



Horizontal Curve Evaluation Handbook

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16. Abstract Horizontal curves are a common and essential element of the rural highway system, and it is essential to sign and mark them consistently to minimize curve crash risk. Curve signing and marking consists primarily of conducting an engineering study to set the curve advisory speed, posting the advisory speed if necessary, and providing other signs and markings (such as Chevrons) based on the curve severity. Additionally, curve safety can be addressed through more significant treatments such as installing a pavement friction treatment or even straightening the curve if the highway can be realigned. Over the past decade, the Texas Department of Transportation has sponsored several research projects to (1) develop new procedures for setting curve advisory speeds on rural two-lane highways, (2) examine crash frequency on rural highways in general, (3) identify conditions when pavement friction treatments are beneficial and cost-effective, and (4) extend curve advisory speed study methods to four-lane rural highways. This <i>Handbook</i> provides engineers and technicians with a consolidated source for applying all the preceding analysis tools to assess curve safety and implement needed treatments.					
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HORIZONTAL CURVE EVALUATION HANDBOOK

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The contents of this report 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 report does not constitute a standard, specification, or regulation. It is not intended for construction, bidding, or permitting purposes. The engineer in charge of the project was Michael P. Pratt, P.E. #102332.

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 report.

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CHAPTER 1. INTRODUCTION

BACKGROUND

Horizontal curves are an essential part of the rural highway system, and they represent a small percentage of overall rural highway mileage, but they experience a disproportionate share of crashes. In particular, curves have been shown to be susceptible to run-off-road crashes and wet-weather crashes (1, 2). Hence, efforts to reduce crash frequency on state-maintained highways need to consider rural highway curves.

Horizontal curve safety is influenced by various factors relating to geometry, traffic volume and speed, pavement, weather patterns, and traffic control devices. One key traffic control device for curve operations and safety is the Advisory Speed Plaque, which provides warning to motorists when a curve is sufficiently severe that speed reduction is needed. In Texas Department of Transportation (TxDOT) research project 0-5439, new criteria were developed to set curve advisory speeds on rural two-lane highways based on the average speed of truck on the curve, as estimated using a curve speed model. In TxDOT implementation project 5-5439, a GPS-based engineering study method was developed to obtain the data needed to apply the updated curve advisory speed criteria.

In addition to curve advisory speeds, the guidance material from TxDOT research project also addresses use of supplemental devices like delineator posts and Chevrons. The *Texas Manual on Uniform Traffic Control Devices* (TMUTCD) has also been updated in recent years to address use of supplemental devices (3). Finally, guidance was developed in TxDOT research projects 0-6714 and 0-6932 to address the use of pavement friction treatments on horizontal curves.

In TxDOT research project 0-6960, researchers extended the 0-5439 guidelines to curves on four-lane rural highways and developed a suite of software tools to assist practitioners in applying the aforementioned guidance sources. This *Horizontal Curve Evaluation Handbook* (*Handbook*) describes the procedures to apply these tools.

HANDBOOK OVERVIEW

The following chapters of the *Handbook* are organized as follows:

- Chapter 2 summarizes signing and marking guidelines for horizontal curves.
- Chapter 3 describes four engineering study methods for setting curve advisory speeds.
- Chapter 4 describes a margin-of-safety analysis framework for assessing curve pavement friction and determining the need for a surface treatment.
- Chapter 5 provides a guide for using the Texas Roadway Analysis and Measurement Software (TRAMS) program, which is used to collect data needed to conduct an engineering study and to evaluate curve safety.
- Chapter 6 provides a guide for using the Texas Curve Evaluation Suite (TCES), which is an Excel®-based spreadsheet program that processes data files assembled by TRAMS.

SOFTWARE OVERVIEW

TRAMS is an executable program that monitors data streams from a global positioning system (GPS) receiver and (optionally) an electronic ball-bank indicator (BBI) and a barometer. The TRAMS program is capable of monitoring data streams while the analyst drives a continuous stretch of highway. The program is used to implement the GPS Method, which is described in Chapter 3. Use of the program is described in detail in Chapter 5.

TCES is a spreadsheet-based program that computes curve advisory speeds and allows the analyst to assess curve severity, determine the need for supplemental traffic control devices, and determine the need for pavement friction treatments. The TCES program is capable of batch-processing files from multiple GPS Method data collection runs and analyzing the individual curves within each data file. It consists of the following worksheets:

- List: the primary worksheet, which consists of one row per curve and contains curve data including the computed advisory speed.
- Traffic control devices (TCD): a supplemental worksheet, which can be used for more detailed analysis of the traffic control device requirements for curves of interest.
- Pavement: a supplemental worksheet, which can be used to examine the curve's margin of safety and estimated crash frequency based on geometry, vehicle speeds, and precipitation rate, and determine the benefit-cost ratio of a proposed pavement friction treatment.

The TRAMS and TCES programs are available from TxDOT's Traffic Safety Division or from TTI.

CHAPTER 2. CURVE SIGNING AND MARKING GUIDELINES

BACKGROUND

In TxDOT research project 0-5439 and implementation project 5-5439 (4, 5), researchers developed guidelines for assessing curve severity, selecting curve traffic control devices, and determining the need for special control-device-based treatments like wide edgelines, profiled markings, oversized signs, or flashers added to signs. These guidelines were based on the principle of curve severity as defined by side friction and energy differentials, which are computed from the curve speed models developed in the research project. TxDOT implementation project 5-5439 was completed in 2009.

Guidelines for selecting curve traffic control devices were added to the federal MUTCD in 2009 and incorporated to the TMUTCD in 2011 (3). These guidelines specify the selection of curve traffic control devices based on speed differential, which is the difference between regulatory speed limit and advisory speed (if posted).

The TMUTCD-based guidelines for selecting curve traffic control devices are the official guidelines for TxDOT, so they are chosen and applied by default in the TCES program. However, both sets of guidelines (TMUTCD and alternative guidelines from project 0-5439) are supported by TCES and can be applied in a curve analysis. The two sets of guidelines are described in the next two sections of this chapter.

TMUTCD-BASED GUIDELINES FOR SELECTING DEVICES

The TMUTCD provides detailed guidelines for providing traffic control devices for horizontal curves. These guidelines address the use of warning signs (TMUTCD Chapter 2C), pavement markings (TMUTCD Chapter 3B), and delineation devices (TMUTCD Chapter 3F). TMUTCD guidelines for these three types of devices are summarized in the following subsections.

Warning Signs

Section 2C.06 of the TMUTCD contains guidelines for posting horizontal alignment warning signs. Figure 1 shows horizontal alignment warning signs relevant to curves.

Guidance Framework for Using Signs

The TMUTCD states the following standard for selecting devices for use on a given curve (emphasis added):

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 engineering judgement using the speed differential between the roadway's posted speed limit, statutory speed limit, or 85th-percentile speed on the approach to the curve and the horizontal curve's advisory speed.

It further states that “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” (emphasis added). TMUTCD Table 2C-5 is repeated as Table 1.

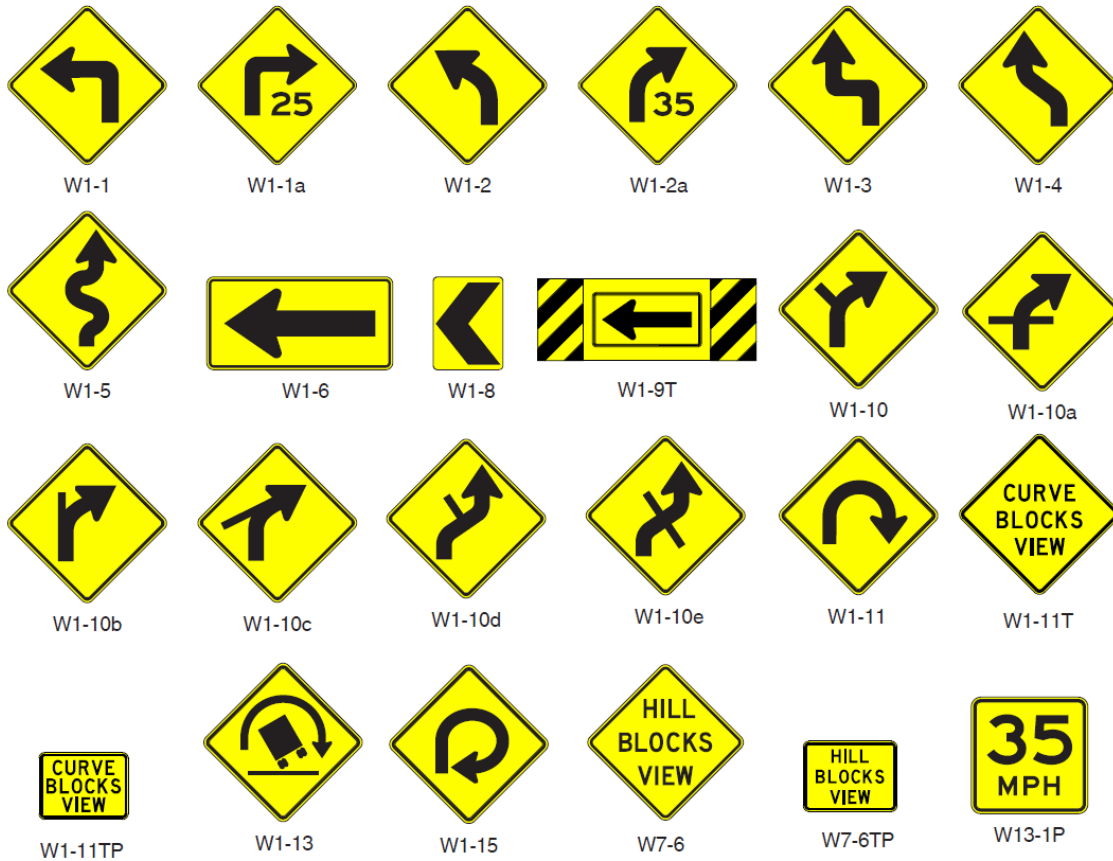


Figure 1. Horizontal Alignment Warning Signs (3).

Table 1. Horizontal Alignment Sign Selection (3, Table 2C-5).

Type of Sign	Difference between Speed Limit and Advisory Speed				
	5	10	15	20	≥ 25
Horizontal Alignment (W1-1, W1-2, W1-3, W1-4, W1-5), Combination Horizontal Alignment / Intersection (W1-10 series)	Rec.	Req.	Req.	Req.	Req.
Advisory Speed Plaque (W13-1)	Rec.	Req.	Req.	Req.	Req.
Chevrons (W1-8), One-Direction Large Arrow (W1-6)	Opt.	Rec.	Req.	Req.	Req.

Opt. = optional (may be used), Rec. = recommended (should be used), Req. = required (shall be used)

The TMUTCD guidance framework is based on the determination of speed limit and advisory speed as the criteria for selecting devices. The TMUTCD offers the following guidelines for determining the speed limit and the advisory speed:

- Speed zones (other than statutory speed limits) shall only be established based on an engineering study that has been performed in accordance with traffic engineering practices. The engineering study shall include an analysis of the current speed distribution of free-flowing vehicles. *The Speed Limit (R2-1) sign shall display the limit established by law, ordinance, regulation, or as adopted by the authorized agency based on the engineering study* (Sections 2B.01-02).
- *The advisory speed shall be determined by an engineering study that follows established engineering practices.* Among the established engineering practices that are appropriate for the determination of the recommended advisory speed for a horizontal curve are the following: . . . Any of the methods outlined in the “Procedures for Establishing Speed Zones” (Section 2C.08).

TxDOT’s *Procedures for Establishing Speed Zones* (6) describes several engineering study methods for determining advisory speeds. These methods are discussed in Chapter 3 of this *Handbook* and are based on estimating the average truck speed on the curve of interest. An advisory speed can be determined for any curve, but it is only necessary to post the advisory speed if the following conditions are met:

1. The determined advisory speed is less than the regulatory speed limit.
2. The plotted difference between 85th-percentile passenger car speeds on the approach tangent and at the curve midpoint is located below the contour line on Figure 2.
3. Engineering study shows that the average truck speed at the curve midpoint is less than the average truck speed on the approach tangent.

The use of average truck speed in the engineering study method is based on the guidance developed in TxDOT research project 0-5439 (4). The third condition further acknowledges that average truck speeds are notably lower than 85th-percentile passenger car speeds on the approach tangent, such that it is possible to find that 85th-percentile passenger cars reduce speed as they traverse a curve while average trucks do not.

Horizontal Alignment Sign Guidelines

As show in the first column of Table 1, there are several types of Horizontal Alignment signs available for curves. Section 2C.07 of the TMUTCD offers the following guidelines to choose between these signs:

- Standard: use the Curve (W1-2) sign as the default option unless guidance calls for a different sign.
- Standard: use the Turn (W1-1) sign if the curve advisory speed is 30 mph or lower.
- Guidance: use the Reverse Turn (W1-3) sign instead of multiple Turn signs if there are two curves in opposite directions that are separated by a tangent of less than 600 ft.
- Guidance: use the Reverse Curve (W1-4) sign instead of multiple Turn signs if there are two curves in opposite directions that are separated by a tangent of less than 600 ft.
- Option: use the Winding Road (W1-5) sign instead of multiple Turn or Curve signs if there are three or more curves that are each separated by a tangent of less than 600 ft.

- Option: use the Hairpin Curve (W1-11) sign instead of a Turn or Curve sign if the curve has a deflection angle of 135° or more.
- Option: use the 270-Degree Loop (W1-15) sign instead of a Turn or Curve sign if the curve has a deflection angle of 270° or more.

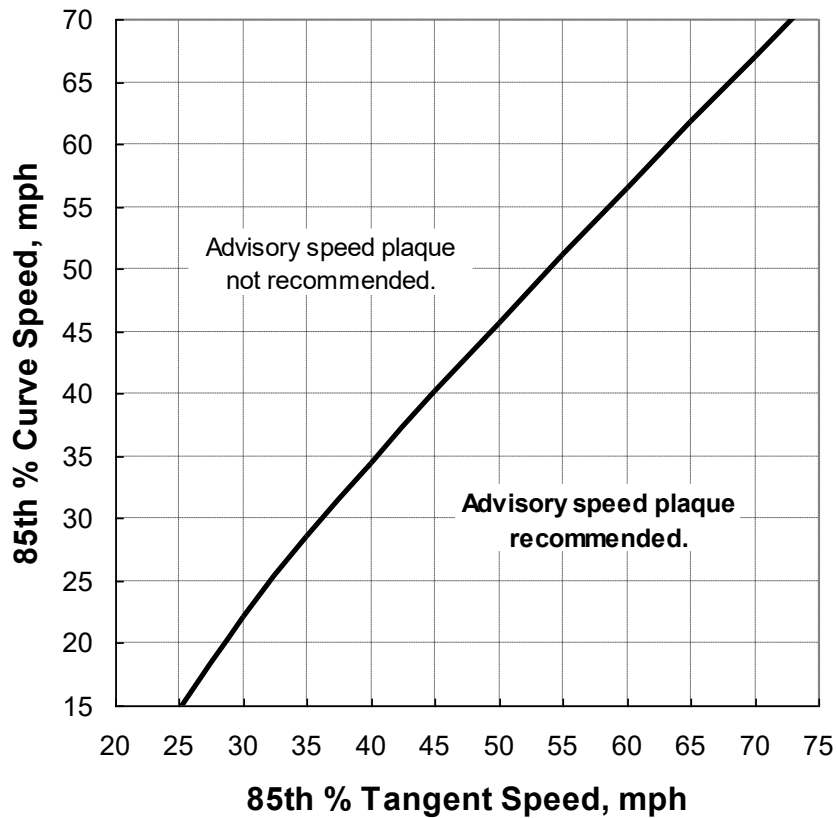


Figure 2. Guidelines for Determining the Need for an Advisory Speed Plaque (6).

Supplemental Sign Guidelines

Table 1 provides guidance on when to use Chevrons (W1-8) and the One-Direction Large Arrow (W1-6). The TMUTCD provides the following additional guidelines for these devices:

- Guidance: use either Chevrons or the One-Direction Large Arrow on the outside of a curve where the Hairpin Curve (W1-11) or 270-Degree Loop (W1-15) signs are used.
- Guidance: the approximate spacing of Chevrons is based on the advisory speed and the curve radius as provided in Table 2.
- Option: the One-Direction Large Arrow may be used as a supplement or alternative to Chevrons.
- Option: the One-Direction Large Arrow may be used to supplement a Turn (W1-1) or Reverse Turn (W1-3) sign.

Table 2. Chevron Spacing (3, Table 2C-6).

Advisory Speed, mph	Curve Radius, ft	Chevron Spacing, ft
≤ 15	< 200	40
20–30	200–400	80
35–45	401–700	120
50–60	701–1250	160
≥ 65	> 1250	200

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

Section 2C.10 of the TMUTCD provides the following guidelines for using the Combination Horizontal Alignment/Advisory Speed signs (W1-1a and W1-2a):

- A W1-1a or W1-2 a sign *may* be used as a *supplement* to an advance Horizontal Alignment sign and Advisory Speed Plaque at a curve.
- If a W1-1a or W1-2a sign is used, it *shall* be placed at the beginning of the turn or curve, and the advisory speed displayed on the sign *should* be based on the advisory speed for the curve using recommended engineering study methods.

Pavement Markings

Chapter 3B of the TMUTCD provides guidelines for the use of pavement markings. The following provisions are applicable specifically to curves:

- Section 3B.12: in general, the spacing for retroreflective raised pavement markers should be $2N$, where N equals the length of one broken line segment plus the gap between segments. However, on sharp curves, the spacing of the markers may be reduced to N .
- Section 3B.13: to improve the visibility of a curve, the centerline may be supplemented with raised pavement markers along the entire length of the curve plus a distance of about 5 seconds of travel time upstream of the curve.
- Section 3B.22: speed reduction markings (see Figure 3) may be used in advance of an unexpected, unexpectedly-severe curve. This treatment shall not be used unless the curve has a full set of longitudinal lines (centerline, lane lines, and edgelines as needed).

Delineation Devices

Chapter 3F of the TMUTCD provides guidelines for using delineators. The chapter states that delineators provide the benefit of clarifying horizontal alignment and will remain visible even when the pavement surface is wet or covered with snow.

Section 3F.03 states that the color of delineators shall comply with the color requirements for edgelines. For curves, this color will be white in most cases, but yellow for delineators located in the median of a divided highway.

Section 3F.04 states that if delineators are used on a curve, they should be spaced on the approaches and inside the curve such that several delineators are always visible to the motorist. TMUTCD Table 3F-1 provides guidance on delineator spacing. This table is repeated as Table 3.

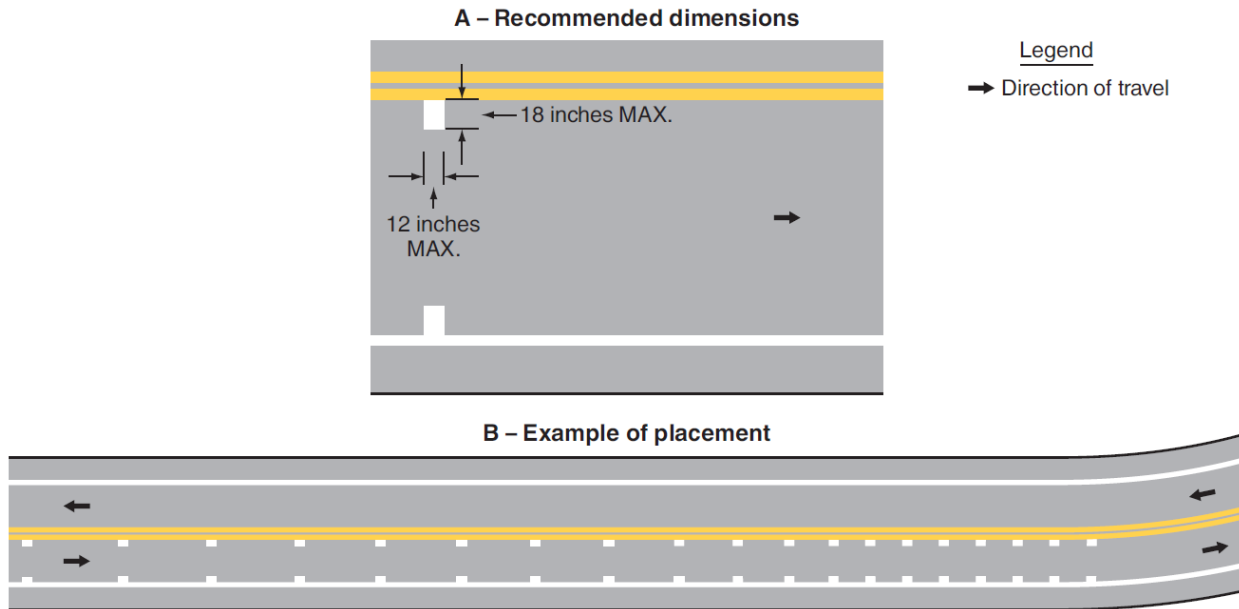


Figure 3. Example Application of Speed Reduction Markings (3, Figure 3B-28).

Table 3. Approximate Delineator Spacing on Horizontal Curves (3, Table 3F-1).

Degree of Curve	Radius, ft	Spacing in Curve, ft	Spacing on Tangents, ft
1	5730	225	450
2	2865	160	320
3	1910	130	260
4	1433	110	220
5	1146	100	200
6	955	90	180
7	819	85	170
8	716	75	150
9	637	75	150
10	573	70	140
11	521	65	130
12	478	60	120
13	441	60	120
14	409	55	110
15	382	55	110
16	358	55	110
19	302	50	100
23	249	40	80
29	198	35	70
38	151	30	60
57	101	20	40

Note: curve delineator applications on the approach and departure tangent should include three delineators spaced at the specified tangent spacing.

ALTERNATIVE GUIDELINES FOR SELECTING DEVICES

The alternative guidelines from TxDOT research project 0-5439 (4) are based on the concepts of side friction and kinetic energy differentials, as estimated using the curve speed models developed in the project. These guidelines provide different levels of curve severity (ranging from A for gradual curves to E for severe curves) and call for more devices for curves in higher severity categories. Curve severity is determined by computing the 85th-percentile passenger car speeds on the approach tangent and the midpoint of the curve using the contour plot in Figure 4, and then choosing devices based on the severity category as shown in Table 4.

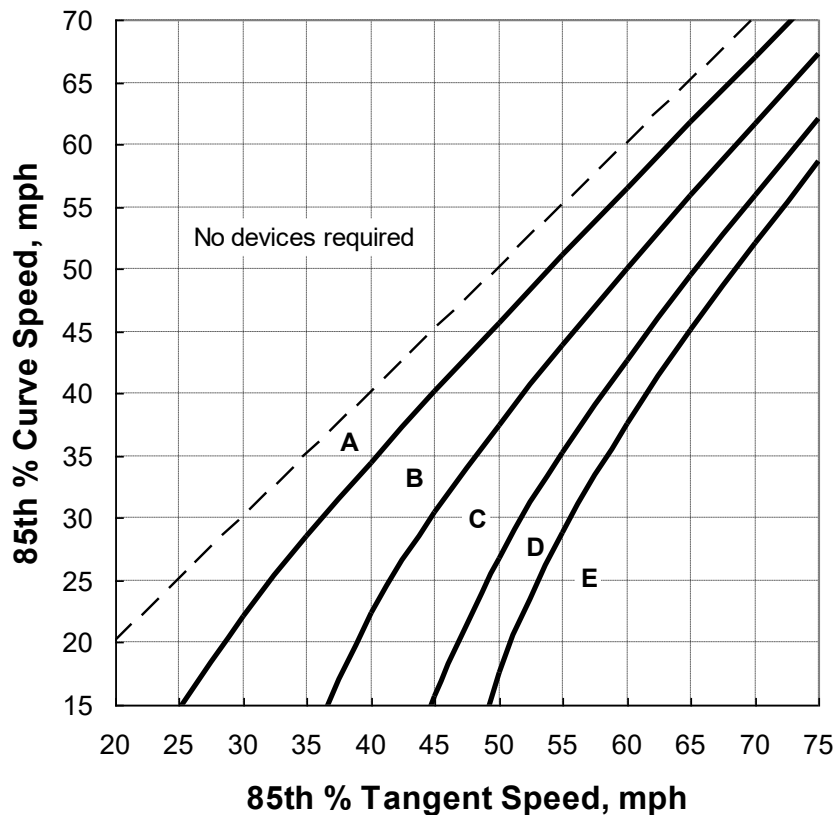


Figure 4. Alternative Guidelines for Choosing Curve Traffic Control Devices (4).

Table 4. Alternative Guidelines for Choosing Curve Traffic Control Devices (4).

Advisory Speed, mph	Device Type	Device Name	Device Number	Curve Severity Category ^a				
				A	B	C	D	E
35 mph or more	Warning Signs	Curve, Reverse Curve, Winding Road, Hairpin Curve ^b	W1-2, W1-4, W1-5, W1-11	✓	✓	✓	✓	✓
		Advisory Speed Plaque	W13-1P		✓	✓	✓	✓
		Combination Curve/ Advisory Speed	W1-2a			✓	✓	✓
		Chevrons ^c	W1-8				✓	✓
30 mph or less	Warning Signs	Turn, Reverse Turn, Winding Road, Hairpin Curve ^b	W1-1, W1-3, W1-5, W1-11	✓	✓	✓	✓	✓
		Advisory Speed Plaque	W13-1P		✓	✓	✓	✓
		Combination Turn/ Advisory Speed	W1-1a			✓	✓	✓
		One-Direction Large Arrow ^c	W1-6, W1-9T				✓	✓
Any	Delineation Devices	Raised Pavement Markers ^d		✓	✓	✓	✓	✓
		Delineators ^e				✓	✓	✓
	Special Treatments ^f						✓	

^a ✓: optional; ✓: recommended.

^b Use the Curve, Reverse Curve, Turn, Reverse Turn, or Winding Road sign if the deflection angle is less than 135°. Use the Hairpin Curve sign if the deflection angle is 135° or more.

^c A One-Direction Large Arrow sign may be used on curves where roadside obstacles prevent the installation of chevrons, or as a supplement to Chevrons or a Turn or Reverse Turn sign.

^d Raised pavement markers are optional in northern regions that experience frequent snowfall.

^e Delineators do not need to be used if Chevrons are used.

^f Special treatments could include oversize advance warning signs, flashers added to advance warning signs, wider edgelines, profiled pavement markings, and speed reduction markings.

CHAPTER 3. ENGINEERING STUDY METHODS FOR SETTING CURVE ADVISORY SPEED

BACKGROUND

Section 2C.08 of the TMUTCD states that advisory speeds shall be determined by an engineering study (3), and further specifies the methods outlined in TxDOT's *Procedures for Establishing Speed Zones* (6) as established practices for conducting engineering studies. These methods include the GPS Method, the Compass Method, the Direct Method, and the Design Method. They were originally documented by Bonneson et al. (5) and are described in the following sections.

GPS METHOD

The GPS 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 then becomes the basis for establishing the advisory speed.

The procedure for implementing the GPS Method consists of three steps. During the first step, measurements are taken in the field while 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 a field trial run. Each of these steps is described in the remainder of this section.

To ensure reasonable accuracy in the model estimates using this method, the total curve deflection angle should be 6° or more. A curve with a smaller deflection angle will rarely justify curve warning signs or an advisory speed plaque.

Equipment

The equipment used includes the following:

- GPS receiver.
- Electronic BBI (optional).
- Barometer (optional).
- Laptop computer.

The GPS receiver is used to estimate curve radius and deflection angle. The electronic BBI is optional and is used to estimate superelevation rate. If an electronic BBI is not used, then superelevation rate will need to be estimated using other means. The barometer is optional and is used to estimate roadway grade. If a barometer is not used, then roadway grade can also be estimated using GPS data. Though a measurement of roadway grade is not required to set advisory speeds or select curve traffic control devices, it is used in other curve safety analysis calculations. Hence, measurement of roadway grade is incorporated into the GPS Method.

The computer is used to run the TRAMS program. This program is designed to monitor the GPS receiver, the electronic BBI, and the barometer while the test vehicle is driven along the

curve. Advisory speed and traffic control device selection guidelines can be determined using the radius and superelevation rate estimates with the TCES spreadsheet program.

Procedure

Step 1: Field Measurements

Before beginning a test run, enter the highway name, test run number, roadway type, and regulatory speed limit in their respective fields provided on the main panel.

Repeat the measurements for the opposing direction of travel if the road is divided or if conditions suggest the need for separate consideration of each curve travel direction. When two or more curves are separated by a tangent of 600 ft or less, one sign should apply for all curves.

Speed Limit. If the 85th-percentile tangent speed is not known, note the regulatory speed limit on the roadway where the curve is located. The speed limit can subsequently be used in TCES to estimate the 85th-percentile tangent speed.

Test Run Speed. The following rules-of-thumb should be considered when selecting the test run speed:

- The test run speed through each curve should be at least 10 mph below the existing curve advisory speed, provided that the resulting test run speed is not less than 15 mph.
- If superelevation rate is being measured, test runs should be conducted at 45 mph or less, with slower speeds considered desirable in terms of yielding more accurate estimates of superelevation.
- The test run speed should never drop below 8 mph. TCES is programmed to ignore data collected at speeds below this minimum threshold as they likely represent parking or turning maneuvers rather than normal traversal of highway segments.

In general, a slower test run speed will improve accuracy in measurement by minimizing tire slip and test vehicle suspension bounce and allowing the driver to track the curve accurately.

Measurement Procedure. The following task sequence describes the field measurement procedure as it would be used to evaluate one direction of travel on the subject roadway:

- a. When the test vehicle is 1 or 2 s travel time in advance of the beginning of the first curve, press the space bar or click the large button on the TRAMS main panel. This action will start the data collection process. Precise location of the beginning of the curve is not required. A reasonable estimate of its location, based on the analyst's judgment, will suffice.
- b. While driving along the roadway, track the centerline as carefully as possible. This process will provide an accurate survey of the intended travel path. The analyst should avoid cutting the corner of sharp curves. The analyst should also avoid letting the vehicle drift to the outside of the lane while traveling along the curve.
- c. When the test vehicle is 1 or 2 s travel time beyond the end of the last curve, press the space bar or click the large button a second time to stop recording data. Precise location

of the end of the curve is not required. A reasonable estimate of its location, based on the analyst's judgment, will suffice.

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.

Step 2: Determine Advisory Speed

Use the TCES spreadsheet program to analyze the data stream from the completed test run. Procedures for using TCES are described in Chapter 6 of this *Handbook*.

Step 3: Confirm Speed for Conditions

During this step, the appropriateness of the advisory speeds determined for each curve in Step 2 and the need for other curve traffic control devices is evaluated. As an initial task, the need for an Advisory Speed plaque is checked. The guidelines in Chapter 2 are used to determine the need for an Advisory Speed plaque and other curve traffic control devices.

If the 85th-percentile tangent speed exceeds the speed limit by a large amount, then it is possible to find that the advisory speed from Step 2 also exceeds the speed limit. In this situation, the disparity between the speed limit and 85th-percentile tangent speed should be addressed and in no instance should the posted advisory speed exceed the speed limit.

A second task involves a field evaluation of curve conditions. The evaluation includes consideration of the following factors:

- Driver approach sight distance to the beginning of the curve.
- Visibility around the curve.
- Unexpected geometric features within the curve.
- Position of the most critical curve in a sequence of closely spaced curves.

The unexpected geometric features noted in the third bullet may 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.
- Broken-back curves.

A final task involves 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 warning sign layout based on consideration of the aforementioned factors. The advisory speed for one direction of travel through the curve may differ from that for the other direction.

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 advisory speed. The procedure for implementing the Compass Method is based on heading and curve length measurements taken at the critical portion of the curve. 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 5. 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.

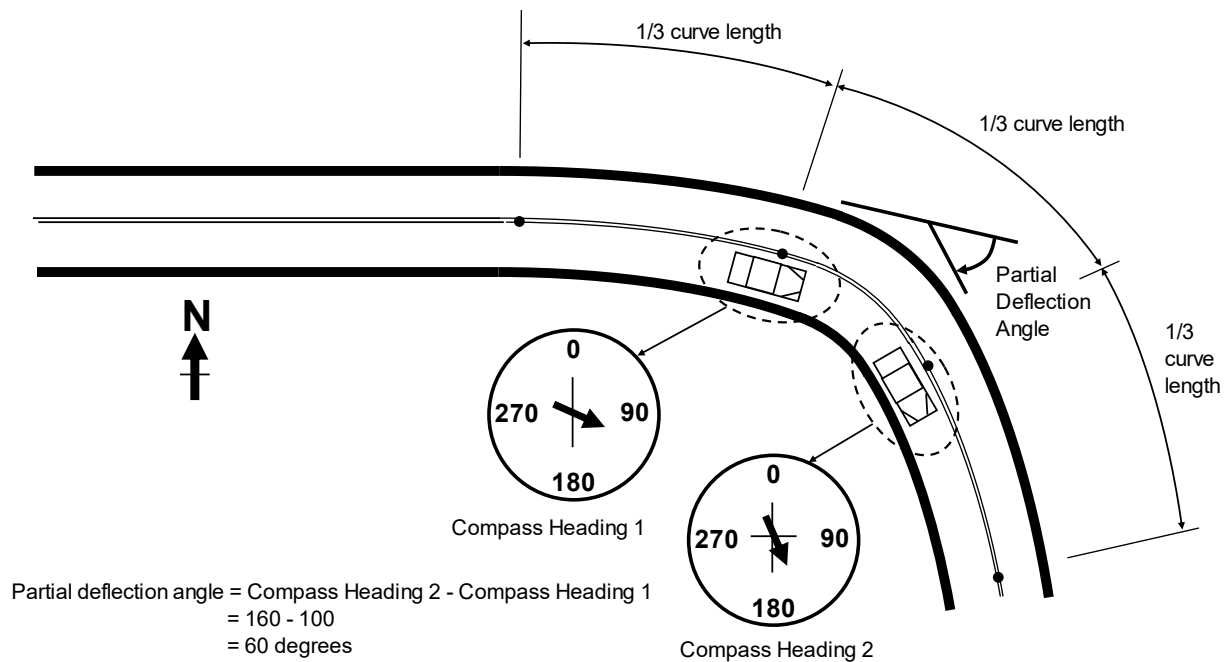


Figure 5. Location of Critical Portion of Curve.

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.”

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 a field trial run. Each of these steps is described in more detail in the next three sections.

To ensure 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 12° or more, and the partial curve deflection angle should be 4° or more. A curve with a deflection angle less than 12° 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.
- 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 using 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.

Repeat the measurements for the opposing direction of travel if the road is divided or if conditions suggest the need for separate consideration of each curve travel direction. When two or more curves are separated by a tangent of 600 ft or less, one sign should apply for all curves. However, each curve should be surveyed separately in this step.

Equipment Setup

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

- Digital compass.
- Distance-measuring instrument (DMI).
- 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° (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 BBI 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° 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 BBI should be firmly mounted so that it cannot move while the test vehicle is in motion.

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

1. Inflate all tires to a pressure that is consistent with the vehicle manufacturer's specification.
2. Calibrate the test vehicle's DMI.
3. Calibrate the BBI.

The instruction manual for the DMI and the BBI should be consulted for specific details of the calibration process.

Measurement Procedure

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. The following task sequence describes the field measurement procedure as it would be used to evaluate one direction of travel through the subject curve:

1. Record the regulatory speed limit and the curve advisory speed.
2. Stay in the same lane for all measurements. 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.
3. Advance the vehicle to the 1/3 point, as shown in Figure 5. 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° reading.

4. Advance the vehicle to the 2/3 point, as shown in Figure 5. 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, it 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.

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 TCD worksheet of the TCES software. Procedures for using TCES are described in Chapter 6 of this *Handbook*.

When two or more curves are separated by a tangent of 600 ft or less, one sign should apply for all curves. However, each curve should be evaluated separately in this step. The Advisory Speed plaque should show the value for the curve having the lowest advisory speed in the series.

For undivided roadways, if an advisory speed is determined to be needed for one curve travel direction but not for the opposite curve travel direction, then both directions of the curve should be posted with the advisory speed determined for the one direction.

Step 3: Confirm Speed for Conditions

During this step, the appropriateness of the advisory speed determined in Step 2 and the need for other curve warning signs is evaluated. The activities conducted during this step are the same as those discussed in Step 3 of the GPS Method.

DIRECT METHOD

The Direct Method is based on the field measurement of vehicle speeds on the subject curve. The procedure for implementing the Direct Method consists of three steps. During the first step, speed 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 a field trial run. Each of these steps is described in the remainder of this section.

Step 1: Field Measurements

Measure the speed of free-flowing passenger cars at about the middle of the curve in one direction of travel. 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. If a radar speed meter is used, then data collection can be discontinued after the speed of 125 cars has been measured or two hours have elapsed, whichever occurs first. If a traffic counter/classifier is used, then data collection can be discontinued after the speed of 125 cars has been measured or four hours have elapsed, whichever occurs first.

Repeat the measurements for the opposing direction of travel if the road is divided or if conditions suggest the need for separate consideration of each curve travel direction. When two or more curves are separated by a tangent of 600 ft or less, one sign should apply for all curves. However, each curve should be surveyed separately in this step.

Compute the arithmetic average of the measured speeds for each direction of travel at each curve studied. Also, compute the 85th percentile speed for each direction and curve.

Step 2: Determine Advisory Speed

Multiply each of the average speeds from Step 1 by the appropriate ratio from Table 5 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.

Table 5. Ratio of Average Truck Speed to Average Passenger Car Speed.

Roadway Configuration	Regulatory Speed Limit, mph	Ratio
Two-lane undivided (2U)	≤ 70	0.97
Two-lane undivided (2U)	75	0.95
Four-lane undivided (4U)	Any	0.95
Four-lane divided (4D)	Any	0.95
Four-lane freeway (4F)	Any	0.95

When two or more curves are separated by a tangent of 600 ft or less, one sign should apply for all curves. However, each curve should be evaluated separately in this step. The Advisory Speed plaque should show the value for the curve having the lowest advisory speed in the series.

For undivided roadways, if an advisory speed is determined to be needed for one curve travel direction but not for the opposite curve travel direction, then both directions of the curve should be posted with the advisory speed determined for the one direction.

Step 3: Confirm Speed for Conditions

During this step, the appropriateness of the advisory speed determined in Step 2 and the need for other curve warning signs is evaluated. The activities conducted during this step are the same as those discussed in Step 3 of the GPS Method.

DESIGN METHOD

The Design Method is based on the use of curve geometry data obtained from files or as-built plans. This method is suitable for evaluating newly constructed or reconstructed curves because the data are available from construction plans.

The procedure for implementing the Design Method consists of three steps. During the first step, curve geometry data are obtained from files or plans. During the second step, the measurements are used to compute the advisory speed. During the last step, the recommended advisory speed is confirmed through a field trial run, if or when the curve exists. Each of these steps is described in the remainder of this section.

Step 1: Obtain Curve Geometry

Consult the appropriate files to obtain the radius, deflection angle, and superelevation rate for the curve. If the curve is circular, the total curve deflection angle is equivalent to the curve deflection angle, as used in TCES. The total curve deflection angle equals the deflection angle in the two intersecting tangents.

If spiral transition curves are included in the design, obtain the radius and superelevation rate data for the central circular curve. The total curve deflection angle is the same as defined in the previous paragraph. The curve deflection angle represents the deflection angle of the central circular curve, defined previously as the partial deflection angle.

If compound curvature is used in the design, obtain the radius and superelevation rate data for the sharpest component curve. The total curve deflection angle is the same as defined in the first paragraph. The curve deflection angle represents the deflection angle of the sharpest component curve.

Obtain the aforementioned data for both directions of travel if the road is divided or if conditions suggest the need for separate consideration of each curve travel direction. When two or more curves are separated by a tangent of 600 ft or less, one sign should apply for all curves. However, data for each curve should be obtained in this step.

Step 2: Determine Advisory Speed

The geometric data obtained in Step 1 are entered into the Design Data columns (shaded light green) in the List worksheet in TCES. If a reasonable estimate of the 85th-percentile tangent speed is not available, the speed limit can be used in the List worksheet to estimate the 85th-percentile tangent speed. Note: the drop-down list at the top of the spreadsheet should be set to “Known curve geometry.”

When two or more curves are separated by a tangent of 600 ft or less, one sign should apply for all curves. However, each curve should be evaluated separately in this step. The Advisory Speed plaque should show the value for the curve having the lowest advisory speed in the series.

For undivided roadways, if an advisory speed is determined to be needed for one curve travel direction but not for the opposite curve travel direction, then both directions of the curve should be posted with the advisory speed determined for the one direction.

Step 3: Confirm Speed for Conditions

During this step, the appropriateness of the advisory speed determined in Step 2 and the need for other curve warning signs is evaluated. The activities conducted during this step are the same as those discussed in Step 3 of the GPS Method.

CHAPTER 4. BENEFIT-COST ANALYSIS FOR CURVE PAVEMENT FRICTION TREATMENTS

BACKGROUND

The safety performance of a horizontal curve is influenced by various factors, including curve geometry, pavement friction, and vehicle speed. Though drivers generally reduce to a safe speed by the time they arrive at the middle of a curve, they often misjudge the sharpness of the curve before entering it and are compelled to decelerate or make correcting maneuvers while in the curve. Excessive deceleration or braking on a curve can lead to a sliding failure of the tire-pavement interface and result in a crash.

One method to improve curve safety performance is to apply a pavement friction treatment. A pavement friction treatment can consist of special materials like calcined bauxite, which is used in a high-friction surface treatment (HFST), or more conventional materials like hot-mix asphalt (HMA) if applied to increase pavement friction. Repaving usually increases pavement skid resistance, but the time duration of the increase depends on the selected treatment, as different materials deteriorate at different rates. A benefit-cost analysis, combined with a service life estimate, allows the expected life-cycle benefit of the proposed treatment to be compared with the cost of the treatment.

The margin of safety analysis framework provides a good method for evaluating curve safety as a function of geometry and pavement friction. Margin of safety is defined as the side friction supply minus the side friction demand. Because vehicle speeds and the superelevation rate change along the length of a curve, it is necessary to evaluate the margin of safety along the entire length of the curve. This type of analysis requires estimation of vehicle speed at key points along the curve length, such as the point of curvature (PC), the midpoint of curve (MC), and the point of tangency (PT). Furthermore, consideration must be given to the occurrence of correcting maneuvers, which are associated with side friction demands well in excess of demands incurred by vehicles tracking the curve with geometric exactness.

This chapter describes the calculation methods used to conduct a benefit-cost analysis for a proposed curve pavement friction treatment and a supplemental margin-of-safety analysis. These methods have been previously described in TxDOT research reports 0-6714-1 and 0-6932-R1 (2, 7). They can be applied by using the Pavement worksheet of the TCES spreadsheet program, as described in Chapter 6 of this *Handbook*.

CALCULATION METHODS

This section describes the calculation methods used to evaluate pavement friction treatments. Specifically, the methods used to compute margin of safety, crash prediction, treatment life span, and life-cycle cost are detailed in the following subsections.

Margin of Safety Analysis

A detailed margin of safety analysis requires knowledge of the side friction supply and the side friction demand. These quantities are influenced by curve geometry, pavement characteristics, and vehicle speeds. Development of the margin-of-safety calculations is described in detail in Chapter 5 of TxDOT research report 0-6714-1 (2). The margin-of-safety concept is summarized by the following equations:

$$M.S = f_s - f_D \quad (1)$$

$$f_s = f(SK) \quad (2)$$

$$f_D = \frac{v^2}{gR_p} \cos\left(\frac{e}{100}\right) - \sin\left(\frac{e}{100}\right) \cos G \quad (3)$$

where:

- $M.S.$ = margin of safety.
- f_s = side friction supply.
- f_D = side friction demand.
- SK = skid number.
- v = vehicle speed, ft/s.
- g = gravitational constant (= 32.2 ft/s²).
- R = curve radius, ft.
- e = superelevation rate, percent.
- G = vertical grade, ft/ft.

The margin of safety analysis framework is formulated to account for changes to skid number and superelevation rate between the before and after periods, consistent with the installation of a new pavement surface or an increase in superelevation.

The margin of safety is computed as the side friction demand subtracted from the side friction supply as shown in Equation 1. Glennon and Weaver (8) suggested that the margin of safety should be at least 0.08–0.12 along the entire length of the curve.

Crash Prediction

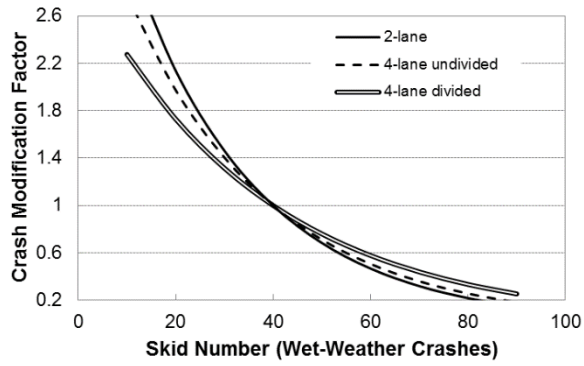
Predicted crash counts are obtained using the crash prediction models that were documented in Chapter 5 of TxDOT research report 0-6932-R1. The way the worksheet is formulated, the only crash modification factor (CMF) that would change based on the input data is the skid number CMF. Hence, the worksheet provides estimates of the predicted change in crash count (in percent) based on the change in skid number CMF that would result from the specified changes to skid number. The skid number used for the computation of this CMF is the skid number measured at 50 mph using a locked-wheel skid trailer with a smooth tire. The analyst may apply an empirical Bayes adjustment to the predicted crash count if desired. The evaluation framework uses the empirical Bayes methodology that Bonneson et al. described (9).

The analyst must provide a precipitation rate to apply the annual precipitation CMF. Table 6 provides precipitation rates for each TxDOT district. TxDOT research report contains a description of the procedure for deriving these precipitation rates and a more-detailed table of precipitation rates by Texas county (7).

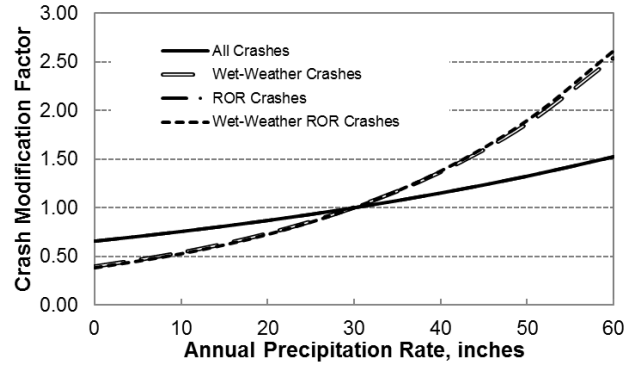
Table 6. Annual Average Precipitation by TxDOT District.

District (Number)	Annual Avg. Precipitation (in.)
Paris (1)	45.91
Fort Worth (2)	35.61
Wichita Falls (3)	31.95
Amarillo (4)	20.76
Lubbock (5)	20.19
Odessa (6)	14.67
San Angelo (7)	23.15
Abilene (8)	23.97
Waco (9)	34.99
Tyler (10)	46.65
Lufkin (11)	52.07
Houston (12)	49.04
Yoakum (13)	41.42
Austin (14)	33.68
San Antonio (15)	30.88
Corpus Christi (16)	32.84
Bryan (17)	42.45
Dallas (18)	39.44
Atlanta (19)	49.01
Beaumont (20)	58.33
Pharr (21)	24.91
Laredo (22)	22.7
Brownwood (23)	29.8
El Paso (24)	15.18
Childress (25)	24.49
All Districts	33.76

Figure 6 shows graphical representations of CMFs for skid number and annual precipitation rate. The trends indicate that crash frequency decreases with increasing skid number and increases with increasing precipitation. These two CMFs can be combined (i.e., multiplied) to obtain a qualitative ranking of curves based on their potential for wet-surface crash reduction. Pavement friction treatments are more likely to be cost-beneficial on curves with low skid resistance and/or high annual precipitation. The combined CMF calculation ($CMF_{sk|ap}$) forms the basis for the guidelines developed in TxDOT research project 0-6932 (10). Threshold values for $CMF_{sk|ap}$ are summarized in Table 7 and illustrated in Figure 7, Figure 8, and Figure 9.



a. Skid Number CMF



b. Annual Precipitation CMF

Figure 6. Skid Number and Annual Precipitation CMFs (7).

Table 7. Recommended Combined CMF Thresholds (10).

Description	Combined CMF Range by Roadway Type (Nomograph Caption)		
	2-Lane (Figure 7)	4-Lane Undivided (Figure 8)	4-Lane Divided (Figure 9)
Friction treatments will not likely yield cost-effective wet-weather crash reduction	$CMF_{sk ap} \leq 1$	$CMF_{sk ap} \leq 1$	$CMF_{sk ap} \leq 1$
Monitor the curve for elevated wet-weather crash frequency	$1 < CMF_{sk ap} \leq 2.5$	$1 < CMF_{sk ap} \leq 1.5$	$1 < CMF_{sk ap} \leq 1.5$
Conduct a detailed analysis to determine potential benefit of a friction treatment	$2.5 < CMF_{sk ap} \leq 4$	$1.5 < CMF_{sk ap} \leq 2$	$1.5 < CMF_{sk ap} \leq 2$
The curve is a high-priority location for a friction treatment	$CMF_{sk ap} > 4$	$CMF_{sk ap} > 2$	$CMF_{sk ap} > 2$

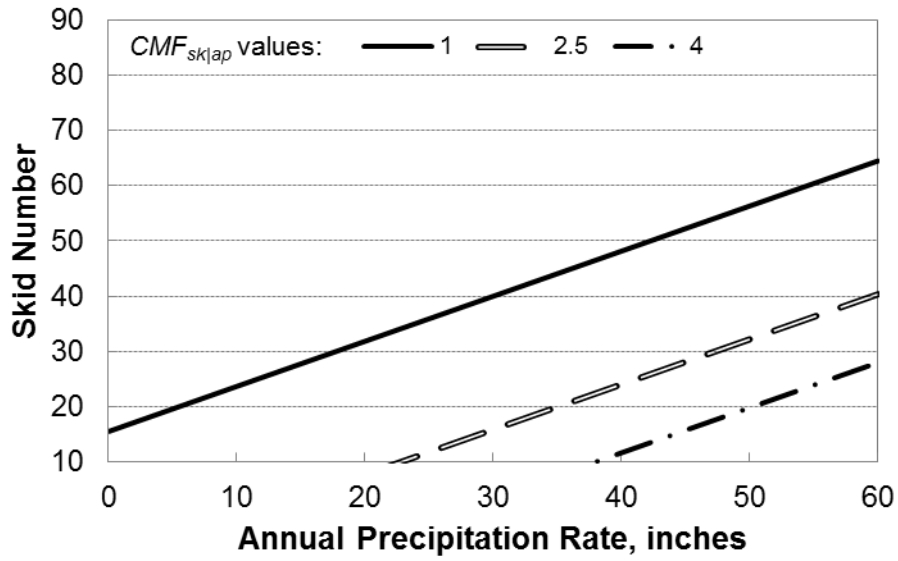


Figure 7. Combined Skid Number and Annual Precipitation Rate Nomograph for Two-Lane Highways.

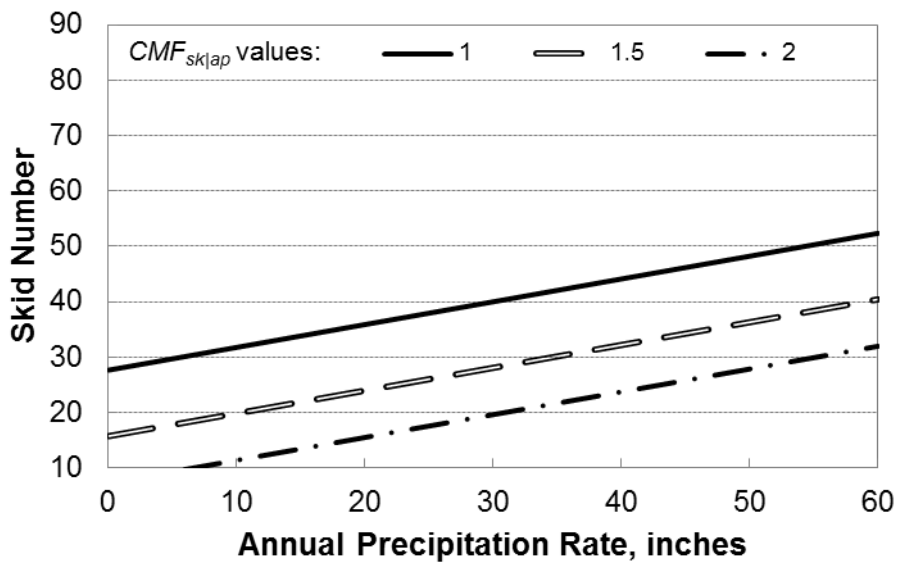


Figure 8. Combined Skid Number and Annual Precipitation Rate Nomograph for Four-Lane Undivided Highways.

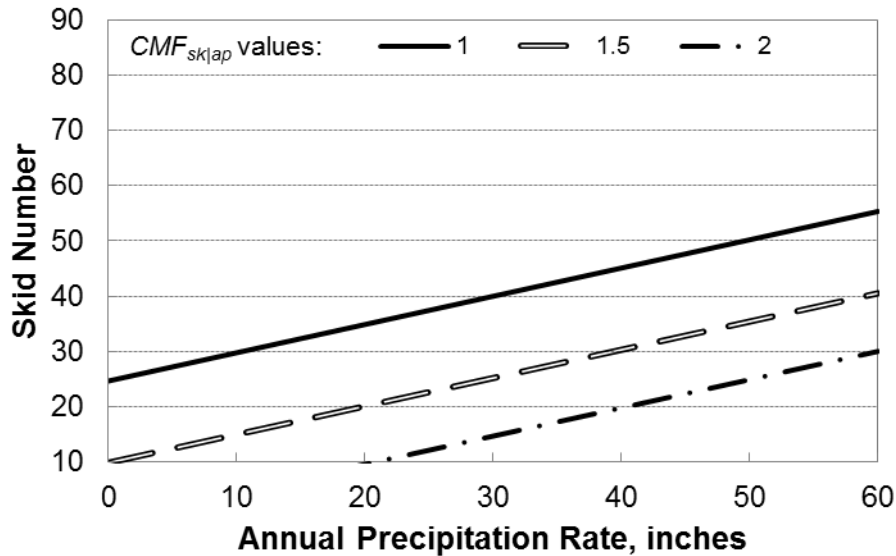


Figure 9. Combined Skid Number and Annual Precipitation Rate Nomograph for Four-Lane Divided Highways.

Pavement Service Life

The service life for a pavement friction treatment is computed based on the following key quantities:

- Initial skid number (immediately after installation).
- Rate of change of skid number.
- Terminal skid number.

The evaluation framework includes these quantities for the following treatment options:

- Seal coat (or chip seal).
- Hot-mix asphalt (HMA).
- Permeable friction course (PFC).
- High-friction surface treatment (HFST).

The derivation of the initial and terminal skid numbers and rates of change for the treatments is described in detail in Chapter 4 of TxDOT research report 0-6932-R1. Table 8 provides key parameters to describe initial and terminal skid number (SK_{50S}), decay rate, and life span for the various treatment options.

Table 8. Predicted Skid Numbers for Typical Treatments.

Treatment Type		Aggregate Type	Skid Number (<i>SK</i> _{50S})		Exponential Decay Rate (<i>SK</i> /yr)	Years to Terminal	
			Initial	Terminal		Urban	Rural
AC Overlay	Type C (DG, SP)	Limestone	35	35	0.11	3	6
		Sandstone	40	35	0.10	3	6
		Gravel (Siliceous)	37	32	0.13	2	5
		Igneous	43	37	0.05	7	14
	SMA (Type D, Type C)	Limestone	40	34	0.11	3	6
		Sandstone	41	36	0.10	3	6
		Gravel (Siliceous)	44	39	0.13	2	5
		Igneous	43	37	0.05	7	14
	TOM, CMHB-F	Limestone	40	34	0.11	3	6
		Sandstone	40	34	0.10	3	6
		Gravel (Siliceous)	36	31	0.13	2	5
		Igneous	34	28	0.05	7	14
	PFC	Limestone	44	39	0.11	3	6
		Sandstone	41	36	0.10	3	6
		Gravel (Siliceous)	41	35	0.13	2	5
		Igneous	39	33	0.05	7	14
Seal Coat	Gr. 3, Gr. 4, Gr. 5	Lightweight	78	53	0.09	7	13
		Limestone	67	42	0.08	7	15
		Sandstone	56	30	0.11	6	11
		Gravel (Siliceous)	55	30	0.04	16	32
		Igneous	47	22	0.14	4	9
HFST		Calcined Bauxite	73	58	1.67	0.3	0.6
		Flint	65	55	0.76	0.6	1.2

Benefit-Cost Analysis

The benefit-cost analysis compares the expected cost to implement one of the pavement treatment products to the benefit of reducing crashes over the life of the treatment. Table 9 gives costs for various treatments. The HFST and seal coat costs come from the literature. The asphalt overlay costs come from asphalt production data from TxDOT for the year 2015.

Table 9. Unit Cost for Various Pavement Treatments.

Treatment Type	Thickness (inches)	Approximate Unit Cost	
		\$/ton	\$/yd ²
HFST	Not applicable	NA	19–25
Seal Coat	Not applicable	NA	2.50
Asphalt Overlay			
Dense Graded	1.5–2.0	79	6.50–8.75
Super Pave	1.5–2.0	86	7.25–9.75
Stone Matrix Asphalt	1.5–2.0	105	7.25–8.75
Thin Overlay Mix	1.0–1.25	116	6.50–8
Permeable Friction Course (SAC A)	1.5	110	9

To compute a benefit-cost ratio for a proposed curve pavement treatment, the following steps are required:

1. Estimate the fatal-and-injury crash frequency of the curve for a time period before the treatment is implemented. This estimated crash frequency is based on the curve's characteristics, particularly its skid number, in the before period.
2. Identify a proposed pavement treatment and determine the increase in skid number that can be obtained from the treatment.
3. Estimate the fatal-and-injury crash frequency of the curve for a time period after the treatment is implemented. The crash frequency will change between the before and after periods due to the change in skid number, but no other variables (and hence no other CMF values) will change. This crash frequency can be improved using the empirical Bayes adjustment (9) if actual crash data are available for the before period.
4. Compute the reduction in fatal-and-injury crashes between the before and after periods.
5. Using default crash severity distribution proportions, compute the number of property-damage-only (PDO) crashes in both time periods and the reduction in these crashes between the time periods.
6. Using crash cost values for all severity levels (K [fatal], A [incapacitating injury], B [non-incapacitating injury], C [possible injury], and PDO), compute the treatment benefit in terms of crash costs reduced following installation of the treatment.
7. Compute the proposed treatment cost.
8. Compute the benefit-cost ratio by dividing the benefit obtained in step 6 by the cost obtained in step 7.

CHAPTER 5. USER GUIDE: TEXAS ROADWAY ANALYSIS AND MEASUREMENT SOFTWARE (TRAMS)

BACKGROUND

The TRAMS program is an executable program that monitors and archives data streams from a GPS receiver, an electronic BBI, and a barometer. The GPS receiver is required, but the BBI and barometer are optional. The program was originally developed in TxDOT implementation project 5-5439 (5) and was updated in TxDOT research project 0-6960. This chapter documents procedures for using TRAMS.

EQUIPMENT REQUIREMENTS

GPS Receiver

The TRAMS program uses a GPS receiver to measure the speed, horizontal position, and elevation of the test vehicle. Any GPS receiver can be used provided it meets the following requirements:

- The GPS receiver provides data updates at a rate of 5 Hz or higher.
- The GPS receiver complies with the National Marine Electronics Association 0183 interface standard for RMC data sentences.
- The GPS receiver is configured to provide both RMC and GGA data sentences.

GPS receivers typically have a software driver that needs to be installed on the computer and may also have companion software or a web interface that is needed to configure the device (such as to activate the GGA data sentences or to adjust the data update rate).

Electronic Ball-Bank Indicator

The TRAMS program uses a BBI to measure the test vehicle's roll angle, which is then used to compute a ball-bank reading and estimate superelevation rate. This device is optional; if it is not used, the analyst must provide a measure of superelevation rate from another source, such as as-built plan sets or a field measurement of the superelevation rate using a smart level.

The BBI used in the development of TRAMS was the Rieker RDS7-BB-C Digital Ball-Banking Indicator (or Inclinometer). Any BBI can be used as long as it has a digital output data stream that matches that of the Rieker product and a data port that can connect to a computer.

The data port on the Rieker RDS7-BB-C Digital Ball-Banking Indicator is a serial port. Rieker makes a serial cable with a 12-volt power connection that must be used to connect the BBI to the laptop computer. A serial-USB adapter is needed to convert the serial data stream to a USB data stream if the computer does not have a serial port. Any serial-USB adaptor can be used for this purpose.

Barometer

The TRAMS program uses a barometer to obtain elevation measurements for the test vehicle, which are then used to compute roadway grade. This device is optional; if it is not used, the GGA data sentence from the GPS receiver can also be used to compute roadway grade. If used, the barometer must be configured to stream elevation data in real time.

SOFTWARE INSTALLATION

The following activities must be completed before TRAMS can be used on the computer:

- Install the driver for the GPS receiver.
- If the BBI is used, an adapter may be needed to convert its RS-232 connection to a USB connection. Install the driver for this adapter.
- If the barometer is used, install any drivers that are needed for the device.
- Install TRAMS (a copy of TCES will also be installed in the TRAMS file directory).

To install TRAMS, copy the entire “TRAMS” zipped folder to the computer’s hard drive and run the “setup.exe” file. This file will be in the “DISK1” folder. When this file is run, the message shown in Figure 10 will appear.



Figure 10. TRAMS Installation Message.

Click the “Next >” button and see the screen where the destination folder for installation will be specified. To avoid file-access errors, it is important to install TRAMS in a location where the program will not be tied to specific users. The following three locations are recommended for installation:

- C:\Users\Public\TRAMS\
- C:\ProgramData\TRAMS\
- C:\TRAMS\

The first option (C:\Users\Public\TRAMS\)) is the default destination folder used by the installer program. To install in a different location, click the “Change” button to access the screen where the destination can be specified. Figure 11 illustrates this step.

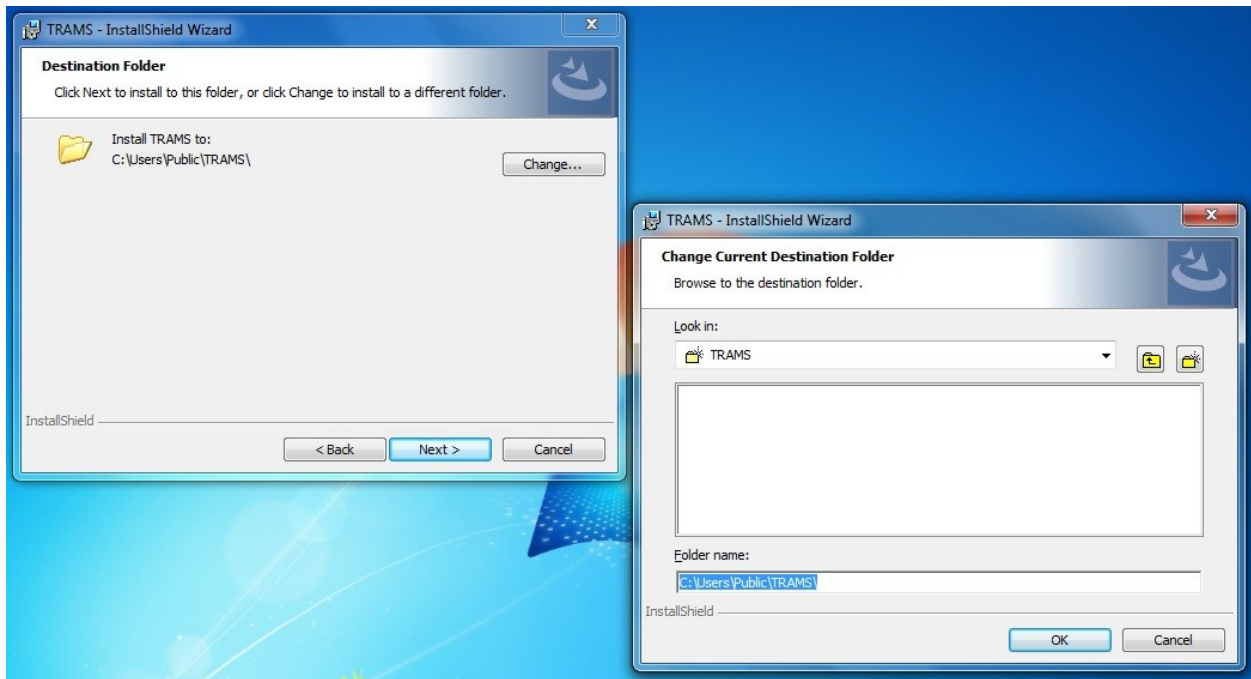


Figure 11. TRAMS Destination Folder Location.

Do not install TRAMS in the “C:\Program Files” or “C:\Program Files (x86)” folders. Programs installed in these locations will be tied to the user who installed the program, and users who log into the computer with a different name will have difficulty accessing TRAMS data files.

After specifying the destination folder, click “OK” and “Next >” to continue the installation. Click “Ignore” if any warning messages appear during installation. When the installation process is complete, the message shown in Figure 12 will appear and the program will be ready for use.

EQUIPMENT SETUP

The following activities must be completed prior to using the measurement devices with the TRAMS program:

- Mount the GPS receiver, BBI (if used), and barometer (if used) on the dashboard in a fixed position. These devices should not be able to move during the test runs. It is especially important to secure the GPS receiver, as it will generate spurious readings of curvature if it is allowed to slide on the dashboard.
- If the BBI is used, activate its auto leveling feature with the test vehicle parked on level pavement. Do this under the same vehicle loading and tire inflation conditions that will be present during the test runs.
- Verify that all measurement devices are active and connect them to the laptop computer.

- If the devices have not previously been used with the laptop computer, use the Device Manager feature in Windows to obtain the COM port numbers assigned to each device. If the devices are properly connected to the computer, their COM port numbers should be specified in the “Ports (COM & LPT)” list (see Figure 13).

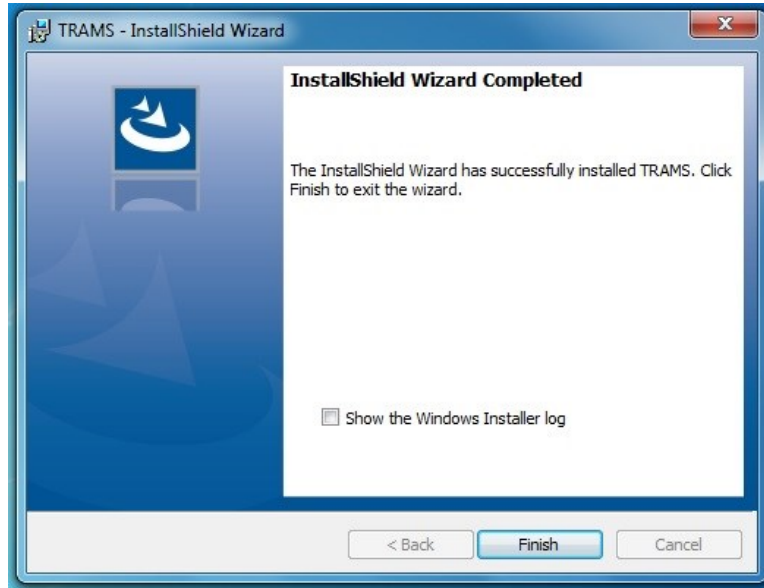


Figure 12. TRAMS Installation Complete Message.

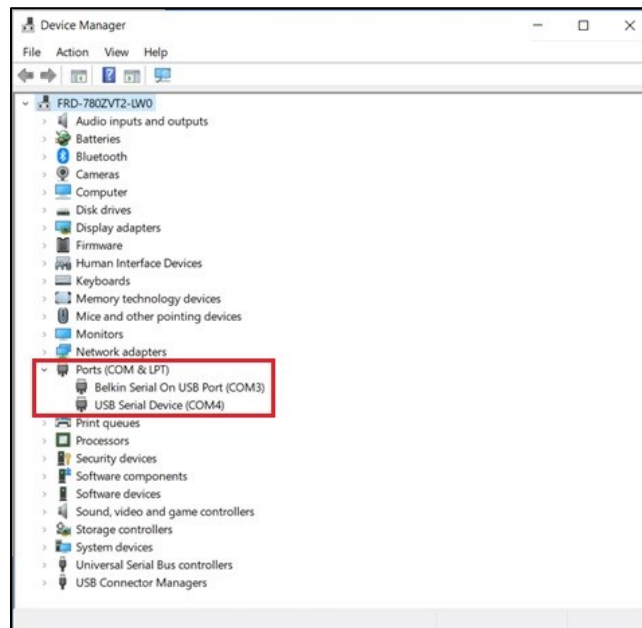


Figure 13. COM Port Number List in Device Manager.

TRAMS PROGRAM DESCRIPTION

Figure 14 shows a screenshot of the main TRAMS screen as it would be used in typical applications. The various features of the program are described in the following paragraphs.

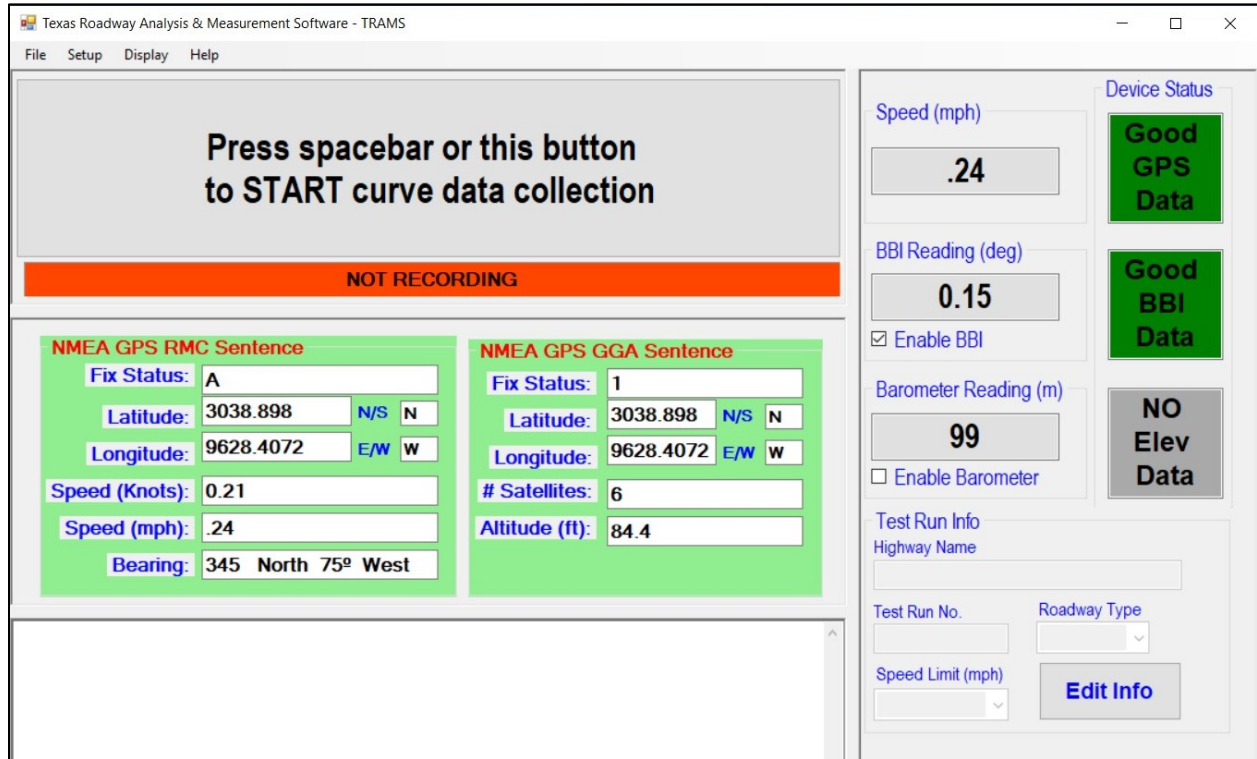


Figure 14. Main TRAMS Screen.

Device Status

The right side of the main screen contains several features to display the status of the data collection devices:

- Three colored squares provide a quick visual check to indicate if the device is providing good data (green), failing to provide data (red), or turned off (gray).
- If the GPS receiver is working and properly connected to the computer, the test vehicle speed will be displayed. Otherwise, a speed of 0 mph will be displayed.
- If the BBI is working and properly connected to the computer, the BBI reading will be displayed. Otherwise, a reading of 0.0° will be displayed.
- If the barometer is working and properly connected to the computer, the barometer's elevation reading will be displayed. Otherwise, an elevation of 99 m will be displayed.

The left side of the screen contains a box that provides details from the GPS data sentences. This feature shows several key data elements from the RMC sentence (satellite fix status, latitude, longitude, and speed) and the GGA sentence (satellite fix status, latitude, longitude, number of satellites, and altitude). This box updates continuously while the GPS receiver is providing data.

Test Run Information

The lower-right portion of the main screen contains several boxes and drop-down menus for the analyst to describe the following details of the test run:

- Highway name: enter the name of the highway being evaluated. This field can contain any combination of letters and numbers.
- Test run number: enter a number to identify the test run.
- Roadway type: choose a value to describe the roadway's cross-sectional configuration. These values include:
 - 2U: two-lane undivided highway.
 - 4U: four-lane undivided highway.
 - 4D: four-lane divided highway.
 - 4F: four-lane freeway.
- Speed limit: specify the regulatory speed limit for the highway.

The analyst must click the “Edit Info” button to activate these input fields. When the fields are activated, new values can be entered or chosen, and the button will change to read “Save Info.” After all input data are correct, click the “Save Info” button to save the input values.

Main Button

The large button in the upper-left portion of the screen is used to activate or deactivate the program during test runs. If the program is not active, the button is colored gray and labeled “Press spacebar or this button to START curve data collection.” When the button is clicked or the space bar is pressed, the program begins archiving the data streams from the measurement devices. The button becomes green and its label changes to “Press spacebar or this button to STOP curve data collection.” The status bar below the main button is also color-coded to indicate if the program is recording (green) or not recording (red).

Status Messages

The dialog box in the lower-left portion of the screen shows messages to describe TRAMS operations such as detection of devices on startup, checking ports for new data messages, or recording messages. By default, this feature is deactivated. To toggle the status of this feature (activated or deactivated), select Verbose Mode in the Display menu. To ensure smooth and stable TRAMS operation, the status messages should not be kept activated for a prolonged period of time.

Menus

The TRAMS program contains the following menus to allow the analyst to configure and operate the program:

- File:
 - Save Settings: save the device configurations (such as port numbers and baud rates) after the settings have been changed.
 - Restart Application: close and reopen the TRAMS program after saving device configuration settings to allow the program to re-detect devices that were not previously detected.
 - Show Data Folder: obtain a dialog box that lists the location of the data folder where TRAMS stores test run files. This dialog box contains a “Copy Data Folder Location to Clipboard” button that can be clicked to allow the analyst to copy the folder location pathname.
 - Exit: close the TRAMS program.
- Setup:
 - GPS Device: specify the COM port number, baud rate, and data settings (including parity, data bits, stop bits, and handshake) for the GPS receiver. Once the correct settings are chosen, click the “Save Port Settings” button.
 - BBI Device: use the check box on the main TRAMS screen to indicate if a BBI is being used. The box is checked by default. Specify the COM port number, baud rate, and data settings (including parity, data bits, stop bits, and handshake) for the BBI. Once the correct settings are chosen, click the “Save Port Settings” button.
 - Barometer Device: use the check box on the main TRAMS screen to indicate if a barometer is being used. The box is unchecked by default. Specify the COM port number, baud rate, data settings (including parity, data bits, stop bits, and handshake), and measurement units (ft or m) for the barometer. Once the correct settings are chosen, click the “Save Port Settings” button.
 - BBI Calibration Factor: specify a calibration factor for the BBI (decimal value, between 0.75 and 1.25). This value is set to 1.0 by default but can be altered to compensate for consistent overestimates or underestimates in the BBI readings. Specify the test vehicle’s body roll rate (decimal value, between 3 and 13 deg/g). This value is set to 6.68 deg/g by default. Once the correct settings are chosen, click the “Save Settings” button.
- Display:
 - GPS RMC Sentence: toggle the GPS RMC sentence display on or off.
 - GPS GGA Sentence: toggle the GPS GGA sentence display on or off.
 - Verbose Mode: activate or deactivate the continuous refreshing of status messages.
- Help:
 - About: provides the version number for the TRAMS program and contact information for technical support.

TRAMS PROGRAM OPERATION

Complete the following steps at the beginning of each data collection session:

1. Set up the laptop computer and measurement devices in the test vehicle as previously described.
2. Click on the TRAMS icon to launch TRAMS. TRAMS will present its main screen and connect with the measurement devices.
3. Verify that TRAMS is receiving valid data from the GPS receiver. Information about the status of this device is in the upper right corner of the main panel. A red square indicates invalid (bad) data. A green square indicates valid (good) data.
 - a. If the BBI and/or the barometer are used, verify that TRAMS is receiving valid data from the device(s). A red square indicates invalid (bad) data. A green square indicates valid (good) data.
 - b. If the BBI is not used, uncheck the box for “Enable BBI” on the main TRAMS screen. A gray square reading “No BBI Data” indicates that the BBI is not being used. This box is checked by default to indicate that the BBI is being used.
 - c. If the barometer is used, check the box for “Enable Barometer Device” on the main TRAMS screen. A gray square reading “No Elev Data” indicates that the barometer is not being used. This box is unchecked by default to indicate that the barometer is not being used.
4. Troubleshoot device connections as needed. If valid data are not being received from the devices, check the following conditions:
 - a. Are the devices turned on and properly connected to the laptop computer?
 - b. Is the GPS receiver blocked from obtaining good satellite reception? Structures (bridges, garage roofs, buildings, etc.) or dense tree coverage may make it difficult to maintain GPS reception.
 - c. Has TRAMS been configured with the proper port numbers and settings for the devices? If not, configure the needed settings in the Setup menu. Once all devices are properly configured, select Save Settings in the File menu to save all settings to file (in which case they will be loaded and used each time TRAMS is launched) and restart the program by selecting Restart Application in the File menu.

Complete the following steps to conduct each test run:

1. Click the “Edit Info” button to activate the Test Run Information fields.
2. Enter the highway name, test run number, roadway type, and regulatory speed limit.
3. Click the “Save Info” button to deactivate the Test Run Information fields.
4. Press the space bar or click the main button to start the test run.
5. Conduct the test run using the procedures described in Chapter 3 of this *Handbook*.
6. Press the space bar or click the main button again to end the test run.

The tools and methods used to post-process and analyze the test run data are described in Chapter 6 of this *Handbook*.

CHAPTER 6. USER GUIDE: TEXAS CURVE EVALUATION SUITE SPREADSHEET PROGRAM (TCES)

OVERVIEW

The TCES program facilitates the analysis of horizontal curve data to identify needed traffic control devices and pavement friction improvements. The primary application of TCES is to analyze roadway data collected by the TRAMS program, locate, and identify curves on the roadway, compute the needed curve advisory speed (if any), and guide the analyst in selecting other traffic control devices for the curve (such as Chevrons). TCES can also be used to evaluate curves if the Design Method was used to obtain geometric data to describe the curve. A secondary application of TCES is to analyze the safety performance of curves and determine if a pavement friction treatment is cost-justified.

The TCES program is based on several previously developed programs, including the TCAS spreadsheet program (5), the Texas Curve Margin of Safety (TCMS) spreadsheet program (2, 7), and a spreadsheet program developed internally by TxDOT to implement TCAS-based calculations with a long list of curves.

SPREADSHEET PROGRAM OPERATION

The TCES spreadsheet program requires the use of Excel® with macros enabled. The program uses macros to open and process data files that were collected using the TRAMS program, analyze the raw data, tabulate the data, and analysis results for the curves identified in the data stream.

It may be necessary for the analyst to check and adjust the macro security setting in Excel®. This setting is accessed by selecting the File ribbon, opening the Trust Center, clicking on “Trust Center Settings,” and choosing “Macro Settings.” The TCES macros can function if any option other than “Disable all macros without notification” is chosen. If “Enable all macros” is not chosen, the analyst will see a yellow bar at the top of the screen every time TCES is opened, and it will be necessary to click the “Enable macros” or “Enable content” button on the yellow bar.

A typical application of TCES with the GPS Method will consist of the following steps:

1. Conduct one or more test runs on a highway using the procedure described in Chapter 3.
2. Open TCES and select the List worksheet, the primary worksheet for analyzing curves.
3. Use the worksheet controls to process the TRAMS data files from the test run(s).
4. If the GPS Method was implemented without a BBI, provide a superelevation rate for each curve. This superelevation rate is entered into the first light green-shaded column.
5. Use the worksheet controls to conduct a traffic control device analysis. This analysis involves computing the advisory speed for each curve and determining which curve traffic control devices are needed.
6. Optionally, provide data to describe the curve’s pavement, cross-sectional width, and traffic volume characteristics.

7. Optionally, use the worksheet controls to conduct a pavement analysis. This analysis involves computing the margin of safety for the curve and estimate the change in crash frequency that can be attributed to wet weather and pavement skid resistance.
8. Optionally, use the worksheet controls to conduct a deeper examination of the curve's traffic control device requirements with the TCD worksheet or the curve's pavement friction characteristics with the Pavement worksheet.

A typical application of TCES with the Design Method will consist of the following steps:

1. Obtain the superelevation rate, radius, and deflection angle for the curve(s) of interest.
2. Open TCES and select the List worksheet, the primary worksheet for analyzing curves.
3. Enter the curve data into the three light-green-shaded columns.
4. Use the worksheet controls to conduct a traffic control device analysis. This analysis involves computing the advisory speed for each curve and determining which curve traffic control devices are needed.
5. Optionally, provide data to describe the curve's pavement, cross-sectional width, and traffic volume characteristics.
6. Optionally, use the worksheet controls to conduct a pavement analysis. This analysis involves computing the margin of safety for the curve and estimate the change in crash frequency that can be attributed to wet weather and pavement skid resistance.
7. Optionally, use the worksheet controls to conduct a deeper examination of the curve's traffic control device requirements with the TCD worksheet or the curve's pavement friction characteristics with the Pavement worksheet.

TCES is programmed with several basic data screening checks in its TRAMS post-processing procedure. Specifically, the program will ignore data collected at a speed of less than 8 mph because these observations were likely collected during a turning or stopping maneuver. The program also identifies curve records based on a minimum degree-of-curve threshold of 2 (or a maximum radius threshold of 2865 ft). Steering corrections on tangent segments can often yield circular vehicle trajectories that have degree-of-curve values between 0.1 and 2.0, so the minimum degree-of-curve threshold prevents the misidentification of such maneuvers as gradual curves.

The following data elements are required for conducting a traffic control device analysis: regulatory speed limit, total deflection angle, curve radius, and superelevation rate. The curve radius and superelevation rate values should be obtained from the critical segment of the curve, which is the segment that has the smallest radius (TRAMS identifies these quantities). If the BBI was not used in the GPS Method implementation, or if a different engineering study method was used to obtain the curve data (such as the Design Method), then the analyst must provide a measured superelevation rate. An actual measure of the 85th-percentile passenger car speed on the curve's approach tangent can optionally be provided to improve the accuracy of the TCD analysis, but this quantity can also be estimated from curve characteristics and the regulatory speed limit if an actual measure is not available.

The following data elements are required for conducting a pavement safety analysis: regulatory speed limit (or 85th-percentile speed on the curve's approach tangent); AADT; skid

number (or skid score) at 50 mph; superelevation rate at the MC; curve radius; total deflection angle; lane width; shoulder width; and grade at the curve PC, MC, and PT. An actual measure of the 85th-percentile passenger car speed on the curve's approach tangent and superelevation rates at the curve PC and PT can optionally be provided to improve the accuracy of the pavement analysis, but these quantities can be estimated from curve characteristics and the regulatory speed limit if actual measures are not available. If the BBI was not used in the GPS Method implementation, or if a different engineering study method was used to obtain the curve data (such as the Design Method), then the analyst must provide a measured superelevation rate.

DESCRIPTION OF WORKSHEETS

TCES consists of the following worksheets:

- Welcome: an introductory worksheet, which provides background information about source documents, analysis procedures, and cell color-coding within the worksheets.
- List: the primary worksheet, which consists of one row per curve and contains curve data including the computed advisory speed.
- TCD: a supplemental worksheet, which can be used for more detailed analysis of the TCD requirements for curves of interest.
- Pavement: a supplemental worksheet, which can be used to examine the curve's margin of safety and estimated crash frequency based on geometry, vehicle speeds, and precipitation rate, and determine the benefit-cost ratio of a proposed pavement friction treatment.

The three analysis worksheets are titled List, TCD, and Pavement. These worksheets are described in detail in the following sections.

List Worksheet

The List worksheet is the primary analysis worksheet for analyzing curve data collected using the GPS Method. It is arranged such that each row contains data for one curve. The number of rows is not limited (other than the capabilities of Excel[®]), but the cells are only formatted up to row 300. It is recommended that additional copies of the TCES program file be made based on logical curve groupings, such as individual highways or control sections.

Figure 15 shows a screenshot of a portion of the List worksheet. The worksheet is organized into logical groups of columns based on the different analyses that can be conducted using TCES. Figure 15 shows the curve input data columns and worksheet control buttons.

The top portion of the List worksheet shows the name and version number of the program and contains a large pale yellow cell where the location of the data file folder must be provided. The default location for this data file folder is "C:\Users\Public\TRAMS\Data" when TRAMS is installed, but the location can be changed if it is moved or TRAMS was installed in a different location.

Texas Curve Evaluation Suite Version 1.3		Data file path: C:\Users\Public\TRAMS\Data																	
Worksheet Control Buttons		Curve Input Data																	
Clear worksheet data		Date	Time	Combined Coordinates			Control Section	Milepoint		Highway Name	Test Run Number	Curve ID Number	Roadway Type (2U, 4U, 4D, 4F)	Regulatory Speed Limit (mph)	85th-% Tangent Car Speed (mph)	Existing Curve Advisory Speed (mph)	Design Data		
Process last run	Process all runs			PC	MC	PT		Begin	End								Superelevation Rate (%)	Curve Radius (ft)	Deflection Angle (deg)
Compute TCD results																			
Compute pavement results																			
Analyze TCDs	Analyze pavement																		
Notes																			

Figure 15. TCES List Worksheet.

Worksheet control buttons are provided near the upper-left corner of the List worksheet. These controls include the following:

- Clear worksheet data: delete data from the worksheet. Use this feature to clear the worksheet and begin with a new analysis. This feature can clear all column groups or just some groups. The analyst will be prompted with a message box to verify if all or some of the data should be cleared.
- Process last run: open and process the data file collected during the most recent GPS Method data collection run. The analyst will be prompted if the specified data folder does not contain a GPS data file.
- Process all runs: open and process all data files stored in the specified data folder. The analyst will be prompted if the specified data folder does not contain a GPS data file.
- Compute TCD results: compute the curve advisory speed, severity category (5, Chapter 5), and speed difference (or difference between regulatory speed limit and recommended advisory speed) for each curve. This analysis requires geometric and operational data obtained from the GPS Method data collection run or provided by the analyst.
- Compute pavement results: conduct a margin-of-safety analysis of the curve and compute an estimate of the curve’s frequency of crashes related to wet weather and pavement skid resistance. This analysis requires geometric and operational data obtained from the GPS Method data collection run or provided by the analyst, plus additional information about pavement friction and traffic volume.
- Analyze TCDs: transfer data for up to six curves from the List worksheet to the TCD worksheet, so the analyst can then examine the curves’ traffic control device requirements in greater detail.
- Analyze pavement: transfer data for one curve from the List worksheet to the Pavement worksheet, so the analyst can then examine the cost-effectiveness of a candidate pavement friction treatment for the curve.

All calculations on the List worksheet are performed using macros. The calculation column groups in the List worksheet are described in the following paragraphs.

Worksheet Controls and Notes

The top portion of column A contains the aforementioned worksheet controls. Column A also provides space where the analyst can provide any needed notes to describe the curve. The notes do not affect analysis calculations. The cells in this column are shaded blue. Additionally, a check box labeled “Report file toggle” is provided above the columns that are used for TCD computations. It is unchecked by default but can be checked to activate an optional feature for TCES that generates text-formatted report log files for each evaluated curve.

Curve Input Data

Columns B–S contain data to describe the location and basic characteristics of each curve. Some of these data are obtained from the TRAMS data files, and others are provided by the analyst. Alternatively, the analyst may obtain these data from other data sources (such as as-built plans) and enter the data into the worksheet manually. Most of the cells in these columns are shaded blue. The curve ID number column that is shaded dark green because the curve ID number is used to link to the TCD and Pavement worksheets. The three columns that are used for design data are shaded light green.

The curve input data columns contain the following information:

- B. Date – this value corresponds to the date of the GPS Method test run.
- C. Time – this value corresponds to the time of the GPS Method test run.
- D. Curve PC Coordinates – the latitude and longitude coordinates for the curve PC.
- E. Curve MC Coordinates – the latitude and longitude coordinates for the curve MC.
- F. Curve PT Coordinates – the latitude and longitude coordinates for the curve PT.
- G. Control Section – the control section number for the curve.
- H. Beginning Milepoint – the beginning milepoint for the curve.
- I. Ending Milepoint – the ending milepoint for the curve.
- J. Highway Name – this value comes from the test run information data in TRAMS if the GPS Method is used.
- K. Test Run Number – this value comes from the test run information data in TRAMS if the GPS Method is used.
- L. Curve ID Number – the curve number along the highway being evaluated. TCES numbers curves sequentially as they are located within GPS Method data files from TRAMS. The analyst may alter the number if desired, but all curve numbers in this column must be unique to avoid overwriting curve data rows if the “Analyze TCDs” or “Analyze pavement” features are used.
- M. Roadway Type – the cross-sectional configuration of the roadway being evaluated. Possible values include 2U (two-lane undivided), 4U, (four-lane undivided), 4D (four-lane divided), and 4F (four-lane freeway). This value comes from the test run information data in TRAMS if the GPS Method is used.
- N. Regulatory Speed Limit (mph) – the posted regulatory speed limit on the highway being evaluated. This value comes from the test run information data in TRAMS if the GPS Method is used.
- O. 85th-% Tangent Car Speed (mph) – the measured 85th-percentile passenger car

speed on the approach tangent to the curve. This value is optional but can be provided to improve the accuracy of the TCD and pavement analyses.

- P. Existing Curve Advisory Speed (mph) – the existing posted advisory speed on the curve being evaluated.
- Q. Design Superelevation Rate (%) – a measured value of superelevation rate. The analyst must provide this value only if the Design Method (see Chapter 3) was used to evaluate the curve, or if the GPS Method was used without the BBI.
- R. Design Curve Radius (ft) – a measured value of curve radius. The analyst must provide this value only if the Design Method was used to evaluate the curve.
- S. Design Deflection Angle (deg) – a measured value of total curve deflection angle. The analyst must provide this value only if the Design Method was used to evaluate the curve.

Several of the curve input data elements are optional and do not affect calculations, but may be desired for roadway inventory and referencing purposes. These data elements include date, time, coordinates, control section, beginning and ending milepoints, county, highway name, test run number, and existing curve advisory speed.

TCD Computation Results

Columns T–Z contain the results of a traffic control device computation. The purpose of this computation is to determine the advisory speed on the curve (if needed) and the criterion for choosing curve traffic control devices. The criterion value is speed difference (or the difference between regulatory speed limit and advisory speed) for the TMUTCD-based guidance or severity category for the guidance developed in TxDOT research project 0-5439. See Chapter 2 for more information about these two sets of guidelines.

The TCD computation results columns contain the following information:

- T. Rounded Advisory Speed – the posted advisory speed for the curve, if needed. The column will be left blank if no posted advisory speed is needed based on the computed vehicle speeds and the sharpness of the curve.
- U. Unrounded Advisory Speed – the computed unrounded advisory speed, which is the estimated average truck speed. This value is provided for all curves.
- V. 85th-Percentile Tangent Car Speed (mph) – the computed 85th-percentile speed for passenger cars on the approach tangent to the curve. This value is equal to the value provided in column O, if any, or estimated from the regulatory speed limit and the curve radius.
- W. Previous Tangent Length (ft) – the length of the approach tangent preceding the curve in the travel direction of the test run. This value may be used to determine if curves are separated by a tangent length of less than 600 ft and need to be signed with a Reverse Curve, Reverse Turn, or Winding Road sign (per TMUTCD Section 2C.07).
- X. Next Tangent Length (ft) – the length of the approach tangent following the curve in the travel direction of the test run. This value may be used to determine if curves are separated by a tangent length of less than 600 ft and need to be signed with a Reverse Curve, Reverse Turn, or Winding Road sign (per

TMUTCD Section 2C.07).

- Y. Severity Category – the categories of A, B, C, D, and E are used with the alternate guidelines provided in Figure 4 for choosing traffic control devices. For four-lane roadways, this value is provided in parentheses because the severity-category methodology was originally developed for two-lane roadways only.
- Z. Speed Difference (mph) – the difference between regulatory speed limit and posted (rounded) advisory speed is used with the TMUTCD guidelines for choosing traffic control devices (see Table 1).

The cells containing the key output quantities (rounded advisory speed and speed difference) are shaded rose, and the other cells are shaded white.

Curve Safety Data

Columns AA–AE contain data needed to conduct a safety analysis of the curve. These data must be provided by the analyst, except for superelevation rate, which can be obtained from data files recorded during a GPS Method test run. The cells in these columns are shaded orange.

The curve safety data columns contain the following information:

- AA. Skid Number at 50 mph – this value is measured with a locked-wheel skid trailer with a smooth tire.
- AB. Superelevation Rate at MC (%) – the superelevation rate at the curve MC can be entered by the analyst or obtained from a GPS Method test run (if the BBI was used). This column gets populated when the “Process last run” and “Process all runs” buttons are clicked to analyze TRAMS data files.
- AC. AADT (veh/d) – the annual average daily traffic for the curve.
- AD. Average Lane Width (ft) – the average of the widths of all lanes on the highway at the curve’s location.
- AE. Average Shoulder Width (ft) – the average of the widths of all shoulders on the highway at the curve’s location.

Pavement Computation Results

Columns AF–AI contain the results of a pavement safety analysis computation. The purpose of this computation is to estimate the margin of safety for the curve at three key locations (PC, MC, and PT), and to obtain a value of the skid number CMF for the curve as a preliminary estimate of the curve’s potential for wet-weather safety improvement.

The pavement computation results columns contain the following information:

- AF. Margin of Safety at the PC – computed for correcting maneuvers.
- AG. Margin of Safety at the MC – computed for correcting maneuvers.
- AH. Margin of Safety at the PT – computed for correcting maneuvers.
- AI. Skid-Number CMF for Wet-Weather Crashes.

The margin-of-safety concept is described in Chapter 4. Glennon and Weaver (8) suggested that the margin of safety should be at least 0.08–0.12 along the entire length of the

curve. The skid number CMF provides a multiplicative factor to indicate the curve's tendency to experience more wet-weather crashes based on its pavement skid resistance and typical drivers' speeds. For example, a skid number CMF value of 1.2 would indicate a 20-percent increase in crashes due to wet-weather conditions, given the described condition of the pavement friction.

Geometric Data

Columns AJ–AU contain geometric data for the analyzed curves. These data are extracted from TRAMS data files obtained during GPS Method test runs and are presented in the List worksheet so they can be used to tabulate roadway inventory data for the curves. The cells in these columns are shaded white.

The geometric data columns contain the following information:

- AJ. Total Curve Deflection Angle (degrees) – the deflection angle for the entire curve, measured from PC to PT.
- AK. Curve Deflection Angle (degrees) – the deflection angle for the critical segment of the curve.
- AL. Curve Deflection Direction – the direction of vehicle deflection, or steering, during the test run (Left or Right).
- AM. Curve Radius (ft) – the overall radius for the entire curve.
- AN. Critical Curve Radius (ft) – the radius for the critical segment of the curve.
- AO. Superelevation Rate at the PC (%) – if the BBI was used, this value is obtained from the TRAMS data file. Otherwise, it is left blank.
- AP. Superelevation Rate at the MC (%) – if the BBI was used, this value is obtained from the TRAMS data file. Otherwise, it is left blank.
- AQ. Superelevation Rate at the PT (%) – if the BBI was used, this value is obtained from the TRAMS data file. Otherwise, it is left blank.
- AR. Critical Superelevation Rate (%) – the superelevation rate on the critical segment of the curve. If the BBI was used, this value is obtained from the TRAMS data file. Otherwise, it is left blank.
- AS. Grade at the PC (%) – if the barometer was used, this value is obtained from the barometer data. Otherwise, it is obtained from the GPS data.
- AT. Grade at the MC (%) – if the barometer was used, this value is obtained from the barometer data. Otherwise, it is obtained from the GPS data.
- AU. Grade at the PT (%) – if the barometer was used, this value is obtained from the barometer data. Otherwise, it is obtained from the GPS data.

Reserved Columns

Columns AV-AX are intentionally left blank to accommodate calculations that may be added into the List worksheet after the publication of this *Handbook*.

Raw Data from Curve Report File

Columns AY-BH contain raw data elements that are also provided in the individual curve report files that are generated from TRAMS data files. These columns get populated when the “Process last run” and “Process all runs” buttons are clicked.

The raw data columns contain the following information:

- AY. Test Run Speed (mph) – the speed of the test vehicle on the critical segment (or sharpest part) of the curve.
- AZ. Critical Combined Coordinates – the latitude and longitude coordinates for the critical segment of the curve.
- BA. Body Roll Rate (deg/g) – this calibration factor is specified in TRAMS (see Chapter 5). The default value is 6.68 deg/g.
- BB. BBI Calibration Factor – this decimal value is limited to the range of 0.75–1.25 and is specified in TRAMS (see Chapter 5). The default value is 1.00.
- BC. BBI Reading (deg) – the reading displayed by the BBI on the critical segment of the curve.
- BD. BBI 95th-% Error min (deg) – the lower bound of the 95th-percentile error range for the BBI reading.
- BE. BBI 95th-% Error max (deg) – the upper bound of the 95th-percentile error range for the BBI reading.
- BF. Superelevation 95th-% Error min (deg) – the lower bound of the 95th-percentile error range for the computed critical superelevation rate.
- BG. Superelevation 95th-% Error max (deg) – the upper bound of the 95th-percentile error range for the computed critical superelevation rate.
- BH. Superelevation Range Width (%) – the width of the range of possible critical superelevation rate values based on the computed error range.

Analysis Status Notes

Column BI is used to display analysis status notes. These notes apply to individual curves in the List worksheet and specify whether the analysis procedure was completed successfully for the curve. They also warn the analyst if the analysis yielded unusual results, such as if the GPS frequency was less than 5 Hz or a “curve” in the data file appears to be a parking lot turn maneuver instead of an actual roadway curve. Table 10 lists the messages and their meanings.

Advisory and Warning Messages

The “Process last run” and “Process all runs” controls are programmed to prompt the analyst with a message box to verify that the analyst intends to run a given procedure, or if file-processing errors occur during analysis. Figure 16 shows an example message box. Table 11 lists the messages and their meanings.

Table 10. TCES List Worksheet Analysis Status Notes.

Procedure	Message	Meaning
Process last run OR Process all runs	GPS data analysis completed.	TCES successfully analyzed the curve data.
	. . .but the GPS frequency was only ω Hz.	TCES analyzed the curve data but found that the GPS frequency ω was less than 5 Hz. (This message is appended to the end of the “GPS data analysis completed” message.)
	. . .Possible parking lot turn.	TCES successfully analyzed the curve data, but the data might describe a parking lot turn, not a roadway curve, based on the following criteria: <ul style="list-style-type: none"> • The critical radius was computed as less than 100 ft. • The critical curve deflection angle was computed as greater than 20°. • The test run speed at the critical segment of the curve was less than 15 mph. To trigger the message, at least two of the criteria must be met. (This message is appended to the end of the “GPS data analysis completed” message.)
	An error occurred during GPS data processing.	A computation error occurred during the processing of the curve data.
Compute TCD results	TCD (re-)analysis calculations completed.	TCES successfully computed the traffic control device requirements for the curve. The analysis is described as a re-analysis if results were already calculated and entered into columns T-Z.
	TCD analysis input data are incomplete.	The curve record is missing one or more of its required data elements for the traffic control device analysis.
	An error occurred while processing this curve. (Computations halted.)	A computation error occurred during the traffic control device analysis. If the analyst stops the analysis when prompted, the message will include “Computations halted” and the remaining curves in the worksheet will not be analyzed. Otherwise, the procedure will skip the curve and analyze the remaining curves.
Compute pavement results	Pavement (re-)analysis calculations completed.	TCES successfully analyzed the pavement friction for the curve. The analysis is described as a re-analysis if results were already calculated and entered into columns AF-AI.
	Pavement analysis input data are incomplete.	The curve record is missing one or more of its required data elements for the pavement friction analysis.
	An error occurred while processing this curve. (Computations halted.)	A computation error occurred during the pavement friction analysis. If the analyst stops the analysis when prompted, the message will include “Computations halted” and the remaining curves in the worksheet will not be analyzed. Otherwise, the procedure will skip the curve and analyze the remaining curves.

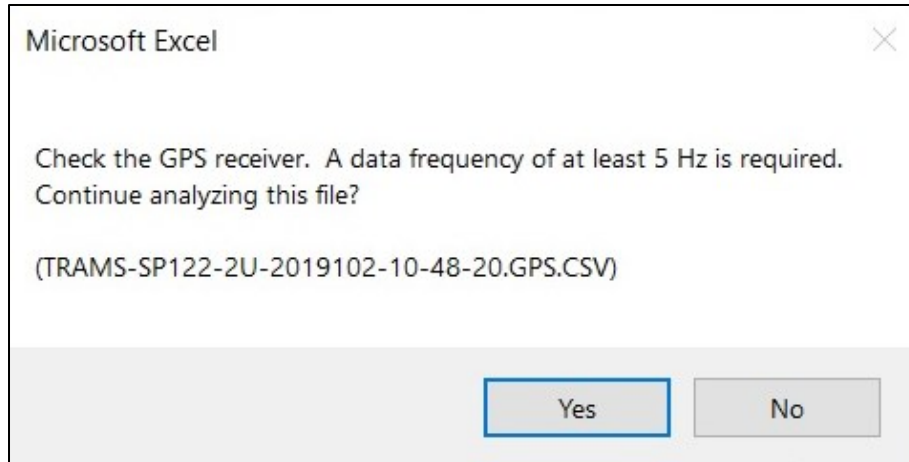


Figure 16. TCES List Worksheet Message Box.

Table 11. TCES List Worksheet Advisory and Warning Messages.

Procedure	Message	Meaning
Clear worksheet data	Do you want to clear all data?	Choose Yes to clear all data from the List worksheet or No to retain the data.
	No GPS files were found in the specified data folder.	The data folder does not contain any GPS.CSV files from TRAMS test runs.
Process last run OR Process all runs	This file is empty. The file cannot be processed. (<file name>)	The GPS data file did not contain records.
	This file contains only one data record. The file cannot be processed. (<file name>)	The GPS data file contained only one record, not a complete measurement of a roadway section or curve.
	Check the GPS receiver. A data frequency of at least 5 Hz is required. Continue analyzing this file? (<file name>)	The GPS data frequency was found to be less than 5 Hz on average during the test run in the specified file. Choose Yes to continue analyzing the file or No to skip the file.
	Check the ball-bank indicator. All readings in the file have the same value. (<file name>)	The BBI readings were found to be the same value for all records in the GPS data file, indicating a likely problem with the BBI itself or its connection to the laptop computer.
	Data file <file name> does not contain curves.	The data file does not contain curves.
	Data file <file name> does not contain curves of sufficient length and deflection angle for analysis.	None of the curves in the data file meet the minimum length and deflection angle thresholds for analysis, which are 100 ft and 5°, respectively.
	Check data file name. File <file name> does not exist or no name specified.	The data file could not be located within the specified data folder.
	An error occurred while processing the following file: <file name>	A data-processing error occurred and cannot be bypassed, so no curves in the data file can be analyzed.

Table 11 (continued). TCES List Worksheet Advisory and Warning Messages.

Procedure	Message	Meaning
Compute TCD results	Check the input data. No Curve ID Numbers are present.	The traffic control device analysis could not be conducted because the List worksheet is empty or the curves in the worksheet lack Curve ID Numbers in column L.
	An error occurred while processing row <i>x</i> . Continue processing the rest of the curves?	A computation error occurred during the traffic control device analysis. Choose Yes to skip the curve and continue analyzing the rest of the curves in the file. Choose No to stop analyzing the curves in the file.
Compute pavement results	Check the input data. No Curve ID Numbers are present.	The pavement analysis could not be conducted because the List worksheet is empty or the curves in the worksheet lack Curve ID Numbers in column L.
	An error occurred while processing row <i>x</i> . Continue processing the rest of the curves?	A computation error occurred during the pavement analysis. Choose Yes to skip the curve and continue analyzing the rest of the curves in the file. Choose No to stop analyzing the curves in the file.
Analyze TCDs	Use the cursor to select the Curve ID Number (column L) for the curve that you want to analyze.	Select the Curve ID Number in column L (dark green cells) to indicate which curve data should be transferred to the TCD worksheet.
	Select a row with a valid Curve ID Number in column L.	Select a non-blank cell in column L (dark green cells) to indicate which curve data should be transferred to the TCD worksheet. A blank Curve ID Number likely corresponds to a row with no curve data.
	The TCD worksheet is full. Clear data from the TCD worksheet and rerun the Analyze TCDs procedure.	No empty columns are available in the TCD worksheet to accommodate the selected curve's data. The curve data can be transferred after the contents of one or more columns in the TCD worksheet are cleared.
	The curve data from row <i>x</i> have been transferred to the TCD worksheet. Do you wish to go to the TCD worksheet?	The specified curve's data have been transferred to the first empty column available in the TCD worksheet. Choose Yes to activate the TCD worksheet or No to continue working with the List worksheet.
Analyze pavement	Use the cursor to select the Curve ID Number (column L) for the curve that you want to analyze.	Select the Curve ID Number in column L (dark green cells) to indicate which curve data should be transferred to the Pavement worksheet.
	Select a row with a valid Curve ID Number in column L.	Select a non-blank cell in column L (dark green cells) to indicate which curve data should be transferred to the Pavement worksheet. A blank Curve ID Number likely corresponds to a row with no curve data.
	The curve data from row <i>x</i> have been transferred to the Pavement worksheet. Do you wish to go to the Pavement worksheet?	The specified curve's data have been transferred to the Pavement worksheet. Choose Yes to activate the Pavement worksheet or No to continue working with the List worksheet.

TCD Worksheet

The TCD worksheet is based on the Texas Curve Advisory Speed spreadsheet that was developed in TxDOT research project 0-5439 (4). The data input and calculation cells are in the left portion of the worksheet, and worksheet control buttons and traffic control device guideline controls are located in the right portion of the worksheet. The following controls are provided (see Figure 17):

- Clear selected column: clear the input data from the selected column. The column is selected by placing the cursor in one of the green cells (which contain curve ID numbers) in row 8.
- Clear all data: clear all input data on the worksheet.
- Return data to List: transfer data and calculation results from the selected column back to the List worksheet. The column is selected by placing the cursor in one of the green cells (which contain curve ID numbers) in row 8.

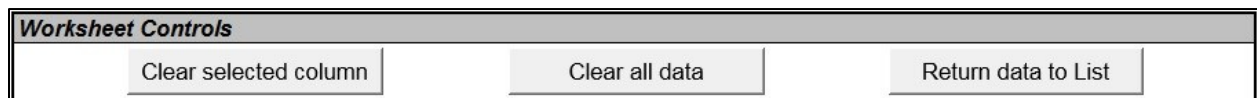
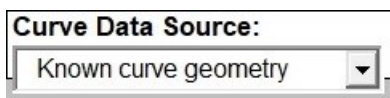


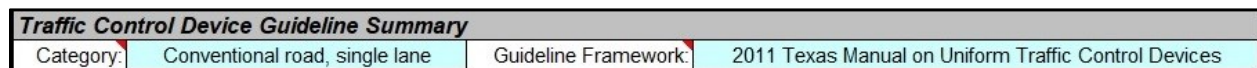
Figure 17. TCES TCD Worksheet Controls.

Additionally, the following menus are provided (see Figure 18).

- Curve Data Source (cell F5): select “survey of curve” to enter data collected using the Compass Method or “known curve geometry” to enter data collected using the GPS or Design Methods. These methods are described in Chapter 3 of this *Handbook*.
- Category (cell N30): select a value in the drop-down menu to specify the roadway category. The options are conventional road, single lane (chosen by default); conventional road, multilane; expressway; and freeway. The roadway category is used for sign size guidelines (3).
- Guideline Framework (cell S30): select the guideline framework to be used in selecting traffic control devices. The options are 2011 TMUTCD (chosen by default) or Horizontal Curve Signing Handbook, Second Edition. Both of these guideline frameworks are discussed in Chapter 2 of this *Handbook*.



a. Curve Data Source.



b. Traffic Control Device Guideline Selection.

Figure 18. TCES TCD Menus.

The TCD worksheet contains six columns that are used to analyze up to six curves of interest. The worksheet can be used with two types of input data. One method is based on data obtained from a survey of the curve, such as when the Compass Method was used to evaluate the

curve as described in Chapter 3 of this *Handbook*. The second method is based on data describing the curve deflection angle, superelevation rate, and radius. These data can be obtained from the GPS Method or the Design Method, as described in Chapter 3 of this *Handbook*. The input data are entered into rows 1-29 of the worksheet. The data entry cells for the two data collection methods are described in the next two subsections.

The cells in rows 30 to 65 that do not have background shading contain equations. These equations document the analysis of advisory speed and traffic control device selection for each of the six curves. Figure 19 shows this portion of the worksheet.

Advisory Speed						
Survey method (Partial or Full)	Partial	Partial	Partial	Partial	Partial	Partial
Total curve deflection angle (degrees)	28	90	30	96	90	93
Curve deflection angle (degrees)	9.3	30.0	10.0	32.0	30.0	31.0
Curve length (ft)	650	712	354	171	141	330
Curve radius (ft)	1331	453	676	102	90	203
Degree of curvature (degrees)	4.3	12.6	8.5	56.2	63.7	28.2
Curve path radius (ft)	1432	463	764	111	100	213
Superelevation rate (percent)	7.4	8.0	11.6	-1.6	-1.6	13.0
Average tangent speed (mph)	58	56	60	52	48	52
Unrounded advisory speed (mph)	57	43	53	21	19	33
Rounded advisory speed (mph)	55	40	50	20	15	30
Traffic Control Device Guidelines						
85th% tangent speed (mph)	66	64	69	60	55	60
85th% curve speed (mph)	66	48	60	24	22	37
Curve severity category	A	C	B	E	E	E
Curve Warning Signs						
Curve sign (W1-2, W1-4, W1-5)	Rec.	Req.	Req.			
Turn sign (W1-1, W1-3, W1-5)				Req.	Req.	Req.
Hairpin Curve sign (W1-11)						
Minimum Curve sign size (in)	26x26	26x26	26x26	26x26	26x26	26x26
Min. advance placement distance (ft)	Distances are computed using the guidance in Table 2C-4 of the Texas MUTCD. Placement distance represents the distance between the curve warning sign and the beginning of the curve. Signs should be located at or beyond this distance.					
Advisory Speed plaque (W13-1P)						
Min. Adv. Speed plaque sign size (in)						
Comb. Curve/Adv. Speed sign (W1-2a)						
Comb. Turn/Adv. Speed sign (W1-1a)				Opt.	Opt.	Opt.
Minimum Comb. sign size (in)		30x30		30x30	30x30	30x30
One-Dir. Large Arrow (W1-6 or W1-9T)	Opt.	Opt.	Opt.	Opt.	Opt.	Opt.
Chevrons (W1-8)	Opt.	Req.	Req.	Req.	Req.	Req.
Chevron spacing (ft)	200	120	120	40	40	80
Delineation Devices						
Raised pavement markers	Opt.	Opt.	Opt.	Opt.	Opt.	Opt.
Delineators	Opt.	Opt.	Opt.	Opt.	Opt.	Opt.
Delineator spacing (ft)	105	60	75	20	20	35
Special Treatments						
				Rec.	Rec.	Rec.
Opt. = optional		Rec. = recommended		Req. = required		

Figure 19. TCES TCD Worksheet, Advisory Speed and TCD Calculations.

This section of the worksheet applies guidance from the TMUTCD and Chapter 2 of this *Handbook*. The guidance applies to the following items:

- Rounded advisory speed.
- Curve warning sign and delineation device selection.
- Minimum sign sizes.
- Chevron and delineator spacings.

Some of the cells, data boxes, or graphs in the TCD worksheet have comment boxes that provide additional clarification about the needed input data or interpretation of the output data. Red triangles indicate the presence of these comments. The comments can be viewed by placing the cursor on top of the red triangles. In Figure 19, a comment is shown for the calculated minimum advance placement distance.

The bottom portion of the TCD worksheet contains calibration parameters, intermediate calculations, and a sign library showing images of various horizontal alignment signs. Figure 20 shows this portion of the worksheet.

Special Treatments				Rec.	Rec.	Rec.
Opt. = optional				Rec. = recommended		Req. = required
CALIBRATION PARAMETERS AND INTERMEDIATE CALCULATIONS						
Travel Path and Ball-Bank Indicator Parameters			Side Friction Demand Increase Thresholds (g)			
Lateral shift in lane (ft)	3		A	0.00	D	0.13
Ball-bank indicator calibration factor	1.00		B	0.03	E	0.16
Roll rate (deg/g)	6.68		C	0.08		
Speed conversion factor (mph to fps)	1.47					
Roadway configuration	2U	2U	2U	2U	2U	2U
Rounded advisory speed (mph)	55	40	50	20	15	30
Ratio of average to 85th% speed	0.90	0.90	0.90	0.90	0.90	0.90
Ratio of truck speed to car speed	0.97	0.97	0.97	0.97	0.97	0.97
Ratio of left-lane speed to right-lane speed	1.00	1.00	1.00	1.00	1.00	1.00
BBI reading adjusted for ball deflection	-4.75	-5.1	-7.4	1	1	-8.25
Equivalent ball-bank reading (deg)	5	11	8	17	16	13
Average side friction demand (g)	0.08	0.18	0.13	0.28	0.25	0.22
85th-% side friction demand increase (g)	0.00	0.13	0.08	0.22	0.19	0.16













Sign Library						
						
W1-1	W1-1a	W1-2	W1-2a	W1-3	W1-4	
						
W1-5	W1-6	W1-8	W1-9T	W13-1P	W1-11	

Figure 20. TCES TCD Worksheet, Parameters, Calculations, and Sign Library.

Compass Method Data Entry

Curve data collected from the Compass Method are used by selecting “Survey of curve” in the “Curve Data Source” menu. The data from the curve survey are entered into the cells that have a blue-shaded background in rows 9 through 20 as shown in Figure 21. The following data are needed:

- Curve deflection (Left or Right). Indicate the direction of curve deflection, or steering, as the test vehicle traversed the curve.
- Roadway Type. Enter the cross-sectional configuration of the roadway being evaluated (2U, 4U, 4D, or 4F).
- Compass headings at points 1 and 2 (degrees). Enter the compass headings that were obtained at points 1 and 2 (see Figure 5). These points may be the 1/3 and 2/3 points as described for the Compass Method, or they may be the curve PC and PT. Note that the figure describing the 1/3 and 2/3 points is also provided on the right portion of the TCD worksheet.
- BBI reading of superelevation (degrees). Enter the glass-vial BBI reading that was obtained at the 1/3 point of the curve, or alternatively at the MC.

- Deflection of ball for superelevation reading (left or right). Specify whether the ball in the glass-vial BBI was located to the right or the left of the 0.0 mark when the BBI reading was recorded.
- Curve length (ft). Enter the curve length between the two measurement points.
- Survey method (partial or full). Choose “Partial” if the 1/3 and 2/3 points were used to obtain the compass headings, or “Full” if the PC and PT were used.
- Regulatory speed limit (mph). Enter the regulatory speed limit that is posted on the highway where the curve is located.
- 85th-percentile tangent speed (mph). Enter the field-measured 85th-percentile tangent speed, if available. This speed should be measured at a location sufficiently far upstream of the curve that the curve geometry does not affect vehicle speeds. If this quantity is not entered, the program will estimate the 85th-percentile tangent speed.

CURVE ADVISORY SPEED WORKSHEET						
General Information						
County:		Curve Data Source:		Date:	November 12, 2019	
Highway:		Survey of curve		Analyst:		
Input Data						
Data Description	Curve ID Number					
	1	2	3	4	5	6
Curve deflection (Left or Right)	Right	Left	Left	Left	Left	Left
Roadway type (2U, 4U, 4D, 4F)	2U	2U	2U	2U	2U	2U
Compass heading 1 (degrees)	251.7	124	254	239	330	189
BBI reading of superelevation (degrees)	4.8	5.1	7.4	1.0	1.0	8.3
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) <i>Caution, curve length outside equation range.</i>	216	237	118	57 <i>See note.</i>	57 <i>See note.</i>	110
Compass heading 2 (degrees)	261	94	244	207	300	158
Survey method (Partial or Full)	Partial	Partial	Partial	Partial	Partial	Partial
Regulatory speed limit (mph)	60	60	65	60	55	60
Estimate of 85th% tangent speed (mph)	66	64	69	60	55	60

Figure 21. TCES TCD Worksheet, Survey of Curve.

GPS or Design Methods Data Entry

Curve data collected from the GPS or Design Methods are used by selecting “Known curve geometry” in the “Curve Data Source” menu. The data from the GPS Method or the Design Method are entered into the cells in rows 26 through 29, as shown in Figure 22. The following data are needed:

- Curve deflection (Left or Right). Indicate the direction of curve deflection, or steering, as the test vehicle traversed the curve.
- Roadway Type. Enter the cross-sectional configuration of the roadway being evaluated (2U, 4U, 4D, or 4F).

- Regulatory speed limit (mph). Enter the regulatory speed limit that is posted on the highway where the curve is located.
- 85th-percentile tangent speed (mph). Enter the field-measured 85th-percentile tangent speed, if available. This speed should be measured at a location sufficiently far upstream of the curve that the curve geometry does not affect vehicle speeds. If this quantity is not entered, the program will estimate the 85th-percentile tangent speed.
- Total curve deflection angle (degrees). Enter the total curve deflection angle as measured from PC to PT.
- Curve deflection angle (degrees). Enter the deflection angle for the critical portion of the curve if the GPS Method was used to evaluate the curve, or the total deflection angle if the Design Method was used.
- Superelevation rate (%). Enter the superelevation rate for the critical portion of the curve if the GPS Method was used to evaluate the curve, or the superelevation rate at the MC if the Design Method was used.
- Curve radius (ft). Enter the radius for the critical portion of the curve if the GPS Method was used to evaluate the curve, or the overall curve radius if the Design Method was used.

CURVE ADVISORY SPEED WORKSHEET						
General Information						
County:		Curve Data Source:		Date:	November 12, 2019	
Highway:		Known curve geometry		Analyst:		
Input Data						
Data Description	Curve ID Number					
	1	2	3	4	5	6
Curve deflection (Left or Right)	Right	Left	Left	Left	Left	Left
Roadway type (2U, 4U, 4D, 4F)	2U	2U	2U	2U	2U	2U
Compass heading 1 (degrees)	251.7	124	254	239	330	189
BBI reading of superelevation (degrees)	4.8	5.1	7.4	1.0	1.0	8.3
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) <small>Caution, curve length outside equation range.</small>	216	237	118	57 <small>See note.</small>	57 <small>See note.</small>	110
Compass heading 2 (degrees)	261	94	244	207	300	158
Survey method (Partial or Full)	Partial	Partial	Partial	Partial	Partial	Partial
Regulatory speed limit (mph)	60	60	65	60	55	60
Estimate of 85th% tangent speed (mph)	66	64	69	60	55	60
Alternate Input Data (if data are entered here, they will be used instead of estimates from the data above)						
85th% tangent speed (mph)						
Total curve deflection angle (degrees)	28	90	30	96	90	93
Curve deflection angle (degrees)	9.3	30.0	10.0	32.0	30.0	31.0
Superelevation rate (percent)	7.4	8.0	11.6	-1.6	-1.6	13.0
Curve radius (ft)	1331	453	676	102	90	203

Figure 22. TCES TCD Worksheet, Known Curve Geometry.

Advisory and Warning Messages

The “Clear selected column”, “Clear all data”, and “Return data to List” controls are programmed to prompt the analyst with a message box to verify that the analyst intends to run a given procedure. Table 12 lists the messages and their meanings.

Table 12. TCES TCD Worksheet Advisory and Warning Messages.

Procedure	Message	Meaning
Clear selected column	Do you want to clear the data in column <i>x</i> ?	Choose Yes to clear the data from the selected column or No to retain the data.
	Use the cursor to select the Curve ID Number (row 8) for the data that you want to clear.	Select the Curve ID Number in row 8 (dark green cells) to indicate which column should be cleared.
Clear all data	Do you want to clear all data?	Choose Yes to clear all data from the TCD worksheet or No to retain the data.
Return data to List	Use the cursor to select the Curve ID Number (row 8) for the data that you want to return to the List worksheet.	Select the Curve ID Number in row 8 (dark green cells) to indicate which curve data should be returned to the List worksheet.
	This is a sample curve. It did not come from the List worksheet.	The selected curve cannot be returned to the List worksheet because it was a sample curve in the TCD worksheet. Only curves originating from the List worksheet can be returned.
	The curve data are incomplete. They cannot be returned to the List worksheet.	The selected curve cannot be returned to the List worksheet because its data in the TCD worksheet are incomplete. (Curves with incomplete data will not have a computed unrounded advisory speed in row 40.)
	The curve data from column <i>x</i> have been returned to the List worksheet. Do you wish to go to the List worksheet?	The specified curve’s data have been returned to its origin row in the List worksheet. Choose Yes to activate the List worksheet or No to continue working with the TCD worksheet.

Pavement Worksheet

The Pavement worksheet is based on the TCMS spreadsheet that was developed in TxDOT research projects 0-6714 and 0-6932 (2, 7). It is organized so the entire worksheet can be printed on six pages. The first page contains input data entry cells, output cells, and calculation of skid number at the curve advisory speed. The second page provides a table and a chart to illustrate margin of safety trends throughout the curve and the change in skid number for a proposed pavement friction treatment over time. The remaining pages contain calibration coefficients and intermediate calculations that are used to produce the output calculations on the first and second pages.

Figure 23 provides a screenshot of a portion of the first page of the Pavement worksheet. The cells are color-coded so the analyst can easily identify data entry cells and output data cells. The main set of data entry cells is blue. Except for the general information data entry cells (describing quantities like district, highway, and curve location), the blue cells must be filled. Several additional data entry cells are orange. The orange cells differ from the blue cells in that

the program requires the quantities that are entered into the orange cells, but can estimate the quantities if the analyst leaves the cells blank. The key output data cells are colored rose. The cells containing calibration factors on the later pages of the program are yellow.

Texas Curve Margin of Safety Worksheet					
General Information					
District	Brazos	Control section	3456-78	Date	November 13, 2019
Highway	FM 1234	Beginning milepoint	1.5	Analyst	
Curve ID Number	2	Ending milepoint	1.7	Curve deflection	Right
Site Characteristics Input Data			Clear data	Return data to List	
Average daily traffic volume (ADT, veh/d)			18000	Crash Prediction Model Calculations	
Truck percentage			10	<i>Predicted Crash Counts in Analysis Period</i>	
ADT growth rate (%)			2		
Roadway type (2U, 4U, 4D, 4F)			2	Before	After
Curve radius (ft)			200	6.974	6.406
Deflection angle (degrees)			2	0.438	0.294
85th % tangent speed (mph)			70	7.085	6.414
Regulatory speed limit (mph)			70	Wet-weather ROR	0.401
Advisory speed (mph)			45	<i>Predicted Change in Crash Count</i>	
Average lane width (ft)			11	All	-9.9%
Average shoulder width (ft)			2	Wet-weather	-35.6%
Grade (%)	PC		2	Run-off-road (ROR)	-10.9%
(Deflection to Right)	MC		0	Wet-weather ROR	-35.6%
	PT		-2	<i>Overall Crash Modification Factors (CMFs)</i>	
Annual precipitation rate (inches)			35	Curve radius	6.179
				Annual precip.	1.632

Figure 23. Pavement Worksheet Screenshot.

Some of the cells, data boxes, or graphs in the Pavement worksheet have comment boxes that provide additional clarification about the needed input data or interpretation of the output data. Red triangles indicate the presence of these comments. The comments can be viewed by placing the cursor on top of the red triangles. In Figure 23, a comment is shown for the roadway type input data cell.

The input and output data cells are organized into logical groups. For example, the site characteristics and pavement treatment input data cells are each contained within a box, and additional output data boxes are provided for margin of safety analysis calculations, crash prediction model calculations, benefit-cost calculations, and calculations of the skid number at the specified curve advisory speed.

Most of the output data cells are white. These cells do not represent key output quantities but are made visible because their contents may be of interest. The output data cells are protected so the analyst cannot inadvertently alter an equation and obtain erroneous calculations from the program.

The input data cells are configured with data validation features to prevent illogical values from being entered. For example, regulatory speed limit and advisory speed must be multiples of 5 mph, and the skid numbers must be between 0 and 100.

Input Data

Cells containing general information are located on the upper portion of the Pavement worksheet (see Figure 23). These cells can be used to document the location of the curve, the date, the analyst's name, and the direction of curve deflection (left or right) corresponding to the grade data that are entered into the Input Data box. Of these quantities, only the curve deflection direction affects the calculations performed by the program.

Figure 24 shows the box containing the site characteristics input data cells. The following data are needed:

- Average daily traffic volume (ADT, veh/d).
- Truck percentage.
- ADT growth rate (%).
- Roadway type, described by the following codes:
 - 2U = two-lane undivided.
 - 4U = four-lane undivided.
 - 4D = four-lane divided (all types of medians, including flush-paved, depressed, unpaved, or raised, with or without a positive barrier).
- Curve radius (ft). Enter the geometric radius of the curve.
- Deflection angle (degrees). Enter the total deflection angle for the curve.
- 85th-percentile tangent speed (mph). Enter the field-measured 85th-percentile tangent speed, if available. This speed should be measured at a location sufficiently far upstream of the curve that the curve geometry does not affect vehicle speeds. If this quantity is not entered, the program will estimate the 85th-percentile tangent speed using a model described by Equation 71 in Reference 2.
- Regulatory speed limit (mph). Enter the regulatory speed limit. This quantity is used to estimate the 85th-percentile tangent speed if a field-measured value is not available.
- Advisory speed (mph). Enter the curve advisory speed, or the regulatory speed limit if no advisory speed is posted.
- Average lane width (ft). Enter the average lane width that exists along the length of the curve.
- Average shoulder width (ft). Enter the average shoulder width that exists along the length of the curve.
- Grade (%). Enter the roadway grade, as measured at the centerline of the roadway in the direction of travel, for the PC, the MC, and the PT. The entered grade numbers should be measured in the direction of travel corresponding with the curve deflection direction that was entered in the General Information box.
- Annual precipitation rate (inches). Rates are provided in the Appendix for TxDOT districts and Texas counties. The analyst may use these rates or rates from a different data source if available.
- Superelevation rate (%). Enter the superelevation rate observed at the MC, and optionally the value observed at the PC and PT. A positive superelevation rate value corresponds to a cross slope that decreases side friction demand. If values are not provided for the PC and the PT, the program estimates the superelevation rate at these points using the default proportion of 0.5, which can be adjusted in the calibration factor cells if desired. A

proportion of 0.5 means that the superelevation rate at the PC and the PT is equal to 0.5 times the value observed at the MC. Cells are provided for the before and after cases so the effects of changing the superelevation rate can be computed. Cells are also provided for the two travel directions so differences in superelevation rate between the two directions can be accommodated.

Site Characteristics Input Data			
Average daily traffic volume (ADT, veh/d)		18000	
Truck percentage		10	
ADT growth rate (%)		2	
Roadway type (2U, 4U, 4D, 4F)		2U	
Curve radius (ft)		500	
Deflection angle (degrees)		40	
85th % tangent speed (mph)			
Regulatory speed limit (mph)		70	
Advisory speed (mph)		45	
Average lane width (ft)		11	
Average shoulder width (ft)		2	
Grade (%) (Deflection to Right)	PC	2	
	MC	0	
	PT	-2	
Annual precipitation rate (inches)		35	
Superelevation rate (%)		Before	After
Deflection to Left	PC	4.5	6.5
	MC	6	8
	PT	4.5	6.5
Deflection to Right	PC	6.5	8.5
	MC	8	10
	PT	6.5	8.5

Figure 24. Site Characteristics Input Data Cells.

In the example described by the input data in Figure 24, a safety improvement project is being considered for a curve with a 500-ft radius and a 40° deflection angle. The proposed project will involve increasing the superelevation rate by 2 percent along the entire length of the curve.

Figure 25 shows the box containing the pavement treatment input data cells. The following data are needed:

- Skid number for the existing surface, which corresponds to the before period.
- Treatment type for the proposed surface, which corresponds to the after period. Table 13 lists the options and categories for each treatment type.
- Aggregate type and percent contribution to coarse aggregate: Describe up to two aggregates to be used in the proposed pavement treatment by specifying the type and the percent contribution that the material makes to the coarse aggregate in the treatment. Coarse aggregate is the portion of aggregate that is retained on the #4 sieve during the standard sieve test. Table 14 lists the options for aggregate type and the treatment

categories for which each aggregate type may be used. Note that the drop-down menus are programmed to allow only the aggregate types that are appropriate for the specified treatment type.

- Economic discount rate: Enter the discount rate to be used in the economic calculations to determine benefit-cost ratio. This value is used to convert the future value of treatment benefits (i.e., the costs of future crashes) to present value.
- Treatment cost: Enter the cost of installing the proposed pavement treatment.

Pavement Treatment Input Data	
Skid number for existing surface	30
Proposed treatment type	PFC
Aggregate type 1	Siliceous Gravel
% contribution to coarse aggregate	50
Aggregate type 2 (optional)	Dolomite
% contribution to coarse aggregate	50
Economic discount rate	3.0%
Treatment cost	\$50,000

Figure 25. Pavement Treatment Input Data Cells.

Table 13. Treatment Type Options.

Option	Category
Type C (DG, SP)	Asphalt overlay
Type D (DG, SP)	
Type F (DG, SP)	
CAM	
SMA (Type C or D)	
TOM	
CMHB-F	
Thin PFC	
PFC	
Seal Coat (Gr. 3, 4, 5)	
High-friction treatment	High-friction surface treatment

Table 14. Aggregate Type Options.

Option	Applicable Treatment Category
Calcined bauxite	High-friction surface treatment
Limestone	Asphalt overlay or seal coat
Dolomite	
Sandstone	
Siliceous Gravel	
Limestone Gravel	
Igneous	
Flint	
Lightweight Agg.	Seal coat

Figure 26 shows the box containing the crash analysis input data cells. The following data are needed:

- Analysis period (yr). Enter the number of years included in the analysis period. This quantity defines the time period for the calculation of predicted crash counts and also the time period for which the benefit (or disbenefit) of the proposed treatment will be computed.
- Crash data period (yr). If empirical Bayes adjustment to the predicted crash counts is desired, enter the number of crashes observed during the time period for which historical crash data are available. If empirical Bayes adjustment is not desired, enter 0.
- Reported crash count by type. If empirical Bayes adjustment to the predicted crash counts is desired, enter the number of crashes observed during the crash data period. Separate cells are provided for four different categories of crashes—all crashes, wet-weather crashes, run-off-road crashes, and wet-weather run-off-road crashes. Leave these cells blank if empirical Bayes adjustment is not desired.

Crash Analysis Input Data		
Analysis period (yr)		7
Crash data period (yr)		7
Reported crash count by type	All	10
	Wet-weather	3
	Run-off-road (ROR)	9
	Wet-weather ROR	2

Figure 26. Crash Analysis Input Data Cells.

Output Data

Calculation results are provided on the first and second pages of the Pavement worksheet. These results include margin of safety analysis, crash prediction model calculations, pavement service life (in terms of skid number over time), and benefit-cost calculations. Details are provided in the following subsections.

Margin of Safety Analysis. Figure 27 shows the margin of safety analysis results in tabular and graphical form. Results are provided in the rose-colored cells for the two directions of travel to compare the before period to the after and terminal periods. These calculations can be made for the ideal or correcting travel path types, as indicated in the blue cell.

In the example shown, the existing configuration (described by the before period) has a margin of safety of 0.000 for correcting travel path type in both travel directions at the PC. This result indicates that there is no margin of safety if a driver makes a correcting maneuver at the PC. The margin of safety at the PT is also borderline acceptable for the before case, based on the suggested minimum of 0.08–0.12 (8). In the after period, the entire curve has a margin of safety of at least approximately 0.09, while the PC still has the lowest margin of safety of any point along the curve. However, in the terminal period, the margin of safety at the PC has degraded to 0.05 in one direction and 0.07 in the other direction.

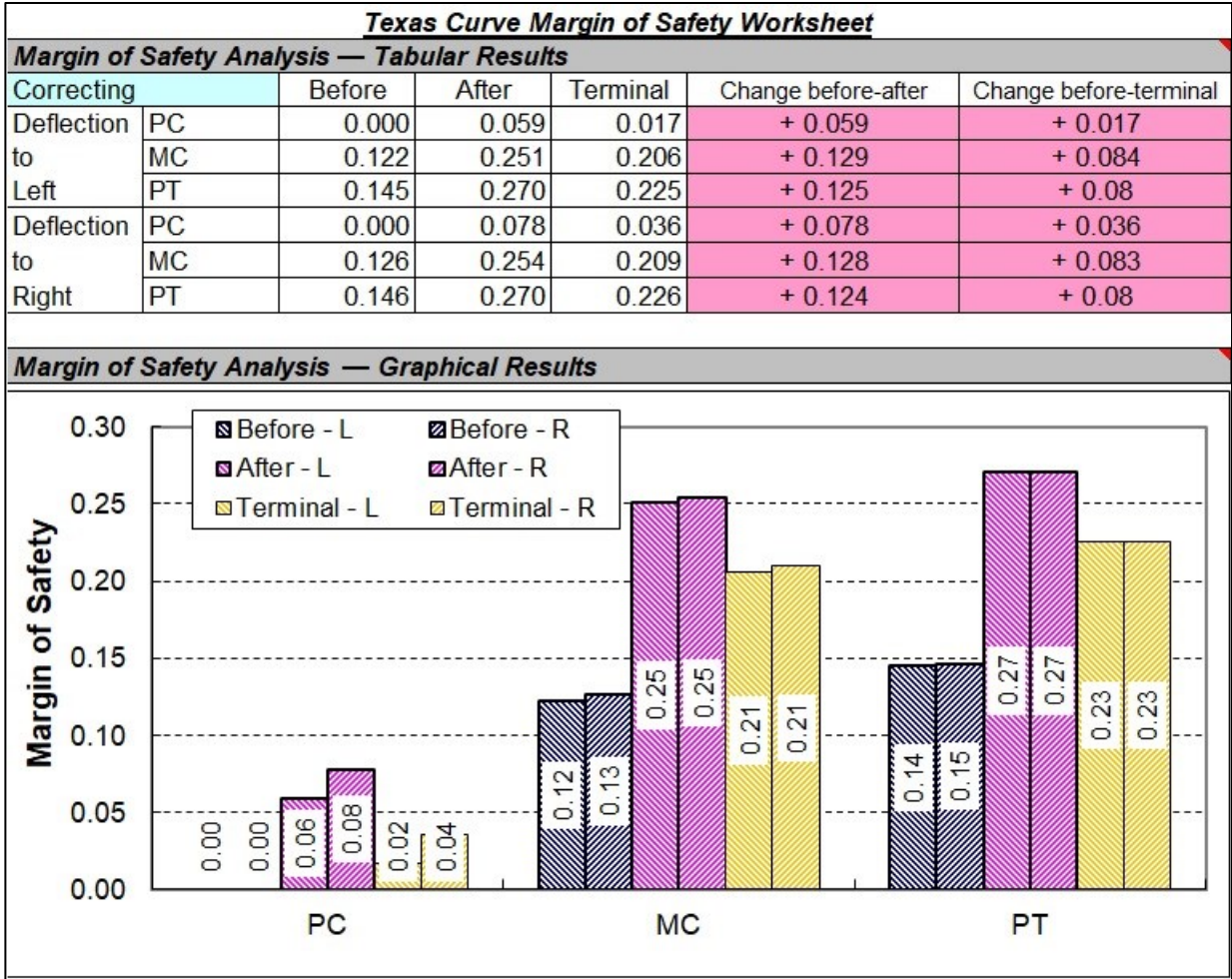


Figure 27. Margin of Safety Analysis Calculations.

The margin of safety analysis results are shown in graphical form on the second page of the Pavement worksheet. The blue, pink, and yellow bars on the graph illustrate the before, after, and terminal cases, respectively. The direction of the hatch lines corresponds to the direction of travel (curve deflecting to the left or the right). In all cases, the pink bars are taller than the blue bars, indicating an improvement in margin of safety following the installation of the safety treatment, with the benefit decreasing between the after and terminal periods but never below the margin of safety that existed in the before period.

Crash Prediction Model Calculations. The crash prediction model calculations are provided on the right side of the first page of the Analysis worksheet. Figure 28 shows these calculations. Crash counts are provided for the four crash categories (all crashes, wet-weather crashes, run-off-road crashes, and wet-weather run-off-road crashes), along with the curve radius, annual precipitation, skid number, and combined skid number–annual precipitation CMFs associated with the four models. The rose-colored cells show the change in skid number and combined skid number–annual precipitation CMFs and resulting change in predicted crash count due to the installation of the friction surface treatment.

Crash Prediction Model Calculations		
<i>Predicted Crash Counts in Analysis Period</i>		
	Before	After
All	6.974	6.406
Wet-weather	0.438	0.294
Run-off-road (ROR)	7.085	6.414
Wet-weather ROR	0.401	0.267
<i>Predicted Change in Crash Count</i>		
All		-9.9%
Wet-weather		-35.6%
Run-off-road (ROR)		-10.9%
Wet-weather ROR		-35.6%
<i>Overall Crash Modification Factors (CMFs)</i>		
Curve radius	6.179	
Annual precip.	1.632	
Skid number	1.094	0.986
Skid x Precip.	1.786	1.609
<i>Wet-Weather CMFs</i>		
Curve radius	1.000	
Annual precip.	2.959	
Skid number	1.462	0.942
Skid x Precip.	4.328	2.787
<i>Run-off-Road CMFs</i>		
Curve radius	7.895	
Annual precip.	1.632	
Skid number	1.105	0.984
Skid x Precip.	1.804	1.607
<i>Wet-Weather Run-off-Road CMFs</i>		
Curve radius	1.000	
Annual precip.	3.065	
Skid number	1.462	0.942
Skid x Precip.	4.482	2.886

Figure 28. Crash Prediction Model Calculations.

One data input cell exists within the crash prediction model calculations. Cell L11 contains a drop-down menu that allows the analyst to choose the time period to compare with the before period. The options include:

- After: Immediately after treatment.
- End: The end of the last year of the specified analysis period.
- Terminal: The end of the year in which the effective skid number is reached. Effective terminal skid number is defined as the skid number at the end of the first year when the skid number drops to within 1 *SK* of the terminal value.

Skid Number and Treatment Service Life. To compute a benefit-cost ratio, it is necessary to compute the service life of the proposed pavement friction treatment in terms of the skid number's change over time. Figure 29 shows a typical trend for the skid number over time. The initial skid number corresponds to year 0, when the treatment is newly installed. The terminal skid number is the final, minimum value on the rightmost portion of the graph.

The Pavement worksheet provides the following numerical outputs below the skid number graph (bottom portion of Figure 29):

- Years to effective terminal *SK*: Number of years until the effective terminal skid number is reached.
- Effective terminal *SK*: The effective terminal skid number is defined as the skid number at the end of the first year when the skid number drops to within 1 *SK* of the terminal value.

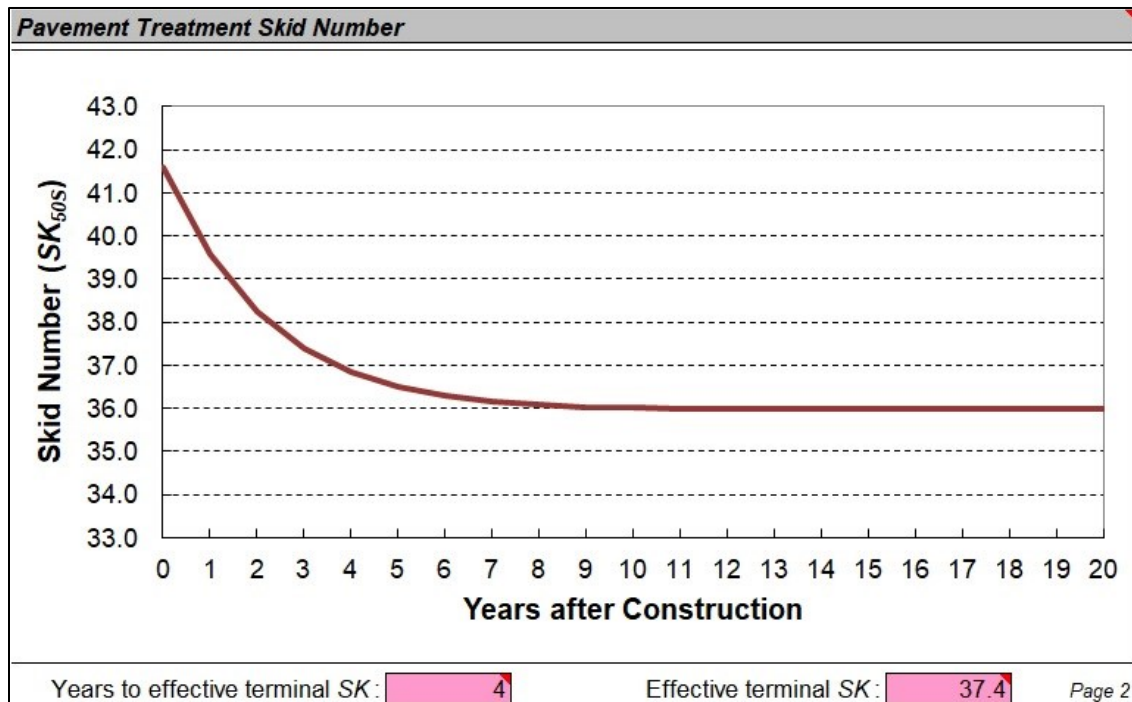


Figure 29. Pavement Treatment Skid Number Change over Time.

Figure 30a shows a set of calculations that provides the skid number at the advisory speed and at the skid test speed for three time periods (before, after, and terminal). These numbers are provided so the analyst can assess skid resistance at typical traffic speeds, which will often vary from the speed used to field-measure skid number (50 mph).

The benefit-cost analysis results are provided in a table on the bottom of the first page, as shown in Figure 30b. The following quantities are given:

- Average crash cost: This number provides the cost of the average crash that occurs on rural highway curves. This cost depends on the distribution of crashes by severity and the costs of crashes by severity.
- For the analysis period:
 - Analysis period duration (yr).
 - *SK* at the end of the analysis period.
 - Benefit-cost ratio for the proposed treatment. The treatment benefit is computed as the value of the crashes reduced, and the treatment cost is provided by the analyst.
 - Net benefit for the proposed treatment, which is defined as benefit minus cost.

- For the period of improved skid number:
 - Duration of period of improved *SK* (yr).
 - *SK* at the end of the period of improved skid number.
 - Benefit-cost ratio for the proposed treatment.
 - Net benefit for the proposed treatment.

Skid Number Calculations			
Skid number	Before	After	Terminal
at advisory speed	31.8	44.0	39.6
at skid test speed	30.0	41.6	37.4

a. Skid Number

Benefit-Cost Analysis Calculations	
Average crash cost	\$668,082
Analysis period (yr)	7
<i>SK</i> at end of analysis period	36.3
Benefit-cost ratio	4.48
Net benefit	\$174,146
Period of improved <i>SK</i> (yr)	21
<i>SK</i> at end of improved period	36.0
Benefit-cost ratio	8.79
Net benefit	\$389,285

b. Benefit-Cost Analysis

Figure 30. Skid Number and Benefit-Cost Calculations.

The provision of calculations for both time periods allows the analyst to consider the service life of the proposed surface treatment. In the example shown, the proposed surface treatment reaches a terminal skid number of about 36, which exceeds the skid number of 30 for the before period, suggesting that the treatment would continue to yield safety benefits even after the end of the specified seven-year analysis period.

Advisory and Warning Messages

The “Clear data” and “Return data to List” controls are programmed to prompt the analyst with a message box to verify that the analyst intends to run a given procedure. Table 15 lists the messages and their meanings.

Table 15. TCES Pavement Worksheet Advisory and Warning Messages.

Procedure	Message	Meaning
Clear data	Do you want to clear the curve data?	Choose Yes to clear the curve data from the Pavement worksheet or No to retain the data.
Return data to List	This is a sample curve. It did not come from the List worksheet.	The selected curve cannot be returned to the List worksheet because it was a sample curve in the Pavement worksheet. Only curves originating from the List worksheet can be returned.
	The curve data are incomplete. They cannot be returned to the List worksheet.	The selected curve cannot be returned to the List worksheet because its data in the Pavement worksheet are incomplete.
	The curve data have been returned to the List worksheet. Do you wish to go to the List worksheet?	The specified curve’s data have been returned to its origin row in the List worksheet. Choose Yes to activate the List worksheet or No to continue working with the Pavement worksheet.

APPENDIX. QUICK-REFERENCE CHECKLISTS

The following checklists provide a brief summary of the key steps and requirements for implementing the curve analysis procedures described in this *Handbook*.

GPS Method Equipment Requirements

Computer and Measurement Devices

- Laptop computer with TRAMS and all device and adapter drivers installed (required)
- GPS receiver (required)
 - Data frequency of at least 5 Hz, preferably 10 Hz
 - Configured to stream RMC and GGA data sentences
 - Complies with the National Marine Electronics Association 0183 interface standard for RMC data sentences
- Electronic ball-bank indicator (BBI) (optional, can be used to measure superelevation)
- Barometer with data-streaming capability (optional, can be used to obtain more precise roadway grade measurements)

Connector Cables

- USB cable for GPS receiver (required)
- BBI power and data cable (required if ball-bank indicator is used)
- Serial-USB adapter for BBI cable (required if computer does not have a serial port)
- Laptop computer power cord (preferably a DC power cord that plugs directly into the vehicle's cigar lighter)
- Y-adapter for cigar lighter (required if the vehicle has only one cigar lighter)

Equipment Setup Procedures

- Place the GPS receiver where it can get good satellite reception and secure it so it is not free to slide around the vehicle.
- Place the BBI on a steady surface (must be within 10° of level) and push the “REL” button to set the relative zero reading while parked on a level pavement surface.
- Connect all measurement devices to the laptop computer in the vehicle.
- To enable the measurement devices in TRAMS:
 - Verify that the devices are enabled (i.e., the appropriate boxes are checked) on the TRAMS main screen.
 - Use the Device Manager feature in Windows to obtain the COM port numbers assigned to each device.
 - Go to the Setup menu and specify the COM port numbers and settings for each device.
 - Go to the File menu, select Save Settings, and then select Restart Application.

TRAMS Operation Procedures

- Verify that TRAMS is receiving good data from all measurement devices. TRAMS shows green squares in the Device Status box to indicate reception of good data.
- Click the “Edit Info” button before each test run to enter the highway name, test run number, roadway type, and regulatory speed limit. Click the “Save Info” button when done entering the information.
 - The test run number should be updated for every run.
 - The other information (highway name, roadway type, and regulatory speed limit) should be updated every time these quantities change on the highway.
- Press the space bar or click the large button to start data collection at the start of each test run.
 - The test run can consist of a single curve or multiple curves along a continuous stretch of highway.
 - Start all test runs on tangents, at least 1-2 seconds ahead of the first curve of interest.
- Track each curve accurately. Follow the pavement markings as precisely as possible.
- Drive through each curve at a “slow but reasonable” speed.
 - Rule of thumb: 10 mph below the posted advisory speed, or 10 mph below the regulatory speed limit if the curve has no posted advisory speed.
 - Do not drive below 15 mph in a curve, even if the curve has a posted advisory speed of 15 or 20 mph.
 - If traffic conditions allow, it is preferable to avoid driving above 45 mph in a curve. Slower speeds provide more accurate superelevation measurements.
 - The vehicle speed does not matter on tangents, so accelerate and decelerate between curves as needed.
- Press the space bar or click the large button to stop data collection at the end of each test run. Consider ending the test run and starting a new one whenever there is a change in the highway name, the roadway type, or the regulatory speed limit.

TRAMS Troubleshooting

- If TRAMS is not receiving good data from one or more of the devices in use:
 - Verify that the device is enabled by checking its box on the TRAMS main screen (applicable for BBI and barometer).
 - Use the Device Manager feature in Windows to verify that the laptop computer has a good connection with the device.
 - Check the port settings for the device in the Setup menu.
- If TRAMS freezes during operation (e.g., the data readings on the main panel stop updating or the program stops responding):
 - Close and reopen the program.
 - Shut off other programs that are running on the laptop computer.
 - Deactivate Verbose Mode in the Display menu. (Verbose Mode is the continuous updating of the status messages in the lower-left portion of the TRAMS main screen.)
 - If a test run was in progress when TRAMS froze, restart the test run.

REFERENCES

- 1 Lord, D., M. Brewer, K. Fitzpatrick, S. Geedipally, and Y. Peng. *Analysis of Roadway Departure Crashes on Two-Lane Rural Roads in Texas*. Report FHWA/TX-11/0-6031-1, Texas Transportation Institute, College Station, Texas, 2011.
- 2 Pratt, M., S. Geedipally, A. Pike, P. Carlson, A. Celozza, and D. Lord. *Evaluating the Need for Surface Treatments to Reduce Crash Frequency on Horizontal Curves*. Report FHWA/TX-14/0-6714-1, Texas A&M Transportation Institute, College Station, Texas, 2014.
- 3 *Texas Manual on Uniform Traffic Control Devices*. Texas Department of Transportation, Austin, Texas, 2011.
- 4 Bonneson, J., M. Pratt, J. Miles, and P. Carlson. *Development of Guidelines for Establishing Effective Curve Advisory Speeds*. Report FHWA/TX-07/0-5439-1, Texas Transportation Institute, College Station, Texas, 2007.
- 5 Bonneson, J., M. Pratt, J. Miles, and P. Carlson. *Procedures for Setting Curve Advisory Speed: Horizontal Curve Signing Workshop Course Notes*. Product 5-5439-01-P1, Texas Transportation Institute, College Station, Texas, 2009.
- 6 *Procedures for Establishing Speed Zones*. Texas Department of Transportation, Austin, Texas, 2015.
- 7 Pratt, M., S. Geedipally, B. Wilson, S. Das, M. Brewer, and D. Lord. *Pavement Safety-Based Guidelines for Horizontal Curve Safety*. Report FHWA/TX-18/0-6932-R1, Texas A&M Transportation Institute, College Station, Texas, 2018.
- 8 Glennon, J., and G. Weaver. *The Relationship of Vehicle Paths to Highway Curve Design*. Research Report 134-5. Texas Transportation Institute, College Station, Texas, 1971.
- 9 Bonneson J., and K. Zimmerman. *Procedure for Using Accident Modification Factors in the Highway Design Process*. Report FHWA/TX-07/0-4703-P5, Texas Transportation Institute, College Station, Texas, 2007.
- 10 Pratt, M., S. Geedipally, B. Wilson, and D. Lord. *Guidelines and Evaluation Framework for Horizontal Curve Wet-Surface Safety Analysis: A User Guide*. Report FHWA/TX-18/0-6932-P1, Texas A&M Transportation Institute, College Station, Texas, 2018.

