve is presented in Equation 25.

$$CMF_{total,isolated-advance} = \exp(0.710 - 0.111 * degcrve) \quad 25$$

Figure H-15 graphically represents the CMFunction for total crashes by degree of curve. For total crashes, Curve or Turn warning signs are significantly associated with fewer crashes when the degree of curve is more than 15 degrees. While the CMF is statistically insignificant for degree of curve less than 15 degrees, the mean CMF value is less than 1.00 (potential safety benefit) when the degree of curve is greater than approximately 6 degrees.

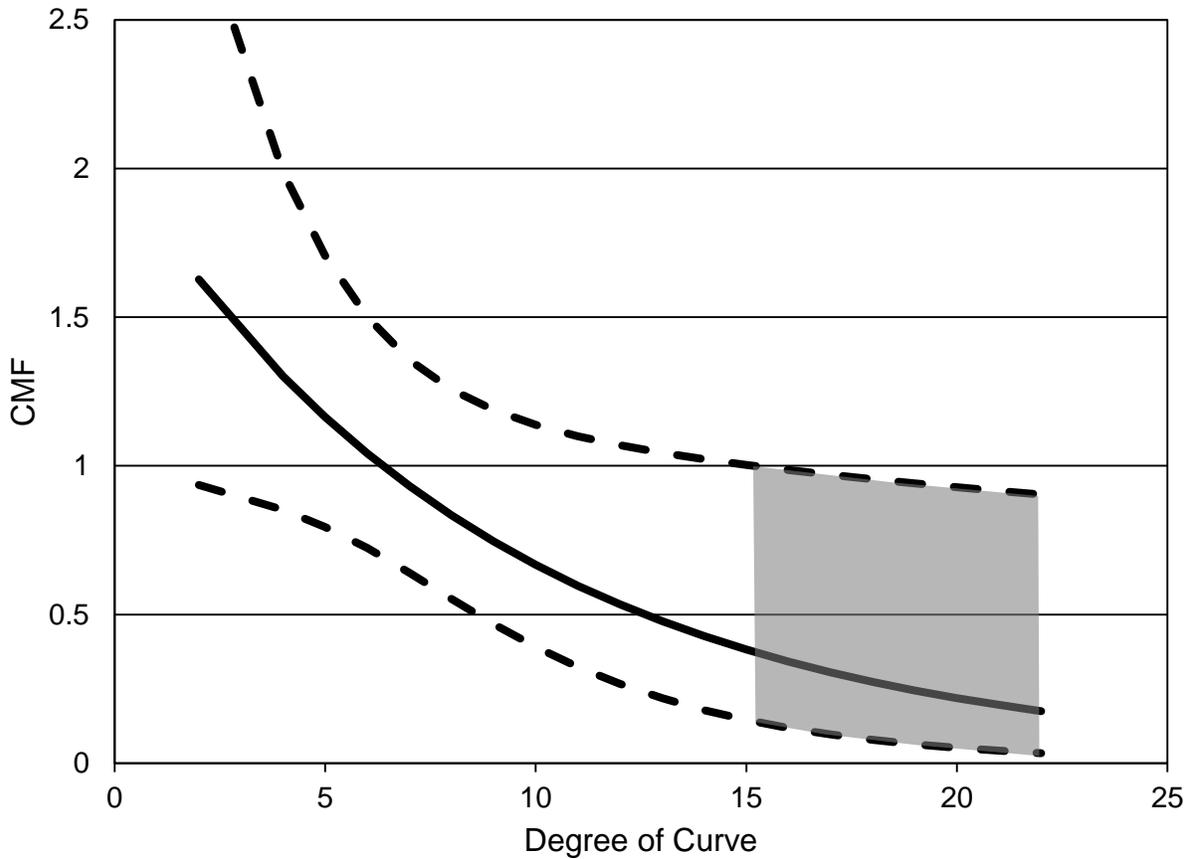


Figure H-15. CMFunction for total crashes for advance warning signs on isolated curves.

Additionally, the CMFunction for Turn signs only is given as Equation 26.

$$CMF_{total,isolated-turn} = \exp(2.094 - 0.205 * degcrve) \quad 26$$

Figure H-16 graphically represents the CMFunction in Equation 26. For total crashes, Turn signs are significantly associated with fewer crashes when the degree of curve is more than 19 degrees. The mean CMF value is less than 1.00 (potential safety benefit) when the degree of curve is greater than approximately 11 degrees. A graphical representation of the disaggregate analysis of each advance warning sign is shown in Figure H-17.

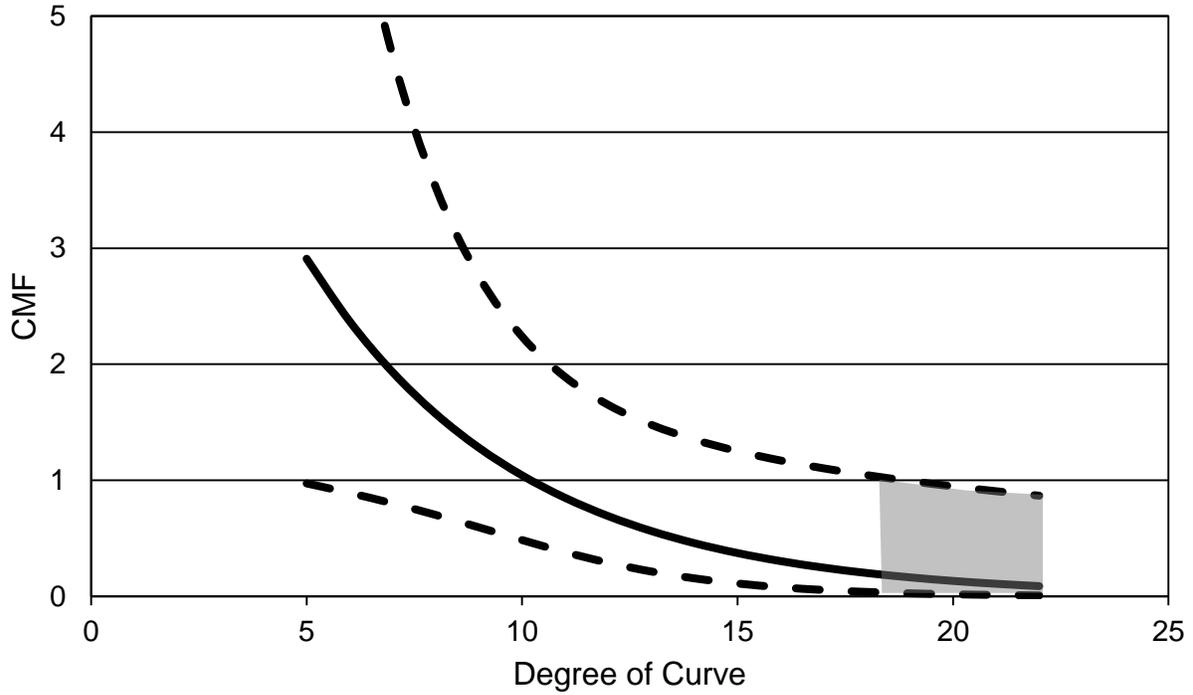


Figure H-16. CMFunction for total crashes for Turn signs on isolated curves.

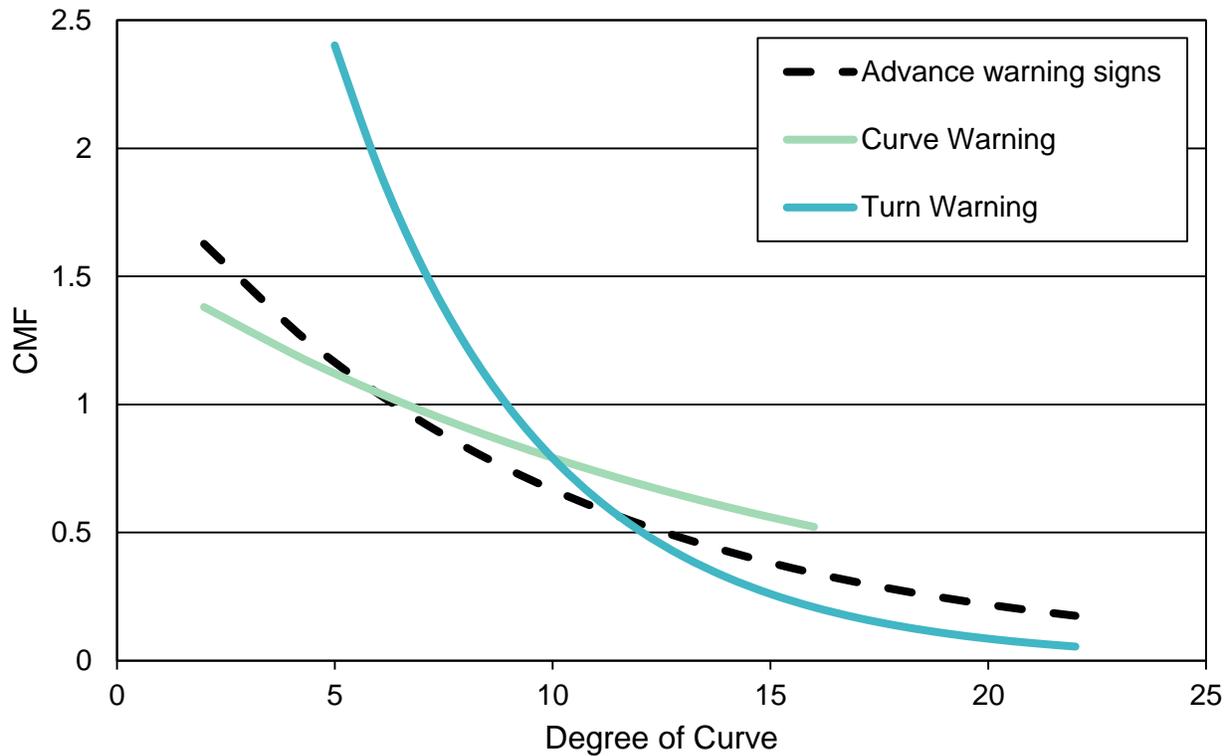


Figure H-17. CMFunctions for total crashes for specific advance warning signs on isolated curves.

It appears from Figure H-17 that Curve warning signs are more effective when the degree of curve is less than 10 degrees and the Turn warning sign is more effective when the degree of curve is 10 or more degrees. Figure H-17 illustrates the mean estimate of CMFunctions, and does not contain confidence intervals, since the confidence intervals are incalculable due to multiple interactions.

Injury Crashes

The functional form of the crash prediction model for injury crashes considering advance warning signs is given by Equation 27 and the coefficients and related statistics are provided in Table H-18. The presence of a Curve or Turn warning sign is indicated with a single variable for advance warning sign (advancetcd).

$$\text{Injury Crashes} = \text{AADT}^{\beta_1} * \text{HCLLEN}^{\beta_2} * \exp(\text{Constant} + C_1X_1 + \dots + C_nX_n) \quad 27$$

Table H-18. Crash Prediction Model Coefficients for Injury Crashes

Variables	Coefficient	St. Error	Z-Score	P-Value	L95 CI	U95 CI
Constant	-9.188	1.652	-5.56	< 0.001	-12.426	-5.950
β1 (log-aadt)	0.747	0.131	5.71	< 0.001	0.491	1.003
β2 (log-hclen)	0.245	0.176	1.39	0.165	-0.101	0.590
C1 (Ohio)	-0.566	0.309	-1.83	0.067	-1.172	0.040
C2 (uptan)	-0.145	0.084	-1.73	0.084	-0.309	0.020
C3 (speedreduc)	0.042	0.017	2.40	0.016	0.008	0.076
C4 (swl2)	0.412	0.221	1.86	0.063	-0.022	0.846
C5 (pmd)	0.672	0.281	2.39	0.017	0.122	1.223
C6 (rumble)	-0.621	0.453	-1.37	0.170	-1.508	0.266
C7 (withintcd)	-0.416	0.301	-1.38	0.167	-1.005	0.174
C8 (degcrve)	0.068	0.042	1.63	0.104	-0.014	0.149
C9 (advancedctd)	0.729	0.520	1.40	0.161	-0.290	1.748
C10 (advancedegint)	-0.096	0.073	-1.31	0.189	-0.240	0.047
Overdispersion	0.036	0.228				
N = 354; Log-likelihood = -214.41; Pseudo R ² = 0.115						

Interpretations for the covariates include:

- **AADT (log-AADT):** A positive association was found between the natural logarithm of AADT and injury crashes. An increase in AADT results in an increase in injury crashes.
- **Horizontal Curve Length (log-hclen):** A positive association was found between the natural logarithm of horizontal curve length and injury crashes. An increase in curve length results in an increase in injury crashes.
- **Ohio Indicator (Ohio):** A negative association was found between injury crashes and the site being located in Ohio. The base condition is that the site location is in Florida, Oregon, or Tennessee. Sites in Ohio experience fewer injury crashes than those in Florida, Oregon, and Tennessee.
- **Average Upstream Tangent Length (uptan):** A negative association was found between upstream tangent length and total crashes, suggesting that longer tangents tend to experience fewer total crashes. Upstream tangent length is expressed in thousands of feet.
- **Speed Reduction (speedreduc):** A positive association was found between speed reduction and injury crashes. An increase in speed reduction is associated with an increase in injury crashes.
- **Shoulder Width Less than Two Feet Indicator (swl2):** A positive association was found between the narrow shoulder width and injury crashes. The base condition is a shoulder width that is two feet or greater. Sites with a narrow shoulder (i.e., less than two feet) experience more injury crashes than sites with wide shoulders.
- **Post-Mounted Delineators (pmd):** A positive association was found between PMDs and injury crashes. The base condition is no PMDs present. Sites with PMDs experience more injury crashes than sites without PMDs.
- **Rumble Strips Indicator (rumble):** A negative association was found between the indicator for the presence of rumble strips and injury crashes. The base condition is no rumble strips present. Sites with rumble strips experience fewer injury crashes than those without rumble strips.
- **Presence of In-Curve Warning Signs (withintcd):** A negative association was found between having an in-curve warning sign and injury crashes. The base condition is no in-curve warning signs. Sites with in-curve warning signs experience fewer crashes than those without in-curve warning signs.

- Degree of Curve (*degcrve*): A positive association was found between degree of curve angle and injury crashes. An increase in degree of curve was associated with an increase in injury crashes. This characteristic was the main effect for an interaction with advance warning signs.
- Advance Warning Sign (*advancetcd*): A positive association was found between the presence of an advance warning sign and injury crashes. The parameter estimate is the main effect for an interaction with degree of curve.
- Advance Warning Sign and Degree of Curve Interaction (*advancedegint*): A negative association was found between the interaction term and injury crashes. The interaction term indicates that advance warning signs become more effective as the degree of curve increases.

A CMFunction relating the effect of advance warning signs to injury crashes by degree of curve is presented in Equation 28.

$$CMF_{injury,isolated-advance} = \exp(0.729 - 0.096 * degcrve) \quad 28$$

Figure H-18 graphically represents the CMFunction for injury crashes by degree of curve. For injury crashes, Curve or Turn warning signs are not significantly associated with fewer crashes for any value of degree of curve. While the CMF is statistically insignificant for all values of degree of curve, the mean CMF value is less than 1.00 (potential safety benefit) when the degree of curve is greater than approximately 7 degrees. Due to small sample size, the effectiveness of individual advance warning signs could not be disaggregated for injury crashes.

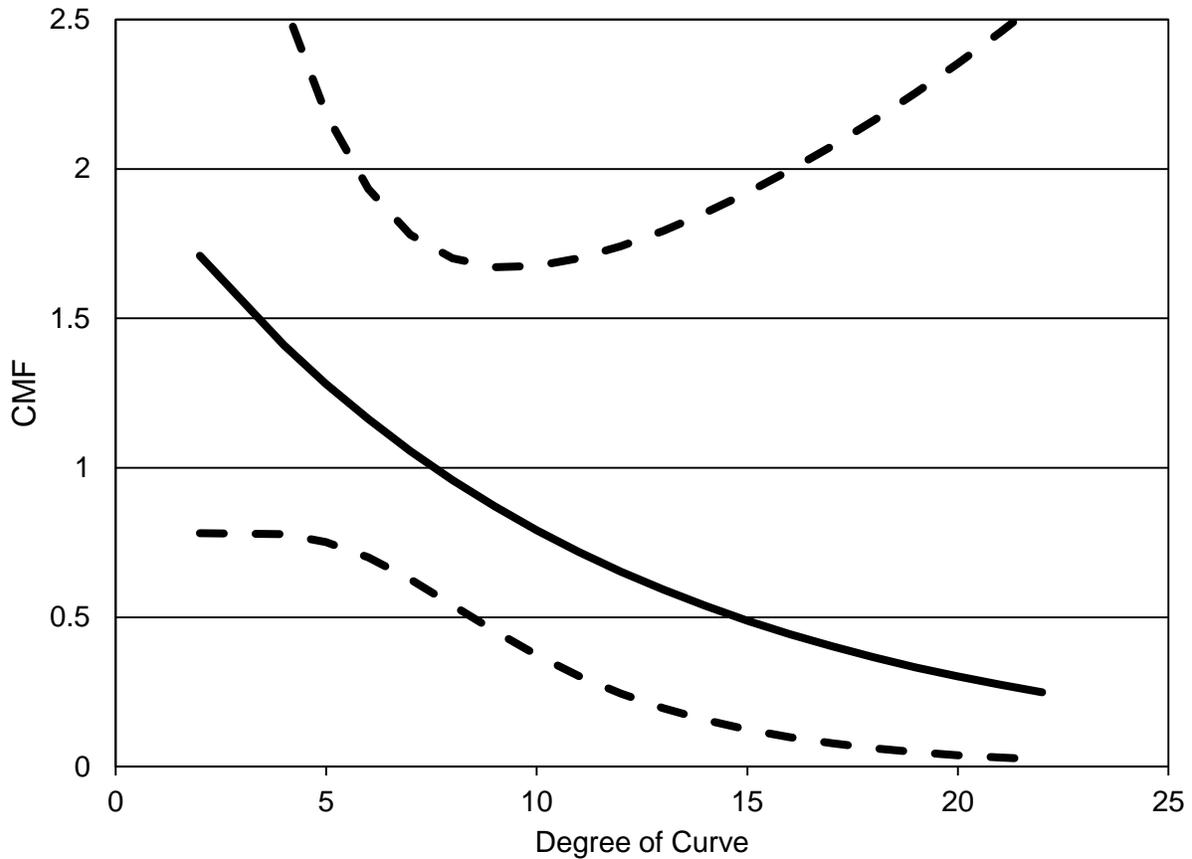


Figure H-18. CMFunction for injury crashes for advance warning signs on isolated curves.

SVROR Crashes

The functional form of the crash prediction model for SVROR crashes considering advance warning signs is given by Equation 29 and the coefficients and related statistics are provided in Table H-19. The presence of a Curve or Turn warning sign is indicated with a single variable for advance curve sign (advancetcd).

$$SVROR\ Crashes = AADT^{\beta_1} * HCLLEN^{\beta_2} * exp(Constant + C_1X_1 + \dots + C_nX_n) \quad 29$$

Table H-19. Crash Prediction Model Coefficients for SVROR Crashes

Variables	Coefficient	St. Error	Z-Score	P-Value	L95 CI	U95 CI
Constant	-7.191	1.368	-5.26	< 0.001	-9.872	-4.510
β1 (log-aadt)	0.458	0.111	4.12	< 0.001	0.240	0.676
β2 (log-hclen)	0.129	0.159	0.81	0.417	-0.183	0.441
C1 (Tennessee)	0.854	0.306	2.79	0.005	0.254	1.453
C2 (Ohio)	0.567	0.285	1.99	0.046	0.009	1.125
C3 (uptan)	-0.167	0.085	-1.96	0.049	-0.333	-0.001
C4 (speedreduc)	0.034	0.016	2.06	0.039	0.002	0.066
C5 (swl2)	0.214	0.209	1.03	0.305	-0.195	0.623
C6 (pmd)	0.759	0.312	2.43	0.015	0.148	1.369
C7 (rumble)	-0.760	0.411	-1.85	0.065	-1.566	0.047
C8 (rhr)	0.246	0.101	2.45	0.014	0.049	0.443
C9 (rrpm)	0.565	0.239	2.36	0.018	0.096	1.034
C10 (degcrve)	0.024	0.033	0.72	0.470	-0.041	0.090
C11 (advancedctcd)	0.623	0.481	1.29	0.195	-0.320	1.566
C12 (advancedegint)	-0.094	0.066	-1.41	0.159	-0.224	0.037
Overdispersion	0.036	0.228				
N = 354; Log-likelihood = -282.08; Pseudo R ² = 0.115						

Interpretations for the covariates include:

- AADT (log-AADT): A positive association was found between the natural logarithm of AADT and SVROR crashes. An increase in AADT results in an increase in SVROR crashes.
- Horizontal Curve Length (log-hclen): A positive association was found between the natural logarithm of horizontal curve length and SVROR crashes. An increase in curve length results in an increase in SVROR crashes. The finding was insignificant, but was retained in the model for consistency.
- Tennessee and Ohio Indicators (Tennessee, Ohio): A positive association was found between the indicator for the site being located in Tennessee or Ohio and SVROR crashes. The base condition is that the site location is in Florida or Oregon. Sites in Tennessee and Ohio experience more SVROR crashes than those in Florida and Oregon.
- Average Upstream Tangent Length (uptan): A negative association was found between upstream tangent length and total crashes, suggesting that longer tangents tend to experience fewer total crashes. Upstream tangent length is expressed in thousands of feet.
- Speed Reduction (speedreduc): A positive association was found between speed reduction and SVROR crashes. An increase in speed reduction is associated with an increase in SVROR crashes.
- Shoulder Width Less than Two Feet Indicator (swl2): A positive association was found between the narrow shoulder width and SVROR crashes. The base condition is a shoulder width that is two feet or greater. Sites with a narrow shoulder (i.e., less than two feet) experience more SVROR crashes than sites with wide shoulders.
- Post-Mounted Delineators (pmd): A positive association was found between PMDs and SVROR crashes. The base condition is no PMDs present. Sites with PMDs experience more SVROR crashes than sites without PMDs.
- Rumble Strips Indicator (rumble): A negative association was found between the indicator for the presence of rumble strips and SVROR crashes. The base condition is no rumble strips present. Sites with rumble strips experience fewer SVROR crashes than those without rumble strips.

- Roadside Hazard Rating (rhr): A positive association was found between roadside hazard rating and SVROR crashes. A unit increase in roadside hazard rating is associated with an increase in SVROR crashes.
- Raised Reflective Pavement Markings (rrpm): A positive association was found between RRPMS and SVROR crashes. The base condition is no RRPMS present. Sites with RRPMS experience more SVROR crashes than sites without RRPMS.
- Degree of Curve (degcurve): A positive association was found between degree of curve angle and SVROR crashes. An increase in degree of curve was associated with an increase in SVROR crashes. This characteristic was the main effect for an interaction with advance warning signs, and was insignificant.
- Advance Warning Sign (advancetcd): A positive association was found between the presence of an advance warning sign and SVROR crashes. The parameter estimate is the main effect for an interaction with degree of curve.
- Advance Warning Sign and Degree of Curve Interaction (advancedegint): A negative association was found between the interaction term and SVROR crashes. The interaction term indicates that advance warning signs become more effective as the degree of curve increases.

A CMFunction relating the effect of advance warning signs to SVROR crashes by degree of curve is presented in Equation 30.

$$CMF_{SVROR,isolated-advance} = \exp(0.623 - 0.094 * degcurve) \quad 30$$

Figure H-19 graphically represents the CMFunction for SVROR crashes by degree of curve. For SVROR crashes, Curve Warning or Turn Warning signs are not significantly associated with fewer crashes for any value of degree of curve. While the CMF is statistically insignificant for all values of degree of curve, the mean CMF value is less than 1.00 (potential safety benefit) when the degree of curve is greater than approximately 6 degrees.

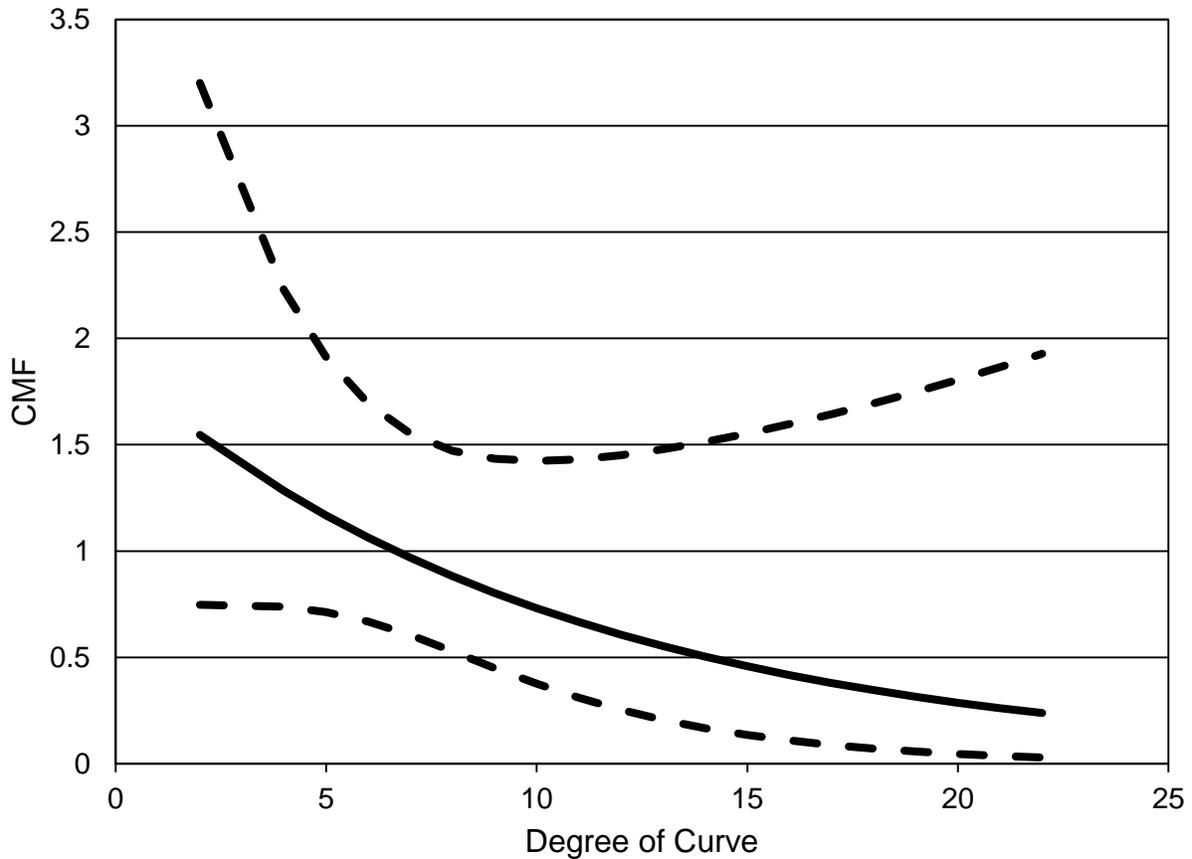


Figure H-19. CMFunction for SVROR crashes for advance curve signs on isolated curves.

A CMFunction for Turn signs alone is given as Equation 31.

$$CMF_{SVROR,isolated-turn} = \exp(2.403 - 0.210 * degcurve) \quad 31$$

Figure H-20 graphically represents the CMFunction for SVROR crashes by degree of curve. For SVROR crashes, Turn signs are never significantly associated with fewer crashes; however, the mean CMF value is less than 1.00 (potential safety benefit) when the degree of curve is greater than approximately 11 degrees.

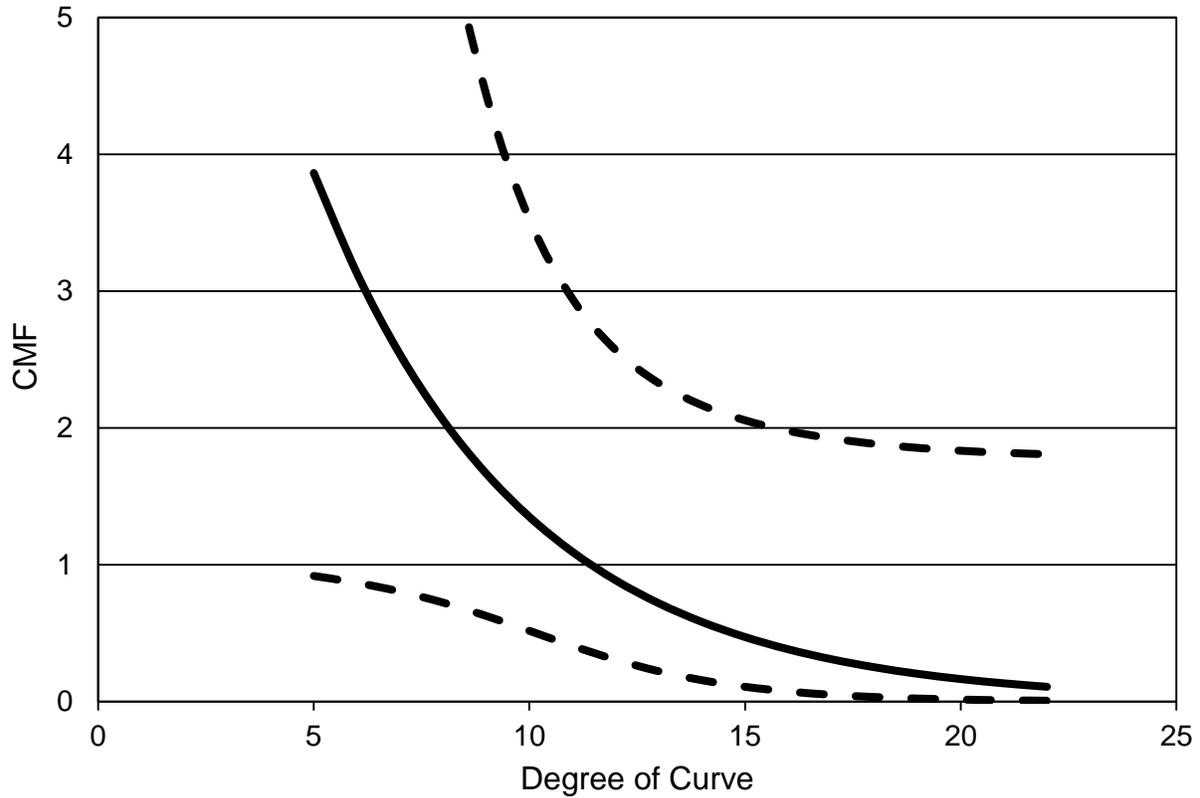


Figure H-20. CMFunction for SVROR crashes for Turn signs on isolated curves.

Adverse Pavement Condition Crashes

The functional form of the crash prediction model for adverse pavement condition crashes considering advance warning signs is given by Equation 32 and the coefficients and related statistics are provided in Table H-20. The presence of a Curve or Turn warning sign is indicated with a single variable for advance curve signs (advancetcd).

$$Adv. Pvmnt. Crashes = AADT^{\beta_1} * HCLLEN^{\beta_2} * exp(Constant + C_1X_1 + \dots + C_nX_n) \quad 32$$

Table H-20. Crash Prediction Model Coefficients for Adverse Pavement Condition Crashes

Variables	Coefficient	St. Error	Z-Score	P-Value	L95 CI	U95 CI
Constant	-12.378	2.029	-6.10	< 0.001	-16.354	-8.402
β1 (log-aadt)	0.555	0.157	3.53	< 0.001	0.247	0.862
β2 (log-hclen)	0.481	0.222	2.17	0.030	0.046	0.917
C1 (Tennessee)	0.810	0.395	2.05	0.040	0.036	1.583
C2 (Ohio)	0.732	0.379	1.93	0.054	-0.011	1.476
C3 (speedreduc)	0.077	0.024	3.29	0.001	0.031	0.124
C4 (pmd)	1.102	0.428	2.57	0.010	0.263	1.942
C5 (rhr)	0.449	0.125	3.60	< 0.001	0.205	0.694
C6 (rrpm)	0.987	0.316	3.13	0.002	0.368	1.606
C7 (degrcve)	0.033	0.049	0.67	0.505	-0.063	0.129
C8 (advancetcd)	0.472	0.639	0.74	0.461	-0.781	1.724
C9 (advancedegint)	-0.107	0.089	-1.20	0.230	-0.283	0.068
Overdispersion	0.580	0.362				
N = 354; Log-likelihood = -196.94; Pseudo R ² = 0.159						

Interpretations for the covariates include:

- AADT (log-AADT): A positive association was found between the natural logarithm of AADT and adverse pavement condition crashes. An increase in AADT results in an increase in adverse pavement condition crashes.
- Horizontal Curve Length (log-hclen): A positive association was found between the natural logarithm of horizontal curve length and adverse pavement condition crashes. An increase in curve length results in an increase in adverse pavement condition crashes.
- Tennessee and Ohio Indicators (Tennessee, Ohio): A positive association was found between the adverse pavement crashes and the site being located in Tennessee or Ohio. The base condition is that the site location is in Florida or Oregon. Sites in Tennessee and Ohio experience more adverse pavement condition crashes than those in Florida and Oregon.
- Speed Reduction (speedreduc): A positive association was found between speed reduction and adverse pavement condition crashes. An increase in speed reduction is associated with an increase in adverse pavement condition crashes.
- Post-Mounted Delineators (pmd): A positive association was found between PMDs and adverse pavement condition crashes. The base condition is no PMDs present. Sites with PMDs experience more adverse pavement condition crashes than sites without PMDs.
- Roadside Hazard Rating (rhr): A positive association was found between roadside hazard rating and adverse pavement condition crashes. An increase in roadside hazard rating is associated with an increase in adverse pavement condition crashes.
- Raised Reflective Pavement Markings (rrpm): A positive association was found between RRPMs and adverse pavement condition crashes. The base condition is no RRPMs present. Sites with RRPMs experience more adverse pavement condition crashes than sites without RRPMs.
- Degree of Curve (degrcve): A positive association was found between degree of curve angle and adverse pavement condition crashes. A unit increase in degree of curve was associated with an increase in adverse pavement condition crashes. This characteristic was the main effect for an interaction with advance warning signs, and was insignificant.
- Advance Warning Sign (advancetcd): A positive association was found between the presence of an advance warning sign and adverse pavement condition crashes. The

parameter estimate is the main effect for an interaction with degree of curve, and was insignificant.

- Advance Warning Sign and Degree of Curve Interaction (*advancedegint*): A negative association was found between the interaction term and adverse pavement condition crashes. The interaction term indicates that advance warning signs become more effective as the degree of curve increases.

A CMFunction relating the effect of advance warning signs to adverse pavement condition crashes by degree of curve is presented in Equation 33.

$$CMF_{adverse,isolated-advance} = \exp(0.472 - 0.107 * degcrve) \quad 33$$

Figure H-21 graphically represents the CMFunction for adverse pavement condition crashes by degree of curve. For adverse pavement condition crashes, warning signs are not significantly associated with fewer crashes for any value of degree of curve. While the CMF is statistically insignificant for all values of degree of curve, the mean CMF value is less than 1.00 (potential safety benefit) when the degree of curve is greater than approximately 4 degrees.

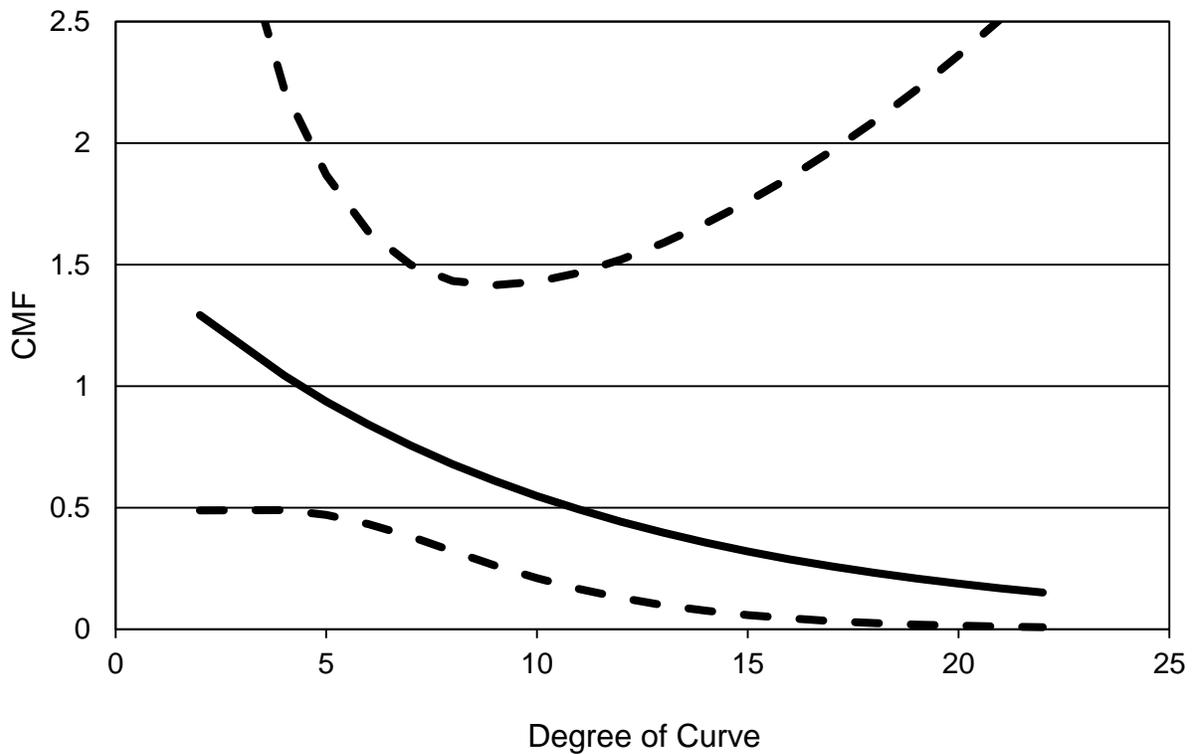


Figure H-21. CMFunction for adverse pavement condition crashes for advance warning signs on isolated curves.

A CMFunction for Turn signs only is given as Equation 34.

$$CMF_{adverse,isolated-turn} = \exp(2.016 - 0.260 * degcrve) \quad 34$$

Figure H-22 graphically represents the CMFunction for adverse pavement condition crashes by degree of curve. For adverse pavement condition crashes, Turn signs are significantly associated with fewer crashes when the degree of curve is greater than 13 degrees. The mean CMF value is less than 1.00 (potential safety benefit) when the degree of curve is greater than approximately 7 degrees

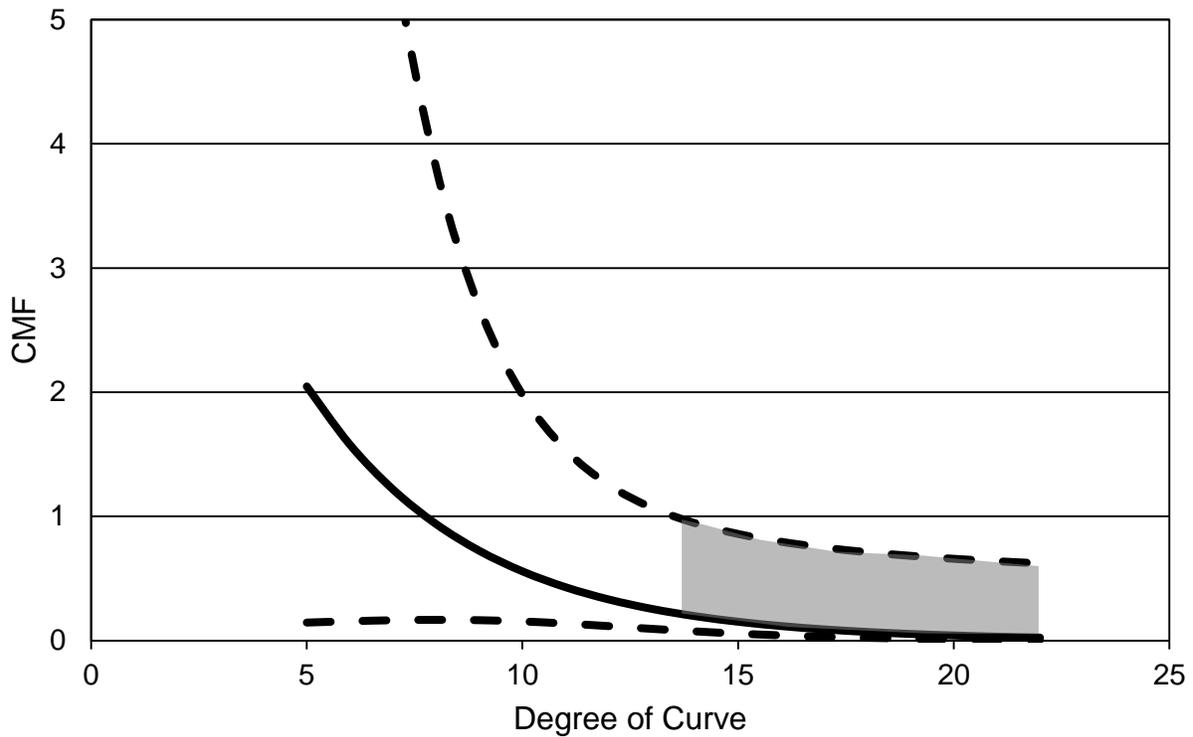


Figure H-22. CMFunction for adverse pavement condition crashes for Turn signs on isolated curves.

Nighttime Crashes

The functional form of the crash prediction model for nighttime crashes considering advance warning signs is given by Equation 35 and the coefficients and related statistics are provided in Table H-21. The presence of a Curve or Turn warning sign is indicated with a single variable for advance curve signs (advancetcd).

$$\text{Nighttime Crashes} = AADT^{\beta_1} * HCLLEN^{\beta_2} * \exp(\text{Constant} + C_1X_1 + \dots + C_nX_n) \quad 35$$

Table H-21. Crash Prediction Model Coefficients for Nighttime Crashes

Variables	Coefficient	St. Error	Z-Score	P-Value	L95 CI	U95 CI
Constant	-9.371	1.909	-4.91	< 0.001	-13.113	-5.629
β1 (log-aadt)	0.848	0.142	5.96	< 0.001	0.569	1.126
β2 (log-hclen)	-0.098	0.216	-0.45	0.649	-0.521	0.325
C1 (Tennessee)	1.785	0.419	4.26	< 0.001	0.965	2.606
C2 (Ohio)	1.305	0.394	3.31	0.001	0.533	2.078
C3 (speedreduc)	0.048	0.021	2.31	0.021	0.007	0.089
C4 (pmd)	0.762	0.485	1.57	0.116	-0.189	1.713
C5 (rumble)	-0.709	0.446	-1.59	0.112	-1.583	0.165
C6 (swl2)	0.369	0.261	1.41	0.157	-0.142	0.880
C7 (ps55g)	0.352	0.293	1.20	0.228	-0.221	0.926
C8 (degcrve)	0.039	0.042	0.93	0.354	-0.043	0.121
C9 (advancedcd)	0.749	0.588	1.27	0.203	-0.403	1.901
C10 (advancedegint)	-0.144	0.086	-1.68	0.092	-0.312	0.024
Overdispersion	0.302	0.279				
N = 354; Log-likelihood = -194.68; Pseudo R ² = 0.150						

Interpretations for the covariates include:

- AADT (log-AADT): A positive association was found between the natural logarithm of AADT and nighttime crashes. An increase in AADT results in an increase in nighttime crashes.
- Horizontal Curve Length (log-hclen): A negative association was found between the natural logarithm of horizontal curve length and nighttime crashes. An increase in curve length results in an increase in adverse pavement condition crashes. The finding was insignificant but was retained in the model for consistency.
- Tennessee and Ohio Indicators (Tennessee, Ohio): A positive association was found between the indicators for the site being located in Tennessee or Ohio and nighttime crashes. The base condition is that the site location is in Florida or Oregon. Sites in Tennessee and Ohio experience more nighttime crashes than those in Florida and Oregon.
- Speed Reduction (speedreduc): A positive association was found between speed reduction and nighttime crashes. An increase in speed reduction is associated with an increase in nighttime crashes.
- Post-Mounted Delineators (pmd): A positive association was found between PMDs and nighttime crashes. The base condition is no PMDs present. Sites with PMDs experience more nighttime crashes than sites without PMDs.
- Rumble Strips Indicator (rumble): A negative association was found between the indicator for the presence of rumble strips and nighttime crashes. The base condition is no rumble strips present. Sites with rumble strips experience fewer nighttime crashes than those without rumble strips.
- Shoulder Width Less than Two Feet Indicator (swl2): A positive association was found between the narrow shoulder width and nighttime crashes. The base condition is a shoulder width that is two feet or greater. Sites with a narrow shoulder (i.e., less than two feet) experience more nighttime crashes than sites with wide shoulders.
- Posted Speed Limit 55 MPH or Greater Indicator (ps55g): A positive association was found between having a higher speed limit and nighttime crashes. The base condition is a speed limit less than 55 mph. Sites with a higher speed limit (i.e., 55 mph or higher) experience more nighttime crashes than sites with lower speed limits.

- Degree of Curve (degrcve): A positive association was found between degree of curve angle and nighttime crashes. An increase in degree of curve was associated with an increase in nighttime crashes. This characteristic was the main effect for an interaction with advance warning signs, and was insignificant.
- Advance Warning Sign (advancetcd): A positive association was found between the presence of an advance warning sign and nighttime crashes. The parameter estimate is the main effect for an interaction with degree of curve.
- Advance Warning Sign and Degree of Curve Interaction (advancedegint): A negative association was found between the interaction term and nighttime crashes. The interaction term indicates that advance warning signs become more effective as the degree of curve increases.

A CMFunction relating the effect of advance warning signs to nighttime crashes by degree of curve is presented in Equation 36.

$$CMF_{nighttime,isolated-advance} = \exp(0.749 - 0.144 * degrcve) \quad 36$$

Figure H-23 graphically represents the CMFunction for nighttime crashes by degree of curve. For nighttime crashes, warning signs are not significantly associated with fewer crashes for any value of degree of curve. While the CMF is statistically insignificant for all values of degree of curve, the mean CMF value is less than 1.00 (potential safety benefit) when the degree of curve is greater than approximately 5 degrees.

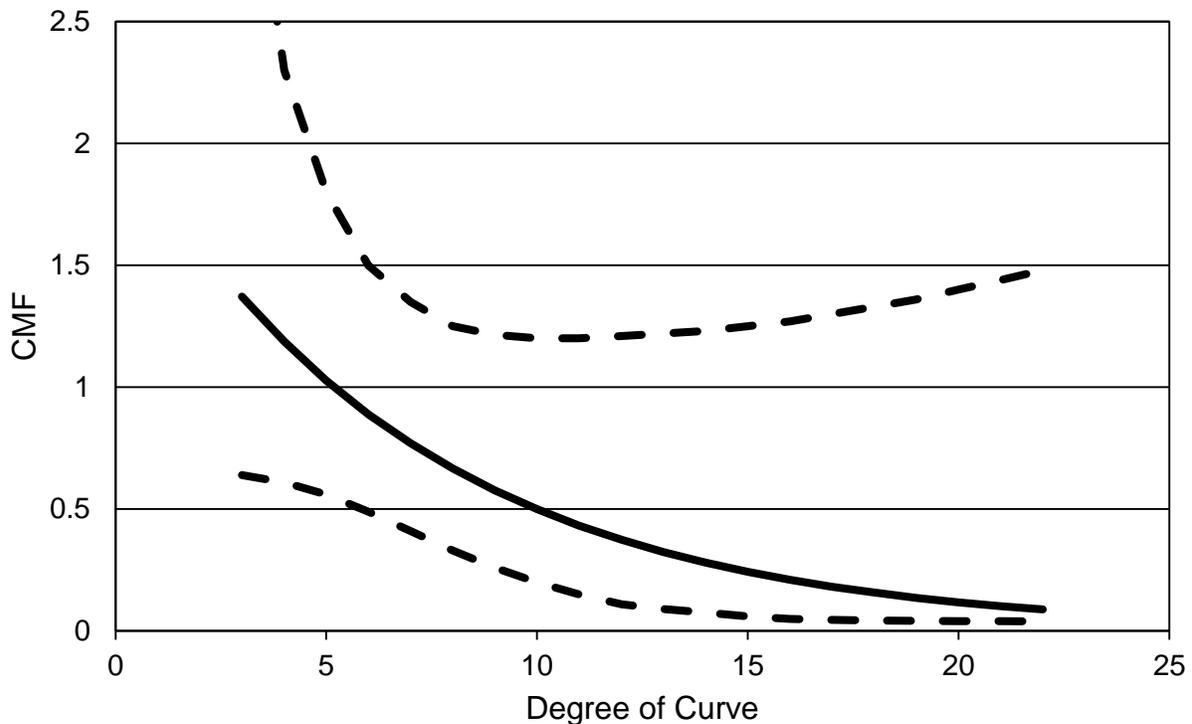


Figure H-23. CMFunction for nighttime crashes for advance warning signs on isolated curves.

Reverse Turn, Reverse Curve, or Winding Road Warning Signs in Advance of Series Curves

The final matched dataset for advance warning signs for series curves considers the presence or absence of a Reverse Curve, Reverse Turn, or Winding Road warning sign. The dataset used for the analysis of advance warning signs for series curves was selected using NN matching without a caliper, because the caliper-based match did not result in a reduction in bias compared to NN matching. While the original series curve dataset consisted of 675 treated curve site-years and 135 untreated curve site-years, the final matched dataset consisted of 135 site-years of treated curves and 135 site-years of untreated curves.

The final crash prediction models are presented below, along with interpretations of the variables included in the models. The results of the models focus on the CMFunctions for the presence of advance warning signs. CMFunctions were developed because the safety effect of advance warning signs was found to be a function of the degree of curve. A relationship with speed reduction was not explored in this case, since speed reduction was defined as the difference between the posted speed limit and posted advisory speed. For untreated horizontal curves, no speed reduction value was calculated since there was no advisory speed, and advisory speeds were not measured. Therefore the final CMFunctions consider only the interaction between advance warning sign application and degree of curvature. Figures for each CMFunction are provided and include 95-percent confidence intervals.

Total Crashes

The functional form of the crash prediction model for total crashes considering advance warning signs is given by Equation 38 and the coefficients and related statistics are provided in Table H-22. The presence of a Curve or Turn warning sign is indicated with a single variable for advance warning signs (advancetcd). Due to a lack of dispersion in the data, a Poisson model was used in place of a Negative Binomial (NB) model regression model. The NB model reduces to a Poisson model when no dispersion is present.

$$\text{Total Crashes} = \text{AADT}^{\beta_1} * \text{Length}^{\beta_2} * \exp(\text{Constant} + C_1X_1 + \dots + C_nX_n) \quad 38$$

Table H-22. Crash Prediction Model Coefficients for Total Crashes

Variables	Coefficient	St. Error	Z-Score	P-Value	L95 CI	U95 CI
Constant	-6.791	0.814	-8.35	< 0.001	-8.385	-5.196
β1 (log-aadt)	0.689	0.085	8.13	< 0.001	0.523	0.855
β2 (log-length)	0.318	0.115	2.76	0.006	0.092	0.544
C1 (Tennessee)	0.345	0.218	1.59	0.112	-0.081	0.772
C2 (Ohio)	0.335	0.225	1.49	0.137	-0.107	0.776
C3 (g)	0.502	0.149	3.38	0.001	0.211	0.794
C4 (lwl12)	0.448	0.163	2.75	0.006	0.128	0.767
C5 (rhr)	0.200	0.080	2.51	0.012	0.044	0.356
C6 (speedreduc)	0.012	0.011	1.12	0.264	-0.009	0.034
C7 (degcurve)	0.012	0.031	0.40	0.693	-0.049	0.074
C8 (advancetcd)	0.133	0.290	0.46	0.646	-0.436	0.702
C9 (advancedegint)	-0.031	0.040	-0.78	0.436	-0.108	0.047
N = 270; Log-likelihood = -312.59; Pseudo R ² = 0.159						

Interpretations for the covariates include:

- AADT (log-AADT): A positive association was found between the natural logarithm of AADT and total crashes. An increase in AADT results in an increase in total crashes.
- Series Length (log-length): A positive association was found between the natural logarithm of series length and total crashes. An increase in length results in an increase in total crashes.
- Tennessee and Ohio Indicators (Tennessee, Ohio): A positive association was found between the indicators for the site location being in Tennessee or Ohio and total crashes. The base condition is that the site location is in Florida or Oregon. Sites in Tennessee and Ohio experience more total crashes than those in Florida and Oregon.
- Grade Indicator (g): A positive association was found between the indicator for an absolute value of grade greater than three percent and total crashes. The base condition is an absolute value of grade less than three percent. Sites with steeper grades experience more total crashes than sites on flatter grades.
- Lane Width Less than 12 feet Indicator (lw12): A positive association was found between narrow lane width and total crashes. The base condition is a lane width that is 12 feet or greater. Sites with a narrow lane (i.e., less than 12 feet) experience more total crashes than sites with wide lanes.
- Roadside Hazard Rating (rhr): A positive association was found between roadside hazard rating and total crashes. An increase in roadside hazard rating is associated with an increase in total crashes.
- Degree of Curve (degrve): A positive association was found between degree of curve angle and total crashes. This characteristic was the main effect for an interaction with advance warning signs, and was insignificant.
- Speed Reduction (speedreduc): A positive association was found between speed reduction and total crashes. An increase in speed reduction is associated with an increase in total crashes.
- Advance Warning Sign (advancetcd): A positive association was found between the presence of an advance warning sign and total crashes. The parameter estimate is the main effect for an interaction with degree of curve and was insignificant.
- Advance Warning Sign and Degree of Curve Interaction (advancedegint): A negative association was found between the interaction term and total crashes. The interaction term indicates that advance warning signs become more effective as the degree of curve increases. The interaction term, however, was insignificant.

A CMFunction relating the effect of advance warning signs to total crashes by degree of curve is presented in Equation 39.

$$CMF_{total,series-advance} = \exp(0.133 - 0.031 * degrve) \quad 39$$

Figure H-24 graphically represents the CMFunction for total crashes by degree of curve. For total crashes, Reverse Curve, Reverse Turn, or Winding Road warning signs are not significantly associated with fewer crashes for any value of degree of curve. While the CMF is statistically insignificant for all values of degree of curve, the mean CMF value is less than 1.00 (potential safety benefit) when the degree of curve is greater than approximately 4 degrees.

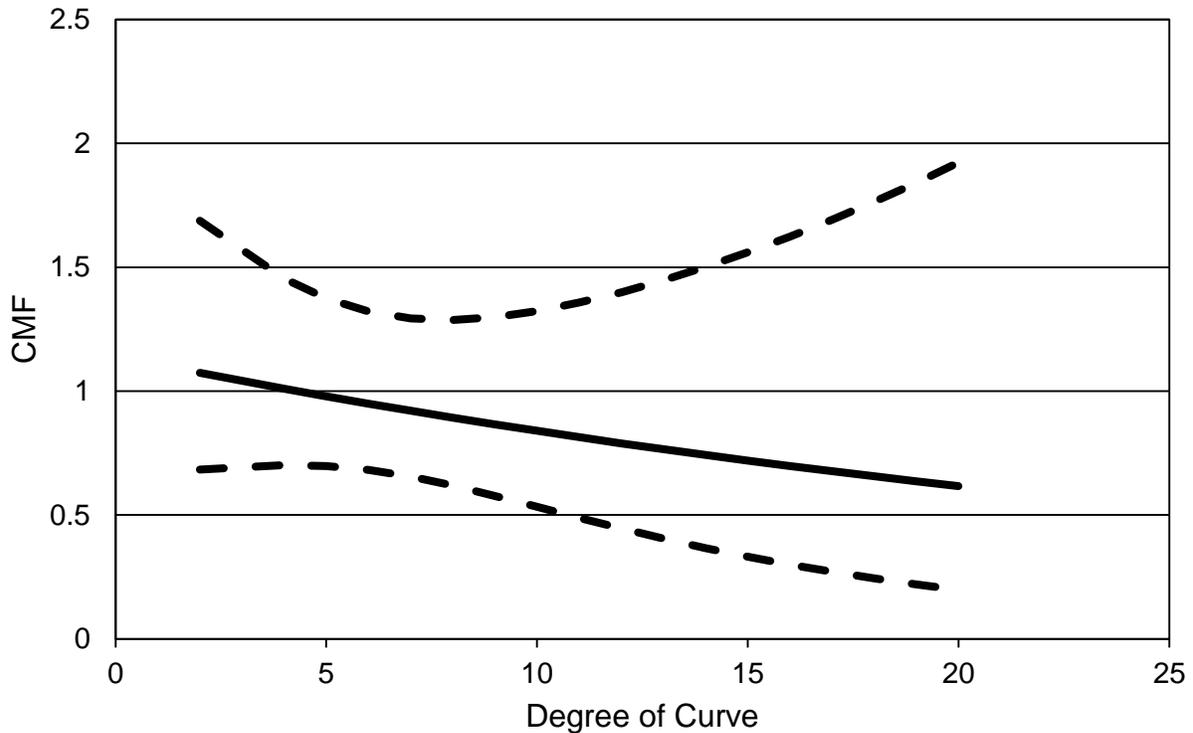


Figure H-24. CMFunction for total crashes for advance warning signs on curve series.

A disaggregate analysis of advance warning signs on series curves was investigated to identify the effects of individual advance warning signs on total crashes. A CMFunction for Reverse Turn and Winding Road signs are given as Equations 40 and 41, respectively.

$$CMF_{total,series-reverseturn} = \exp(0.769 - 0.087 * degcrve) \quad 40$$

$$CMF_{total,series-winding} = \exp(0.274 - 0.061 * degcrve) \quad 41$$

Figure H-25 graphically represents the CMFunction for Reverse Turn signs on total crashes by degree of curve. For total crashes, Reverse Turn signs are never significantly associated with fewer crashes; however, the mean CMF value is less than 1.00 (potential safety benefit) when the degree of curve is greater than approximately 8 degrees.

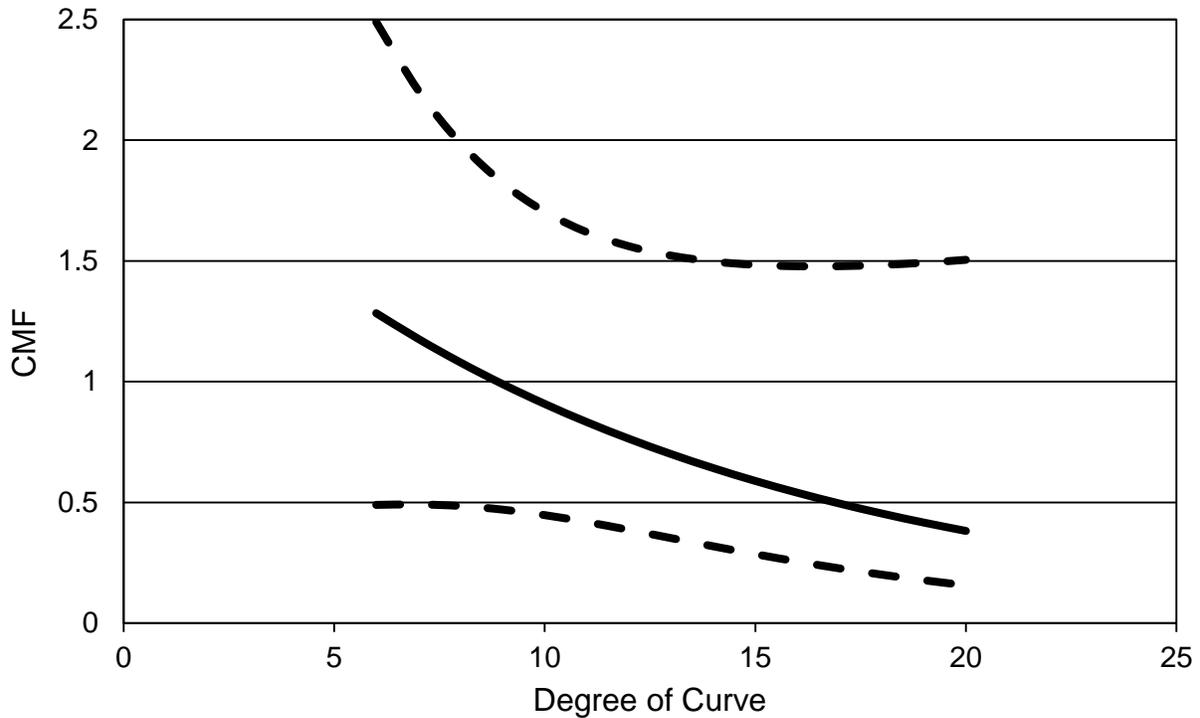


Figure H-25. CMFunction for total crashes for Reverse Turn signs on curve series.

Figure H-26 graphically represents the CMFunction for Winding Road signs on total crashes by degree of curve. Winding Road Warning signs are never significantly associated with fewer crashes; however, the mean CMF value is less than 1.00 (potential safety benefit) when the degree of curve is greater than approximately 4 degrees.

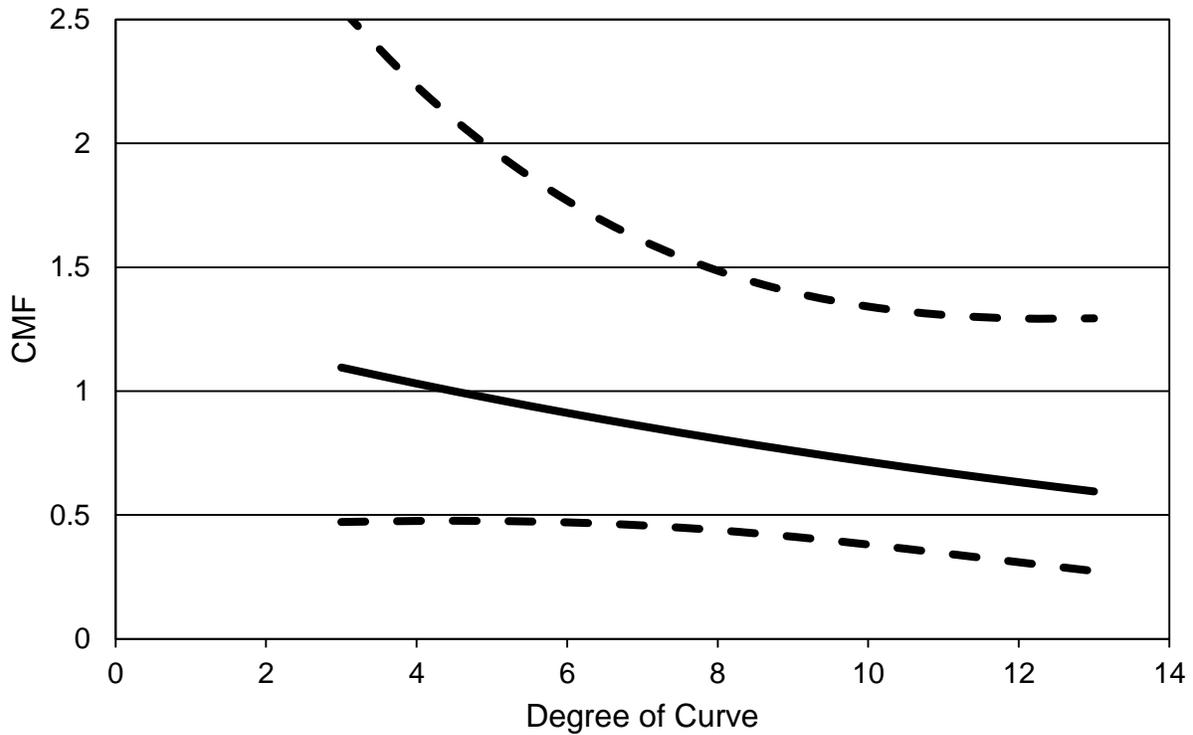


Figure H-26. CMFunction for total crashes for Winding Road signs on curve series.

Figure H-27 shows the CMFunctions for individual warning signs placed in advance of curve series. It appears that Reverse Curve signs are more effective than Reverse Turn signs when the degree of curve is less than 8 degrees, but the effectiveness of Reverse Curve signs decreases as the degree of curve increases. Other signs appear to increase in effectiveness as the degree of curve increases. Winding Road signs are the most effective advance warning sign when the degree of curve is 5 or more degrees; however, this sign is only used when there are three or more successive curves. Figure H-27 shows only the mean estimate of CMFunctions, and does not contain confidence intervals.

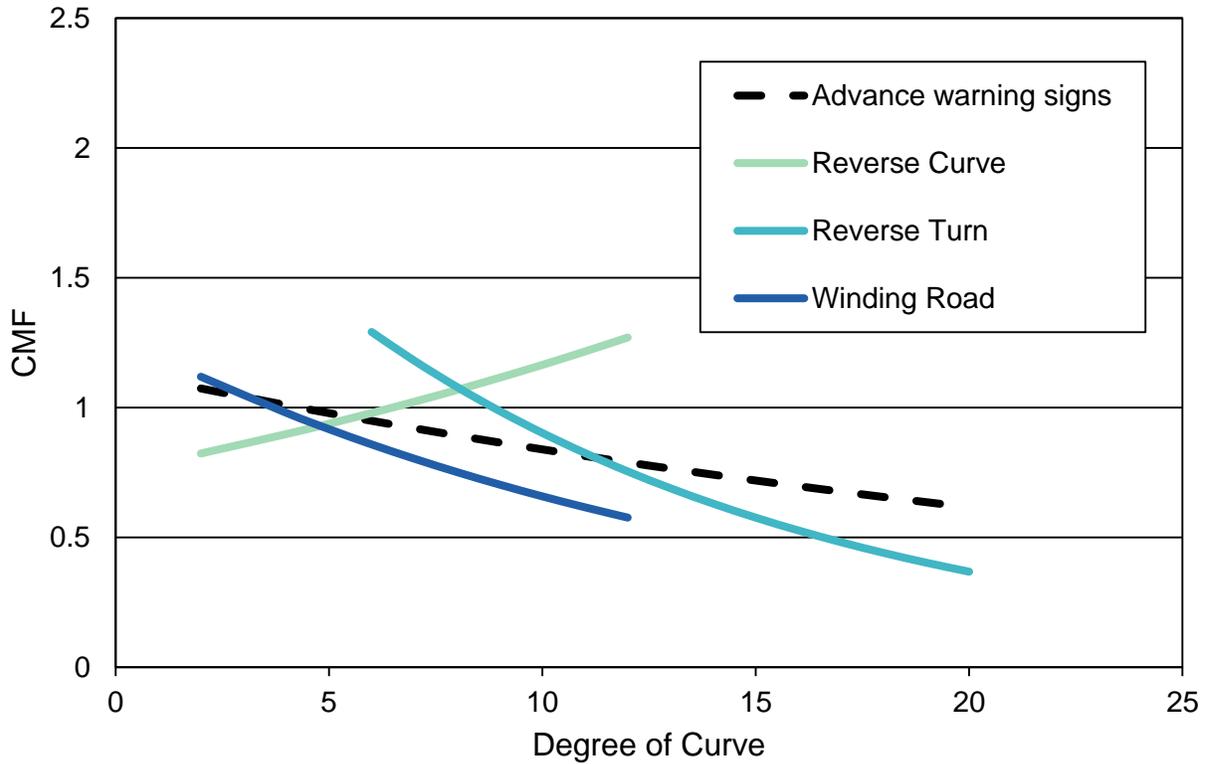


Figure H-27. CMFunction for total crashes for specific advance warning signs on curve series.

Injury Crashes

The functional form of the crash prediction model for injury crashes considering advance warning signs is given by Equation 42 and the coefficients and related statistics are provided in Table H-23. The presence of a Reverse Curve, Reverse Turn, or Winding Road warning sign is indicated with a single variable for advance warning signs (advancetcd).

$$Injury\ Crashes = AADT^{\beta_1} * Length^{\beta_2} * exp(Constant + C_1X_1 + \dots + C_nX_n) \quad 42$$

Table H-23. Crash Prediction Model Coefficients for Injury Crashes

Variables	Coefficient	St. Error	Z-Score	P-Value	L95 CI	U95 CI
Constant	-7.167	1.194	-6.00	< 0.001	-9.507	-4.827
β_1 (log-aadt)	0.809	0.135	5.98	< 0.001	0.544	1.075
β_2 (log-length)	0.176	0.173	1.02	0.309	-0.163	0.514
C1 (rrpm)	-0.328	0.231	-1.42	0.155	-0.780	0.124
C2 (lwl12)	0.395	0.240	1.65	0.099	-0.074	0.865
C3 (g)	0.674	0.228	2.95	0.003	0.226	1.121
C4 (rhr3l)	-0.609	0.295	-2.06	0.039	-1.187	-0.030
C5 (speedreduc)	0.029	0.017	1.72	0.085	-0.004	0.063
C6 (advancetcd)	-0.161	0.444	-0.36	0.718	-1.032	0.711
C7 (degrcve)	0.012	0.047	0.25	0.800	-0.079	0.103
C8 (advancedegint)	-0.043	0.061	-0.71	0.480	-0.162	0.076
Overdispersion	0.262	0.228				
N = 270; Log-likelihood = -212.98; Pseudo R ² = 0.106						

Interpretations for the covariates include:

- **AADT (log-AADT):** A positive association was found between the natural logarithm of AADT and injury crashes. An increase in AADT results in an increase in injury crashes.
- **Series Length (log-length):** A positive association was found between the natural logarithm of series length and injury crashes. An increase in length results in an increase in injury crashes.
- **Raised Reflective Pavement Markings (rrpm):** A negative association was found between RRPMs and injury crashes. The base condition is no RRPMs present. Sites with RRPMs experience fewer injury crashes than sites without RRPMs.
- **Lane Width Less than 12 feet Indicator (lwl12):** A positive association was found between the narrow lane width and injury crashes. The base condition is a lane width that is 12 feet or greater. Sites with a narrow lane (i.e., less than 12 feet) more injury crashes than sites with wide lanes.
- **Grade Indicator (g):** A positive association was found between the indicator for an absolute value of grade greater than three percent and injury crashes. The base condition is an absolute value of grade less than three percent. Sites with steeper grades experience more injury crashes than sites on flatter grades.
- **Roadside Hazard Rating Three or Less (rhr3l):** A negative association was found between having a roadside hazard rating of three or less and injury crashes. The base condition is a roadside hazard rating greater than three. Sites with a roadside hazard rating of three or less are associated with fewer injury crashes.
- **Speed Reduction (speedreduc):** A positive association was found between speed reduction and injury crashes. An increase in speed reduction is associated with an increase in injury crashes.
- **Advance Warning Sign (advancetcd):** A negative association was found between the presence of an advance warning sign and injury crashes. The parameter estimate is the main effect for an interaction with degree of curve and was insignificant.
- **Degree of Curve (degrcve):** A positive association was found between degree of curve angle and injury crashes. This characteristic was the main effect for an interaction with advance warning signs, and was insignificant.
- **Advance Warning Sign and Degree of Curve Interaction (advancedegint):** A negative association was found between the interaction term and injury crashes. The interaction

term indicates that advance warning signs become more effective as the degree of curve increases. The interaction term, however, was insignificant.

A CMFunction relating the effect of advance warning signs to injury crashes by degree of curve is presented in Equation 43.

$$CMF_{injury,series-advance} = \exp(-0.161 - 0.043 * degcrve) \quad 43$$

Figure H-28 graphically represents the CMFunction for injury crashes by degree of curve. For injury crashes, Reverse Curve, Reverse Turn, or Winding Road warning signs are not significantly associated with fewer crashes for any value of degree of curve. While the CMF is statistically insignificant for all values of degree of curve, the mean CMF value is less than 1.00 (potential safety benefit) for all values of degree of curve.

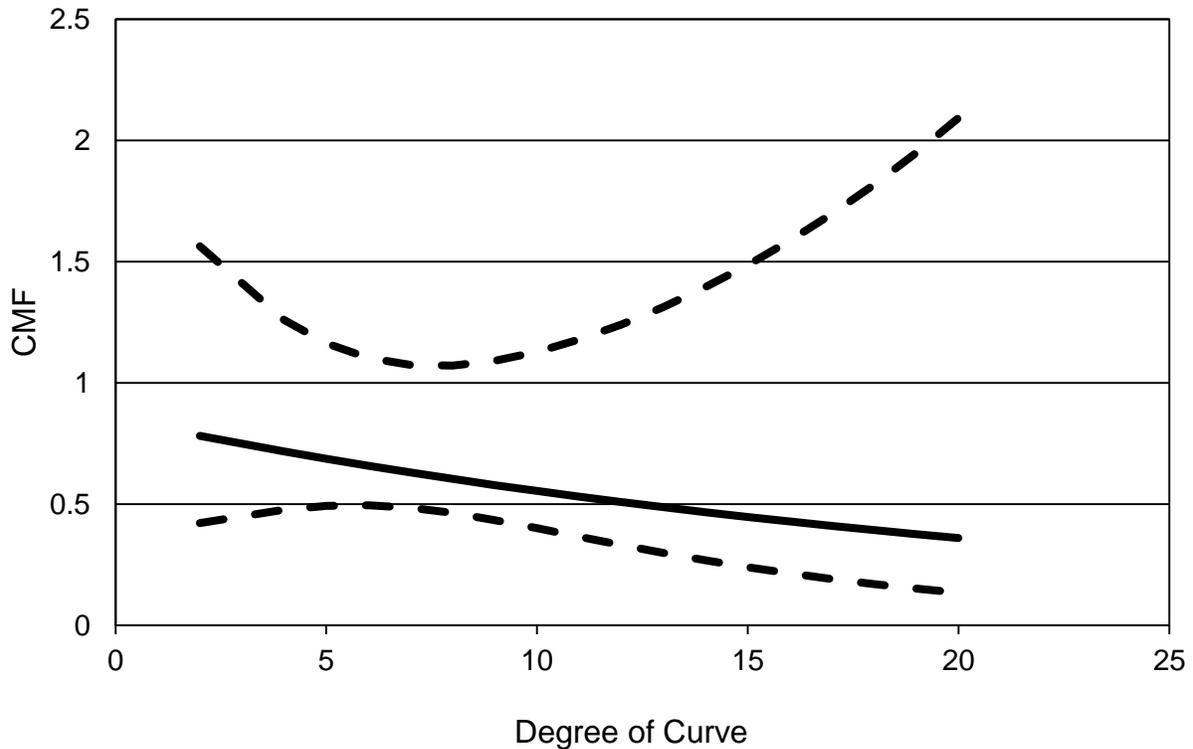


Figure H-28. CMFunction for injury crashes for advance warning signs on curve series.

CMFunctions for Reverse Turn and Winding Road signs are given as Equations 44 and 45.

$$CMF_{injury,series-reverseturn} = \exp(1.169 - 0.088 * degcrve) \quad 44$$

$$CMF_{injury,series-winding} = \exp(0.396 - 0.191 * degcrve) \quad 45$$

The CMFunctions are illustrated in Figures H-29 and H-30. For fatal and injury crashes, Reverse Turn signs are never significantly associated with fewer crashes; however, the mean CMF value is less than 1.00 (potential safety benefit) when the degree of curve is greater than approximately 13 degrees. Winding Road signs are significantly associated with fewer crashes when the degree of curve is greater than 5 degrees. The mean CMF value is less than 1.00 (potential safety benefit) when the degree of curve is greater than approximately 2 degrees.

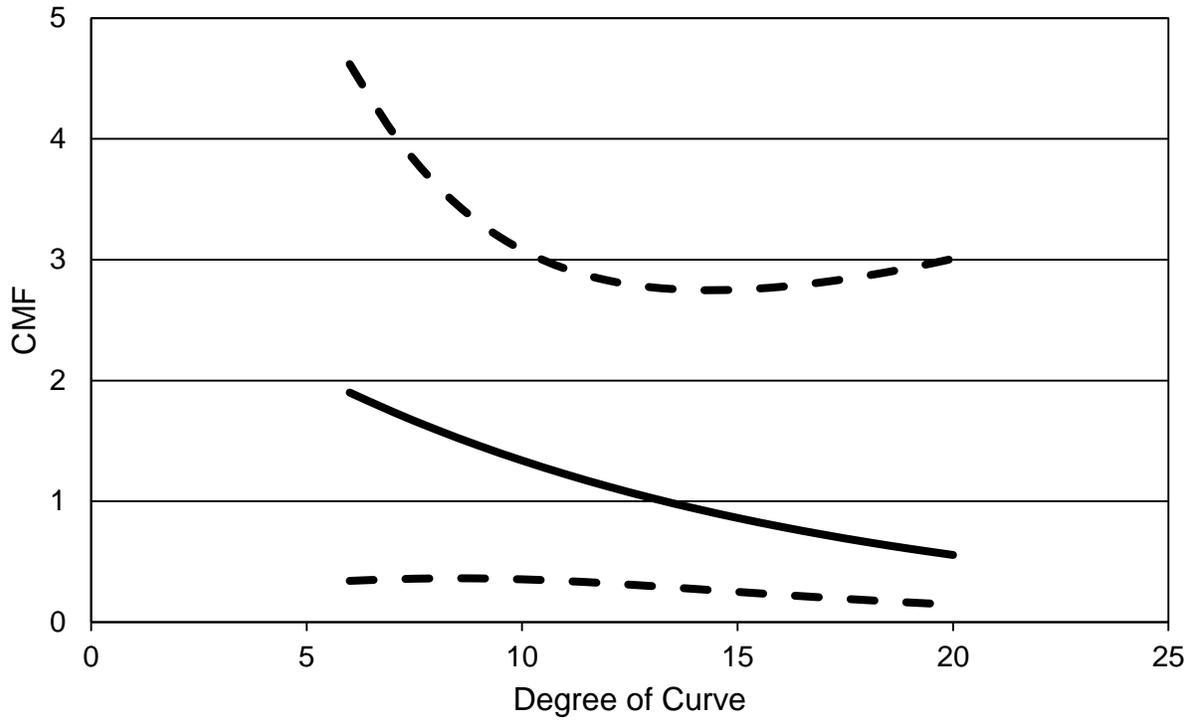


Figure H-29. CMFunction for injury crashes for Reverse Turn signs on curve series.

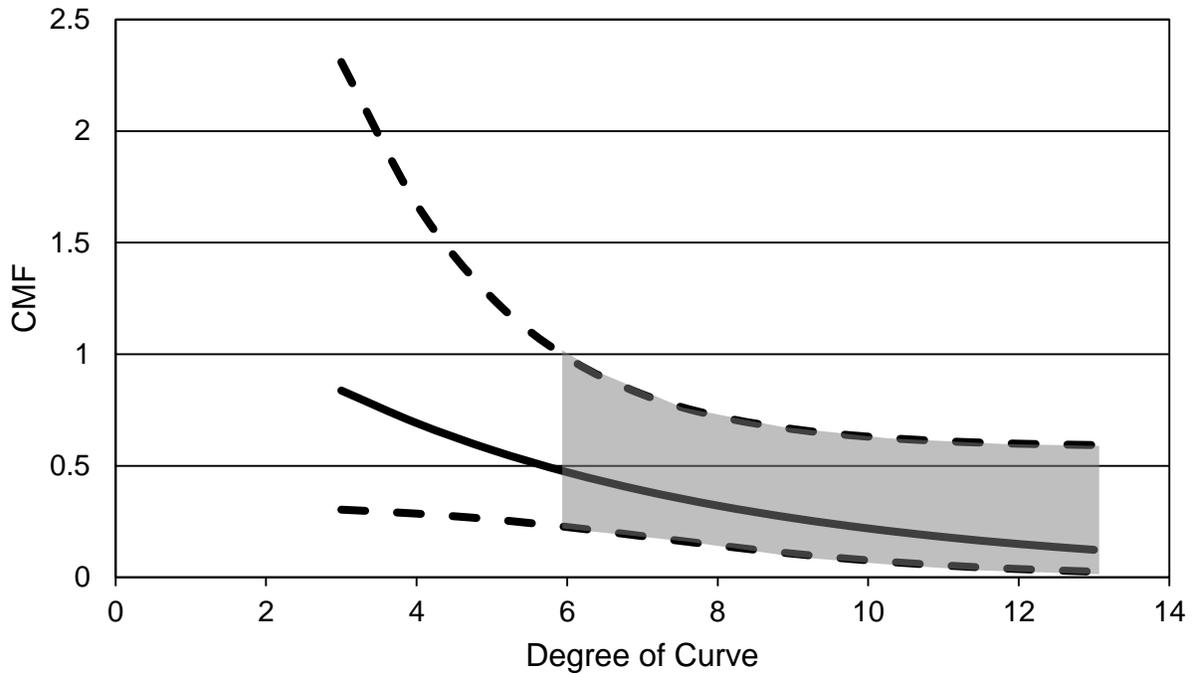


Figure H-30. CMFunction for injury crashes for Winding Road signs on curve series.

SVROR Crashes

The functional form of the crash prediction model for SVROR crashes considering advance warning signs is given by Equation 46 and the coefficients and related statistics are provided in Table H-24. The presence of a Reverse Curve, Reverse Turn, or Winding Road warning sign is indicated with a single variable for advance warning signs (*advancetcd*). Due to a lack of dispersion in the data, a Poisson model was used in place of a Negative Binomial (NB) model regression model. The NB model reduces to a Poisson model when no dispersion is present.

$$SVROR\ Crashes = AADT^{\beta_1} * Length^{\beta_2} * exp(Constant + C_1X_1 + \dots + C_nX_n)$$

Table H-24. Crash Prediction Model Coefficients for SVROR Crashes

Variables	Coefficient	St. Error	Z-Score	P-Value	L95 CI	U95 CI
Constant	-5.395	0.966	-5.59	< 0.001	-7.288	-3.502
β_1 (log-aadt)	0.536	0.103	5.20	< 0.001	0.334	0.738
β_2 (log-length)	0.332	0.154	2.15	0.031	0.030	0.633
C1 (Tennessee)	0.345	0.278	1.24	0.216	-0.201	0.890
C2 (Ohio)	0.560	0.309	1.81	0.070	-0.046	1.166
C3 (rrpm)	-0.262	0.251	-1.04	0.297	-0.755	0.230
C4 (lwl12)	0.376	0.217	1.73	0.083	-0.049	0.801
C5 (g)	0.360	0.188	1.91	0.056	-0.009	0.729
C6 (rhr)	0.165	0.102	1.62	0.105	-0.034	0.365
C7 (rumble)	-0.518	0.335	-1.55	0.122	-1.175	0.139
C8 (advancedctd)	-0.132	0.367	-0.36	0.720	-0.851	0.588
C9 (degrve)	-0.004	0.037	-0.11	0.913	-0.076	0.068
C10 (advancedegint)	-0.008	0.045	-0.18	0.857	-0.096	0.080
N = 270; Log-likelihood = -255.01; Pseudo R ² = 0.109						

Interpretations for the covariates include:

- **AADT (log-AADT):** A positive association was found between the natural logarithm of AADT and SVROR crashes. A unit increase in AADT results in an increase in SVROR crashes.
- **Series Length (log-length):** A positive association was found between the natural logarithm of series length and SVROR crashes. A unit increase in length results in an increase in SVROR crashes.
- **Tennessee and Ohio Indicators (Tennessee, Ohio):** A positive association was found between the indicators for the site location being in Tennessee or Ohio and SVROR crashes. The base condition is that the site location is in Florida or Oregon. Sites in Tennessee and Ohio experience more SVROR crashes than those in Florida and Oregon.
- **Raised Reflective Pavement Markings (rrpm):** A negative association was found between RRPMs and SVROR crashes. The base condition is no RRPMs present. Sites with RRPMs experience fewer SVROR crashes than sites without RRPMs.
- **Lane Width Less than 12 feet Indicator (lwl12l):** A positive association was found between the narrow lane width and SVROR crashes. The base condition is a lane width that is 12 feet or greater. Sites with a narrow lane (i.e., less than 12 feet) experience more SVROR crashes than sites with wide lanes.
- **Grade Indicator (g):** A positive association was found between the indicator for an absolute value of grade greater than three percent and SVROR crashes. The base condition is an absolute value of grade less than three percent. Sites with steeper grades (i.e., greater than three percent) experience more SVROR crashes than sites on flatter grades.
- **Roadside Hazard Rating (rhr):** A positive association was found between roadside hazard rating and SVROR crashes. An increase in roadside hazard rating is associated with an increase in SVROR crashes. The finding was marginally significant.
- **Rumble Strips Indicator (rumble):** A negative association was found between the indicator for the presence of rumble strips and SVROR crashes. The base condition is no rumble strips present. Sites with rumble strips experience fewer SVROR crashes than those without rumble strips. The finding was marginally significant.

- Advance Warning Sign (advancetcd): A negative association was found between the presence of an advance warning sign and SVROR crashes. The parameter estimate is the main effect for an interaction with degree of curve and was insignificant.
- Degree of Curve (degcrve): A negative association was found between degree of curve angle and SVROR crashes. This characteristic was the main effect for an interaction with advance warning signs, and was insignificant.
- Advance Warning Sign and Degree of Curve Interaction (advancedegint): A negative association was found between the interaction term and SVROR crashes. The interaction term indicates that advance warning signs become more effective as the degree of curve increases. The interaction term, however, was insignificant.

A CMFunction relating the effect of advance warning signs to SVROR crashes by degree of curve is presented in Equation 47.

$$CMF_{SVROR,series-advance} = \exp(-0.132 - 0.008 * degcrve) \quad 47$$

Figure H-31 graphically represents the CMFunction for SVROR crashes by degree of curve. For SVROR crashes, Reverse Curve, Reverse Turn, or Winding Road warning signs are not significantly associated with fewer crashes for any value of degree of curve. While the CMF is statistically insignificant for all values of degree of curve, the mean CMF value is less than 1.00 (potential safety benefit) for all values of degree of curve.

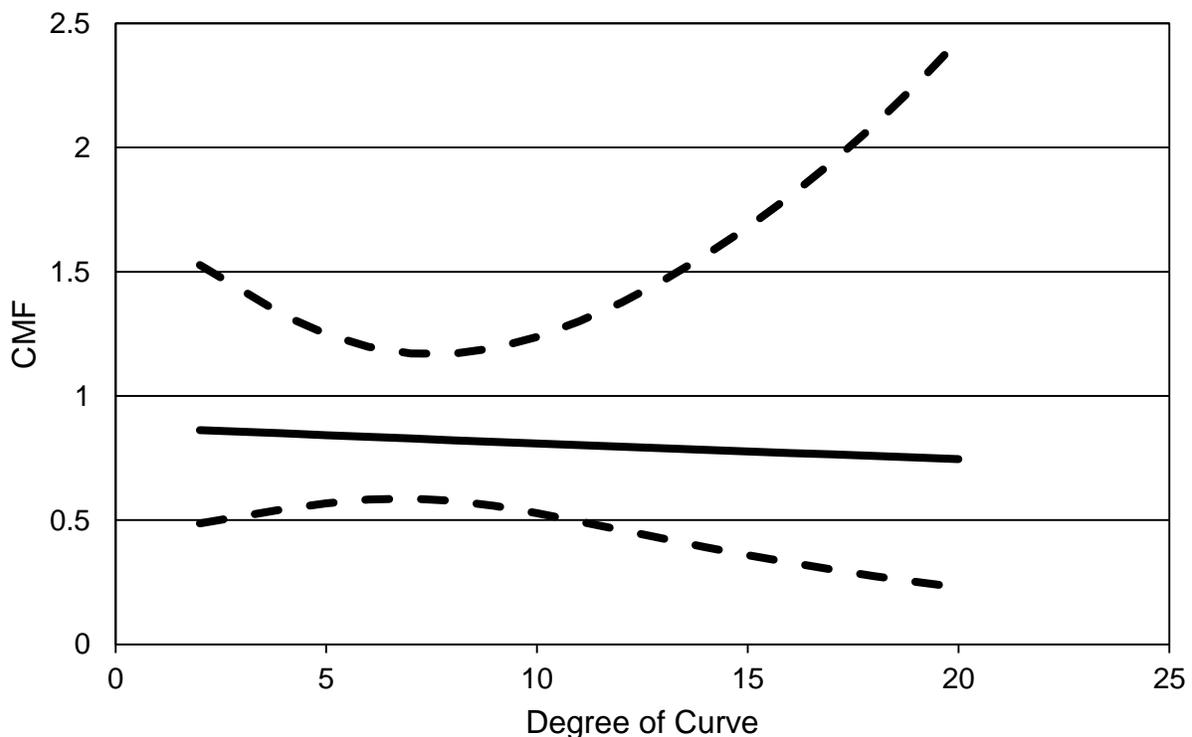


Figure H-31. CMFunction for SVROR crashes for advance warning signs on curve series.

There were no significant or marginally significant interactions for individual advance warning signs for SVROR crashes.

Adverse Pavement Condition Crashes

The functional form of the crash prediction model for adverse pavement condition crashes considering advance warning signs is given by Equation 48 and the coefficients and related statistics are provided in Table H-25. The presence of a Reverse Curve Warning, Reverse Turn Warning, or Winding Road Warning sign is indicated with a single variable for advance warning signs (advancetcd). Due to a lack of dispersion in the data, a Poisson model was used in place of a Negative Binomial (NB) model regression model. The NB model reduces to a Poisson model when no dispersion is present.

$$Adv. Pvmnt. Crashes = AADT^{\beta_1} * Length^{\beta_2} * exp(Constant + C_1X_1 + \dots + C_nX_n) \quad 48$$

Table H-25. Crash Prediction Model Coefficients for Adverse Pavement Condition Crashes

Variables	Coefficient	St. Error	Z-Score	P-Value	L95 CI	U95 CI
Constant	-5.725	1.426	-4.01	< 0.001	-8.521	-2.930
β1 (log-aadt)	0.667	0.142	4.71	< 0.001	0.389	0.944
β2 (log-length)	0.183	0.202	0.91	0.364	-0.212	0.579
C1 (Tennessee)	-0.648	0.314	-2.06	0.039	-1.262	-0.033
C2 (Florida)	-1.126	0.666	-1.69	0.091	-2.431	0.179
C3 (lwl12)	0.823	0.295	2.79	0.005	0.246	1.401
C4 (g)	0.423	0.253	1.68	0.094	-0.072	0.918
C5 (rhr)	0.307	0.157	1.96	0.050	0.000	0.614
C6 (epm)	-2.570	0.811	-3.17	0.002	-4.160	-0.980
C7 (degcrve)	0.019	0.053	0.35	0.728	-0.086	0.123
C8 (advancetcd)	0.775	0.565	1.37	0.170	-0.333	1.882
C9 (advancedegint)	-0.059	0.065	-0.92	0.359	-0.186	0.067

N = 270; Log-likelihood = -168.52; Pseudo R² = 0.144

Interpretations for the covariates include:

- AADT (log-AADT): A positive association was found between the natural logarithm of AADT and adverse pavement condition crashes. A unit increase in AADT results in an increase in adverse pavement condition crashes.
- Series Length (log-length): A positive association was found between the natural logarithm of series length and adverse pavement condition crashes. An increase in length results in an increase in adverse pavement condition crashes. The result was insignificant, but was retained in the model for consistency.
- Tennessee and Florida Indicators (Tennessee, Florida): A negative association was found between the indicators for the site location being in Tennessee or Florida and adverse pavement condition crashes. The base condition is that the site location is in Ohio or Oregon. Sites in Tennessee and Florida experience fewer adverse pavement condition crashes than those in Ohio and Oregon.
- Lane Width Less than 12 feet Indicator (lwl12): A positive association was found between the narrow lane width and adverse pavement condition crashes. The base condition is a lane width that is 12 feet or greater. Sites with a narrow lane (i.e., less than 12 feet) experience more adverse pavement condition crashes than sites with wide lanes.

- Grade Indicator (g): A positive association was found between the indicator for an absolute value of grade greater than three percent and adverse pavement condition crashes. The base condition is an absolute value of grade less than three percent. Sites with steeper grades (i.e., greater than three percent) experience more adverse pavement condition crashes than sites on flatter grades.
- Roadside Hazard Rating (rhr): A positive association was found between roadside hazard rating and adverse pavement condition crashes. An increase in roadside hazard rating is associated with an increase in adverse pavement condition crashes.
- Edge line Pavement Markings Indicator (epm): A negative association was found between the indicator for edge line pavement markings and adverse pavement condition crashes. The baseline condition was the absence of edge line pavement markings. Sites with edge line pavement markings are associated with fewer adverse pavement condition crashes than sites without edge line pavement markings.
- Degree of Curve (degcrve): A positive association was found between degree of curve angle and adverse pavement condition crashes. This characteristic was the main effect for an interaction with advance warning signs, and was insignificant.
- Advance Warning Sign (advancetcd): A positive association was found between the presence of an advance warning sign and adverse pavement condition crashes. The parameter estimate is the main effect for an interaction with degree of curve.
- Advance Warning Sign and Degree of Curve Interaction (advancedegint): A negative association was found between the interaction term and adverse pavement condition crashes. The interaction term indicates that advance warning signs become more effective as the degree of curve increases. The interaction term, however, was insignificant.

A CMFunction relating the effect of advance warning signs to adverse pavement condition crashes by degree of curve is presented in Equation 49.

$$CMF_{adverse,series-advance} = \exp(0.775 - 0.059 * degcrve) \quad 49$$

Figure H-32 graphically represents the CMFunction for adverse pavement condition crashes by degree of curve. For adverse pavement condition crashes, Reverse Curve, Reverse Turn, or Winding Road warning signs are not significantly associated with fewer crashes for any value of degree of curve. While the CMF is statistically insignificant for all values of degree of curve, the mean CMF value is less than 1.00 (potential safety benefit) when the degree of curve is greater than 13 degrees.

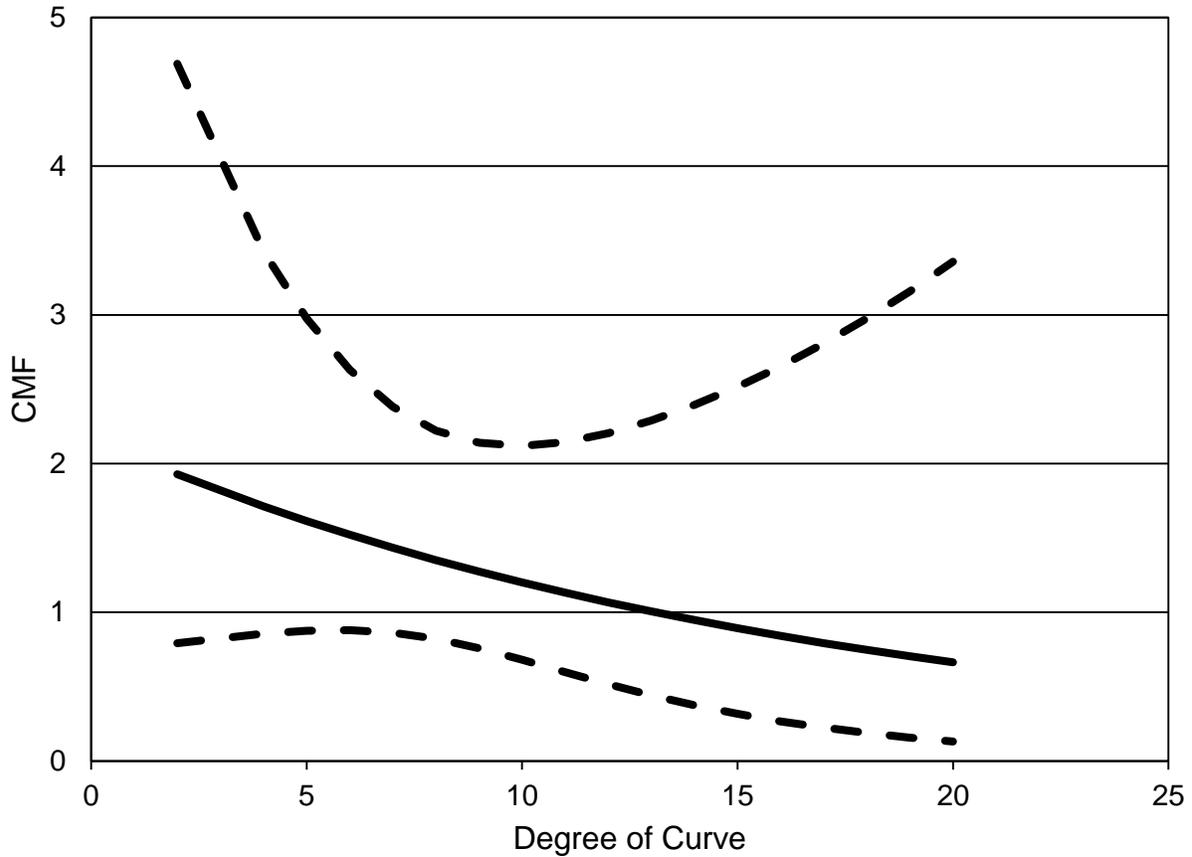


Figure H-32. CMFunction for adverse pavement condition crashes for advance warning signs on curve series.

A disaggregate analysis of the interactions between individual signs and degree of curve for adverse pavement crashes on series curves only produced significant results for Reverse Turn warning signs. A CMFunction for Reverse Turn signs is given as Equation 50. The CMFunction is illustrated in Figure H-33. There is never a significant decrease in crashes, but the mean CMF indicates a potential safety benefit when the degree of curvature is greater than approximately 8 degrees.

$$CMF_{adverse,series-reverseturn} = \exp(2.114 - 0.249 * degcrve) \quad 50$$

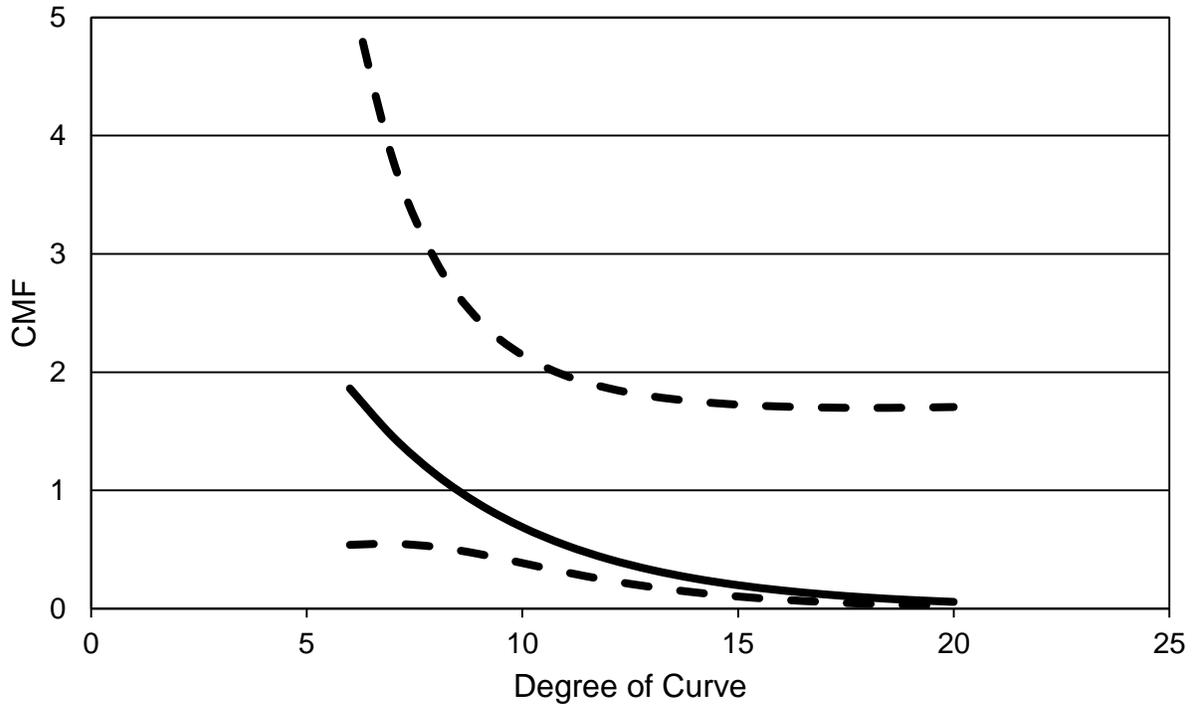


Figure H-33. CMFunction for adverse pavement condition crashes for Reverse Turn signs on curve series.

Nighttime Crashes

The functional form of the crash prediction model for nighttime crashes considering advance warning signs is given by Equation 51 and the coefficients and related statistics are provided in Table H-26. The presence of a Reverse Curve, Reverse Turn, or Winding Road warning sign is indicated with a single variable for advance warning signs (advancetcd). Due to a lack of dispersion in the data, a Poisson model was used in place of a Negative Binomial (NB) model regression model.

$$\text{Nighttime Crashes} = AADT^{\beta_1} * \text{Length}^{\beta_2} * \exp(\text{Constant} + C_1X_1 + \dots + C_nX_n) \quad 51$$

Table H-26. Crash Prediction Model Coefficients for Nighttime Crashes

Variables	Coefficient	St. Error	Z-Score	P-Value	L95 CI	U95 CI
Constant	-8.431	1.374	-6.13	< 0.001	-11.125	-5.737
β1 (log-aadt)	0.768	0.137	5.59	< 0.001	0.499	1.038
β2 (log-length)	0.175	0.174	1.01	0.314	-0.166	0.515
C1 (Oregon)	-0.416	0.244	-1.02	0.307	-1.213	0.382
C2 (lwl12)	0.531	0.244	2.18	0.029	0.053	1.009
C3 (g)	0.719	0.221	3.26	0.001	0.286	1.151
C4 (rhr)	0.166	0.111	1.50	0.135	-0.052	0.383
C5 (degcrve)	0.052	0.044	1.19	0.236	-0.034	0.139
C6 (advancetcd)	0.524	0.437	1.20	0.231	-0.342	1.414
C7 (advancedegint)	-0.079	0.054	-1.44	0.149	-0.184	0.028
Overdispersion	0.029	0.179				

N = 270; Log-likelihood = -197.06; Pseudo R² = 0.124

Interpretations for the covariates include:

- AADT (log-AADT): A positive association was found between the natural logarithm of AADT and nighttime crashes. An increase in AADT results in an increase in nighttime crashes.
- Series Length (log-length): A positive association was found between the natural logarithm of series length and nighttime crashes. An increase in length results in an increase in nighttime crashes.
- Oregon Indicator (Oregon): A negative association was found between the indicator for the site being located in Oregon and nighttime crashes. The base condition is that the site location is in Florida, Ohio, or Tennessee. Sites in Oregon experience fewer nighttime crashes than those in Florida, Ohio, and Tennessee.
- Lane Width Less than 12 feet Indicator (lwl12): A positive association was found between the narrow lane width and nighttime crashes. The base condition is a lane width that is 12 feet or greater. Sites with a narrow lanes (i.e., less than 12 feet) experience more nighttime crashes than sites with wide lanes.
- Grade Indicator (g): A positive association was found between the indicator for an absolute value of grade greater than three percent and nighttime crashes. The base condition is an absolute value of grade less than three percent. Sites with steeper grades experience more nighttime crashes than sites on flatter grades.
- Roadside Hazard Rating Three or Less (rhr3l): A negative association was found between the indicator for roadside hazard rating three or less and nighttime crashes. The base condition is a roadside hazard rating more than 3. Sites with lower roadside hazard rating (i.e., three or less) are associated with fewer nighttime crashes than sites with a higher roadside hazard rating.
- Degree of Curve (degrve): A positive association was found between degree of curve angle and nighttime crashes. An increase in degree of curve is associated with an increase in nighttime crashes. This characteristic was the main effect for an interaction with advance warning signs.
- Advance Warning Sign (advancetcd): A positive association was found between the presence of an advance warning sign and nighttime crashes. The parameter estimate is the main effect for an interaction with degree of curve.
- Advance Warning Sign and Degree of Curve Interaction (advancedegint): A negative association was found between the interaction term and nighttime crashes. The interaction term indicates that advance warning signs become more effective as the degree of curve increases.

A CMFunction relating the effect of advance warning signs to nighttime crashes by degree of curve is presented in Equation 52.

$$CMF_{nighttime,series-advance} = \exp(0.524 - 0.079 * degrve) \quad 52$$

Figure H-34 graphically represents the CMFunction for nighttime crashes by degree of curve. For nighttime crashes, Reverse Curve, Reverse Turn, or Winding Road warning signs are not significantly associated with fewer crashes for any value of degree of curve. While the CMF

is statistically insignificant for all values of degree of curve, the mean CMF value is less than 1.00 (potential safety benefit) when the degree of curve is greater than 6 degrees.

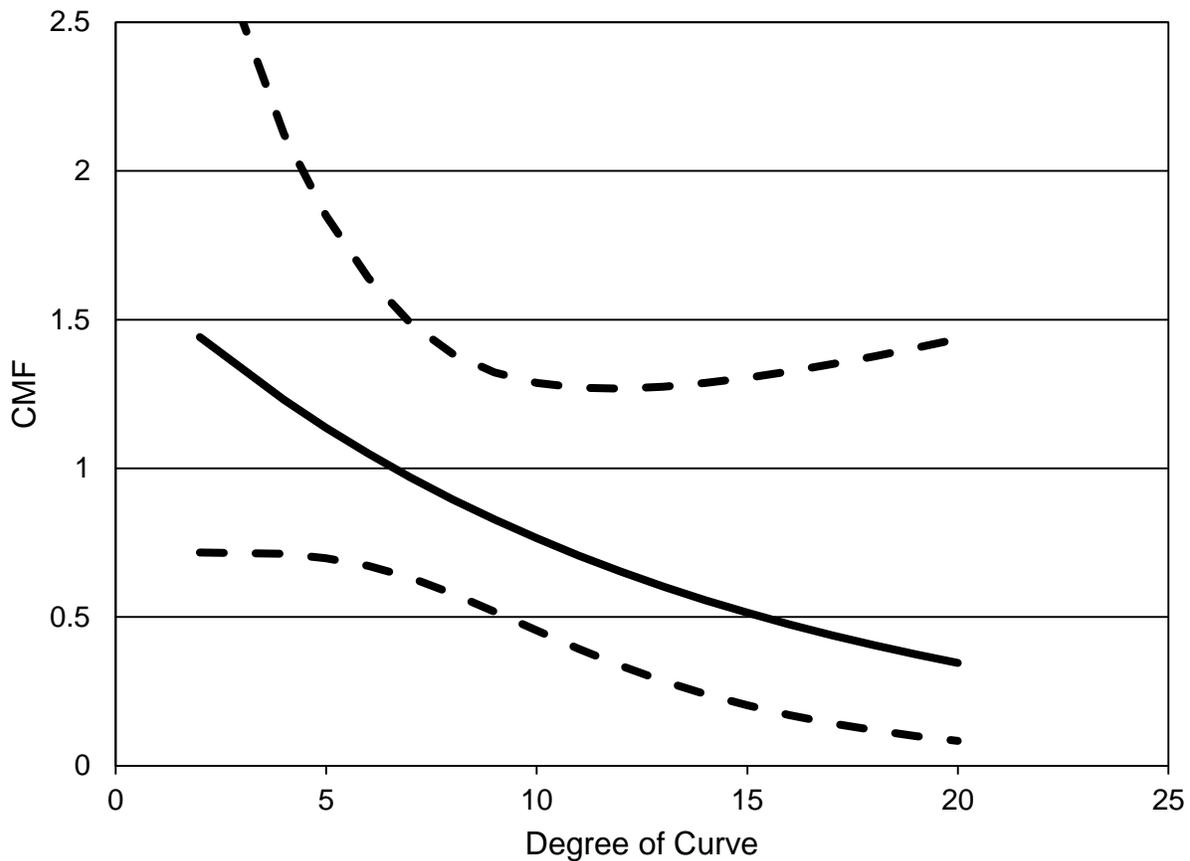


Figure H-34. CMFunction for nighttime crashes for advance warning signs on curve series.

SUMMARY OF CRASH-BASED ANALYSIS

Crash prediction models were developed to estimate the effects of horizontal alignment warning signs on total, injury, SVROR, adverse pavement condition, and nighttime crashes. Separate crash prediction models were developed for each type of crash at isolated curves and series curves, with separate consideration for the use of advance and in-curve warning signs. The specific TCDs of interest included:

- In-curve Horizontal Alignment signs (at isolated and series curves).
 - W1-6: One-Direction Large Arrow sign.
 - W1-8: Chevron Alignment sign.
- Advance Isolated Horizontal Alignment signs.
 - W1-1: Turn sign.
 - W1-2: Curve sign.
- Advance Series Horizontal Alignment signs.
 - W1-3: Reverse Turn sign.

- W1-4: Reverse Curve sign.
- W1-5: Winding Road sign.

In-Curve Warning Signs

The safety effect of chevrons and/or Large Arrow signs was found to vary by traffic volume for both isolated and series curves. Equation 55 can be used to estimate the CMF for the installation of chevrons and/or Large Arrow signs within the curve (or curve series). The results apply to curves that are already treated with advance warning signs. The coefficients for isolated and series curves are presented by crash type in Table H-27. The CMFs are a function of AADT in thousands of vehicles per day.

$$CMF_{TCD-in-curve} = \exp(c - d * AADT(\text{thousands})) \quad (55)$$

Table H-27. Recommended Coefficients for In-Curve Sign CMFs

Crash Type	Isolated Curve		Curve Series	
	c	d	c	d
Total	0.203	0.089	0.401	0.065
Injury	0.564	0.157	0.860	0.150
SVROR	0.179	0.079	0.278	0.041
Adverse Pavement	0.015	0.117	0.583	0.076
Nighttime	N/A	N/A	0.455	0.136

For isolated curves, chevrons and/or Large Arrow signs were found to significantly reduce crashes for all crash types except nighttime crashes, as long as AADT was above a particular threshold. For series curves, the in-curve warning signs were only found to reduce crashes at 95 percent confidence for nighttime crashes on roadways with high AADT. The other crash types experienced probable decreases in crashes. It is possible that in-curve signs lose effectiveness for series curves because they may be installed at only the first curve in a series for each direction of travel. The locations of crashes within a curve series were not investigated, so it cannot be determined whether or not crashes occurred at the first or subsequent curves.

In-Curve Warning Signs for Isolated Curves

Significant crash reductions occur with in-curve warning signs beginning between 4,000 and 7,000 AADT across all crash types on isolated curves. While there are no significant crash reductions across all crash types when AADT is less than 4,000, insignificant (probable) crash reductions were observed beginning at an AADT of 2,000 for total and SVROR crashes. In disaggregate analyses Large Arrow signs were more effective at reducing crashes than chevrons, though Large Arrows tend to have more limited applications (usually sharp curves and low-volume roads). The effectiveness of Large Arrow signs increased as curve radius decreased. There seems to be no benefit from combinations of chevrons and Large Arrow signs, though the sample size was very small.

In-Curve Warning Signs within Curve Series

The effectiveness of in-curve warning signs on crash reductions was not as clear for curve series as for isolated curves. Only for nighttime crashes did in-curve signs result in statistically significant crash reductions, which occurred when AADT was above 7,000. There were probable reductions (CMFunction less than 1) in total and injury crashes when AADT was above 6,000. Large Arrow signs appear to be more effective than chevrons when AADT is greater than 2,000, though the data suggest they are applied on low volume roads and only at severe curves.

Advance Warning Signs

The effect of advance warning signs was found to vary by degree of curvature. Degree of curvature was used in the crash prediction models because it was the functional form of the geometric variable provided by all four states in the study. Moreover, degree of curvature is appropriately scaled with other predictor variables, leading to coefficients that are similar in magnitude to other variables. However, practitioners typically use and have a better understanding of curve radius, which is consistent with design guidelines in the AASHTO Green Book and the MUTCD. For simplicity in applying the results, the following summary transforms the results to reflect the influence of horizontal curve radius rather than degree of curve. The curve radius is calculated as 5,729.6 divided by the degree of curve.

Equation 54 can be used to estimate the CMF for any crash type from the installation of advance warning signs at isolated or series curves. The appropriate coefficients for isolated and series curves are given in Table H-28. The CMFs are a function of the curve radius for isolated curves, and average radius for the curve series.

$$CMF_{TCD-advance} = \exp\left(a - b * \frac{1}{radius}\right) \quad 54$$

Table H-28. Recommended Coefficients for Advance Warning Sign CMFs

Crash Type	Isolated Curve		Curve Series	
	a	b	a	b
Total	0.710	638.48	0.133	176.55
Injury	0.729	551.98	-0.161	246.19
SVROR	0.623	536.34	-0.132	46.24
Adverse Pavement	0.472	614.77	0.775	339.27
Nighttime	0.749	827.17	0.524	446.68

Though most models were not able to identify reductions in crashes due to advance warning signs that are *significant* at a 95 percent confidence level, all were able to indicate that there is a likely decrease in crashes as the degree of curvature increases beyond a particular threshold. For example, the model for total crashes on isolated curves indicates that advance warning signs reduce crashes with 95 percent confidence at a curvature of 15 degrees or greater. A 15-degree curvature is approximately equivalent to a radius of 400 ft. The results do not completely reflect the impacts of posted advisory speed on advance warning sign effectiveness.

Speed reduction from the posted speed limit to the advisory speed was included in the crash prediction models; however, speed reduction is assumed to be zero for curves with no advisory speed, regardless of the posted speed limit and curve radius. Additionally, radius and speed reduction were found to be highly correlated with AADT (roadways with less severe horizontal curvature have higher traffic volumes), confounding the effects of horizontal curvature.

Advance Warning Signs for Isolated Curves

The analyses of advance warning signs at isolated curves indicate that Curve and Turn warning signs result in statistically significant reductions in crashes when the curve radius is less than approximately 400 ft. Probable crash reductions (the CMFunction is less than 1 with no consideration for confidence intervals) occur when the curve radius is shorter than 950 ft. When evaluating specific crash types (rather than total crashes), statistically significant reductions were not observed, but probable reductions were identified for specific radii, and the effect tends to increase as the radius decreases. A disaggregate analysis suggests that Turn warning signs are more effective than Curve warning signs when the radius is approximately 575 ft or less.

Advance Warning Signs at Curve Series

The analyses of advance warning signs at curve series indicate that Reverse Curve, Reverse Turn, and Winding Road warning signs only result in *probable* crash reductions (not statistically significant), though the effectiveness increases with curve severity. A disaggregate analysis of the different signs with total crashes suggests that Reverse Turn warning signs may be preferred over Reverse Curve warning signs when the average radius is approximately 700 ft or less. The Winding Road sign also appears to be more effective than the Reverse Turn and Curve warning signs, though statistical significance could also not be established and the Winding Road sign has different guidelines that control its application.

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Appendix I: Recommended Changes to the MUTCD

In the current (2009) MUTCD, the language addressing TCDs for changes in horizontal alignment appears in the following sections:

- Section 2C.06: Horizontal Alignment Warning Signs
- Section 2C.07: Horizontal Alignment Signs
- Section 2C.09: Chevron Alignment Sign
- Section 2C.10: Combination Horizontal Alignment/Advisory Speed Signs
- Section 2C.11: Combination Horizontal Alignment/Intersection Signs
- Section 2C.12: One-Direction Large Arrow Sign
- Section 2C.13: Truck Rollover Warning Sign
- Section 2C.14: Advisory Exit and Ramp Speed Signs
- Section 2C.15: Combination Horizontal Alignment/Advisory Exit and Ramp Speed Signs
- Section 3B.12: Raised Pavement Markers as Vehicle Positioning Guides with Other Longitudinal Markings
- Section 3B.13: Raised Pavement Markers Supplementing Other Markings
- Section 3F.01: Delineators
- Section 3F.04: Delineator Placement and Spacing

Although it is not technically a horizontal alignment warning sign, the Advisory Speed Plaque is addressed in Section 2C.08 because its predominant use is for changes in horizontal alignment. While there are eight sections addressing the warning signs for changes in horizontal alignment and four related to markings, the key criteria for the use of warning devices are in Sections 2C.06, 07, 09, and 12. Chapter 2 contains a more detailed review of the criteria associated with the use of each of these devices and Appendix A identifies current practices for treating curves.

This appendix presents the research team's recommendations for changes to the 2009 MUTCD language related to changes in horizontal alignment. Additions to the 2009 MUTCD language are indicated by blue underlined text. Deletions from the 2009 MUTCD language are indicated by ~~red strikethrough~~ text. Footnotes are used to explain the significant changes proposed to help the reader connect the recommendations with the research. The footnotes are not intended for inclusion in the MUTCD. New sections/paragraphs added between existing sections/paragraphs are numbered by adding a letter to the number for the previous paragraph (i.e., a new paragraph inserted between paragraphs 1 and 2 is numbered 1a).

It is worth noting that these recommended changes are not expected to be adopted in a future edition of the MUTCD without amendments. The thorough review involving the National Committee on Uniform Traffic Control Devices (NCUTCD) and the FHWA rulemaking process increase the likelihood that several changes will be made before final adoption.

Section 1A.13 Definitions of Headings, Words, and Phrases in this Manual

xx. Speed Reduction – The difference between the speed limit and the advisory speed.¹

Section 2C.06 Horizontal Alignment Warning Signs

Support:

01 Changes in horizontal alignment are a common feature in roadway design that road users expect to encounter when traveling on a roadway. When the severity of a change in horizontal alignment reaches a specific threshold, warning devices or other treatments help inform the road user of the change in horizontal alignment. There are many devices that can be used to warn road users of a change in horizontal alignment or provide other types of assistance in navigating the alignment change.² These devices include a variety of horizontal alignment warning signs (see Figure 2C-1), pavement markings (see Chapter 3B), and delineation (see Chapter 3F). Uniform application of these traffic control devices with respect to the amount of change in the roadway alignment conveys a consistent message establishing driver expectancy and promoting effective roadway operations. The design and application of horizontal alignment warning signs to meet ~~those requirements~~ the needs of motorists are addressed in Sections 2C.06 through 2C.15.

02 The following list identifies possible treatments (some of which are not traffic control devices) that can be used in advance of or within a change in horizontal alignment.³

- A. Horizontal alignment sign (Turn (W1-1), Curve (W1-2), Reverse Turn (W1-3), Reverse Curve (W1-4), Winding Road (W1-5)).
- B. Advisory Speed Plaque (W13-1P).
- C. Chevrons (W1-8).
- D. Delineators (Chapter 3F).
- E. Large Arrow (W1-6) sign.
- F. Retroreflective raised pavement markers (Section 3B.12 through 3B.13).
- G. Increased sign or marking retroreflectivity.
- H. Increased sign size and/or width of marking.
- I. Horizontal pavement markings (symbol or words) (Section 3B.20).
- J. Improved surface friction.
- K. Roadway lighting in the vicinity of the horizontal alignment change.

Standard:

~~02—In advance of horizontal curves on freeways, on expressways, and on roadways with more than 1,000 AADT that are functionally classified as arterials or collectors, horizontal alignment warning signs shall be used in accordance with Table 2C-5 based on~~

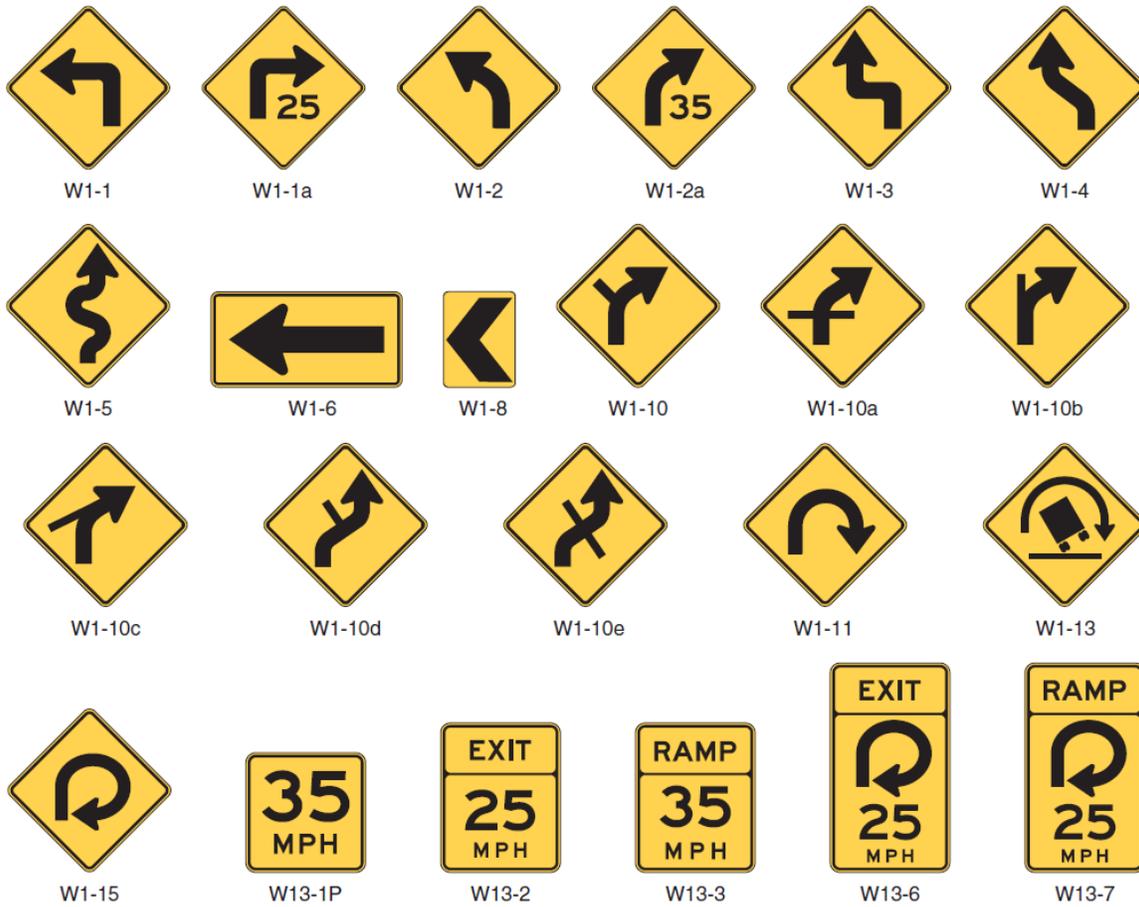
¹ This definition is to be added to Section 1A.13 to support the use of Speed Reduction in discussing appropriate treatments.

² Acknowledging that alignment changes are expected reduces the need to treat curves that are not demanding. This addition supports the proposed methodology for selecting an appropriate treatment using the operational demands of a change in alignment.

³ This list is similar to revisions recommended by the NCUTCD (June 2013).

~~the speed differential between the roadway's posted or statutory speed limit or 85th-percentile speed, whichever is higher, or the prevailing speed on the approach to the curve, and the horizontal curve's advisory speed.~~⁴

Figure 2C-1. Horizontal Alignment Signs and Plaques



Note: Turn arrows and reverse turn arrows may be substituted for the curve arrows and reverse curve arrows on the W1-10 series signs where appropriate.

⁴ The Standard statement is removed based on the findings identifying the traffic volumes for which safety improvements can be attributed to horizontal alignment traffic control devices. Additionally, the Standard is replaced with a Guidance statement that provides greater flexibility in addressing site-specific conditions.

Table 2C-5. Horizontal Alignment Sign Selection

Type of Horizontal Alignment Sign	Difference Between Speed Limit and Advisory Speed				
	5 mph	10 mph	15 mph	20 mph	25 mph or more
Turn (W1-1), Curve (W1-2), Reverse Turn (W1-3), Reverse Curve (W1-4), Winding Road (W1-5), and Combination Horizontal Alignment/Intersection (W10-1) (see Section 2C.07 to determine which sign to use)	Recommended	Required	Required	Required	Required
Advisory Speed Plaque (W13-1P)	Recommended	Required	Required	Required	Required
Chevrons (W1-8) and/or Opposite Direction Large Arrow (W1-6)	Optional	Recommended	Required	Required	Required
Exit Speed (W13-2) and Ramp Speed (W13-3) on exit ramp	Optional	Optional	Recommended	Required	Required

Note: Required means that the sign and/or plaque shall be used, recommended means that the sign and/or plaque should be used, and optional means that the sign and/or plaque may be used.

See Section 2C.06 for roadways with less than 1,000 ADT.

Option:

~~03—Horizontal Alignment Warning signs may also be used on other roadways or on arterial and collector roadways with less than 1,000 AADT based on engineering judgment.~~

Guidance:

03 Except as provided in Paragraph 04, the selection of traffic control devices used to warn road users of a change in horizontal alignment or to provide guidance in navigating the change in horizontal alignment should be based on an engineering study. The engineering study should consider one or more of the following factors:⁵

1. The speed of traffic on the approach to the change in horizontal alignment.
2. The recommended speed for the change in horizontal alignment.
3. The speed reduction for the change in horizontal alignment.
4. Daily traffic volume on the roadway.
5. The typical mix of vehicle types on the roadway.
6. Sight distance throughout the change in horizontal alignment.
7. Other types of traffic control devices that are used in advance of and within the change in horizontal alignment.
8. The consistency of the change in horizontal alignment with respect to other changes in horizontal alignment upstream and downstream of the location.
9. The crash history of the change in horizontal alignment.

⁵ The research team believes that engineers are capable of selecting appropriate traffic control devices at changes in horizontal alignment by studying the conditions at each site. A thorough engineering study will have more value than a generic application of the guidelines in Section 2C.06a.

Standard:

04 If an engineering study is not performed, the selection of traffic control devices to be used near a change in horizontal alignment shall be based on the criteria indicated in Section 2C.06a.

Section 2C.06a Changes in Horizontal Alignment

Support:

01 For purposes of selecting traffic control devices for changes in horizontal alignment, a roadway is considered to have pavement markings when a center line and/or an edge line is present.

Guidance:

02 The devices indicated in Table 2C-5 represent the minimum traffic control that should be used when the AADT on the roadway is greater than 2,000 vehicles per day and the roadway has pavement markings.⁶ If the roadway does not have pavement markings, the devices should be used according to Table 2C-5 if the AADT is greater than 1,000 vehicles per day.⁷

03 An Advisory Speed Plaque should be used with a Horizontal Alignment sign when the speed reduction is greater than 10 mph if the roadway has pavement markings. If the roadway does not have pavement markings, an Advisory Speed Plaque should be used if the speed reduction is greater than 5 mph.⁸

Standard:

04 The devices indicated in Table 2C-5 represent the minimum traffic control that shall be used when the AADT on the roadway is greater than 4,000 vehicles per day and the roadway has pavement markings.⁹ If the roadway does not have pavement markings, the devices shall be used according to Table 2C-5 if the AADT is greater than 2,000 vehicles per day.¹⁰

05 An Advisory Speed Plaque shall be used with a Horizontal Alignment sign when the speed reduction is greater than 15 mph if the roadway has pavement markings. If the roadway does not have pavement markings, an Advisory Speed Plaque shall be used if the speed reduction is greater than 10 mph.

⁶ AADT thresholds are based on findings from the safety study. As discussed in Chapter 6, traffic control devices have a **probable** effect on reducing crash frequency when there are approximately 2,000 vehicles per day. **Significant** reductions were observed starting at approximately 4,000 vehicles per day. Probable and significant effects justify the use of Guidance and Standard statements, respectively.

⁷ The data analyzed by the research team came exclusively from roads that contained pavement markings. The findings (including the traffic volume thresholds that justify the level of mandate) are therefore only applicable on facilities with pavement markings. The research team has exercised judgment in identifying appropriate guidelines for treating roads without pavement markings. The guidelines include reduced traffic volume thresholds for roads without pavement markings.

⁸ The research was not able to establish data-based criteria for the use of an Advisory Speed Plaque.

⁹ See note 6.

¹⁰ See note 7.

Option:

- 06 The 85th percentile speed may be used instead of the posted speed limit to determine the speed reduction at the change in horizontal alignment.
- 07 A Large Arrow (W1-6) sign may be used in place of delineators or Chevrons when geometric conditions limit the number of delineators or Chevrons that are visible or can be installed within the change in horizontal alignment below the number specified in Sections 2C.09 or 3F.04.¹¹
- 08 Additional or supplemental devices may be used for a change in horizontal alignment on the basis of engineering judgment or an engineering study.
- 09 Warning devices may be omitted for changes in horizontal alignment when the speed limit on the approach to an alignment change is less than 25 mph.¹²
- 10 Warning devices may be omitted for changes in horizontal alignment on urban roadways on the basis of an engineering study.¹³

¹¹ Findings from the safety study in Chapter 5 indicate that the Large Arrow sign may be more effective than Chevron Alignment signs at curves with a short radius. Data collected in the study suggest that current practice reflects a preference for a Large Arrow sign in such conditions.

¹² Data collected in the research did not include low approach speeds. However, the methodology used to select traffic control at changes in alignment as discussed in Chapter 6 supports the exclusion of alignment changes with low-speed approaches from regulation in the MUTCD.

¹³ The research did not address urban roads, but the research team believes that the higher prevalence of markings, lighting, and curbs provides justification for reducing the use of warning devices in urban areas.

Table 2C-5. Selection of Devices for Changes in Horizontal Alignment¹⁴

Speed Limit ^a (mph)	Devices for Curve Advisory Speed (mph) ^b										
	20	25	30	35	40	45	50	55	60	65	70
25	M ^c	—	—	—	—	—	—	—	—	—	—
30	W	M ^c	—	—	—	—	—	—	—	—	—
35	D	W	M ^c	—	—	—	—	—	—	—	—
40	D	D	W	M ^c	—	—	—	—	—	—	—
45	D	D	D	W	M ^c	—	—	—	—	—	—
50	C	C	D	D	W	M ^c	—	—	—	—	—
55	C	C	C	D	D	W	M ^c	—	—	—	—
60	C	C	C	C	D	D	W	M ^c	—	—	—
65	C	C	C	C	C	D	D	W	M ^c	—	—
70	C	C	C	C	C	C	C	D	W	M ^c	—
75	C	C	C	C	C	C	C	C	D	W	M ^c

Notes:

^aThe 85th percentile speed may be used in place of the speed limit (Section 2C.06a, Paragraph 06).

^bDevice abbreviations: M – markings, W – advance warning sign, D – delineators plus advance warning sign, C – chevrons plus advance warning sign.

^cAn advance warning sign shall be used on roads without pavement markings as defined in Section 2C.06a, Paragraph 01.

Section 2C.07 Horizontal Alignment Signs (W1-1 through W1-5, W1-11, W1-15)¹⁵

Standard:

~~01—If Table 2C-5 indicates that a horizontal alignment sign (see Figure 2C-1) is required, recommended, or allowed, the sign installed in advance of the curve shall be a Curve (W1-2) sign unless a different sign is recommended or allowed by the provisions of this Section.~~

¹⁴ As discussed in Chapter 6, the guidelines in Table 2C-5 were developed to provide information to drivers at enough distance before a change in alignment so the drivers can execute a natural, proper response. The present research did not evaluate how pavement markings affect driver behavior at curves; therefore, findings from previous research (reports FHWA/TX-07/0-5008-2 and FHWA-HRT-07-059) and proposed MUTCD regulations for pavement marking retroreflectivity were considered in estimating the contribution of pavement markings in providing motorists information relevant to changes in alignment. The present research also did not identify the contribution of advance warning signs; the proposed guidelines regarding advance warning signs are based on judgment of the research team and guidelines in the current (2009) edition of the MUTCD. The contributions of delineators and Chevrons which justify their use in Table 2C-5 are identified in Chapter 4.

¹⁵ The Standard and Guidance statements in this section have been deleted in favor of a simpler illustration of the guidelines in Table 2C-5a. The only substantive change is the flexibility provided to agencies in substituting the Standard statement for a Guidance statement.

~~02—A Turn (W1-1) sign shall be used instead of a Curve sign in advance of curves that have advisory speeds of 30 mph or less (see Figure 2C-2).~~

Guidance:

~~03—Where there are two changes in roadway alignment in opposite directions that are separated by a tangent distance of less than 600 feet, the Reverse Turn (W1-3) sign should be used instead of multiple Turn (W1-1) signs and the Reverse Curve (W1-4) sign should be used instead of multiple Curve (W1-2) signs.~~

Guidance:

01 If used, the selection of a horizontal alignment sign should be based on Table 2C-5a.

Table 2C-5a. Horizontal Alignment Sign Usage

<u>Number of Alignment Changes</u>	<u>Advisory Speed (mph)^b</u>	
	<u>≤ 30 mph</u>	<u>≥ 35 mph</u>
<u>1</u>	<u>Turn (W1-1)</u>	<u>Curve (W1-2)</u>
<u>2^a</u>	<u>Reverse Turn (W1-3)</u>	<u>Reverse Curve (W1-4)</u>
<u>3 or more^a</u>	<u>Winding Road (W1-5)</u>	

Notes:

^aThe designation for 2 or 3 or more alignment changes is appropriate when each alignment change is separated by 600 feet or less.

^bWhen there are two or more changes in alignment separated by 600 feet or less, the selected advisory speed should be the lowest advisory speed of all the changes in alignment.

Support:

02 Figure 2C-2 provides an example of warning sign use for a turn.

Option:

~~04—A Winding Road (W1-5) sign may be used instead of multiple Turn (W1-1) or Curve (W1-2) signs where there are three or more changes in roadway alignment each separated by a tangent distance of less than 600 feet.¹⁶~~

05 A NEXT XX MILES (W7-3aP) supplemental distance plaque (see Section 2C.55) may be installed below the Winding Road sign where continuous roadway curves exist for a specific distance.

06 If the curve has a change in horizontal alignment of 135 degrees or more, the Hairpin Curve (W1-11) sign may be used instead of a Curve or Turn sign.

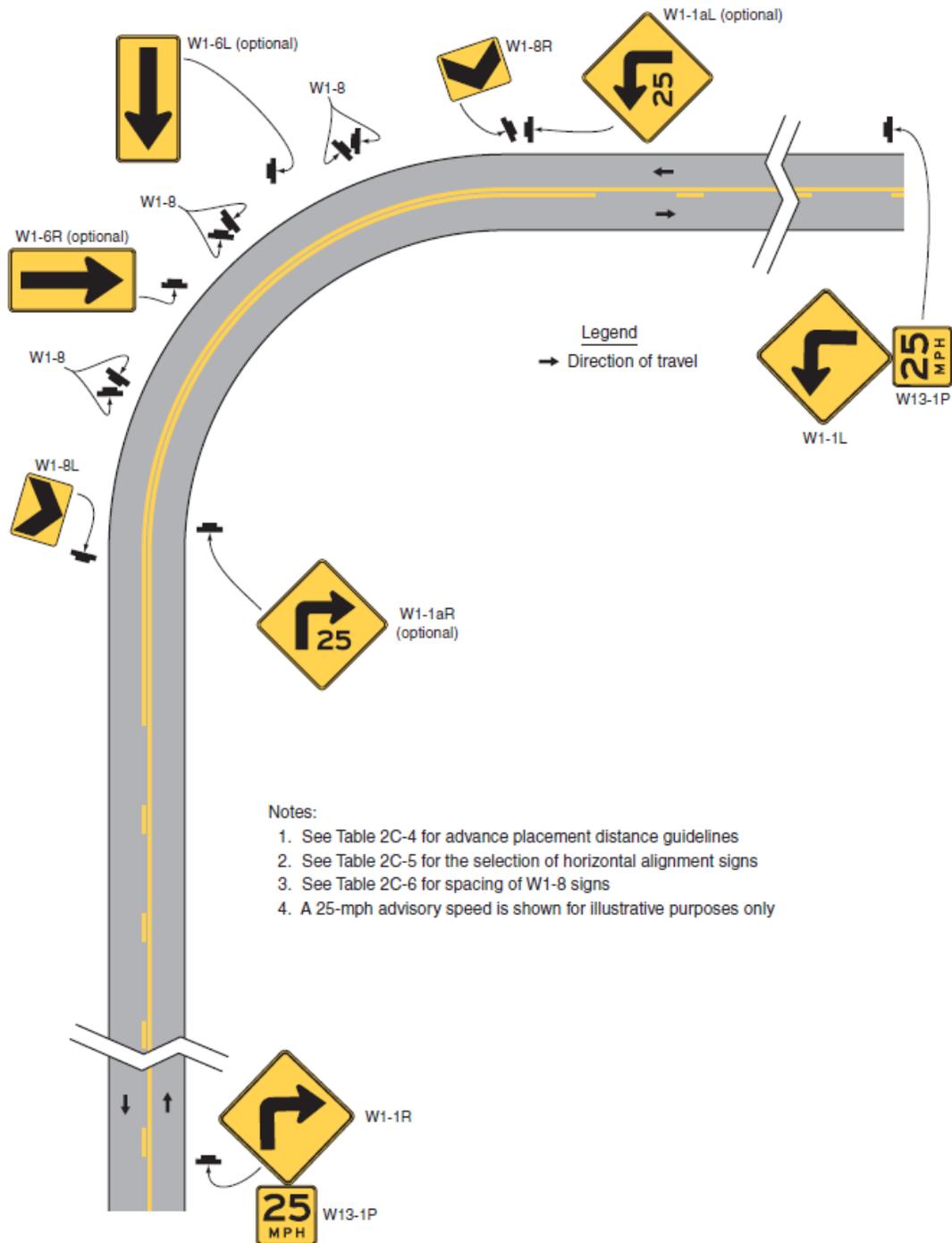
07 If the curve has a change of direction of approximately 270 degrees, such as on a cloverleaf interchange ramp, the 270-degree Loop (W1-15) sign may be used instead of a Curve or Turn sign.

¹⁶ This statement is removed in favor of the use of Table 2C-5a as discussed in note 15.

Guidance:

08 When the Hairpin Curve sign or the 270-degree Loop sign is installed, either a One-Direction Large Arrow (W1-6) sign or Chevron Alignment (W1-8) signs should be installed on the outside of the turn or curve.

Figure 2C-2. Example of Warning Signs for a Turn



Section 2C.08 Advisory Speed Plaque (W13-1P)

Option:

- 01 The Advisory Speed (W13-1P) plaque (see Figure 2C-1) may be used to supplement any warning sign to indicate the advisory speed for a condition.

Standard:

- 02 **The use of the Advisory Speed plaque for horizontal curves shall be in accordance with [Section 2C.06a](#) or [Section 2C.06b](#) ~~the information shown in Table 2C-5~~. The Advisory Speed plaque shall also be used where an engineering study indicates a need to advise road users of the advisory speed for other roadway conditions.**
- 03 **If used, the Advisory Speed plaque shall carry the message XX MPH. The speed displayed shall be a multiple of 5 mph.**
- 04 **Except in emergencies or when the condition is temporary, an Advisory Speed plaque shall not be installed until the advisory speed has been determined by an engineering study.**
- 05 **The Advisory Speed plaque shall only be used to supplement a warning sign and shall not be installed as a separate sign installation.**
- 06 **The advisory speed shall be determined by an engineering study that follows established engineering practices.**

Support:

- 07 Among the established engineering practices that are appropriate for the determination of the recommended advisory speed for a [change in alignment](#) ~~horizontal curve~~ are the following:
- A. An accelerometer that provides a direct determination of side friction factors
 - B. A design speed equation
 - C. A traditional ball-bank indicator using the following criteria:
 - 1. 16 degrees of ball-bank for speeds of 20 mph or less
 - 2. 14 degrees of ball-bank for speeds of 25 to 30 mph
 - 3. 12 degrees of ball-bank for speeds of 35 mph and higher
- 08 The 16, 14, and 12 degrees of ball-bank criteria are comparable to the current AASHTO horizontal curve design guidance. ~~Research has shown that drivers often exceed existing posted advisory curve speeds by 7 to 10 mph.~~¹⁷

Guidance:

- 09 *The advisory speed should be determined based on free-flowing traffic conditions.*
- 10 *Because changes in conditions, such as roadway geometrics, surface characteristics, or sight distance, might affect the advisory speed, each location should be evaluated periodically or when conditions change.*

Section 2C.09 Chevron Alignment Sign (W1-8)

¹⁷ The current research indicates a reasonable correlation between posted advisory speed and the minimum vehicular speed in the curve.

Standard:

01 **The use of the Chevron Alignment (W1-8) sign (see Figures 2C-1 and 2C-2) to provide additional emphasis and guidance for a change in horizontal alignment shall be in accordance with the information shown in Table 2C-5.**

Option:

02 When used, Chevron Alignment signs may be used instead of or in addition to standard delineators.

Standard:

03 **The Chevron Alignment sign shall be a vertical rectangle. No border shall be used on the Chevron Alignment sign.**

04 **If used, Chevron Alignment signs shall be installed on the outside of a turn or curve, in line with and at approximately a right angle to approaching traffic. Chevron Alignment signs shall be installed at a minimum height of 4 feet, measured vertically from the bottom of the sign to the elevation of the near edge of the traveled way.**

Guidance:

05 *The approximate spacing of Chevron Alignment signs on the turn or curve measured from the point of curvature (PC) should be as shown in Table 2C-6.*

06 *If used, Chevron Alignment signs should be visible for a sufficient distance to provide the road user with adequate time to react to the change in alignment.*

Table 2C-6. Typical Spacing of Chevron Alignment Signs on Horizontal Curves

Advisory Speed	Curve Radius	Sign Spacing
15 mph or less	Less than 200 feet	40 feet
20 to 30 mph	200 to 400 feet	80 feet
35 to 45 mph	401 to 700 feet	120 feet
50 to 60 mph	701 to 1,250 feet	160 feet
More than 60 mph	More than 1,250 feet	200 feet

Note: The relationship between the curve radius and the advisory speed shown in this table should not be used to determine the advisory speed.

Standard:

07 **Chevron Alignment signs shall not be placed on the far side of a T-intersection facing traffic on the stem approach to warn drivers that a through movement is not physically possible, as this is the function of a Two-Direction (or One-Direction) Large Arrow sign.**

08 **Chevron Alignment signs shall not be used to mark obstructions within or adjacent to the roadway, including the beginning of guardrails or barriers, as this is the function of an object marker (see Section 2C.63).**

Section 2C.10 Combination Horizontal Alignment/Advisory Speed Signs (W1-1a, W1-2a)

Option:

- 01 The Turn (W1-1) sign or the Curve (W1-2) sign may be combined with the Advisory Speed (W13-1P) plaque (see Section 2C.08) to create a combination Turn/Advisory Speed (W1-1a) sign or combination Curve/Advisory Speed (W1-2a) sign (see Figure 2C-1).
- 02 The combination Horizontal Alignment/Advisory Speed sign may be used to supplement the advance Horizontal Alignment warning sign and Advisory Speed plaque based upon an engineering study.

Standard:

- 03 **If used, the combination Horizontal Alignment/Advisory Speed sign shall not be used alone and shall not be used as a substitute for a Horizontal Alignment warning sign and Advisory Speed plaque at the advance warning location. The combination Horizontal Alignment/Advisory Speed sign shall only be used as a supplement to the advance Horizontal Alignment warning sign. If used, the combination Horizontal Alignment/Advisory Speed sign shall be installed at the beginning of the turn or curve.**

Guidance:

- 04 *The advisory speed displayed on the combination Horizontal Alignment/Advisory Speed sign should be based on the advisory speed for the horizontal curve using recommended engineering practices (see Section 2C.08).*

Section 2C.11 Combination Horizontal Alignment/Intersection Signs (W1-10 Series)

Option:

- 01 The Turn (W1-1) sign or the Curve (W1-2) sign may be combined with the Cross Road (W2-1) sign or the Side Road (W2-2 or W2-3) sign to create a combination Horizontal Alignment/Intersection (W1-10 series) sign (see Figure 2C-1) that depicts the condition where an intersection occurs within or immediately adjacent to a turn or curve.

Guidance:

- 02 *Elements of the combination Horizontal Alignment/Intersection sign related to horizontal alignment should comply with the provisions of Section 2C.07, and elements related to intersection configuration should comply with the provisions of Section 2C.46. The symbol design should approximate the configuration of the intersecting roadway(s). No more than one Cross Road or two Side Road symbols should be displayed on any one combination Horizontal Alignment/Intersection sign.*

Standard:

- 03 The use of the combination Horizontal Alignment/Intersection sign shall be in accordance with the appropriate Turn or Curve sign information shown in Table 2C-5 [and Table 2C-5a](#).

Section 2C.12 One-Direction Large Arrow Sign (W1-6)

Option:

- 01 A One-Direction Large Arrow (W1-6) sign (see Figure 2C-1) may be used either as a supplement or alternative to Chevron Alignment signs [or delineators](#) in order to delineate a change in horizontal alignment (see Figure 2C-2).
- 02 A One-Direction Large Arrow (W1-6) sign may be used to supplement a Turn or Reverse Turn sign (see Figure 2C-2) to emphasize the abrupt curvature.

Standard:

- 03 The One-Direction Large Arrow sign shall be a horizontal rectangle with an arrow pointing to the left or right.
- 04 The use of the One-Direction Large Arrow sign shall be in accordance with the information shown in Table 2C-5.
- 05 If used, the One-Direction Large Arrow sign shall be installed on the outside of a turn or curve in line with and at approximately a right angle to approaching traffic.
- 06 The One-Direction Large Arrow sign shall not be used where there is no alignment change in the direction of travel, such as at the beginnings and ends of medians or at center piers.
- 07 The One-Direction Large Arrow sign directing traffic to the right shall not be used in the central island of a roundabout.

Guidance:

- 08 *If used, the One-Direction Large Arrow sign should be visible for a sufficient distance to provide the road user with adequate time to react to the change in alignment.*

Section 2C.13 Truck Rollover Warning Sign (W1-13)

Option:

- 01 A Truck Rollover Warning (W1-13) sign (see Figure 2C-1) may be used to warn drivers of vehicles with a high center of gravity, such as trucks, tankers, and recreational vehicles, of a curve or turn where geometric conditions might contribute to a loss of control and a rollover as determined by an engineering study.

Support:

- 02 Among the established engineering practices that are appropriate for the determination of the truck rollover potential of a horizontal curve are the following:
- A. An accelerometer that provides a direct determination of side friction factors
 - B. A design speed equation
 - C. A traditional ball-bank indicator using 10 degrees of ball-bank

Standard:

03 If a Truck Rollover Warning (W1-13) sign is used, it shall be accompanied by an Advisory Speed (W13-1P) plaque indicating the recommended speed for vehicles with a higher center of gravity.

Option:

04 The Truck Rollover Warning sign may be displayed as a static sign, as a static sign supplemented by a flashing warning beacon, or as a changeable message sign activated by the detection of an approaching vehicle with a high center of gravity that is traveling in excess of the recommended speed for the condition.

Support:

05 The curved arrow on the Truck Rollover Warning sign shows the direction of roadway curvature. The truck tips in the opposite direction.

Section 2C.14 Advisory Exit and Ramp Speed Signs (W13-2 and W13-3)¹⁸

Standard:

~~01—Advisory Exit Speed (W13-2) and Advisory Ramp Speed (W13-3) signs (see Figure 2C-1) shall be vertical rectangles. The use of Advisory Exit Speed and Advisory Ramp Speed signs on freeway and expressway ramps shall be in accordance with the information shown in Table 2C-5.~~

Standard:

01 The Advisory Exit Speed and Advisory Ramp Speed signs on freeway and expressway ramps shall be used when the speed reduction is 20 mph or greater.

Guidance:

01a The Advisory Exit Speed and Advisory Ramp Speed signs on freeway and expressway ramps should be used when the speed reduction is 15 mph or greater.

Option:

01b The Advisory Exit Speed and Advisory Ramp Speed signs on freeway and expressway ramps may be used on any ramp on the basis of engineering judgment or engineering study.

Guidance:

02 *If used, the Advisory Exit Speed sign should be installed along the deceleration lane and the advisory speed displayed should be based on an engineering study. When a Truck Rollover (W1-13) sign (see Section 2C.13) is also installed for the ramp, the advisory exit speed should be based on the truck advisory speed for the horizontal alignment using recommended engineering practices.*

¹⁸The new Standard, Guidance, and Option statements in this section are based on the selection criteria in Table 2C-5 of the 2009 MUTCD. The researchers had no data upon which to base a change in the MUTCD language.

03 *If used, the Advisory Exit Speed sign should be visible in time for the road user to decelerate and make an exiting maneuver.*

Support:

04 Table 2C-4 lists recommended advance sign placement distances for deceleration to various advisory speeds.

Guidance:

05 *If used, the Advisory Ramp Speed sign should be installed on the ramp to confirm the ramp advisory speed.*

06 *If used, Chevron Alignment (W1-8) signs and/or One-Direction Large Arrow (W1-6) signs should be installed on the outside of the exit curve as described in Sections 2C.09 and 2C.12.*

Option:

07 Where there is a need to remind road users of the recommended advisory speed, a horizontal alignment warning sign with an advisory speed plaque may be installed at or beyond the beginning of the exit curve or on the outside of the curve, provided that it is apparent that the sign applies only to exiting traffic. These signs may also be used at intermediate points along the ramp, especially if the ramp curvature changes and the subsequent curves on the ramp have a different advisory speed than the initial ramp curve.

Support:

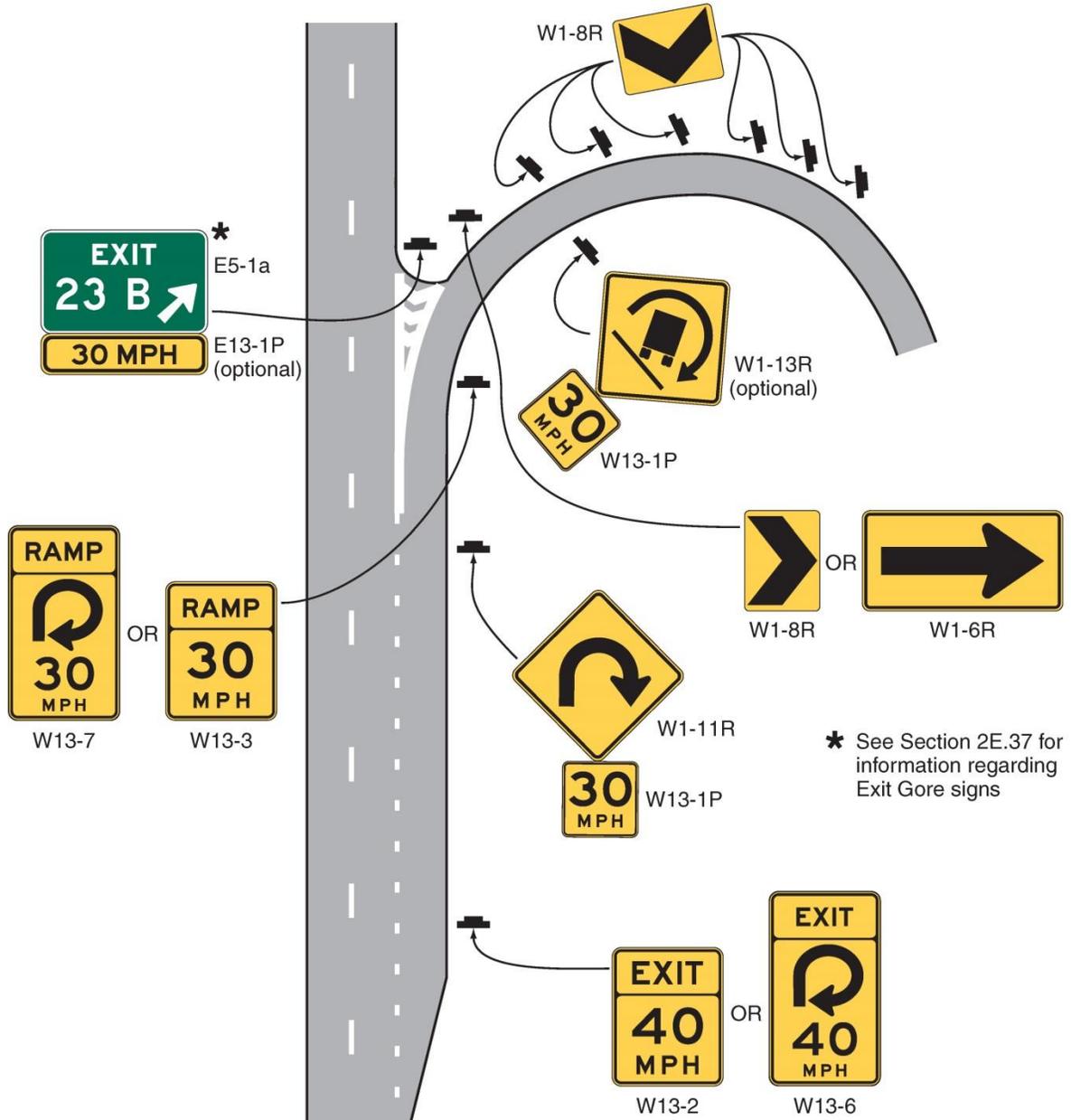
08 Figure 2C-3 shows an example of advisory speed signing for an exit ramp.

Section 2C.15 Combination Horizontal Alignment/Advisory Exit and Ramp Speed Signs (W13-6 and W13-7)

Option:

01 A horizontal alignment sign (see Section 2C.07) may be combined with an Advisory Exit Speed or Advisory Ramp Speed sign to create a combination Horizontal Alignment/Advisory Exit Speed (W13-6) sign or a combination Horizontal Alignment/Advisory Ramp Speed (W13-7) sign (see Figure 2C-1). These combination signs may be used where the severity of the exit ramp curvature might not be apparent to road users in the deceleration lane or where the curvature needs to be specifically identified as being on the exit ramp rather than on the mainline.

Figure 2C-3. Example of Advisory Speed Signing for an Exit Ramp



* See Section 2E.37 for information regarding Exit Gore signs

- Notes:
1. See Table 2C-4 for advance placement distance guidelines
 2. See Table 2C-5 for the selection of horizontal alignment signs
 3. See Table 2C-6 for spacing of W1-8 signs
 4. A 30-mph ramp advisory speed and 40-mph exit advisory speed are shown for illustrative purposes only