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16. Abstract

This document summarizes the research conducted and the findings from a two-year investigation of driver behavior on horizontal curves on rural two-lane highways. This research included a review of existing procedures for setting curve advisory speed, the collection of speed data on horizontal curves, and the calibration of speed prediction models.

The findings from the research were used to develop criteria for setting the curve advisory speed, a method for determining this speed, and guidelines for identifying appropriate curve-related traffic control devices. A conclusion of this research is that there are some challenges associated with the use of the ball-bank indicator that make difficult the task of achieving curve advisory speeds that are uniform among curves and consistent with driver expectation. A method for establishing advisory speeds is described that overcomes these challenges. The method is based on the measurement of curve geometry and the use of these measurements to estimate the average curve speed of truck traffic. The average truck speed is then used as the basis for establishing the advisory speed.

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DEVELOPMENT OF GUIDELINES FOR ESTABLISHING EFFECTIVE CURVE ADVISORY SPEEDS

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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

OVERVIEW

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

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

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

OBJECTIVE AND SCOPE

The objectives of this research project were to: (1) develop guidelines for determining when advisory speeds are needed to maintain safe operation, (2) develop criteria for identifying appropriate advisory speeds, and (3) develop a cost-effective engineering study method for determining the advisory speed for a given curve. These objectives were achieved through the satisfaction of the following goals:

- Evaluate the crash history of sharper curves in Texas and quantify the curve safety problem.
- Evaluate car and truck driver curve speed choice as may be influenced by various factors.
- Develop recommended guidelines and procedures for setting advisory speeds in conjunction with other warning signs and devices that enhance pavement edge delineation.
- Evaluate the effects of the recommended guidelines through field testing.

The research project focused on horizontal curves that exist on rural highways in Texas. However, the research findings may be useful for establishing advisory speeds for urban streets.

RESEARCH APPROACH

The research approach was based on a 2-year program of field investigation, data analysis, and guideline development. The research findings were used to develop a guideline document to assist TxDOT engineers with signing for changes in horizontal alignment. During the first year of research, candidate application guidelines, speed setting criteria, and engineering study methods were developed, and data were collected for the purpose of evaluating the guidelines, criteria, and methods. During the second year, the data were analyzed and the guidelines, criteria, and methods refined.

The main product of this research project is a *Horizontal Curve Signing Handbook*. This document provides technical guidance for engineers and technicians responsible for designing the traffic control device layout for horizontal curves. The handbook provides guidance for identifying curves that can substantially benefit from warning signs and supplemental pavement edge delineation. It also describes a method for accurately, consistently, and cost-effectively identifying the advisory speed. The guidelines and procedures described in the *Handbook* are intended to promote the uniform application of curve warning signs in Texas, as well as advisory speeds that are consistent with driver expectancy.

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2. *Manual on Uniform Traffic Control Devices*. Federal Highway Administration, U.S. Department of Transportation, Washington, D.C., 2003.

3. Chowdhury, M., D. Warren, H. Bissell, and S. Taori. "Are the Criteria for Setting Advisory Speeds on Curves Still Relevant?" *ITE Journal*. Institute of Transportation Engineers, Washington, D.C., February 1998, pp. 32-45.

CHAPTER 2. LITERATURE REVIEW

OVERVIEW

This chapter documents a review of the literature on topics related to the use of traffic control devices to inform road users of a change in horizontal alignment. The focus is on curve warning signs and associated delineation devices. The discussion identifies various curve-related traffic control devices, describes the guidance provided in various authoritative documents for their use, and summarizes their effectiveness.

The chapter consists of five main parts. The first part reviews the literature related to the safety and operation of horizontal curves. The second part reviews the various warning signs that are used to sign horizontal curves. The third part examines the various criteria being used to set advisory speeds for horizontal curves. The fourth part describes three engineering study methods that have been used in the field to determine the appropriate advisory speed for a specified curve. The last part addresses several issues related to horizontal curve signing and the selection of advisory speed.

HORIZONTAL CURVE SAFETY AND OPERATION

This part of the chapter examines the factors that influence the safety and operation of horizontal curves. The focus of the examination is on factors related to the curve's geometric design. The relationship between horizontal curve design and driver speed choice is described in the first section. Then, the relationship between curve design and crash rate is explored in the second section. The insights obtained from this investigation provide a foundation for the development of guidelines for the use of curve-related warning signs and the setting of advisory speeds.

Curve Speed

The following equation has traditionally been used to describe the relationship between vehicle speed and side friction demand on a curve of specified radius and superelevation rate:

$$v_c = \sqrt{g R \left(f_D + \frac{e}{100} \right)} \qquad (1)$$

where,
   v_c = curve speed, ft/s;
   f_D = side friction demand factor (or lateral acceleration);
    e = superelevation rate, percent;
    g = gravitational acceleration (= 32.2 ft/s^2); and
    R = radius of curve, ft.

This equation indicates that side friction demand, radius, and superelevation rate have a direct influence on vehicle speed. Speed increases with an increase in any one of these three variables. Studies of driver behavior have demonstrated that drivers choose a curve speed that yields an

acceptable side friction demand. Those studies that focused on the level of side friction associated with driver comfort tend to agree that comfortable friction values fall in the range of 0.30 to 0.10, for speeds ranging from 25 to 70 mph, respectively. One of the more notable references on this topic is the AASHTO document *A Policy on Geometric Design of Highways and Streets* (*Green Book*) (*1*). It specifies friction factors that are implied to reflect the limit of driver comfort and recommends these factors for design. These factors are listed in Table 2-1.

Table 2-1. Side Friction Factors Based on Driver Comfort Limits.

	Design Speed, mph												
	10	**15**	**20**	**25**	**30**	**35**	**40**	**45**	**50**	**55**	**60**	**65**	**70**
Side Friction Factor	0.38	0.32	0.27	0.23	0.20	0.18	0.16	0.15	0.14	0.13	0.12	0.11	0.10

A review of the literature indicates that several variables, other than those listed in Equation 1, can have some influence on curve speed (*2*). These variables include:

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

Of the variables listed, tangent speed and vehicle type are considered key factors in the specification of an appropriate advisory curve speed. These two factors are examined more fully in the following two subsections.

Tangent Speed

Research indicates that tangent speed has a significant influence on driver curve speed choice. In a review of the literature, Bonneson (*3*) identified three curve speed prediction models that include this variable (*4, 5, 6*). He used data (collected at 55 curves located in eight states) to develop the following relationships between side friction demand and speed:

$$f_{D,85,pc} = 0.256 - 0.00245\, v_{t,85,pc} + 0.0146\,(v_{t,85,pc} - v_{c,85,pc})\, I_v \qquad (2)$$

where,
$f_{D,85,pc}$ = 85th percentile side friction demand factor;
$v_{t,85,pc}$ = 85th percentile tangent speed of passenger cars, ft/s;
$v_{c,85,pc}$ = 85th percentile curve speed of passenger cars, ft/s; and
I_v = indicator variable (= 1.0 if $v_{t,85,,pc} > v_{c,85,pc}$; 0.0 otherwise).

Equations 1 and 2 were combined to develop a curve speed model similar to those reported in the literature. The speeds predicted by this model are shown in Figure 2-1 using thick trend lines (those obtained from three other models are shown using lighter line weights). The trends in this figure are very consistent among the various models and suggest that a driver's curve speed choice is strongly influenced by tangent speed. For example, the Bonneson model indicates that a curve with a 500 ft radius and 6.0 percent superelevation rate will likely be associated with an 85th percentile speed of 50 mph when the 85th percentile tangent speed is 60 mph. This same model indicates this same radius and superelevation combination will have an 85th percentile speed of 44 mph if the tangent speed is 50 mph and a curve speed of 39 mph if the tangent speed is 40 mph.
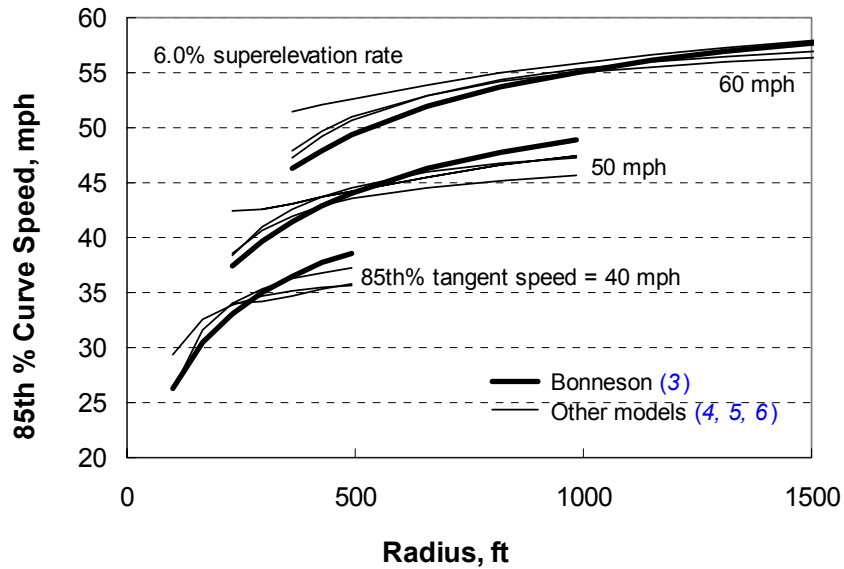
Figure 2-1. Influence of Tangent Speed on Curve Speed.

The effect of superelevation on curve speed is secondary to that of radius and tangent speed. Its estimated effect tends to vary, depending on the speed prediction model used to estimate its value. For example, the combination of Equations 1 and 2 indicate a 0.3 mph increase in speed for every 1 percent increase in superelevation. Thus, for a superelevation rate of 10 percent, the speed obtained from Figure 2-1 would be increased by about 1.2 mph (= 0.3 × [10 − 6]). Equation 1, combined with the friction factors in Table 2-1, indicates an increase in speed of about 1.0 mph for every 1 percent increase in superelevation. Regardless of the speed prediction model used, the effect of superelevation rate on speed is relatively small when compared to the effect of radius or tangent speed.

Fitzpatrick et al. (2) developed a series of models that collectively reflect the effect of radius, grade, vertical curvature, and sight distance on passenger car curve speed. The model that they developed for curves with grades in the range of 0 to 4 percent, no vertical curvature, and adequate sight distance is:

$$V_{c,85,pc} = 65.1 - \frac{7290}{R} \tag{3}$$

where,

$V_{c,85,pc}$ = 85th percentile curve speed of passenger cars, mph.

Figure 2-2 compares Equation 3 with other curve speed models. The thin solid line in this figure corresponds to Equation 3. The dashed trend line corresponds to the speed-radius relationship obtained from Equation 1 using the side friction factors in Table 2-1. It provides an indication of the speed that, as suggested in the *Green Book*, equates to the upper limit of "comfortable" lateral acceleration. The thick line corresponds to speed estimates obtained from Equation 1 using side friction factors from Equation 2. In general, the model developed by Fitzpatrick et al. is consistent with the model developed by Bonneson for a tangent speed of 60 to 65 mph.
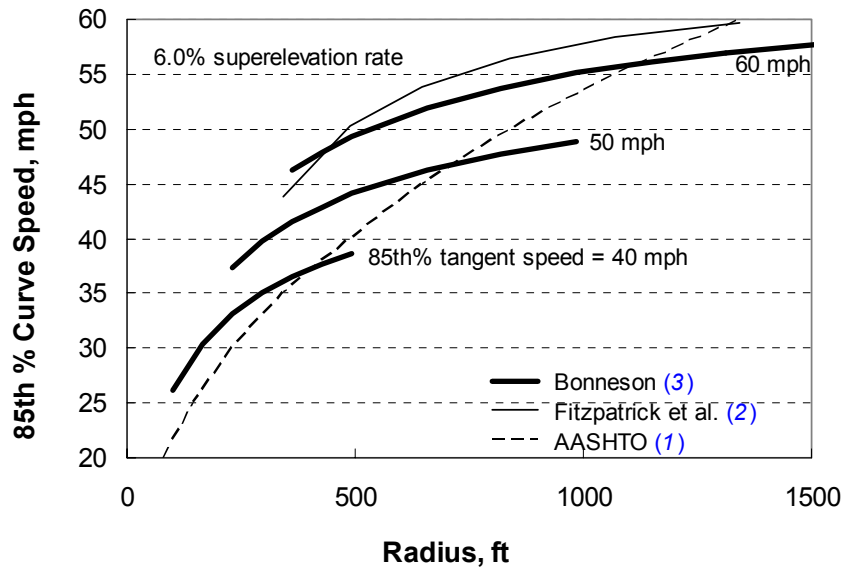
Figure 2-2. Comparison of Passenger Car Curve Speed Prediction Models.

For the sharper radii in Figure 2-2, the dashed line is below that of the solid trend lines. This relationship suggests that drivers are accepting a lateral acceleration that is not comfortable. Any discomfort they experience is apparently acceptable to them and reflects a desire to minimize their speed reduction. For example, the comfortable speed on a curve with a 500 ft radius is about 40 mph. However, as noted in a previous paragraph, drivers choose a curve speed of 50 mph when the tangent speed is 60 mph. Thus, they accept a level of lateral acceleration that exceeds the comfort limit and, by doing so, limit their speed reduction to only 10 mph.

Vehicle Type

Bonneson (*3*) also developed a model to predict truck driver speed choice, as influenced by tangent speed and curve design. The speeds predicted by this model are shown in Figure 2-3. The trends shown indicate that truck speeds equal about 95 percent of passenger car speeds, which is consistent with the findings of Fitzpatrick et al. (*2*).
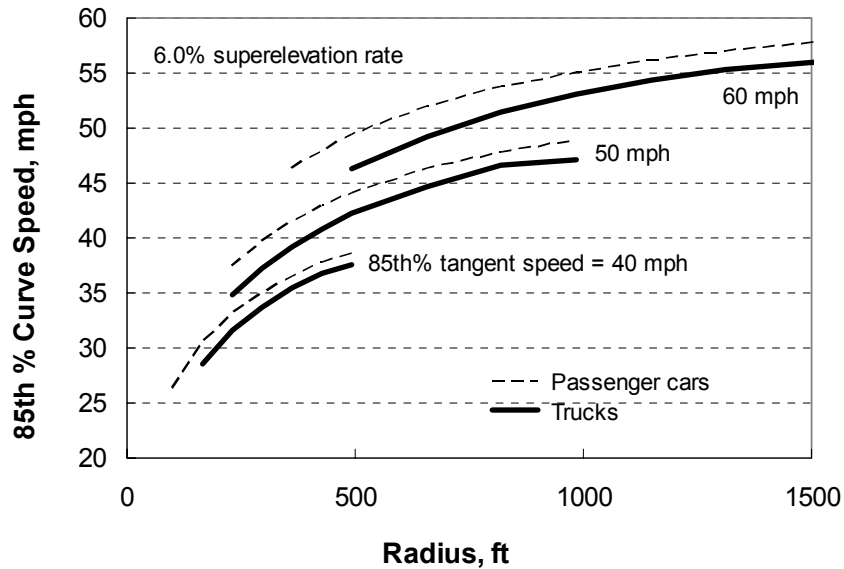
Figure 2-3. Comparison of Passenger Car and Truck Curve Speeds.

Curve Speed Selection

The trend lines in Figure 2-2 indicate that drivers on sharper curves slow from the tangent speed to an acceptable curve speed. The amount of speed reduction increases with decreasing radius. For curves with a 500 ft radius and a 60 mph tangent speed, the reduction is about 10 mph. In contrast, for a 1000 ft radius and 60 mph tangent speed, the reduction is only about 5 mph.

A detailed study of vehicle speed was undertaken by Glennon et al. (7) to determine when drivers start their deceleration and reach the curve speed, relative to the point of curvature (PC). The findings from this study indicate that drivers maintain their speed on the tangent up to a point about 3 s travel time from the PC. At this point, they begin to decelerate at a constant rate until they reach the mid-point of the curve. The deceleration rate increases with decreasing radius. Subsequent research has shown that this behavior is consistent among drivers and is generally independent of tangent speed and radius (3).

The implications of the findings by Glennon et al. (7) are that drivers wait until they are very close to the curve before they begin to adjust their speed, regardless of the curve's radius. It has been speculated that this behavior reflects the drivers' desire to estimate an appropriate curve speed based on their assessment of curve sharpness. However, they are unable to make this judgment until they are very close to, or traveling along, the curve (8). This behavior suggests that advance information about an upcoming curve, as provided by a curve warning sign, may heighten driver awareness of the curve, but it does not appear to cause them to begin slowing sooner.

Curve Safety

An analysis of curve crash data was undertaken by Fitzpatrick et al. (*2*). Specifically, they evaluated the relationship between curve speed reduction and crash frequency. Their data apply to total crashes (i.e, fatal, injury, and property-damage-only [PDO]) on two-lane rural highways. They found the following relationship between crash frequency and speed reduction:

$$CR = CR_b \times AMF_{sr}$$ (4)

with,

$$AMF_{sr} = e^{0.126 \, (V_{t,85,pc} - V_{c,85,pc})}$$ (5)

where,

CR = total curve crash rate, crashes/million-vehicle-miles (crashes/mvm);
CR_b = base crash rate (= 0.68), crashes/million-vehicle-miles;
AMF_{sr} = accident modification function for curve speed reduction; and
$V_{t,85,pc}$ = 85th percentile tangent speed of passenger cars, mph.

Equations 4 and 5 indicate that total crash rate increases with an increase in the speed reduction accepted by drivers. Equation 4 indicates that the curve crash rate increases from 0.68 crashes/mvm to 2.4 crashes/mvm when the curve speed reduction is 10 mph. This latter speed reduction was noted previously to correspond to a curve with a 500 ft radius.

Bonneson et al. (*9*) developed a relationship between injury (plus fatal) crash frequency and curve design using data from 1757 curves in Texas. The form of their equation is consistent with that shown in Equation 4; however, the base injury (plus fatal) crash frequency is 0.26 crashes/mvm, and the accident modification function has the following form:

$$AMF_{cr} = 1 + 0.106 \left(\frac{5730}{R} \right)^2$$ (6)

These equations were used to examine the relationship between curve radius and crash rate. Equations 3, 4, and 5 were used together to compute the curve total crash rate based on the models developed by Fitzpatrick et al. (*2*). A tangent speed of 65 mph was used because it is representative of the data used to derive Equations 5 and 6. The relationships found from this examination are shown in Figure 2-4. The two trend lines shown in this figure are in fairly good agreement. They indicate that the crash rate increases sharply for curves with a radius of less than 1000 ft. They also indicate that most crashes on sharper curves result in an injury or fatality.

An additional examination was undertaken to determine the relationship between side friction demand and crash rate. For this examination, Equation 1 was used with Equations 3, 4, and 5 to estimate the relationship between friction and rate implied by the Fitzpatrick et al. (*2*) models. Also, Equation 2 was used with Equations 1 and 6 to estimate the relationship between friction and rate predicted by the Bonneson et al. (*3, 9*) models. The results of this examination are shown in Figure 2-5. The superelevation rate was assumed to equal 6 percent for this comparison.
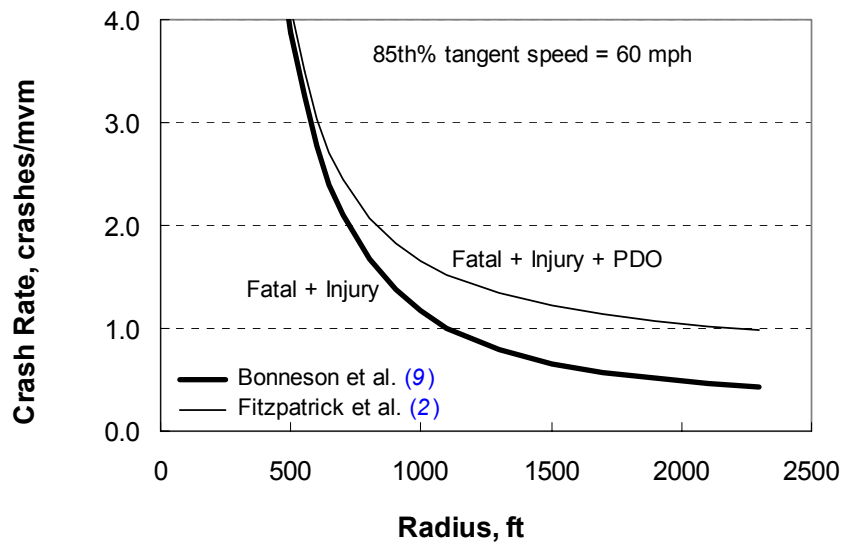
Figure 2-4. Curve Crash Rate as a Function of Radius.
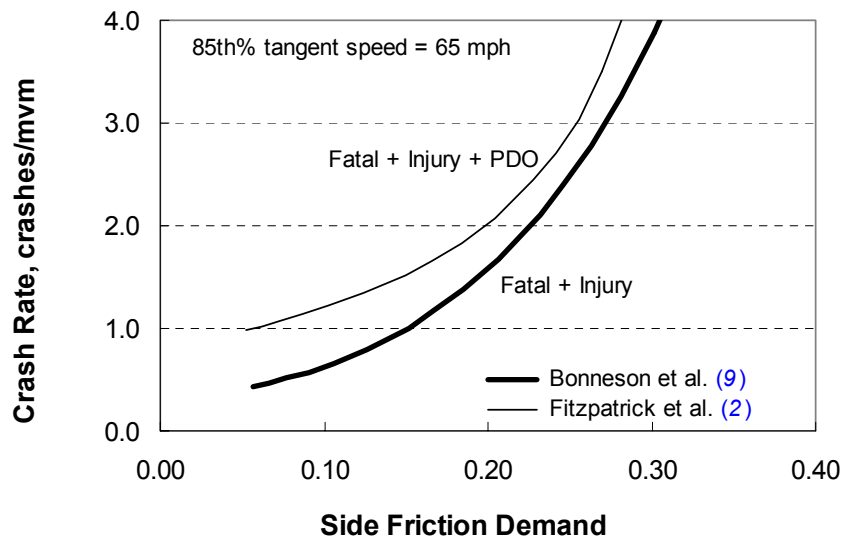
Figure 2-5. Curve Crash Rate as a Function of Side Friction Demand.

The trends in Figure 2-5 indicate that crash frequency increases as side friction demand increases. The rate of increase is significant when side friction demand exceeds about 0.20. This level of friction demand is about one-third of the friction supply available to passenger cars on wet pavements *(3)*. Thus, it is unlikely that the passenger car crashes reflected in this crash rate are attributable to slide failure. Harwood et al. *(10)* suggest that roll-over by fully-loaded trucks can occur at friction levels of 0.35 or more. However, the percentage of truck-involved, curve-related crashes is only about 5 percent *(11)*. Thus, it is unlikely that truck crashes are contributing significantly to the crash rate trends shown in Figure 2-5.

Based on the discussion in this and the previous sections, it is likely that the trends in Figure 2-5 are reflecting driver error while entering or traversing a curve. It is possible that some drivers are distracted or impaired and do not track the curve. It is also possible that some drivers detect the curve but do not correctly judge its sharpness. In both instances, traffic control devices have the potential to improve safety by making it easier for drivers to detect the curve and judge its sharpness.

WARNING SIGNS FOR CHANGES IN HORIZONTAL ALIGNMENT

Most transportation agencies use a variety of traffic control devices to inform road users of a change in horizontal alignment. These devices include curve warning signs, delineation devices, and pavement markings. The focus of this part of the chapter is on curve warning signs; however, conditions where other traffic control devices may be helpful are also identified. The guidance offered in this section reflects consideration of the findings from a survey of TxDOT engineers in five districts, a survey of practitioners with six state departments of transportation (DOT), a review of TxDOT procedure and policy manuals, and a review of the literature related to curve safety and operations.

Curve Warning Signs

The *MUTCD* (*12*) identifies a variety of warning signs that can be used where the horizontal alignment changes in an unexpected or restrictive manner. These signs are shown in Figure 2-6a. There are two sign categories shown: advance signs and supplemental signs. Advance signs are located in advance of the curve. Signs in this category include: Turn (W1-1), Curve (W1-2), Reverse Turn (W1-3), Reverse Curve (W1-4), Winding Road (W1-5), Hairpin (W1-11), Truck Rollover Warning (W1-13), and 270-degree Loop (W1-15). These signs are recognized in the *Texas Manual on Uniform Traffic Control Devices* (*TMUTCD*) (*13*). In contrast, the Combination Horizontal Alignment/Intersection (W1-10) is not recognized in the *TMUTCD*.

One additional sign that falls in the advance sign category is the Advisory Speed plaque (W13-1). This sign is shown in Figure 2-6b. It is used to advise drivers of the speed found to be appropriate based on an engineering study. When used, it is combined with one of the advance horizontal alignment signs and mounted on the same sign post.

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

Guidelines for Curve Signing Based on Speed Differential

This section describes guidelines for curve signing that are based on speed differential. In this regard, speed differential is defined as the difference between the regulatory speed limit and the

advisory speed. It is the most commonly found criterion for identifying where and when a curve warning sign is appropriate. Other criteria have been proposed for guiding the selection of curve signing. These criteria are discussed in the next section.

W1-1   W1-2   W1-3   W1-4

W1-5   W1-6 *   W1-8 *

W1-10   W1-11   W1-13   W1-15

W1-1a *   OR   W1-2a *   OR
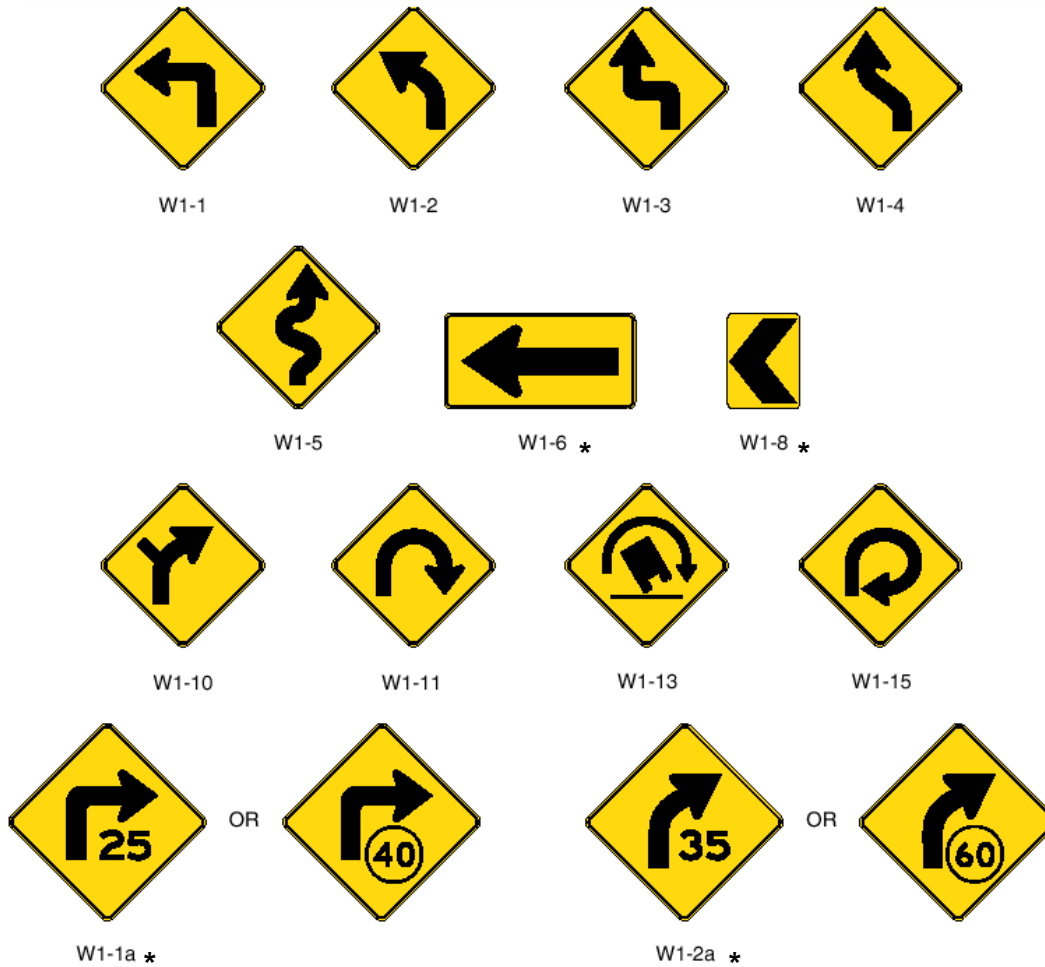
a. Horizontal Alignment Signs.

W13-1   W13-5 *
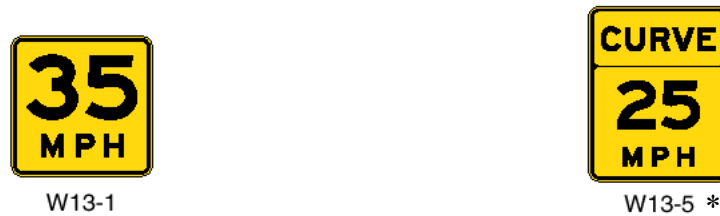
* Denotes "supplemental" sign.
  Signs without asterisk represent "advance" signs.

b. Advisory Speed Plaques.

Figure 2-6. Curve Warning Signs.

The *MUTCD* guidance regarding the use of curve warning signs can be described as flexible. It encourages engineers to base their signing decisions on engineering studies and judgment. However, as noted by Lyles and Taylor (*14*), this flexibility has the disadvantage of occasionally promoting the inconsistent application of traffic control devices. Inconsistent device application makes it difficult for drivers to develop expectancies and, consequently, promotes disrespect for the device and mistrust of its message. As noted previously, the Advisory Speed plaque is one of most renowned examples of the consequences of inconsistent sign usage. Research has found it to be one of the more disrespected traffic control devices (*15*).

In recognition of the aforementioned contradiction between having both flexible guidelines and consistent device application, many state agencies have adopted explicit guidelines for use of horizontal alignment signs. In this regard, explicit guidance is that which provides specific criteria indicating when a device may (or should) be considered. This guidance is summarized in Table 2-2. The shaded cells in this table indicate the speed differentials for which the corresponding sign may (or should) be considered. The guidance provided in this table is discussed in the following subsections.

Table 2-2. Guidance for Curve Warning Signs Based on Speed Differential.

Source	Sign	Speed Differential,[1] mph								Additional Guidance
		0	5	10	15	20	25	30	>30	
MUTCD (*12*)	W1-1a or W1-2a				▓	▓				Use one of these two devices at point of curvature (PC).
	W13-5 (Curve Speed)				▓	▓				
	W1-1a or W1-2a						▓	▓	▓	Use all devices. W1-1a, W1-2a, or W13-5 at PC. W13-5 also along curve.
	W13-5 (Curve Speed)						▓	▓	▓	
TMUTCD (*13*)	W1-8 (Chevron)									Use with raised pavement markers (RPM) along curve.
TCDH[2] (*16*)	W1-1, 1-2, 1-3, 1-4, 1-5	▓	▓	▓	▓	▓	▓	▓		--
	W13-1 (Advisory Speed)		▓	▓	▓	▓	▓	▓		--
	W1-1a or W1-2a				▓	▓				Use one of these two devices at point of curvature.
	W13-5 (Curve Speed)				▓	▓				
	W1-1a or W1-2a							▓	▓	Use all devices. W1-1a, W1-2a, or W13-5 at PC. W1-8 also along curve.
	W13-5 (Curve Speed)							▓	▓	
	W1-8 (Chevron)							▓	▓	
Lyles & Taylor (*14*)	W1-1, 1-2, 1-3, 1-4, 1-5	▓	▓	▓	▓	▓	▓	▓		--
	W13-1 (Advisory Speed)			▓	▓	▓	▓	▓		

Notes:

1 - Speed differential: difference between the regulatory speed limit and the advisory speed. Shaded cells indicate speed differentials for which the corresponding sign is applicable.

2 - *Traffic Control Devices Handbook* (*TCDH*) (*16*).

Advance Signs

This subsection summarizes explicit guidance provided in various reference documents for horizontal alignment signs used in advance of a curve (e.g., W1-1, W1-2, W1-3, W1-4, and W1-5). For example, the *Traffic Control Devices Handbook (16)* suggests that an advance sign should be used when the advisory speed is equal to, or less than, the regulatory speed limit. This guidance is also recommended by Lyles and Taylor *(14)*, based on their nationwide survey of engineers.

The *MUTCD (12)* indicates that the Turn (W1-1) or Reverse Turn (W1-3) sign should be used when the advisory speed is 30 mph or less. In contrast, the Curve (W1-2) or Reverse Curve (W1-4) sign should be used when the advisory speed exceeds 30 mph. The Reverse Turn or Reverse Curve sign should be used when there are two alignment changes in opposite direction and separated by a tangent distance of 600 ft or less. This guidance is repeated in the *TMUTCD (13)*.

Guidance for using the Advisory Speed plaque (W13-1) is also summarized in Table 2-2. For example, the *TCDH (16)* suggests that a plaque should be provided when the speed differential (i.e., the difference between the regulatory speed limit and the advisory speed) is 6 mph or more. The *TCDH* reports that several state departments of transportation require a minimum speed differential of 5 or 10 mph to justify the use of the Advisory Speed plaque. Based on a nationwide survey of engineers, Lyles and Taylor *(14)* recommended the use of a plaque only when the speed differential is 10 mph or greater.

Supplemental Signs

Chevrons. Guidance for using Chevrons (W1-8) is provided in two documents. The *TCDH (16)* suggests that one or more Chevrons should be used along the curve when the speed differential *exceeds* 25 mph. The *TMUTCD* provides similar guidance; however, to be precise, it specifies that Chevrons may be used when the speed differential is 25 mph or greater. Chapter 3 of the *TMUTCD* also provides guidance on the spacing for Chevrons along the curve. This guidance is repeated in Table 2-3. The equation for Chevron spacing in the table footnote was derived for this report using the tabulated values in the *TMUTCD*.

Curve or Turn/Advisory Speed Sign. Guidance for using the Curve/Advisory Speed sign (W1-2a) and Turn/Advisory Speed sign (W1-1a) is provided in the *MUTCD*. It states that this sign may be used when the speed differential is 15 mph or greater. It also states that, if used, this sign *shall* be installed at the beginning of the turn or curve. Guidance for use of this sign is also discussed in the *TCDH*. This handbook recommends use of either the Curve/Advisory Speed sign or the Curve Speed sign (W13-5) when the speed differential is 16 mph to 25 mph. It goes further to recommend that the Curve/Advisory Speed sign should always be used when the speed differential exceeds 25 mph. The W1-1a and W1-2a signs are not recognized in the *TMUTCD*.

Curve Speed Sign. Guidance for using the Curve Speed (W13-5) sign is provided in the *MUTCD*. It states that a curve speed sign may be used when the speed differential is 15 mph or greater. It also states that, if the speed differential is 25 mph or greater, then one or more additional signs may be installed along the curve. Guidance for use of this sign is also discussed in the *TCDH*.

This handbook recommends use of either the Curve/Advisory Speed sign (W1-2a) or the Curve Speed sign when the speed differential is 16 mph to 25 mph. It goes further to recommend that the Curve Speed sign should always be used when the speed differential exceeds 25 mph.

Table 2-3. Delineator and Chevron Sign Spacing.

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

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

Travel Path Delineation

Chapter 3 of the *MUTCD* identifies raised pavement markers and delineators as guidance devices that can be used to improve travel path delineation. It is generally recognized that delineators are appropriate for more gradual curves while Chevrons are appropriate for sharper curves. The *TMUTCD* recommends the installation of raised pavement markers on all highways. It also recommends the use of delineators on curves where the speed differential is 15 to 24 mph. In contrast, the *TCDH* recommends the use of raised pavement markers or delineators when the speed differential is 6 mph or greater. The delineator spacing recommended in the *TMUTCD* is listed in Table 2-3. The equation underlying the tabulated values is also provided in the *MUTCD*.

Guidelines for Curve Signing Based on Friction or Energy Differential

This section describes guidelines for the use of curve-related traffic control devices based on friction, or energy, differential. In this regard, the friction differential is expressed as the difference between an acceptable limit of side friction and that actually required to negotiate the curve. The energy differential is expressed as the decrease in a vehicle's kinetic energy (i.e., work) required to slow the vehicle from the tangent speed to the curve speed.

Guidelines Based on Friction Differential

Glennon (*17*) developed guidelines for curve warning signs based on side friction demand. He rationalized that curves associated with higher friction demand should be associated with a heightened need to inform drivers of the change in alignment. He offered the candidate side friction thresholds and corresponding curve signing guidance shown in columns 1 and 2 of Table 2-4. The values listed in column 3 represent the difference between the side friction thresholds and 0.19.

Table 2-4. Guidelines for Curve Warning Signs Based on Friction Differential.

Side Friction Demand Range	Curve Warning Signs	Friction Differential [1]
0.19 or less	None	0.00
0.20 to 0.23	Curve warning sign	0.01 to 0.04
0.24 to 0.27	Curve warning sign with Advisory Speed plaque	0.05 to 0.08
0.27 to 0.30	Redundant curve warning sign and Advisory Speed plaque	0.08 to 0.11
0.30 to 0.34	Redundant curve warning sign, Advisory Speed plaque, and Chevrons	0.11 to 0.15
0.35 and up	Other measures to reduce speed or improve curve design	0.16 or greater

Note:
1 - Friction differential represents the difference between the side friction demand range and 0.19.

The friction differential concept described by Glennon (*17*) can be more generally defined as the difference between the side friction demand incurred by the vehicle and the upper limit of comfortable friction. This differential can be computed as:

$$\Delta f = \frac{v_{c,85,pc}^2}{g\,R} - f_{accept} \tag{7}$$

where,
Δf = side friction demand differential; and
f_{accept} = accepted upper limit of comfortable side friction demand.

In Equation 7, the accepted side friction demand limit can be specified as a constant (e.g., 0.19), or it can be represented as a function of speed (as in Table 2-1). In fact, the first two terms of Equation 2, and the trends in Table 2-1, suggest that the accepted side friction demand limit can be expressed as a linear function of tangent speed (i.e., $f_{accept} = b_0 - b_1 \times v_{t,85,pc}$).

Guidelines Based on Energy Differential

Herrstedt and Greibe *(18)* rationalized that curves associated with higher "risk" should be associated with a heightened need to inform drivers of the change in alignment. They suggested that curve risk is a function of the change in kinetic energy (or work) required to reduce the vehicle's speed from the tangent speed to the curve speed. This change in energy (or energy differential) is based on the tangent speed, curve speed, and vehicle mass. Using the principles of physics, the change in a vehicle's kinetic energy is computed as:

$$\Delta E = W \frac{v_{t,85,pc}^2 - v_{c,85,pc}^2}{2g} \tag{8}$$

where,
  $\Delta E =$ energy differential, ft-lb; and
  $W =$ vehicle weight, lb.

Herrstedt and Greibe *(18)* developed guidelines for curve signing in Denmark. Their guidelines are based on the specification of five risk categories. These categories are listed in Table 2-5. Category A coincides with a small energy differential such that the need for traffic control devices is modest. In contrast, Category E denotes a large energy differential and a need for many complementary devices. It should be noted that the traffic control device combinations listed in Table 2-5 are consistent with the practice of many international transportation agencies.

Table 2-5. Guidelines for Curve Warning Signs Based on Energy Differential.

Risk Category	Curve Warning Signs [1]	Travel Path Delineation	Energy Differential, ft-lbs [2]
A	None	Ordinary markings, Delineators	0.0 to 108,000
B	Curve warning sign	Ordinary markings, Delineators	108,000 to 200,000
C	Curve warning sign, Chevrons	Ordinary markings	200,000 to 287,000
D	Curve warning sign, Advisory Speed plaque, Chevrons	Profiled markings	287,000 to 384,000
E	Curve warning sign, Advisory Speed plaque, Long Chevron	Profiled markings	more than 384,000

Notes:

1 - A Long Chevron sign is formed by placing the legends from four Chevron signs together on one wide rectangular sign board.

2 - Energy differentials shown are based on a 4000 lb vehicle.

The relationship between speed and risk category, as developed by Herrstedt and Greibe *(18)*, are shown in Figure 2-7. In application, the analyst uses Figure 2-7 to identify the curve risk category based on knowledge of the 85th percentile tangent speed and curve design speed. Then, this risk category is used with Table 2-5 to determine the appropriate curve warning signs and travel path

delineation. It should be noted that these guidelines are based on knowledge of the 85th percentile tangent speed. This approach is in contrast to guidelines described in U.S. reference documents that use the regulatory speed limit (see Table 2-2).
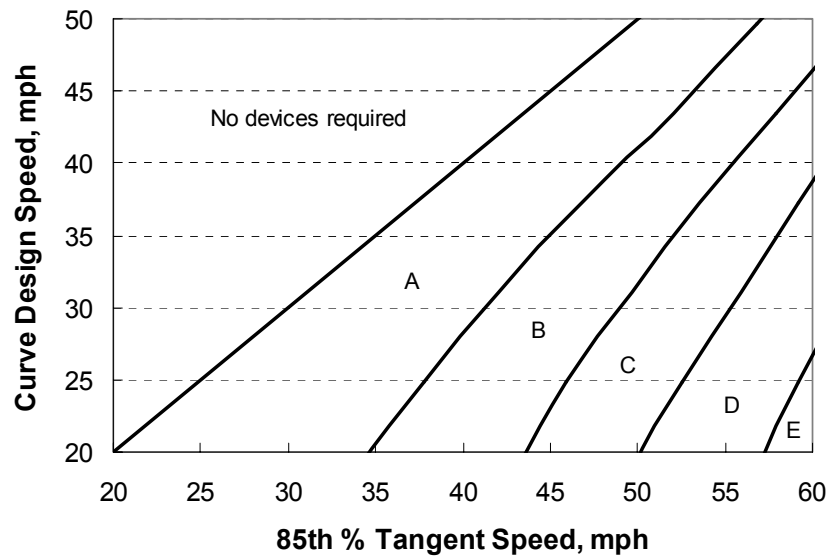
Figure 2-7. Curve Risk Categories.

Effectiveness of Curve Warning Signs

Research indicates that the inconsistent use of horizontal alignment signs, especially those with an Advisory Speed plaque, may have lessened the average motorist's respect for the message the signs convey (*19, 20*). On familiar highways, drivers come to learn that they can comfortably exceed the advisory speed for most curves. The concern is that these drivers may occasionally travel on roadways that are less familiar to them and where the advisory speed is posted at the maximum safe speed. These drivers may find themselves traveling too fast for conditions and experience a crash.

When making investment decisions, it is the expected safety benefit of an improvement that the engineer must ultimately weigh.   Hence, the most relevant measure for assessing the effectiveness of curve signing treatments is crash frequency. However, crash data have an inherent randomness that makes it difficult to detect a change in safety due to treatment, especially when the data represent a relatively short period of time. As a result, some researchers have evaluated sign effectiveness using safety surrogates such as speed reduction, lane placement, and advisory speed compliance percentage. A newly installed sign that is associated with a measurable speed reduction (or an increase in compliance percentage), is logically inferred to be associated with fewer crashes. But, unless the surrogate has previously been correlated with crash frequency, it cannot be used to determine whether the observed reduction in speed (or increase in compliance) will result in one less crash in 20 years or 20 fewer crashes every year.

Taylor et al. (21) discuss the issues and challenges associated with the use of surrogates to evaluate sign or marking effectiveness. Through a pilot study of nine intersection curves, they showed that lane placement variance, curve speed, and curve speed change were correlated with crash rate. An increase in lane placement variance, curve speed, or speed change corresponded to an increase in crashes.

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

Several reports were found that documented the effect of horizontal curve signing on speed. A study by Ritchie (23) examined driver response to the Curve sign and the Advisory Speed plaque. He found that average curve speeds exceeded the advisory speed when the advisory speed was less than 45 mph. The amount by which the average speed exceeded the advisory speed increased with decreasing advisory speeds. Thus, for an advisory speed of 40 mph, the average speed exceeded the advisory speed by only 2 mph (i.e., the average speed was 42 mph). However, for an advisory speed of 20 mph, the average speed exceeded the advisory speed by 10 mph.

Lyles (20) examined the use of a wide range of curve-related warning signs and regulatory signs. His base of comparison was the sole use of a curve warning sign. Sign alternatives included the Curve sign with one of the following speed-based signs: Advisory Speed, "maximum safe speed," and regulatory speed limit. He found that none of the sign alternatives was more effective at reducing speed than the sole use of the Curve sign. More recently, Vest and Stamatiadis (24) evaluated the addition of several traffic control devices intended to reduce driver speed prior to curve entry. These devices included: addition of flags to the Curve sign, addition of flashers to the Curve sign, installation of the Curve/Advisory Speed sign (W1-2a) at the point of curvature, and transverse pavement lines at the curve warning sign. They found that each device combination resulted in a ±1.0 mph change in speed. The speed decreased by 1.0 mph for two of the combinations. However, it *increased* by 1.0 mph for two other combinations.

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

ADVISORY SPEED CRITERIA

This part of the chapter summarizes a review of the literature related to advisory speed setting criteria. Initially, the objectives of horizontal curve signing are reviewed. Then, the guidance offered in several authoritative documents is described, along with the current practices of several

agencies. Finally, several issues associated with current practice are identified and described in terms of their implications on compliance and safety.

Objectives of Horizontal Curve Signing

An important objective in horizontal curve signing is having a uniform and consistent display of advisory speed on curves of similar geometry, character (e.g., sight distance, intersection presence, etc.), and road surface condition. As stated in the *MUTCD*, "uniformity of the meaning of traffic control devices is vital to their effectiveness" (*12*, Section 1A.02). It further describes the benefits of uniformity in the following statement.

> "Uniformity of devices simplifies the task of the road user because it aids in recognition and understanding, thereby reducing perception/reaction time. Uniformity means treating similar situations in a similar way." (*12*, Section 1A.06).

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

Lyles and Taylor (*14*) conducted a nationwide survey of 344 practitioners on the topic of horizontal curve signing practices. Questions were asked about the uniformity and consistency of advisory speeds in the practitioner's state. The findings from this survey question are summarized below, as they relate to the respondents' perceptions of jurisdictions other than their own.

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

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

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

With regard to consistency with driver expectation, 62 percent of the respondents believe that advisory speeds are too low. In contrast, 3 percent believe that advisory speeds are too high. These findings imply that only 35 percent of respondents believe that advisory speeds are about right. Based on their survey findings, Lyles and Taylor (*14*) offered the following observation:

> "Advisory speed signing appears to be largely ineffective if the goal is for drivers to actually travel at the posted advisory speed: drivers either fail to notice advisory

speed plaques, or, more likely, they simply reject the literal advisory speed recommendations, driving at a reduced speed that they feel is appropriate" (*14,* p. 2).

Lyles and Taylor (*14*) also conducted focus groups with practitioners in three states. From these discussions, it was found that practitioners generally agreed that "almost all curves signed with advisory speed plates can easily and safely be traversed at "+10" mph over the posted advisory speed..." (*14*, p. 5). However, they noted a concern expressed by the practitioners about any change in the advisory speed criteria. They rationalized that an advisory speed that is more consistent with the majority of drivers would likely lead to larger inconsistencies in the short term and possibly have an adverse effect on safety.

Current Practice

This section reviews the criteria recommended by two reference documents for establishing the curve advisory speed. It focuses on the criteria offered in the *MUTCD* (*12*) and the *Green Book* (*1*). One subsection is devoted to the criteria described in each document. The last subsection compares the two sources of criteria.

MUTCD Criteria

The *MUTCD* (*12*) indicates that the advisory speed may be based on any of the following criteria:

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

The *TMUTCD* (*13*), and previous editions of the *MUTCD*, recognizes the engineering study as the basis for determining the advisory speed.

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

The second bullet item in the preceding list specifies a threshold ball-bank indicator reading as the criterion for defining a curve's advisory speed. The ball-bank indicator is a convenient device for measuring the lateral acceleration experienced by motorists traveling along a curve. The relationship between the ball-bank reading and lateral acceleration (expressed as side friction demand) is defined by following equation:

$$\alpha = 57.3 \left(\tan^{-1}(f_D + \frac{e}{100}) - \tan^{-1}(\frac{e}{100}) \right) (1 + k) \tag{9}$$

where,

  $\alpha =$ ball-bank indicator angle (or "reading"), degrees; and

  $k =$ roll rate, radians/radian (or r/r).

The derivation of Equation 9 is provided in Appendix A. A roll rate k of 0.121 r/r is applicable to most late model passenger car sedans. Using this constant, the threshold angle of 16 degrees corresponds to a side friction factor of 0.26 for superelevation rates in the range of 2 to 10 percent.

Figure 2-8 illustrates the relationship between the 85th percentile speed and the ball-bank angle criteria. Shown in this figure are side friction factors computed using Equation 1, with data reported by Chowdhury et al. (19) for 28 curves in three states. Each data point represents the data for one curve. The solid data points correspond to the side friction demand associated with the 85th percentile curve speed. The open circles correspond to the side friction demand associated with the 50th percentile speed measured at each curve. The two thin lines sloping downward represent lines of best fit to the two sets of data points. The thick, horizontal line corresponds to a side friction factor of 0.26 (i.e., 16 degrees).
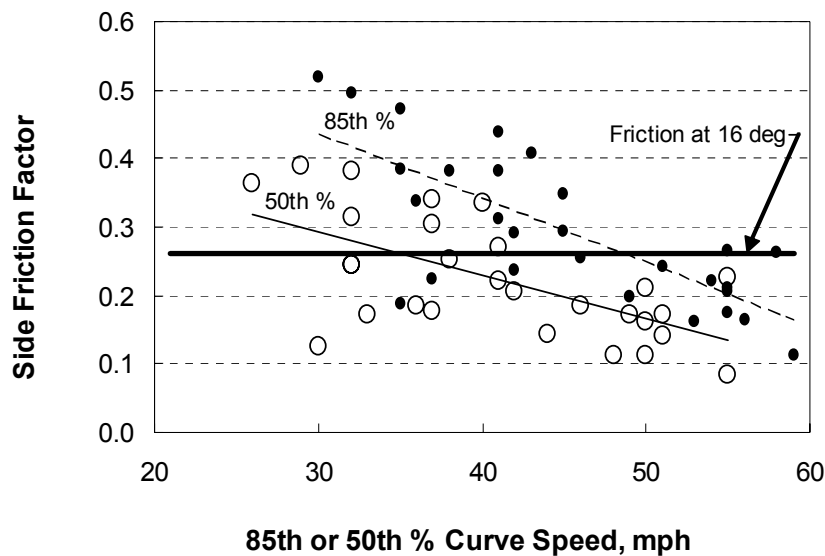
Figure 2-8. Distribution of Side Friction as a Function of Curve Speed.

Comparing the three trend lines, it can be seen that the 16 degree reading corresponds to about the 50th percentile speed when the curve speed is 35 mph. Similarly, it corresponds to about the 85th percentile speed when the curve speed is 50 mph. In other words, the 16 degree criterion suggested by the *MUTCD* does not have a unique relationship with one percentile speed value (nor would any other single ball-bank angle). Hence, if the two criteria offered by the *MUTCD* are both used by an agency, they are not likely to yield consistent advisory speeds. Moreover the use of the 16 degree criterion is likely to yield advisory speeds that are more nearly equal to the 85th percentile speed on high speed curves, and more nearly equal to the 50th percentile speed on low-speed curves.

AASHTO-Based Criteria

The basis for using the ball-bank indicator stems from research conducted in the 1930s and cited in the earliest editions of the *Green Book* (*1*). The *Green Book* states that curve speeds that do not cause "driver discomfort" correspond to ball-bank readings of 14 degrees for speeds of 20 mph or less, 12 degrees for speeds of 25 to 30 mph, and 10 degrees for speeds of 35 mph or more. It notes that these angles are consistent with side friction factors of 0.21, 0.18, and 0.15, respectively. In the years following the presentation of this discussion in the *Green Book,* the *TCDH* (*16*) notes that most transportation agencies have adopted ball-bank criteria of 14, 12, and 10 degrees (for the speed ranges noted previously) as the basis for defining the curve advisory speed. However, some agencies are noted in the *TCDH* to use 10 degrees, regardless of speed.

The relationship between curve speed and radius is shown in Figure 2-9 for ball-bank readings of 10 and 14 degrees. This relationship was defined using Equation 1. The thin trend line was computed using Equations 1 and 2 for an 85th percentile tangent speed of 60 mph.
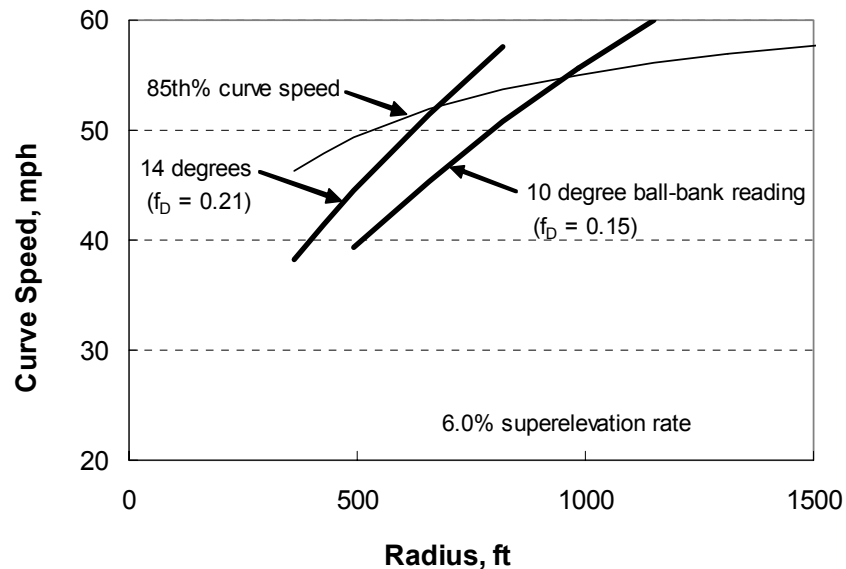
Figure 2-9. Relationship between Curve Speed, Ball-Bank Reading, and Radius.

The "10 degree" trend line in Figure 2-9 intersects the thin trend line at about 950 ft. An engineer who uses the 10-degree criterion to establish an advisory speed for a curve with an 950 ft radius would likely determine that the advisory speed should be 55 mph. For this one combination of radius and tangent speed, the advisory speed would be consistent with the 85th percentile curve speed. However, for sharper radii, the 85th percentile curve speed would exceed that established using the 10-degree criterion. For example, if the 10-degree criterion is used on a 500 ft curve with a tangent speed of 60 mph, the advisory speed is likely to be 40 mph, but the 85th percentile curve speed is likely to be 50 mph.

The trends in Figure 2-9 indicate that drivers traveling on sharp curves do not necessarily adopt a speed that is associated with a constant level of side friction. Rather, they reduce their speed as they enter the curve based on their consideration of both the added travel time associated with the speed reduction and their level of comfort associated with the side friction demand. They accept a level of side friction that reflects a compromise between comfort and added travel time. Thus, driver comfort may be an appropriate basis for highway geometric design, but it may not form the appropriate basis for selecting an advisory speed because "comfort" is not the only factor a driver considers when choosing curve speed.

Guidance Comparison

The criteria identified in the previous two subsections are compared in this subsection. Equation 9 was used to convert the stated ball-bank criteria to equivalent side friction factors. The ball-bank angles and corresponding side friction factors are listed in Table 2-6. Guidance offered by Chowdhury et al. (*19*) is also listed in Table 2-6, but it has not been adopted by any agency. It is listed in the table to facilitate its comparison with the guidance described in this section. This comparison will be discussed in a subsequent section.

Table 2-6. Ball-Bank Readings Recommended by Various Agencies.

Source	Ball-Bank Indicator Reading (in degrees) by Curve Speed, mph										
	10	**15**	**20**	**25**	**30**	**35**	**40**	**45**	**50**	**55**	**60**
AASHTO-Based (*1*)	14	14	14	12	12	10	10	10	10	10	10
Chowdhury et al. (*19*)	20	20	20	20	16	16	16	12	12	12	12
MUTCD (*12*)	16	16	16	16	16	16	16	16	16	16	16
	Side Friction Demand Factors[1]										
AASHTO-Based (*1*)	0.23	0.23	0.23	0.19	0.19	0.16	0.16	0.16	0.16	0.16	0.16
Chowdhury et al. (*19*)	0.33	0.33	0.33	0.33	0.26	0.26	0.26	0.19	0.19	0.19	0.19
MUTCD (*12*)	0.26	0.26	0.26	0.26	0.26	0.26	0.26	0.26	0.26	0.26	0.26

Note:
1 - Equation 9 was used to compute equivalent side friction factors for the stated ball-bank indicator readings.

Equation 1 was used compute the curve speed associated with each side friction demand factor listed in Table 2-6. The results are shown in Figure 2-10 for a superelevation rate of 6 percent. Also shown is the 85th percentile curve speed shown previously in Figure 2-2 for a tangent speed of 60 mph. The speed obtained from Figure 4-10 of the *TCDH* (*16*) is also shown. This figure in the *TCDH* shows a nomograph that can be used to estimate the advisory speed based on consideration of curve radius and superelevation rate.

The trends in Figure 2-10 indicate that a wide range in advisory speeds is possible, depending on the criterion used (e.g., friction factor, ball-bank reading, or 85th percentile speed). To illustrate the implications of this range, consider a 500 ft curve with 6 percent superelevation rate and an 85th percentile tangent speed of 60 mph. Figure 2-10 indicates that this curve will likely be

associated with an 85th percentile speed of 50 mph. In contrast, the AASHTO-based guidance would suggest an advisory speed of 40 mph.
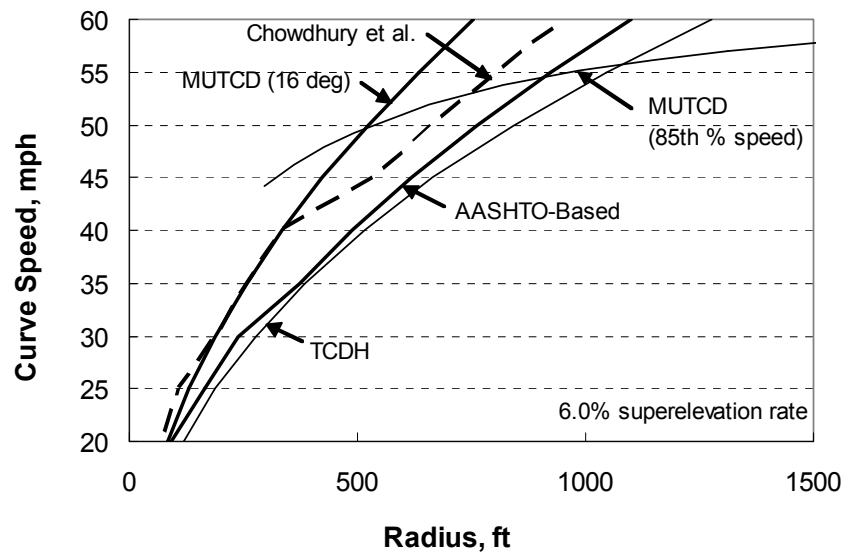
Figure 2-10. Curve Speed Associated with Various Advisory Speed Criteria.

Issues with Current Practice

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

- uniformity in advisory speed among curves,
- consistency in advisory speed with driver expectation,
- determinating the appropriate advisory speed criteria, and
- consequences of a change in criteria.

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

Uniformity in Advisory Speed among Curves

This subsection uses data reported in the literature to examine the uniformity in advisory speed among the curves in various jurisdictions. This examination focuses on the range of ball-bank readings that have been obtained for a given curve and discusses possible sources of this variability. The consequences of a lack of uniformity are examined by comparing posted advisory speeds with those established by researchers using a ball-bank indicator under controlled conditions.

Evidence: Variable Ball-Bank Readings. Chowdhury et al. (*19*) measured the speed distribution at 28 rural two-lane highway curves. Collectively, these curves represent three states. For each curve, they quantified the 85th percentile curve speed, curve radius, and superelevation rate.

They then drove each curve at the 85th percentile speed and recorded the maximum ball-bank reading. These data were used by the authors of this report to estimate the side friction *angle* for each of the 28 curves. This angle represents the portion of the ball-bank angle that is attributable to side friction. It is computed using the following equation:

$$ f_r = \tan^{-1}\left[\frac{(1.47\ V_c)^2}{g\ R}\right] - \tan^{-1}\left(\frac{e}{100}\right) \qquad (10) $$

where,
   f_r = side friction angle, radians.

The derivation of Equation 10 is provided in Appendix A. The relationship between side friction angle and the ball-bank readings reported by Chowdhury et al. is shown in Figure 2-11. Each data point shown in the figure represents one curve.
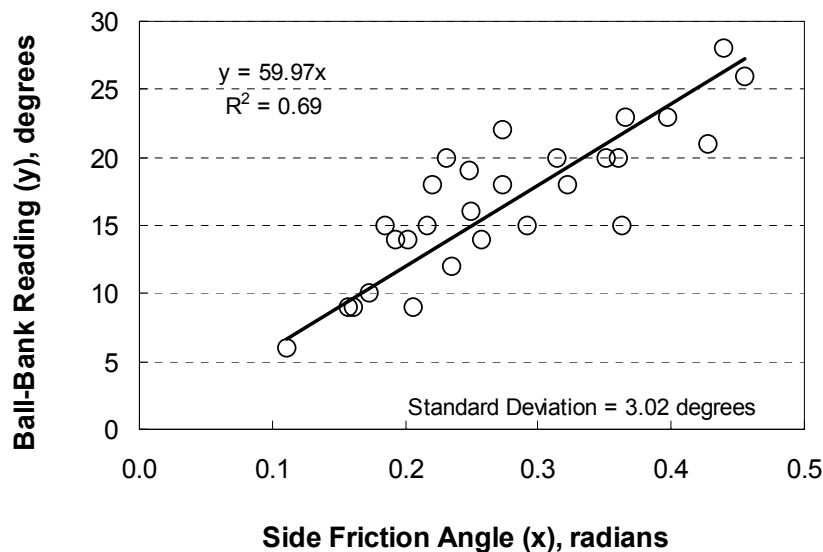
Figure 2-11. Variation in Ball-Bank Readings in Chowdhury Data.

The trend line shown in Figure 2-11 represents the best-fit regression line. The root mean square error (hereafter, referred to as the "standard deviation") of the regression is 3.02 degrees. This statistic indicates the variability of the observed readings about the trend line. A standard deviation of 0.0 degrees would have been obtained if conditions were ideal for each curve, the curve was circular, and the driver exactly tracked the curve radius.

The following equation describes the theoretic relationship between the ball-bank reading and side friction angle:

$$ \alpha = 57.3\ f_r\ (1\ +\ k) \qquad (11) $$

The derivation of Equation 11 is provided in Appendix A. This equation indicates that the relationship between ball-bank reading and friction angle is linear, with an intercept through the

origin and a slope slightly larger than 57.3 deg/r (the amount by which it exceeds 57.3 is attributable to body roll). If the curve is circular, the vehicle tracks the curve, and the pavement surface is smooth, then the observed ball-bank reading should equal the value obtained from Equation 11.

The slope of the line in Figure 2-11 suggests that the test vehicle used by Chowdhury et al. (19) had a roll rate of 0.047 r/r (= 59.97/57.3 – 1). The 95 percent confidence interval of this estimate is 0.0 to 0.12 r/r. The rate of 0.047 r/r is lower than the 0.121 r/r noted previously as representative of most late model passenger cars. However, it is likely that the estimate is low due to random variation and that the test vehicle had a roll rate nearer to 0.12 r/r.

More recently, Carlson et al. (25) evaluated 18 curves on rural two-lane highways in Texas. They conducted a series of test runs at each curve for the purpose of evaluating the posted advisory speed. They reported the observed ball-bank reading for each test run. Equation 10 was used with the reported curve geometry and test run speed to estimate the side friction angle for each curve. The relationship between side friction angle and reported ball-bank readings is shown in Figure 2-12. Each data point shown in the figure represents one test run.
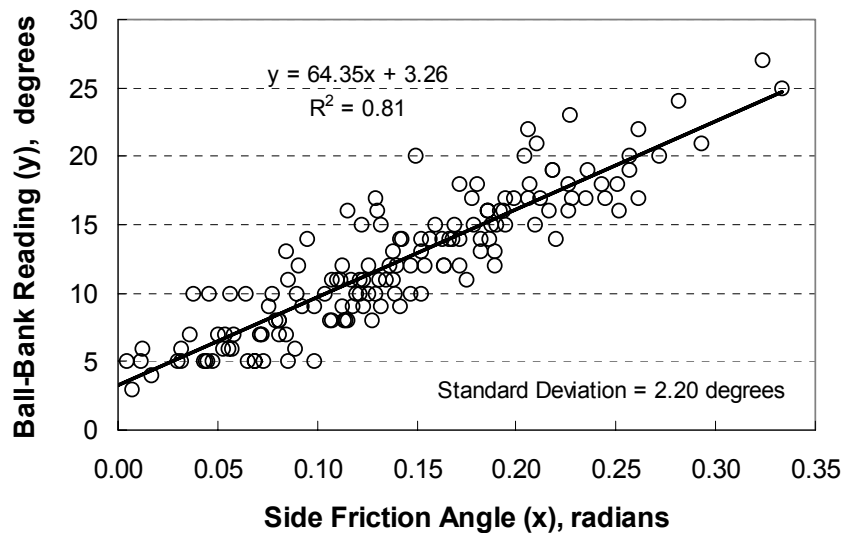
Figure 2-12. Variation in Ball-Bank Readings in Carlson Data.

As with Figure 2-11, the trend line shown in Figure 2-12 represents the best-fit regression line. The standard deviation associated with this line is 2.20 degrees. This value is smaller than that found in Figure 2-11 because many of the data points in Figure 2-12 were obtained at the same curve. Readings obtained in successive runs at the same curve will control (or remove) some of the variability in readings that would otherwise be obtained had each test run been conducted at a different curve.

The variability associated with Figures 2-11 and 2-12 is relatively large and suggests that any given test run using a ball-bank indicator is likely to be associated with a high degree of uncertainty.

With regard to Figure 2-12, the standard deviation of 2.20 degrees translates to a 95 percent confidence interval of ±4.4 degrees for the true reading. This range translates into a 95 percent confidence interval of ±8 to ±10 mph for the estimate of advisory speed. In other words, the variability inherent to the ball-bank indicator makes it likely that advisory speeds will vary by 5 mph, and sometimes 10 mph, among curves of similar geometry and condition.

The variability in the ball-bank readings among curves in a jurisdiction is likely due to a variety of sources, such as:

- rough pavement surface,
- occasional steering corrections made while traveling along the curve,
- variation in pavement friction supply,
- suspension differences in the vehicles used to establish advisory speeds,
- quality of ball-bank indicator and speedometer calibration, and
- diligence and training of persons using the device.

The first three sources contribute to variability in the ball-bank readings at the same curve as well as among similar curves. In this regard, even when the same vehicle and driver are used during a series of test runs at the same curve, the maximum observed reading will likely vary on successive test runs due to one or more of the first three sources listed.

With regard to pavement surface roughness, Moyer and Berry (26) noted that ball-bank readings are likely to be biased high by 1 or 2 degrees on curves with rough pavements. They noted that this bias would translate into an advisory speed that would be about 5 mph too low. In a subsequent re-examination of this issue, Merritt (27) suggested that "...the application of the ball-bank indicator criteria may be questionable on rough surfaces or gravel roads where surface variability may be extreme" (27, p. 17).

Pavement surface roughness can be a consequence of any type of pavement deformation or settlement that causes the superelevation to vary along the length of the curve. A detailed examination of 18 rural two-lane highway curves in Texas by Carlson et al. (25) indicated a wide range in superelevation along the length of the curve. In fact, they found it to range from 0 to 8 percent among the 18 curves, with a typical variation along any one curve of 2 to 3 percent.

With regard to steering corrections, the steering system of most vehicles has a slight understeer or oversteer that makes it difficult for their drivers to track the curve radius (26). Tire slip angles (as are influenced by tire pressure, loading, camber, caster, suspension, etc.) dictate whether a vehicle exhibits understeer or oversteer. When either state exists, the driver has to correct the path of the vehicle to avoid spinning out or sliding off of the roadway. These steer corrections translate into the vehicle tracking a sharper radius (than that of the roadway) for short sections of the curve. This behavior was observed by Glennon and Weaver (28). They found that the radius of the vehicle's tracked path was, at its sharpest point, equal to 0.7 to 0.9 times the highway curve radius. This finding is also consistent with that of MacAdam et al. (29) who reported that side friction demand peaks can be 15 percent higher than the average friction level because of "steering fluctuations" along the curve.

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

Several of the aforementioned sources of variability were likely present in the ball-bank indicator readings observed by Chowdhury et al. (19) and by Carlson et al. (25). Thus, the standard deviations listed in Figures 2-11 and 2-12 reflect the collective effect of these sources. The smaller standard deviation in the data from Carlson et al. is likely a reflection of the fact that many of the observations are obtained from repeated test runs at the same curve.

The last three sources of variability listed are also likely to be present when the ball-bank indicator is used by an agency on an area-wide basis. The extent to which they would increase the standard deviations noted in Figures 2-11 and 2-12 has not been researched.

Consequences: Posted Advisory Speed vs. Ball-Bank-Based Advisory Speed. The previous section quantified the variability associated with the ball-bank indicator when it is used to establish curve advisory speeds on an area-wide basis. Numerous sources of variability were identified. This section examines the consequences of this variability in terms of the uniformity of advisory speeds among curves.

The data used for this examination were obtained from Chowdhury et al. (19) and Carlson et al. (25). Both groups of researchers used the ball-bank indicator method to establish the advisory speed for a set of curves. Their choice of this method is likely in recognition of the fact that it is the most widely used method to determine curve advisory speed. A survey by Lyles and Taylor (14) indicates that 82 percent of agencies use the ball-bank indicator method to determine advisory speed.

For this discussion, a curve's posted advisory speed is defined as uniform when it matches the speed determined by using the ball-bank indicator for the following "threshold" ball-bank readings: 14 degrees for speeds of 20 mph or less, 12 degrees for speeds of 25 to 30 mph, and 10 degrees for speeds of 35 mph or more. These readings are obtained from the *Green Book* and are used in Texas to establish advisory speeds on the state highway system (30). It is recognized that this approach may introduce some variability beyond that identified in the previous section. For example, an agency may use different threshold readings and thereby, may appear non-uniform when compared to the stated readings. Also, an agency may not even use the ball-bank indicator, but instead may choose to base the advisory speed on a measured speed distribution or curve radius. Regardless, it is believed that the variability due to these sources is small, relative to that due to the sources noted in the previous section.

Chowdhury et al. (19) examined advisory speed uniformity in three states. They recorded the posted advisory speed for each of 28 curves and then used the ball-bank indicator to estimate the appropriate advisory speed. Their findings are shown in Figure 2-13 using the open circles. Each data point in this figure represents one curve study site. Also shown are similar data recorded by

Carlson et al. (25) for 18 curves in Texas. Their findings are shown using black squares. The thin trend line shown in this figure is a "y = x" line, such that a data point would fall on this line if the corresponding site had a posted advisory speed equal to the ball-bank-based advisory speed.
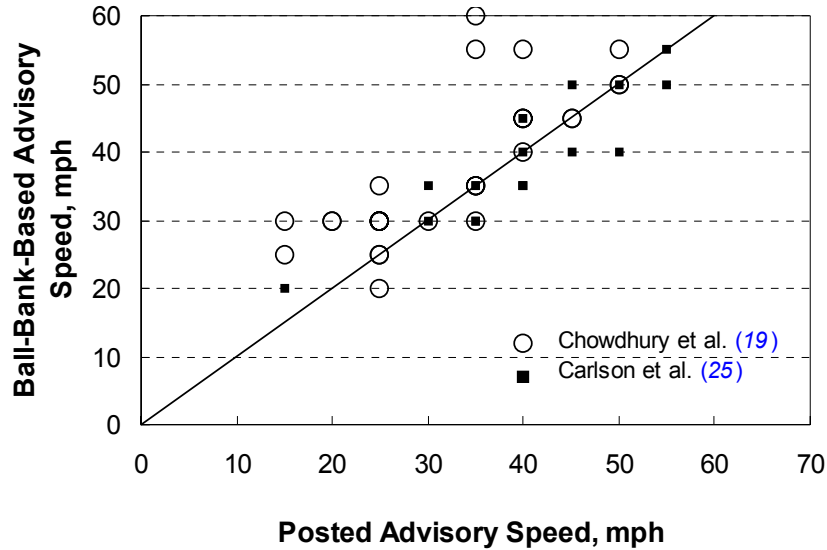
Figure 2-13. Comparison of Posted and Estimated Advisory Speeds.

Chowdhury et al. (19) found that only 36 percent of the curves had posted advisory speeds that were consistent with their estimate of the appropriate advisory speed. The variation ranged from -5 mph to +25 mph, with an average difference of +5 mph. Carlson et al. (25) found only 33 percent of curves had their advisory speeds set in accordance with TxDOT policy. The variation was ±5 mph, with an average difference of -1 mph.

Consistency in Advisory Speed with Driver Expectation

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

Evidence: Curve Speed Choice and Corresponding Ball-Bank Angles. Research indicates that tangent speed has a significant influence on driver curve speed choice (3). The model developed by Bonneson (3) was shown previously in Figure 2-1. A variation of this model that estimates average curve speed (as opposed to the 85th percentile speed) is shown in Figure 2-14a. The trends in this figure indicate that a driver's curve speed choice is influenced by tangent speed. For example, a curve with a 500 ft radius and 6 percent superelevation rate will likely be associated with an average speed of 48 mph when the tangent speed is 60 mph. This same radius and superelevation combination would have an average speed of 43 mph if the tangent speed was 50 mph, and a curve speed of 37 mph if the tangent speed was 40 mph.

a. Curve Speed.
b. Ball-Bank Reading.
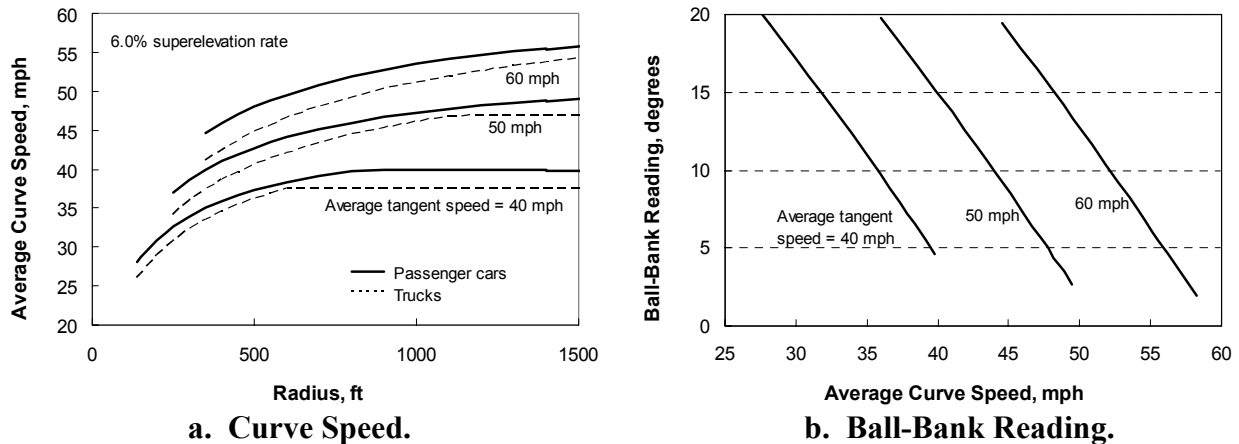
Figure 2-14. Relationship between Radius, Speed, and Ball-Bank Reading.

Figure 2-14b illustrates the ball-bank readings that correspond to the curve speed and radius combinations shown in Figure 2-14a. Several points can be made from the trends shown in this figure. First, the ball-bank reading that corresponds to driver speed choice is not a constant. Rather, it decreases with increasing curve speed and reflects the driver's desire for less side friction at higher curve speeds. No one ball-bank reading describes driver speed choice for the full range of radii and tangent speeds.

Second, the relationship between ball-bank reading and curve speed is dependent on the tangent speed. For example, consider a curve with an average curve speed of 39 mph. A 5 degree ball-bank reading is likely to accurately reflect driver speed choice when this curve has a tangent speed of 40 mph. In contrast, a 17 degree reading is more likely to reflect driver speed choice when the tangent speed is 50 mph.

Third, a ball-bank reading of 10 degrees corresponds to a speed reduction of between 4 and 8 mph, depending on tangent speed. For typical speed distributions, this range equates to a 9 to 13 mph reduction below the 85th percentile speed. It suggests that the use of a 10 degree threshold will equate to an advisory speed that is 9 to 13 mph below the regulatory speed limit. This range is consistent with the experiences of the engineers surveyed by Lyles and Taylor (*14*).

Consequences: Advisory Speed vs. Measured Curve Speed. The previous section quantified the relationship between driver speed choice and radius. It then related this speed to the corresponding ball-bank reading associated with the average speed chosen by drivers. It was noted that the traditional use of a 10 degree threshold does not yield advisory speeds that are consistent with driver speed choice. This section examines the consequences of this inconsistency by examining the relationship between the advisory speed and the measured speed distribution for several curves.

The data cited by Chowdhury et al. (*19*) are used for this examination. They measured the speed distribution on each of 28 curves in three states. They also recorded the posted advisory speed

associated with each curve. Figure 2-15a compares the posted advisory speed with the observed 50th percentile speed. Each data point in this figure corresponds to one curve. The data points shown indicate that the 50th percentile speed exceeds the posted advisory speed by as much as 20 mph. The large variability in the data is a reflection of the sources of variability noted in the previous section.

a. Posted Advisory Speed.   b. Estimated Advisory Speed.
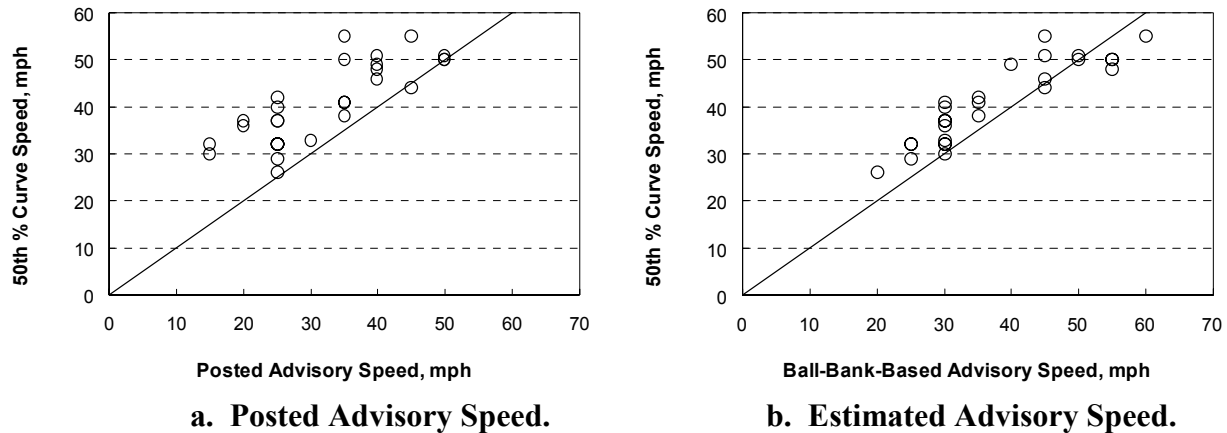
Figure 2-15. Comparison of the 50th Percentile Curve Speed with the Advisory Speed.

Chowdhury et al. (*19*) also used a ball-bank indicator to estimate the appropriate advisory speed for each curve. The thresholds they used are: 14 degrees for speeds of 20 mph or less, 12 degrees for speeds of 25 to 30 mph, and 10 degrees for speeds of 35 mph or more. These estimated advisory speeds are shown in Figure 2-15b. Compared to Figure 2-15a, the variability in Figure 2-15b is reduced because Chowdhury et al. used the same test vehicle and a consistent technique. It is noted that the 50th percentile speed exceeds the estimated advisory speed by no more than 10 or 11 mph. For higher curve speeds, the 50th percentile speed is about equal to, or slightly lower than, the advisory speed.

The sources of variability (as described in the previous section) have a tendency to introduce a bias in the advisory speed estimate, relative to the speed of the average (or 50th percentile) driver. Evidence of this bias can be seen by comparing Figures 2-15a and 2-15b. In Figure 2-15a, the posted advisory speed is an average of 10 mph below the 50th percentile speed. Yet in Figure 2-15b, the posted advisory speed is only about 5 mph below the 50th percentile speed for advisory speeds less than 50 mph. The additional 5 mph of bias (= 10 - 5) stems from the practice of using the *maximum* ball-bank reading obtained while traveling along the curve. As the vehicle travels along the curve, momentary spikes in the ball-bank reading may occur because of one or more sources of variability. These spikes are likely to be recorded as the maximum ball-bank reading and thus, are used to establish the advisory speed. As a consequence, the advisory speed is established at a lower value than it would have otherwise been set if the variability had not been experienced.

The common practice of signing both directions of the curve using the same advisory speed can also contribute to the variability shown in Figures 2-15a and 2-15b. Specifically, this practice adds variability when the superelevation along the curve is different for the two travel directions.

Data collected by Carlson et al. (*25*) for 18 curves on rural two-lane highways in Texas indicate that superelevation rate was different by direction for 16 of 18 curves. The range of differences was 0 to 8 percent, with a typical variation along any one curve of 2 to 3 percent.

Determining the Appropriate Advisory Speed Criteria

As indicated in the section titled Current Practice, several different criteria are used to define the advisory speed. The guidance in the *MUTCD* (*12*) is sufficiently general as to allow considerable flexibility in curve signing and advisory speed setting. This flexibility is viewed as a positive attribute by many engineers because it allows the use of engineering judgment when making decisions about curve signing or advisory speed setting (*14*). However, it has led to a wide variability in signing practices and advisory speed setting procedures. Moreover, the AASHTO-based criteria appear to be inconsistent with the speed chosen by both passenger car and truck drivers. Finally, the ball-bank indicator appears to be an imprecise device for establishing advisory speeds. These factors have combined to result in inconsistent curve signing and caused nearly universal disrespect for curve advisory speeds. These findings raise the questions of "What are the appropriate advisory speed criteria?" and "How can they be used to establish a consistent advisory speed?"

The use of the 85th percentile speed as the basis for advisory speed setting procedures was posed to 39 practitioners in a series of focus groups convened by Lyles and Taylor (*14*). The consensus was that the 85th percentile curve speed was too high, such that it would be dangerous to post on an Advisory Speed plaque.

In recognition of the aforementioned concerns, Chowdhury et al. (*19*) recommended ball-bank readings that they believe reflect side friction demand of the 50th percentile driver. These ball-bank readings are 20 degrees for speeds of 25 mph or less, 16 degrees for speeds of 30 to 40 mph, and 12 degrees for speeds of 45 mph or more. Based on Equation 9, ball-bank angles of 20, 16, and 12 degrees correspond to side friction factors of 0.33, 0.26, and 0.19. They are shown in Figure 2-16 along with the same friction factors previously shown in Figure 2-8.

The criteria recommended by Chowdhury et al. (*19*) are shown in Figure 2-16 using the thick trend line. In general, the criteria are roughly equivalent to the side friction demand of the 50th percentile driver for speeds less than 50 mph. For speeds of 50 mph or more, the "12 degree" threshold (equal to a side friction factor of 0.19) ranges from the 50th percentile driver at 45 mph to the 85th percentile driver at about 55 mph. Figure 2-10 (shown previously) illustrates the relationship between radius and advisory curve speed obtained using the criteria recommended by Chowdhury et al. (*19*).

Consequences of a Change in Criteria

A survey of practitioners by Lyles and Taylor (*14*) indicated that some practitioners are opposed to using the 85th percentile speed because it would be "dangerous." The danger stems from a recognition that drivers have grown accustomed (and expect) to be able to exceed the advisory speed, which they believe is currently set at a value that is about 10 mph below the average speed.

If the criteria were changed such that the posted advisory speed was increased (and drivers were not made aware of the change), then the driver's expectancy would be violated and there would likely be an increase in crash risk. It should be noted that the trend in Figure 2-15b suggests that an advisory speed based on commonly used criteria is, on average, about 5 mph below the 50th percentile speed. This advisory speed is roughly equal to the 20th percentile speed.
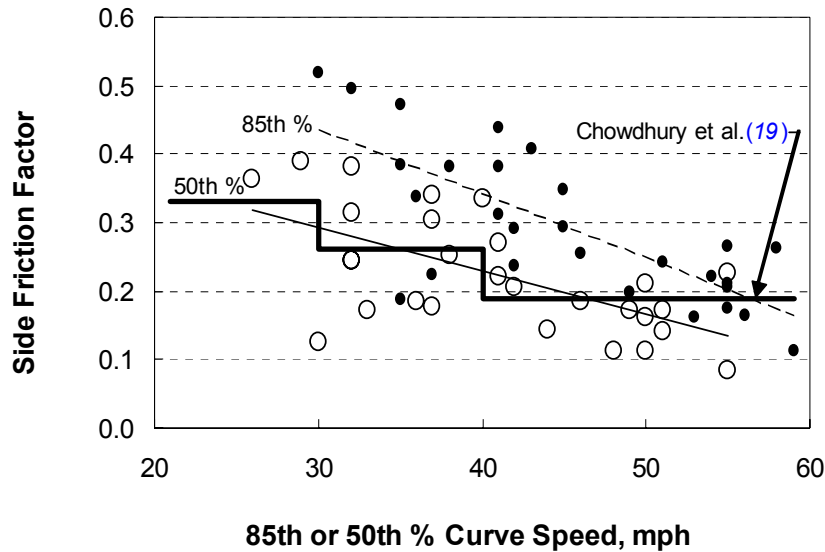
Figure 2-16. Examination of Chowdhury Guidance.

ENGINEERING STUDY METHODS FOR SETTING A CURVE ADVISORY SPEED

Three methods have been used to establish advisory curve speeds as part of an engineering study. The most commonly used method is based on the ball-bank indicator. A recent survey by Lyles and Taylor (*14*) revealed that 82 percent of the agencies represented used a ball-bank indicator to determine advisory speeds. A second method is based on Equation 1 and requires knowledge of curve radius and superelevation rate. It is referred to herein as the "compass method." The survey by Lyles and Taylor indicated that 22 percent of the agencies have used this method. A third method is based on the direct measurement of curve speed. The survey indicated that 18 percent of agencies have used this method. Each method is summarized in this part of the chapter.

Ball-Bank Indicator

This method requires the use of a ball-bank indicator (digital or vial) mounted on the dashboard of a test vehicle. Threshold values of the ball-bank reading are specified in advance of the test runs and are presumed to reflect a speed that reasonable (and likely unfamiliar) drivers would feel is appropriate for the curve. The advisory speed for a specific curve is established through a series of test runs using a typical passenger car. When the vial-type ball-bank indicator is used, the analyst in the test car monitors the device and determines the maximum reading obtained during

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each test run. The highest test speed for which the maximum reading does not exceed the threshold value is specified as the advisory speed.

Compass Method

This method is based on the use of an equation to estimate the advisory speed for a curve of specified radius and superelevation rate. This method requires the acquisition of curve radius and superelevation rate information about each curve--data that can be obtained from as-built plan sheets or measured in the field.

Radius can be measured in the field using a variety of techniques. However, the most efficient method is based on the use of a compass (hence the name of this method) and a distance-measuring instrument. The compass is used to measure the vehicle heading at two points along the curve. The difference in the two headings represents the curve deflection angle between these two points. The distance-measuring instrument is used to measure the length of the curve between the two points. The curve radius is estimated by dividing the curve length by the deflection angle (in radians). When the curve is known to be circular, any two points can be selected on the curve. However, if compound curvature or spiral transitions exist, then the two points should be located at about the "1/3 points" (i.e., one third of the length of the curve).

Superelevation rate can also be measured using a variety of techniques. However, the most efficient method is based on the use of a ball-bank indicator. In this application, the ball-bank indicator is mounted on the vehicle dashboard (just as it is in the ball-bank indicator method), and a reading is taken when the vehicle is stopped near the middle of the curve. The superelevation rate (in percent) is estimated as 1.56 times the ball-bank reading.

The advisory speed nomograph described in the *TCDH* (*16*) is based on information about radius and superelevation. Thus, it represents a variation of this method. The curve speed prediction equation depicted in Figure 2-1 represents a refinement of this method because it incorporates an important sensitivity to tangent speed.

Direct Measurement of Curve Speed Distribution

This method requires the direct measure of vehicle speed at the curve mid-point. Speed can be measured using a traffic classifier or a radar gun. The former device would be left unattended for one day at the curve of interest for the purpose of measuring the distribution of speed in a typical traffic stream. The latter device would be used by a technician to measure vehicle speed during a specified time period. The issue of sample size has not been established for curve speed evaluation, but it is likely to be similar to that needed for establishing regulatory speed limits. Sample sizes for this application typically consist of about 100 vehicle speed measurements. It should be noted that Chowdhury et al. (*19*) suggest that a sample size of only 10 vehicles is sufficient for establishing the advisory curve speed.

Regardless of the device used to measure speed, the advisory speed is established as that speed equal to a specified percentile speed. Only free-flowing vehicles are measured. This method

has the advantage of directly measuring the curve speed preferences of the population of drivers (including both car and truck drivers) as they interact with the subject curve. Another advantage is that the method inherently reflects all of the factors that affect curve speed choice (e.g., tangent speed, radius, etc.). The disadvantage of this method is that it is likely to take more resources to determine the appropriate advisory speed for a given curve than the other two methods.

RELATED ISSUES

This part of the chapter discusses several issues that are related to curve signing. The topics addressed include:

- regulatory speed limit vs. measured tangent speed,
- curve speed choice based on vehicle type, and
- engineering study.

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

Regulatory Speed Limit vs. Measured Tangent Speed

Several recent studies of vehicle speed on rural highways have found that drivers consistently exceed the regulatory speed limit. The amount by which the speed limit is exceeded varies with the speed limit and tends to be largest for lower speed limits. The findings from two studies are shown in Figure 2-17. Each data point represents the free-flow speed measured on one highway tangent.
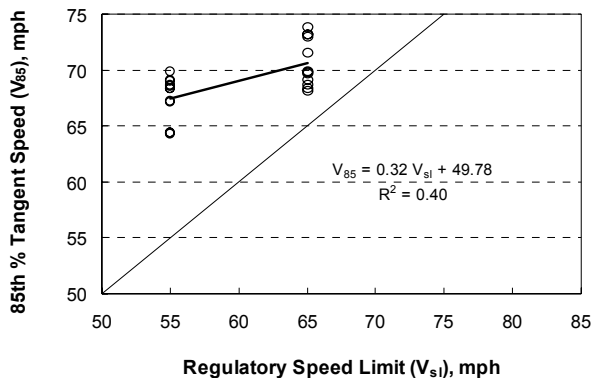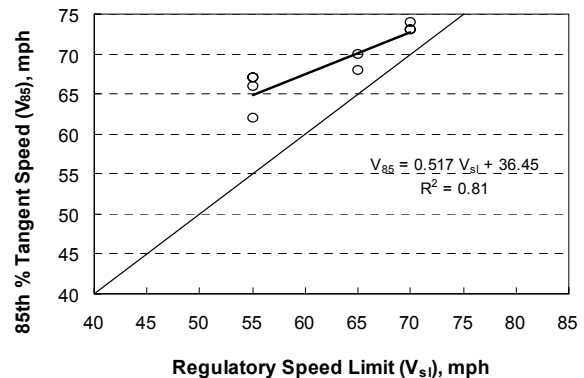
a. Dixon et al. b. Fitzpatrick et al.

Figure 2-17. Relationship between Speed Limit and 85th Percentile Speed.

The data shown in Figure 2-17a were observed by Dixon et al. (*31*) on 12 multilane rural highways in Georgia. The speed limit was raised from 55 to 65 mph on each highway, and the data shown represent measurements taken "before" and "after" the change in speed limit. The data shown in Figure 2-17b were observed by Fitzpatrick et al. (*32*) on two-lane rural highways in six states.

The trends in Figures 2-17a and 2-17b are similar among the two sources. The 85th percentile speed always exceeds the regulatory speed limit; however, the amount of excess is not constant. Extrapolation of the trend lines suggests that the 85th percentile speed may equal the speed limit on rural highways if their speed limit is 70 to 75 mph. In contrast, a speed limit of 55 mph is likely to be exceeded by 7 to 12 mph.

The trends in Figure 2-17 have implications on guidelines for horizontal curve signing. Many of the existing guidelines are based on the regulatory speed limit of the highway. Some guidelines explicitly indicate that the 85th percentile speed can (or should) be used to make the determination. However, other guidelines suggest that the speed limit can be used as an estimate of the 85th percentile speed. It is not clear to what extent any of these guidelines recognize the likely difference between the speed limit and the 85th percentile speed, as suggested by Figure 2-17. However, any guideline that is based on an assumed equality in the two speeds is not likely to yield its desired result.

Curve Speed Choice Based on Vehicle Type

Research indicates that curve speed varies by vehicle type (2, 3). Truck speed on curves is about 5 percent (i.e., 2 to 3 mph) slower than that of passenger cars. This relationship was shown previously in Figures 2-3 and 2-14. The slower speed adopted by truck drivers is likely a reflection of the reduced performance capability of trucks and, perhaps, greater caution exercised by truck drivers. The trend in the two figures suggests that an advisory speed that is determined to be adequate for cars may be too fast for trucks. Thus, the advisory speed should be conservatively low such that it is reasonable for all vehicle types.

Engineering Study

Based on extensive practitioner interviews and surveys, Lyles and Taylor (14) recommended that the need for curve warning signs, pavement markings, and delineation devices should be based on the findings from an engineering study. This study would consider the following factors:

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

The unexpected geometric features that may be considered include:

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

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CHAPTER 3. SPEED MODEL DEVELOPMENT AND CALIBRATION

OVERVIEW

This chapter describes the research undertaken to develop and calibrate a model for predicting the speed of traffic on horizontal curves. The model is calibrated using data measured at curves on rural two-lane highways. The data collected included measurements of vehicle speed and curve geometry. The calibrated model is used in a subsequent chapter to develop criteria for determining the appropriate advisory speed for rural highway curves.

The chapter consists of four parts. The first part describes the development of the speed prediction model. The second part describes the data collected to calibrate the model. The third part summarizes the data collected and describes the analysis undertaken to calibrate the model. The last part describes an evaluation of alternative methods for establishing the advisory speed.

MODEL DEVELOPMENT

This part of the chapter describes the development of a model for estimating vehicle speed on a horizontal curve. The first section describes a relationship between side friction demand and speed. The second section uses this relationship to derive the speed prediction model.

Side Friction Demand Model

This section describes the development of a model for estimating curve speed. It is based on a model developed previously by Bonneson (*1*). The data used to calibrate this model were measured at 55 curves on three facility types (i.e., rural highways, low-speed streets, and turning roadways). These data are shown in Figure 3-1.
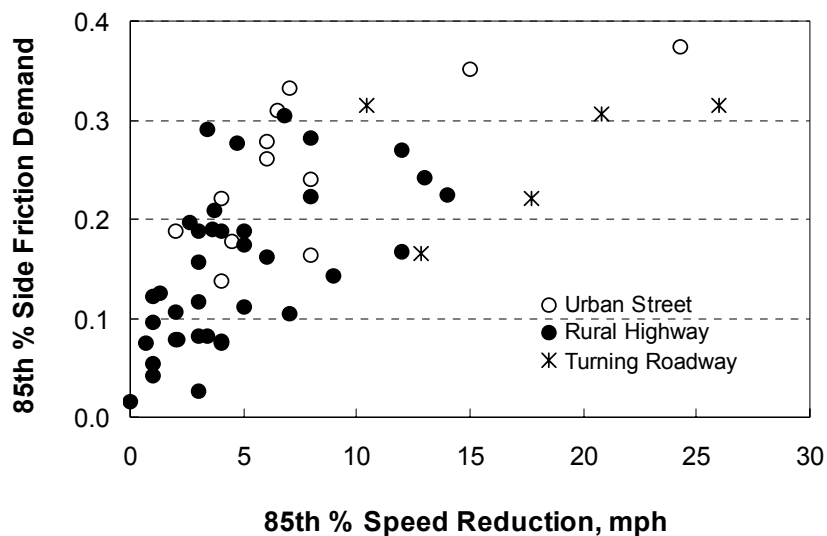
Figure 3-1. Relationship between Speed Reduction and Side Friction Demand.

Each data point shown in Figure 3-1 represents the 85th percentile speed reduction and side friction for one horizontal curve. The side friction demand was computed for each curve by substituting the measured 85th percentile speed in Equation 12.

$$f_D = \frac{(1.47\,V_c)^2}{g\,R} - \frac{e}{100} \qquad (12)$$

where,

$f_D =$ side friction demand factor (or lateral acceleration);
$e =$ superelevation rate, percent;
$V_c =$ curve speed, mph;
$g =$ gravitational acceleration ($= 32.2$ ft/s^2); and
$R =$ radius of curve, ft.

Equation 13 was used to estimate the 85th percentile speed reduction for each curve shown in Figure 3-1. This speed reduction represents the difference between the 85th percentile tangent speed and the 85th percentile curve speed.

$$\Delta V = V_t - V_c \qquad (13)$$

where,

$\Delta V =$ speed reduction, mph; and
$V_t =$ tangent speed, mph.

A positive value of speed reduction occurs when the speed on the curve is slower than the speed on the tangent. It indicates that drivers reduce their speed as they enter a sharp curve. The speed to which they slow is characterized as an "accepted" speed. It is based on the drivers' assessment of radius, superelevation, and comfort. It is also based on the drivers' general desire to maintain speed (i.e., a reluctance to slow down unless necessary).

The overall trend in Figure 3-1 suggests that side friction demand increases with increasing speed reduction. This trend suggests that drivers are willing to accept a larger, less comfortable side friction to minimize their speed reduction. However, the data also suggest that side friction demands are limited to about 0.35. A side friction demand of about 0.35 corresponds to a lateral acceleration of 11 ft/s^2. This level of acceleration is likely to be uncomfortable for most motorists. Moreover, side friction in excess of 0.35 may be unsafe for some vehicles, especially those with a high center of gravity.

Careful examination of the trend shown in Figure 3-1 suggests that the rate of increase in side friction declines with increasing speed reduction. This trend probably reflects the fact that small speed reductions are associated with a small increase in side friction and a corresponding decrease in driving comfort. In contrast, large speed reductions are associated with a large increase in side friction and a corresponding reduction in safety.

Based on an examination of the trends shown in Figure 3-1, Bonneson (*1*) hypothesized the following relationship between speed and side friction demand.

$$f_D = b_0 - b_1 V_t + b_2 (V_t - V_c) I_v \tag{14}$$

where,

b_i = calibration coefficients, i = 0, 1, 2, 3; and

I_v = indicator variable (= 1.0 if $V_t > V_c$; 0.0 otherwise).

The second term in Equation 14 (i.e., $b_1 V_t$) indicates that side friction demand decreases with increasing speed. This trend suggests that drivers have a lower tolerance for side force at higher speeds. The third term in Equation 14 (i.e., $b_2 [V_t - V_c] I_v$) models the driver's willingness to increase side friction demand to avoid a significant speed reduction, as suggested by the data shown in Figure 3-1. The value of the coefficient b_2 was found to vary, depending on whether the curve was on a turning roadway, urban street, or a rural highway.

The third term in Equation 14 is illustrated in Figure 3-2. It is labeled the "Linear Model" and is shown separately for the rural-highway/low-speed-street category (RHS & LS) and the turning roadway (TR) category. The calibration coefficient b_2 represents the slope of the line as shown.
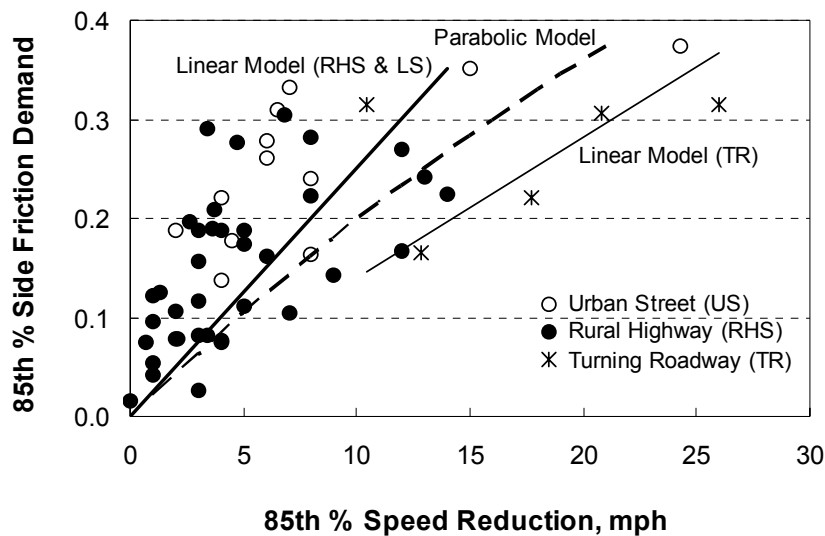
Figure 3-2. Alternative Side Friction Model Forms.

The trends in the data in Figure 3-2 suggest that a revised form of Equation 14 may be appropriate. The intent of the revision is to modify the third term of this equation such that it eliminates the need for separate values of b_2 based on facility type. In this manner, one calibrated model could be used to explain the friction demand for rural highways, urban streets, and turning roadways. The revised form is based on a parabolic relationship between speed reduction and side friction demand. This relationship follows from the energy differential concept described previously in Chapter 1. It suggests that the increase in side friction demand that a driver accepts is proportional to the energy required to slow the vehicle to the curve speed. It is described using the following equation:

$$f_D = b_0 - b_1 V_t + b_2 (V_t^2 - V_c^2) I_v \tag{15}$$

The fit of Equation 15 to the data is shown in Figure 3-2 using a dashed line. There is general agreement between the linear and parabolic models for the lower range of speed reductions. In fact, for speed reductions less than 10 mph, the difference between the predicted side friction demands is relatively small. In contrast, for speed reductions of 15 mph or more, the parabolic model bends downward toward the turning roadway side friction demand data.

Curve Speed Prediction Model

Equations 12 and 14 can be combined to obtain the curve speed prediction model developed by Bonneson (*1*). The form of this model is:

$$V_c = 11.0 R \left(-b_2 + \sqrt{b_2^2 + \frac{4c}{32.2R}} \right) \leq V_t \tag{16}$$

with,

$$c = \frac{e}{100} + b_0 + (b_2 - b_1) V_t \tag{17}$$

Bonneson (*1*) reported that the following calibration coefficients provide the best estimate of 85th percentile passenger car speed on rural highway curves: 0.256, 0.00245, and 0.0146 for b_o, b_1, and b_2, respectively. For turning roadways, b_2 was reported to equal 0.0065. The reported coefficient of determination R^2 for Equation 16 was 0.96.

Equations 12 and 15 can be combined to obtain the curve speed prediction model based on the parabolic relationship between speed reduction and friction. The form of this model is:

$$V_c = \left(\frac{15.0 R (b_0 - b_1 V_t + b_2 V_t^2 + e/100)}{1 + 32.2 R b_2} \right)^{0.5} \leq V_t \tag{18}$$

A regression analysis was conducted to make a preliminary assessment of the predictive ability of Equation 18. The data shown in Figure 3-1 were used to calibrate this equation using the regression technique described by Bonneson (*1*). The calibrated model is compared in Figure 3-3 with Equation 16 for rural highways and for turning roadways. The relationship between radius and curve speed shown in this figure represents an 85th percentile tangent speed of 60 mph.

The trend lines shown in Figure 3-3 indicate that the parabolic model form transitions between the two linear model trends, as expected. For the sharpest curves, the predicted speeds from the parabolic model are consistent with those from the linear model for turning roadways. For the flatter curves, the parabolic model speed predictions are more consistent with those from the linear model for rural highways.
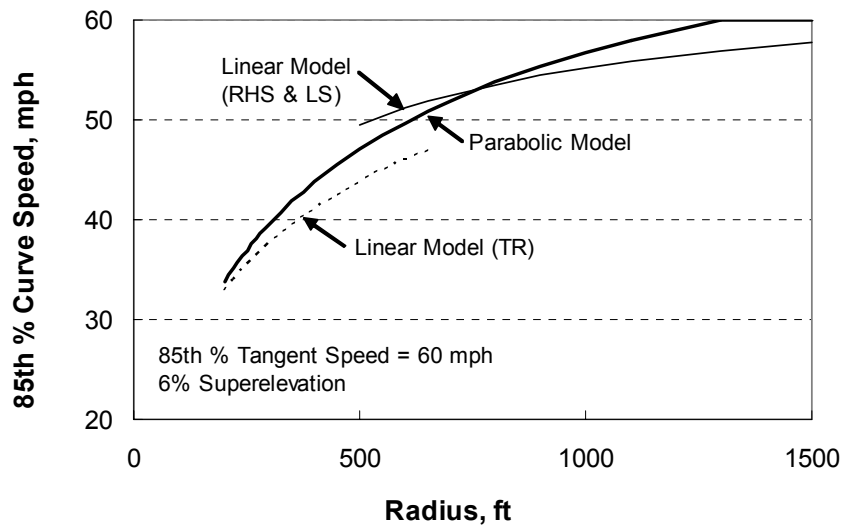
Figure 3-3. Comparison of the Linear and Parabolic Speed Prediction Model.

DATA COLLECTION

This part of the chapter describes the curve speed data collection plan. The description is provided in two sections. The first section describes the database composition in terms of the database elements, study site locations, and site characteristics. In this regard, a "site" is defined as one direction of travel through one horizontal curve on a rural, two-lane highway. The second section describes the data collection procedure. This description includes a discussion of the site survey and speed data collection methods.

Database Composition

The objective of the data collection activity was to provide the data needed to calibrate the curve speed prediction model described in the previous part of this chapter. As described in Chapter 2, curve speed is influenced by curve radius, superelevation rate, and tangent speed. It was also noted that several issues would need to be investigated before appropriate advisory speed criteria could be established. Specifically, the following three issues were identified:

- **Daytime vs. Nighttime.** Most of the models documented in the literature were calibrated using data collected during daytime conditions. It is unclear whether the relationships reported are equally applicable to nighttime conditions.
- **Truck Curve Speed.** Only one model was calibrated to predict truck speed. Examination of this model indicated that truck drivers choose slower speeds on curves than passenger car drivers.
- **Large Speed Reduction.** The models that include a sensitivity to tangent speed were calibrated using data for rural highway curves that required no more than about 12 mph speed reduction (i.e., the average curve speed was no more than 12 mph below the average tangent

speed). As a result, there is some doubt as to whether the models reported in the literature can be reliably extended to rural highway curves where the speed reduction exceeds 12 mph.

The data collection plan described in this section was devised to provide the data needed to address these three issues.

Database Elements

Table 3-1 lists the data that were needed to calibrate the curve speed model described in a previous part of this chapter.

Table 3-1. Primary Data for the Curve Speed Database.

Variable	Basis	Desired Range among Sites
Tangent speed	Each Vehicle	
Curve midpoint speed	Each Vehicle	
Headway (leading and trailing)	Each Vehicle	
Vehicle classification	Each Vehicle	
Lighting condition	Each Vehicle	
Curve radius	Site	300 to 1500 ft
Regulatory speed limit	Site	55 to 70 mph
Speed reduction (regulatory speed - advisory speed)	Site	0 to 30 mph
Functional classification	Site	Rural two-lane highway
Average superelevation (over mid section)	Site	2 to 8 %
Grade	Site	-4.0 to +4.0 %

Tangent speed is an important variable in the development of the curve speed model. It is used for two purposes. First, it is an input variable in the curve speed model and is needed for its calibration. Second, tangent speed is used during data reduction to identify drivers who maintain their speed or slow to negotiate the curve. Only drivers who maintain their speed through the curve, or slow to enter the curve, provide an indication of acceptable side friction demand. Drivers having a higher speed in the curve than on the tangent are excluded from the database.

Drivers who increase their speed from the tangent to the curve are not likely to yield useful information about the impact of the curve geometry on speed choice. For example, these drivers may have recently entered the highway from a side road and be in the process of accelerating to a desired speed when they reach the curve. These drivers' curve speed is not likely to be reflective of the impact of curve geometry on their speed choice, but rather, it is only an indication that they did not have the distance needed to accelerate to a higher speed before reaching the curve. This approach to calibration of a curve speed model constitutes a significant departure from most previous studies of curve speed and side friction demand.

Headway data were used to insure that the driver's choice of curve speed is not influenced by nearby vehicles. Specifically, the headway measurements were used to remove the effect of traffic density on speed choice. This screening was accomplished by removing vehicles from the database that had a "short" headway between themselves and any leading or following vehicles in the same traffic lane. The criteria used to define short headways is described in a later section.

Additional data were collected at each curve study site to supplement the primary data listed in Table 3-1. These supplemental data include: deflection angle, shoulder width, lane width, and the presence of various traffic control devices (e.g., pavement edge lines, Chevrons, delineators, etc.). These data were used to explore their possible correlation with curve speed.

Site Selection Criteria

A list of desirable characteristics of the field study sites was prepared to aid in the site selection process. The basis for this list was the information obtained from the literature review, the survey of practitioners, and the insight obtained while formulating the proposed curve speed model. These characteristics are described in the following paragraphs.

Geographic Diversity. It was determined that the collective set of sites in the database should have sufficient geographic diversity to insure transferability of the findings to all TxDOT districts. This diversity was achieved by collecting data in the following four districts: Bryan, Dallas, Lufkin, and Waco.

Geometric and Traffic Demand Criteria. To minimize sources of variability that are irrelevant to the study, candidate sites were further screened to insure similarity whenever possible. For example, an effort was made to insure that:

- stopping sight distance was adequate for the length of the curve,
- curve length exceeded 3 s travel time at the advisory speed,
- no spiral transitions were present,
- pavement surface was in good condition, and
- travel time on the tangent prior to the subject curve was 8 s or more (based on a speed that is 5 mph above the regulatory speed limit).

In addition, sites were selected such that their average daily traffic volume exceeded 400 veh/d whenever possible. This minimum volume requirement was intended to insure that the minimum sample size for both cars and trucks was realized within a reasonable data collection time period. The desired minimum sample size for each site is described in a later section.

Study Site Locations

Number of Studies. It was determined that data from at least 40 sites would be needed to provide a reasonable range in the desired site-specific variables, as described in the previous subsection. To achieve this number in a cost-effective manner, the curves selected for study had to be amenable to study in both travel directions.

Candidate sites were identified through an examination of the Texas Reference Marker System (TRM) database maintained by TxDOT. Software was developed to screen this database for curves in four TxDOT districts that collectively offered the range of values cited in Table 3-1.

A preliminary visit to each of the candidate sites was subsequently conducted to identify those sites that were most consistent with the needs of this project and were suitable for field study. Additional activities conducted during the site visit included:

- gather traffic control device or geometric information;
- assess sight distance adequacy; and
- survey and photograph the study site.

Based on an evaluation of the data collected during the preliminary site visits, 20 curves were selected as primary study sites. Both travel directions would be studied at each curve to yield data for 40 sites. Three additional sites were identified to serve as alternates in the event of unforeseen events (e.g., construction) on the day of the field study at a primary site. Data were also collected for one travel direction at one alternate site to yield a total of 41 study sites. This supplemental dataset was intended to serve as a reserve dataset in the event that the processing and analysis of data for the primary sites revealed that one dataset was unusable. After the processing and analysis steps were completed, the data for all primary sites were found to be adequate, so the reserve dataset was added to the database as the 41st site. Table 3-2 describes the distribution of the 41 sites in terms of their facility type and location.

Table 3-2. Distribution of Field Study Sites.

District	Number of Sites by Radius Category				Total Sites
	0 to 400 ft	401 to 800 ft	801 to 1200 ft	1201 to 1600 ft	
Bryan	0	6	10	7	23
Dallas	2	4	0	0	6
Lufkin	0	4	0	0	4
Waco	0	6	2	0	8
Total:	2	20	12	7	41

As indicated in Table 3-2, the curves are located in four TxDOT districts. These four districts were chosen because the review of the TRM database revealed a large number of curves in these districts that satisfied the site selection criteria. There was an intentional emphasis on selecting curves with a smaller radius (i.e., less than 800 ft) because these curves tend to be candidates for advisory speed signing. However, curves with a larger radius were also included in the database to insure that the analysis and resulting criteria reflected the consideration of a full range of radii.

The specific location of each of the 40 study sites is provided in Table 3-3. Also provided in this table is an estimate of the average daily traffic demand (ADT) at each site.

Table 3-3. Site Location and Traffic Demand.

District	Nearest City	Curve Number	Highway	ADT,[1] veh/d	Truck ADT,[1] veh/d
Bryan	Deanville	1	F.M. 60	1100	160
	Chappell Hill	2	F.M. 1155	590	130
	Tunis	3	F.M. 166	470	50
	Crabbs Prairie	5	F.M. 1696	2350	190
	Hearne	8	F.M. 2549	590	140
	Quarry	11	F.M. 1948	970	110
	Madisonville	12	F.M. 2289	750	90
	Madisonville	13	F.M. 2289	750	90
	Midway	22	F.M. 247	890	110
	Burton	39	F.M. 1697	420	190
	Teague [2]	41	F.M. 80	910	120
	Wheelock	65	F.M. 391	310	30
Dallas	Waxahachie	19	F.M. 875	800	120
	Corsicana	23	F.M. 709	1930	160
	Bristol	67	F.M. 660	560	50
Lufkin	Oakhurst	27	F.M. 946	630	110
	Groveton	30	F.M. 355	550	90
Waco	Bee House	14	F.M. 183	280	60
	Itasca	20	F.M. 66	520	140
	Carlton	28	F.M. 219	520	70
	Mount Calm	53	F.M. 339	310	20

Notes:
1 - ADTs represent an average for the years 1999, 2000, and 2001.
2 - Only one travel direction on this curve was studied.

Geometric Characteristics. Geometric characteristics for each site are listed in Table 3-4. These characteristics include curve radius, degree-of-curvature, deflection angle, presence of a paved shoulder, curve deflection direction, curve superelevation rate, and alignment grade. Grade was measured at the same two points on the highway where speed was measured. These two points were the upstream tangent location and the curve midpoint.

The grades listed in Table 3-4 represent the average of three measurements taken at 40 ft intervals in the vicinity of the speed measurement locations. Curve superelevation rate represents the average of three measurements that were made near the curve midpoint.

Table 3-4. Site Geometric Characteristics.

Curve No.	Radius, ft	Degree of Curve	Deflection Angle, deg	Paved Shld.	Curve Direction [1]	Superelevation Rate, [2] percent	Grade, [4] percent Tangent [3]	Grade, [4] percent Curve [2]
1	716	8	51	Yes	I	13.1	-1.6	1.3
					O	9.2	0.9	-1.3
2	1432	4	18	Yes	I	7.3	-5.4	-4.0
					O	4.6	0.0	4.0
3	573	10	32	Yes	I	9.0	0.0	-0.3
					O	8.3	1.1	0.3
5	1145	5	33	Yes	I	6.3	-0.3	-1.5
					O	1.4	-0.2	1.5
8	1145	5	48	Yes	I	6.3	1.2	5.2
					O	4.5	0.4	-5.2
11	1432	4	30	No	I	7.3	-2.3	-2.9
					O	7.0	-0.3	2.9
12	1145	5	35	No	I	6.1	-1.3	2.7
					O	6.0	3.0	-2.7
13	1145	5	46	No	I	3.3	0.7	-2.3
					O	2.5	1.1	2.3
14	955	6	90	Yes	I	5.5	-0.5	3.1
					O	5.6	-5.5	-3.1
19	409	14	56	Yes	I	6.4	3.2	2.6
					O	4.6	3.8	-2.6
20	716	8	47	No	I	4.5	-0.7	-1.6
					O	1.4	0.4	1.6
22	819	7	28	No	I	7.9	-0.3	-2.2
					O	5.9	0.2	2.2
23	716	8	51	Yes	I	7.8	1.0	-1.7
					O	9.3	1.6	1.7
27	674	8.5	44	No	I	8.1	-2.8	1.8
					O	4.6	0.3	-1.8
28	441	13	52	No	I	11.7	2.2	-0.9
					O	8.1	-1.8	0.9
30	441	13	34	Yes	I	6.5	2.0	1.0
					O	6.1	-1.3	-1.0
39	1432	4	37	Yes	I	5.0	-0.4	-2.0
					O	5.7	-2.8	2.0
41	1432	4	34	No	I	6.8	-0.4	-0.8
53	477	12	89	No	I	7.8	2.7	-1.2
					O	8.3	-6.5	1.2
65	573	10	41	No	I	7.0	0.3	-2.9
					O	3.2	0.6	2.9
67	318	18	84	No	I	6.7	-1.4	-3.4
					O	5.5	-0.5	3.4

Notes:

1 - Lane position of vehicle then traveling along the curve ("I" = inside, "O" = outside).

2 - Measured at the curve midpoint.

3 - Measured on the tangent, upstream of the curve.

4 - A positive grade denotes an uphill condition as the vehicle travels toward, or through, the curve.

Of particular note in Table 3-4 is the difference in superelevation rate for the two directions of travel at a given curve. Rarely was the superelevation the same in both directions of travel. Carlson et al. (2) found the same trend in their measurements of superelevation at 18 curves in two TxDOT districts. With respect to the rates in Table 3-4, the difference in rate between the two travel directions ranged from -1.5 to 4.9 percent, with an average of 1.6 percent. When the difference exceeds about 3 percent, the additional superelevation may be associated with a speed differential of 5 mph or more, which would justify a different curve advisory speed for each direction of travel.

Traffic Control Characteristics. Table 3-5 summarizes the traffic control characteristics of the study sites. These characteristics include the presence of supplemental traffic control devices like delineators and Chevrons, as well as the posted regulatory and advisory speeds.

Table 3-5. Site Traffic Control Characteristics.

Curve No.	Regulatory Speed Limit, mph	Advisory Speed, mph	Marked Edge Line Presence	Delineator or Chevron Presence
1	65	45	Yes	Chevrons
2	65	No sign	Yes	None
3	65	35	Yes	None
5	70	40	Yes	Chevrons
8	65	55	Yes	Delineators
11	65	No sign	Yes	None
12	70	55	No	None
13	70	50	No	None
14	60	50	Yes	None
19	55	35	Yes [1]	None
20	60	45	Yes	Delineators
22	70	45	No	None
23	55	50	Yes [1]	None
27	55	40	No	None
28	60	35	No	Chevrons
30	55	35	Yes	Chevrons
39	70	No sign	Yes	None
41	60	50	No	None
53	60	40	No	Delineators
65	65	35	No	Delineators
67	55	30	Yes	None

Note:
1 - A wide (i.e., 8-inch) edge line was provided at this site. All other sites identified by "Yes" have a 4-inch edge line.

An examination of the data in Table 3-5 indicates a wide range of traffic control devices and speed limits at the collective set of study sites. For example, the regulatory speed limit ranges from

55 to 70 mph. An advisory speed is present at 18 of the 21 curves (i.e., 35 of the 40 sites). Pavement edge lines are present at 13 of the 21 curves (i.e., 26 of the 40 sites). Delineators are used at four curves (i.e., eight sites), and Chevrons are used at four curves (i.e., eight sites). The traffic control devices were found to be in good physical condition at each site.

Data Collection Procedure

This section describes the data collection procedure. The procedure included a survey of the geometric conditions at each site as well as the measurement of vehicle speeds in advance, and at the midpoint, of the subject horizontal curve.

Vehicle speed was measured using sensors adhered to the pavement and monitored by a traffic data collection computer (commonly referred to as a "traffic classifier"). The sensors were deployed in pairs to form a speed trap. For each site, one speed trap was located on the tangent, in advance of the beginning of the curve. The second speed trap was located at the curve midpoint. The classifier was used to monitor the sensors and record the time that each vehicle entered the speed trap. It also used the sensor inputs to estimate vehicle speed and headway.

Figure 3-4 illustrates the sensor locations and the types of equipment used at a typical site. Additional details regarding the measurement locations and methods are provided in the following subsections.
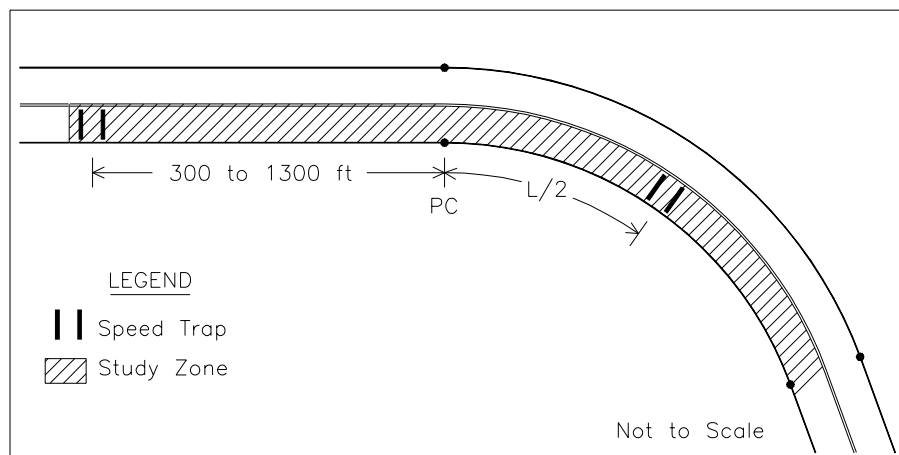
Figure 3-4. Field Study Design for a Typical Horizontal Curve.

Speed Measurement Locations

Vehicle speed was measured both on the curve and on the tangent. Curve speed was measured at the midpoint of the curve. Tangent speed was measured at a point upstream of the curve that was determined to be well in advance of the point at which the driver might begin decelerating for the curve. The distance to the measurement point was estimated using the following equation:

$$D_{min} = 1.47 \, t_{pr} \, (V_{sl} + 5) + 1.47^2 \, \frac{(V_{sl} + 5)^2 - (V_{al} + 5)^2}{2 \, d_r} \qquad (19)$$

where,

D_{min} = minimum distance between sensor speed trap and beginning of curve, ft;

t_{pr} = 85th percentile perception reaction time (use 1.0 s), s;

V_{sl} = regulatory speed limit, mph;

V_{al} = advisory speed, mph; and

d_r = deceleration rate (use 3.3 ft/s^2), ft/s^2.

The regulatory and advisory speeds were each increased by 5 mph to reflect a conservative estimate of the 85th percentile speed on the tangent and curve, respectively. Values computed using Equation 19 for the study sites averaged 760 ft, and ranged from 300 to 1300 ft.

Site Survey

The physical layout of the roadway at each study site was surveyed, and the following geometric elements were measured:

- curve radius,
- curve length,
- width of traffic lanes and shoulders,
- superelevation at curve midpoint, and
- grade along the curve.

In addition to these measurements, weather conditions were monitored during the time period that speeds were measured. Trace amounts of rainfall were noted to occur for a few nighttime hours at each of three sites. It did not rain at the other 38 sites during the study periods. For these reasons, it was determined that the effect of rainfall on driver behavior was negligible and that all of the collected sensor data could be used for analysis.

Curve radius was determined using two methods. One method employed the Radiusmeter developed by the Texas Transportation Institute (*2*). This device was found to have an average error range of about 4 percent (i.e., ± 4 ft of error for each 100 ft of radius). The second method consisted of using the radius listed in the TRM database. For 9 of the 21 curves, the two methods were in sufficient disagreement as to justify a field survey using a total station instrument. The radius obtained from this survey was used to reconcile the difference in radius estimates from the Radiusmeter and the TRM database.

A level was used to measure superelevation rate and alignment grade. Superelevation rate was computed from elevations taken in the center of each traffic lane. They were measured at the curve midpoint as well as at locations 40 ft upstream and downstream of this point. The three rates were then averaged to yield the average superelevation rate for the site. The longitudinal grade of the roadway in the vicinity of the curve midpoint was measured at each site in a similar manner.

It was determined that speed measurements for a minimum of 50 trucks and 100 cars were needed for each site. Each vehicle would need to cross both speed traps to be considered an "observation." At some sites, it was doubtful whether a study site would have sufficient truck volume to yield the minimum number of truck observations in a 24-hour period. However, these sites were considered desirable because they had other site-specific attributes that provided the range needed in the database for one or more geometric or traffic control device variables. Data were collected at these marginal sites for a second 24-hour period to bolster the truck sample size.

DATA REDUCTION AND ANALYSIS

This part of the chapter describes the data reduction process and summarizes the data collected at 41 curve study sites. Initially, the procedures used to reduce the data are described. Then, the database assembled from the reduced data is summarized. Next, the findings from a preliminary examination of the data are discussed. Then, the results of the speed prediction model calibration are described. Finally, the model is validated using data from several curves located in other states.

Data Reduction

The traffic data collected at each site included the speed, wheelbase, and axle count for each vehicle that traversed the curve. These data were collected at an upstream tangent location and at the curve midpoint. The data recorded at the upstream location were matched with the data recorded at the midpoint location on a vehicle-by-vehicle basis. They were matched by comparing the recorded wheelbase and axle-count measurements at the upstream location with those recorded at the midpoint location. In this manner, the database included only those vehicles that crossed both speed measurement locations.

A vehicle was considered to be a truck if it satisfied one of the following conditions: (1) it had more than two axles, or (2) it had two axles and a wheelbase greater than 12.2 ft. The threshold wheelbase of 12.2 ft was defined based on a review of the range of wheelbase values for the existing fleet of passenger cars and pickup trucks.

Once the matched-pair database was assembled, it was further screened to include only free-flowing vehicles. A vehicle was considered to be freely-flowing if its "leading" headway (i.e., the time headway to the preceding vehicle) was 7.0 s or larger, and its "trailing" headway (i.e., the time headway to the following vehicle) was 7.0 s or larger. The trailing headway requirement for trucks was relaxed to 3.0 s due to the paucity of truck traffic at some sites and the belief that truck drivers are less likely than passenger car drivers to be influenced by closely-following vehicles.

The database was further screened to exclude drivers who may not have had their curve speed choice influenced by the curvature. Specifically, it was determined that drivers who increase their speed from the tangent to the curve are not likely to yield useful information about the impact of the curve geometry on their speed choice. For example, these drivers may have just entered the highway

from a side road and be in the process of accelerating to a desired speed when they reach the curve. These drivers' curve speed is not likely to be reflective of the impact of geometry on their speed choice. In fact, it is only in indication that they did not have the distance needed to accelerate to a higher speed before reaching the curve. Thus, vehicles that had a higher speed on the curve than on the tangent were excluded from the database.

Data Summary

The database assembled for the evaluation of curve speed characteristics includes the vehicular, geometric, and traffic control data collected at each site. The vehicular data consist of the speed and wheelbase for each free-flow vehicle whose driver was influenced by curve geometry. These data were separated into daytime and nighttime measurements, based on the beginning and ending times of civil twilight specified by the U.S. Naval Observatory. A total of 8418 vehicle observations are included in the daytime database, of which 1741 (21 percent) are trucks. The number of passenger car observations at a study site varied from 51 to 399 cars, and the number of truck observations varied from 13 to 91 trucks. An additional 1675 vehicles (16 percent trucks) were measured during nighttime hours.

The mean, standard deviation, and 85th percentile speed statistics were calculated for both cars and trucks. These statistics were computed for the speeds measured on the tangent and at the curve midpoint at each site. The statistics from the daytime data for passenger cars are shown in Table 3-6. The average speed for passenger cars was 59.8 mph on the tangent and 51.0 mph on the curve. The 85th percentile speed for passenger cars was 68 mph on the tangent and 61 mph on the curve. The 85th percentile speed on the curve was 7 mph slower than that on the tangent. The average and the 85th percentile passenger car speeds were about 2.0 mph slower during nighttime hours than during daytime hours.

The speed statistics from the daytime data for trucks are shown in Table 3-7. The average speed for trucks was 58.0 mph on the tangent and 49.6 mph on the curve. The 85th percentile speed for trucks was 67 mph on the tangent and 60 mph on the curve. These latter two speeds indicate that the 85th percentile speed on the curve was 7 mph slower than that on the tangent. The average and the 85th percentile truck speeds are slower than those for passenger cars by 1 to 2 mph. This trend in speed is consistent at both the tangent and at the curve speed measurement locations. The average and the 85th percentile truck speeds were about 1.0 mph slower during nighttime hours than during daytime hours.

Table 3-6. Summary Statistics from Daytime Data for Passenger Cars.

Curve No.	Deflection Direction	Obs.	Tangent Speed, mph			Curve Speed, mph			85th % Speed Diff., [1] mph
			Average	Standard Deviation	85th Percentile	Average	Standard Deviation	85th Percentile	
1	R	80	61.7	8.3	69.5	52.4	8.2	60.0	9.5
	L	51	61.5	7.0	68.0	51.5	5.3	57.0	11.0
2	R	81	63.2	5.3	69.0	62.0	5.6	68.0	1.0
	L	99	63.7	6.6	70.0	60.8	7.6	67.0	3.0
3	R	120	60.7	7.1	67.0	50.9	6.3	56.5	10.5
	L	98	58.2	6.2	64.0	49.6	5.7	55.0	9.0
5	R	200	60.4	6.7	67.0	55.2	6.6	62.0	5.0
	L	214	63.6	7.4	71.0	54.6	6.5	61.0	10.0
8	R	165	63.5	8.8	70.0	57.0	8.6	65.0	5.0
	L	176	66.9	7.0	74.0	61.2	6.5	67.0	7.0
11	R	77	61.8	7.8	69.0	59.5	8.0	67.0	2.0
	L	87	61.2	8.2	70.0	58.5	7.7	67.0	3.0
12	R	116	62.5	7.1	70.0	58.1	6.6	65.0	5.0
	L	233	63.8	7.2	71.0	58.3	6.4	65.0	6.0
13	R	278	63.3	6.9	70.0	58.3	6.5	65.0	5.0
	L	333	63.8	8.7	72.0	55.4	8.3	64.0	8.0
14	R	117	62.0	7.8	70.0	55.4	6.9	63.0	7.0
	L	86	60.3	8.5	69.0	54.1	9.4	62.0	7.0
19	R	371	56.1	6.0	61.0	41.4	4.6	45.0	16.0
	L	350	53.8	5.4	59.0	40.0	3.5	43.0	16.0
20	R	98	61.8	6.7	68.0	50.5	5.0	55.0	13.0
	L	122	58.2	7.4	65.0	48.7	6.1	55.0	10.0
22	R	163	65.9	7.0	72.0	59.0	6.3	66.0	6.0
	L	203	64.8	7.4	72.0	57.9	6.7	65.0	7.0
23	R	399	58.1	6.0	64.0	51.4	5.6	57.0	7.0
	L	238	52.8	6.2	58.0	49.5	6.0	55.0	3.0
27	R	156	62.6	6.3	69.0	52.2	5.1	57.0	12.0
	L	103	61.0	6.8	68.0	51.5	5.7	58.0	10.0
28	R	118	53.4	7.1	59.0	44.4	6.2	50.0	9.0
	L	142	58.0	6.4	63.0	44.3	4.4	48.0	15.0
30	R	127	57.2	6.1	63.0	44.2	4.6	49.0	14.0
	L	115	60.0	7.8	66.0	45.3	5.3	50.0	16.0
39	R	116	68.2	7.5	75.0	61.0	7.0	67.0	8.0
	L	100	63.3	8.5	71.5	60.3	8.2	67.5	4.0
41	R	287	60.4	8.5	69.0	55.8	7.7	63.0	6.0
53	R	64	53.6	10.4	64.0	42.1	6.1	48.0	16.0
	L	63	56.4	7.1	64.0	42.6	5.5	48.0	16.0
65	R	125	56.8	7.2	64.0	46.1	9.2	53.0	11.0
	L	111	57.3	7.9	65.0	46.2	6.0	52.0	13.0
67	R	262	51.6	5.6	58.0	36.5	4.0	41.0	17.0
	L	233	56.3	7.6	65.0	36.0	3.9	40.0	25.0
	Combined:	6677	59.8	8.3	68.0	51.0	9.8	61.0	7.0

Note:

1 - 85th percentile speed differential equals the 85th percentile tangent speed minus the 85th percentile curve speed.

Table 3-7. Summary Statistics from Daytime Data for Trucks.

Curve No.	Deflection Direction	Obs.	Tangent Speed, mph			Curve Speed, mph			85th % Speed Diff.,[1] mph
			Average	Standard Deviation	85th Percentile	Average	Standard Deviation	85th Percentile	
1	R	39	58.6	7.9	69.0	51.6	6.2	59.0	10.0
	L	25	55.0	7.3	65.0	47.6	6.2	55.0	10.0
2	R	34	63.4	7.1	71.0	62.5	6.9	70.0	1.0
	L	34	62.3	6.1	69.0	60.4	6.1	68.0	1.0
3	R	23	58.3	9.6	67.0	50.0	6.8	57.0	10.0
	L	15	55.5	10.7	67.0	48.0	7.2	53.0	14.0
5	R	62	59.0	7.5	65.0	54.8	7.0	61.0	4.0
	L	64	62.8	7.5	72.0	54.6	6.1	61.0	11.0
8	R	35	64.7	7.1	71.0	57.8	6.8	64.0	7.0
	L	35	66.2	6.6	74.0	60.5	5.6	66.0	8.0
11	R	31	60.8	4.5	64.0	58.9	3.9	63.0	1.0
	L	31	56.3	6.7	64.0	54.3	6.3	61.0	3.0
12	R	17	58.9	5.9	65.0	55.7	6.3	63.0	2.0
	L	35	60.4	11.0	73.0	56.5	9.1	65.0	8.0
13	R	57	58.4	8.6	67.0	53.6	7.8	62.0	5.0
	L	67	61.0	9.0	70.0	52.1	10.4	61.0	9.0
14	R	34	60.3	7.3	69.0	53.6	7.4	61.0	8.0
	L	15	54.3	11.1	61.0	50.5	10.7	57.0	4.0
19	R	82	56.0	7.8	62.0	39.8	5.9	45.0	17.0
	L	63	52.2	7.0	58.0	39.3	3.6	43.0	15.0
20	R	31	58.7	7.2	64.0	46.2	8.8	53.0	11.0
	L	28	55.8	7.7	63.0	46.3	5.8	53.0	10.0
22	R	41	64.0	7.2	72.0	56.5	6.6	64.0	8.0
	L	55	62.5	6.3	68.0	55.5	5.1	60.0	8.0
23	R	91	57.6	6.9	64.0	50.5	5.6	56.0	8.0
	L	54	50.7	7.0	58.0	48.3	6.6	54.0	4.0
27	R	47	59.4	9.0	67.0	49.0	6.7	57.0	10.0
	L	47	58.7	7.3	65.0	48.8	5.7	54.0	11.0
28	R	60	49.9	8.1	58.5	41.9	5.8	48.0	10.5
	L	56	55.5	5.6	61.0	42.1	4.1	46.0	15.0
30	R	50	54.2	7.3	61.0	40.8	5.0	46.0	15.0
	L	31	58.4	8.5	68.0	44.2	5.0	50.0	18.0
39	R	28	63.5	6.1	69.0	57.6	5.3	63.0	6.0
	L	32	63.6	8.4	70.0	60.6	7.3	65.0	5.0
41	R	85	59.7	9.3	69.0	54.8	9.1	63.0	6.0
53	R	13	52.3	8.0	61.0	41.8	4.4	47.0	14.0
	L	22	57.2	8.8	64.0	42.1	4.4	46.0	18.0
65	R	37	56.0	8.7	65.0	46.3	7.8	54.0	11.0
	L	43	55.7	10.2	62.0	43.8	8.1	50.0	12.0
67	R	50	50.7	7.4	58.0	35.8	3.9	39.0	19.0
	L	42	54.6	8.4	64.0	34.9	4.4	39.0	25.0
	Combined:	1741	58.0	8.7	67.0	49.6	9.7	60.0	7.0

Note:
1 - 85th percentile speed differential equals the 85th percentile tangent speed minus the 85th percentile curve speed.

Preliminary Examination

This section reviews the findings from a preliminary analysis of the daytime data. It consists of six subsections. The first subsection compares the 85th percentile speed with the regulatory speed limit at each site. The second subsection compares the curve advisory speed with that obtained from a ball-bank indicator. The third subsection examines the relationship between daytime and nighttime speeds. The fourth subsection examines the relationship between car and truck speeds. The fifth subsection examines the difference between vehicle path radius and roadway radius. The last subsection describes a model for predicting the 85th percentile tangent speed.

Driver Compliance with Posted Speeds

This subsection examines driver compliance with the posted speed at each site. The 85th percentile passenger car speeds observed during daytime hours on the tangent sections were used for the examination.

Figure 3-5 shows a site-by-site comparison of the 85th percentile tangent speed with the regulatory speed limit. The thin trend line shown in the figure is a "$y = x$" line, such that a data point would fall on this line if the corresponding site had an 85th percentile speed equal to its regulatory speed limit. The thick trend line shown represents the best-fit relationship derived from a regression analysis. This relationship is very similar to one derived by Fitzpatrick et al. (*3*) for rural highways and shown in Figure 2-17b. The data in the figure indicate that the 85th percentile speed at 36 of the 41 sites (88 percent) exceeds the regulatory speed limit.

$$V_{85} = 0.54 \ V_{sl} + 33.6$$
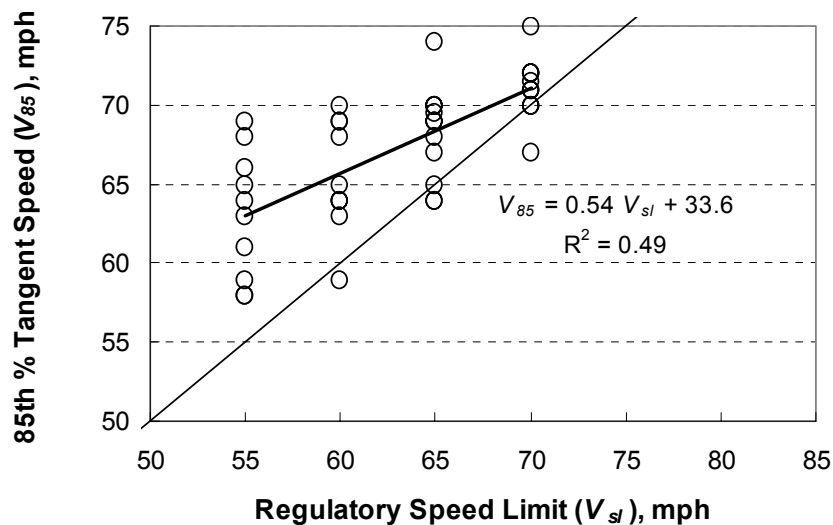$$R^2 = 0.49$$

Figure 3-5. Comparison of Tangent Speed and Regulatory Speed Limit.

Figure 3-6 shows a site-by-site comparison of the curve speed with the posted curve advisory speed. Only the 35 sites that have a curve advisory speed are shown. The trend in the data points is similar to that shown in Figure 2-15a with respect to a large majority of the sites having a 50th

3-18

percentile curve speed in excess of the advisory speed. In comparison, all of the sites have an 85th percentile curve speed that exceeds the advisory speed.
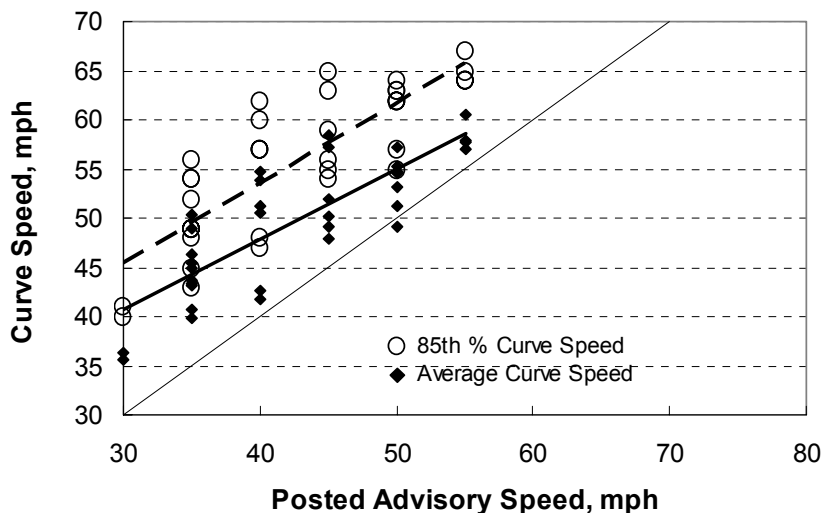
Figure 3-6. Comparison of Curve Speed and Advisory Speed.

The data in Figure 3-6 indicate that the average curve speed exceeds the advisory speed by 5 to 10 mph at most sites. It is consistent with the findings reported by other researchers (*4, 5*). It is also consistent with the belief among engineers that curve advisory speeds are generally lower than the speed most drivers adopt when negotiating a sharp curve, as noted in Chapter 2.

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

The policy of TxDOT, and most state DOTs, is to determine the appropriate advisory speed by using a ball-bank indicator. The procedure used by TxDOT is described in Chapter 5 of *Procedures for Establishing Speed Zones* (*6*). It requires the use of a test vehicle and one or more traversals of the subject curve. The objective is to identify the highest speed at which the curve can be traversed without having the ball-bank reading exceed the angle shown in Table 3-8.

Table 3-8. Threshold Ball-Bank Angles for Establishing a Curve Advisory Speed.

Speed Range, mph	Ball-Bank Angle, degrees	Equivalent Side Friction Factor
≤ 20	14	0.23
25-30	12	0.19
≥ 35	10	0.16

The TxDOT procedure for establishing advisory speeds was used to estimate the advisory speed for each of 41 rural two-lane highway curves. The test-vehicle method was not replicated in

the field using a ball-bank indicator. Rather, the speed that would be obtained if a ball-bank indicator were used was estimated using the following equation:

$$V_c = 0.68 \sqrt{g R \left(f_D + \frac{e}{100} \right)}$$ (20)

where,
V_c = curve speed, mph;
g = gravitational acceleration (= 32.2 ft/s^2), ft/s^2;
R = radius of curve, ft;
f_D = side friction demand factor; and
e = superelevation rate, percent.

The curve advisory speed was estimated as equal to the curve speed V_c from Equation 20, but rounded downward to the nearest 5 mph increment. If the advisory speed estimate is different for the two directions of travel on the same curve, then the lower advisory speed is posted for both directions of travel.

Equation 9 was used to estimate the equivalent side friction factor for each ball-bank angle in Table 3-8. These factors are listed in the last column of the table. They were used for f_D in Equation 20 to compute the speed corresponding to the specified ball-bank angle.

The "computed" ball-bank-based speed represents the best estimate of the advisory speed, as would be obtained if the ball-bank indicator were used and the sources of variability were minimal.

Figure 3-7 compares the computed ball-bank-based advisory speed with the actual advisory speed posted at each curve. The trend is consistent with that found in Figure 2-13. The posted advisory speed was the same as the estimated ball-bank-based speed at only 6 of the 18 curves at which posted advisory speeds exist. The trends in Figure 3-7 are further evidence that uniformity is not likely to be improved among curves if the ball-bank indicator is used to establish advisory speeds.

Nighttime Speed

This subsection examines the relationship between the average daytime and nighttime speeds of cars and trucks, as measured on the tangent at each curve study site. This relationship is shown in Figure 3-8. Each data point represents the average tangent speed at one site. The "$y = x$" line is shown, as is the best-fit trend line. The best-fit line is shown using a slightly thicker line that extends only for the range of the data.
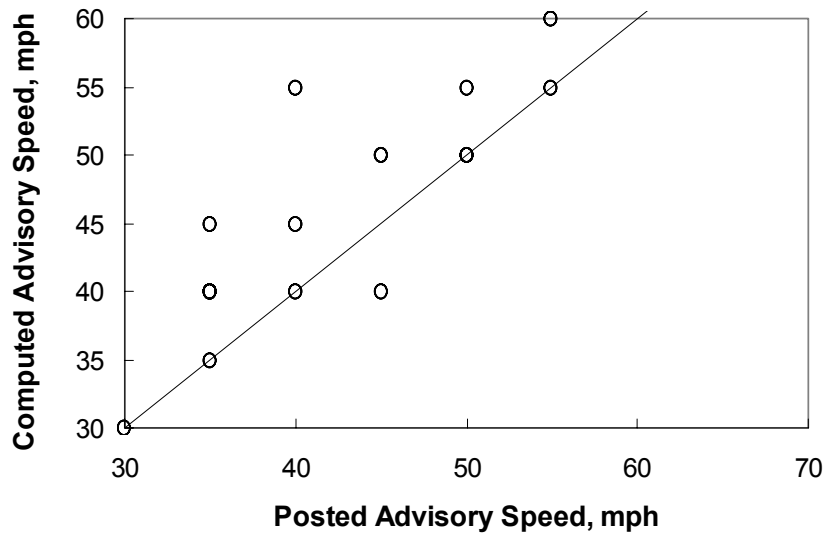
Figure 3-7. Comparison of Posted and Computed Advisory Speeds.
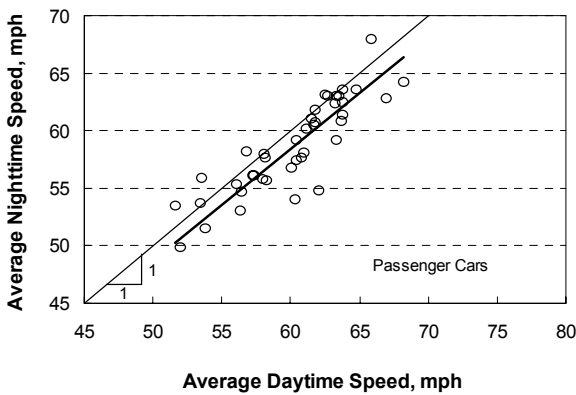
a. Passenger Car Speed.

b. Truck Speed.

Figure 3-8. Relationship between Average Daytime and Nighttime Speed.

The trends shown in Figures 3-8a and 3-8b indicate that nighttime speeds tend to be slower than daytime speeds for both cars and trucks, respectively. Passenger car drivers tended to adopt speeds that were about 2.0 mph slower during nighttime hours. Truck drivers tended to adopt speeds that were only about 1.0 mph slower during nighttime hours. The trend in the data is more varied in Figure 3-8b, relative to Figure 3-8a, because of the smaller number of truck observations at each site.

An analysis of the distribution of the data shown in Figure 3-8 indicated that least-squares regression could be used to quantify the relationship between daytime and nighttime speeds.

However, because of variations in the number of observations between these two time periods, it was determined that weighted least-squares regression would be needed to yield an unbiased estimate. The following equation was used to compute the weight associated with each site, as used in the regression analysis:

$$W_v = \left(\frac{\sigma_d^2}{n_d} + \frac{\sigma_i^2}{n_i} \right)^{-1.0} \tag{21}$$

where,
  W_v = weight function for regression;
  σ_d^2 = variance of the dependent variable in the regression model;
  n_d = number of observations used to estimate the dependent variable;
  σ_i^2 = variance of the independent variable in the regression model; and
  n_i = number of observations used to estimate the independent variable.

The following model form was found to provide the best fit to the data:

$$V_{a,N} = b_o \, V_{a,D} \tag{22}$$

where,
  $V_{a,N}$ = average nighttime speed, mph;
  $V_{a,D}$ = average daytime speed, mph; and
  b_0 = calibration coefficient.

The results of the regression analysis are summarized in Table 3-9. The calibration coefficients listed in the table can be used with Equation 22 to estimate average nighttime speed for a given daytime speed. The coefficients listed indicate that passenger car speed in nighttime hours is about 97.5 percent of the daytime speed (= 100×0.975). Truck nighttime speed is about 98.6 percent of the daytime speed. The model fit statistics indicate that the estimated car nighttime speed would have a 70 percent confidence interval of ±1.62 mph. Truck nighttime speeds are predicted with less precision, having a confidence interval of ±2.99 mph. Similar trends were found in the analysis of the 85th percentile tangent speeds.

Table 3-9. Calibrated Nighttime Speed Model.

Vehicle Type	Calibration Coefficient		Model Fit Statistics [1]	
	b_0	p-value [2]	RMSE, [3] mph	Coeff. of Determination (R^2)
Passenger Car	0.975	0.000	1.62	0.85
Truck	0.986	0.099	2.99	0.68

Notes:
1 - Computed using weighted residuals.
2 - Test of the hypothesis that the calibration coefficient b_0 is equal to 1.0. Value shown indicates the probability of making an error should we reject the hypothesis. Small values of this probability suggest the observed difference in speed is statistically significant.
3 - RMSE: root mean square error. An estimate of the standard deviation of the predicted speed.

Truck Speed

This subsection examines the relationship between the average speed of cars and trucks during daytime and nighttime periods, as measured on the tangent at each curve study site. This relationship is shown in Figure 3-9. Each data point represents the average tangent speed at one site. The "$y = x$" line is shown as is the best-fit trend line. The best-fit line is shown using a slightly thicker line that extends only for the range of the data.
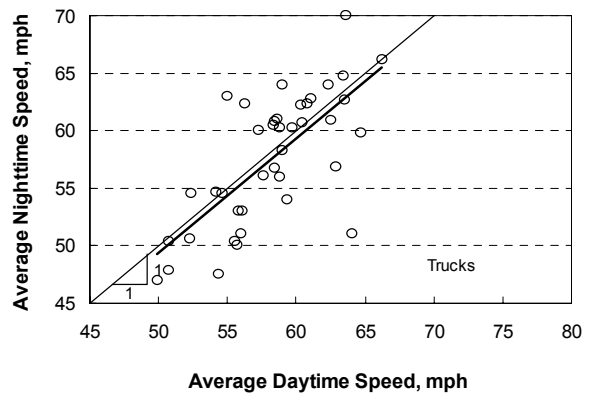

a. Daytime Hours.   **b. Nighttime Hours.**
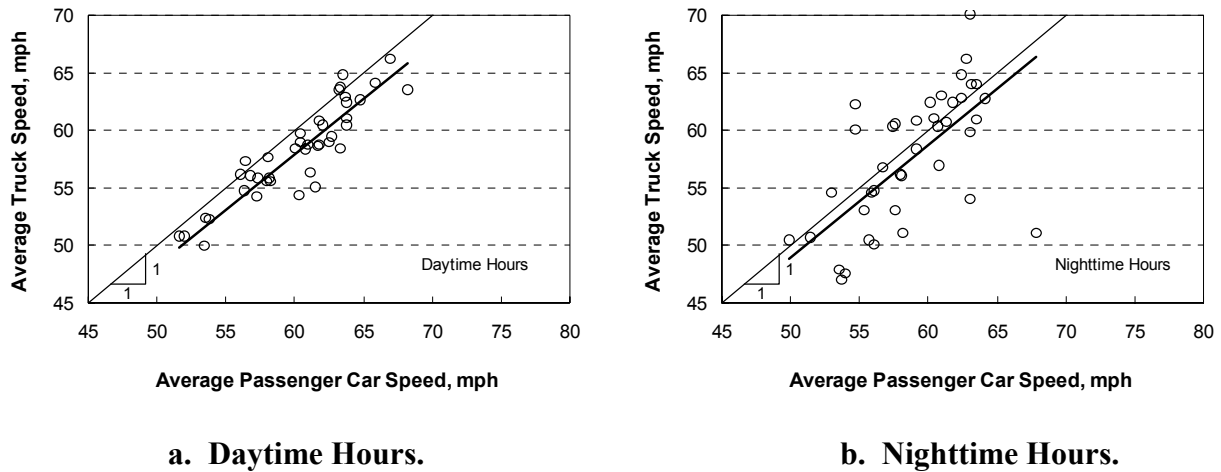
Figure 3-9. Relationship between Average Passenger Car and Truck Speed.

The trends shown in Figures 3-9a and 3-9b indicate that truck speeds tend to be slower than passenger car speeds for both daytime and nighttime hours, respectively. During daytime hours, truck drivers tended to adopt speeds that were 2.0 mph slower than car drivers. During nighttime hours, truck drivers tended to adopt speeds that were only about 1.0 mph slower than car drivers. The trend in the data is more varied in Figure 3-9b, relative to Figure 3-9a, because of the smaller number of nighttime observations at each site.

The following model form was found to provide the best fit to the data:

$$V_{a,tk} = b_o \, V_{a,pc} \tag{23}$$

where,
$V_{a,tk}$ = average truck speed, mph;
$V_{a,pc}$ = average passenger car speed, mph; and
b_0 = calibration coefficient.

The results of the regression analysis are summarized in Table 3-10. The calibration coefficients listed in the table can be used with Equation 23 to estimate average truck speed for a given passenger car speed. The coefficients listed indicate that truck speed in daytime hours is about 96.9 percent of passenger car speed (= 100×0.969). Truck nighttime speed is about 97.9 percent of car speed. The model fit statistics indicate that the estimated truck daytime speed would have a

70 percent confidence interval of ±1.47 mph. Truck nighttime speeds are predicted with less precision, having a confidence interval of ±3.03 mph. Similar trends were found in the analysis of the 85th percentile tangent speeds.

Table 3-10. Calibrated Truck Speed Model.

| Time Period	Calibration Coefficient		Model Fit Statistics [1]	
	b_0	p-value [2]	RMSE, [3] mph	Coeff. of Determination (R^2)
Daytime	0.969	0.000	1.47	0.88
Nighttime	0.979	0.011	3.03	0.67

Notes:

1 - Computed using weighted residuals.

2 - Test of the hypothesis that the calibration coefficient b_0 is equal to 1.0. Value shown indicates the probability of making an error should we reject the hypothesis. Small values of this probability suggest the observed difference in speed is statistically significant.

3 - RMSE: root mean square error. An estimate of the standard deviation of the predicted speed.

Effect of Lateral Shift on Travel Path Radius

Past observations of driver behavior while negotiating sharp curves indicate that vehicles shift laterally inward while cornering (*1, 7*). This behavior was observed to occur at many of the sites identified in Table 3-3. A lateral shift results in the vehicle tracking a larger radius than that of the lane. Its effect on path radius is shown in Figure 3-10.
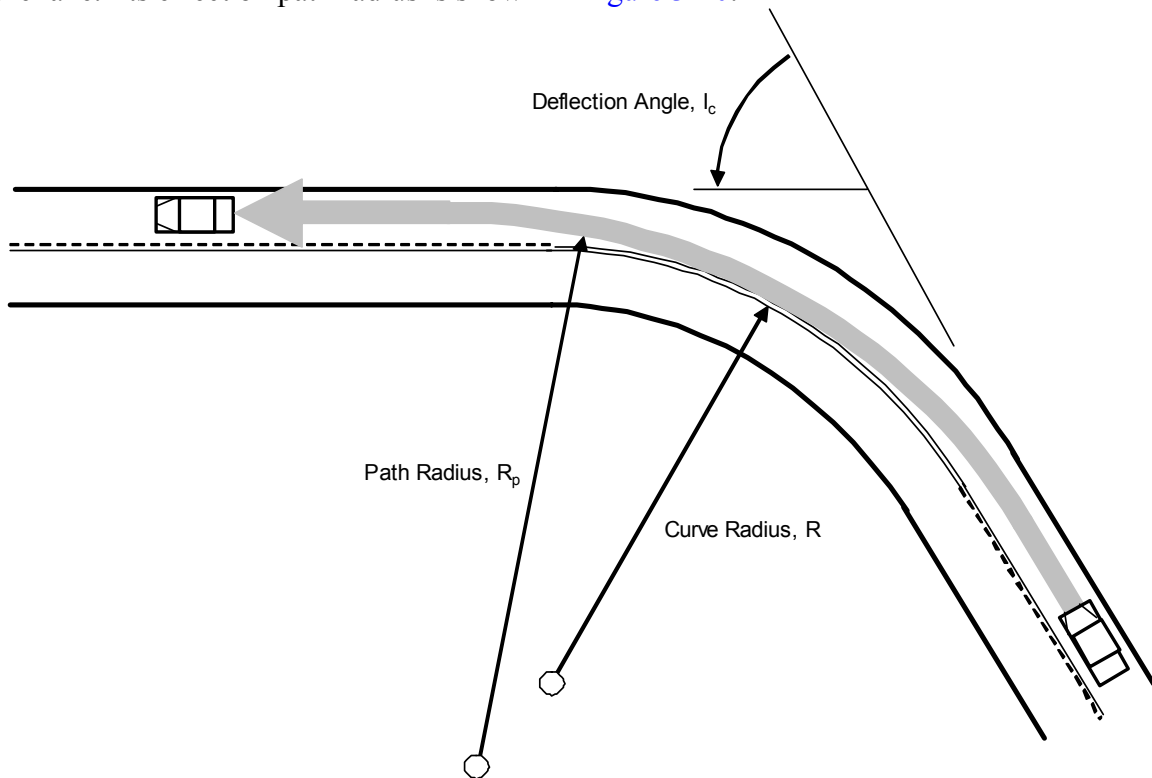
Figure 3-10. Effect of Lateral Shift on Travel Path Radius.

Figure 3-10 illustrates the actual path of the typical vehicle as it traverse a horizontal curve. This path is shown using a thick grey line. The vehicle is traveling from right to left in the figure, and its position is shown to shift laterally from "centered in the lane" on curve entry to "adjacent to the inside edge of the lane" near the midpoint of the curve. The radius of this travel path R_p is compared to that of the curve radius R in the figure. Lateral shift always results in a path radius larger than the curve radius. The driver is motivated to accomplish this shift because it reduces side friction demand.

Using the geometric relationships indicated in Figure 3-10, the following equation was derived for computing the effective increase in curve radius due to a lateral shift within the lane:

$$dr = \frac{y_{max}}{1 - Cosine\,(0.5\,I_c)} \tag{24}$$

where,
dr = increase in curve radius, ft;
y_{max} = maximum lateral shift of vehicle, ft; and
I_c = curve deflection angle, degrees.

Based on the observation of several vehicles, Emmerson (7) offered a value of 3.0 ft as being representative of the lateral shift of most vehicles.

Examination of Equation 24 indicates that the value of dr increases rapidly with decreasing curve deflection angle. Typical values of dr are shown in Table 3-11. To illustrate the use of the values in this table, consider a two-lane highway curve with a radius of 1000 ft and a deflection angle of 20 degrees. A lateral shift of 3.0 ft on this curve produces a travel path radius of 1197 ft (= 1000 + 197).

Table 3-11. Increase in Lane Radius Due to a Lateral Shift in Lane Position.

Increase in Radius, ft	Curve Deflection Angle, degrees											
	5	10	15	20	25	30	35	40	45	50	55	60
	3152	788	351	197	127	88	65	50	39	32	27	22

Tangent Speed

This subsection examines the relationship between the 85th percentile speed and the regulatory speed limit at each site. The 85th percentile passenger car speeds observed during daytime hours on the tangent sections were used for the examination.

As shown previously in Figure 3-5, the 85th percentile tangent speed is correlated with speed limit. However, the coefficient of determination indicates that speed limit explains only 49 percent of the variability in the data. The data were examined further to determine if the remaining variability could be explained by other factors. The factors considered included lane width, shoulder width, curve deflection angle, and curve radius. The examination of radius was motivated by

research conducted Polus et al. (*8*). They rationalized that the radii at the ends of the tangent section tended to reflect the highway's environment and overall design character. They demonstrated that these radii were correlated to tangent speed.

Weighted least-squares regression was used for the analysis because of the wide variation in sample size among the study sites. The following equation was used to compute the weight associated with each site:

$$W_v = \frac{n_d}{\sigma_d^2} \qquad (25)$$

where,
W_v = weight function for regression;
σ_d^2 = variance of the dependent variable in the regression model; and
n_d = number of observations used to estimate the dependent variable.

The analysis indicated that lane width, shoulder width, and deflection angle did not have a significant correlation with tangent speed. However, curve radius was found to have a notable effect on tangent speed. The following model form was found to provide the best fit to the data:

$$V_{t,85,pc} = b_o \sqrt{V_{sl}} \left(1 - e^{b_1 (R + 100)/5730}\right) \qquad (26)$$

where,
$V_{t,85,pc}$ = 85th percentile tangent speed of passenger cars, mph;
V_{sl} = regulatory speed limit, mph;
R = radius of curve, ft; and
b_i = calibration coefficients ($i = 0, 1$).

The results of the regression analysis are summarized in Table 3-12. The coefficient of determination R^2 in this table indicates that the model explains 69 percent of the variability in the measured tangent speeds. The root mean square error suggests that the 70 percent confidence interval for the predicted speed is about ±2.8 mph. The t-statistics in the lower right corner of the table provide information about the precision of the calibration coefficients. A t-statistic whose absolute value is 1.9 or larger is considered statistically significant, with only 5 percent or less chance of an error in this conclusion. All of the coefficients in this model are statistically significant.

The calibrated tangent speed prediction model is shown in the following equation:

$$V_{t,85,pc} = 8.57 \sqrt{V_{sl}} \left(1 - e^{-35.21 (R + 100)/5730}\right) \qquad (27)$$

This equation can be used to estimate the 85th percentile tangent speed when information about the speed distribution on a specified tangent is not available.

Table 3-12. Calibrated Tangent Speed Prediction Model Statistics.

Model Statistics				
R^2:	0.69			
Root Mean Square Error (mph):	2.8			
Observations:	41 sites (6677 passenger cars)			
Range of Model Variables				
Variable	Variable Name	Units	Minimum	Maximum
V_{sl}	Regulatory speed limit	mph	55	70
R	Radius of curve	ft	318	1432
Calibrated Coefficient Values				
Coefficient	Coefficient Definition	Value	Standard Deviation	t-statistic
b_0	Intercept	8.57	0.08	111.6
b_1	Effect of radius	-35.21	3.59	-9.8

Data Analysis

This section describes the findings from the analysis of the daytime curve speed data. The focus of the analysis was the calibration of a speed prediction model. This model was described previously in the discussion associated with Equation 18. This section consists of three subsections. Initially, several statistical analysis issues are addressed. Then, the calibrated model is described. Finally, the last subsection provides the findings from a sensitivity analysis of the calibrated model.

Statistical Considerations

The SAS non-linear regression procedure (i.e., NLIN) was used for model calibration. Linear regression was not used to calibrate the model because it does not have a linear form. The side friction model (i.e., Equation 15) does have a linear form, but it is not the preferable model for coefficient calibration for three reasons. First, the dependent variable (i.e., friction) is a computed value rather than a measured quantity. Second, computed friction variance is neither constant nor normally distributed, as is assumed for least-squares regression modeling. Its standard deviation increases with curve speed. Third, computed friction is based on curve speed, which would put curve speed on both sides of the equality sign in Equation 15, when used as the regression model.

Regression analysis based on curve speed prediction does not share the aforementioned limitations. The non-linear regression approach, combined with Equation 18 as the appropriate model form, offers an unbiased means of quantifying the true relationship between side friction, curve speed, and tangent speed. The calibration coefficients then can be used directly in Equation 15 to estimate side friction demand. This modeling approach represents an important distinction between this and other efforts to define a relationship between curve geometry, side friction, and speed.

Model Calibration

The speed prediction model used for calibration is:

$$V_c = \left(\frac{15.0\, R_p\, [b_0 - b_1(1.47\, V_t) + 0.001\, b_2(1.47\, V_t)^2 + b_3 I_{tk} + b_4 I_x + e/100]}{1 + 0.0322\, R_p\, b_2} \right)^{0.5} \le V_t \quad (28)$$

with,

$$R_p = R + \frac{3.0}{1 - Cosine\,(0.5\, I_c)} \quad (29)$$

where,

V_c = curve speed, mph;
V_t = tangent speed, mph;
R_p = travel path radius, ft;
b_3 = calibration coefficient for trucks;
I_{tk} = indicator variable for trucks (= 1.0 if model is used to predict truck speed; 0.0 otherwise);
b_4 = calibration coefficient for other factors (e.g., Chevron presence);
I_x = indicator variable (= 1.0 if factor is present; 0.0 otherwise);
e = superelevation rate, percent; and
I_c = curve deflection angle, degrees.

The indicator variable I_x was included in the model to explore the effect of various factors on curve speed. The factors considered include: Chevron presence, delineator presence, and edge line marking presence. Also, the "grade" variable was substituted for the indicator variable I_x to evaluate the effect of grade on speed. Each factor was evaluated separately to determine its effect on speed, in isolation of the other factors. The corresponding calibration coefficient from each regression analysis was then evaluated to determine if the factor had a significant influence on speed. Based on this analysis, it was determined that Chevron presence, delineator presence, edge line marking presence, and grade do not have a significant effect on curve speed.

The effects of curve radius R and path radius R_p were separately evaluated in the regression model. The model that included path radius was found to provide a significant improvement in model fit. For this reason, the variable for path radius was retained in the model.

As noted previously, the number of observations at each site was not the same. Thus, the squared residuals were weighted during the regression. The weight for each site observation was computed using Equation 25.

The results of the regression analysis are summarized in Table 3-13. The analysis was based on the daytime speed for each site. Separate models were calibrated using the 85th percentile speed and the average speed estimates. The preliminary examination of daytime versus nighttime speeds indicated that drivers adopted slightly slower speeds during the nighttime hours. However, from a practical standpoint, the magnitude of the speed reduction was not sufficiently large as to dictate the selection of an advisory speed based on nighttime speeds. Moreover, given that the daytime sample

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size was adequate, it was rationalized that no statistical benefit would be realized by increasing the sample size through inclusion of the nighttime data.

Table 3-13. Calibrated Curve Speed Prediction Model Statistics.

Model Statistics		85th Percentile Speed			Average Speed		
R^2:		0.97			0.98		
Root Mean Square Error (mph):		1.5			1.2		
Observations:		41 sites (6677 passenger cars, 1741 trucks)					
Range of Model Variables							
Variable	Variable Name	Units	Minimum	Maximum	Units	Minimum	Maximum
f_D	Side friction demand factor	g's	0.10	0.32	g's	0.07	0.25
V_t	Tangent speed	mph	58	75	mph	50	68
V_c	Curve speed	mph	39	70	mph	35	63
R	Radius of curve	ft	318	1432	ft	318	1432
I_c	Curve deflection angle	degrees	18	90	degrees	18	90
e	Superelevation rate	%	1.4	13.1	%	1.4	13.1
Calibrated Coefficient Values							
Coefficient	Coefficient Definition	Value	Standard Deviation	t-statistic	Value	Standard Deviation	t-statistic
b_0	Intercept	0.1962	0.0501	3.9	0.1118	0.0398	2.8
b_1	Effect of tangent speed	0.00072	0.0005	1.5	0.00045	0.0004	1.1
b_2	Effect of speed reduction	0.0338	0.0031	11.0	0.0423	0.0031	13.8
b_3	Effect of Truck	-0.0150	0.0079	-1.9	-0.0108	0.0062	-1.8

With regard to the model calibrated with the 85th percentile speed data, the coefficient of determination R^2 in Table 3-13 indicates that the model explains 97 percent of the variability in the measured curve speeds. The root mean square error suggests that the 70 percent confidence interval for the predicted speed is about ±1.5 mph. For the model calibrated to the average speed estimates, the model explains 98 percent of the variability in the measured speeds. The root mean square error suggests that the 70 percent confidence interval for the predicted speed is about ±1.2 mph.

The t-statistics in the lower right corner of the table provide information about the precision of the calibration coefficients. A t-statistic whose absolute value is 1.9 or larger is considered statistically significant, with only 5 percent or less chance of an error in this conclusion. The coefficient b_1 in both model variations does not meet this level of confidence. It is highly correlated with the intercept coefficient, which tends to increase the standard deviation of both variables when both are included in the model. Nevertheless, the effect of speed on friction demand is well documented (see Chapter 2) and is consistent in magnitude with the b_1 coefficient in Table 3-13. Therefore, this variable is retained in the model. The quality of fit to the measured 85th percentile curve speeds is illustrated in Figure 3-11. The fit of the average speed prediction model is very similar to that shown in Figure 3-11.
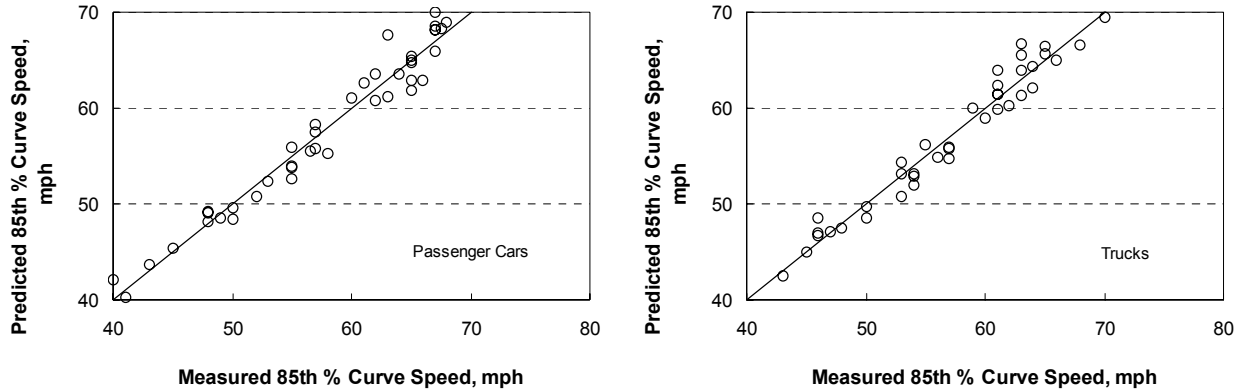
a. **Passenger Car Speeds.**   **b.** **Heavy Truck Speeds.**

Figure 3-11. Comparison of Measured and Predicted Curve Speeds.

The calibration coefficients in Table 3-13 were combined with Equation 28 to yield the following calibrated forms of the curve speed prediction model.

$$V_{c,85} = \left(\frac{15.0\,R_p\,(0.196 - 0.00106\,V_{t,85} + 0.000073\,V_{t,85}^2 - 0.0150\,I_{tk} + e/100)}{1 + 0.00109\,R_p} \right)^{0.5} \leq V_{t,85} \quad (30)$$

$$V_{c,a} = \left(\frac{15.0\,R_p\,(0.112 - 0.00066\,V_{t,a} + 0.000091\,V_{t,a}^2 - 0.0108\,I_{tk} + e/100)}{1 + 0.00136\,R_p} \right)^{0.5} \leq V_{t,a} \quad (31)$$

where,
$V_{c,85}$ = 85th percentile curve speed, mph;
$V_{t,85}$ = 85th percentile tangent speed, mph;
$V_{c,a}$ = average curve speed, mph; and
$V_{t,a}$ = average tangent speed, mph.

The average tangent speed $V_{t,a}$ used in Equation 31 is estimated as being 90 percent of the 85th percentile tangent speed $V_{t,85}$ (i.e., $V_{t,a} = 0.90 \times V_{t,85}$). This relationship was derived from the data in Table 3-6. The coefficient of determination R^2 is 0.93.

When Equation 30 or 31 is used to estimate truck curve speed, the average tangent speed for truck traffic must be input. This speed is estimated as 97 percent of that for passenger cars (i.e., $V_{t,a,tk} = 0.97 \times V_{t,a,pc}$). This relationship is obtained from Table 3-10.

Sensitivity Analysis

The calibrated curve speed models were used to estimate the 85th percentile and average curve speed for a range of curve radii. The results of this analysis are shown in Figures 3-12a and 3-12b for the 85th percentile and average speed, respectively. Both figures were developed using three specified 85th percentile tangent speeds.
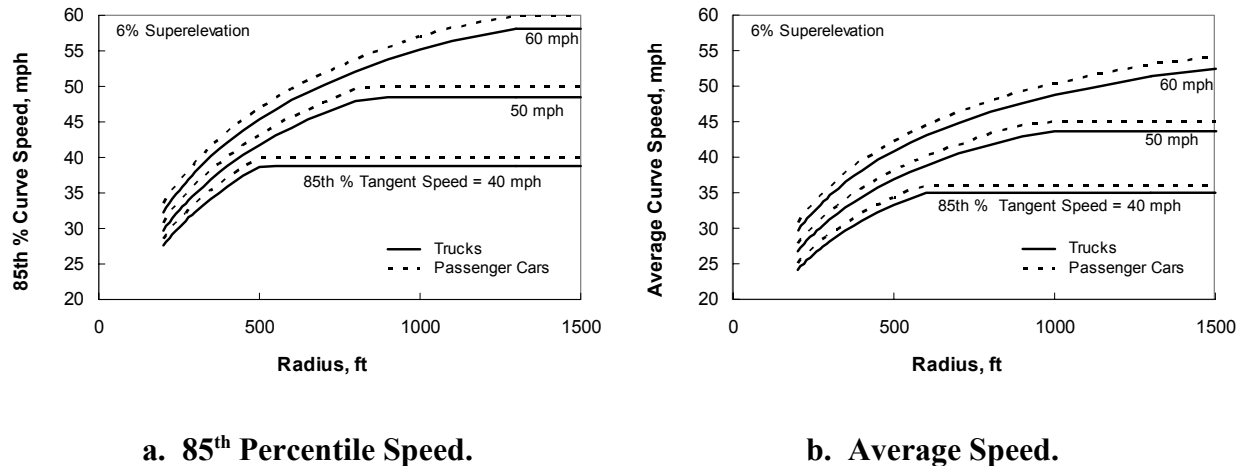
a. 85th Percentile Speed.   b. Average Speed.

Figure 3-12. Effect of Radius and Tangent Speed on Curve Speed.

The trend lines shown in Figures 3-12a and 3-12b indicate that curve speed increases with increasing radius and tangent speed. Truck speeds are about 2 mph slower than passenger car speeds. The influence of radius and tangent speed is consistent with the trends found in the literature (see Figure 2-1).

The recommended 85th percentile curve speed model (i.e., Equation 30) was compared with the linear model developed by Bonneson (*1*) (i.e., Equation 16). The comparison focused on the speeds predicted for trucks; similar findings were obtained from a comparison for passenger cars. The comparison of model predictions considered both the rural highway and the turning roadway forms of the linear model. The results of this comparison are shown in Figure 3-13.

The trends in Figure 3-13 that are associated with the recommended model indicate a general agreement with the rural highway and the turning roadway trends from the linear model. As expected, the recommended model provides a desirable transition from the turning roadway trend line at smaller radii to the rural highway trend line at larger radii. These characteristics, combined with the model's fit to the data, are a good indication that the parabolic model accurately explains driver side friction demand and curve speed choice.
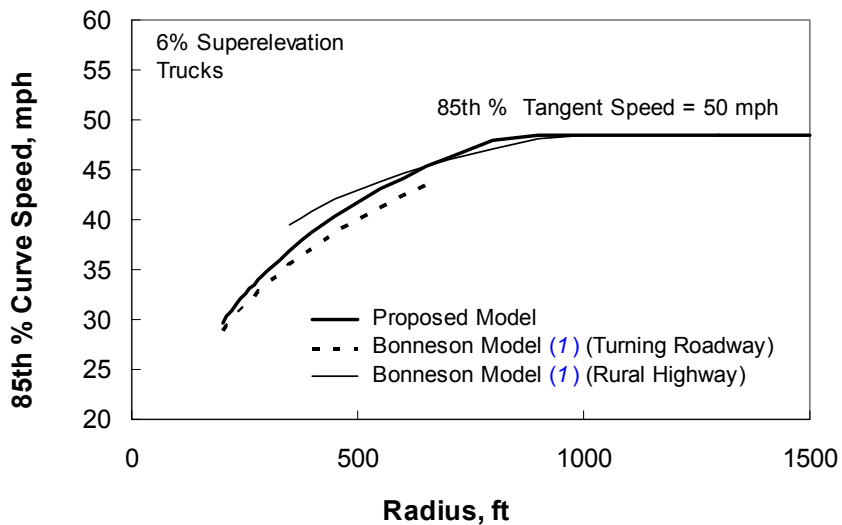
Figure 3-13. Comparison of Two Curve Speed Prediction Models.

Model Validation

The data reported by Bonneson (*1*) were used to validate the calibrated curve speed model described in the previous section. Data for 39 rural two-lane highway curves were obtained from this reference, representing curves in eight states. Equation 29 was used to predict the average passenger car speed for each of the 39 curves. This prediction is compared with the average speed reported for each curve in Figure 3-14. The trend line shown in this figure is a "$y = x$" line. If the reported and predicted speeds were equal for each curve, the data points would lie on this line.

Figure 3-14. Comparison of Reported and Predicted Average Speeds.

The trends in the data in Figure 3-14 indicate that Equation 31 is able to accurately predict the reported speeds. An analysis of the data indicates that the prediction has a bias of less than 0.3 mph and a standard deviation of 2.8 mph. The co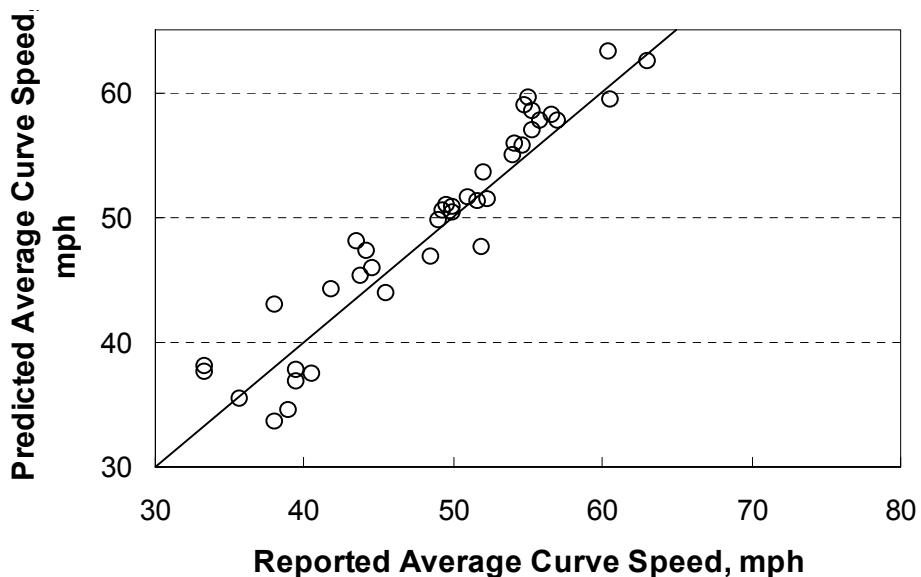efficient of determination R^2 is 0.86. The bias is negligible for the intended application. About one-half the standard deviation is attributable to unexplained variation in the data and is consistent with the standard deviation of 1.2 mph obtained for the calibrated model (see Table 3-13). The remaining deviation may be partially due to a variety of factors in the validation database, such as smaller sample size per site, shorter distance between the curve and the tangent speed measurement location, and differences in data collection procedures and equipment.

EVALUATION OF METHOD FOR ESTABLISHING ADVISORY SPEED

This part of the chapter documents the findings from the evaluation of two engineering study methods. The objective of this evaluation was to evaluate the accuracy and repeatability of each method when used to establish curve advisory speeds. The first section to follow describes the evaluation of the ball-bank indicator method. The second section describes an evaluation of the compass method.

Ball-Bank Indicator Method

This section describes the findings from an evaluation of the ball-bank indicator method, previously described in Chapter 2. The first section describes the findings from a series of field studies that evaluated the stability of the ball-bank indicator when traveling along a curve. The second section examines the relationship between ball-bank reading and driver curve speed choice. The last section examines the accuracy of the ball-bank indicator method.

Variability of Ball-Bank Readings

It was noted during the field studies that the superelevation rate on most of the horizontal curves varied along the length of the curve. The variation within a 100-ft mid-curve section was found to range from 0.0 to 2.7 percent, depending on the curve. This variation was not found to cause a significant change in curve speed because it generally occurred in a fraction of a second and did not allow drivers to react to the change before the road returned to normal superelevation. However, it was found to have a significant effect on the ball-bank reading. In spite of the damping fluid in the ball-bank vial (or the electronic equivalent in a digital device), the reading varied by several degrees when traveling along the middle portion of the curve. This variation was noted to be further magnified when the driver made steering corrections to compensate for tire slip or changes in pavement friction or superelevation rate.

The variation in ball-bank reading at one curve is shown in Figures 3-15a and 3-15b. The first and last readings shown in each figure are small because of the superelevation runoff that occurs at the start and end of the curve. However, the intermediate readings can be seen to vary by several degrees with travel time along the curve and also by curve direction and technician. Similar trends were found at the other curves studied.

a. Technician A.   b. Technician B.
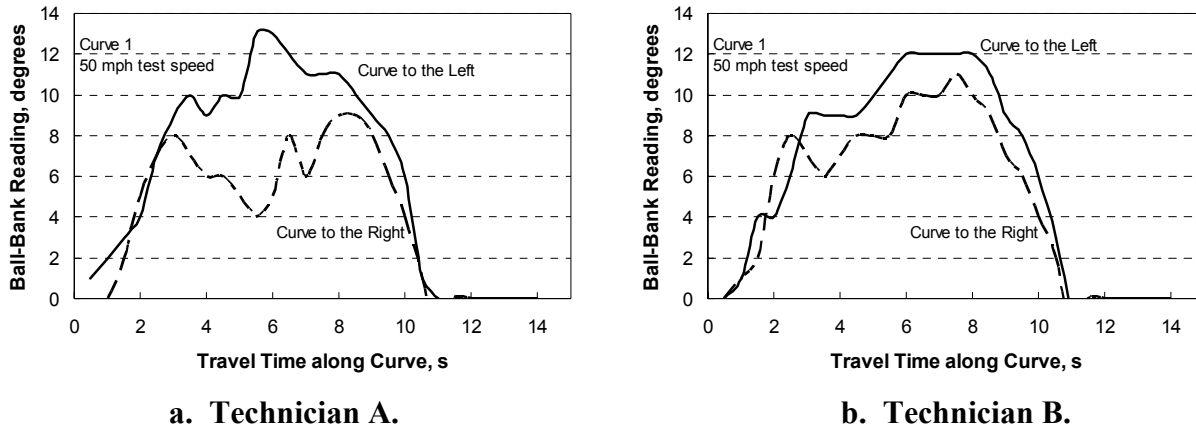
**Figure 3-15. Ball-Bank Readings from Two Test Runs with Different Technicians.**

The variation in readings along the curve is likely due to steering corrections. In Figure 3-15a, the ball-bank reading on the curve to the right varies from 4 to 9 degrees for travel time between 2.5 and 8.5 s. The average reading in this range is 7.3 degrees. As shown in Figure 3-15b, the second technician driving the same car and curve to the right observed readings that vary from 6 to 11 degrees with an average of 8.2 degrees. The variability within any one technician's test run is significant and, when considering the additional variability among technicians, it is not difficult to understand why there is so little uniformity in advisory speeds among curves. Moreover, this finding suggests the ball-bank method has the undesirable trait of not being a "repeatable" process.

Standard practice in using the ball-bank indicator is to use the *maximum* ball-bank reading observed during the test run to establish the advisory speed. Thus, for the curve shown in Figure 3-15, a 12 or 13 degree maximum (depending on technician) is observed for the curve to the left, and a 9 or 11 degree maximum is observed for the curve to the right. However, this maximum reading is likely the result of a random event–an aberration due to steer correction. Thus, the practice of selecting the maximum reading has the undesirable trait of allowing the advisory speed to be based on a momentary random spike in the reading. This finding is also consistent with the trend noted in Chapter 2 that advisory speeds are too low, relative to the observed speed distribution.

A series of test runs were conducted at each of six curves for the purpose of evaluating the variability in ball-bank readings. Equation 10 was used with the curve geometry and test run speed to estimate the side friction angle for each curve. The relationship between side friction angle and maximum observed ball-bank reading is shown in Figure 3-16. Each data point shown in the figure represents one test run.

The trend line shown in Figure 3-16 represents the best-fit regression line. The standard deviation associated with this line is 1.27 degrees. This value is smaller than that found in Figures 2-11 and 2-12 because many of the data points in Figure 3-16 represent a common curve. Readings obtained in successive runs at the same curve will control (or remove) some of the variability in readings that would otherwise be obtained had each test run been conducted at a different curve.

Also, the researchers who conducted these test runs were aware of the variability issues and were focused on minimizing them to the extent possible. The trend in Figure 3-16 confirms the existence of large variability in ball-bank readings (as found in previous research projects), which undermines its ability to yield uniform advisory speeds.
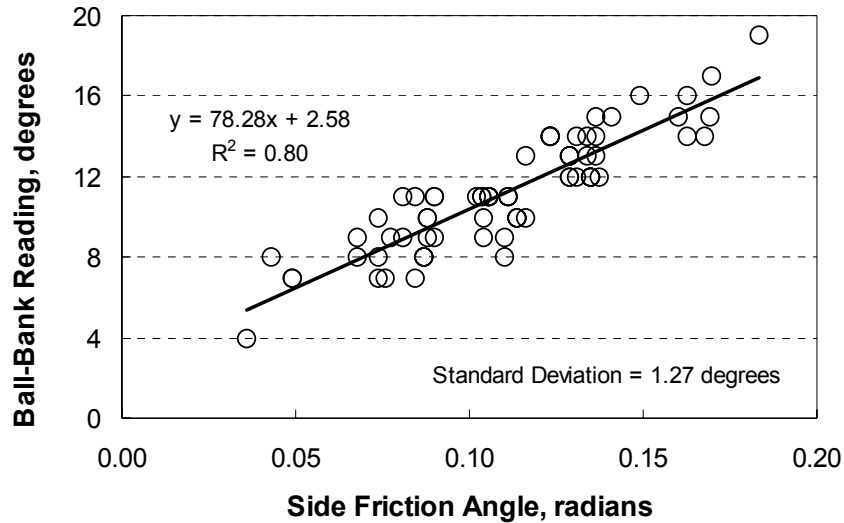

Figure 3-16. Variation in Ball-Bank Readings in Field Data.

Curve Speed Choice and Corresponding Ball-Bank Angles

The advantage of using Equation 30 or 31 for predicting curve speed, relative to Equation 20, is that Equations 30 and 31 do not require specification of the side friction demand factor. As a result, their calibration with field data eliminates the need to define the appropriate side friction demand for advisory speed determination. Equations 30 and 31 also incorporate a sensitivity to tangent speed that is not reflected in Equation 20 or its associated friction factors in Table 3-8.

The calibrated curve speed model was used to estimate the average curve speed for a range of curve radii. This speed was then used with Equations 10 and 11 to estimate an equivalent ball-bank reading. The results of this analysis are shown in Figure 3-17. The trend lines shown in this figure illustrate the ball-bank readings that correspond to the curve speed. They are similar to those shown in Figure 2-14b. It confirms that the ball-bank reading that corresponds to driver speed choice is not a constant (e.g., 10 degrees). Rather, this reading decreases with increasing curve speed, reflecting the driver's choice of less side friction at higher curve speeds. It also confirms that the relationship between ball-bank reading and curve speed is dependent on the tangent speed. Finally, it confirms that a ball-bank reading of 10 degrees corresponds to a speed reduction of between 7 and 10 mph, depending on tangent speed. This reduction is consistent with the experiences of the engineers surveyed by Lyles and Taylor (9).
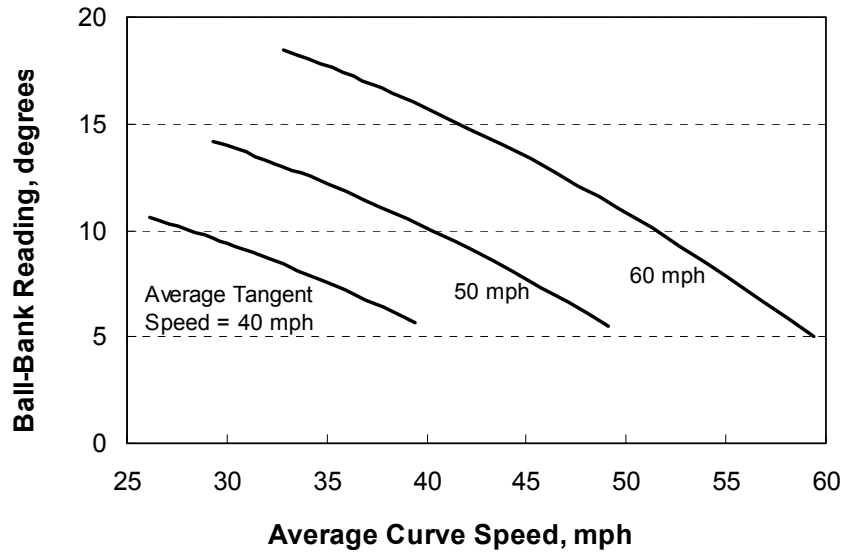
Figure 3-17. Relationship between Speed and Ball-Bank Reading.

Estimated Accuracy of Advisory Speed

This subsection describes an equation that can be used to estimate the variability of the ball-bank indicator method. This equation is used in the next section to compare the ball-bank indicator method and the compass method for the purpose of determining which method yields the estimate of advisory speed that is most accurate. In this report, accuracy is quantified in terms of the standard deviation of the estimated advisory speed.

Equation 10 relates a dependent variable (e.g., friction) to one or more independent variables (e.g., radius). However, if the independent variable is not known with certainty, then there is similar uncertainty in the dependent variable. A method is described by Benjamin and Cornell (*10*) for relating the standard deviation of a function's dependent variable to the standard deviation of its input variables. It is based on the first derivative of the underlying function. This method is used herein to derive the desired equations for estimating the standard deviation of advisory speed.

The function relating speed to the corresponding ball-bank reading is described by the combination of Equations 10 and 11. It was used to derive the following equation for estimating the standard deviation of the curve speed estimate using the ball-bank indicator method:

$$\sigma_V = 0.13 \left(\frac{1 + (1.47 \, V_c)^4/(g \, R_p)^2}{1 + k} \right) \frac{R_p}{V_c} \, \sigma_\alpha \tag{32}$$

where,
  σ_V = standard deviation of the curve speed estimate, mph; and
  σ_α = standard deviation of the ball-bank reading, degrees.

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A review of three data sets (shown in Figures 2-11, 2-12, and 3-16) indicates that the standard deviation of the ball-bank reading can vary from 1.27 to 3.02 degrees. Lower values in this range are believed to represent controlled conditions where the test runs were conducted in a manner that minimizes variability from many sources. Higher values in this range are believed to be more representative of typical test runs where several sources of variability are present. The standard deviation of 2.20 degrees shown in Figure 2-12 is used for the comparison provided in the next section.

Compass Method

This section summarizes the findings from an evaluation of the compass method. The first section describes the findings from a series of field studies that evaluated the accuracy of field measurements of radius and superelevation. The last section examines the accuracy of the compass method.

Variability of Measured Radius and Superelevation

A method for measuring superelevation rate and radius is described in this section. These variables would be used with Equation 30 or 31 to estimate curve speed. Other methods for their measurement exist; however, the method described is believed to be a viable method for most public agencies to implement in the course of establishing an advisory speed.

Superelevation is estimated using a ball-bank indicator mounted in the test vehicle. The vehicle travels at a speed of 15 mph or less along the middle portion of the curve. This relatively slow speed is used to minimize much of the variability inherent to the ball-bank indicator. The ball-bank reading obtained in this manner is then used with an equation (shown as Equation A-12 in Appendix A) to estimate the superelevation rate. Experience using this technique indicates that the variability in the estimated superelevation rate is about 1 percent.

Curve radius is estimated using the compass method. With this method, a compass is used to measure the azimuth of the vehicle heading at two points along the curve. The difference between the two measurements equals the curve deflection angle. Experience using a compass based on global positioning system (GPS) technology for heading estimation indicates that deflection angle can be estimated with a standard deviation of 2.0 degrees (= 0.035 radians) or less. A distance-measuring instrument (DMI) is used to measure the length of the curve between the same two points at which a heading was measured. A series of field measurements indicate that curve length can be estimated in this manner with a standard deviation of about 3.0 ft.

Estimated Accuracy of Advisory Speed

This section describes a set of equations that can be used to estimate the variability of the compass method. These equations are then used to compare the compass and ball-bank indicator methods for the purpose of determining which method yields the estimate of advisory speed that is most accurate. As in the previous section, the method described by Benjamin and Cornell (10) is used to derive the necessary equations.

The function relating average speed to the corresponding radius measurement is described by Equation 31. It was used to derive the following equation:

$$\sigma_{VL} = \frac{0.0334 \; V_{c,a}^3}{(0.112 - 0.00066 \; V_{t,a} + 0.000091 \; V_{t,a}^2 - 0.0108 \; I_{tk} + e/100) \; R_p^2} \; \sigma_R \tag{33}$$

with,

$$\sigma_R = \frac{57.3}{I_c} \left(\sigma_L^2 + (R_p \; \sigma_I)^2 - 2 \rho_c \; \sigma_L \; \sigma_I \; R_p \right)^{0.5} \tag{34}$$

where,

σ_{VL} = standard deviation of curve speed based on radius variability, mph;
σ_R = standard deviation of the radius estimate, ft;
σ_I = standard deviation of the deflection angle estimate (= 0.035), radians;
ρ_c = correlation between curve length and deflection angle (= 0.50); and
σ_L = standard deviation of the curve length measurement (= 3.0), ft.

Equation 31 was also used to derive a similar relationship for estimating the standard deviation of curve speed based on superelevation variability. This equation is:

$$\sigma_{Ve} = \frac{0.0748 \; R}{V_{c,a} \; (1 + 0.00136 \; R_p)} \; \sigma_e \tag{35}$$

where,

σ_{Ve} = standard deviation of curve speed based on superelevation variability, mph; and
σ_e = standard deviation of the superelevation measurement (= 1.0), percent.

Finally, Equation 31 was also used to derive a relationship for estimating the standard deviation of curve speed based on the variability of the estimate of tangent speed. Table 3-12 indicates that the estimate of tangent speed has a standard deviation σ_T of 2.8 mph. The equation for estimating the impact of this variability on curve speed is:

$$\sigma_{VT} = 7.48 \; \frac{R_p \; (-0.00066 + 0.000182 \; V_{t,a})}{V_{c,a} \; (1 + 0.00136 \; R_p)} \; \sigma_T \tag{36}$$

where,

σ_{VT} = standard deviation of curve speed based on tangent speed estimate variability, mph; and
σ_T = standard deviation of the tangent speed estimate (= 2.8), mph.

As indicated in Table 3-13, the estimate of curve speed has a standard deviation σ_M of 1.2 mph. These standard deviations are combined with that from Equations 33, 35, and 36 in the following equation to estimate the standard deviation of the curve speed estimate using the compass method:

$$\sigma_V = \sqrt{\sigma_{VL}^2 + \sigma_{Ve}^2 + \sigma_{VT}^2 + \sigma_M^2} \tag{37}$$

where,

σ_V = standard deviation of the curve speed estimate, mph; and
σ_M = standard deviation of the estimate from Equation 31 (= 1.2), mph.

The standard deviation estimated from Equation 32 is compared with that from Equation 37 in Figure 3-18. The dashed trend lines in this figure correspond to the standard deviation obtained from Equation 32 for the ball-bank indicator method. The solid trend line was computed using Equation 37. It indicates the standard deviation obtained from the compass method. The ball-bank indicator method exhibits a slight sensitivity to deflection angle and tangent speed. Specifically, the dashed trend lines tend to shift upward about 0.4 mph for a 10 mph decrease in speed.
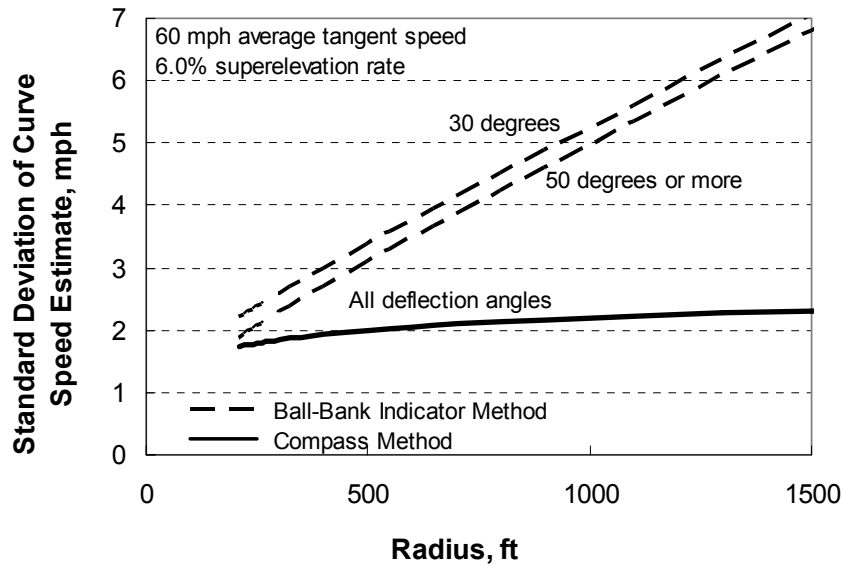
Figure 3-18. Comparison of Ball-Bank Indicator and Compass Methods.

The dashed trend lines in Figure 3-18 indicate that the standard deviation of the curve advisory speed estimated with the ball-bank method can range from 2 to 7 mph, depending on curve radius. This range is consistent with the variation found in the "estimated" and "computed" advisory speeds shown in Figures 2-13 and 3-7, respectively.

The trend lines in Figure 3-18 indicate that the compass method has a significantly smaller standard deviation than the ball-bank method. This finding suggests that the compass method is more stable than the ball-bank method and more likely to produce advisory speeds that are uniform among curves.

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CHAPTER 4. ADVISORY SPEED CRITERIA AND METHOD

OVERVIEW

This chapter describes the recommended advisory speed criteria and engineering study method used to establish the advisory speed in the field. It consists of four parts. The first part provides a brief summary of the key findings identified in previous chapters. This summary is then used as a basis for the recommendations made at the conclusion of the first part. The second part describes the procedures used to implement the recommended method in the field. The last part describes an evaluation of the recommended criteria and method in terms of their impact on existing curve advisory speeds in Texas.

RECOMMENDED ADVISORY SPEED CRITERIA AND METHOD

The objective of this part of the chapter is to describe the recommended curve advisory speed criteria and engineering study method. It consists of three sections. The first section provides a brief review of the findings from the literature review documented in Chapter 2. The second section provides a brief review of the findings from the method evaluation described in Chapter 3. The last section describes the recommended criteria and method.

Summary of Findings from Literature Review

The literature review documented in Chapter 2 yielded several important findings related to horizontal curve signing and findings related to procedures for establishing the advisory speed. These findings are summarized in the following list:

- An important objective in horizontal curve signing is having a uniform and consistent display of advisory speed on curves of similar geometry, character, and road surface condition. A uniformly applied advisory speed will be more likely to command the respect of drivers and achieve the desired safety benefits.

- Many engineers believe that the posted advisory speeds in their state are not uniform among curves. They also believe that uniformity among curves is more important than consistency with driver expectation.

- Most engineers believe that advisory speeds are usually too low by 5 to 10 mph. In fact, advisory speed signing appears to be largely ineffective if the goal is for drivers to actually travel at the posted advisory speed.

- The variability in ball-bank indicator readings taken on any given curve is relatively large and often varies by several degrees on successive test runs. This variability makes it likely that advisory speeds will vary by 5 mph, and sometimes 10 mph, among curves of similar geometry and road surface condition.

- The variability in ball-bank readings is likely due to a variety of sources, such as: rough pavement surface, occasional steering corrections made while traveling along the curve, variation in pavement friction supply, suspension differences in the vehicles used to establish advisory speeds, quality of initial ball-bank indicator calibration, and diligence and training of persons using the device.

- If the difference in superelevation rate between the two travel directions is large, then the appropriate advisory speed for each direction may be different.

- Research indicates that the tangent speed has a significant influence on driver curve speed choice; however, this influence is not reflected in current methods for establishing advisory speed.

- The ball-bank reading that corresponds to driver speed choice is not a constant (e.g., 10 degrees) for all curves. Rather, this reading decreases with increasing curve speed, reflecting driver desire for less side friction at higher curve speeds. No one reading describes driver speed choice for the range of radii and tangent speeds.

- Most drivers on rural highways exceed the regulatory speed limit. The amount by which the speed limit is exceeded varies with the speed limit and tends to be largest for lower speed limits. The implications of this trend are important when using guidelines for horizontal curve signing that have some basis in speed. Any guideline that is based on an assumed equality between the 85th percentile speed and the speed limit is not likely to yield the desired result.

- The average truck speed on curves is 2 to 3 mph slower than that of passenger cars. This trend should be considered when establishing the advisory speed.

- The *MUTCD* (*1*) suggests that the 85th percentile curve speed can be considered when selecting an advisory speed. However, some practitioners are opposed to using the 85th percentile speed because it would result in most curves having the advisory speed raised, which may have some adverse safety implications.

- The need for curve warning signs, delineation devices, and pavement markings should be based on the findings from an engineering study. This study would consider the 85th percentile speed, sight distance and visibility, unexpected geometric features within the curve, and the proximity of adjacent curves.

Summary of Findings from Alternative Method Evaluation

The compass method and the ball-bank indicator method were evaluated in Chapter 3 in terms of the accuracy of the resulting advisory speed estimate. This accuracy was quantified in terms of the variability of the advisory speed estimate if the method is repeatedly applied to a given curve. The compass method was found to be more accurate than the ball-bank indicator method for all combinations of radius and deflection angle. This finding suggests that the compass method is more

stable than the ball-bank method and more likely to produce advisory speeds that are uniform among curves.

Recommendations

Recommendations are offered in this section regarding horizontal curve signing and the selection of a curve advisory speed. They are based on the premise that "uniformity in advisory speed among curves" and "consistency in advisory speed with driver expectation" are important to the safe operation of highway curves. To achieve uniformity among curves, the method used to establish advisory speeds must be "repeatable" such that the same advisory speed is identified for curves of similar geometry and condition. To achieve consistency with driver expectation, the advisory speed criteria must be based on a specified percentile of the speed distribution.

Recommendation No. 1: Method

The compass method is recommended for establishing the curve advisory speed. With this method, the curve radius, superelevation rate, and tangent speed are used to compute the advisory speed.

The ball-bank indicator method has not been found to provide uniform advisory speeds among curves. In fact, successive applications at the same curve are not found to be repeatable by the same technician. If any improvement in the uniformity of advisory speeds is to be achieved, a different method will have to be used.

The advisory speed should be determined for both travel directions through the curve. If superelevation or other conditions are distinctly different between the two directions, then each direction should have its own unique advisory speed determined.

Recommendation No. 2: Criteria

The advisory speed should be based on the average speed selected by truck drivers. This speed is 2 or 3 mph below that of passenger car drivers and thereby, represents about the 40th percentile car driver.

It is rationalized that driver speed choice on sharp horizontal curves is largely influenced by safety concerns. Thus, the advisory speed should be conservative such that it informs drivers of the speed that is considered appropriate for the unfamiliar driver. Given that the speed distribution is approximately normal, the speed most commonly chosen by drivers is the average speed. This recommendation is consistent with the guidance offered by Chowdhury et al. (*2*).

Recommendation No. 3: Need for Engineering Study

The need for an Advisory Speed plaque and other traffic control devices should be based on the findings from an engineering study. This study would consider the following factors:

- the regulatory speed limit and the 85th percentile speed of free-flowing traffic;
- driver approach sight distance to the beginning of the curve;
- visibility around the curve;
- unexpected geometric features within the curve, such as an intersection or a change in the curve radius; and
- position of the most critical curve in a sequence of closely-spaced curves.

Also, the appropriateness of the recommended advisory speed should be verified in the field by driving a test vehicle through the curve at the advisory speed.

RECOMMENDED PROCEDURE FOR ESTABLISHING ADVISORY SPEED

Overview

The recommended procedure for establishing the curve advisory speed is described in this part of the chapter. The procedure is based on the compass method, which makes use of curve radius, superelevation rate, and tangent speed data to estimate the advisory speed. The use of radius to guide traffic control device application on curves is consistent with the recommendation by Carlson et al. (3) and the direction taken in recent editions of the *MUTCD*.

The procedure described in this chapter is applicable to curves that have a constant radius, those that have compound curvature, and those that have spiral transitions. This flexibility is achieved by focusing the field measurements on the "critical" portion of the curve. The critical portion of the curve is defined as the section that has a radius and superelevation rate that combine to yield the largest side friction demand. When spiral transitions or compound curves are present, this critical portion of the curve is typically found in the middle third of the curve, as shown in Figure 4-1. 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.

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."

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

The procedure consists of three steps. During the first step, measurements are taken in the field when traveling along the curve. During the second step, the measurements are used to compute the advisory speed. During the last step, the recommended advisory speed is confirmed through field trial. Each of these steps is described in more detail in the next three sections.
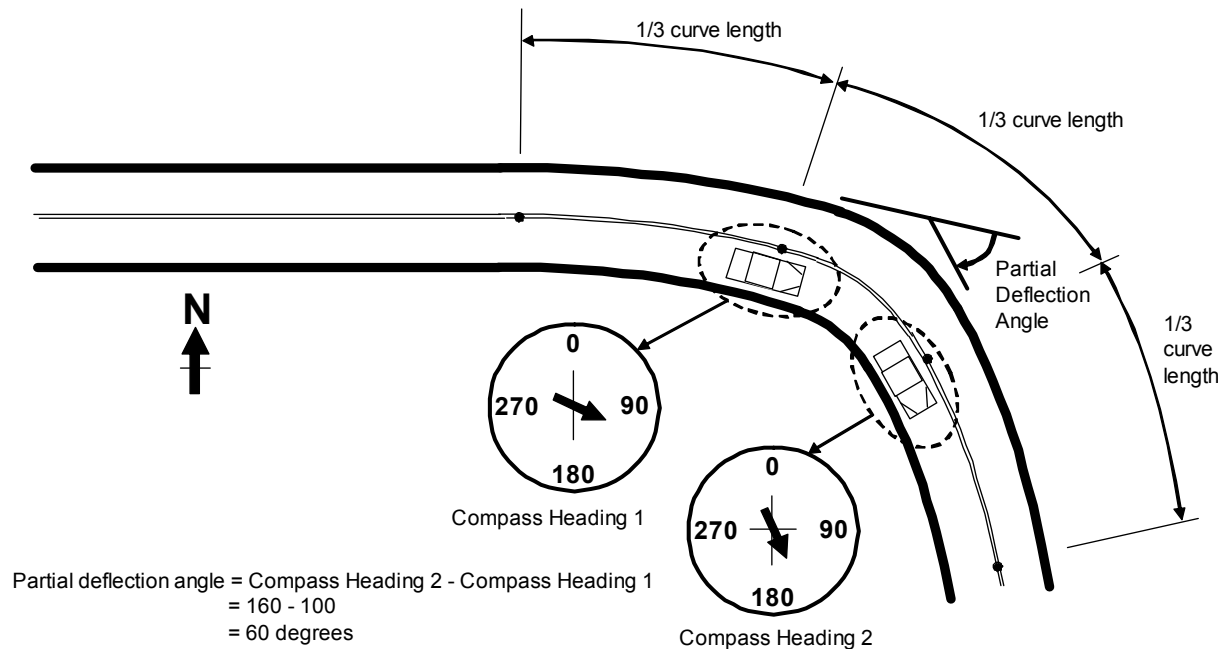
Figure 4-1. Curve with Compound Curvature.

Step 1: Field Measurements

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

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

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

Equipment Setup

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

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

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

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

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

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

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

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

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

Measurement Procedure

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

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

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

c. Advance the vehicle to the "1/3 point," as shown in Figure 4-1. This point is about one-third of the way along the curve when measured from the beginning of the curve in the direction of travel. It does not need to be precisely located. The technician's best estimate of this point's location is sufficient. This point is referred to hereafter as the point of partial curvature (PPC).

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

d. Advance the vehicle to the "2/3 point," as shown in Figure 4-1. This point is about two-thirds of the way along the curve. This point is referred to hereafter as the point of partial tangency (PPT).

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

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

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

Table 4-1 illustrates a worksheet that can be used to record the field measurements. Sample field data are shown for Curve No. 1. The computed and the recommended advisory speed can be determined in the field or back in the office using the procedures described in Step 2.

Table 4-1. Data Collection and Summary Sheet for Advisory Speed Determination.

District: County:	Curve Identification Number					
Highway: Date:	1	2	3	4	5	6
Curve deflection, left or right	Right					
Compass heading 1, degrees	79					
Ball-bank reading of superelevation, degrees	4					
Deflection of ball for superelevation, left or right	Right					
Speed when recording the BBI reading, mph	0					
Curve length, ft	212					
Compass heading 2, degrees	96					
Regulatory speed limit, mph	55					
85th percentile tangent speed (if available), mph	66					
Engineering Study Data						
Approach sight distance to curve OK?, yes/no	Yes					
Adequate visibility around curve? yes/no	Yes					
Intersection or unexpected features within curve?	No					
Adjacent curve is less than 600 ft, yes/no	No					
Existing advisory speed, mph	50					
Other						
Recommended advisory speed, mph						

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.

Compute Deflection Angle

The deflection angle represents the angular change in the road alignment between the "1/3 point" and the "2/3 point." The relationship between the recorded compass headings and deflection angle is shown in Figure 4-1. The test vehicle shown in this figure is traveling from the west to the south.

As suggested by Figure 4-1, the deflection angle is computed as:

$$I_c = Heading\,2 - Heading\,1 \qquad\qquad (38)$$

where,
  I_c = partial curve deflection angle, degrees.

Equation 38 is appropriate when the curve deflects to the right (i.e., a right-hand deflection). When it deflects to the left, the deflection angle is computed as:

$$I_c = Heading\ 1\ -\ Heading\ 2 \qquad (39)$$

If either Equation 38 or 39 yield a negative value, then this value should be added to 360 to obtain the correct deflection angle. If either equation yields a value that exceeds 360, then 360 should be subtracted from this value to obtain the correct deflection angle.

Compute Curve Radius

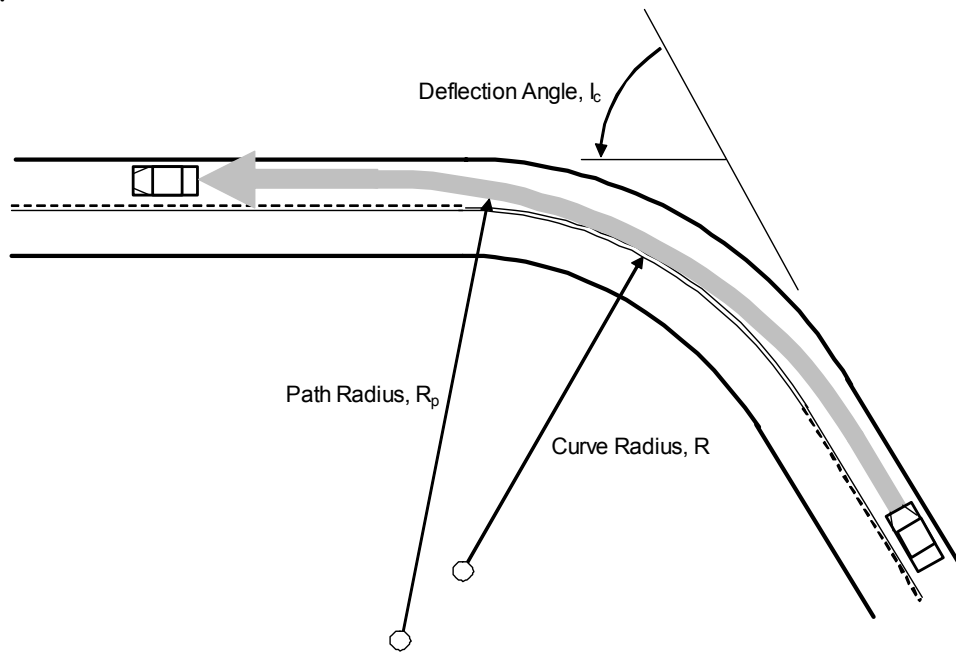The radius of the curve is computed using the following equation:

$$R = 57.3\ \frac{Curve\ Length}{I_c} \qquad (40)$$

where,
  $R =$ radius of curve, ft.

Compute Path Radius

When traveling through a curve, drivers shift their vehicle laterally in the traffic lane such that they flatten the curve slightly. This behavior allows them to limit the speed reduction required by the curve. The difference between the radius of the curve and the travel path radius is shown in Figure 4-2.

Figure 4-2. Effect of Lateral Shift on Travel Path Radius.

The radius of the travel path is computed using the following equation:

$$R_p = R + \frac{3.0}{1\ -\ Cosine\ (1.5\ I_c)} \qquad (41)$$

where,

R_p = travel path radius, ft.

Compute Superelevation Rate

The ball-bank reading can be used to estimate the curve superelevation rate using the following equation:

$$e = 1.56\,(Ball\text{-}Bank\ Reading) \tag{42}$$

where,

e = superelevation rate, percent.

The sign of the reading used in Equation 42 is determined using the following rules:

- The reading is positive (+) if the deflection of the ball is:
  - to the right of "0.0 degrees" on a right-hand curve, or
  - to the left of "0.0 degrees" on a left-hand curve.
- The reading is negative (-) if the deflection of the ball is:
  - to the left of "0.0 degrees" on a right-hand curve, or
  - to the right of "0.0 degrees" on a left-hand curve.

Equation 42 is based on the vehicle being stopped when the ball-bank reading is taken. Equation A-12 (in Appendix A) can be used to estimate superelevation rate if the vehicle is moving slowly during the ball-bank reading.

Acquire or Estimate the 85th Percentile Tangent Speed

The speed a driver chooses when driving along a curve is partially influenced by his or her speed on the tangent approach to the curve. For this reason, the tangent speed is an important input to the curve speed prediction model. The 85th percentile speed is used for this purpose. Desirably, the analyst will know the 85th percentile speed of the highway on which the subject curve is located or can make an informed estimate of it.

Research indicates that the 85th percentile tangent speed is related to the regulatory speed limit for the highway and the radius of the subject curve. If the 85th percentile tangent speed is not known, it may be estimated using the following equation:

$$V_{t,85} = 8.57\,\sqrt{V_{sl}}\,\left(1 - e^{-35.21\,(R + 100)/5730}\right) \tag{43}$$

where,

$V_{t,85}$ = 85th percentile tangent speed, mph; and
V_{sl} = regulatory speed limit, mph.

Compute Curve Speed

The following equation can be used to compute the speed on the subject curve:

$$V_c = \left(\frac{15.0 \, R_p \, (0.101 - 0.000576 \, V_{t,85} + 0.0000693 \, V_{t,85}^2 + e/100)}{1 + 0.00136 \, R_p} \right)^{0.5} \leq 0.87 \, V_{t,85} \qquad (44)$$

where,
V_c = curve speed, mph.

Determine Advisory Speed

To determine the advisory speed, 1.0 mph should be added to the curve speed obtained from Equation 44 and the sum rounded *down* to the nearest 5 mph increment. This technique yields a conservative estimate of the advisory speed by effectively rounding curve speeds that end in 4 or 9 up to the next higher 5 mph increment, while rounding all other speeds down. For example, applying this rounding technique to a curve speed of 54, 55, 56, 57, or 58 mph yields an advisory speed of 55 mph.

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

Step 3: Confirm Speed for Conditions

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

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

The unexpected geometric features that may be considered include:

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

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

EVALUATION OF ADVISORY SPEED CRITERIA

This part of the chapter describes an evaluation of the recommended advisory speed criteria. It consists of two sections. The first section describes an application of the procedure to the 41 field study sites described in Chapter 3. The second section describes an application of the procedure to 81 curves that were specifically selected to offer a range in curve geometry and tangent speed.

Application to Field Study Sites

The procedure described in the previous part of this chapter was used to evaluate the 41 curve study sites at which calibration data were collected. The objective of this evaluation was to determine the extent to which the recommended procedure could improve the uniformity in advisory speed among curves. A secondary objective was to determine whether the procedure yields an advisory speed that is consistent with driver expectation.

Figure 4-3a shows a site-by-site comparison of the average curve speed at the 35 sites that have a curve advisory speed. As indicated in this figure, most of the sites have an average speed that exceeds the existing advisory speed. Changes to the advisory speed criteria that are intended to make the advisory speed more uniform among curves would result in the data points more tightly clustered around the best-fit trend line. Changes to the advisory speed criteria that are intended to make the advisory speed more consistent with driver expectation should cause the best-fit trend line to become parallel with the "$y = x$" line. In this manner, there would be a constant relationship between the advisory speed and the average speed.

a. Posted Advisory Speed.　　　　b. Computed Advisory Speed.
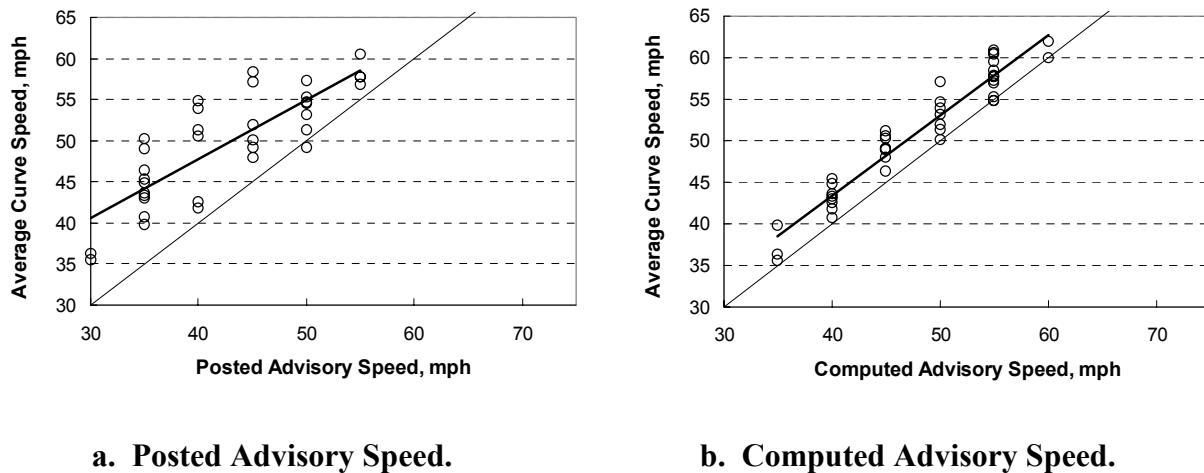
Figure 4-3. Comparison of the Average Curve Speed with the Advisory Speed.

Figure 4-3b compares the "computed" advisory speed with the average speed at each site. The equations described in Step 2 of the recommended procedure were used to obtain the computed speed. The data points in this figure exhibit much less variability than those in Figure 4-3a. The reduced variability is evidence that the proposed procedure results in less variability in advisory

speed among curves. The best-fit trend line is parallel with the "$y = x$" line, which indicates that the proposed criteria yield advisory speeds that will be consistent with driver expectancy (in this case, that the average driver will exceed the advisory speed by 5 mph, regardless of the advisory speed).

The best-fit trend line shown in Figure 4-3b is shifted to the left of the "$y = x$" line for two reasons. First, the advisory speed is based on the average speed of *trucks*, which tends to be about 2 mph slower than passenger cars. This basis effectively "shifts" the trend line to the right in Figure 4-3b by 2 mph. Second, the rounding technique (i.e., add 1.0 mph to the speed obtained from Equation 44 and then round *down*) further lowers the advisory speed by 1.5 mph (i.e., shifts it to the right). The net effect of both factors is that the proposed advisory speed is about 3.5 mph below that of the average passenger car, which equates to about the 30th percentile passenger car driver and 40th percentile truck driver. This approach is believed to offer the best compromise between the desire for advisory speed consistency and the desire to avoid safety concerns associated with revised procedures that significantly increase the advisory speed.

The approach described in the previous paragraph should be viewed as an "interim" approach that would be implemented for a period of five or more years. It provides a gradual transition between what drivers are currently experiencing (i.e., Figure 4-3a) and what is more appropriate (i.e., an advisory speed equal to the average curve speed of trucks). Research should be conducted after the criteria and methods described in this report have been implemented for a period of five or more years. If the relationship between average curve speed and posted advisory speed is similar to that shown in Figure 4-3b, then it is recommended that future postings of curve advisory speed are based on the speed obtained from Equation 44, without "adding 1 mph and rounding down." That is, future postings should equal the speed from Equation 44 rounded to the *nearest* even increment of 5 mph. This subsequent change in policy would yield a posted advisory speed equal to that of the 42rd percentile passenger car driver and the 50th percentile truck driver.

Application to Selection of Curves

This section describes an application of the procedure to 81 curves that were specifically selected to offer a range in curve geometry and tangent speeds. The first section describes the procedure used to select the sites and evaluate the recommended advisory speed criteria. The second section summarizes the findings from the evaluation.

Evaluation Procedure

The evaluation procedure consisted of two stages. During the first stage, 38 curves were identified for evaluation of the recommended advisory speed criteria. Collectively, these curves are believed to be representative of sharper curves found on rural two-lane highways in Texas. During the second stage, 43 curves were identified along a 20 mile length of F.M. 531 in the Yoakum District. This roadway represents a typical rural two-lane highway in Texas with a range of radii, deflection angles, and transition designs. The characteristics of the 81 curves are summarized in Table 4-2.

Table 4-2. Evaluation Curve Characteristics.

| Characteristic	Count	Average	Minimum	Maximum
Regulatory speed limit, mph	81 curves	55	35	60
Advisory speed, mph	56 curves with advisory speed	37	15	55
Deflection angle, degrees	81 curves	38	2	98
Radius, ft	81 curves	960	87	3700
Superelevation rate, %	81 curves	6.2	-1.6	12.9
Spiral transitions	13 curves known to have spirals	--	--	--

The evaluation procedure focused on the measurement and assessment of each curve, one curve at a time. As a first step, the compass method was used to measure the two headings, a curve length, and a ball-bank indicator reading of cross slope at each curve. Then, while parked at a safe location, these data were used to estimate the curve deflection angle, radius, superelevation rate, and recommended advisory speed. A spreadsheet was used to automate these computations. Then, the curve was re-driven at the computed advisory speed to determine its suitability. Curves at which it was determined that an advisory speed was not needed were re-driven at the regulatory speed limit.

During the first stage, TxDOT engineers accompanied the researchers in the test vehicle and provided commentary on the computed advisory speed before and after each test run. During the second stage, TxDOT engineers independently reevaluated each of the 43 curves on F.M. 531 curves and recommended appropriate advisory speeds. Following each stage, minor modifications or enhancements were made to the advisory speed procedure. These changes are reflected in the recommended procedure presented in the previous part of this chapter. They are also reflected in the findings reported in the next subsection.
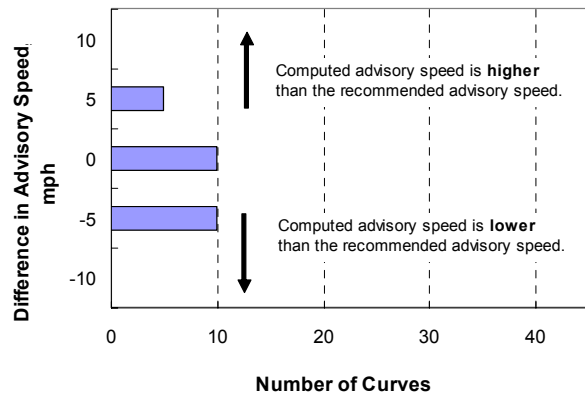
Evaluation of Recommended Advisory Speed Criteria

The evaluation of the advisory speed criteria consisted of comparing the computed advisory speed with the existing advisory speed. For the curves on F.M. 531, the evaluation also included a comparison of the computed speed with TxDOT-recommended advisory speeds. Figure 4-4 shows the findings from this evaluation. The range of the x-axis in this figure is equal to the number of curves evaluated and, as such, represents the maximum length of any one bar.

Figure 4-4a indicates the findings from an analysis of 45 of the 81 curves for which an Advisory Speed plaque exists and the procedure recommends that the plaque remain. Of these curves, the computed advisory speed is consistent with the existing advisory speed at 16 curves. However, it is 10 mph higher than the existing advisory speed at 10 curves and 5 mph higher than the existing advisory speed at 17 curves. In contrast, it is 5 mph lower than the existing advisory speed at only two curves. These trends suggest that the existing advisory speeds are too low at many curves. This finding is consistent with that of other researchers, as noted in Chapter 2.
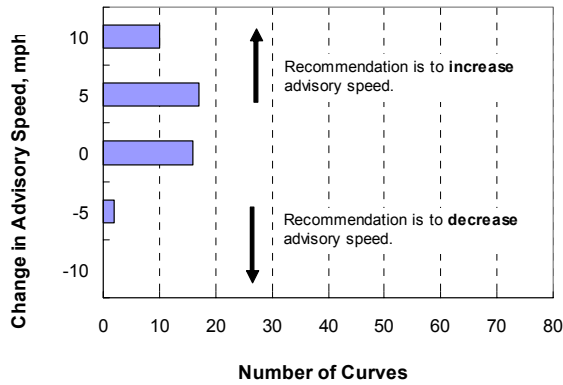
a. Change in Advisory Speed.   b. Difference in Advisory Speed.

Figure 4-4. Evaluation of Computed Advisory Speed.

Figure 4-4b compares the computed advisory speed with the TxDOT-recommended advisory speed. The trends shown indicate that the computed advisory speed is the same as the TxDOT-recommended speed at 10 of the 43 curves. The computed advisory speed is 5 mph slower than the TxDOT-recommended speed at 10 curves and 5 mph faster at five curves. Those curves at which the computed speed is lower than the TxDOT-recommended speed tend to have larger radii and a higher advisory speed. In contrast, the curves at which the computed speed is higher than the TxDOT-recommended speed tend to have smaller radii and lower advisory speeds. This outcome was intended, as discussed with regard to Figure 4-3.

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CHAPTER 5. CURVE SIGNING GUIDELINES

OVERVIEW

This chapter describes the development and evaluation of guidelines for the signing of horizontal curves on rural highways. These guidelines were derived largely through a review and synthesis of guidelines offered in the literature. They are intended to complement the recommended advisory speed criteria and method that are described in Chapter 4. Together, these materials provide a rational basis for establishing uniform signing for rural highway curves.

This chapter consists of three main parts. The first part describes the development of traffic control device guidelines for highway curves. The second part describes the recommended guidelines. The last part describes an evaluation of these guidelines.

GUIDELINE DEVELOPMENT

The purpose of curve warning signs and travel path delineation devices is to alert drivers to a downstream horizontal curve and assist them in determining an appropriate curve negotiation speed. The Advisory Speed plaque is the most important device for conveying the appropriate speed message to drivers. However, additional devices are often used at sharp curves to amplify the plaque's message and heighten driver awareness of the sharp curvature.

This part of the chapter describes the rationale for the development of guidelines for the use of various traffic control devices on rural highway curves. The devices addressed are categorized as curve warning signs and delineation devices. The rationale for their selection is based on the concept of curve "severity," where the number of signs or devices used increases with increasing curve severity. Alternative measures of quantifying the severity of a curve are identified in the first section. Then, the use of friction differential as a means of defining curve severity is evaluated in the second section.
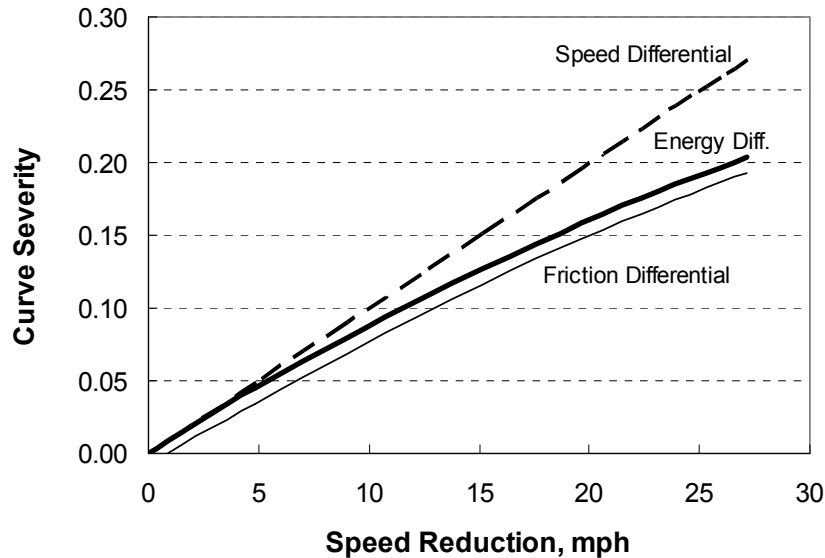
Measures of Curve Severity

The review of the literature, as documented in Chapter 2, indicates that there are three viable measures of curve severity, they are:

- speed differential,
- energy differential, and
- friction differential.

Each of these measures describes the relationship between tangent speed and curve speed. Speed differential refers to the difference between these two speeds. Energy differential refers to the difference between the speeds after each has been squared (see Equation 8). Friction differential refers to the difference between the side friction demand associated with the curve speed and the

accepted upper limit of side friction demand (see Equation 7). These three concepts are illustrated in Figure 5-1.

Figure 5-1. Comparison of Three Curve Severity Measures.

The trend lines in Figure 5-1 compare the three severity measures on a conceptual basis. The y-axis is idealized and does not have units for this comparison. The x-axis represents the difference between the tangent speed and the curve speed (i.e., the speed reduction). The speed differential measure represents a small constant multiplied by the speed reduction. Hence, it plots as a straight line. Equation 8 was used to develop the trend line for energy differential. A value for the "vehicle weight" term was selected such that the energy and speed trend lines would have the same slope for speed reductions up to 5 mph. The friction differential trend line was computed using Equation 7 for a range of radii. Equation 30 was used to compute the curve speed. This trend line does not intersect the origin because of the presence of a nominal level of cross slope on even the flattest curves. However, its basic shape tracks closely with that of the energy differential curve.

Both of the curved trend lines in Figure 5-1 imply that the rate of increase in curve severity decreases with increasing speed reduction. From an energy standpoint, this trend indicates that the additional energy required to slow 25 mph, instead of 20 mph, is not as large as that required to slow 10 mph, instead of 5 mph. The impact on side friction demand has a similar trend. Both trends recognize that large speed reductions are associated with relatively slow curve speeds. Once a vehicle has had to slow to a curve speed of say, 20 mph, it requires little additional effort (or energy) to slow further to 15 mph. Thus, the energy and side friction differential measures are rationalized to be better indicators of curve severity than the speed differential measure.

Also related to the discussion of curve severity measures is the basis for the speeds used to compute this measure. Many guideline documents describing the use of traffic control devices base their guidance on regulatory speed limit (presumably as a surrogate for tangent speed) and advisory

speed (presumably as a surrogate for the curve speed). However, as shown in Chapters 2 and 3, the correlation between speed limit and 85th percentile tangent speed is weak. The two speeds can differ by up to 10 mph in some cases. Likewise, the correlation between advisory speed and curve speed is weak, and the two can differ by up to 15 mph in some cases. For these reasons, most transportation agencies outside of the U.S. base their guidelines on the 85th percentile speed as opposed to the posted speed limit or advisory speed.

Evaluation of Friction Differential

The guidelines offered in the literature for the selection of curve-related traffic control devices are compared in this section. The basis of comparison is friction differential, as defined in Chapter 2 (Equation 7) and discussed in the previous section. Guidance that is based on speed differential is converted to an equivalent friction differential to facilitate the comparison. The objective of this evaluation is to define the threshold friction differential that, if exceeded, would indicate the need for a specific combination of traffic control devices.

Differentials from Reference Documents

Table 5-1 lists combinations of devices that are typically used together, depending on the severity of the curve (*1, 2, 3, 4, 5*). This guidance is summarized in the text associated with Tables 2-2 and 2-4. The letters A, B, C, D, and E are used in Table 5-1 to characterize curve severity and associated device combinations. The threshold friction differentials specified by Glennon (*5*) are also shown. These differentials were previously listed in Table 2-4.

Table 5-1. Curve Severity Categories and Combinations of Traffic Control Devices.

Curve Severity	Typical Traffic Control Device Treatments	Threshold Friction Differential[1]			
		Glennon (*5*)	*TCDH* (*2*)	*TMUTCD* (*3*)	Lyles & Taylor (*4*)
A	Curve or Turn sign	0.01	0.00	--	--
	Raised pavement markers	--	0.05	0.00	--
B	Curve warning sign with Advisory Speed plaque	0.05	0.05	--	0.08
C	Redundant curve warning sign and Adv. Speed plaque[2]	0.08	0.12	0.11	--
	Delineators	--	0.12	0.11	--
D	Redundant curve warning sign, Advisory Speed plaque, and Chevrons (or Large Arrow sign)	0.11	0.18	0.17	--
E	Special treatments[3]	0.16	--	--	--

Notes:

"--" – No data available.

1 - Friction values listed represent the friction differential that if exceeded would indicate the associated traffic control devices are appropriate.

2 - The *MUTCD* identifies two Combination Horizontal Alignment/Advisory Speed signs that can be used for curves and turns, respectively (W1-2a and W1-1a). These two signs are also specified in the *TCDH* guidance. They are not currently recognized in the *TMUTCD*.

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

The combinations of devices recommended in the *Traffic Control Devices Handbook (2)*, the *Texas Manual on Uniform Traffic Control Devices (3)*, and Lyles and Taylor (4) also are listed in Table 5-1. The guidance indicating when each combination should be considered is stated in these documents in terms of speed differential, where the speeds referenced are the regulatory speed limit and advisory speed. The manner by which these stated speed differentials were converted into the friction differentials listed in Table 5-1 is described in the next few paragraphs.

As indicated in Equation 7, the friction differential is computed as:

$$\Delta f = \frac{(1.47\ V_{c,85})^2}{g\ R} - f_{accept} \tag{45}$$

where,
Δf = side friction demand differential;
$V_{c,85}$ = 85th percentile curve speed, mph;
g = gravitational acceleration (= 32.2 ft/s²);
R = radius of curve, ft; and
f_{accept} = accepted upper limit of comfortable side friction demand.

The calibration coefficients for the 85th percentile speed prediction model (i.e., Equation 30) were substituted into Equation 15 to obtain the following model relating side friction demand to curve speed:

$$f_{D,85} = 0.1962 - 0.00106\ V_{t,85} + 0.000073\ (V_{t,85}^2 - V_{c,85}^2)\ I_v \tag{46}$$

where,
$f_{D,85}$ = 85th percentile side friction demand;
$V_{t,85}$ = 85th percentile tangent speed, mph; and
I_v = indicator variable (= 1.0 if $V_{t,85} > V_{c,85}$; 0.0 otherwise).

As discussed in Chapter 3, the first two terms in Equation 46 describe the side friction accepted by the 85th percentile motorist when the curve is sufficiently flat that speed reduction is negligible. The friction level suggested by these two terms is compared in Figure 5-2 with the side friction demand factors recommended in the AASHTO document *A Policy on Geometric Design of Highways and Streets* (i.e., *Green Book*) (6).

As shown in Figure 5-2, the 85th percentile side friction demand predicted by the first two terms of Equation 46 is in reasonably good agreement with the friction factors used for highway design. Thus, these first two terms are rationalized to represent "accepted upper limit of comfortable side friction demand," as used in Equation 45. This friction demand can be computed as:

$$f_{accept} = 0.1962 - 0.00106\ V_{t,85} \tag{47}$$
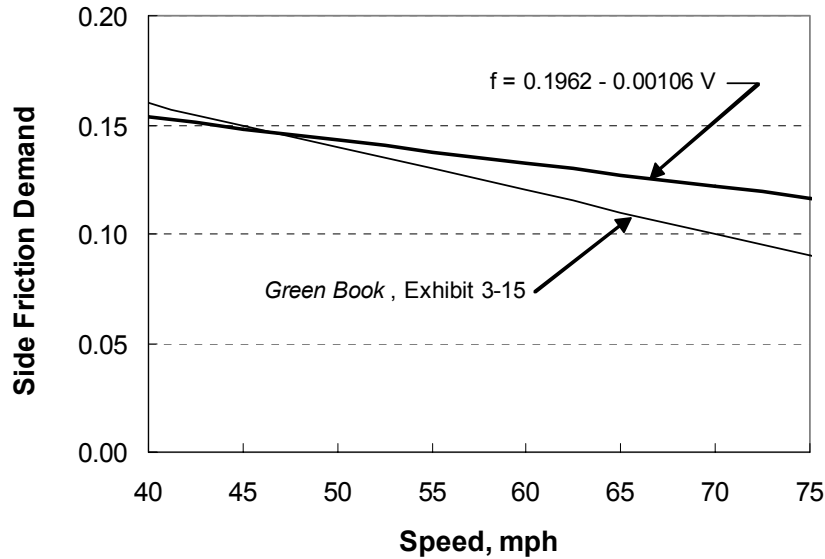
Figure 5-2. Comparison of Predicted Side Friction Demand with *Green Book* Factors.

The first term of Equation 45 represents the side friction demand associated with a specified curve speed. This friction demand can also be estimated by Equation 46. It follows then that the friction differential is equal to the difference between the friction obtained from Equation 46 and that from Equation 47. Mathematically, this relationship can be stated as:

$$\Delta f = 0.000073 \ (V_{t,85}^2 - V_{c,85}^2) \ I_v \tag{48}$$

This equation replicates the energy differential approach used by some agencies to describe curve severity. This approach was described previously in the text associated with Table 2-5.

Equation 48 was used to compute the equivalent friction differentials stated in Table 5-1 for the stated speed differentials in the *TCDH (2)*, the *TMUTCD (3)*, and Lyles and Taylor *(4)*. The 85th percentile tangent speed used for these computations was set to 60 mph for this analysis.

Differentials from Existing Practice

Equation 30 was used to estimate the 85th percentile curve speed at each of 81 rural highway curves in Texas. These curves were previously described in the last section of Chapter 4. Equation 27 was used to estimate the 85th percentile tangent speed. Equation 48 was then used to estimate the friction differential. The distribution of friction differential for those curves without an Advisory Speed plaque is shown in Figure 5-3. A similar distribution was created for those curves with Chevrons or Large Arrow signs. It is also shown in Figure 5-3.

The trends in Figure 5-3 provide a tangible indication of the friction differentials associated with Advisory Speed plaques and Chevrons. These two signs correspond to curve severity categories B and D, respectively, as shown in Table 5-1. The distribution of "curves without Advisory Speed plaques" is based on 22 of the 81 curves. The distribution of "curves with Chevrons" is based on

9 of the 81 curves. The "knee" of each distribution curve is rationalized as representative of the logical friction differential that best defines curve signing practice in Texas. Thus, the threshold associated with the Advisory Speed plaque (i.e., severity category B) is estimated as 0.03. Similarly, the threshold associated with Chevrons (i.e., severity category D) is estimated as 0.13.
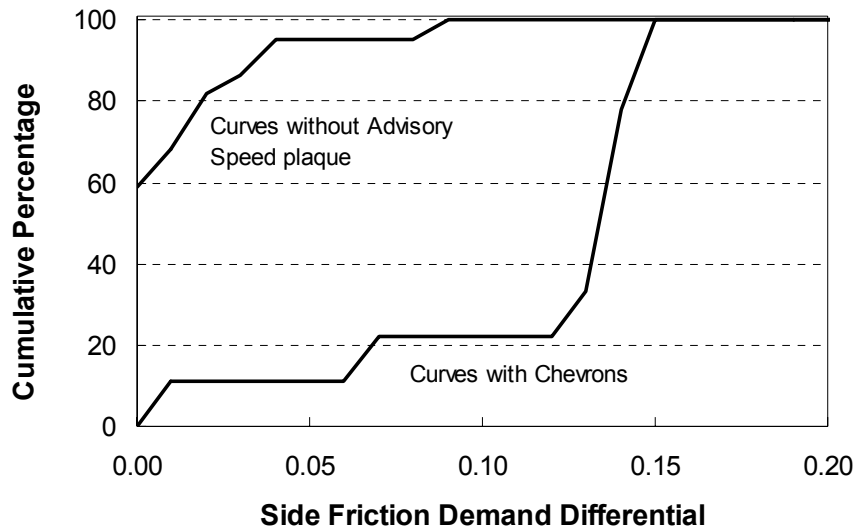
Figure 5-3. Distribution of Friction Differential at Existing Curves.

Recommended Threshold Friction Differentials

Based on the analysis described in the preceding two sections, the thresholds identified in Table 5-2 are recommended for the selection of the associated traffic control devices. Equation 48 would be used to compute the friction threshold for a specific curve.

Table 5-2. Recommended Friction Differential Thresholds.

Curve Severity	Typical Traffic Control Device Treatments	Threshold Friction Differential [1]
A	Curve or Turn sign and raised pavement markers	0.00
B	Curve warning sign with Advisory Speed plaque	0.03
C	Redundant curve warning sign and Adv. Speed plaque[2] and delineators	0.08
D	Redundant curve warning sign, Adv. Speed plaque, and Chevrons (or Large Arrow sign)	0.13
E	Special treatments[3]	0.16

Notes:

1 - Friction values listed represent the friction differential that if exceeded would indicate the associated traffic control devices are appropriate.

2 - The *MUTCD* identifies two Combination Horizontal Alignment/Advisory Speed signs that can be used for curves and turns, respectively (W1-2a and W1-1a). These two signs are also specified in the *TCDH* guidance. They are not currently recognized in the *TMUTCD*.

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

RECOMMENDED CURVE SIGNING GUIDELINES

Guidelines for selecting curve-related traffic control devices are described in this section. The guidelines are based largely on the existing practices of many transportation agencies, as described in Chapter 2. They consist of recommended combinations of traffic control devices associated with each of the curve severity categories identified in Table 5-2. The recommended guidelines were developed to reflect a balance of the following goals:

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

Application of the guidelines begins with a determination of the curve's severity category. This assessment can be obtained using Figure 5-4. The curve's severity category is based on consideration of the 85th percentile tangent speed and the 85th percentile curve speed.
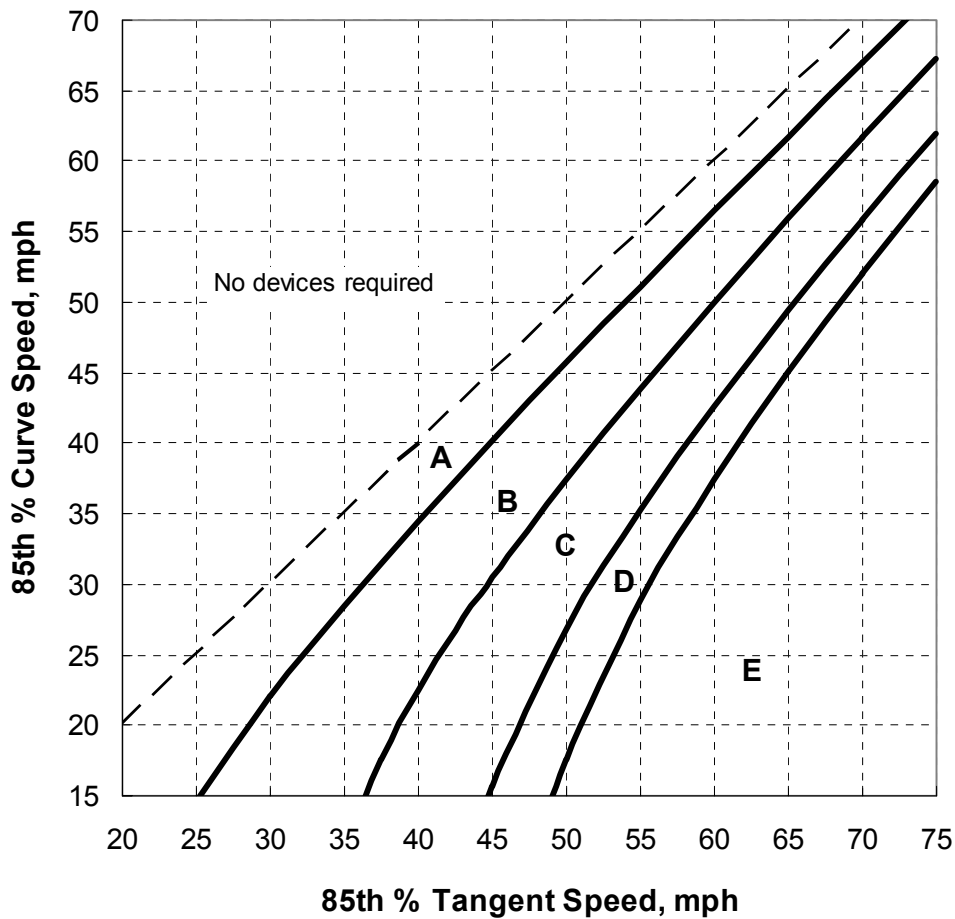

Figure 5-4. Guidelines for the Selection of Curve-Related Traffic Control Devices.

Examination of Figure 5-4 indicates that curve severity category D exists only for 85th percentile tangent speeds of 45 mph and higher. This finding suggests that curves on roadways where the 85th percentile tangent speed is less than 45 mph are not sufficiently "severe" to justify the need for Chevrons or other "special" treatments. A tangent speed of less than 45 mph is uncommon for a rural highway.

Application of Figure 5-4 requires knowledge of the 85th percentile tangent speed for passenger cars. This speed can be obtained from a survey of speeds on a tangent section of highway in the vicinity of the curve. The location at which tangent speed data are collected should be sufficiently distant from the curve that it does not influence the observed speeds. The TxDOT document *Procedures for Establishing Speed Zones* describes the survey procedure (7). If the 85th percentile tangent speed is not available, Equation 27 can be used to estimate this speed.

Use of Figure 5-4 also requires an estimate of the 85th percentile curve speed for passenger cars. This speed can be estimated using Equation 30.

To illustrate the use of Figure 5-4, consider a curve with an 85th percentile tangent speed of 55 mph and an 85th percentile curve speed of 45 mph. Proceeding upward from the 55-mph tick mark on the x-axis of Figure 5-4 and over from the 45-mph tick mark on the y-axis, find their intersection point in severity category B.

Table 5-3 shows the recommended traffic control device treatment for each severity category. The treatments have been categorized into two groups: warning signs and delineation devices. For each category, a combination of devices from both groups is offered. The guidance differentiates between recommended and optional treatments. This approach is intended to provide some flexibility in the selection of devices used at a given curve. An optional device is indicated by an outlined check (✓), and a recommended device is indicated by a solid check (✔).

To illustrate the use of Table 5-3, consider a curve associated with severity category B. The solid check marks in Table 5-3 for this category indicate that a curve warning sign (e.g., Curve sign), Advisory Speed plaque, and raised pavement markers are recommended for this curve.

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

Table 5-3. Guidelines for the Selection of Curve-Related Traffic Control Devices.

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

Notes:
1 - Use the Curve, Reverse Curve, Turn, Reverse Turn, or Winding Road sign if the deflection angle is less than 135 degrees. Use the Hairpin Curve sign if the deflection angle is 135 degrees or more.
2 - Use with Advisory Speed plaque. The *MUTCD* indicates that the Combination Horizontal Alignment/Advisory Speed signs (W1-2a and W1-1a) can be also used to supplement other advance warning signs. However, these signs are not recognized in the *TMUTCD*.
3 - A Large Arrow sign may be used on curves where roadside obstacles prevent the installation of Chevrons.
4 - Raised pavement markers are optional in northern regions that experience frequent snowfall.
5 - Delineators do not need to be used if Chevrons are used.
6 - Special treatments could include oversize curve warning signs, flashers added to curve warning signs, wider edge lines approaching (and along) the curve, and profiled edge lines and center lines.
7 - ✐: optional; ✔: recommended.

EVALUATION OF CURVE SIGNING GUIDELINES

This part of the chapter describes an evaluation of the recommended curve signing guidelines. The evaluation was based on an application of the guidelines to 81 curves that were specifically selected to offer a range in curve geometry and tangent speeds. The first section describes the procedure used to select the sites and evaluate the advisory speed. The second section summarizes the findings from the evaluation.

Evaluation Procedure

The evaluation procedure consisted of applying the recommended guidelines to 81 curves on rural, two-lane highways in Texas. Collectively, these curves are believed to be representative of sharper curves found on rural two-lane highways in Texas. The characteristics of these curves were summarized previously in Table 4-2.

The evaluation procedure focused on the measurement and assessment of each curve, one curve at a time. As a first step, the procedure described in Chapter 4 was used in the field to estimate the deflection angle, radius, and superelevation rate. These data were then used with Equations 27 and 30 to estimate the 85th percentile tangent speed and the 85th percentile curve speed, respectively. Then, Equation 48 was used to estimate the friction differential. Finally, Table 5-3 was used to identify the recommended traffic control devices. A spreadsheet was used to automate these computations.

TxDOT engineers were present in the test vehicle during the evaluation of 38 of the 81 curves. Input from these engineers was used to assess the adequacy of the recommended devices. The feedback received was positive regarding the guidelines. However, there were some suggestions for further improvement. As a result, minor modifications were made to the guidelines. These modifications are reflected in the recommended procedure described in a previous part of this chapter. They are also reflected in the findings reported in the next subsection.

Evaluation of Recommended Guidelines

The evaluation of the recommended guidelines consisted of a comparison of the recommended devices with the existing devices. This comparison was made on a curve-by-curve basis. Figure 5-5 illustrates the findings from this evaluation. The range of the x-axis in this figure is equal to the number of curves evaluated and, as such, represents the maximum length of any one bar.

a. Change in Advisory Speed Plaque Use.   **b. Change in Chevron Use.**
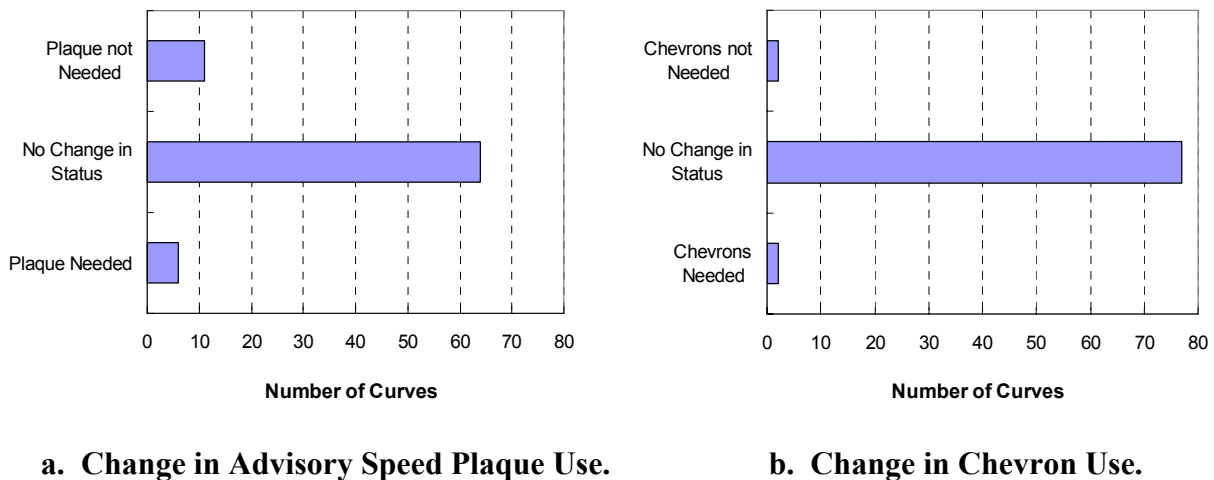
Figure 5-5. Evaluation of Recommended Curve Signing Guidelines.

Figure 5-5a indicates the findings from the evaluation of the Advisory Speed plaque guidance. All total, 56 of the 81 curves currently have these plaques. The guidelines indicate that there is no change in status for 64 curves. Those curves with a plaque in this group should retain the plaque and those curves without a plaque should continue operating without a plaque. However, the guidelines indicate that a plaque may be needed at six curves and may not be needed at 11 curves.

The six curves at which a plaque may be needed are all instances where the recommended advisory speed is 50 mph.

Figure 5-5b indicates the findings from the evaluation of Chevron use. All total, nine of the 81 curves have Chevrons. The guidelines indicate that there is no change in status for 77 curves. Those curves with Chevrons in this group should retain the Chevrons and those curves without Chevrons should continue operating without Chevrons. However, the guidelines indicate that Chevrons may be needed at two curves and may not be needed at two curves.

TxDOT engineers were asked about the two curves at which the guidelines suggest Chevrons are not needed. They indicated that Chevrons were installed at one of these locations based on its crash history (its current speed differential is only 5 mph). The other curve with Chevrons is on a roadway with a 40 mph regulatory speed limit and an estimated 85th percentile tangent speed of 37 mph. As noted in the discussion associated with Figure 5-4, highways with an 85th percentile tangent speed of less than 45 mph are not likely to need Chevrons because of the nominal amount of energy required to slow vehicles to the turn speed.

REFERENCES

1. *Manual on Uniform Traffic Control Devices*. Federal Highway Administration, U.S. Department of Transportation, Washington, D.C., 2003.

2. *Traffic Control Devices Handbook.* Chapter 4. Institute of Transportation Engineers, Washington, D.C., 2001.

3. *Texas MUTCD: Manual on Uniform Traffic Control Devices*. Texas Department of Transportation, Austin, Texas, 2006.

4. Lyles, R.W., and W.C. Taylor. *NCHRP Report 559: Communicating Changes in Horizontal Alignment*. Transportation Research Board, National Research Council, Washington, D.C., 2006.

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6. *A Policy on Geometric Design of Highways and Streets.* 5th Edition. American Association of State Highway and Transportation Officials, Washington, D.C., 2004.

7. *Procedures for Establishing Speed Zones.* Texas Department of Transportation, Austin, Texas, November 2003.

APPENDIX A. KINEMATICS OF CURVE DRIVING

This appendix provides a review of the kinematic relationships that define the dynamics of vehicle motion in a circular travel path.

SIDE FRICTION DEMAND

A vehicle moving in a circular path with a constant speed undergoes a centripetal acceleration directed toward the center of the circle. This acceleration is supplied by the friction between the vehicle's tires and the pavement surface. A portion of it is also supplied by the weight of the vehicle when the pavement surface has superelevation. The magnitude of the friction demand can be computed using the following equation:

$$f_D = \frac{(1.47\ V_c)^2}{g\,R} - \frac{e}{100} \tag{A-1}$$

where,
   f_D = side friction demand factor (or lateral acceleration);
   e = superelevation rate, percent;
   V_c = curve speed, mph;
   g = gravitational acceleration (= 32.2 ft/s²); and
   R = radius of curve, ft.

If this friction demand exceeds the friction supply that is available between the pavement surface and the vehicle's tires, then the vehicle will slide off of the roadway.

BALL-BANK ANGLE

A ball-bank indicator can be used to measure the lateral acceleration on the vehicle's occupants. When properly mounted in the vehicle, the steel ball in the indicator moves laterally outward until its weight counters the centripetal acceleration acting on it and the vehicle. Analysis of forces acting on the steel ball, as shown in Figure A-1, yield the following relationship between centripetal acceleration, ball-bank reading α, superelevation angle Φ, and body roll angle ρ.

$$\frac{(1.47\ V_c)^2}{g\,R} = \tan(\alpha + \Phi - \rho) \tag{A-2}$$

where,
   α = ball-bank indicator angle (or "reading"), radians;
   Φ = superelevation angle, radians; and
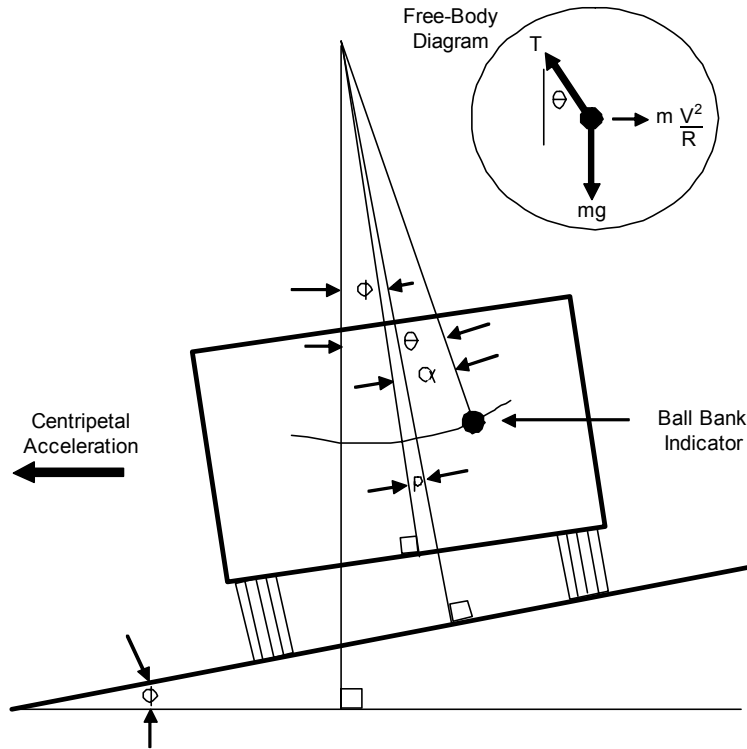 ρ = body roll angle, radians.

The following two relationships can also be defined:

$$\Phi = \tan^{-1}\left(\frac{e}{100}\right) \tag{A-3}$$

$$f_r = \tan^{-1}\left[\frac{(1.47\ V_c)^2}{g\ R}\right] - \tan^{-1}(\frac{e}{100}) \qquad\qquad \textbf{(A-4)}$$

where,

   f_r = side friction angle (= θ − Φ), radians.

Figure A-1. Geometry of Forces Acting on the Ball-Bank Indicator.

The side friction angle f_r corresponds to the lateral acceleration acting at the tire-pavement interface and equals the centripetal acceleration angle θ less the superelevation angle Φ. Combining the previous three equations yields the following equation for estimating body roll:

$$\alpha = f_r + \rho \qquad\qquad \textbf{(A-5)}$$

The body roll angle corresponds to the lateral acceleration acting on the vehicle occupants. This lateral acceleration is larger than that acting on the tire-pavement interface because body roll reduces the superelevation available to the vehicle body and its occupants.

Research by Moyer and Berry (*1*) revealed that the magnitude of body roll is related to the side friction angle by a constant k, that is:

$$\rho = k\ f_r \qquad\qquad \textbf{(A-6)}$$

where,

k = roll rate, radians/radian (or r/r).

They found that the roll rate k ranged from 0.16 to 0.31 r/r, with an average of 0.24 r/r for automobiles manufactured in the 1930s.

Subsequently, Carlson and Mason (*2*) related side friction demand f_D to body roll angle. They found that a 1992 Ford Taurus had a roll rate of 6.68 deg/g. This rate equates to a roll rate of 0.121 r/r (= 6.68 × 1.036 / 57.3; where the factor 1.036 g's/r represents the approximate conversion between side friction demand and side friction angle). Alternatively, the rates reported by Moyer and Berry equate to a range of 8.8 to 17 deg/g, with an average of 13 deg/g. The smaller roll rate found by Carlson and Mason is likely a result of modern vehicles having lower centers of gravity and more responsive suspension systems that intentionally limit body roll and improve vehicle handling within horizontal curves.

Combining the previous two equations, the following equation is used to estimate the ball-bank indicator reading α:

$$\alpha = f_r\,(1\,+\,k) \tag{A-7}$$

Equations A-1 and A-4 can be combined to yield the following relationship between side friction angle and side friction demand.

$$f_r = \tan^{-1}(f_D + \frac{e}{100}) - \tan^{-1}(\frac{e}{100}) \tag{A-8}$$

As noted previously, for typical superelevation rates, Equation A-8 yields the following approximate relationship between these two variables.

$$f_r \approx \frac{f_D}{1.036} \tag{A-9}$$

Equations A-7 and A-8 can be further combined to yield the following relationship between ball-bank reading and side friction demand.

$$\alpha = \left(\tan^{-1}(f_D + \frac{e}{100}) - \tan^{-1}(\frac{e}{100}) \right) (1\,+\,k) \tag{A-10}$$

Carlson and Mason (*2*) measured the lateral acceleration and ball-bank indicator readings at a test track facility consisting of five curves ranging in radius from 25 to 545 ft. Each curve was traversed at several different speeds and with several replications. A total of 3465 trials were conducted at the set of curves. They developed the following relationship from this data:

$$\alpha = \frac{1.115\,+\,52.627\,f_D}{57.3} \tag{A-11}$$

Equation A-11 is compared to Equation A-10 in Figure A-2. The computed ball-bank indicator reading obtained from each equation was multiplied by "57.3" to convert it from radians

to degrees. In general, the two equations are in good agreement, with a small deviation at the largest side friction demand levels. Equation A-10 is logically bounded at the origin (i.e., a ball-bank reading of 0.0 degrees when side friction demand is 0.0).
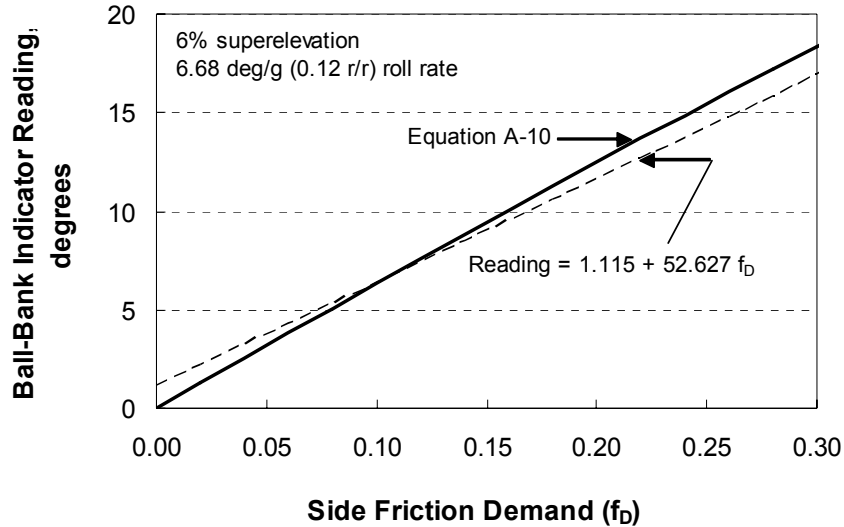
Figure A-2. Relationship between Side Friction Demand and Ball-Bank Reading.

Equations A-4 and A-7 can be used to derive the following relationship between ball-bank angle and superelevation rate:

$$e = 100 \ \tan\left[\tan^{-1}\left(\frac{(1.47 \ V_c)^2}{g \ R}\right) - \frac{\pm\alpha}{(1 + k)}\right] \qquad \textbf{(A-12)}$$

When the curve speed is small, there is nominal centripetal acceleration and, if superelevation is present, side friction acts in an opposite direction such that the vehicle is kept from sliding into the center of the curve. In this situation, the ball in the ball-bank indicator deflects toward the inside of the curve. This inward deflection is opposite of that shown in Figure A-1 and represents a negative value for the ball-bank reading α, as defined in Equation A-12. Thus, the sign of the ball-bank reading used in Equation A-12 is determined using the following rules:

- The reading is negative (-) if the deflection of the ball is:
  - to the right of "0.0 degrees" on a right-hand curve, or
  - to the left of "0.0 degrees" on a left-hand curve.
- The reading is positive (+) if the deflection of the ball is:
  - to the left of "0.0 degrees" on a right-hand curve, or
  - to the right of "0.0 degrees" on a left-hand curve.

A-4

REFERENCES

1. Moyer, R.A., and D.B. Berry. "Marking Highway Curves with Safe Speed Indications." *Highway Research Board Proceedings.* Highway Research Board, National Research Council, Washington, D.C., 1940, pp. 399-428.

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

APPENDIX B. SELECTED TABLES FROM THE *TMUTCD*

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

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

Notes:

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

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

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

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

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

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

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

Notes:

1 - Engineering judgment should be used to determine whether the Turn or Curve sign should be used.

2 - Alignment changes are in opposite directions and are separated by a tangent distance of 600 ft or less.

3 - A Right Reverse Turn (W1-3R), Right Reverse Curve (W1-4R), or Right Winding Road (W1-5R) sign is used if the first change in alignment is to the right; a Left Reverse Turn (W1-3L), Left Reverse Curve (W1-4L), or Left Winding Road (W1-5L) sign is used if the first change in alignment is to the left.