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16. Abstract

Horizontal curves are a necessary component of the highway alignment; however, they tend to be associated with a disproportionate number of severe crashes. Warning signs are intended to improve curve safety by alerting the driver of a change in geometry that may not be apparent or expected. However, several research projects conducted in the last 20 years have consistently shown that drivers are not responding to curve warning signs nor complying with the Advisory Speed plaque.

The procedures described in this handbook are intended to improve consistency in curve signing and driver compliance with the advisory speed. The handbook describes guidelines for determining when an advisory speed is needed, criteria for identifying the appropriate advisory speed, an engineering study method for determining the advisory speed, and guidelines for selecting other curve-related traffic control devices.

The handbook is intended for use by traffic engineers and technicians that have been given the responsible charge of evaluating and maintaining horizontal curve signing and delineation devices. The procedures described in this handbook are applicable to rural highways. However, they may be useful for establishing advisory speeds for urban streets.

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HORIZONTAL CURVE SIGNING HANDBOOK

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DISCLAIMER

The contents of this handbook reflect the views of the authors, who are responsible for the facts and the accuracy of the data published herein. The contents do not necessarily reflect the official view or policies of the Federal Highway Administration (FHWA) and/or the Texas Department of Transportation (TxDOT). This handbook does not constitute a standard, specification, or regulation. It is not intended for construction, bidding, or permit purposes. The engineer in charge of the project was James Bonneson, P.E. #67178.

NOTICE

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

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- Ms. Marla Jasek, Project Director;
- Mr. James Bailey;
- Mr. Herbert Bickley;
- Mr. Carlos Ibarra; and
- Mr. Darren McDaniel.

All of the committee members are employees with TxDOT. In addition, the researchers would like to acknowledge the valuable assistance provided by Mr. Todd Hausman (with TTI) during the data collection and reduction phase of the project. The effort of these individuals is greatly appreciated.

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CHAPTER 1. INTRODUCTION

OVERVIEW

Horizontal curves are a necessary component of the highway alignment; however, they tend to be associated with a disproportionate number of severe crashes. Each year in the United States, about 38,000 fatal crashes occur on the highway system with 25 percent of the fatalities found to occur on horizontal curves (*1*). Texas accounts for about 3200 of these fatal crashes, with about 44 percent of Texas' crashes occurring on horizontal curves. Hence, Texas is over-represented in terms of its proportion of fatal curve-related crashes, relative to the national average.

Warning signs are intended to improve curve safety by alerting the driver to a change in geometry that may not be apparent or expected. These signs notify drivers of the change through the use of one or more of the curve warning signs identified in the *Manual on Uniform Traffic Control Devices* (*MUTCD*) (*2*). These drivers may also be notified of the need to reduce their speed through the use of an Advisory Speed plaque.

Several research projects conducted in the last 20 years have consistently shown that drivers are not responding to curve warning signs nor complying with the Advisory Speed plaque. Evidence of this non-responsiveness is evidenced by the aforementioned curve crash statistics. Chowdhury et al. (*3*) suggest that current practice in the U.S. for setting advisory speeds is contributing to this lack of compliance and the poor safety record. They advocate the need for a procedure that can be used to: (1) identify when a curve warning sign and advisory speed are needed, and (2) select an advisory speed that is consistent with driver expectation. They also recommend the uniform use of this procedure on a nationwide basis, such that driver respect for curve warning signs is restored and curve safety records are improved.

PURPOSE AND SCOPE

The procedures described in this handbook are intended to improve consistency in curve signing and driver compliance with the advisory speed. The handbook describes guidelines for determining when an advisory speed is needed, criteria for identifying the appropriate advisory speed, an engineering study method for determining the advisory speed, and guidelines for selecting other curve-related traffic control devices.

The handbook is intended for use by traffic engineers and technicians who have been given the responsible charge of evaluating and maintaining horizontal curve signing and delineation devices. The procedures described in this handbook are applicable to rural highways. However, they may be useful for establishing advisory speeds for urban streets.

The curve advisory speed and other curve-related traffic control devices should be checked periodically to ensure that they are appropriate for the prevailing conditions. Changes in the regulatory speed limit, curve geometry, or crash history may justify the conduct of an engineering study to re-evaluate the appropriateness of the existing signs and the need for additional signs.

CHAPTER 2. COMMUNICATING CHANGES IN HORIZONTAL ALIGNMENT

OVERVIEW

This chapter provides a brief overview of topics related to horizontal curve safety, operation, and curve warning signs. It consists of three parts. The first part examines the safety and operation of horizontal curves. The second part reviews the various warning signs that are used to sign horizontal curves. The last part provides an overview of the Texas Curve Advisory Speed (TCAS) software that was developed to automate the procedures and guidelines described in Chapters 3 and 4, respectively.

Additional background information about curve advisory speed is provided in Appendix A. The information in this appendix examines more broadly the objectives of curve signing and the challenges associated with establishing advisory speeds that are uniform among curves and consistent with driver expectation. This appendix also reviews the various criteria that have been used to set advisory speeds.

HORIZONTAL CURVE SAFETY AND OPERATION

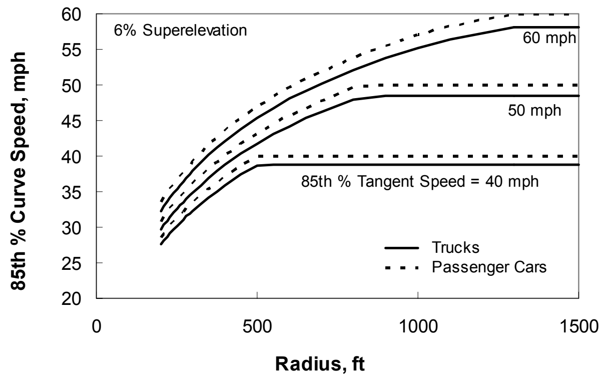
This part of the chapter examines the factors that influence the safety and operation of horizontal curves. The focus of the examination is on factors related to the curve's geometric design. The relationship between curve design and driver speed choice is described in the first section. Then, the relationship between curve design and crash rate is explored in the second section.

Curve Speed

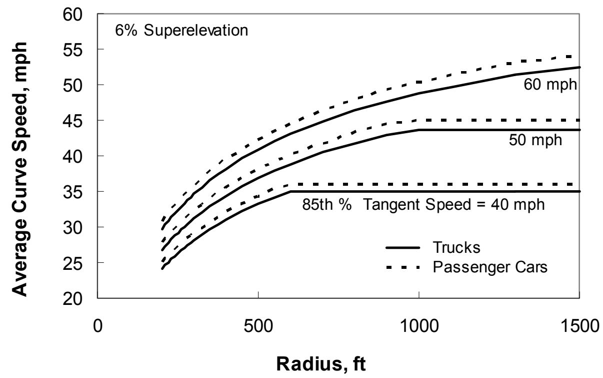
A review of the literature indicates that several variables can have an influence on curve speed. These variables include:

- radius,
- superelevation rate,
- tangent speed,
- vehicle type,
- curve deflection angle,
- tangent length,
- curve length,
- available stopping sight distance,
- grade, and
- vertical curvature.

Of those variables in the aforementioned list, research indicates that the first five variables have the most significant effect on curve speed. Using data collected on rural highways in Texas, Bonneson et al. (*4*) developed a curve speed prediction model that includes a sensitivity to these variables. The speeds predicted by this model are shown in Figure 1. The trends shown indicate that the average truck speed equals about 97 percent of the average passenger car speed.



a. 85th Percentile Speed.



b. Average Speed.

Figure 1. Effect of Radius, Tangent Speed, and Vehicle Type on Curve Speed.

The trend lines in Figure 1 indicate that drivers on sharper curves slow from the tangent speed to an acceptable curve speed. The amount of speed reduction increases with decreasing radius. For curves with a 500 ft radius and a 60 mph tangent speed, the reduction is about 10 mph. In contrast, for a 1000 ft radius and 60 mph tangent speed, the reduction is only about 5 mph.

The effect of superelevation rate is not shown in Figure 1. However, the model indicates that curve speed increases about 1.0 mph for every 2.0 percent increase in superelevation rate.

Curve Safety

Bonneson et al. (*4*) examined the relationship between curve radius and crash rate using safety relationships documented in the literature (*5, 6*). These relationships are shown in Figure 2. Crash rate is defined in this figure in terms of crashes per million vehicle miles (crashes/mvm). One trend line represents the combination of fatal and injury crashes. The other trend line represents the combination of fatal, injury, and property-damage-only (PDO) crashes.

The two trend lines in Figure 2 are in fairly good agreement. They indicate that the crash rate increases sharply for curves with a radius of less than 1000 ft. They also indicate that most crashes on sharper curves result in an injury or fatality.

Based on the discussion in this and the previous sections, it is likely that the trends in Figure 2 are reflecting driver error while entering or traversing a curve. It is possible that some drivers are distracted or impaired and do not track the curve. It is also possible that some drivers detect the curve but do not correctly judge its sharpness. In both instances, traffic control devices have the potential to improve safety by making it easier for drivers to detect the curve and judge its sharpness.

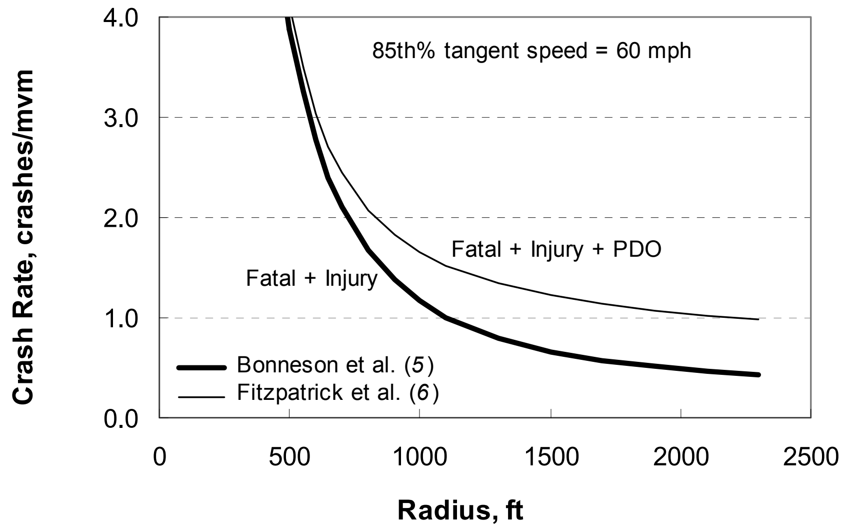


Figure 2. Curve Crash Rate as a Function of Radius.

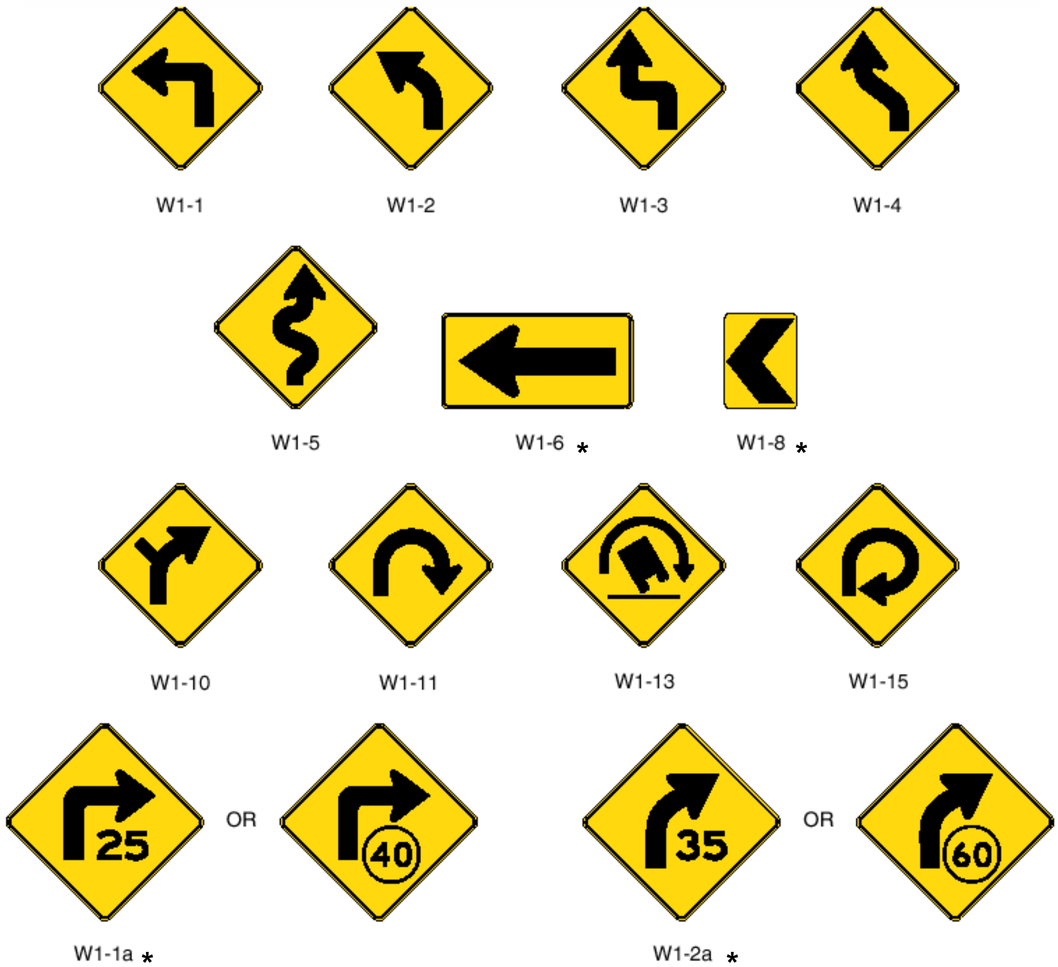
WARNING SIGNS FOR CHANGES IN HORIZONTAL ALIGNMENT

Most transportation agencies use a variety of traffic control devices to inform road users of a change in horizontal alignment. These devices include curve warning signs, delineation devices, and pavement markings. The focus of this part of the chapter is on curve warning signs; however, conditions where other traffic control devices may be helpful are also identified.

Curve Warning Signs

The *MUTCD* (*2*) identifies a variety of warning signs that can be used where the horizontal alignment changes in an unexpected or restrictive manner. These signs are shown in Figure 3a. There are two sign categories shown: advance signs and supplemental signs. Advance signs are located in advance of the curve. Signs in this category include: Turn (W1-1), Curve (W1-2), Reverse Turn (W1-3), Reverse Curve (W1-4), Winding Road (W1-5), Hairpin (W1-11), Truck Rollover Warning (W1-13), and 270-degree Loop (W1-15). These signs are recognized in the *Texas Manual on Uniform Traffic Control Devices* (*TMUTCD*) (*7*). In contrast, the Combination Horizontal Alignment/Intersection (W1-10) is not recognized in the *TMUTCD*.

One additional sign that falls in the advance sign category is the Advisory Speed plaque (W13-1). This sign is shown in Figure 3b. It is used to advise drivers of the speed found to be appropriate based on an engineering study. When used, it is combined with one of the advance horizontal alignment signs and mounted on the same sign post.



a. Horizontal Alignment Signs.

* Denotes "supplemental" sign.
Signs without asterisk represent "advance" signs.

b. Advisory Speed Plaques.

Figure 3. Curve Warning Signs.

The second category of sign is the supplemental sign. They are shown in Figures 3a and 3b, and are denoted by an asterisk ("*"). Signs in this category are used with advance signs to amplify or reinforce their message. Supplemental signs are used at, or within, the curve. Supplemental signs include: One-Direction Large Arrow (W1-6), Chevron (W1-8), Turn/Advisory Speed (W1-1a), Curve/Advisory Speed (W1-2a), and Curve Speed (W13-5). The W1-1a and W1-2a signs are not recognized in the *TMUTCD*.

The *MUTCD* guidance regarding the use of curve warning signs can be described as flexible. It encourages engineers to base their signing decisions on engineering studies and judgment. However, this flexibility has the disadvantage of occasionally promoting the inconsistent application of traffic control devices. Inconsistent device application makes it difficult for drivers to develop expectancies and, consequently, promotes disrespect for the device and mistrust of its message. The Advisory Speed plaque is one of most renowned examples of the consequences of inconsistent sign usage. Research has found it to be one of the more disrespected traffic control devices (*8*).

Effectiveness of Curve Warning Signs

Research indicates that the inconsistent use of horizontal alignment signs, especially those with an Advisory Speed plaque, may have lessened the average motorist's respect for the message the signs convey. On familiar highways, drivers come to learn that they can comfortably exceed the advisory speed for most curves. The concern is that these drivers may occasionally travel on roadways that are less familiar to them and where the advisory speed is posted at the maximum safe speed. These drivers may find themselves traveling too fast for conditions and experience a crash.

Only one report was found in the literature that documented the effect of horizontal curve signing on safety. This report documented a before-after study by Hammer (*9*) of the installation of warning signs in advance of several curves. He found that the implementation of advance horizontal alignment signs reduced crashes by 18 percent. He also offered that the combined use of advance signing with an Advisory Speed plaque reduced crashes by 22 percent.

Research by Ritchie (*10*) examined driver response to the Curve sign and the Advisory Speed plaque. He found that average curve speeds exceeded the advisory speed when the advisory speed was less than 45 mph. The amount by which the average speed exceeded the advisory speed increased with decreasing advisory speeds. Thus, for an advisory speed of 40 mph, the average speed exceeded the advisory speed by only 2 mph (i.e., the average speed was 42 mph). However, for an advisory speed of 20 mph, the average speed exceeded the advisory speed by 10 mph.

The findings of this review are consistent with those noted in the previous part of this chapter. Specifically, drivers do not appear to be responding to the Advisory Speed plaque by reducing their speed to the advisory speed. Hence, speed reduction may be of limited value in assessing the effect this sign has on safety. Moreover, these findings suggest that advance information about an upcoming curve, as provided by a curve warning sign, may heighten driver awareness of the curve, but it does not cause them to slow significantly. It is this heightened awareness that likely produced the safety benefit found by Hammer (*9*).

TEXAS CURVE ADVISORY SPEED SOFTWARE

This part of the chapter provides an overview of the TCAS software. This software was developed to automate the procedures and guidelines described in this handbook. The software is implemented as a spreadsheet. The background for the development of the equations in this spreadsheet is documented in a research report by Bonneson et al. (*4*).

The "Welcome" worksheet for TCAS is shown in Figure 4. This screen provides background information about the software, with reference to the aforementioned research report and this handbook. The tabs at the bottom of the Welcome worksheet can be used to select the other worksheets included in the software. The "Field Data Sheet" tab provides a template for the field data collection sheet. This sheet is also shown in Appendix C. The "Analysis" tab accesses the worksheet containing the curve advisory speed calculations. This worksheet is shown in Figure 5.

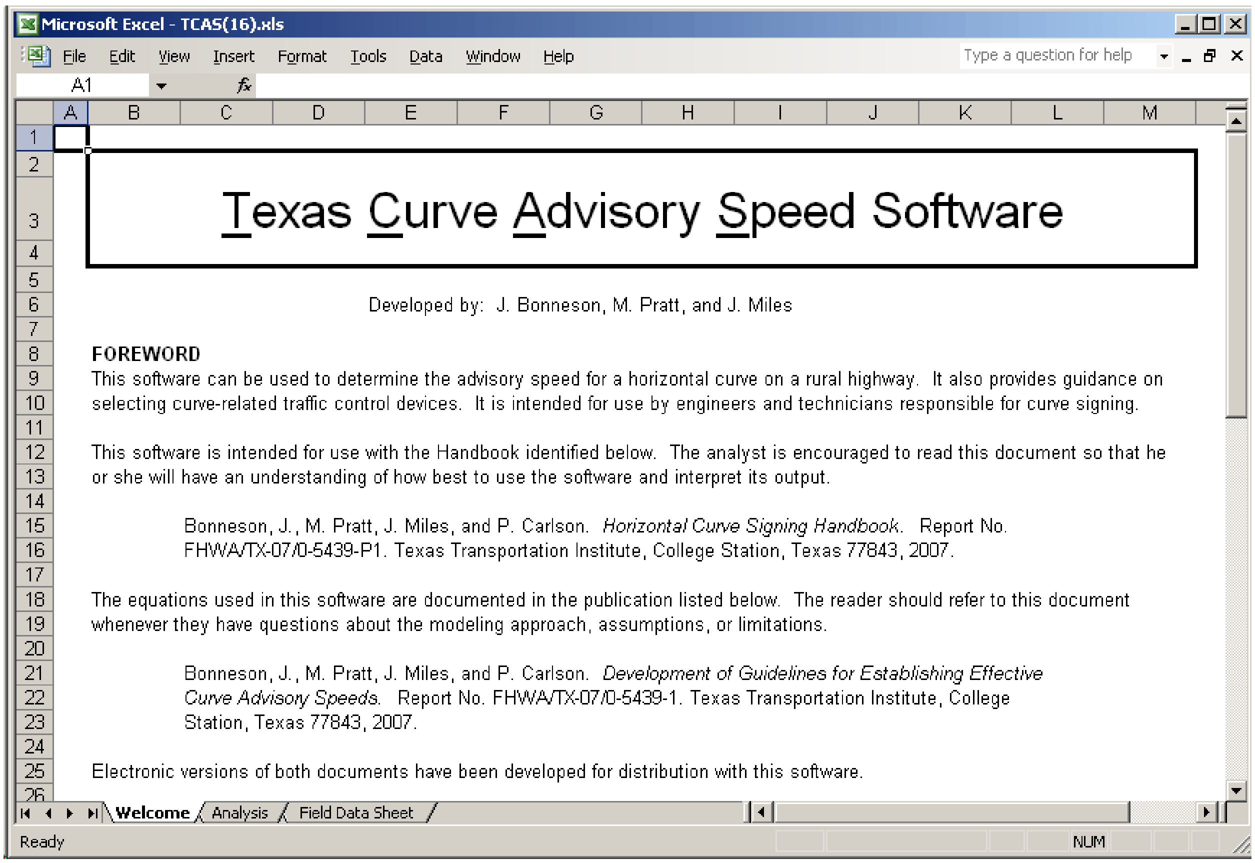
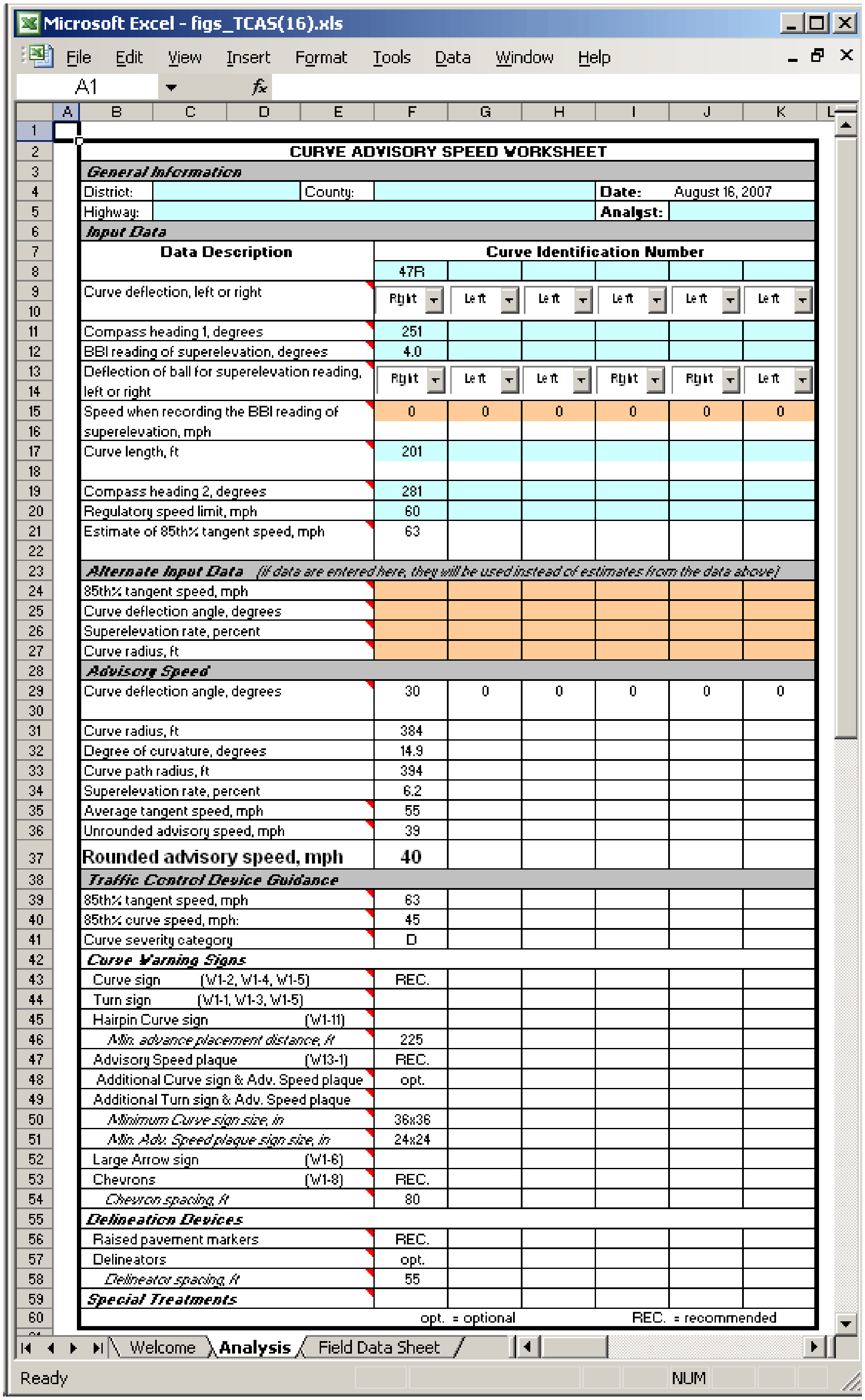


Figure 4. TCAS Welcome Worksheet.



Microsoft Excel - figs_TCAS(16).xls

CURVE ADVISORY SPEED WORKSHEET						
General Information						
District:	County:				Date:	August 16, 2007
Highway:					Analyst:	
Input Data						
Data Description	**Curve Identification Number**					
	47R					
Curve deflection, left or right	Right	Left	Left	Left	Left	Left
Compass heading 1, degrees	251					
BBI reading of superelevation, degrees	4.0					
Deflection of ball for superelevation reading, left or right	Right	Left	Left	Right	Right	Left
Speed when recording the BBI reading of superelevation, mph	0	0	0	0	0	0
Curve length, ft	201					
Compass heading 2, degrees	281					
Regulatory speed limit, mph	60					
Estimate of 85th% tangent speed, mph	63					
Alternate Input Data *(if data are entered here, they will be used instead of estimates from the data above)*						
85th% tangent speed, mph						
Curve deflection angle, degrees						
Superelevation rate, percent						
Curve radius, ft						
Advisory Speed						
Curve deflection angle, degrees	30	0	0	0	0	0
Curve radius, ft	384					
Degree of curvature, degrees	14.9					
Curve path radius, ft	394					
Superelevation rate, percent	6.2					
Average tangent speed, mph	55					
Unrounded advisory speed, mph	39					
Rounded advisory speed, mph	**40**					
Traffic Control Device Guidance						
85th% tangent speed, mph	63					
85th% curve speed, mph:	45					
Curve severity category	D					
Curve Warning Signs						
Curve sign (W1-2, W1-4, W1-5)	REC.					
Turn sign (W1-1, W1-3, W1-5)						
Hairpin Curve sign (W1-11)						
Min. advance placement distance, ft	225					
Advisory Speed plaque (W13-1)	REC.					
Additional Curve sign & Adv. Speed plaque	opt.					
Additional Turn sign & Adv. Speed plaque						
Minimum Curve sign size, in	36x36					
Min. Adv. Speed plaque sign size, in	24x24					
Large Arrow sign (W1-6)						
Chevrons (W1-8)	REC.					
Chevron spacing, ft	80					
Delineation Devices						
Raised pavement markers	REC.					
Delineators	opt.					
Delineator spacing, ft	55					
Special Treatments						
	opt. = optional			REC. = recommended		

Welcome | Analysis | Field Data Sheet

Figure 5. TCAS Analysis Worksheet.

The cells in the Analysis worksheet shown in Figure 5 are color-coded to help the analyst identify the parts of the worksheet where input data are needed. The cells shown with grey shading in the figure are designated "input data" cells. These input data cells are entered in the top one-third of the spreadsheet.

The cells that do not have a background color have text information or contain equations. The basis for each equation is documented in the aforementioned research report. The calculation cells are typically found in the bottom two-thirds of the worksheet. Six columns are provided in the worksheet. One column is used for each curve being evaluated.

The middle one-third of the worksheet documents the analysis of advisory speed for each of the six curves. Shown in Figure 5 are the calculations associated with one curve. The speed limit of 60 mph correlates with an 85^{th} percentile tangent speed of 63 mph. The field measurements indicate that the partial curve has a deflection angle of 30 degrees and a length of 201 ft. These two measures are used to compute the curve radius of 384 ft. The ball-bank reading of 4.0 degrees corresponds to a superelevation rate of 6.2 percent. All of these data are used to estimate the curve speed as 39 mph. This estimate is then rounded to 40 mph to obtain the recommended advisory speed.

The bottom third of the spreadsheet documents the traffic control device guidance. The third row in this section indicates the curve severity category. The guidelines described in Chapter 4 and those in the *TMUTCD* are consulted, and the information is summarized in the spreadsheet. For the example curve shown in Figure 5, a curve severity category D is indicated. For this category, a Curve sign and an Advisory Speed plaque are recommended. The sign and plaque should be posted 225 ft or more from the beginning of the curve.

The worksheet also provides information about other curve-related traffic control devices. For example, the worksheet indicates that the example curve is sufficiently severe that it may benefit from an additional Curve sign and Advisory Speed plaque located at the beginning of the curve. Chevrons are also recommended for this curve. If used, they should be spaced at 80 ft intervals along the curve. Delinators are optional for this curve. However, if they are used, they should be spaced at 55 ft intervals along the curve. Raised pavement markers are recommended if the curve is located in an area where snowfall is not frequent.

CHAPTER 3. PROCEDURE FOR ESTABLISHING ADVISORY SPEED

OVERVIEW

The recommended procedure for establishing the curve advisory speed is described in this chapter. The procedure is applicable to curves that have a constant radius, those that have compound curvature, and those that have spiral transitions. This flexibility is achieved by focusing the field measurements on the "critical" portion of the curve. The critical portion of the curve is defined as the section that has a radius and superelevation rate that combine to yield the largest side friction demand. When spiral transitions or compound curves are present, this critical portion of the curve is typically found in the middle third of the curve, as shown in Figure 6. If the curve is truly circular for its entire length, then measurements made in the middle third will yield the same radius estimate as those made in other portions of the curve.

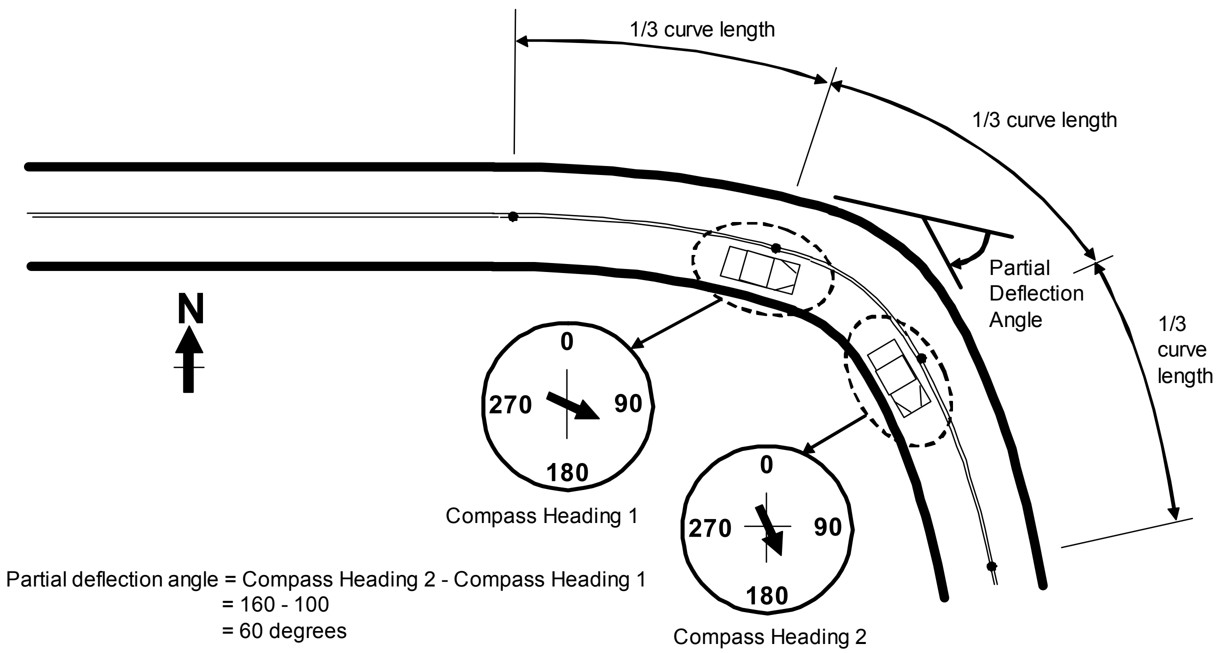


Figure 6. Location of Critical Portion of Curve.

The deflection angle associated with the critical portion is referred to as the "partial deflection angle." The curve length associated with the critical portion is referred to as the "partial curve length."

There are two methods by which the advisory speed can be estimated. The first method is called the "direct" method, and the second method is called the "compass" method. The procedure for implementing the Direct Method is described in the next part of this chapter. The procedure for implementing the Compass Method is described in the last part.

DIRECT METHOD

The Direct Method is based on the field measurement of vehicle speeds on the subject curve. It is available as a method of establishing the advisory speed because this speed is defined in terms of the distribution of vehicle speeds. Specifically, it has been recommended that the advisory speed equal the average speed of trucks (*4*).

The procedure for implementing the Direct Method consists of three steps. During the first step, measurements are taken in the field. During the second step, the measurements are used to compute the advisory speed. During the last step, the recommended advisory speed is confirmed through field trial. Each of these steps is described in more detail in the next three sections.

Step 1: Field Measurements

Measure the speed of 125 or more free-flowing passenger cars as they travel through the critical portion of the curve in one direction of travel. Repeat the measurements for the opposing direction of travel. A radar speed meter can be used for this purpose. A free-flowing vehicle will be at least 3 s ahead of the next following vehicle and at least 3 s behind the previous vehicle.

Compute the arithmetic average of the measured speeds for each direction. Two averages are obtained at the conclusion of this step.

Step 2: Determine Advisory Speed

Multiply each of the averages from Step 1 by 0.97 to obtain an estimate of the average truck speed for each direction of travel. The advisory speed for each direction of travel is then computed by first adding 1.0 mph to the corresponding average and then rounding the sum *down* to the nearest 5 mph increment. This technique yields a conservative estimate of the advisory speed by effectively rounding curve speeds that end in 4 or 9 up to the next higher 5 mph increment, while rounding all other speeds down. For example, applying this rounding technique to a curve speed of 54, 55, 56, 57, or 58 mph yields an advisory speed of 55 mph.

When two or more curves are separated by a tangent of 600 ft or less, the Advisory Speed plaque should show the value for the curve having the lowest advisory speed in the series.

Step 3: Confirm Speed for Conditions

During this step, the appropriateness of the advisory speed determined in Step 2 and the need for other horizontal alignment signs is evaluated. The evaluation is based on consideration of a range of factors. These factors include:

- the regulatory speed limit and the 85^{th} percentile speed of free-flowing traffic,
- driver approach sight distance to the beginning of the curve,
- visibility around the curve,
- unexpected geometric features within the curve, and
- position of the most critical curve in a sequence of closely-spaced curves.

The unexpected geometric features that may be considered include:

- presence of an intersection,
- presence of a sharp crest curve in the middle of the horizontal curve,
- sharp curves with changing radius (including curves with spiral transitions),
- sharp curves after a long tangent section, and
- broken-back curves.

The study should include a test run through the curve while traveling at the advisory speed determined in Step 2. The engineer may choose to adjust the advisory speed or modify the horizontal alignment sign layout if the findings from the engineering study indicate the need for these changes.

COMPASS METHOD

The Compass Method is based on the field measurement of curve geometry. The geometric data are then used with a speed-prediction model to compute the average speed of trucks. This speed is recommended for use as the advisory speed (*4*).

The procedure for implementing the Compass Method consists of three steps. During the first step, geometry measurements are taken in the field when traveling along the curve. During the second step, the measurements are used to compute the advisory speed. During the last step, the recommended advisory speed is confirmed through field trial. Each of these steps is described in more detail in the next three sections.

To insure reasonable accuracy in the model estimates using this method, the total curve length should be 200 ft or more and the partial curve length should be 70 ft or more. Also, the curve deflection angle should be 15 degrees or more and the partial curve deflection angle should be 5 degrees or more. A curve with a deflection angle less than 15 degrees will rarely justify curve warning signs.

Step 1: Field Measurements

In the first step of the procedure, the technician travels through the subject curve and makes a series of measurements. These measurements include:

- curve deflection in direction of travel (i.e., left or right);
- heading at the "1/3 point" (i.e., a point that is located along the curve at a distance equal to 1/3 of curve length and measured from the beginning of the curve);
- ball-bank reading of curve superelevation rate at the "1/3 point";
- length of curve between the "1/3" and "2/3 points";
- heading at the "2/3 point"; and
- 85th percentile speed (can be estimated using the regulatory speed limit).

These measurements may require two persons in the test vehicle–a driver and a recorder. However, with some practice or through the use of a voice recorder, it is possible that the driver can also serve as the recorder such that a second person is not needed. The next two subsections describe the procedure for making the aforementioned field measurements.

Equipment Setup

The test vehicle will need to be equipped with the following three devices:

- digital compass,
- distance-measuring instrument (DMI), and
- ball-bank indicator (BBI).

The digital compass' heading calculation should be based on global positioning system (GPS) technology with a position accuracy of 10 ft or less 95 percent of the time and a position update interval of 1 s or less. It must also have a precision of 1 degree (i.e., provide readings to the nearest whole degree).

The compass should be installed in the vehicle in a location that is easily accessed and in the recorder's field of view. The type of mounting apparatus needed may vary; however, the compass should be firmly mounted so that it cannot move while the test vehicle is in motion.

The DMI is used to measure the length of the curve. It should have a precision of 1 ft (i.e., provide readings to the nearest whole foot). The DMI can also be used to: (1) locate a specific curve (in terms of travel distance from a known reference point), and (2) verify the accuracy of the test vehicle's speedometer. The DMI can be mounted in the vehicle but should be removable such that it can be hand-held during the test run.

The ball-bank indicator must have a precision of at least 1 degree (i.e., provide readings to the nearest whole degree). Indicators with less precision (e.g., 5 degree increments) cannot be used with this method. The indicator should be installed along the center of the vehicle in a location that is easily accessed and in the recorder's field of view. The center of the dash is the recommended position because it allows the driver to observe both the road and the indicator while traversing the curve. The type of mounting apparatus needed may vary; however, the ball-bank indicator should be firmly mounted so that it cannot move while the test vehicle is in motion.

To insure proper operation of the devices, it is important that the following steps are taken before conducting the test runs:

- Inflate all tires to a pressure that is consistent with the vehicle manufacturer's specification.
- Calibrate the test vehicle's DMI.
- Calibrate the ball-bank indicator.

The instruction manual for the DMI and the ball-bank indicator should be consulted for specific details of the calibration process.

Measurement Procedure

The following sequence of steps describes the field measurement procedure as it would be used to evaluate one direction of travel through the subject curve. Measurement error and possible differences in superelevation rate between the two directions of travel typically justify repeating this procedure for the opposing direction. Only one test run should be required in each direction.

a. Record the regulatory speed limit and the curve advisory speed.

b. Record the curve deflection (i.e., left or right) relative to the direction of travel. This designation indicates which direction the vehicle turns as it tracks the curve. A turn to the driver's right is designated as a right-hand deflection.

c. Advance the vehicle to the "1/3 point," as shown in Figure 6. This point is about one-third of the way along the curve when measured from the beginning of the curve in the direction of travel. It does not need to be precisely located. The technician's best estimate of this point's location is sufficient. This point is referred to hereafter as the point of partial curvature (PPC).

   Stop the vehicle and complete the following four tasks while at the PPC:
   - Record the vehicle heading (in degrees).
   - Press the Reset button on the DMI to zero the reading.
   - Record the ball-bank indicator reading (in degrees).
   - Record whether the ball has rotated to the left or right of the "0.0 degree" reading.

d. Advance the vehicle to the "2/3 point," as shown in Figure 6. This point is about two-thirds of the way along the curve. This point is referred to hereafter as the point of partial tangency (PPT).

   Stop the vehicle and complete the following two tasks while at the PPT:
   - Record the vehicle heading (in degrees).
   - Press the Display Hold button on the DMI.

   The value shown on the DMI is the partial curve length. With some practice, it may be possible to complete the two tasks listed above while the vehicle is moving slowly (i.e., 15 mph or less). However, if the measurements are taken while the vehicle is moving, is imperative that they represent the heading and length for the same exact point on the roadway. Error will be introduced if the heading is noted at one location and then the length is measured at another location.

The procedure should be applied to each direction of travel through the curve. Measurements from the two test runs will provide for some ability to check the partial deflection angle and curve length measurements. If the deflection angle varies by more than two degrees or the curve length varies by more than 50 ft (or 10 percent of the average length, whichever is less), then there may be an error and the procedure should be repeated. Superelevation rates may vary by direction.

Alternative Step 1: Field Measurements

This section describes an alternative procedure for obtaining the necessary data. This procedure can be used instead of that described in the previous section, if desired. This method does not require the vehicle to be stopped on the curve. With this procedure, a camcorder is positioned in the vehicle such that the compass, DMI, and ball-bank indicator are in the camera field of view. This type of view is shown in Figure 7.

Figure 7. Camcorder View of Measuring Devices.

During the test run through a curve, the camcorder is used to record the instrument readings on videotape. When reaching the critical portion of the curve, the driver slows the vehicle to 15 mph or less for a distance of at least 70 ft. When this speed is reached, the driver so notes this event on the videotape's audio track by making a statement such as "start of critical portion." A similar statement is made when the end of the critical portion is reached.

The videotape is replayed at the office. When the start of the critical portion is reached, the playback unit is paused and the instrument readings recorded. These readings include the vehicle speed (as shown on the DMI), travel distance, compass heading, and ball-bank reading. The tape is then advanced to the point where the end of the critical portion is reached. The unit is paused at this point and the instrument readings recorded. These readings include the travel distance and compass heading. The curve length is computed as the difference between the two travel distances.

Other options may also be available for directly obtaining the desired measurements. For example, an aerial photograph of the curve can be used to locate the critical portion and scale the two headings and partial curve length. The superelevation of the curve will still need to be estimated in the field by some method and should be accurate to within ±2 percent of the true value.

Step 2: Determine Advisory Speed

During this step, the field measurements are used to determine the appropriate advisory speed for a specified travel direction through the subject curve. The calculations are repeated to obtain the advisory speed for a different curve or for the opposing direction of travel through the same curve.

Initially, the data collected in Step 1 are entered in the Analysis worksheet of the TCAS software. The entry of data for example curve "47R" is shown in Figure 8. The measurements taken at this curve are shown in the column headed by the curve's identification number. The curve deflected to the right, relative to the direction of travel during curve measurement.

CURVE ADVISORY SPEED WORKSHEET						
General Information						
District:	County:			Date:	August 16, 2007	
Highway:				Analyst:		
Input Data						
Data Description	**Curve Identification Number**					
	47R					
Curve deflection, left or right	Right	Left	Left	Left	Left	Left
Compass heading 1, degrees	251					
BBI reading of superelevation, degrees	4.0					
Deflection of ball for superelevation reading, left or right	Right	Left	Left	Right	Right	Left
Speed when recording the BBI reading of superelevation, mph	0	0	0	0	0	0
Curve length, ft	201					
Compass heading 2, degrees	281					
Regulatory speed limit, mph	60					
Estimate of 85th% tangent speed, mph	63					
Alternate Input Data *(if data are entered here, they will be used instead of estimates from the data above)*						
85th% tangent speed, mph						
Curve deflection angle, degrees						
Superelevation rate, percent						
Curve radius, ft						

Figure 8. TCAS Input Data.

The compass heading at the first "1/3 point" was 251 degrees. A ball-bank indicator reading of 4 degrees was noted at this point. The ball deflected to the right of the "0.0 degrees" tick mark. This direction indicates that a positive (i.e., beneficial) superelevation is provided along the curve.

The vehicle was stopped for these two measurements, so “0 mph” was input as the vehicle speed when the ball-bank indicator was read.

A curve length of 201 ft was measured at the “2/3 point.” The compass heading at this point was 281 degrees. Finally, the regulatory speed limit of 60 mph is entered into the spreadsheet.

The speed limit is used to estimate the 85th percentile speed on the highway tangents in the vicinity of the curve. If the 85th percentile tangent speed is known, then it can be directly entered in the first row of the Alternate Input Data section of the worksheet (i.e., the fourth row from the bottom, in Figure 8). If a value is entered in the Alternate Input Data section, then it will be used instead of the value estimated using the field measurements entered in the Input Data section. This priority is extended to the direct entry of 85th percentile tangent speed, curve deflection angle, superelevation rate, curve radius, or any combination of these data.

The advisory speed is computed using the estimated (or directly input) curve radius, deflection angle, and superelevation rate. A curve-speed prediction model is used for this purpose. The estimate obtained from this model represents the “unrounded advisory speed” and is shown in the second row from the bottom of Figure 9. The advisory speed is computed by first adding 1.0 mph to the unrounded speed and then rounding the sum *down* to the nearest 5 mph increment. The rationale for this rounding technique is discussed in Step 2 of the Direct Method. The rounded advisory speed is shown in the last row of Figure 9.

Advisory Speed						
Curve deflection angle, degrees	30	0	0	0	0	0
Curve radius, ft	384					
Degree of curvature, degrees	14.9					
Curve path radius, ft	394					
Superelevation rate, percent	6.2					
Average tangent speed, mph	55					
Unrounded advisory speed, mph	39					
Rounded advisory speed, mph	**40**					

Figure 9. TCAS Advisory Speed Calculation.

It should be noted that the computed advisory speed is based on the estimated radius of the vehicle travel path, as opposed to that of the curve. When traveling through a curve, drivers shift their vehicle laterally in the traffic lane such that they flatten the curve slightly. This behavior allows them to limit the speed reduction required by the curve. The difference between the radius of the curve and the travel path radius is shown in Figure 10. The estimated path radius for the subject curve is listed in the Advisory Speed section of the Analysis worksheet, as shown in Figure 9. It will always equal or exceed that of the curve radius. The path radius will be notably larger than the curve radius on curves with a smaller deflection angle.

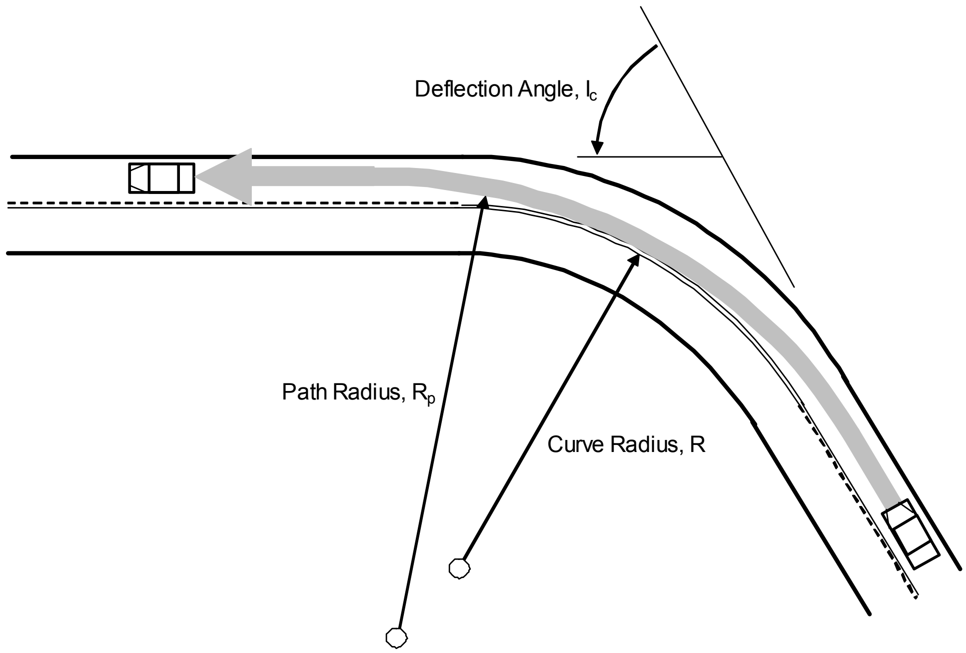


Figure 10. Effect of Lateral Shift on Travel Path Radius.

Step 3: Confirm Speed for Conditions

The activities to be conducted for this step are the same as identified previously for the Direct Method.

CHAPTER 4. CURVE SIGNING GUIDELINES

OVERVIEW

This chapter describes guidelines for the signing of horizontal curves on rural highways. These guidelines were derived largely through a review and synthesis of guidelines offered in the literature. They are intended to complement the procedure for establishing the advisory speed that is described in Chapter 3. Together, the procedure and guidelines provide a rational basis for establishing uniform signing for rural highway curves.

GUIDELINES

Guidelines for selecting curve-related traffic control devices are described in this section. The guidelines are based largely on the existing practices of many transportation agencies. They consist of recommended combinations of traffic control devices associated with a specified curve severity category. The guidelines were developed to reflect a balance of the following goals:

- Promote the uniform and consistent use of traffic control devices.
- Base guidance for these devices on curve severity.
- Avoid overuse of devices.
- Limit the number of devices used at a given curve.

Application of the guidelines begins with a determination of the curve's severity category. This assessment can be obtained using Figure 11. The curve's severity category is based on consideration of the 85th percentile tangent speed and the 85th percentile curve speed. Category A represents curves that are just sharp enough that drivers tend to reduce speed slightly. They accomplish the necessary speed reduction by lifting their foot slightly off the accelerator at the start of the curve. At the other extreme, category E represents the sharpest curves. Drivers will have to begin braking well before they reach the curve, and the degree of braking will be very notable to the vehicle's occupants. These curves can require special treatments such as oversize curve warning signs, flashers added to curve warning signs, wider edge lines approaching (and along) the curve, and profiled edge lines and center lines.

Application of Figure 11 requires knowledge of the 85th percentile tangent speed for passenger cars. This speed can be obtained from a survey of speeds on a tangent section of highway in the vicinity of the curve. The location at which tangent speed data are collected should be sufficiently distant from the curve that it does not influence the observed speeds. The TxDOT document *Procedures for Establishing Speed Zones* describes the survey procedure (*12*). If the 85th percentile tangent speed is not available, an equation is provided in the TCAS software for estimating this speed.

To illustrate the use of Figure 11, consider a curve with an 85th percentile tangent speed of 55 mph and an 85th percentile curve speed of 45 mph. Proceeding upward from the 55-mph tick mark on the x-axis of Figure 11 and over from the 45-mph tick mark on the y-axis, find their intersection point in severity category B.

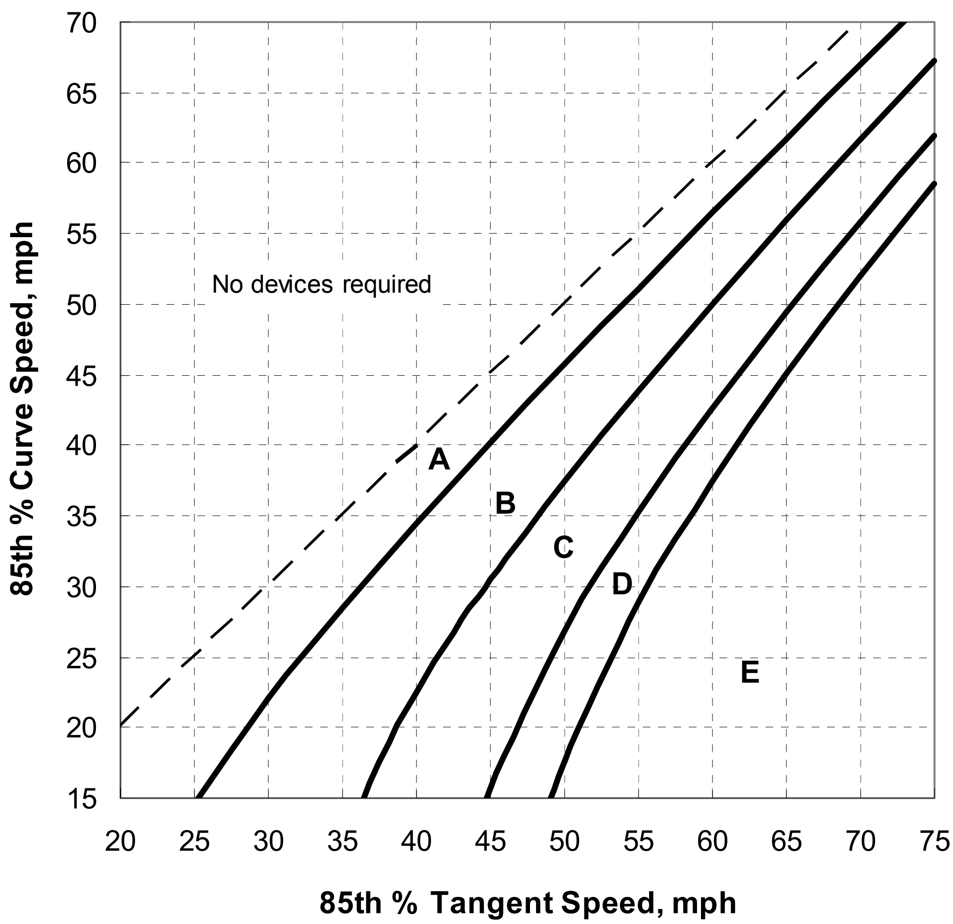


Figure 11. Guidelines for the Selection of Curve-Related Traffic Control Devices.

Table 1 shows the recommended traffic control device treatment for each severity category. The treatments have been categorized into two groups: warning signs and delineation devices. For each category, a combination of devices from both groups is offered. The guidance differentiates between recommended and optional treatments. This approach is intended to provide some flexibility in the selection of devices used at a given curve. An optional device is indicated by an outlined check (✅), and a recommended device is indicated by a solid check (✔).

To illustrate the use of Table 1, consider a curve associated with severity category B and an advisory speed of 40 mph. The solid check marks in Table 1 for this category indicate that a curve warning sign (e.g., Curve sign), Advisory Speed plaque, and raised pavement markers are recommended for this curve.

The curve warning signs listed in Table 1 include: Turn (W1-1), Curve (W1-2), Reverse Turn (W1-3), Reverse Curve (W1-4), Winding Road (W1-5), and Hairpin Curve (W1-11). Guidance on selecting the appropriate sign from this group is specified in Table 2C-5 of the *TMUTCD* (*7*). This guidance is repeated in Appendix B. It is based on the number of alignment changes and the advisory speed. The placement of advance signs, relative to the point of curvature, is described in Table 2C-4 of the *TMUTCD* (and repeated in Appendix B). The delineator and Chevron spacing at a given curve is provided in Table 3D-2 of the *TMUTCD*. This table is reproduced in Appendix B.

Table 1. Guidelines for the Selection of Curve-Related Traffic Control Devices.

Advisory Speed, mph	Device Type	Device Name	Device Number	Curve Severity Category[7]				
				A	B	C	D	E
35 mph or more	Warning Signs	Curve, Reverse Curve, Winding Road, Hairpin Curve[1]	W1-2, W1-4, W1-5, W1-11	✓	✔	✔	✔	✔
		Advisory Speed plaque	W13-1		✔	✔	✔	✔
		Additional Curve, Hairpin Curve[1,2]	W1-2, W1-11			✓	✓	✓
		Chevrons[3]	W1-8				✔	✔
30 mph or less	Warning Signs	Turn, Reverse Turn, Winding Road, Hairpin Curve[1]	W1-1, W1-3, W1-5, W1-11	✓	✔	✔	✔	✔
		Advisory Speed plaque	W13-1		✔	✔	✔	✔
		Additional Turn, Hairpin Curve[1,2]	W1-1, W1-11			✓	✓	✓
		Large Arrow sign	W1-6				✔	✔
Any	Delineation Devices	Raised pavement markers[4]		✔	✔	✔	✔	✔
		Delineators[5]				✓	✓	✓
	Special Treatments[6]							✔

Notes:

1 - Use the Curve, Reverse Curve, Turn, Reverse Turn, or Winding Road sign if the deflection angle is less than 135 degrees. Use the Hairpin Curve sign if the deflection angle is 135 degrees or more.

2 - Use with Advisory Speed plaque. The *MUTCD* indicates that the Combination Horizontal Alignment/Advisory Speed signs (W1-2a and W1-1a) can be also used to supplement other advance warning signs. However, these signs are not recognized in the *TMUTCD*.

3 - A Large Arrow sign may be used on curves where roadside obstacles prevent the installation of Chevrons.

4 - Raised pavement markers are optional in northern regions that experience frequent snowfall.

5 - Delineators do not need to be used if Chevrons are used.

6 - Special treatments could include oversize curve warning signs, flashers added to curve warning signs, wider edge lines approaching (and along) the curve, and profiled edge lines and center lines.

7 - ✓: optional; ✔: recommended.

Figure 12 illustrates the how the guidelines represented in Table 1 and the *TMUTCD* are shown in the TCAS software. The values shown in column two of this figure correspond to the example curve discussed previously for Figures 8 and 9. The speed prediction model indicates that the 85th percentile driver will travel at 63 mph on the highway tangent but slow to 45 mph to negotiate the curve. This 18 mph speed reduction is associated with curve severity category "D." Figure 9 previously indicated that the recommended advisory speed for this curve is 40 mph (which is representative of the average speed of trucks).

As shown in Figure 12 (and confirmed with Table 1), a Curve sign, Advisory Speed plaque, and Chevrons are recommended for the example curve. An additional Curve sign and Advisory Speed plaque located at the beginning of the curve are optional. Engineering judgment should be used to determine whether the additional signs would be beneficial. The Curve sign and Advisory Speed plaque should be located at least 225 ft in advance of the beginning of the curve. The Chevrons should be spaced at 80 ft along the curve. Raised pavement markers are recommended, provided that the curve is not located in a northern region with frequent snowfall. Delineators are also optional, and judgment should be used to determine whether they would be beneficial. If delineators are used, they should be spaced at 55 ft along the curve.

Traffic Control Device Guidance						
85th% tangent speed, mph	63					
85th% curve speed, mph:	45					
Curve severity category	D					
Curve Warning Signs						
Curve sign (W1-2, W1-4, W1-5)	REC.					
Turn sign (W1-1, W1-3, W1-5)						
Hairpin Curve sign (W1-11)						
Min. advance placement distance, ft	225					
Advisory Speed plaque (W13-1)	REC.					
Additional Curve sign & Adv. Speed plaque	opt.					
Additional Turn sign & Adv. Speed plaque						
Minimum Curve sign size, in	36x36					
Min. Adv. Speed plaque sign size, in	24x24					
Large Arrow sign (W1-6)						
Chevrons (W1-8)	REC.					
Chevron spacing, ft	80					
Delineation Devices						
Raised pavement markers	REC.					
Delineators	opt.					
Delineator spacing, ft	55					
Special Treatments						
	opt. = optional			REC. = recommended		

Figure 12. TCAS Traffic Control Device Guidance.

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APPENDIX A. ADVISORY SPEED CRITERIA AND ISSUES

APPENDIX A. ADVISORY SPEED CRITERIA AND ISSUES

OVERVIEW

This appendix summarizes a review of the literature related to advisory speed setting criteria. Initially, the objectives of horizontal curve signing are reviewed. Then, the guidance offered in two authoritative documents is summarized. Finally, several issues associated with current practice are identified and described in terms of their implications on compliance and safety.

OBJECTIVES OF HORIZONTAL CURVE SIGNING

An important objective in horizontal curve signing is having a uniform and consistent display of advisory speed on curves of similar geometry, character (e.g., sight distance, intersection presence, etc.), and road surface condition. As stated in the *MUTCD*, "uniformity of the meaning of traffic control devices is vital to their effectiveness" (*2*, Section 1A.02). It further describes the benefits of uniformity in the following statement.

> "Uniformity of devices simplifies the task of the road user because it aids in recognition and understanding, thereby reducing perception/reaction time. Uniformity means treating similar situations in a similar way." (*2*, Section 1A.06).

The uniform application of a traffic control device allows drivers to develop appropriate expectations that lead to the correct interpretation of its message. In this manner, a uniformly applied advisory speed will be more likely to command the respect of drivers and achieve the desired safety benefits.

Lyles and Taylor (*11*) conducted a nationwide survey of 344 practitioners on the topic of horizontal curve signing practices. Questions were asked about the uniformity and consistency of advisory speeds in the practitioner's state. The findings from this survey question are summarized below, as they relate to the respondents' perceptions of jurisdictions other than their own.

<u>Uniformity in Advisory Speed among Curves</u>
- Forty-five percent believe that advisory speeds are not uniform throughout the state.
- Only 58 percent believe that the advisory speed message is consistently estimated.

<u>Consistency in Advisory Speed with Driver Expectation</u>
- Sixty-two percent believe that advisory speeds are too low.
- Three percent believe that advisory speeds are too high.

With regard to uniformity among curves, almost half (45 percent) of the respondents believe that the posted advisory speeds in their state are not uniform among curves. From this response, it could be inferred that 55 percent believe that these signs are uniform. In fact, when asked about advisory speed uniformity, only 58 percent of respondents indicated that they believe that advisory speeds are consistently estimated.

With regard to consistency with driver expectation, 62 percent of the respondents believe that advisory speeds are too low. In contrast, 3 percent of respondents believe that advisory speeds are too high. These findings imply that only 35 percent of respondents believe that advisory speeds are about right.

Based on their survey findings, Lyles and Taylor (*11*) offered the following observation:

> "Advisory speed signing appears to be largely ineffective if the goal is for drivers to actually travel at the posted advisory speed: drivers either fail to notice advisory speed plaques, or, more likely, they simply reject the literal advisory speed recommendations, driving at a reduced speed that they feel is appropriate" (*11,* p. 2).

CURRENT PRACTICE

This section reviews the criteria recommended by two reference documents for establishing the curve advisory speed. It focuses on the criteria offered in the *MUTCD* (*2*) and the *TMUTCD* (*7*). One subsection is devoted to the criteria described in each document.

MUTCD *Criteria*

The *MUTCD* (*2*) indicates that the advisory speed may be based on any of the following criteria:

- 85^{th} percentile speed of free-flowing traffic,
- speed corresponding to a 16 degree ball-bank indicator reading, or
- speed determined appropriate following an engineering study.

The first bullet item in the preceding list implies that the advisory speed is directly tied to the distribution of speeds measured on the curve. Specification of the 85^{th} percentile speed as the threshold value is likely intended to insure consistency between driver curve speed choice and the regulatory speed limit (the latter of which is based on the 85^{th} percentile tangent speed).

TxDOT Criteria

The *TMUTCD* (*7*) recognizes the engineering study as the basis for determining the advisory speed. However, one element of this study is the use of the ball-bank indicator. The TxDOT document *Procedures for Establishing Speed Zones* (*12*) describes the correct use of the ball-bank indicator to establish an advisory speed. It recommends the use of a ball-bank reading of 14 degrees for speeds of 20 mph or less, 12 degrees for speeds of 25 to 30 mph, and 10 degrees for speeds of 35 mph or more.

The relationship between curve speed and radius is shown in Figure A-1 for ball-bank readings of 10 and 14 degrees. The thin trend line represents the actual curve speed found on these curves and is based on the trends shown in Figure 1.

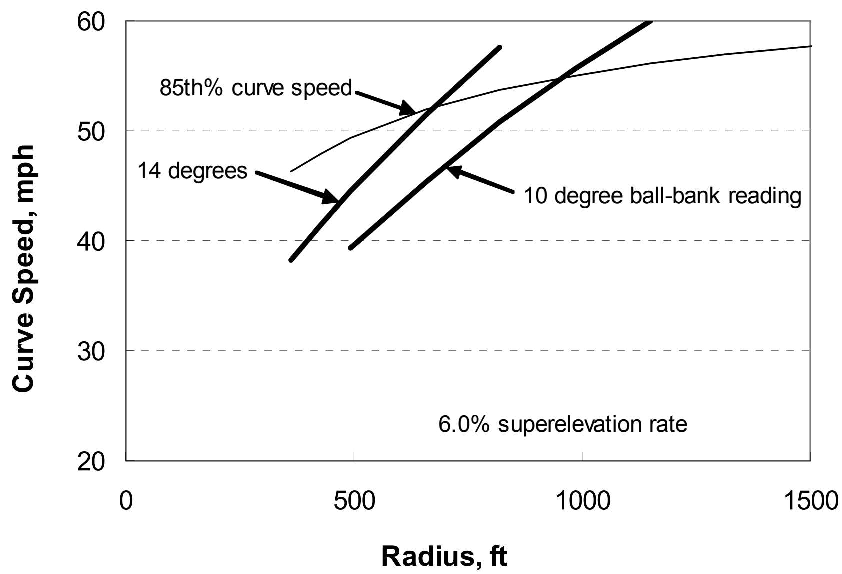


Figure A-1. Relationship between Curve Speed, Ball-Bank Reading, and Radius.

The "10 degree" trend line in Figure A-1 intersects the thin trend line at about 950 ft. An engineer who uses the 10-degree criterion to establish an advisory speed for a curve with an 950 ft radius would likely determine that the advisory speed should be 55 mph. For this one combination of radius and tangent speed, the advisory speed would be consistent with the 85^{th} percentile curve speed. However, for sharper radii, the 85^{th} percentile curve speed would exceed that established using the 10-degree criterion. For example, if the 10-degree criterion is used on a 500 ft curve with a tangent speed of 60 mph, the advisory speed is likely to be 40 mph, but the 85^{th} percentile curve speed is likely to be 50 mph.

The trends in Figure A-1 indicate that drivers traveling on sharp curves do not necessarily adopt a speed that is associated with a constant ball-bank reading. Rather, they reduce their speed as they enter the curve based on their consideration of both the added travel time associated with the speed reduction and their level of comfort associated with side forces. They accept a level of side force that reflects a compromise between comfort and added travel time.

ISSUES WITH CURRENT PRACTICE

This section discusses several issues related to current curve signing practices. The discussion focuses on the following topics:

- uniformity in advisory speed among curves,
- consistency in advisory speed with driver expectation, and
- regulatory speed limit versus measured tangent speed.

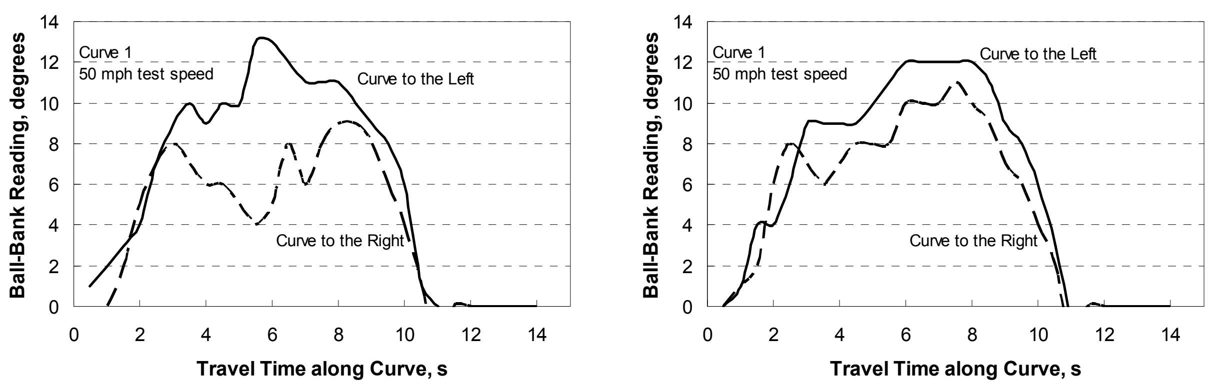
Each of the topics listed above is addressed in the following subsections.

Uniformity in Advisory Speed among Curves

This subsection examines variability of the ball-bank indicator reading and its impact on the uniformity in advisory speed among the curves in various jurisdictions. This examination focuses on the range of ball-bank readings that are typically obtained for a given curve and discusses possible sources of this variability. The consequences of a lack of uniformity are examined by comparing posted advisory speeds with those established by researchers using a ball-bank indicator.

Evidence: Variable Ball-Bank Readings

Experience using the ball-bank indicator reveals that it is a sensitive device that is influenced by variations in the vehicle's travel path and variations in the road surface. The variation in ball-bank readings obtained at one curve is shown in Figure A-2. The first and last readings shown in each figure are small because of the superelevation runoff that occurs at the start and end of the curve. However, the intermediate readings can be seen to vary by several degrees with travel time along the curve and also by curve direction and technician. Similar trends are found at most other curves.



a. Technician A. **b. Technician B.**

Figure A-2. Ball-Bank Readings from Two Test Runs with Different Technicians.

In Figure A-2a, the ball-bank reading on the curve to the right varies from 4 to 9 degrees for travel time between 2.5 and 8.5 s. The average reading in this range is 7.3 degrees. As shown in Figure A-2b, the second technician driving the same car and curve to the right observed readings that vary from 6 to 11 degrees with an average of 8.2 degrees. The variability within any one technician's test run is significant and, when considering the additional variability among technicians, it is not difficult to understand why there is so little uniformity in advisory speeds among curves. Moreover, this finding suggests the ball-bank method has the undesirable trait of not being a "repeatable" process.

Standard practice in using the ball-bank indicator is to use the *maximum* ball-bank reading observed during the test run to establish the advisory speed. Thus, for the curve shown in

Figure A-2, a 12 or 13 degree maximum (depending on technician) is observed for the curve to the left, and a 9 or 11 degree maximum is observed for the curve to the right. However, this maximum reading is often the result of a random event–an aberration due to steer correction. Thus, the practice of selecting the maximum reading has the undesirable trait of allowing the advisory speed to be based on a momentary random spike in the reading. This finding is also consistent with the trend noted previously that advisory speeds are too low, relative to the observed speed distribution.

The variation in readings along a curve is likely due to a variety of sources, such as:

- rough pavement surface,
- occasional steering corrections made while traveling along the curve, and
- variation in pavement friction supply.

Even when the same vehicle and driver are used during a series of test runs at the same curve, the maximum observed reading will likely vary on successive test runs due to one or more of these sources.

With regard to pavement surface roughness, ball-bank readings are likely to be biased high by 1 or 2 degrees on curves with rough pavements. Pavement surface roughness can be a consequence of any type of pavement deformation or settlement that causes the superelevation to vary along the length of the curve.

With regard to steering corrections, the steering system of most vehicles has a slight understeer or oversteer that makes it difficult for their drivers to track the curve radius. Tire slip angles (as are influenced by tire pressure, loading, camber, caster, suspension, etc.) dictate whether a vehicle exhibits understeer or oversteer. When either state exists, the driver has to correct the path of the vehicle to avoid spinning out or sliding off of the roadway. These steer corrections translate into the vehicle tracking a sharper radius (than that of the roadway) for short sections of the curve.

With regard to variation in pavement friction supply, the condition of the pavement at the time the advisory speed is established can have significant influence on the resulting advisory speed. Pavement surface friction supply changes each time the road is resurfaced. The friction supply has a direct effect on tire slip and thus, it affects the frequency and extent of steer corrections. As noted in the previous paragraph, steer corrections tend to cause fluctuations in the steering that introduce short-term spikes in friction demand, with a corresponding jump in the observed ball-bank reading.

Variability in the ball-bank reading, when extreme, can translate into variability in the recommended advisory speed on curves of similar geometry, character, or condition. Other factors that can lead to variation in the advisory speed among similar curves include:

- suspension differences in the vehicles used to establish advisory speeds,
- quality of ball-bank indicator and speedometer calibration, and
- diligence and training of persons using the device.

The extent to which theses sources contribute to advisory speed variability has not been researched.

Consequences: Posted Advisory Speed vs. Ball-Bank-Based Advisory Speed

The previous section demonstrated the variability associated with the ball-bank indicator when it is used to establish curve advisory speeds. Numerous sources of variability were identified. This section examines the consequences of this variability in terms of the uniformity of advisory speeds among curves.

For this discussion, a curve's posted advisory speed is defined as uniform when it matches the speed determined by using the ball-bank indicator. Chowdhury et al. (*3*) examined advisory speed uniformity in three states. They recorded the posted advisory speed for each of 28 curves and then used the ball-bank indicator to estimate the appropriate advisory speed. Their findings are shown in Figure A-3. Each data point in this figure represents one curve study site. The trend line shown in this figure is a "*y* = *x*" line, such that a data point would fall on this line if the corresponding site had a posted advisory speed equal to the ball-bank-based advisory speed.

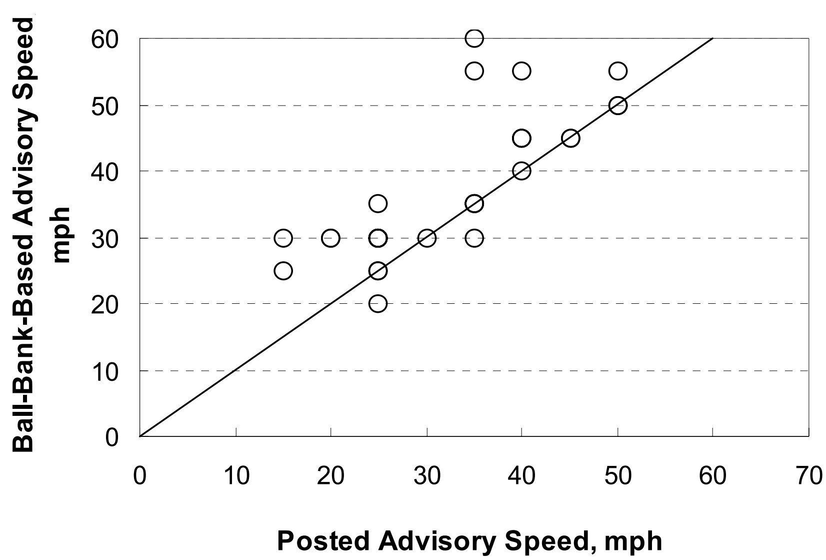


Figure A-3. Comparison of Posted and Estimated Advisory Speeds.

Chowdhury et al. (*3*) found that only 36 percent of the curves had posted advisory speeds that were consistent with their estimate of the appropriate advisory speed. The variation ranged from -5 mph to +25 mph, with an average difference of +5 mph. This finding is consistent with that of Carlson et al. (*13*), who used a ball-bank indicator to evaluate advisory speeds on curves in Texas.

Consistency in Advisory Speed with Driver Expectation

This subsection uses data reported in the literature to examine the consistency between advisory speed and driver expectancy. This examination focuses on the driver's choice of speed for a given curve. The consequences of a lack of consistency are examined by comparing curve advisory speed with the measured curve speed distribution.

Evidence: Curve Speed Choice and Corresponding Ball-Bank Angles

Research indicates that tangent speed has a significant influence on driver curve speed choice. The speed prediction model developed by Bonneson et al. (*4*) was used to estimate the ball-bank readings that correspond to the curve speed and radius combinations shown in Figure 1b. These readings are shown in Figure A-4.

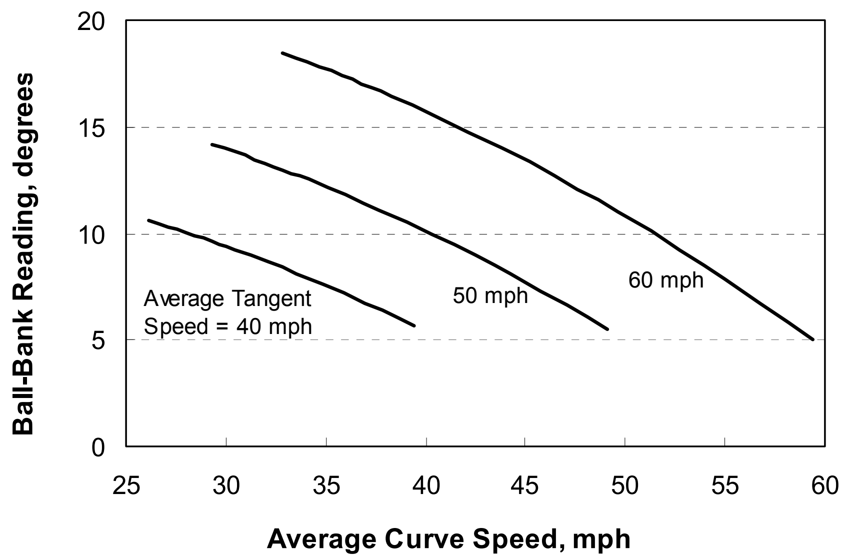


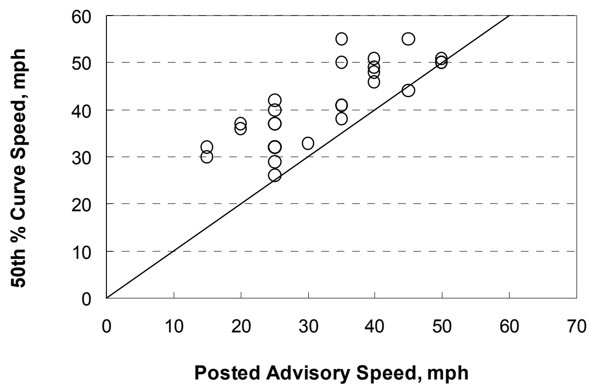
Figure A-4. Relationship between Radius, Speed, and Ball-Bank Reading.

Two important points can be made from the trends shown in Figure A-4. First, the ball-bank reading that corresponds to driver speed choice is not a constant. Rather, it decreases with increasing curve speed and reflects the driver's desire for less side force at higher curve speeds. No one ball-bank reading describes driver speed choice for the full range of radii and tangent speeds.

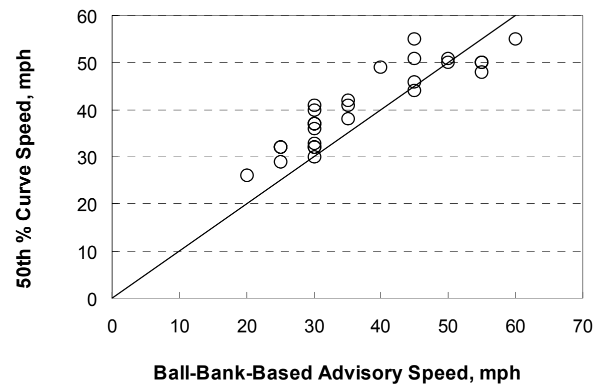
Second, the relationship between ball-bank reading and curve speed is dependent on the tangent speed. For example, consider a curve with an average curve speed of 40 mph. A 5 degree ball-bank reading is likely to accurately reflect driver speed choice when this curve has a tangent speed of 40 mph. In contrast, a 16 degree reading is more likely to reflect driver speed choice when the tangent speed is 60 mph.

Consequences: Advisory Speed vs. Measured Curve Speed

This section examines the consequences of inconsistent advisory speeds by examining the relationship between the advisory speed and the measured speed distribution for several curves. The data cited by Chowdhury et al. (*3*) are used for this examination. They measured the speed distribution on each of 28 curves in three states. They also recorded the posted advisory speed associated with each curve. Figure A-5a compares the posted advisory speed with the observed 50th percentile speed. Each data point in this figure corresponds to one curve study site. The data points shown indicate that the 50th percentile speed exceeds the posted advisory speed by as much as 20 mph. Similar trends were noted in an examination of data collected on rural two-lane highways in Texas (*4*).



a. Posted Advisory Speed.



b. Estimated Advisory Speed.

Figure A-5. Comparison of the 50th Percentile Curve Speed with the Advisory Speed.

Chowdhury et al. (*3*) also used a ball-bank indicator to estimate the appropriate advisory speed for each curve. The estimated advisory speeds are shown in Figure A-5b. Compared to Figure A-5a, the variability in Figure A-5b is reduced because Chowdhury et al. used the same test vehicle and a consistent technique. It is noted that the 50th percentile speed exceeds the estimated advisory speed by no more than 10 or 11 mph. For higher curve speeds, the 50th percentile speed is about equal to, or slightly lower than, the estimated advisory speed.

The common practice of signing both directions of the curve using the same advisory speed can also contribute to the variability shown in Figures A-5a and A-5b. Specifically, this practice adds variability when the superelevation along the curve is different for the two travel directions. Data collected by Carlson et al. (*13*) for 18 curves on rural two-lane highways in Texas indicate that superelevation rate was different by direction for 16 of 18 curves. The range of differences was 0 to 8 percent, with a typical variation along any one curve of 2 to 3 percent.

Regulatory Speed Limit vs. Measured Tangent Speed

Several recent studies of vehicle speed on rural highways have found that drivers consistently exceed the regulatory speed limit. The amount by which the speed limit is exceeded varies with the speed limit and tends to be largest for lower speed limits. The findings reported by Bonneson et al. (*4*) for rural highways in Texas are shown in Figure A-6. Each data point represents the free-flow speed measured on one highway tangent. The trend shown is consistent with that reported in the literature.

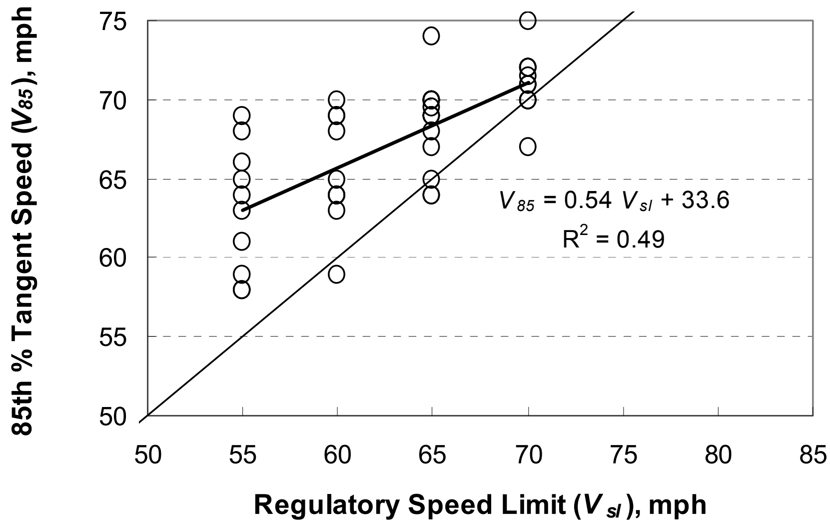


Figure A-6. Relationship between Speed Limit and 85th Percentile Speed.

The trend in Figure A-6 indicates that the 85th percentile speed always exceeds the regulatory speed limit; however, the amount of excess is not constant. Extrapolation of the trend line suggests that the 85th percentile speed is more likely to equal the speed limit on rural highways if the speed limit is 70 to 75 mph. In contrast, a speed limit of 55 mph is likely to be exceeded by 7 to 10 mph.

The trend in Figure A-6 has implications on guidelines for horizontal curve signing. Many of the existing guidelines are based on the regulatory speed limit of the highway. Some guidelines explicitly indicate that the 85th percentile speed can (or should) be used to make the determination. However, other guidelines suggest that the speed limit can be used as an estimate of the 85th percentile speed. It is not clear to what extent any of these guidelines recognize the likely difference between the speed limit and the 85th percentile speed, as suggested by Figure A-6. However, any guideline that is based on an assumed equality in the two speeds is not likely to yield its desired result.

APPENDIX B. SELECTED TABLES FROM THE *TMUTCD*

Table B-1. Guidelines for Advance Placement of Warning Signs.
(Table 2C-4 of the *TMUTCD*)

Posted or 85th Percentile Speed, mph	Advance Placement Distance, ft[1]									
	Condition A: Speed reduction and lane changing in heavy traffic[2]	Condition B: Stop Condition[3]	Condition C: Deceleration to the listed advisory speed (mph) for the condition[4]							
			10	20	30	40	50	60	70	75
20	225	N/A[5]	N/A[5]	-	-	-	-	-	-	-
25	325	N/A[5]	N/A[5]	N/A[5]	-	-	-	-	-	-
30	450	N/A[5]	N/A[5]	N/A[5]	-	-	-	-	-	-
35	550	N/A[5]	N/A[5]	N/A[5]	N/A[5]	-	-	-	-	-
40	650	125	N/A[5]	N/A[5]	N/A[5]	-	-	-	-	-
45	750	175	125	N/A[5]	N/A[5]	N/A[5]	-	-	-	-
50	850	250	200	150	100	N/A[5]	-	-	-	-
55	950	325	275	225	175	100	N/A[5]	-	-	-
60	1100	400	350	300	250	175	N/A[5]	-	-	-
65	1200	475	425	400	350	275	175	N/A[5]	-	-
70	1250	550	525	500	425	350	250	150	-	-
75	1350	650	625	600	525	450	350	250	100	-
80	1475	725	725	700	625	550	475	350	200	125

Notes:

1 - The distances are adjusted for a sign legibility distance of 175 ft for Condition A and B. The distances for Condition C have been adjusted for a sign legibility distance of 250 ft, which is appropriate for an alignment warning symbol sign.

2 - Typical conditions are locations where the road user must use extra time to adjust speed and change lanes in heavy traffic because of a complex driving situation. Typical signs are Merge and Right Lane Ends. The distances are determined by providing the driver a perception-reaction time (PRT) of 14.0 to 14.5 s for vehicle maneuvers (2004 AASHTO Policy, Exhibit 3-3, Decision Sight Distance, Avoidance Maneuver E) minus the legibility distance of 175 ft for the appropriate sign.

3 - Typical condition is the warning of a potential stop situation. Typical signs are Stop Ahead, Yield Ahead, Signal Ahead, and Intersection Warning signs. The distances are based on the 2001 AASHTO Policy, Stopping Sight Distance, Exhibit 3-1, providing a PRT of 2.5 s, a deceleration rate of 11.2 ft/s^2 minus the sign legibility distance of 175 ft.

4 - Typical conditions are locations where the road user must decrease speed to maneuver through the warned condition. Typical signs are Turn, Curve, Reverse Turn, or Reverse Curve. The distance is determined by providing a 2.5 s PRT, a vehicle deceleration rate of 10 ft/s^2, minus the sign legibility distance of 250 ft.

5 - No suggested distances are provided for these speeds, as the placement location is dependent on site conditions and other signing to provide an adequate advance warning for the driver.

Table B-2. Horizontal Alignment Sign Usage.
(Table 2C-5 of the *TMUTCD*)

Number of Alignment Changes	Advisory Speed	
	30 mph or Less	35 mph or more
1	Turn (W1-1) [1]	Curve (W1-2) [1]
2 [2]	Reverse Turn (W1-3) [3]	Reverse Curve (W1-4) [3]
3 or more [2]	Winding road (W1-5) [3]	

Notes:
1 - Engineering judgment should be used to determine whether the Turn or Curve sign should be used.
2 - Alignment changes are in opposite directions and are separated by a tangent distance of 600 ft or less.
3 - A Right Reverse Turn (W1-3R), Right Reverse Curve (W1-4R), or Right Winding Road (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 Road (W1-5L) sign is used if the first change in alignment is to the left.

Table B-3. Delineator and Chevron Sign Spacing.
(Table 3D-2 of the *TMUTCD*).

Degree of Curve	Radius, ft	Delineator Spacing (S_d) in Curve, ft [1]	Chevron Spacing (S_c) in Curve, ft [2]
5	1146	100	160
6	955	90	160
7	819	85	160
8	716	75	160
9	637	75	120
10	573	70	120
11	521	65	120
12	478	60	120
13	441	60	120
14	409	55	80
15	382	55	80
16	358	55	80
19	302	50	80
23	249	40	80
29	198	35	40
38	151	30	40
57	101	20	40

Notes:
1 - Delineator spacing refers to the spacing for specific radii computed from the equation: $S_d = 3\ (R - 50)^{0.5}$
2 - Chevron spacing refers to the spacing for specific radii computed from the equation: $S_d = 5.3\ (R - 70)^{0.5}$

APPENDIX C. DATA COLLECTION SHEET

Version 6 7/21/2007

Horizontal Curve Advisory Speed Field Data Sheet Texas Department of Transportation Traffic Operations Division

Date: **Analyst:**

District: **County:** **Roadway:** **Reference Roadway:**

		Field Measurements													Recommendations			
		Posted Speed (mph)				Cross Slope											
Curve ID Number	Mileage from Reference Roadway	Regulatory Limit	Advisory	Curve Deflection (Left, Right)	Entry Heading (deg)	Ball-Bank Reading	Ball-Bank Deflection (Left, Right)	Speed During Measurement (mph)	Curve Length (ft)	Exit Heading (deg)	Sight Distance OK? (yes,no)	Intersection in Curve (yes, no)	Adjacent Curve < 600 ft (yes,no)	Curve Warning Sign Needed (Yes, No)	Recommended Advisory Speed (mph)	Additional Devices	Comments
1																	
2																	
3																	
4																	
5																	
6																	
7																	
8																	
9																	
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