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16. Abstract

Design speed is used in selecting the vertical and horizontal elements for new roadways while speed limits are based on a statistical analysis of individual vehicular speeds. At some locations, the posted speed limit based on an 85th percentile speed exceeds the roadway's design speed. This situation is a result of the fact that criteria used in highway design incorporate a significant factor of safety -- i.e., roadways are designed for near worst-case conditions. When posted speed exceeds design speed, however, liability concerns arise even though drivers can safely exceed the design speed. Research conducted in this project clearly indicated that DOT officials are concerned with the potential liability; however, only a few of the respondents to surveys and interviews actually experienced a lawsuit relevant to the design speed-posted speed issue. The respondents indicated that the primary liability concern rests with the current AASHTO definition of design speed. If the definition were changed to reflect its actual meaning, then liability concern would be reduced substantially.

During this project, researchers conducted field studies on suburban highways at horizontal curves and limited sight distance crest vertical curves. The field studies found that inferred design speed (for vertical curves) and curve radius (for horizontal curves) are moderately good predictors of the 85th percentile curve speeds. For design speeds less than 90 km/h, the regression equation developed based on the vertical curve field data predicts 85th percentile speeds that are greater than the design speed of the curve. The horizontal curve findings demonstrated that the 85th percentile driver operates at speeds less than design speed on curves with inferred design speeds greater than 70 km/h.

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COMPATIBILITY OF DESIGN SPEED, OPERATING SPEED, AND POSTED SPEED

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IMPLEMENTATION STATEMENT

The revision of the term "design speed" by AASHTO and TxDOT will reduce substantially the liability concern of posting a speed limit that is in excess of a roadway's actual or inferred design speed. Adopting the guidelines developed during this research (see Appendix A) will benefit the Department of Transportation by providing a concise statement of the relationships among design speed, operating speed, and posted speed. It also will provide the department with guidelines that are reasonable, usable, and defensible. In addition to the guidelines, researchers prepared a document (see Report FHWA/TX-95/1465-1) that could be used to explain the design speed/operating speed/posted speed concepts to citizens. Use of this material will provide a consistent and reliable means of communicating these concepts to others, including lawyers and juries during a court case and elected officials. The material documented in this publication will also benefit the department by providing insights into design and operating speeds issues which can produce a safer roadway.

DISCLAIMER

The contents of this report reflect the views of the authors who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official view or policies of the Texas Department of Transportation (TxDOT) or the Federal Highway Administration (FHWA). This report does not constitute a standard, specification, or regulation, nor is it intended for construction, bidding, or permit purposes. This report was prepared by Kay Fitzpatrick (PA-037730-E), Joseph D. Blaschke (TX-42200), C. Brian Shamburger, Raymond A. Krammes (TX-66413), and Daniel B. Fambro (TX-47535).

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The research could not have been conducted without the cooperation provided by the individuals who participated in the mail-out surveys and the on-site and phone interviews. The authors acknowledge their time and efforts. We would also like to recognize the students and research associates who assisted in collecting the speed data in the field as well as those who provided the data collection team with needed roadway plans during the site selection process.

The research was directed by an exceptional group of department representatives. Wallace Ewell (Ft. Worth District) was the panel director and John Gaynor (Houston District), David Greear (Traffic Operations Division), Terry McCoy (San Antonio District), and Robert Nell (Lufkin District) served on the panel. The panel provided valuable insight into the department's concerns and was always available to assist or attend meetings when called upon.

This study was performed in cooperation with the Texas Department of Transportation and the U.S. Department of Transportation, Federal Highway Administration.

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SUMMARY

Design speed is used in selecting the vertical and horizontal elements for new roadways. Posted speed limits are based on a statistical analysis of individual vehicular speeds observed at a spot on a roadway. Concerns arise at locations where the posted speed limit based on an 85th percentile speed exceeds the roadway's inferred design speed. This inconsistency is a result of the fact that criteria used in highway design incorporate a significant factor of safety -- i.e., roadways are designed for near worst-case conditions. Consequently, it is not surprising that motorists feel comfortable traveling at speeds in excess of the roadway's design speed during good weather conditions. When posted speed exceeds design speed, however, liability concerns arise even though drivers can safely exceed the design speed.

Research conducted in this project clearly indicated that DOT officials are concerned with posting speed limits in excess of the roadway's actual or inferred design speed; however, only a few of the respondents to surveys and interviews actually experienced a lawsuit relevant to the design speed--posted speed issue. The respondents indicated that the primary liability concern associated with the posted speed versus design speed issue rests with the current AASHTO definition for "design speed." This definition is "the maximum safe speed that can be maintained over a specified section of highway when conditions are so favorable that the design features of the highway govern." Although it is obvious that the "maximum" safe speed can be exceeded without difficulty on vertical and horizontal curves when good weather conditions are present, it is difficult to convince the general public that a roadway's design speed can be exceeded with safety. If the AASHTO definition for design speed were changed to reflect its actual meaning, the liability concern would be reduced substantially.

In addition to examining the liability issue associated with posting a speed limit in excess of a roadway's design speed, researchers investigated other areas of the design speed/operating speed/posted speed concerns. Based on those evaluations, several guidelines were developed during this research, including the following: The 85th percentile speed is considered to be the appropriate posted speed limit even for those sections of roadway that have an inferred design speed less than the 85th percentile speed. Posting a roadway's speed limit based on its 85th percentile speed is considered good engineering practice. This practice remains valid even where the inferred design speed is less than the resulting posted speed limit. In such situations, the posted speed limit would not be considered excessive or unsafe.

During this project, researchers conducted field studies on suburban highways at limited sight distance crest vertical and horizontal curves. The field studies found that inferred design speed (for vertical curves) and curve radius (for horizontal curves) are moderately good predictors of the 85th percentile curve speeds. For design speeds less than 90 km/h (56 mph), the regression equation based on the vertical curve field data predicts 85th percentile speeds that are greater than the design speed of the curve. The horizontal curve findings demonstrated that the 85th percentile driver operates at speeds less than design speed on curves with inferred design speeds greater than 70 km/h (44 mph).

CHAPTER 1

INTRODUCTION

The use of design speed as a primary factor in selecting the vertical and horizontal alignments of roadways was initiated in the United States in the 1930s. Since then, highway design criteria, based on the selection of design speed, were developed to suggest appropriate horizontal curve radii, superelevation rates, and vertical curve elements for new roadways.

The practice of basing posted speed limits upon statistical analysis of the individual vehicular speeds observed at a spot on the roadways was initiated at about the same time. This procedure has been followed since the 1930s and the engineering profession has accepted it as an effective and reasonable procedure. An assumption basic to the procedure is that motorists can decide the appropriate speed at which to travel on the roadway, and the 85th percentile speed is assumed to be a reasonable speed to use as the posted speed limit.

Concerns exist in those locations where the posted speed limit based on an 85th percentile speed exceeds the roadway's design speed. This situation is a result of the fact that criteria used in highway design incorporate a significant factor of safety -- i.e., roadways are designed for a near worst-case condition. Consequently, it is not surprising that motorists feel comfortable traveling at speeds greater than the roadway's design speed during good weather conditions; however, when posted speed exceeds design speed, liability concerns arise. Convincing a jury and others that it is appropriate and safe to allow motorists to drive at speeds greater than the design speed is difficult.

RESEARCH OBJECTIVES

The primary goals of the study are: (1) to document concerns and difficulties the profession is experiencing with the relationship among design speed, operating speed, and posted speed; and (2) to identify solutions for these concerns and difficulties. To date, most design speed research has been conducted on two-lane rural or low volume (residential) streets. An additional goal of this project is to add to the profession's knowledge of the design speed/operating speed relationship by collecting speed data on suburban roadways. Specific objectives to meet the study goals include:

Objective 1: Identification of Texas Concerns. The types and extent of the concerns of engineers in rural districts may be different from those of engineers in urban districts. Experiences with relevant lawsuits also provide insight into Texas concerns. Researchers conducted a mailout survey of design and traffic engineers in the Texas Department of Transportation (TxDOT) districts and engineers in Texas cities and counties to identify concerns.

Objective 2: Identification of Current National Concerns. The issue of design speed versus posted speed limit is a concern not only in Texas but also in other states. A recent survey of all 50 states to discuss the tort liability issues associated with stopping sight distances indicated that many states were concerned about roadways designed many years ago for an 89 km/h (55 mph) design speed. This criterion has changed and these roadways today have geometric conditions that relate to a lower inferred design speed based on today's suggested design criteria. If the roadway is posted for 89 km/h (55 mph), a liability concern arises. Several states have had to deal with this issue. Other states' officials are concerned that such discrepancies may become a liability issue. A mailout survey was sent to traffic engineers and highway designers across the country to identify other concerns, existing policies, suggested treatments, etc.

Objective 3: Identification of Federal Highway Administration (FHWA) involvement. Researchers met with the FHWA to gain insight into the following: Has the FHWA addressed this concern? What are their current philosophies? Is there any discussion of a proposed policy on this issue? Based upon FHWA comments and the mail-out survey findings, researchers interviewed members of the American Association of State Highway and Transportation Officials (AASHTO) Task Force on Geometric Design.

Objective 4: Determination of the Relationship Between Design Speed and Operating Speed on Suburban Roadways. Is the relationship between design speed and operating speed different for suburban roadways than for rural roadways? Speed data at control and curve locations were collected on low design speed horizontal and vertical curves on four-lane suburban roadways.

Objective 5: Evaluation of Solutions Including an Identification of Legal Liability Concerns. Having a situation where the posted speed limit is higher than the design speed of a roadway could pose a liability for an agency. How frequently do representatives of various highway departments feel that the situation occurs? How frequently does this issue arise in court cases? Proposed solutions may create more of a liability problem than posting a speed limit that is just below the design speed for one element. This objective used the information gathered from the mail-out surveys and interviews to assess the legal liability concerns.

Objective 6: Recommendations for Texas Guidelines. Should TxDOT establish guidelines or a policy to address the conflict between design speed and posted speed limit? If so, what should the guidelines address? It is imperative that any recommendations and/or suggestions remain non-standard, require engineering judgment, and not create liability issues. A set of proposed guidelines was developed during this project.

ORGANIZATION OF REPORT

The research findings are presented in seven chapters. A brief summary of the material in each chapter follows.

Chapter 1: Introduction contains a brief presentation of the design speed, operating speed, and posted speed limit issues. It also explains the research objectives and provides an overview of the contents of the report.

Chapter 2: Literature Review includes information from several research projects and the AASHTO *A Policy on Geometric Design of Highways and Streets*[1] (commonly known as the *Green Book*) and other reference materials.

Chapter 3: Mailout Surveys presents information on the methodology and findings from the mailout surveys conducted for this project.

Chapter 4: Interviews describes the findings from the telephone interviews with selected traffic and design engineers, and selected members of the AASHTO Task Force on Geometric Design who responded to the mailout survey. Findings from the meeting with the FHWA are also included in this chapter.

Chapter 5: Concerns with Design Speed, Operating Speed, and Posted Speed Relationships summarizes the issues discussed in the surveys and interviews, and discusses the liability concerns associated with the relationship among design speed, operating speed, and posted speed.

Chapter 6: Field Studies provides information on the field studies. The site selection procedures and the methods used to collect, reduce and analyze data are included, as well as the findings from the horizontal curve field studies and the vertical curve field studies.

Chapter 7: Conclusions and Recommendations provides the conclusions and recommendations of the study.

The **References** section lists the material referenced in the report.

The **Appendix** contains the suggested guidelines developed for use by the department.

CHAPTER 2

BACKGROUND

ORIGINS OF DESIGN SPEED CONCEPT

Horizontal and vertical elements of a highway are designed based upon an assumed design speed. The design-speed concept was developed in the 1930s as a mechanism for designing rural alignments to permit the majority of drivers to operate uniformly at their desired speed. Barnett, who originated the design-speed concept, defined "assumed design speed" as "the maximum reasonably uniform speed which would be adopted by the faster driving group of vehicle operators, once clear of urban areas." He urged that all features of geometric design be made consistent with the chosen design speed. The design-speed or "balanced design" concept became a permanent feature of geometric design policy in the United States when the American Association of State Highway Officials (AASHO) adopted it in 1938. AASHO defined design speed as "the maximum approximately uniform speed which probably will be adopted by the faster group of drivers but not, necessarily, by the small percentage of reckless ones."[2]

Even as early as 1938, AASHO recognized that drivers will select a speed influenced by the roadway environment rather than an assumed design speed. They wrote, "A low design speed should not be assumed for a secondary road, however, if the topography is such that vehicle operators probably will travel at high speeds..." and "Drivers do not adjust their speed to the importance of the road but to the physical limitations of curvature, grade, sight distance, smoothness of pavement..."[2]

A problem posed by the design-speed concept was deciding what the design speed should be for a particular set of conditions -- i.e., what was the "maximum approximately uniform speed adopted by the faster group of drivers?" To find a solution to that question for roads not yet built, Bureau of Public Roads engineers used data from 260,000 vehicles measured at 40 different locations in 1934, 1935, and 1937. Ratios of the speed of the fastest drivers to the average speed of all drivers for various percentiles of total traffic were developed. Based on these data, the engineers recommended that the design speed of a future highway should be the speed that only 5 or possibly 2 percent of the drivers will exceed after the road is built; i.e., the 95th percentile speed.

CURRENT USE OF DESIGN SPEED

The current definition of design speed in the 1994 *Green Book* is "the maximum safe speed that can be maintained over a specified section of highway when conditions are so favorable that the design features of the highway govern."[1] The *Green Book* also provides clarification on both the selection and application of design speed. Examples of guidance provided in the *Green Book* include:

- "The assumed design speed should be a logical one with respect to the topography, the adjacent land use, and the functional classification of the highway."

- "Except for local streets where speed controls are frequently included intentionally, every effort should be made to use as high a design speed as practicable to attain a desired degree of safety, mobility, and efficiency while under the constraints of environmental quality, economics, aesthetics, and social or political impacts."

- "Above minimum design values should be used where feasible, but in view of the many constraints often encountered, practical values would be recognized and used."

- "The design speed chosen should be consistent with the speed a driver is likely to expect. Where a difficult condition is obvious, drivers are more apt to accept lower speed operation than where there is no apparent reason for it."

- "Where it is necessary to reduce design speed, many drivers may not perceive the lower speed condition ahead, and it is important that they be warned well in advance. The changing condition should be shown by such controls as speed-zone signs and curve-speed signs."

INFLUENCES ON OPERATING SPEEDS

In a 1962 study on operating speeds within the urban environment, Rowan et al.[3] concluded that substantial speed reductions occurred when sight distance was below 305 to 366 m (1000 to 1200 ft) and that the introduction of a curbed urban cross-section and the adjacent land use (residential or commercial development) had a speed-reduction influence. Lateral restrictions (trees and shrubbery) were found be more of an influence on speed-reduction than development density.

In 1966 Oppenlander[4] reviewed the literature to identify variables influencing spot speed. The variables were organized into driver, vehicle type, roadway, traffic, and environment categories. The roadway characteristics determined to be most significant included functional classification, curvature, gradient, length of grade, number of lanes, and surface type. Sight distance, lateral clearance, and frequency of intersections were also determined to have an influence.

Garber and Gadiraju [5] in 1989 examined the speed variance at 36 roadway locations including interstates, arterials, and rural collectors. Analysis of variance (ANOVA) tests were used to decide which traffic characteristics of design speed, highway type, time (by year), and traffic volume had a significant effect on average speed and speed variance at the 0.05 significance level. Design speed (a surrogate for highway geometric characteristics) and highway types were significant whereas time (year in which data were obtained) and traffic volume was not significant.

DISPARITY BETWEEN DESIGN AND OPERATING SPEEDS

Recent studies have shown that a noticeable disparity exists between design and operating speeds. In a 1991 *Public Roads* article on advisory speed setting criteria, Chowdhury et al.[6] reported on speed data for 28 horizontal curves in three states (Maryland, Virginia, and West Virginia). Figure 2-1 shows the measured 85th percentile speed and the corresponding horizontal curve design speed. The inferred design speed was computed using the standard superelevation equation given the degree of curvature and measured superelevation rate near the midpoint of the curve, and assuming that the maximum coefficient of side friction recommended by AASHTO was not exceeded. All of the curves with a design speed of 81 km/h (50 mph) or less had 85th percentile speeds that exceeded the design speed. Only on the single 97 km/h (60 mph) design speed curve was the observed 85th percentile speed less than the design speed.

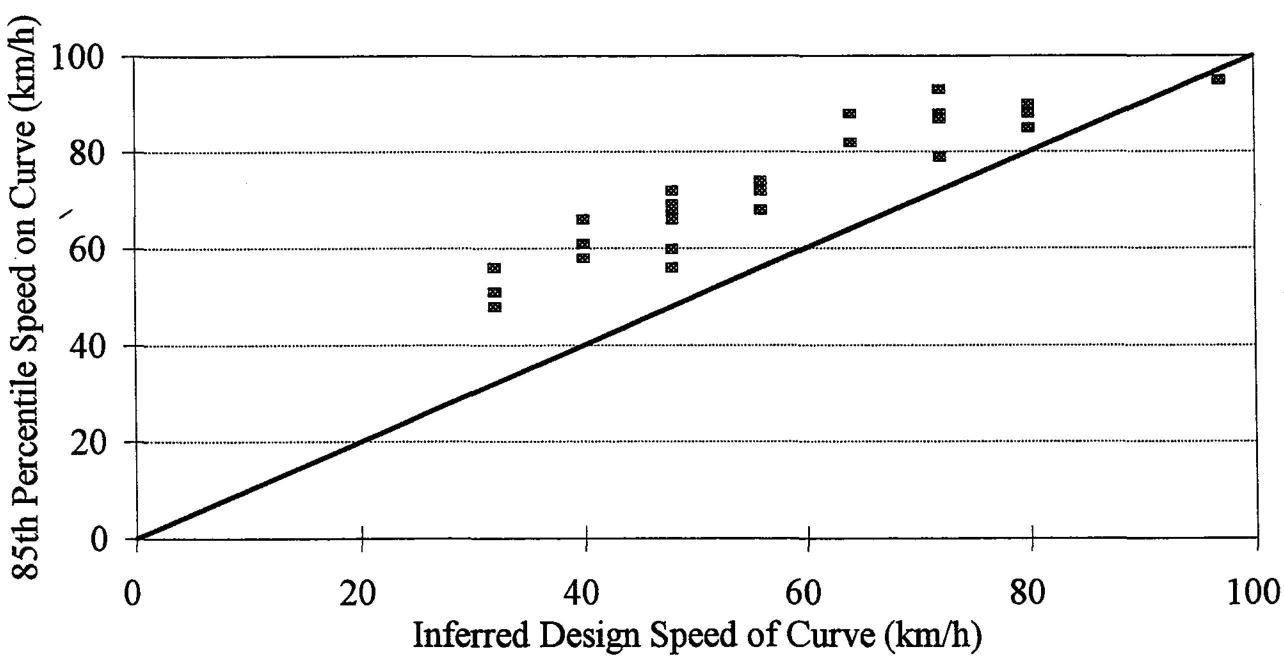

Figure 2-1. 85th Percentile Speed versus Inferred Design Speed for 28 Horizontal Curves in 3 States[6].

A FHWA study[7] on design consistency produced similar results. Speed data were collected during 1992 at 138 horizontal curves on 29 rural two-lane highways in five states (New York, Oregon, Pennsylvania, Texas, and Washington). The data in Figure 2-2 shows that the 85th percentile speed exceeded the inferred design speed on all but two curves that had design speeds of 89 km/h (55 mph) or less, whereas the 85th percentile speed was less than the inferred design speed for all curves that had design speeds of 105 km/h (65 mph) or more. For the curves with 97 km/h (60 mph) design speeds, an almost equal number had 85th percentile speeds greater than and less than the design speed. Note that the disparity between the 85th percentile speeds and inferred design speeds is greatest for the lowest design speeds. For curves with design speeds between 40 and 64 km/h (25 and 40 mph), 85th percentile speeds average 18 to 19 km/h (11 to 12 mph) faster than the design speed.

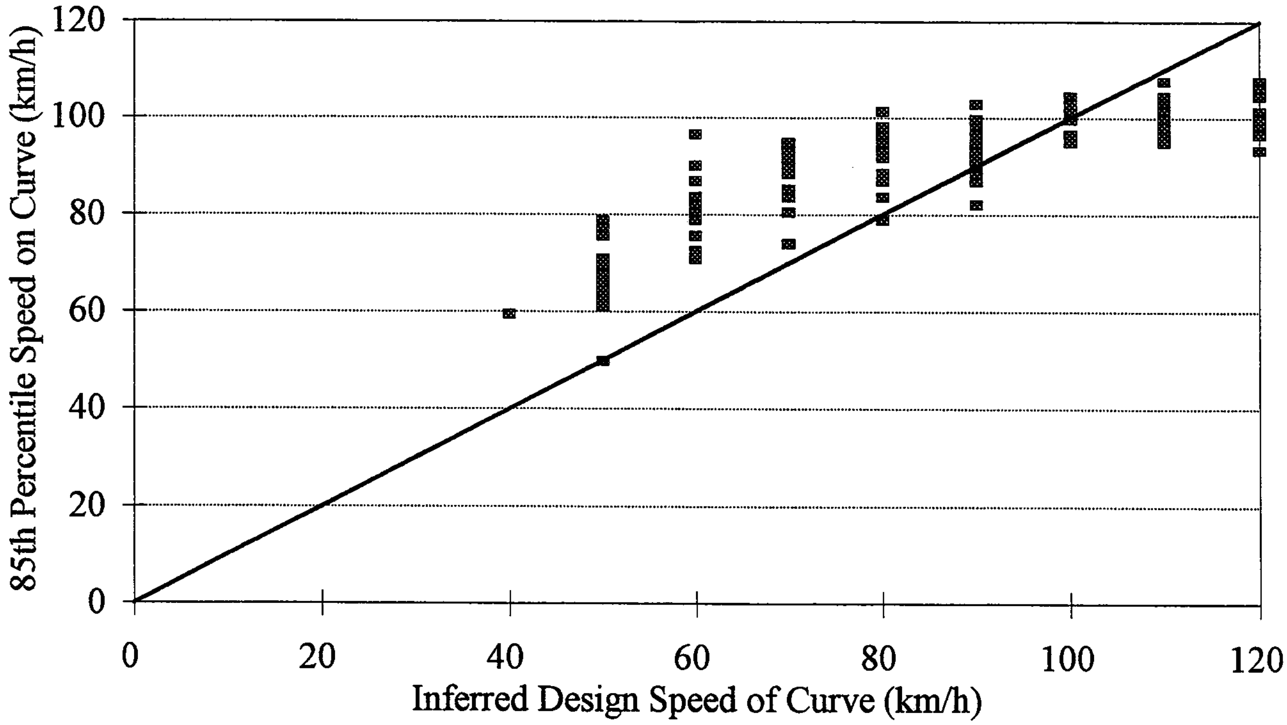

Figure 2-2. 85th Percentile Speed versus Inferred Design Speed for 138 Horizontal Curves in 5 States[7].

In the Garber and Gadiraju study[5] of 36 roadway locations that included interstates, arterials, and rural collector sites, and where design speed was used as a surrogate for geometric characteristics, the following conclusions were made:

- Speed variance on a highway segment maintains at a minimum when the difference between the design speed and the posted speed limit is between 8 and 16 km/h (5 and 10 mph).

- For average speeds between 40 and 113 km/h (25 and 70 mph), speed variance decreases with increasing average speed.

- The difference between the design speed and the posted speed limit statistically greatly affects the speed variance.

- Drivers generally drive at increasing speeds as roadway geometric characteristics improve, despite the posted speed limit.

- Accident rates do not necessarily increase with an increase in average speed but do increase with an increase in speed variance.

To achieve a reduction in speed-related accidents, the authors recommended speed limits for different design speeds as shown in Table 2-1.

McLean[8,9] also found similar design speed/operating speed disparities on rural two-lane highways in Australia. McLean found that horizontal curves with design speeds less than 90 km/h (55.8 mph) had 85th percentile speeds that were consistently faster than the design speed, whereas curves with design speeds greater than 90 km/h had 85th percentile speeds that were consistently slower than the design speed. McLean's findings prompted a revision of the Australian design procedures for lower-design speed roadways.

Table 2-1. Recommended Speed Limits to Reduce Speed-Related Accidents[5].

Design Speed km/h (mph)	Posted Speed Limit km/h (mph)
113 (70)	97 or 105 (60 or 65)
97 (60)	81 or 89 (50 or 55)
81 (50)	64 or 72 (40 or 45)

Ongoing research at the Pennsylvania Transportation Institute (PTI)[10] is examining the use of a target operating speed as the preselected design speed for the design of low-speed urban streets. The goal is to provide street designs that reflect the operating environment so that a complementary relationship would exist between the preselected design speed, actual operating speed, and posted speed limits. Engineers must be able to predict probable operating speeds along the proposed alignment for such a design process to become practical. A determination must be made of the relationship between the probable operating speed (and operating speed variability) and the geometric elements (line, grade, and cross-section), land use, and traffic engineering elements. One objective of the PTI study is to develop a speed-prediction model for low-speed urban streets.

The National Highway Cooperative Research Program (NCHRP) Project 3-42, Determination of Stopping Sight Distance[11] is examining the relationship between design speed and operating speed. Preliminary findings suggest that motorists drive higher speeds than the design speed on limited sight distance crest vertical curves (i.e., curves with design speeds less than 89 km/h (55 mph)). Figure 2-3 shows the results of 34 crest vertical curves in three states (Illinois, Texas, and Washington).

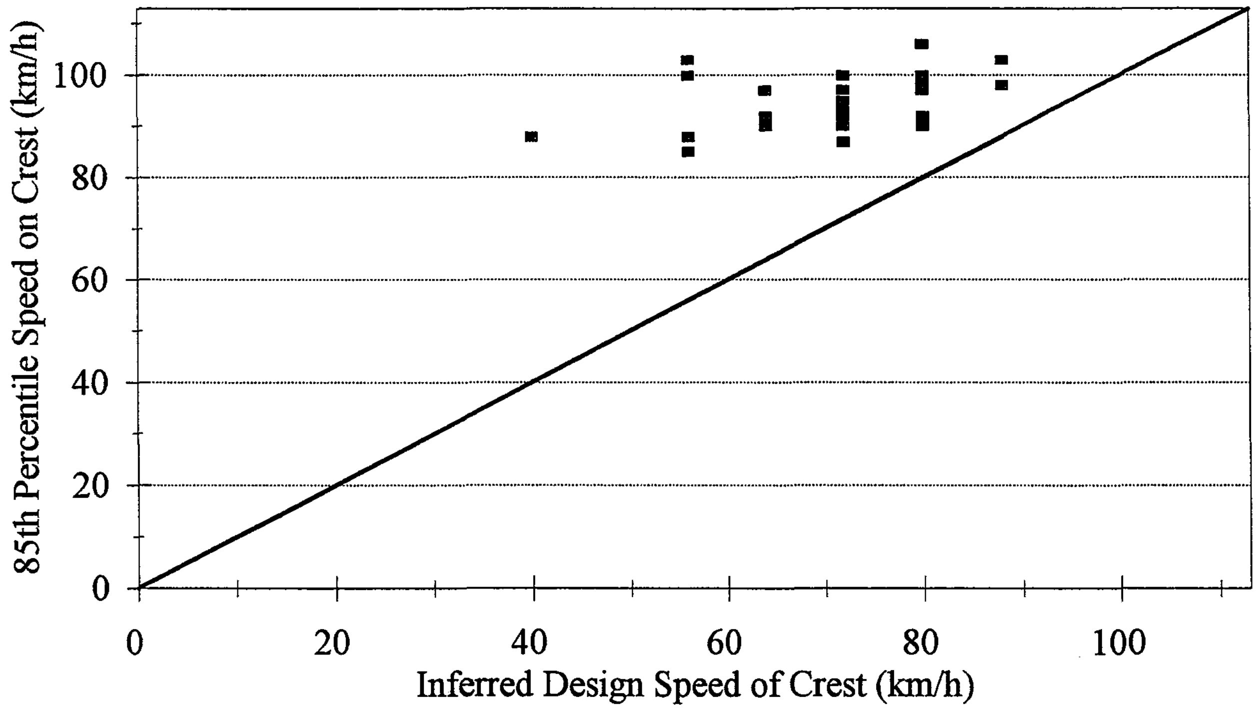

Figure 2-3. 85th Percentile Crest Speeds for Various Design Speeds[11].

CRITIQUE OF THE DESIGN SPEED CONCEPT

Krammes[12] provided a critique of the weaknesses in U.S. policy in selecting and applying design speed. These weaknesses contribute to the disparity between design and operating speeds on rural highways. A summary of his discussion follows.

Design Speed Selection Process

Because studies indicate that the disparity between design and operating speed on horizontal curves is restricted almost entirely to curves with design speeds less than 97 km/h (60 mph), and AASHTO recommends a minimum design speed for collectors in rolling terrain as low as 48 km/h (30 mph), U.S. design policy makers should reconsider recommended minimum values for new construction.

Design Speed Application Process

Several fundamental flaws exist in the logic and assumptions underlying how the design speed concept is applied in U.S. design practice. These flaws are likely to create problems, however, only if the selected design speed is less than drivers' desired speeds. A fundamental limitation is that the design speed applies only to horizontal and vertical curves, and not to the tangents that connect those curves. Although AASHTO suggests general controls that address qualitatively the coordination of and consistency between horizontal and vertical alignment elements, neither quantitative guidance nor formal procedures are provided to help insure alignment consistency. The design speed concept does not provide sufficient coordination among individual geometric features to insure consistency.

Driver Speed Choice

The limited data available on operating speed profiles approaching and traversing curves that require some speed reductions indicate that drivers begin decelerating only a short distance before the curve and that drivers continue to decelerate between the beginning and midpoint of the curve. These data suggest that drivers have difficulty judging the sharpness of curvature and appropriate speed before reaching the curve. According to Chowdhury et al.,[6] "The absence of adequate and universally accepted criteria for determining advisory speeds creates the problem of nonuniform and subjective applications; this problem in turn poses a potential safety threat to unfamiliar drivers. The posted advisory speeds have little significance for the motorists." Data showing that drivers consistently exceed posted advisory speeds on curves suggest that drivers tolerate greater lateral acceleration (side friction factors) than assumed for design and signing purposes.

INTERNATIONAL REVISIONS TO THE DESIGN SPEED CONCEPT

According to Krammes[12], at one time, most country policies on design speed were identical to current U.S. policy. Procedures for selecting a design speed are still similar to U.S. practice (i.e., based on the class of roadway, development environment, and topography). During the last 20 years, however, several countries revised their procedures on how the design speed is applied for new construction. The principal revisions include: (1) incorporating a feedback loop in the design process to assess the consistency of speeds along an alignment and to make revisions necessary to improve consistency, (2) specifying superelevation and sight distance based upon the estimated 85th percentile speed if it exceeds the design speed, and (3) providing quantitative guidelines on the coordination of alignment elements.

Rural highway alignment design policies in Australia, England, France, Germany, and Switzerland include feedback loops to identify and resolve operating speed inconsistencies. The basic approach for new construction is to design a preliminary alignment based upon the selected design speed, to evaluate that alignment for speed consistency, and, as necessary, to revise the alignment to eliminate inconsistencies that exceed critical values. Generally, the speed consistency evaluation is based upon empirical relationships that estimate 85th percentile operating speeds as a function of alignment, cross section, and topography.

Examples of quantitative guidelines provided are: (1) when a curve follows a long tangent (since sharp curves following long tangents cause the most serious consistency problem), and (2) sight distance available to horizontal curves. For example, the French guidelines for new rural highways indicate that if the preceding tangent length exceeds 500 m (1639 ft), the minimum curve radius is 200 m (656 ft), and if the preceding tangent length exceeds 1000 m (3279 ft), the minimum curve radius is 300 m (984 ft). France and Switzerland also provide guidelines on the minimum sight distance to the beginning of a horizontal curve. The French guidelines call for a distance corresponding to 3 seconds of travel time at the 85th percentile speed on the approach to the curve.

SPECIAL REPORT 214 RECOMMENDATIONS

Recognizing the safety consequences of disparities between design and operating speeds, Transportation Research Board Special Report 214[13] made the following recommendations:

> Highway agencies should increase the superelevation of horizontal curves when the design speed of an existing curve is below the running speeds [defined as the 85th percentile speed measured before the vehicle slows for the curve] of approaching vehicles and the existing superelevation is below the allowable maximum specified by AASHTO new construction policies. Highway agencies should evaluate reconstruction of horizontal curves when the design speed of existing curves is more than 24 km/h (15 mph) below the running speeds of approaching vehicles (assuming improved superelevation cannot reduce this difference below 24 km/h (15 mph)) and the average daily traffic volume is greater than 750 vehicles per day.

CHAPTER 3

MAIL-OUT SURVEYS

Mail-out surveys were distributed to design and traffic engineers in (1) TxDOT districts, (2) the 50 state transportation departments, and (3) selected cities and counties. The surveys were used to identify concerns and difficulties the profession is experiencing with the relationship among design speed, operating speed, and posted speed and to identify solutions for these concerns and difficulties. This chapter presents the methodology used in the mail-out surveys and the findings from the surveys. Interpretations of the survey findings and of follow-up interviews are included in Chapter 5.

SURVEY METHODOLOGY AND DISTRIBUTION

The project team began development of the written surveys by listing potential questions that could provide insight into concerns about design speed and operating speed. The team decided during the development of the survey that certain questions should be answered by a traffic engineer and others by a design engineer. Therefore, two basic surveys were developed—a design survey and a traffic operations survey. After the questions were refined, the general design survey and traffic operations survey were tailored for TxDOT districts and for states. A combined survey was also developed for cities and counties. Because of questions and concerns raised by individuals pretesting the surveys, the surveys were modified to include a list of keyword definitions. Table 3-1 lists the definitions included in each survey.

Design Surveys

The design survey included questions to identify the design process used by engineers. Questions were related to whether anticipated operating speed is considered when designing a roadway and whether the selected design speed is reviewed/reevaluated at later stages in the design process. Questions on how to design a roadway whose function is expected to

Table 3-1. Keyword Definitions Listed in Each Survey.

KEYWORD DEFINITIONS

Design Speed is used to establish the horizontal and vertical curve alignment of a roadway. It is the maximum safe speed that can be maintained over a specified section of highway when conditions are so favorable that the design features of the highway govern.[1]

Operating Speed is the speed at which drivers are observed operating their vehicles. The 85th percentile of the distribution of observed speeds is the most frequently used descriptive statistic for the operating speed associated with a particular location or geometric feature.

85th Percentile Speed is the speed below which 85 percent of motorists travel. It is frequently used to set speed limits.

Posted Speed is the maximum speed limit posted on the facility.

Advisory Speed is the suggested safe speed for specific conditions (such as a horizontal curve) on a highway.

change over time—such as the change from a high functional class to a lower functional class or when the change is from a rural environment to a suburban environment—were also included. Besides questions on design processes, the survey gathered information on any concerns including liability that the engineer may have.

Traffic Operations Surveys

The traffic operations surveys gathered information on operations and liability concerns. They included questions on procedures used to set posted speed limits, methods used when the design speed is below the operating speed, and procedures followed to set advisory speeds on horizontal curves. For example, one question was "What factors do you consider when determining the posted speed limit for an *existing* facility?" Questions relating to how one determines the appropriate posted speed limit to be used for a *new* facility were also included.

Other questions probed additional issues, such as whether an engineering speed study is done before setting or changing a speed limit. Follow-up questions on the monitoring of operating speeds of a facility after posting a speed limit were also asked. Finally each agency was asked whether they have been involved in a lawsuit related to a posted speed limit that exceeded the design speed of the roadway.

Distribution of Surveys

Two surveys entitled *Design Survey* (I) and *Traffic Operations Survey* (II) were sent to each TxDOT district in October 1994. The district engineer was asked to identify a design engineer and a traffic engineer to complete the appropriate survey. The two surveys developed for other state DOTs were entitled *Design Survey* (III) and *Traffic Operations Survey* (IV). These surveys were similar to the TxDOT surveys, with the primary difference being the absence of questions relating to staged construction on frontage roads. A fifth survey, entitled *Design, Operating, & Posted Speed Survey* (V), was developed and sent to approximately 130 cities and counties throughout the United States. This survey combined questions from *Surveys III* and *IV* because cities and counties usually employ a single transportation engineer responsible for the duties of both.

Names and addresses used for the state highway agencies were obtained from the most current issue of the AASHTO Reference Book of Member Department Personnel and Committees. Chief traffic and design engineers were selected for each state highway agency. The mailing list for local highway agencies (cities and counties) was based on the Institute of Transportation Engineers (ITE) directory or on the National Association of County Engineers (NACE) directory. The sample of local highway agencies included at least one agency in each state; additional local agencies were selected in the larger states.

RESPONSES

Table 3-2 lists the number of surveys distributed and returned, and the resulting return rates. Of the 282 surveys distributed, 168 were returned for a final return rate of 58 percent. Because surveys of this type generally have response rates between 20 and 50 percent, the high response rate shows a high level of interest in the topic, especially among the state agencies.

Table 3-2. Mail-out Survey Response Rates.

Survey Number	Survey Title	Survey Respondent	Number of Surveys Mailed	Number of Surveys Returned	Response Rate (%)
I	*Design Survey (I)*	TxDOT Design Engineer	25	19	76
II	*Traffic Operations Survey (II)*	TxDOT Traffic Operations Engineer	25	20	80
III	*Design Survey (III)*	State Design Engineer	51	33*	65
IV	*Traffic Operations Survey (IV)*	State Traffic Engineer	51	41	80
V	*Design, Posted, & Operating Speed Survey (V)*	City/County Transportation Engineer	130	51	39
TOTAL			**282**	**164**	**58**

* Three of the 33 states responding sent multiple surveys. A total of 38 State Design Surveys were received.

RESPONSES TO DESIGN SURVEYS

Nineteen of the 25 TxDOT districts responded to the *Design Survey* (I). Responses to the *Design Survey* (III) were received from 33 of the 51 states surveyed. Three of the 33 states responding to the survey returned multiple surveys. A total of 38 State Design Surveys were received. For the fifth survey entitled, *Design, Operating, and Posted Speed Survey* (V), 51 of the 130 cities/counties surveyed responded.

Due to similarity among surveys I, III, and V (Part A) concerning issues related to design speed considerations, the following sections summarize the responses from the 19 TxDOT districts, 38 state DOT design engineers, and the 51 city/county transportation engineers who returned the survey.

Do you use the design speed concept when designing roadways in your city or county?

This question was exclusively directed to *Survey V* respondents (city/county transportation engineers) in an attempt to determine what criteria they use to establish horizontal and vertical alignment. Of those agencies responding to this question, 90 percent (46 of 51 agencies) said that they use the design speed concept when designing roadways.

Which of the following do you consider when selecting a design speed (See Figure 3-1 for the list of factors provided)?

This question was asked to find out whether anticipated operating speed or posted speed are significant factors in the selection of a design speed. Figure 3-1 summarizes the findings from the different surveys. More than half of the TxDOT respondents said that the anticipated operating speed and posted speed limit are used in their design speed selection process. Other significant factors considered are the department's design criteria and policies, whether or not the design is rural or urban, the roadway's functional classification, and site topography.

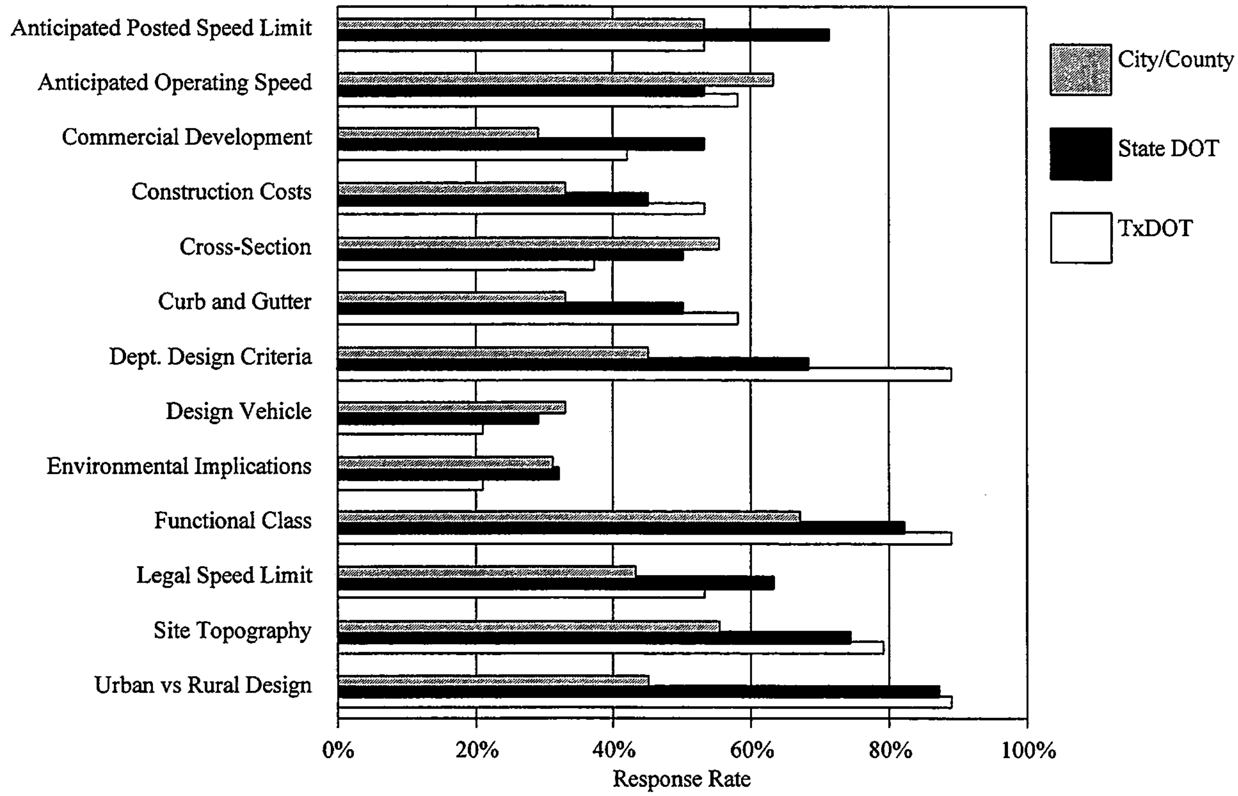

Figure 3-1. Factors Considered When Selecting a Design Speed.

More than half of the state highway engineers surveyed said they use the anticipated operating speed or posted speed limit in their design speed selection process. Other significant factors considered by those responding are whether the design is rural or urban, roadway functional class, site topography, department design criteria, and legal speed limit.

More than half of the city/county transportation engineers responding to this question stated that they consider the anticipated operating speed and posted speed limit in their selection process. Other significant factors considered are roadway functional class, roadway cross-section, and site topography. One respondent suggested the use of access control as part of the selection criteria.

Consideration of the anticipated operating speed when selecting the design speed of a roadway has been recommended. Do you agree?

Approximately 90 percent (17 of 19 districts) of the TxDOT design engineers surveyed agree that anticipated operating speed should be considered when selecting the design speed of a roadway. Several of those responding said that although operating speed is considered, it is not always cost effective to provide for a desired operating speed on low-volume facilities. In opposition, one district representative stated that "[anticipated operating speed]... leaves room for too much supposition and therefore inconsistency on the part of the design engineer."

More than 65 percent (25 of 38 agencies) of the out-of-state design engineers responding agree that anticipated operating speed should be considered when selecting the design speed of a roadway. Many respondents suggested designers should avoid artificially lowering the design speed to accommodate a typical section or design feature when possible. If needed, a design exception or variance should be obtained for the deficient element rather than lowering the overall design speed.

Approximately 80 percent (41 of 51 agencies) of those responding from cities and counties agree that the operating speed should be considered when selecting the design speed of a roadway. A few individuals said that once they estimate the anticipated operating speed, they choose a design speed that is five to ten miles per hour higher. For the most part, respondents simply restated the understanding that design speed should always exceed or equal expected operating speed.

After the initial roadway design speed is completed, are there any review procedures in your agency's current design process to review/reevaluate the design speed selected?

Almost 70 percent (13 of 19 districts) of the TxDOT design engineers surveyed responded positively to this question. Typically, responses indicated that plans are submitted to district staff for review and to ensure compliance with TxDOT procedures and then sent to Austin for final review and approval. One respondent stated that when the plans comply with the *TxDOT Highway Design Division's Operation and Procedures Manual* [14], the design speed initially selected is no longer an issue.

Less than 35 percent (13 of 38 state agencies) of those states surveyed said review procedures were available in their state's current design process to review/reevaluate the design speed selected after an initial design is completed. Five of the 13 respondents said that their traffic operations division performs traffic surveys for 85th percentile speeds and accidents once the facility is in operation. The posted speed limit can be changed at this time based on the 85th percentile speed. One respondent stated that their Traffic Engineering Division has the option of recommending a different design speed after the initial design plans are completed.

A similar percentage of the city/county transportation engineers responding (33 percent) said there are review procedures in their current design process. The initial design speed selected is frequently lowered due to constraints such as site specific topography, right-of-way, and excessive costs.

When the use of a facility is expected to change over time from a high functional class to a lower functional class or from a rural environment to a suburban environment, does this influence your selection of an appropriate design speed?

More than half of the TxDOT design engineers responding (11 of 19 districts) said that an anticipated change in functional class over time does influence their selection of an appropriate design speed. One respondent spoke of a current project in which they are designing a rural section of roadway that will eventually (in 10 years) operate as an urban section. The respondent stated that they are using minimum rural design values for the horizontal alignment and cross-section designs.

Of those out-of-state design engineers responding to this question, approximately half (18 of 38) said that such a change would influence their selection of an appropriate design speed. One respondent suggested the use of a range of design speeds based on functional classification. Many of those in disagreement said that justifying lower design criteria knowing that traffic will initially operate at a higher operating speed was very difficult.

Has your agency ever been involved in a lawsuit related to a posted speed limit that exceeded the design speed of the roadway?

Seven of the TxDOT respondents answering this question said their district had not been involved in a lawsuit related to a posted speed limit that exceeded the design speed of a roadway. The remaining 12 said they did not know of any prior lawsuits surrounding this issue.

Two of the 38 out-of-state design engineers respondents said their state had been involved in a lawsuit related to this issue. One respondent said that the case was currently in litigation. Another said that while the posted speed exceeding the design speed has been a side issue in some cases, it has never been a substantive one.

In your agency, do (or did) you have a facility where the operating speed or the posted speed of a section exceeds(ed) the design speed? If so, were any actions taken to lower the operating speed or the posted speed or to warn drivers of the conditions?

Eleven of the 19 TxDOT design engineers responded yes to the first part of this question. Of those 11 respondents, no significant actions were taken to lower the operating speed, the posted speed, or to warn drivers of the conditions other than the installation of advanced warning signs on curved sections. The respondents said no action is taken unless there is an increase in accidents or the presence of a suspected unsafe condition. Typical practice is to request a design exception by the state Design Division in Austin.

Approximately 65 percent (26 of 38 districts) of the out-of-state design engineers said that they had a facility where the operating speed or the posted speed of a section exceeds(ed) the design speed. Of those 26, 22 said actions were taken to reduce speeds or warn drivers of the situation. The majority of those actions consisted of the installation of advance warning signs. Several respondents stated that design exceptions are requested for any portion of a facility that does not meet the design speed. Should the design exception not be approved, the posted speed limit would not exceed the design speed for that section.

RESPONSES TO TRAFFIC OPERATIONS SURVEYS

Twenty of the 25 TxDOT districts responded to the *Traffic Operations Survey* (II). Forty-one of the 51 state highway agencies surveyed responded to the *Traffic Operations Survey* (IV). The fifth survey entitled, *Design, Operating, & Posted Speed Survey* (V), was sent to approximately 130 cities and counties throughout the United States. Currently, 51 of the 130 city/counties surveyed have responded.

Due to the similarity among surveys II, IV and V (Part B) concerning questions related to posted speed limit considerations, the following sections summarize the responses by question from the 20 TxDOT districts, the 41 state DOT traffic engineers, and the 51 city/county transportation engineers who returned the surveys.

What factors do you consider when determining the posted speed limit for an *existing* facility?

This question was asked to determine whether or not design speed plays a key role in the determination of the posted speed for an *existing* facility. The respondents were asked to choose from a list of various factors considered important in the selection of posted speed limits. Figure 3-2 illustrates the findings from the surveys. Those factors considered more important than design speed by TxDOT traffic engineers were 85th percentile speed, recent accident experience, and state mandated maximum speed limit. Only five of the 20 TxDOT engineers responding said that they considered design speed when posting speed limits.

More than 95 percent of the out-of-state traffic engineers surveyed indicated that the 85th percentile speed is their primary consideration in determining the posted speed. Other significant factors are roadside development, recent accident experience, state mandated maximum speed limit, and various geometric design features of the roadway. Thirteen of the 41 out-of-state traffic engineers surveyed stated that they considered design speed when determining the posted speed for an *existing* facility. Several engineers surveyed mentioned the use of the upper limit of the 10 mile per hour pace as an additional factor to consider.

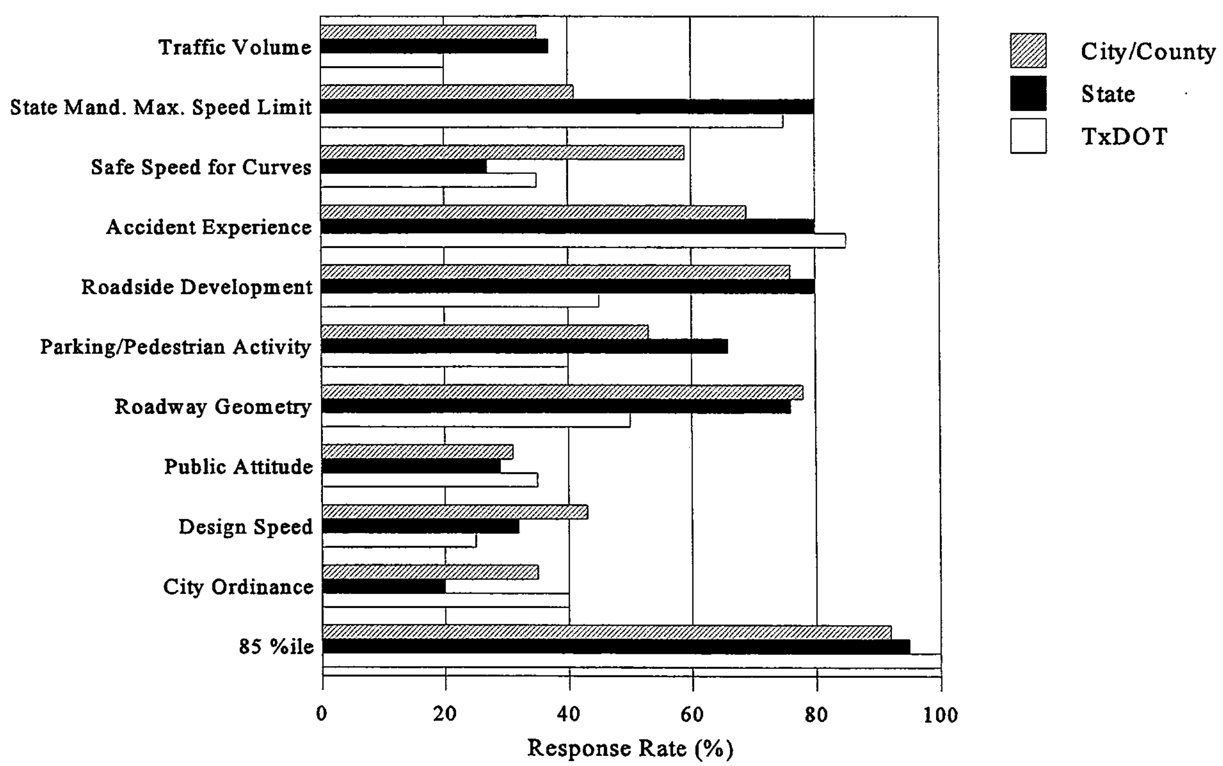

Figure 3-2. Factors Considered in Determining Posted Speeds for Existing Facilities.

As in the previous two surveys, the Design, Operating, and Posted Speed Survey (V) reveals that the 85th percentile speed is the predominant factor used when determining the posted speed limit. Over half of those surveyed stated that they also consider recent accident experience, roadside development, and the geometry of the roadway. Twenty-two of the 51 city/county engineers surveyed said that they considered design speed. Additional comments by respondents ranged from use of the state DOT's prescribed values of posted speed to estimates based on functional classification of the roadway.

How do you determine the appropriate posted speed limit to be used for a *new* facility in your agency?

This question attempted to determine if design speed is used when selecting the posted speed of a *new* facility. Almost half of the TxDOT respondents stated that design speed is used as the initial speed and that the speed is modify after the facility is in operation using the 85th percentile operating speed. One respondent suggested the use of the state mandated maximum speed limit if the value is below the design speed.

The response for this question from out-of-state traffic engineers was similar to that of the TxDOT traffic engineers. Almost half of the respondents said they post speed limits initially based on the design speed. The speed is modified after the facility is in operation using the 85th percentile operating speed determined from field measurements. Six of the 41 out-of-state respondents wrote that they post speed limits based on state mandated maximum speed limit.

Less than half of the city/county transportation engineers surveyed said they initially post speed limits based on the design speed and modify the speed limit after the facility is in operation using the 85th percentile operating speed. Several respondents stated that they initially post speed limits based on adjacent sections of roadway in order to establish continuity and later modify them if a need arises.

Do you perform an engineering speed study prior to setting or changing a speed limit?

Every TxDOT district surveyed said that they perform an engineering speed study prior to setting or changing a speed limit. Almost every out-of-state engineer (36 of 41) surveyed said that they perform an engineering study prior to setting or changing a speed limit. Forty of the 51 city/county transportation engineers responding to this question said that they perform an engineering study prior to setting or changing a speed limit. Thirty-four of the 51 city/county engineers provided copies of the regulations or provided instructions on how copies of the regulations used to perform an engineering study can be obtained.

Do you monitor the operating speeds of a facility after posting a speed limit?

Of the TxDOT traffic engineers responding, 95 percent (19 of 20 districts) indicated they monitor the operating speeds of a facility after posting a speed limit. Follow-up questions probed the time frame associated with such a response. Of those engineers responding, two TxDOT districts perform a study each year and six said they perform a study every five years. The majority of the respondents said they monitor operating speeds when a complaint is made (e.g., by the police or by a citizen), or when there is a change that would affect operating speed (e.g., elimination of parking, lane additions, signal coordination, etc.).

Of the out-of-state traffic engineers responding to this question, 88 percent (36 of 41 state DOTs) said they monitor operating speeds after posting a speed limit. Five engineers surveyed said they perform a study every five years, while one state DOT reevaluates the posted speed limits on approximately 300 miles of state highway annually. The majority of the respondents said they monitor operating speeds when a complaint is made or when there is a change that would affect operating speed.

Forty-one of the 51 city/county transportation engineers responding to this question said they monitor the operating speeds of a facility after posting a speed limit. As in the previous two groups, more than half of the respondents said they would monitor speed upon receiving a complaint or when there was a change in the operation of the facility.

What procedures do you follow to set advisory speeds on horizontal curves?

All 20 TxDOT respondents said that they use a ball bank indicator to set advisory speeds on horizontal curves. Two districts said that in addition to using the ball bank indicator, they verify engineering data associated with the curve such as degree of curve, percent superelevation, and sight distance.

Of the out-of-state traffic engineers responding to this question, 88 percent indicated they use a ball bank indicator to set advisory speeds on horizontal curves. One respondent said they initially post advisory speeds based on design speeds and later perform field tests to determine the appropriate values. One suggestion made was to post advisory speeds for horizontal curves on new facilities using the design speed of the curve, and for existing roadways using the ball bank indicator.

Forty-five of the 51 city/county transportation engineers indicated they use a ball bank indicator to establish advisory speeds on horizontal curves. Three of the respondents indicated that design speed or minimum radius is used to select the advisory speed.

Do you modify your standard procedure for posting advisory speeds on horizontal curves based upon approach conditions to the curve (e.g., for a horizontal curve that follows a long tangent as opposed to a horizontal curve on a winding roadway)?

Of the 20 TxDOT districts responding to this question, three said they modified their standard procedures. The advisory speed posted reflects the speed for the "slowest curve" within a series of curves.

Seven of the 41 out-of-state traffic engineers said they would modify their procedures. The majority of the responses included some mention of advanced warning signs and/or chevrons when curves did not meet the ball bank indicator requirements. One agency stated that it does not reduce the speed limit on a section of roadway which contains several horizontal curves, but rather establishes a speed limit based upon the 85th percentile speed and uses advisory speeds for the horizontal curves. Another state indicated that if several miles of horizontal curves are present, it posts an advisory speed for curves with a distance value below the advisory speed. Another respondent stated that depending upon the speed differential between the tangent section and the horizontal curve, and the geometrics of the site, the agency may use larger signs possibly with flashing beacons as traffic control.

Of the city/county transportation engineers responding to this question, eight said they modify their standard procedures for posting advisory speeds on horizontal curves that follow a long tangent. The typical response was to increase the size of advanced warning signs and install flashing beacons, delineators, and/or enhanced pavement markings.

Please list any additional comments or concerns about the *strengths* and *weaknesses* of your agency's advisory speed limit selection process. Do you have any suggestions or recommendations for an improved procedure?

Very few TxDOT engineers responding made any comments concerning an improved advisory speed limit selection process. One respondent questioned the use of the ball bank indicator, yet indicated that another reliable method is not known.

Many of the state traffic engineers responding to this question said they believed that the values they use to set advisory speeds on horizontal curves (either their own agency's or AASHTO's) are too conservative. One respondent suggested that advisory speed procedures should consider approach conditions to horizontal curves to account for driver expectancy.

No suggestions or recommendations for an improved advisory speed selection process were made by the city and county engineers surveyed.

Has your agency ever been involved in a lawsuit related to a posted speed limit that exceeded the design speed of the roadway?

Six of the TxDOT respondents answering this question said their district has not been involved in a lawsuit related to a posted speed limit that exceeded the design speed of a roadway. The remaining 14 respondents said they did not know of any prior lawsuits relative to this issue.

Of those responding to this question, two out-of-state traffic engineers said they have been involved in a lawsuit related to a posted speed limit that exceeded the design speed of the roadway. One respondent said that although design inconsistency was named as one of the defects in the case, the suit was not lost on this basis. Another respondent said that the state has not been involved in any lawsuit related to posted speed limits exceeding the design speeds of the roadways; however, lawsuits have been filed where advisory speeds were the issue.

Only one of the 41 city/county transportation engineers responding to this question said that the agency has been involved in a lawsuit related to this issue. The suit was settled at the deposition stage. Consistency of policy over the entire jurisdiction was stated as being a significant factor along with state mandates in this suit.

In your agency, do (or did) you have a facility where the operating speed or the posted speed of a section exceeds(ed) the design speed? If so, were any actions taken to lower the operating speed or the posted speed or to warn drivers of the conditions?

Of the 12 TxDOT districts who responded yes to the first part of this question, only eight responded to the second part. Of those eight, five respondents said they try to install advisory speed warning signs where appropriate. One individual said that while it is a problem, a design exception was granted because of the short duration of the reduced speeds. Another stated that they have installed oversized speed limit signs.

Of the 21 out-of-state traffic engineers who responded yes to the first part of this question, 19 responded to the second part. Of those 19, eight respondents said they install warning signs (with advisory speeds in some cases) where appropriate. Several respondents said that increased or selective enforcement is the only practical method to reduce operating speeds. Others stated that they reduced the posted speed limit to match the design speed. One respondent noted that because the design speed of several highways is unknown in their state, when the road is re-designed or re-constructed and it becomes known that the design speed is less than the posted speed limit, corrective action is taken or a design exception is requested. Sometimes the corrective action is a change of the posted speed limit. Vertical curves on bridge replacement projects are a common problem.

Of the 51 city/county transportation engineers responding to this question, 20 suggested the use of advisory warning signs to lower operating speeds or to warn drivers of the conditions. Increased enforcement was recommended by three of the respondents with one of these respondents noting that they typically do not try to lower posted speed limits because experience has shown that lowering the posted speed limit does not reduce the 85th percentile speed on a street unless there is strict enforcement. One individual argued that no action is taken because inducing uneven flow on a facility, which may already be under-designed, only compounds the problem of vehicle conflicts. A second respondent indicated that there is no doubt that there are streets with posted speeds above the design speed, given the safety factors of the design speed. A third respondent said that the agency is not able to determine the design speeds of all roadways--a condition that probably exists for many agencies.

CHAPTER 4

INTERVIEWS

Interviews were conducted with FHWA engineers, members of the AASHTO Task Force on Geometric Design, and selected traffic engineers who responded to the mail-out survey. This chapter contains the findings from the interviews while Chapter 5 presents a summary and interpretation of the findings.

FEDERAL HIGHWAY ADMINISTRATION

On January 26, 1995, an interview with two engineers employed with the FHWA in Washington, D.C. was held to obtain specific comments about the design speed versus posted speed limit issue as viewed from a national level. The interview revealed the following specific comments.

1. Having increased speeds on roadways was fairly common after 3R Projects have been completed due to improved operational characteristics. Based on current geometric design criteria, having posted speed limits greater than design speeds for those roadways was common.

2. A roadway should be designed to operate at a speed equal to or less than the roadway's design speed. If a roadway's current design speed is greater than its posted speed limit, then a factor of safety is assumed to exist. Finding out if accident rates at locations with posted speeds greater than design speeds support this theory would be interesting.

3. A new concern for the FHWA is the existence of many miles of interstate highways that no longer satisfy the sight distance requirements for posted speed limits since design criteria have been updated.

4. The current definition of design speed (by AASHTO) needs to be changed. Some terminology may be preferred instead of the term "design speed."

5. It is appropriate to redefine, explain more fully, or find substitutes for the terms design speed, posted speed, and operating speed.

AASHTO TASK FORCE ON GEOMETRIC DESIGN

Based upon the responses by the FHWA engineers, the project team decided to contact members of the AASHTO Task Force on Geometric Design to obtain some feedback from the AASHTO committee that addresses the design speed issues. Six members of the task force were identified and contacted. Questions were developed and sent to the Task Force members for review. A telephone conversation with each member provided the following results.

1. Note the current AASHTO definition for design speed. "Design speed is the maximum safe speed that can be maintained over a specified section of highway when conditions are so favorable that the design features of the highway govern." Do you agree with this definition?

Only one member agreed with the definition. The remaining five members believed that the definition was incorrect or required major revision. The portion of the definition that refers to the "maximum safe speed" was specifically mentioned by the five members who wanted a change to the definition.

What changes would you make to the definition?

The term "maximum safe speed" was considered improper because speeds greater than the design speed can be safely negotiated on many sections of highway when "conditions are favorable." Consequently, they felt that the definition was not accurate.

Do you believe that the term "design speed" should continue to be used or should an alternate term or method replace it?

Again, only one individual favored continuing to use the term "design speed." The remaining five members suggested that an alternate term would be more desirable. The same five individuals emphatically agreed that if the term "design speed" remained in use, its definition should be changed.

2. **The AASHTO *Green Book* states that "some sections of low-design-speed highways are frequently overdriven, with an appreciable number of drivers exceeding the design speed." Do you agree with this?**

Four members of the committee agreed with this statement. One member did not agree, and the final member stated that this statement was correct "sometimes."

Do you believe that this type of condition is inherently unsafe?

Two members of the committee believed that this condition was unsafe. The four remaining members did not believe that such highway sections were unsafe. The basic belief was that drivers could (and should) adapt to changing roadway conditions and travel at lower speeds when weather or visibility conditions were less than desirable.

3. Do you agree with the statement that roadways are designed with factors of safety such that drivers can typically exceed the roadway's design speed without creating a hazardous condition?

Five members of the committee agreed with this statement. The single dissenting member stated that having a hazardous condition when exceeding the roadway's design speed was possible under certain circumstances.

4. Do you believe it is appropriate to post speed limits on roadways based on operating speeds, even though the posted speed would be higher than the roadway's design speed based on <u>current</u> design criteria for new roadways?

Four members of the committee favored the statement. The remaining two felt such postings were not appropriate.

5. Do you believe it would be appropriate for AASHTO to prepare documentation that clarifies the definitions of the terms "design speed," "posted speed," and "operating speed" and how the three relate to one another?

All six members of the committee favored this action by AASHTO.

The results of the survey showed that the AASHTO Task Force on Geometric Design generally either favored completely modifying or eliminating the term "design speed" and replacing it with another term or terms. Also, to reduce confusion, clearer definitions of "design speed," "operating speeds," and "posted speeds" are desired.

The Task Force members also generally agreed that posting of speed limits greater than design speeds was not necessarily unsafe; however, this opinion was not unanimous.

SELECTED TRAFFIC ENGINEERS

Following the survey of the AASHTO Task Force on Geometric Design members, the project team conducted a more detailed survey on some traffic engineers who responded to the initial survey. Seventeen traffic engineers from 13 states were contacted by correspondence and asked to participate in the follow-up interview. Ultimately, 13 traffic engineers from 10 states were contacted and interviewed. The results of these interviews follow.

1. Do you believe it is appropriate to post speed limits higher than the road's design speed based on <u>current</u> design criteria for new roadways?

Yes - 10 No - 3

The percentage of engineers in agreement with the statement was slightly higher than the percentage of AASHTO Task Force members who were in agreement; however, it must be understood that this is primarily an operational question instead of a design question. As operational specialists, it would not be surprising for traffic engineers to support the traditional method for establishing speed limits on roadways.

2. Do you believe that roadway traffic conditions are safe if speed limits are posted based on 85th percentile speeds regardless of the roadway's design speed?

Yes - 12 No - 1

Again, the overwhelming support of the operational safety associated with the traditional method of establishing posted speed limits would be expected from traffic engineers. Of those interviewed, indications suggest that motorists can determine the most appropriate (and therefore safest) operational speed for a roadway.

3. Do you agree that the MUTCD method for determining posted speeds is a reasonable and appropriate method?

Yes - 12 No - 1

The MUTCD method is the traditional spot speed study and determination of the 85th percentile speed. Again, this method has been very successful for so many years that it is difficult for traffic engineers to challenge it.

4. Note the current AASHTO definition for design speed. "Design speed is the maximum safe speed that can be maintained over a specified section of highway when conditions are so favorable that the design features of the highway govern." Do you agree with this definition?

Yes - 3 No - 9 No Answer - 1

Similar to the AASHTO Task Force, the traffic engineers were not pleased with the current definition of design speed. Again, the portion of the definition that included the words "maximum safe speed" was the most objectionable.

What changes would you make to the definition?

Redefine. Remove or change the reference to "maximum safe speed." Call it a design feature. Use another term. Totally revamp the definition.

Do you believe that the term "design speed" should continue to be used or should an alternate term or method replace it?

Continue to Use - 2 Replace It - 8 No Answer - 1

Those who said that the term should continue to be used also preferred to have the term redefined.

5. **Do you foresee potential tort liability concerns if the posted speed limit on a roadway exceeds its design speed?**

Yes - 12 No - 0 No Answer - 1

The traffic engineers obviously recognized the potential liability problems associated with the condition; however, as responses to the following question indicated, the number of cases involving the specific issue was very low among the group.

Have you had any cases relative to this specific issue other than advisory speeds for roadway curves or freeway ramps?

Yes - 2 No - 10 No Answer - 1

6. **The AASHTO *Green Book* states that "some sections of low-design-speed highways are frequently overdriven, with an appreciable number of drivers exceeding the design speed." Do you agree with this?**

Yes - 13 No - 0

The overwhelming affirmative answer illustrates that traffic engineers recognize the behavioral characteristics of many motorists who will generally drive faster than the suggested speeds on advisory speed plates or within construction zones.

Do you believe that this type of condition is inherently unsafe?

Yes - 2 No - 11

The answer clearly reflects the simple fact that most motorists who drive faster than the posted speed limits seldom have difficulty maintaining control of their vehicles. Also, regarding the two affirmative answers, the individuals clearly indicated that the term "unsafe" was relative and that it did not mean that an accident was imminent.

7. **In section 2B-10 of the MUTCD, specific reference is made to factors to be considered relative to design features; however, a reference to design speed is <u>not</u> made. Do you believe that the MUTCD should address the relationship between design speed and posted speed limits?**

Yes - 6 No - 7

The question was unique because it was the only one that had responses evenly split between yes and no responses. Those who answered negatively were much more emphatic than the affirmative responders. Six of the respondents thought it would be a good idea for the MUTCD to address the issue; however, the seven negative responders strongly believed that the MUTCD should not address a design issue and should remain as an operational manual.

8. Do you agree with the statement that the MUTCD permits posted speed limits that are greater than the roadway's design speed?

Yes - 13 No - 0

This response was expected.

9. Do you believe that posted speed limits can exceed the roadway's design speed?

Yes - 13 No - 0

With the response to Question No. 8, a unanimous response was expected.

Do you believe that the posted speed limit should be set lower than the 85th percentile speed simply because the design speed is below the 85th percentile speed?

Yes - 3 No - 10

The responses strongly supported the contention that posted speed limits should correspond to the traditional spot speed study and the 85th percentile speed. Two of the three affirmative respondents were not rigid in their positions. They agreed that some type of warning or information signing should be provided and that posting a lower speed limit was satisfactory.

10. If the posted speed limit exceeds the design speed of the roadway, should some type of informational or warning sign be installed as well?

Yes - 10 No - 2 Posted Speed Should Not Exceed Design Speed - 1

What kind of sign would you suggest?

Limited Sight Distance Warning Sign - 5

Advisory Speed Signs - 1

Curve Warning Signs - 1

Intersection Ahead Warning Sign - 1

No Suggestions - 5

11. Assume that a lawsuit has been filed and the argument is that the posted speed limit exceeded the roadway's design speed and that the plaintiff was allowed to travel at an unsafe speed. What defensive argument would you present to this allegation?

This is not an operational problem. - 5

Show application of the 85th percentile speed. - 2

Define the terms and explain the difference. - 1

Explain typical traffic engineering practices. - 1

Show support of posting speeds in MUTCD. - 1

Not sure. - 3

12. Would you like to have some type of documentation authorized by a recognized organization (ITE or AASHTO for instance) that clearly addresses design speed, posted speed, and operating speed and how the three relate to one another?

Yes - 12 No - 1

The traffic engineers were very emphatic about their responses. They want better definitions and less confusion.

13. Do you agree with the statement that roadways are designed with factors of safety such that drivers can typically exceed the roadway's design speed without creating a hazardous condition?

Yes - 12 No - 0 Usually - 1

The response to this question was expected based upon answers to previous questions.

14. Is there a specific concern that you have related to the design speed versus posted speed limit controversy that has not been addressed?

The roadway class (or type of roadway) should play a more important role in the design process and should be a primary factor when considering design speed selection.

CHAPTER 5

CONCERNS WITH DESIGN SPEED, OPERATING SPEED, AND POSTED SPEED RELATIONSHIPS

INTERPRETATION OF MAIL-OUT SURVEY FINDINGS

Anticipated operating and/or posted speeds are frequently considered when selecting design speed; however, they were not the factors most commonly identified by the respondents. Factors such as urban versus rural and functional classification were selected more often by the state respondents, and cross section was selected more often by the city/county respondents. More than 75 percent of the respondents agreed with the comment that anticipated operating speed should be considered when selecting the design speed of a roadway.

As expected, almost every respondent agreed that the factor considered in setting the posted speed limit on an existing road is the 85th percentile speed. Other factors frequently considered include accident experience, roadside development, and state mandated maximum speed limit. Approximately 36 percent of the respondents consider design speed. When considering a new facility, about half the state respondents said that design speed was used as the initial posted speed. The posted speed is modified using the 85th percentile operating speed determined from field measurements after the facility is in operation.

Almost every respondent to the survey showed that a ball bank indicator is used to set advisory speeds on horizontal curves. Several respondents indicated that they would adjust their procedure to reflect approach conditions to a curve such as with a horizontal curve that follows a long tangent. For example, one state uses larger signs possibly with flashing beacons when a horizontal curve follows a long tangent section. While many respondents expressed concern with the ball bank indicator, no suggestions or recommendations for an improved advisory speed selection process were provided.

Several agencies acknowledged that they have or had sites with an operating speed greater than the design speed of the facility. The most frequent action taken was to install advance warning signs. One concern noted is that the design speed of several highways is unknown. Few respondents stated that they reduce the posted speed limit to match the design speed when the 85th percentile speed is greater than the design speed.

Few of the respondents had experience with lawsuits that involved a posted speed limit that exceeded the design speed of a roadway. Three of the six lawsuits discussed in the survey involved advisory speed issues rather than design speed issues. The arguments for one lawsuit focused on consistency of policy for the entire jurisdiction. Although few lawsuits involving the posted speed/design speed issue have occurred (according to this survey), liability concerns still exist. Several respondents provided comments that showed their concern with current definitions and procedures. For example, one city engineer indicated that they are reevaluating how design speed is determined and how to defend/explain it to citizens and in court, if necessary.

The high response rates for the survey and the types of comments made in the survey clearly show significant interest in the topic. The findings from the survey indicated the following:

- Documentation is needed that explains why posting a speed limit that is above a design speed is reasonable. The document could include information on the meaning of design speed, posted speed, and operating speed and their interrelationships. It would also require discussions on the assumptions, especially relating to safety of the design speed process.

- Development of a new procedure for selecting advisory speeds at horizontal curves is desired.

- As in most surveys on posted speed-related issues, several respondents expressed their desire for a decrease in political and public intervention when selecting an appropriate posted speed limit for a given roadway. Also, several respondents stated the rationale behind the 85th percentile speed process is not well understood by the public and police departments.

INTERPRETATION OF INTERVIEW FINDINGS

The interviews showed that modifying or replacing the "design speed" term is appropriate. Several individuals stated that the current definition is incorrect or required major revision. The term "maximum safe speed" was the most objectionable portion of the current definition.

Most of those interviewed agreed that posting speed limits greater than the roadway's design speed is appropriate and that roadway traffic conditions are safe if speed limits posted are based on 85th percentile speeds despite the roadway's design speed. Recognition was made of the potential liability problems associated with the condition; however, the number of cases involving the specific issue was very low among those interviewed.

The types of informational or warning signs suggested for installation at a location where the posted speed limit exceeds the design speed included: Limited Sight Distance warning signs, Advisory Speed signs, Curve or Turn warning signs, and Intersection Ahead warning signs.

LEGAL LIABILITY CONCERNS

Survey results clearly showed that all respondents were concerned with the potential liability associated with posting speed limits greater than the roadway's actual or inferred design speed; however, only a few actually experienced a lawsuit relating to the design speed--posted speed issue. Those who were experienced with litigation said that they were comfortable discussing reasons for the difference between the two speeds, and none believed that the issue was relevant to the juries.

Many reasons support the conclusion that liability potential will apparently always exist and the number of lawsuits relating to the design speed versus posted speed conflict will remain low.

First, relatively few locations exist where the actual or inferred design speed of the roadway is lower than the posted speed. These locations are often found at sharp horizontal curves and vertical alignments with limited sight distances; however, because of the factors of safety used in roadway design, few locations exist where sight distances are extremely short for the resultant operating speeds. Where such locations are present, engineers typically place warning signs (curve warning sign, for instance) with advisory speed plates. If advisory speeds are posted based on ball bank tests, then the advisory speeds will be lower than the roadway's inferred design speed.

Second, if the sight distance is restricted due to a vertical curve, often some type of warning sign (Intersection Ahead, for instance) is posted before the vertical curve to warn of the sight distance deficiency. Such a warning is often sufficient to reduce potential conflicts that may arise due to sight restriction.

Third, if the lawsuit claims that the posted speed limit was too high, often the public entity can successfully argue that the speed limit was posted based on the results of a spot speed study that provided the 85th percentile speed used to identify the posted speed limit. The 85th percentile speed has been used for many years and has been accepted as the appropriate method for selecting the posted speed.

Finally, most sections of high-speed roadways that have less than desirable sight distances are usually associated with older roadways that carry lower traffic volumes. Most high-volume roadways are relatively new or have been improved to accommodate the traffic demand. In the future, those older roadways having less than desirable sight distance AND high traffic volumes will be improved to adapt to these future demands. Consequently, the higher priority roadway sections having less than desirable sight distances will be modified to alleviate or remove the sight restrictions.

The liability associated with the actual design speed versus posted speed limit may seem insignificant, but the liability issue itself should not be ignored. Simply posting a speed that is appropriate for the available sight distance should not be considered as a solution or good engineering practice. Drivers travel at speeds at which they are comfortable, despite the posted speed limits. Therefore, posting a lower speed limit on a roadway does not guarantee lower speeds.

The survey respondents also said that the primary liability concern associated with the posted speed versus design speed issue rests with the current AASHTO definition of design speed. This definition is "the maximum safe speed that can be maintained over a specified section of highway when conditions are so favorable that the design features of the highway govern." Although it is obvious that exceeding the "maximum" safe speed can be accomplished without difficulty on vertical and horizontal curves under good weather conditions, convincing a jury of non-engineers that exceeding a roadway's design speed can be done safely is difficult. If the roadway is posted at a speed greater than the design speed, the logical conclusion is that the public entity is encouraging unsafe behavior.

The AASHTO definition for design speed does not accurately reflect current conditions and should be changed. If the definition is changed to reflect its actual meaning, the liability concern will be reduced substantially.

CHAPTER 6

FIELD STUDIES

Recently, several research projects have examined the relationship between operating speed and design speed.[7,10,11] These projects have concentrated on rural, two-lane roadways and low-speed residential streets. An additional goal of this project is to add to the profession's knowledge of the design speed/operating speed relationship by collecting speed data on suburban roadways.

OVERVIEW OF FIELD STUDIES

This chapter describes the field study design and data analysis procedures used in this research. Suburban arterial functional class roadways were identified and reviewed to determine their appropriateness for inclusion in the study. The experimental design included a procedure for collecting speed data on both control and curve sections (i.e., both horizontal and vertical) to examine driver behavior associated with these curves. The following sections describe the site selection controls and criteria, and the data collection procedures used in this research.

Site Selection Controls and Criteria

Many factors influence drivers' speed behavior at curve sections. Since data collection sites were limited in this study, site selection controls and criteria were established. The goal was to isolate the effect of a few variables, shown by previous research as having the most significant influence on speed behavior on other roadway types, and control the effect of other variables.

The analysis of speed behavior on vertical curves focused on two variables: inferred design speed and approach density. Table 6-1 lists the proposed inferred design speed and approach density groups. One objective of this study was to locate two vertical curves for each combination of inferred design speed group and approach density group.

The two variables selected for horizontal curves—curve radius and approach density—were selected for reasons similar to those for vertical curves. Again, to test across a range of curve radii and approach densities, a test matrix was established. One horizontal curve site was selected for each combination of curve radius group and approach density groups. Table 6-2 lists the proposed groups.

The effects of other variables were controlled by specifying site selection criteria that limited the range of values of those variables. Table 6-3 summarizes those criteria.

Table 6-1. Proposed Inferred Design Speed and Approach Density Groups.

Inferred Design Speed Groups (km/h)	Approach Density Groups (Approaches / km)
<55 >55	2 ± 2 7 ± 2 12 ±2 *
* may include sites with > 14 approaches/km	

Table 6-2. Proposed Curve Radius and Approach Density Groups.

Curve Radius Groups (m)	Approach Density Groups (Approaches / km)
>700 650 - 375 350 - 270 250 - 200 <200	2 ± 2 7 ± 2 12 ±2 *
* may include sites with > 14 approaches/km	

Table 6-3. Site Selection Variables and Criteria.

Variables	Criteria
Area Type	Suburban
Functional Classification	Arterial
Design Classification	Four-Lane
Median Type	Raised-Divided
Median Width	2-61 m
Curb and Gutter	Present
Posted Speed Limit	≤ 88.6 km/h
Terrain*	Level
Maximum Grade*	± 5 percent
Pavement	High Type
Lane Widths	3.1-3.7 m
Shoulder Widths	0-3 m
Tangent Length	≥ 200 m
Distance from Intersection	≥ 200 m
* Used only in the selection of horizontal curves	

Data Collection

Site Plan Information Databases

The process of determining potential study sites involved finding suburban arterials with curve sections of varying curve radius/inferred design speed and approach density. To identify potential study sites, curve geometry data were extracted from plan and profile sheets obtained from various cities and TxDOT districts and used to compile a curve geometry database. Included in the horizontal curve database were data for the following variables: curve radius, length of curve, approach tangent length, departure tangent length, superelevation (taken from the plan and profile sheets), and side-friction factor. The vertical curve database included information on approach and departure grades, curve length, and inferred design speed. Control section and milepost location or station of geometric features were also included in the databases.

Approach density was also included in the databases. This information could not be obtained from roadway construction plans and, therefore, was measured in the field. Approach density was measured for each study site by manually counting the number of approaches within 0.5 km before and after the midpoint of the curve. Approaches were defined as residential and commercial driveways or any intersection approach. The threshold values for approach density listed in Tables 6-1 and 6-2 were selected based on preliminary site investigations. The values reflect a practical range of roadside development (i.e., low, medium, and high).

Two hypotheses were developed relating to the effect of approach density on driver speed behavior. Each of these hypotheses was tested during the analyses of this study.

1. On any given roadway section, a driver's desired speed decreases as approach density increases. This decrease translates into lower operating speeds on tangents and horizontal curves, which will lower the speed reduction at horizontal curves.

2. On roadways with limited sight distance crest vertical curves, the potential of a hidden intersection is greater on high approach density roads than on low approach density roads. The potential of a hidden intersection may cause a decrease in speed between a section of roadway with minimal visual limitations and a section of roadway with sight restrictions. In summary, limited sight distance crest vertical curves with a high approach density are hypothesized as having greater speed reductions between a

control and a crest section than similar crest vertical curves with a low approach density.

Speed Data

Spot speed data were collected at a sample of horizontal and vertical curves and their approaches on suburban arterials in various cities in Texas (Fort Worth, Garland, Houston, Mesquite, and Plano). Speeds were collected for vehicles at both a control and a curve section. The speeds on the control section were collected at a location where the vehicles were expected to be operating at their desired speeds. The speeds for the horizontal curve were measured just before the midpoint of the curve, while speeds for vertical curves were measured near the crest of the curve where the minimum sight distance occurs (i.e., vehicle speeds were measured at the location where the speeds are assumed to be lowest). The minimum speed along the curve sections was required to determine the maximum speed reduction from control to curve section for each vehicle observed. Distances between control and curve sections varied from 150 to approximately 300 meters (approximately 500 to 1000 feet).

Vehicles had to fit certain criteria for their inclusion in this study. Only free-flow passenger cars, pick-up trucks, and vans were considered in this study. Neither heavy trucks nor recreational vehicles were included in the analysis. A vehicle was considered free-flow if it was the lead vehicle in a platoon or headways were greater than or equal to five seconds. With headways greater than or equal to five seconds, a vehicle's speed is probably not influenced by other traffic within or entering the study site. In addition, the sample of vehicles included also met the following criteria:

- Must be traveling in the outside lane only,
- Must not have entered or exited the roadway at or near the study site, and
- Must not be towing a trailer or another vehicle.

A description of each vehicle (i.e., color and classification) was recorded along with its speed. This description enabled the tracking of the vehicle through both the control and curve sections to monitor changes in an individual vehicle's speed.

Speeds were measured using both laser and radar guns. Laser guns can pinpoint accuracy (i.e., they use a narrow beam to isolate individual vehicles during platoon-like conditions, in which radar is not as effective) and can detect individual vehicle speed responses within 0.3 seconds. Consequently, laser guns are undetectable by laser and radar detection devices. Most speeds collected with radar guns were measured with guns that had been detuned to be undetectable by radar detection devices. Some speeds, however, were collected with non-detuned radar guns. At these locations, considerable care was taken to ensure that drivers did not detect the presence of radar. For those vehicles that slowed dramatically or for any driver that reacted to the data collection process (i.e., head movement or some unusual behavior), the speed data were discarded. It was anticipated that vehicle speeds would be influenced if data collectors were detected by drivers; therefore, data collectors concealed themselves as much as possible when taking speed readings to avoid influencing the measured speeds.

Speed data were only collected during daylight hours and when the weather was clear and the pavement was dry. Speed data were collected until at least 150 vehicles were matched at both the tangent and curve midpoint. Vehicles were matched from tangent to curve in the field using walkie-talkies. The quantity of 150 vehicles provides a reliable database on which to perform a statistical analysis.

HORIZONTAL CURVE FIELD STUDIES

Results of the analyses performed for the horizontal curve field studies are presented in four parts:

- Summary of the study site characteristics,
- Observed speeds on tangents,

- Observed speeds on horizontal curves, and
- Calculated speed reduction from tangent to horizontal curve.

Study Site Characteristics

Operating speed and roadway geometry data were collected at 15 horizontal curves and their approach tangents on eight roadways in Texas. Each site satisfied the site selection controls and criteria listed in Table 6-3. Table 6-4 lists the characteristics of the sites. The inferred design speed and superelevation rate for each site were estimated based on curve geometry and existing roadway plans. The posted speed limit for each site is also included. An evaluation of the data was made using SAS[15]. Table 6-5 lists the descriptive speed statistics for the tangent and curve sections.

Upon initial review of the speed data collected for Site HC-7, it was determined that Site HC-7 should not be used in further analysis. Reasons for excluding Site HC-7 were as follows: (1) the roadway was fronted by residential housing, (2) the approach density of 16 was significantly different from the target value of 12, and (3) desired speed on tangent may not have been achieved. The general nature of the site was very different from the other 14 sites, and in retrospect, the site should not have been considered for data collection.

85th Percentile Speeds on Tangents

Individual speeds observed on the tangents ranged from 48 to 124 km/h (30 to 77 mph). The 85th percentile speeds on the tangents ranged from 71 to 101 km/h (44 to 63 mph). The mean of the 85th percentile speeds on tangents was 81 km/h (50 mph). Figure 6-1 is a scatter plot of 85th percentile speed versus approach density for the 14 tangents in the data base. The scatter plot illustrates that 85th percentile speeds decrease as the approach density increases.

Table 6-4. Characteristics of Horizontal Curve Sites.

Number	Radius (m)	Superelevation e (%)	Inferred Design Speed (km/h)	Approach Density (approaches/km)	Speed Limit (km/h)
HC-1	156	2	60	7	72
HC-2	183	2	65	12	64
HC-3	229	2	70	3	72
HC-4	305	2	80	3	72
HC-5	314	-2	73	7	64
HC-6	335	2	85	11	72
HC-7	701	2	110	16	48
HC-8	580	4	105	1	81
HC-9	573	-2	90	6	72
HC-10	991	4	125	1	81
HC-11	990	-2	107	5	72
HC-12	437	2	85	12	64
HC-13	220	-2	65	7	64
HC-14	220	2	65	11	64
HC-15	175	2	65	4	64

Table 6-5. Measured Speeds at Horizontal Curve Sites.

Site Number	Number of Vehicle Speeds Measured	85th Percentile Speed (km/h)		Average Speed Difference (km/h)
		Tangent	Curve	
HC-1	268	82	69	8.1
HC-2	250	74	69	6.4
HC-3	242	79	72	4.8
HC-4	190	79	69	9.6
HC-5	217	74	69	4.8
HC-6	233	82	76	6.4
HC-7	154	68	68	0.0
HC-8	174	101	90	7.3
HC-9	196	82	79	1.6
HC-10	158	95	89	3.2
HC-11	300	85	81	3.2
HC-12	164	82	81	0.0
HC-13	149	71	68	3.2
HC-14	146	76	69	8.0
HC-15	150	77	64	11.3

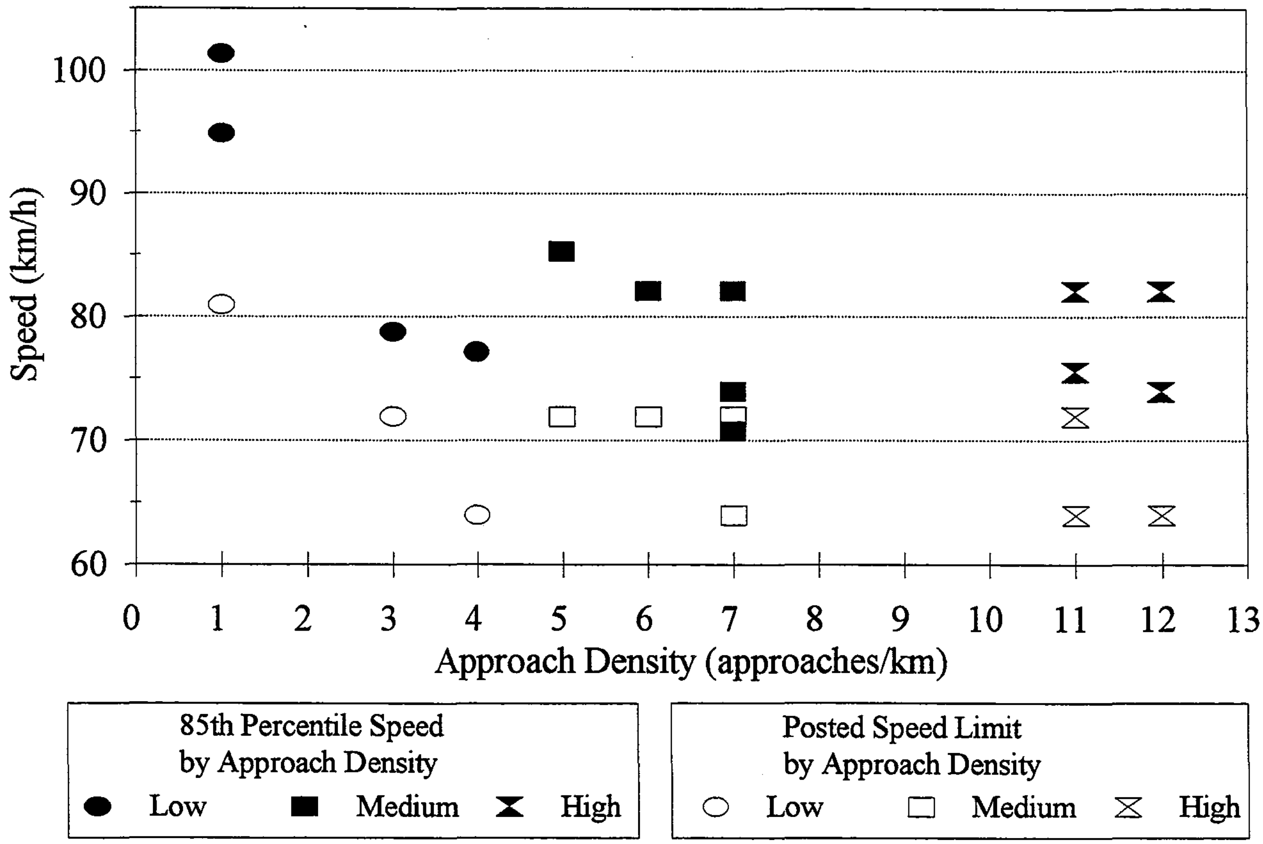

Figure 6-1. Scatter Plot of Speed on Tangent Sections Versus Approach Density.

Regression analysis was used to predict 85th percentile speed on a tangent using approach density. Table 6-6 lists the equation forms tested along with the results from the SAS analysis. Figure 6-2 superimposes the three regression equations on the scatter plots of the data.

The equations were compared with respect to their goodness-of-fit and simplicity. Overall, the curvilinear equation forms performed better than the linear form. No real improvement was noticed between the two curvilinear equation forms. Although the higher-order curvilinear equation form produced a slightly higher R^2-value, the improvement was minimal and the lower-order curvilinear is the preferred form due to its conformity to the scatter plot and its simplicity.

Table 6-6. Regression Analysis Results for 85th Percentile Speed on Tangents Versus Approach Density.

Regression Parameter Estimate	Equation Form		
	Linear	Curvilinear	
	$V85_{tan} = \beta_0 + \beta_1(AD)$	$V85_{tan} = \beta_0 + \beta_1/AD$	$V85_{tan} = \beta_0 + \beta_1/AD^2$
β_0	88.94	74.91	77.01
β_1	-1.18	22.29	20.82
F-Statistic	5.29	29.44	33.03
P-Value	0.0401	0.0002	0.0001
R^2-Value	0.31	0.71	0.73
AD = Approach Density (approaches/km)			

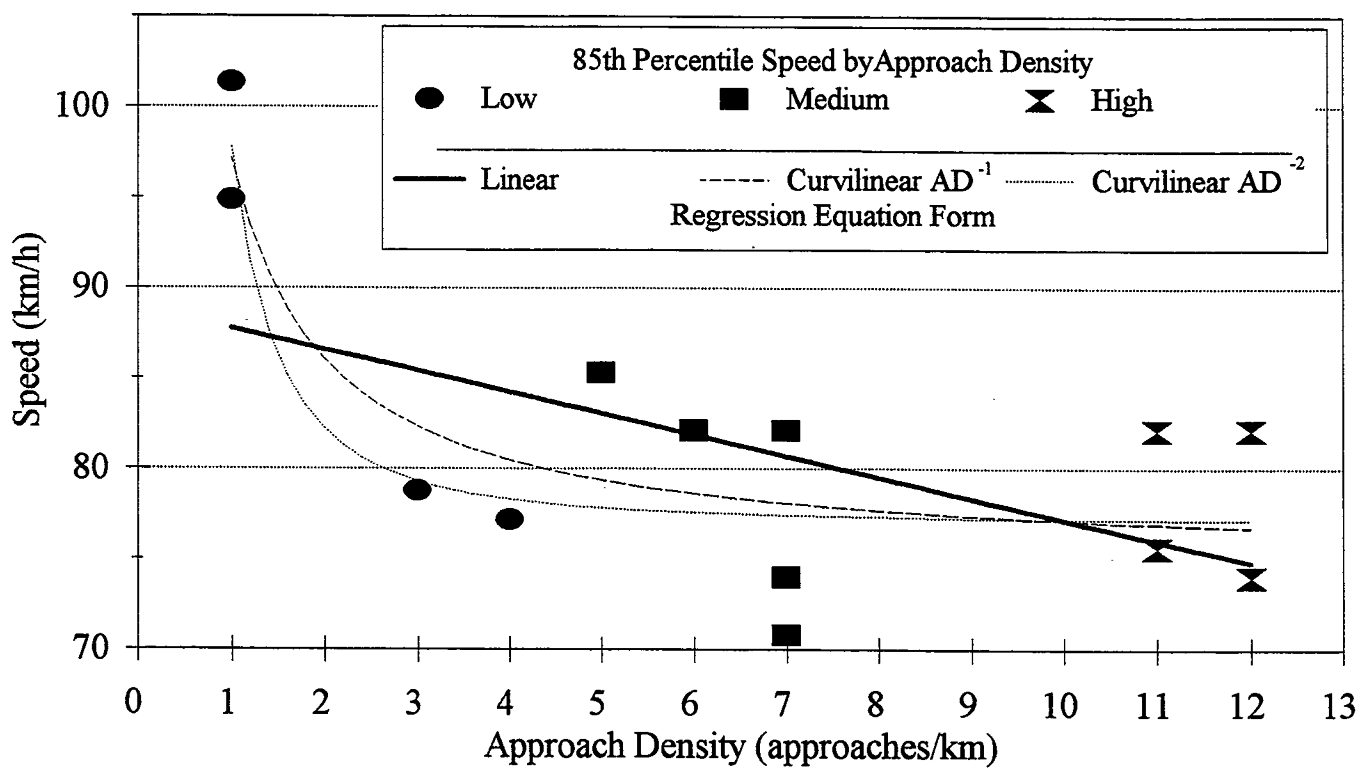

Figure 6-2. Regression Equations for 85th Percentile Speed and Approach Density.

The preferred regression equation for 85th percentile speed on tangents using approach density only is as follows:

$$V85_{\tan} = 74.91 + \frac{22.29}{AD} \quad (1)$$

where: $V85_{tan}$ = 85th percentile speed on the tangent (km/h) and
AD = approach density (approaches/km).

An objective of this study was to determine the general effect of approach density on 85th percentile speed on tangents. The scatter plot of data and the regression analysis results show that tangent speeds decrease as approach density increases for the study sites selected.

Several other observations can be made. In general, the 85th percentile speeds on tangents are similar for both medium and high approach density levels. The slope of the regression plot is approximately level for approach densities greater than four approaches per kilometer. The sensitivity of the model changes for approach densities less than three approaches per kilometer. Speeds on tangents increase dramatically when approach densities fall below three approaches per kilometer. The difference in 85th percentile speeds on tangents between approach densities of one and three is approximately 20 km/h (12 mph).

These measurements may reflect a driver's desired speed on tangents for roadways with extremely low approach density. Approach density was used to *imply* roadside development. For the five low approach density sites, the roadside development characteristics were quite different. Although cross-sections for all sites were similar, the development for sites with approach densities of one reflected a more rural environment and exhibited higher speed. Results of regression analyses indicate approach density does influence tangent speed. Additional data would be required, however, to verify the large difference in sensitivity of tangent speed to approach density between low and high density sites.

85th Percentile Speeds on Horizontal Curves

Relationship Between 85th Percentile Speed and Inferred Design Speed on Horizontal Curves

Previous research[7] suggests that disparities exist between 85th percentile speeds and the inferred design speeds of horizontal curves on low design speed rural highways. The speed data collected during this research study were also examined to see if similar disparities exist on suburban arterials.

Figure 6-3 summarizes the comparisons made between 85th percentile speeds and inferred design speeds for the 14 horizontal curves studied. Figure 6-4 shows the magnitude of the differences between the 85th percentile speeds and design speeds. The 85th percentile speeds were less than the inferred design speeds for all curves with design speeds greater than or equal to 73 km/h (45 mph) and greater than the inferred design speeds for the majority of curves with design speeds less than or equal to 70 km/h (43.5 mph).

A comparison was made between the side-friction factors implied by the 85th percentile speed on curves and AASHTO's recommended maximum side-friction factors, which are a function of design speed, to assess the reasonableness of current horizontal curve design standards relative to actual driver speed behavior. The comparison is shown in Figure 6-5. The results of the comparison show that side-friction factors based on the observed 85th percentile speeds are less than the AASHTO maximum side-friction factors for most of the sites examined. The side-friction factors were less than the AASHTO maximum side-friction factors at curves with design speeds greater than or equal to 73 km/h (45 mph). Side friction factors were either above or very similar to AASHTO maximum side-friction factors for most curves with design speeds less than or equal to 70 km/h (44 mph).

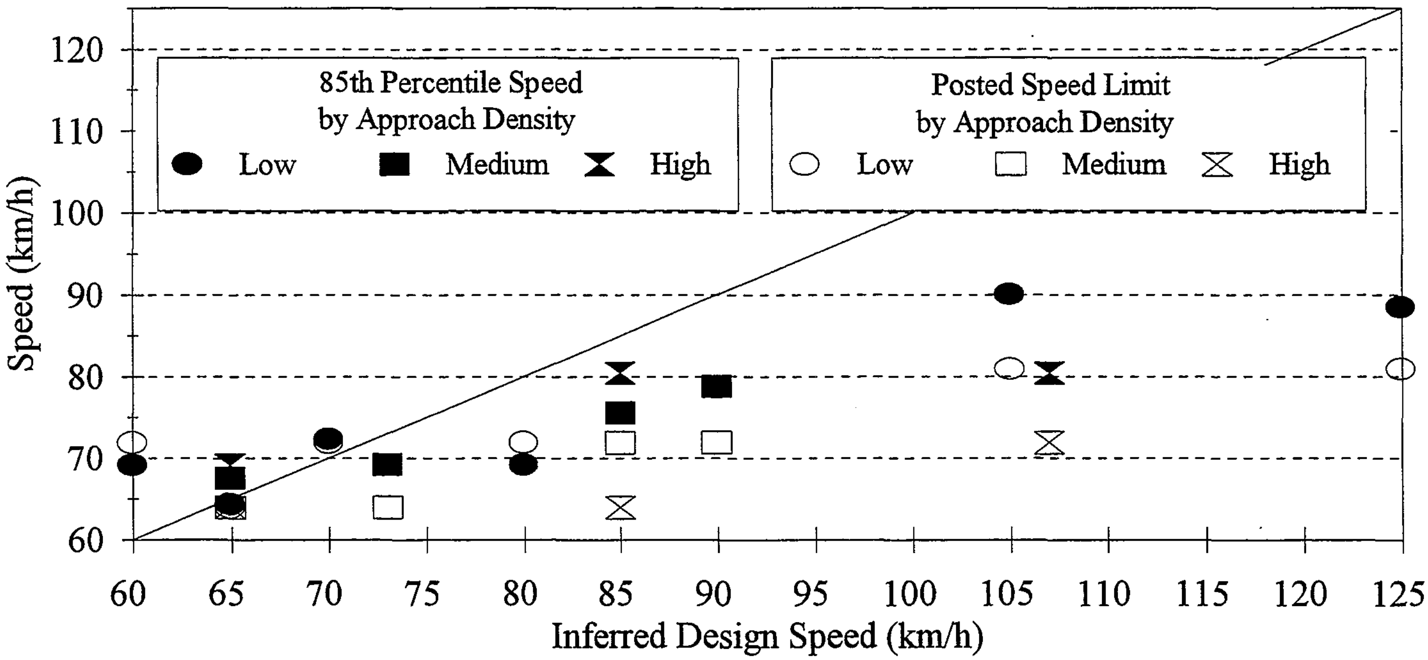

Figure 6-3. Speed on Horizontal Curves Versus Inferred Design Speed.

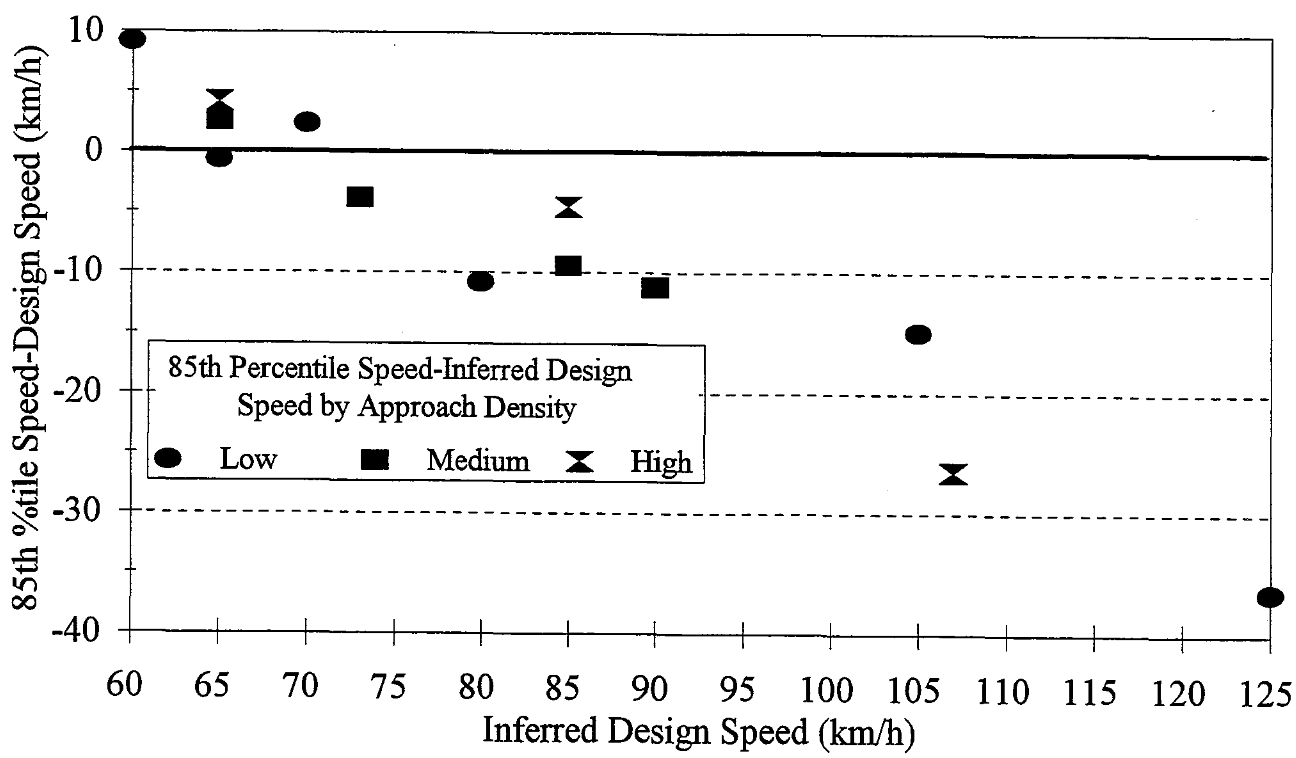

Figure 6-4. Difference between 85th Percentile Speed and Inferred Design Speed.

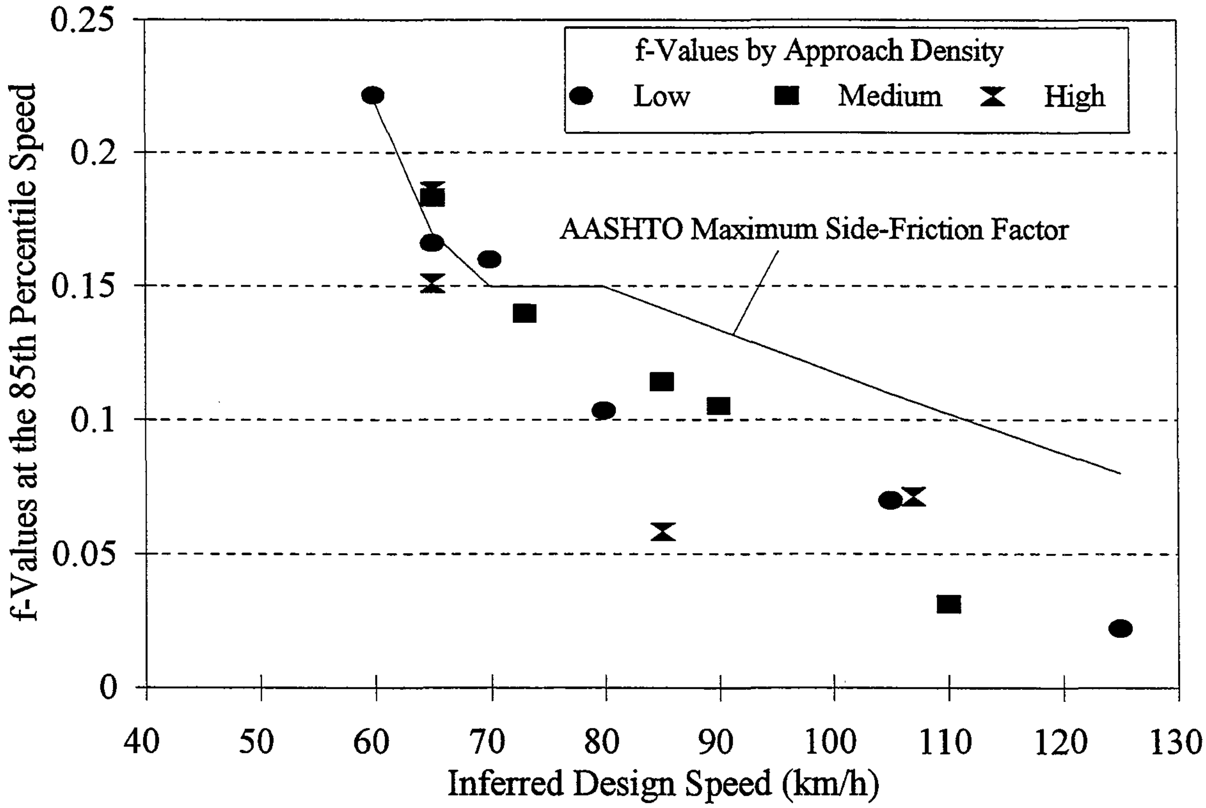

Figure 6-5. Side-Friction Factor at the 85th Percentile Speed Versus Inferred Design Speed.

Both comparisons indicate a common breakpoint of 73 km/h (45 mph), at which drivers begin to exceed maximum recommended design values. The similarities in these two breakpoints are not surprising considering AASHTO's maximum side-friction factors are a function of design speed, and the inferred design speeds are calculated based on those maximum side-friction factors.

The results presented for suburban arterials are not consistent with previous research on rural highways. Chowdhury et al.[6] and Krammes et al.[7] found that horizontal curves with inferred design speeds less than 90 km/h (56 mph) had 85th percentile speeds that were consistently faster than the design speed, whereas curves with inferred design speeds greater than 90 km/h (56 mph) had 85th percentile speeds that were consistently slower than the design speed. On suburban arterials, the 85th percentile driver usually operates at speeds less than the design speed and corresponding side-friction factor on curves with inferred design speeds greater than or equal to 73 km/h (45 mph). Only when design speed are below 70 km/h (44 mph) do motorists begin to exceed the design speed and corresponding maximum side-friction factors of horizontal curves. The difference in these results can be attributed to differences in drivers' desired speeds, which are lower on suburban arterials than on rural highways.

Relationship Between Curve Radius and 85th Percentile Speed on Horizontal Curves

The 85th percentile speeds on the horizontal curves studied ranged from 64 to 90 km/h (40 to 60 mph). The mean of the 85th percentile speeds on curves was 75 km/h (46 mph). Figure 6-6 is a scatter plot of 85th percentile speed versus curve radius for the 14 curves examined. The plot also shows the approach density group for each point. The scatter plot shows that 85th percentile speeds increase as curve radius increases.

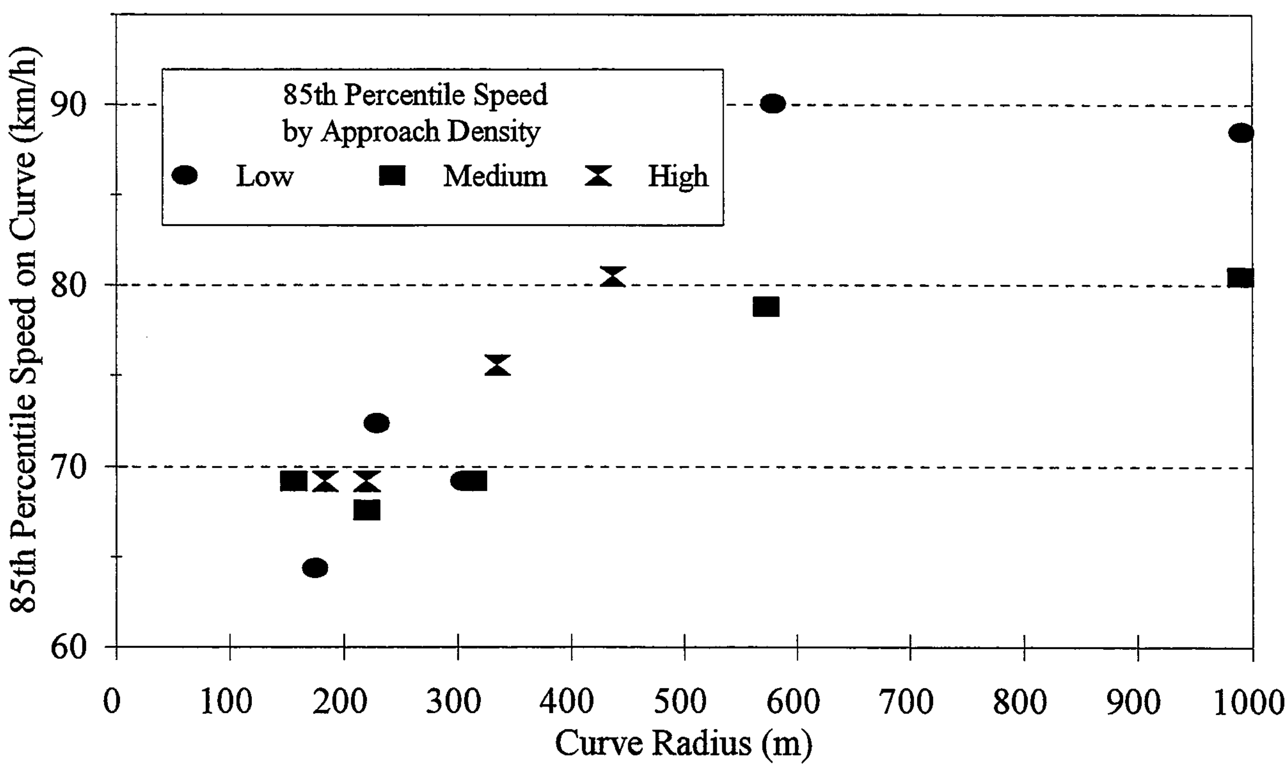

Figure 6-6. Scatter Plot of Speed Versus Curve Radius and Approach Density.

The regression results for 85th percentile speeds on horizontal curves using only curve radius are summarized in Table 6-7. The table also lists the equations tested (the equations are labeled by using curve radius in the equation, e.g., the "R equation" is $V85_{curve} = \beta_0 + \beta_1 R$). The equations were compared with respect to their goodness-of-fit and simplicity. The R^2-value was 0.66 for the linear equation and ranged from 0.57 to 0.73 for the four curvilinear equations. The confidence level (i.e., 1 - P-values) was 0.998 or better for all five equations. The curvilinear equations performed marginally better than the linear form, while the $R^{0.5}$ equation performed almost as well as the best-fit curvilinear equation. As curve radius increases (i.e., degree of curvature approaches zero), the curvilinear equations produce 85th percentile operating speeds closer to the observed mean of the 85th percentile speed on tangents (81 km/h [50 mph]). Another important observation is that the $R^{0.5}$ equation is consistent with the horizontal curve equation. Therefore, the curvilinear equation as a function of $R^{0.5}$, which was comparable or superior with respect to the other criteria, was deemed the preferred form due to its conformity

Table 6-7. Regression Analysis Results for 85th Percentile Speeds on Curves Versus Curve Radius.

Regression Parameter Estimate	Equation Form*				
	Linear	Curvilinear			
	R	$R^{0.5}$	$R^{-0.5}$	R^{-1}	R^{-2}
β_0	65.22	54.18	98.90	87.56	87.55
β_1	0.023	1.061	-428.65	-3757.8	-469899
F-Statistic	23.4	30.1	33.1	27.4	16.2
P-Value	0.0004	0.0001	0.0001	0.0002	0.0017
R^2-Value	0.66	0.72	0.73	0.70	0.57
Root MSE	4.82	4.43	4.28	4.58	5.41

* R : $V85_{curve} = \beta_0 + \beta_1 R$
$R^{0.5}$: $V85_{curve} = \beta_0 + \beta_1 (R)^{0.5}$
$R^{-0.5}$: $V85_{curve} = \beta_0 + \beta_1 / R^{0.5}$
R^{-1} : $V85_{curve} = \beta_0 + \beta_1 / R$
R^{-2} : $V85_{curve} = \beta_0 + \beta_1 / R^2$
where: R = Curve Radius (meters)

with the data and consistency with the horizontal curve equation. Figure 6-7 shows the plot of the regression equation on the scatter plot of the data. In summary, the preferred regression equation for 85th percentile speed on curves using curve radius only is as follows:

$$V85_{curve} = 54.18 + 1.061\ R^{0.5} \qquad \textbf{(2)}$$

where: $V85_{curve}$ = 85th percentile speed on the curve (km/h) and

R = curve radius (m).

In theory, as curve radius increases (i.e., degree of curvature approaches zero) the model's estimate of 85th percentile speed on curves should equal the mean 85th percentile speed on long tangents, assuming that speeds on all tangents are similar. One concern with Equation 2 is that it over estimates the mean 85th percentile speed on long tangents (81 km/h [50 mph]) as curve radius continues to increase. For example, if the radius of a curve is 1500 m (4920 ft), the estimate for 85th percentile speed would be 95 km/h (59 mph). Results from this research suggest that on this class of roadway (i.e., suburban arterials) 85th percentile speeds on long tangents are not constant and tangent speeds actually increase as approach density increases. The estimate of 95 km/h (59 mph) is comparable to observed 85th percentile speeds on the two tangents with long curve radii and low approach densities (95 and 101 km/h [59 and 63 mph]).

These regression results are consistent with previous research on horizontal curves that suggests that 85th percentile speeds on curves decrease approximately linearly as degree of curvature increases. A linear relationship with respect to degree of curvature corresponds to an inverse or curvilinear relationship with respect to curve radius.

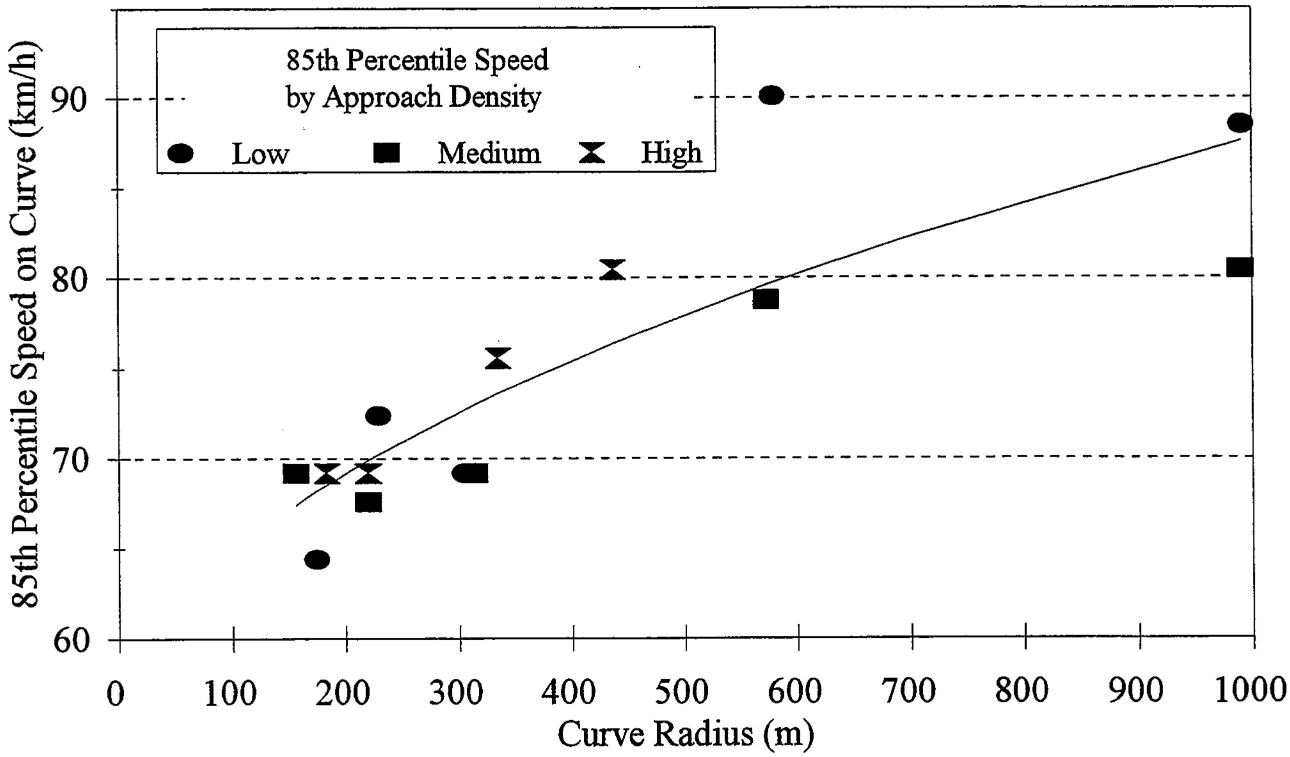

Figure 6-7. Regression Equation for 85th Percentile Speed on Curves Versus Curve Radius.

Evaluation of Other Independent Variables

Other independent variables such as approach density and superelevation were tested for their statistical significance and contribution to the explanatory power of the preferred curvilinear regression equation (Equation 2) for 85th percentile speed on horizontal curves using curve radius only. The only independent variable significant at a 5 percent significance level was approach density. The linear form of the regression equation using the variable approach density (AD) was not significant at a 5 percent significance level, whereas equations using curvilinear forms of approach density, such as AD^{-1} and AD^{-2}, were significant. It was also noticed that the same approach density variable form (AD^{-1}) was significant in estimating 85th percentile speeds on tangents, which shows that the effect of approach density is similar for both tangents and curves. Although the format of the equation with respect to AD^{-2} produced a higher R^2-value and better confidence levels, the improvement was minimal and the equation form using AD^{-1} was preferred based on tangent speed results. The recommended multiple-variable model is the following curvilinear regression equation, which had an R^2-value of 0.81 and a root mean square error 3.8 km/h (2.4 mph):

$$V85_{curve} = 56.34 + 0.808\ R^{0.5} + 9.34/AD \qquad \textbf{(3)}$$

where: $V85_{curve}$ = 85th percentile speed on the curve (km/h),
R = curve radius (m), and
AD = approach density (approaches/km).

The results of the regression analyses using curve radius and approach density are presented in Table 6-8. Figure 6-8 presents a three-dimensional representation of the equation. Caution must be exercised in interpreting these results because the number of observations within each approach density level is small. For curves with approach densities greater than three approaches per km, the effect of approach density is negligible and 85th percentile speed increases approximately linearly (or curvilinear) as curve radius increases. For curves with approach densities less than or equal to three approaches per km, the effect of approach density is more evident as shown by the increase in 85th percentile speeds as approach density decreases. It was hypothesized that 85th percentile speeds on curves increase as approach density decreases. The regression analyses support this hypothesis; however, additional data is required within each approach density level (especially the low approach density level) to verify these results.

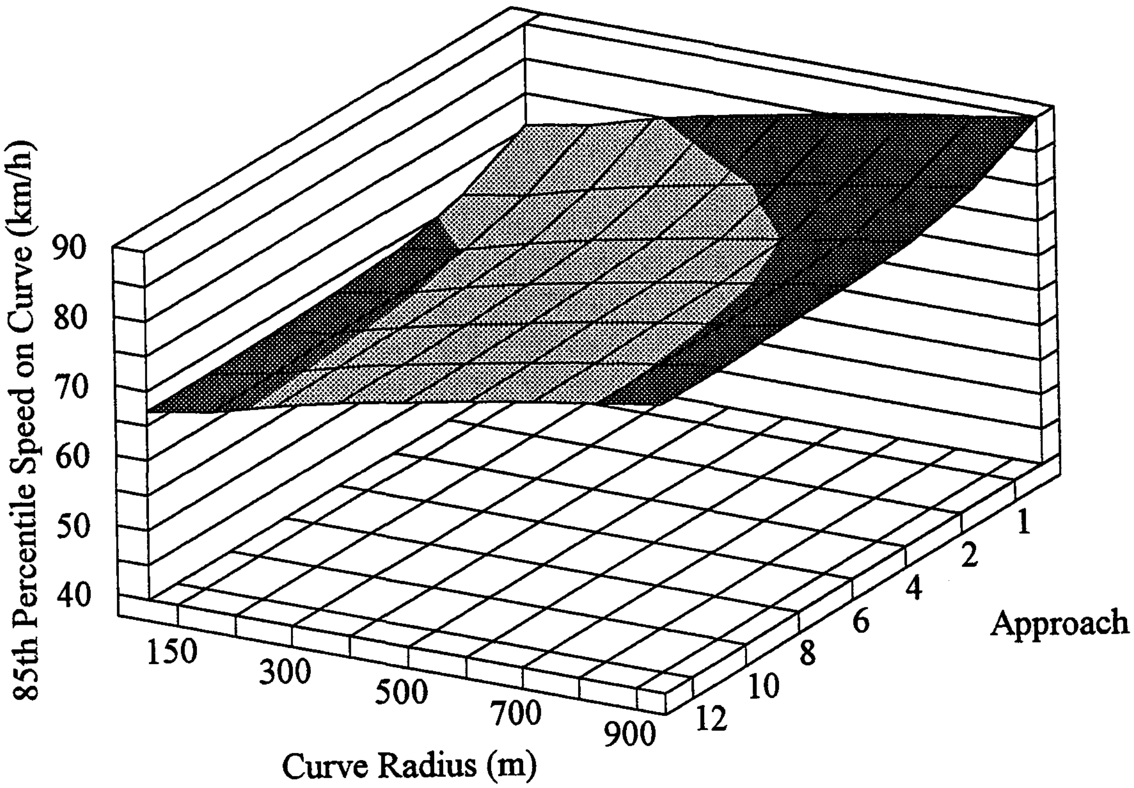

Figure 6-8. Regression Equation for 85th Percentile Speed on Curves Versus Curve Radius and Approach Density.

Table 6-8. Regression Analysis Results Multiple-Variable Non-Linear Equation for Speed on Curves.

	Regression Parameter Estimate		
	β_0	β_1	β_2
Parameter Estimate	56.34	0.808	9.34
Standard Error	3.48	0.20	4.04
P-Value for t-test	0.0001	0.0019	0.0415

$$V85_{curve} = \beta_0 + \beta_1 R^{0.5} + \beta_2 AD^{-1}$$

Where:

R = Curve Radius (m)

AD = Approach Density (approaches/km)

Mean Speed Reductions at Horizontal Curves

An objective of this study was to examine the effect of curve radius and approach density on mean speed reductions from tangent to horizontal curve. Data for this project indicate that curve radius influences speed on horizontal curves. No evidence to date has been produced showing the influence of approach density on speed reductions from tangent to curve. Table 6-9 lists mean speed reduction for the curve radius approach density groups. Figure 6-9 is a plot of mean speed reduction versus curve radius and approach density. The effect of curve radius and approach density is not evident from the scatter plot. Additional analyses were done to test for significant relationships.

Table 6-9. Mean Speed Reduction by Curve Radius and Approach Density Groups.

Curve Radius Groups (m)	Average Mean Speed Reduction (km/h)		
	Approach Density Groups*		
	Low	Medium	High
> 700	3.2	3.2	--
650 - 375	7.3	1.6	0
350 - 275	9.6	4.8	6.4
250 - 200	4.8	3.2	8.0
< 200	11.3	8.1	6.4

* Low: 1 to 4 approaches/km
Medium: 5 to 7 approaches/km
High: 11 to 12 approaches/km

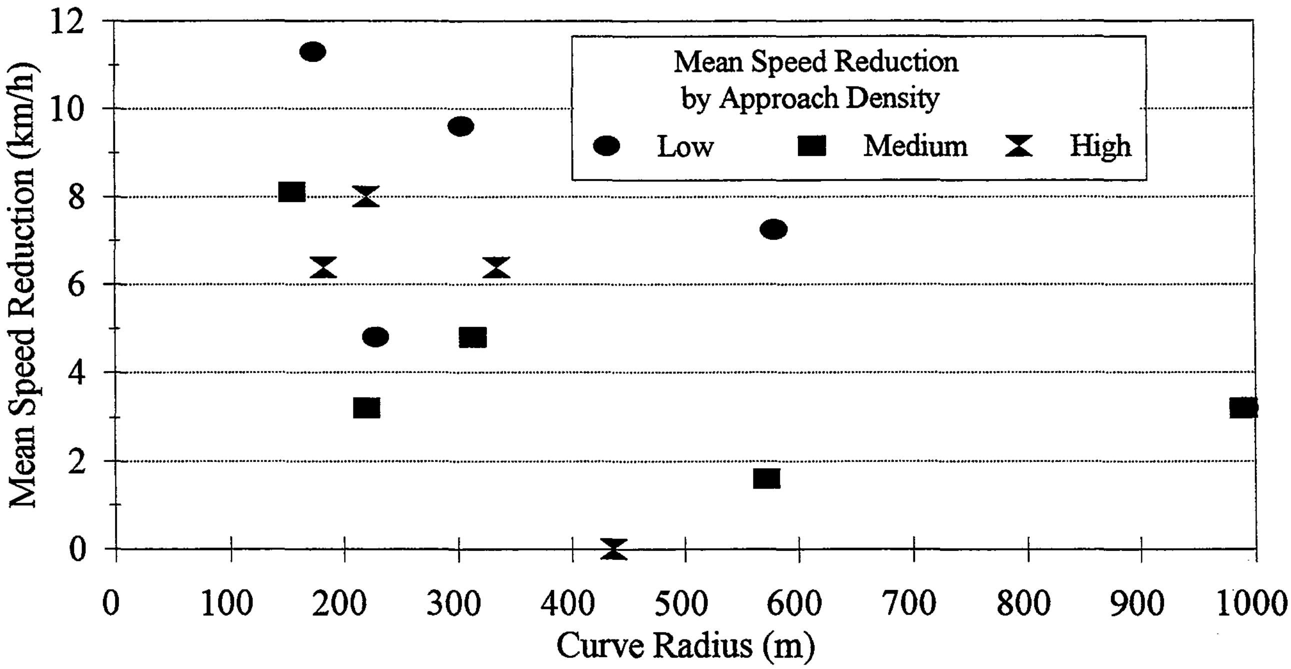

Figure 6-9. Mean Speed Reduction Versus Curve Radius and Three Approach Density Levels.

A hypothesis of this study was that mean speed reductions from tangent to horizontal curve are influenced by curve radius and approach density. Past studies have shown that speed reductions increase as curve radius decreases. An original objective of this study was to develop a regression equation as a function of curve radius only; however, attempts to develop a single regression equation to estimate mean speed reduction using only curve radius was not successful. These results were not surprising considering the results of regression analyses for 85th percentile speeds on tangents and curve sections. Therefore, regression analyses focused on estimating mean speed reductions using both curve radius and approach density.

Figure 6-10 shows a scatter plot of the mean speed reduction data for each approach density group plus the three lines representing the fitted regression equations for this model. The parameter estimates and the form of the regression equation are listed in Table 6-10. The results show no statistically significant differences among the approach density levels in either the slopes or intercepts of their regression equation for mean speed reduction versus curve radius. Although the regression results do not show a statistically significant effect of curve radius on mean speed reduction, Figure 6-10 illustrates the hypothesized trend of decreasing speed reductions with increasing curve radius. In summary, the regression results do not indicate a statistically significant effect of curve radius and approach density on mean speed reductions. The combined variability of speeds on the control and curve sections probably caused the poor results, given the small number of sites examined.

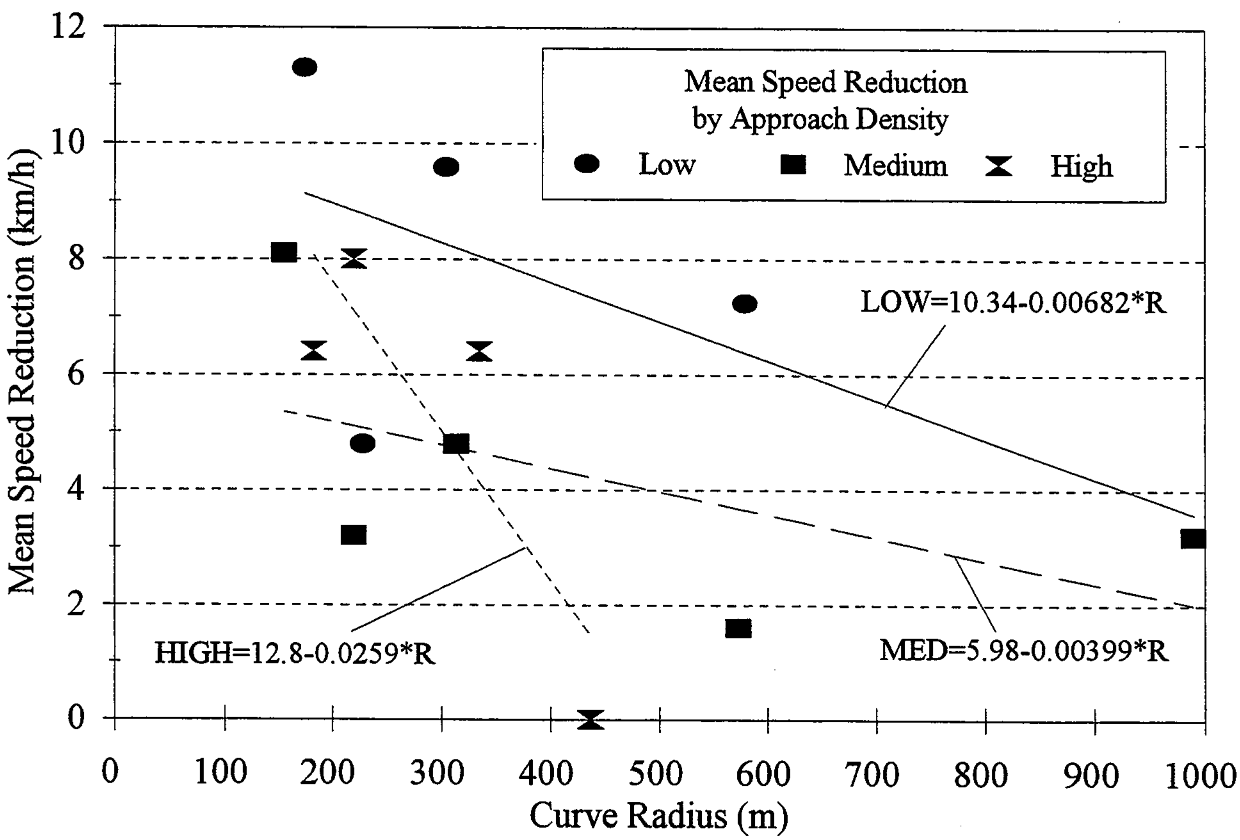

Figure 6-10. Regression Analysis Results for Mean Speed Reduction Versus Curve Radius and Approach Density.

Table 6-10. Regression Analysis Results for Mean Speed Reduction Versus Curve Radius by Approach Density Level.

Parameter	Estimate	Standard Error
β_0	10.34	2.05
β_1	-0.0068	0.0037
β_2	-4.36	2.87
β_3	2.47	4.42
β_4	0.0028	0.0053
β_5	-0.0191	0.0132

$$\text{Mean } \Delta V = \beta_0 + \beta_1 R + \beta_2 AD_m + \beta_3 AD_h + (\beta_4 AD_m + \beta_5 AD_h)R$$

Where:

Mean ΔV = Mean speed reduction (km/h)

R = Curve radius (m)

AD_m = Indicator variable that equals 1 for the medium approach density level and 0 otherwise

AD_h = Indicator variable that equals 1 for the high approach density level and 0 otherwise

β_0, β_1, β_2, β_3, β_4, β_5 = Regression coefficients

VERTICAL CURVE FIELD STUDIES

The objectives of the vertical curve field studies were to determine if suburban road drivers reduce their speeds at limited sight distance (LSD) crest vertical curves, and if approach density or the design speed of a curve can influence driver operating speeds. Evaluations performed were split into the following general areas:

- Determine if approach density influence drivers' speeds.
- Determine the relationship between the measured 85th percentile speed on a LSD vertical curve and the curve's inferred design speed.
- Compare the speeds measured at the control sections to the crest sections.

Study Site Characteristics

Data were collected at 10 sites in the Dallas/Ft. Worth area. Characteristics of the sites are listed in Table 6-11. K values were calculated using the approach and departure grades and the curve length shown on the plans for each selected site. (The K value reflects the horizontal distance in meters required to effect a 1 percent change in gradient. It can be used to determine minimum length of vertical curves for various design speeds.) The calculated K value was then used to determine the inferred design speed for each crest vertical curve. The speed limit and the number of approaches at the site were also collected during field data collection. Based upon the study sites selected, the approach density groups were defined as 3 to 4 approaches/km for the low group, 6 to 7 approaches/km for the medium group, and 12 to 15 approaches/km for the high group.

The speeds measured at each site are listed in Table 6-12. Table 6-12 includes the 85th percentile speed at both the control and the crest sections and the mean speed difference between the control and crest section for the measured vehicles. The number of vehicle speeds measured at each site is also listed in Table 6-12.

Table 6-11. Characteristics of Vertical Curve Sites.

Site Number	Speed Limit (km/h)	App/km	Approach Grade	Departure Grade	Curve Length (m)	K value	Inferred Design Speed (km/h)
VC-1	64	3	0.75	-2.51	61	19	66
VC-2	56	12	3.00	-2.00	46	9	50
VC-3	56	12	3.00	-2.00	46	9	50
VC-4	56	12	-1.76	-8.10	99	16	62
VC-5	56	7	-1.76	-8.10	99	16	62
VC-6	56	6	4.60	-8.60	61	5	35
VC-7	64	15	1.20	-2.40	61	17	64
VC-8	64	15	1.20	-2.40	61	17	64
VC-9	64	4	4.30	1.54	31	11	54
VC-10	64	4	-0.41	-3.00	46	15	65

Table 6-12. Measured Speeds at Vertical Curve Sites.

Site Number	Number of Vehicle Speeds Measured	85th Percentile Speed (km/h)		Average Speed Difference (km/h)
		Control	Crest	
VC-1	150	87	84	4.7
VC-2	150	74	69	4.8
VC-3	150	72	66	7.3
VC-4	146	81	72	5.9
VC-5	148	79	72	6.4
VC-6	146	71	74	-2.0
VC-7	150	76	72	3.9
VC-8	150	79	72	5.4
VC-9	140	72	71	2.0
VC-10	169	84	76	6.8

85th Percentile Speeds on Control Sections

The 85th percentile speeds on the control sections of the 10 vertical curve sites ranged from 71 to 87 km/h (44 to 54 mph). Figure 6-11 shows a scatter plot of the speeds versus approach density. The posted speed limits for the sites are also shown. As shown in the plot, the lower approach density values contained both the highest and some of the lowest 85th percentile speeds. Figure 6-11 and regression analyses showed that for the data collected in this project, approach density is not a good predictor of operating speed on approaches to LSD vertical curves. Several potential regression equations similar to those used in the horizontal curve evaluations were tested. The best fitting model had an R^2 value of only 0.30. Statistical evaluation also showed that the mean values for each approach density group are not significantly different (see Table 6-13).

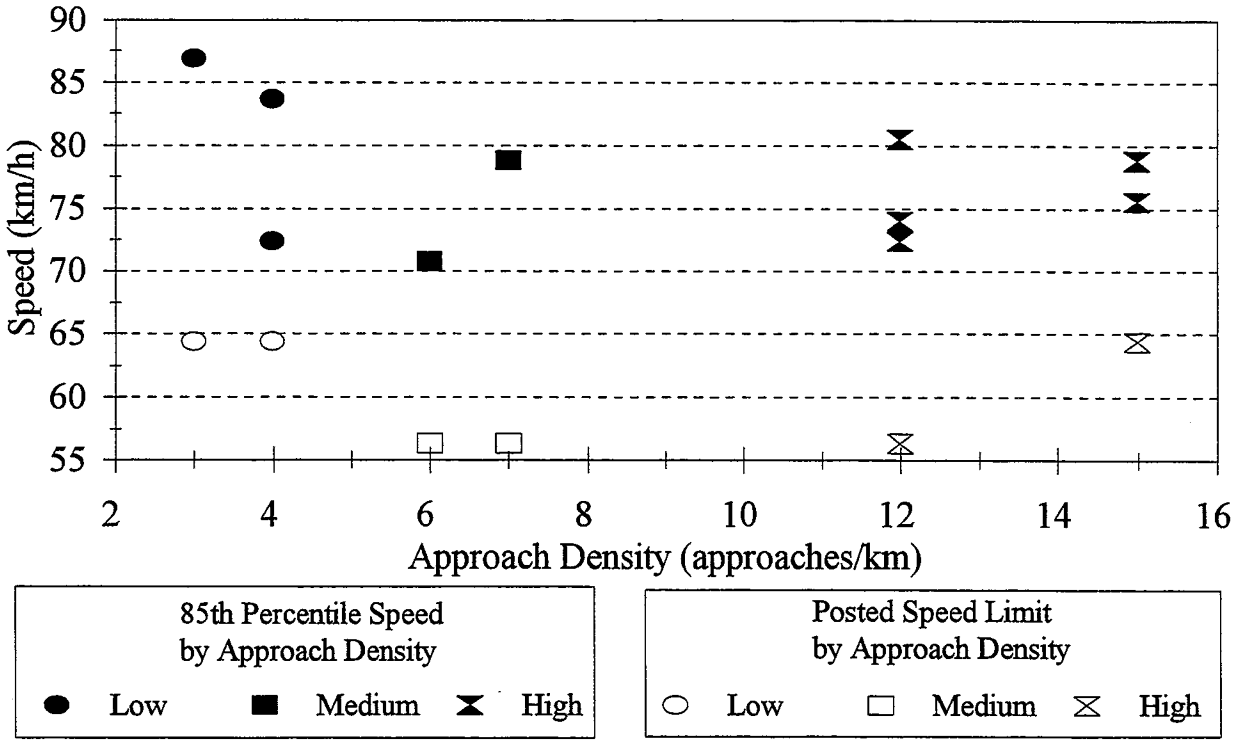

Figure 6-11. Scatter Plot of Speed on Control Sections Versus Approach Density.

Table 6-13. Mean 85th Percentile Speed for Control Sections by Approach Density Group.

Approach Density Group (approaches/km)	Site Number	Mean 85th Percentile Speed for Group (km/h)
Low (3 to 4)	1, 9, and 10	81.0
Medium (6 to 7)	5 and 6	74.8
High (12 to 15)	2, 3, 4, 7, and 8	76.3

85th Percentile Speeds on Limited Sight Distance Crest Vertical Curves

Figure 6-12 illustrates the 85th percentile speed for each of the 10 crest vertical curve sections versus its corresponding inferred design speed. The posted speed limits for the sites are also shown in the figure. The heavy diagonal line represents those points where the 85th percentile speed at a crest would equal the design speed of the crest curve. As expected, the difference between the 85th percentile speed and the design speed of the crest curve was greatest for the lower design speeds and slightly less for the higher design speeds (see Figure 6-13); however, the difference at the higher design speeds is still rather large (almost 20 km/h).

The plot of the vertical curve data (see Figure 6-12) can be interpreted in two ways. Initial reviews of the plot showed that the observed 85th percentile speed is independent of design speed (i.e., the regression analysis resulted in a relatively level and straight line—see Figure 6-14). Despite the design speed of the roadway, drivers on the selected suburban highways were operating at approximately 72 km/h (45 mph). When the data for individual sites were examined, however, Site VC-6 appears to be an outlier. Almost 75 percent of the drivers at Site VC-6 accelerated between the control and the LSD crest curve section. The site location is approximately 0.5 km before the entrance of an interstate believed to have resulted in drivers accelerating between the control and crest sections of the study site.

Regression analyses were done with and without the potential outlier point. Table 6-14 summarizes the results of these tests and Figure 6-14 shows the plot of the regression lines. The removal of the outlier (or Site VC-6) data point results in a regression equation that better explains the variability of the data (as demonstrated by the much higher R^2 value). Additional sites where the crest vertical curve design speed is between 30 and 50 km/h are needed to evaluate whether the findings from Site VC-6 represent a typical or non-typical situation; however, based upon current knowledge, Site VC-6 appears to be a non-typical site with unusually high speeds.

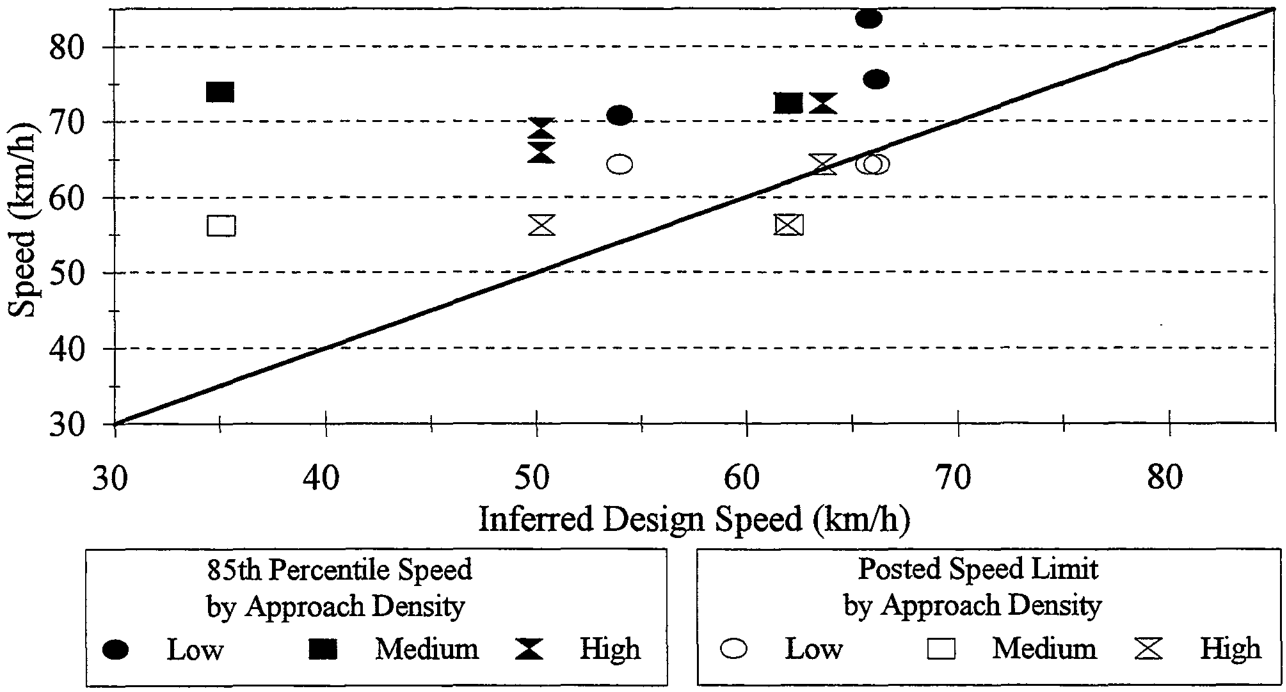

Figure 6-12. Speed on Vertical Curves Versus Inferred Design Speed.

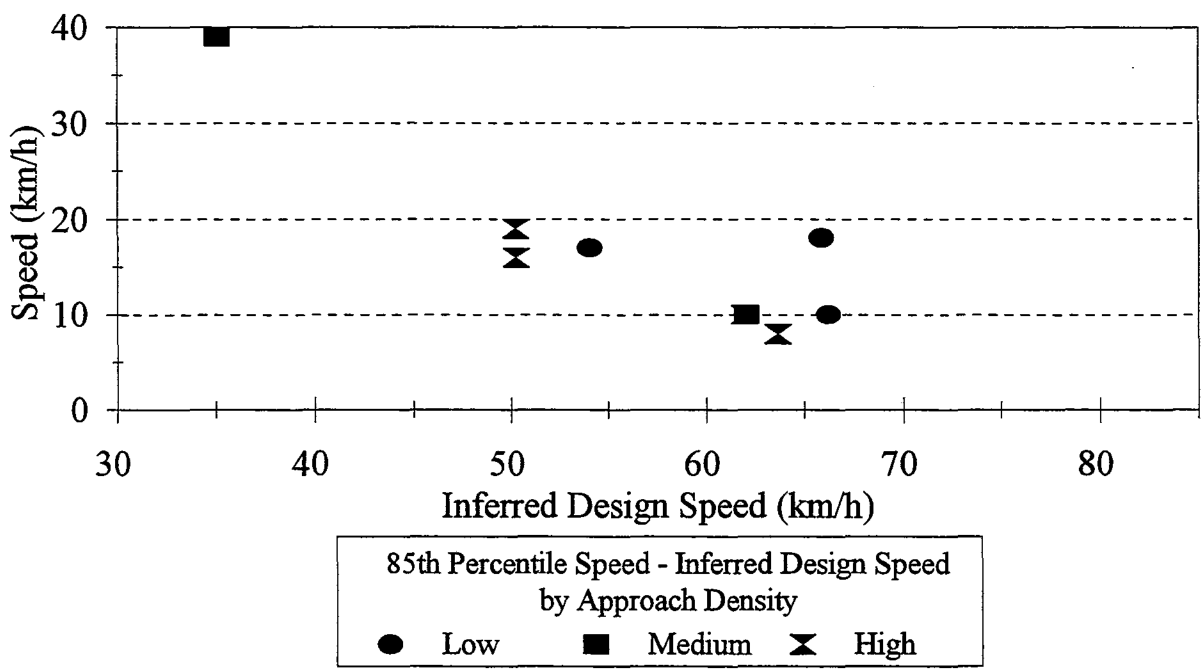

Figure 6-13. Difference in 85th Percentile Speed and Inferred Design Speed for Vertical Curves.

Table 6-14. Summary of Regression Analysis for 85th Percentile Crest Speeds.

	With Site VC-6	Without Site VC-6
Number of Observations	10	9
y-intercept (β_0)	62.32	39.51
Slope of Prediction Line (β_1)	0.184	0.556
Coefficient of Determination (R^2)	0.16	0.56
Prob>F	0.26	0.02

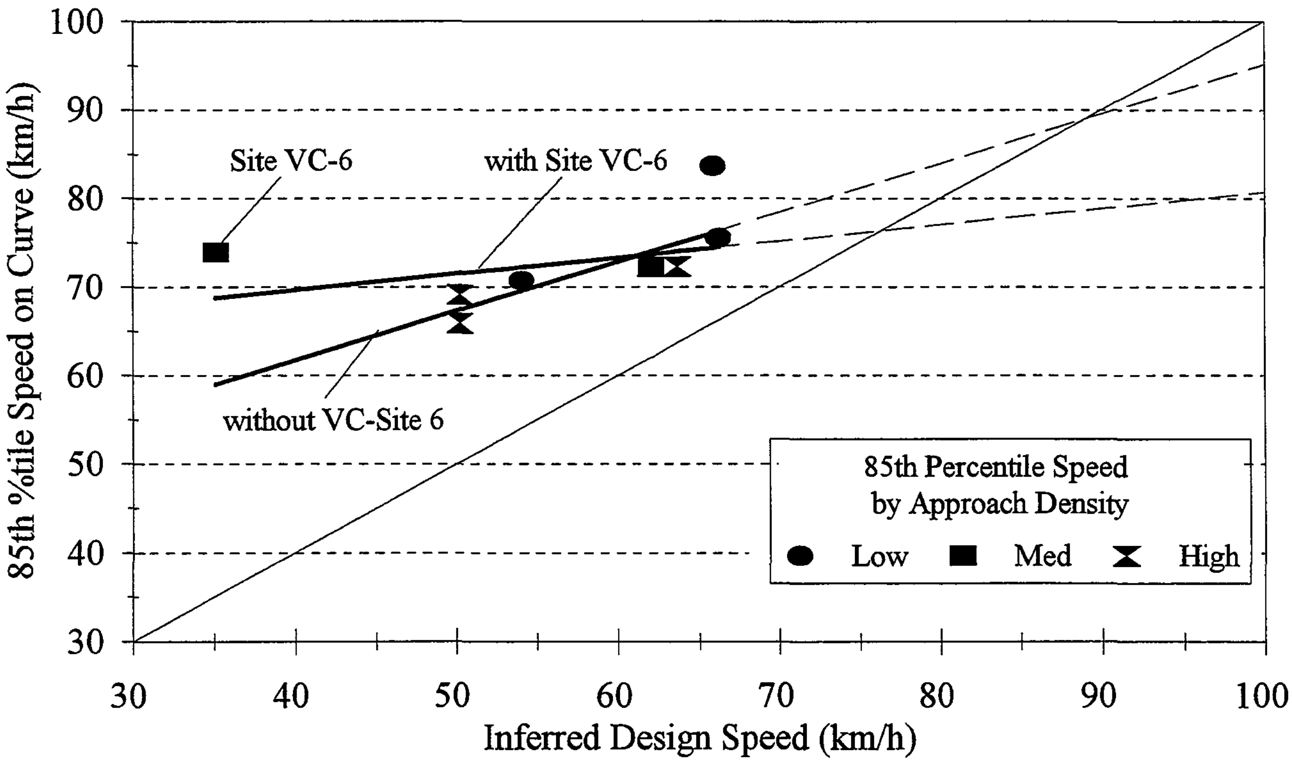

Figure 6-14. Regression Analysis Results for 85th Percentile Speed and Inferred Design Speed.

The regression analysis for the nine data points between 50 and 66 km/h inferred design speeds shows that, at least in the range of conditions examined, the inferred design speed (or available sight distance) of the crest curve is a moderately good predictor of 85th percentile crest speeds. In other words, the operating speed selected by drivers is dependent on the available sight distance of the crest curve for suburban highways. Similar regression analyses showed that the speed limit is not a good predictor of the operating speed on either the tangent or crest sections (R^2 values were less than 0.29).

None of the selected study sites had 85th percentile speeds that were less than the LSD curve's inferred design speed. Therefore, to estimate the inferred design speed where operating speed would equal design speed, one would need to extrapolate beyond the data limits, which should only be done with caution. The dashed portion of the lines in Figure 6-14 shows an extrapolation of the regression equations. Using the extrapolated line at design speeds greater than about 90 km/h, the regression equation for the nine sites produces 85th percentile speeds that are less than the design speed of the curve. For design speeds less than 90 km/h, the regression equation predicts 85th percentile speeds that are greater than the design speed of the curve. These findings are consistent with findings in other studies.[11,16] Messer et al.[16] found on two-lane highways that 85th percentile operating speeds were higher than the design speed of 81 and 97 km/h (50 and 60 mph) design speed roadways and less than the design speed of 113 km/h (70 mph) design speed roadways. Fambro et al.[11] found that 85th percentile speeds on rural roads are less than the design speed at design speeds greater than about 97 to 105 km/h (60 to 65 mph).

Mean Speed Reductions at Vertical Curves

The difference in each vehicle's speed from the control section to the crest curve was calculated. These differences were then used to determine the average difference for all measured speeds at a site. Table 6-12 lists the mean difference for each of the 10 sites.

The data collected in this project were divided into three approach density categories: low (3 to 4 approaches/km), medium (6 to 7 approaches/km), and high (12 to 15 approaches/km). Table 6-15 lists the average mean difference for each approach density group while Figure 6-15 shows a plot of the individual data points.

The initial review of Figure 6-15 and Table 6-15 does not support the hypothesis that as approach density increases, speed reduction between a control section and a crest section also increases. If the hypothesis is supported, one would expect that the average mean speed reductions listed in Table 6-15 would consistently increase in speed difference value from the low to the high category. The medium approach density value is either "too high" or "too low" (depending upon whether Site VC-6 is included in the analysis) to provide the consistent increase in mean speed difference. Because the high approach density sites experienced less speed reductions than the low approach density sites, and because the medium approach density category contained only two sites, the hypothesis may be valid. Additional data, especially in the medium category, is needed. Based on the current information, the evaluation of approach density's effect on speed reductions is inconclusive.

Table 6-15. Mean Speed Reductions by Approach Density Groups.

Approach Density Groups (approaches/km)	Vertical Curve Site Numbers	Average Mean Speed Reduction (km/h)	
		with Site VC-6	without Site VC-6
Low (3 to 4)	1, 9, and 10	4.5	4.5
Medium (6 to 7)	5 and 6	2.2	6.4
High (12 to 15)	2, 3, 4, 7 and 8	5.5	5.5

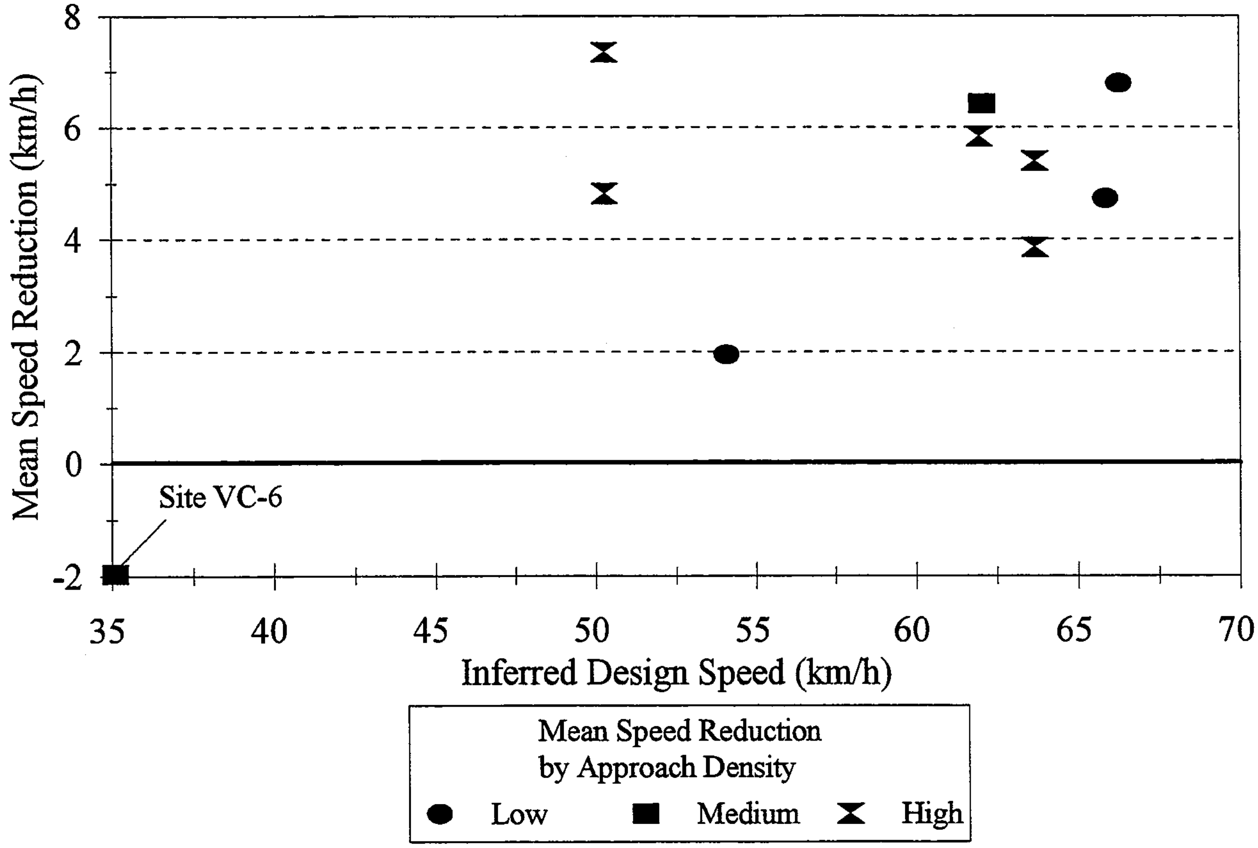

Figure 6-15. Mean Differences in Speed for Design Speed/Approach Density Groups.

SUMMARY

Field studies were conducted on suburban highways at limited sight distance crest vertical and horizontal curves. Free-flow speeds were collected for individual vehicles at both a control and a curve section at 15 horizontal curve sites and 10 vertical curve sites. Curve radius for the horizontal curves and inferred design speed for the vertical curves, along with approach density, were the variables examined to determine their effects on the 85th percentile speed on the control section, the 85th percentile speed on the curve section, and the speed reduction from the control section to the curve section.

85th Percentile Speed on Control Sections

The 85th percentile speed observed on the control sections approaching the horizontal curves ranged between 71 and 101 km/h while on the control sections approaching the vertical curves the range was between 71 and 87 km/h. The scatter plots of 85th percentile speed versus approach density indicate that speeds decrease as approach density increases for the horizontal curve sites; however, for the vertical curve sites, approach density did not show a similar (or any definable) relationship. One reason for the difference is that the strongest decrease in speed for an increase in density on the horizontal curve sites occurred when density was less then 3 approaches/km. None of the vertical curve sites had data for sites with less than 3 approaches/km.

The regression analysis of the 85th percentile speed on tangents approaching a horizontal curve found that the curvilinear equation form performed better than the linear form. None of the models tested for the control sections approaching the vertical curve sites were acceptable.

85th Percentile Speed on Curves

Regression analysis found that curve radius for horizontal curves and inferred design speed for vertical curves are good predictors of the 85th percentile speed on curves. For horizontal curve sites, a curvilinear relationship exists between curve radius and 85th percentile speed. Using approach density in the horizontal curve regression analysis resulted in a slightly better regression model than just using curve radius. A linear relationship provided the best fit between inferred design speed and 85th percentile speed for the vertical curve sites. Previous research has found the inferred design speed or the range of inferred design speeds at which the operating speed is approximately equal to the inferred design speed. This study also found that point for the horizontal and vertical curves studied. Table 6-16 lists the values found for this study and for previous studies.

Table 6-16. Comparison of When 85th Percentile Speed is Approximately Equal to Inferred Design Speed.

Roadway Type	Reference	Point Where 85th Percentile Speed is Approximately Equal to Inferred Design Speed (km/h) [a]
Vertical Curves		
Rural roadways	Fambro et al.[11]	97 to 105
2 Lane Rural Highways	Messer et al.[16]	between 97 and 113
Suburban Highways	This study	90 [b]
Horizontal Curves		
2 Lane Highways	Chowdhury et al.[6]	90
2 Lane Rural Highways	Krammes et al.[7]	90
Suburban Highways	This study	70

[a] Operating speeds are greater than the inferred design speeds at inferred design speeds less than this value, and operating speeds are less than the inferred design speeds at inferred design speeds greater than this value.

[b] The 90 km/h point was found by extrapolating a regression equation past its data limits. All of the sites studied had 85th percentile speeds greater than the curves inferred design speed. The curves inferred design speeds ranged between 35 and 66 km/h.

For vertical curves, the point where 85th percentile speed becomes less than inferred design speed is fairly consistent between the different studies on rural and suburban roadways (90 or 97 km/h) with the suburban roadways having a slightly lower point. For the horizontal curve sites, the suburban roadways also had a lower point than the studies for the rural, two-lane roadways; however, the difference was much greater. Suburban horizontal curve drivers operate at speeds in excess of the inferred design speed for curves designed with 70 km/h or less, while on rural, two-lane roadways, drivers operate above the inferred design speed for curves designed with 90 km/h or less.

Mean Speed Reductions at Curves

The reduction of speed from a control section to a curve is theorized to be affected by: (1) the sharpness of the downstream curve (defined by radius for horizontal curves or inferred design speed for vertical curves) and (2) the number of approaches along the roadway section. The general trends in the data collected for this study support this theory, but the results from the statistical analyses do not show a statistically significant effect of curve radius/inferred design speed and approach density on mean speed reductions. Data from additional sites are needed, especially in certain approach density groups.

CHAPTER 7

CONCLUSIONS AND RECOMMENDATIONS

The research for this project documented the concerns and difficulties the profession is experiencing with the relationship among design speed, operating speed, and posted speed. Legal liability concerns associated with that relationship also were examined. Field studies were conducted to collect data to identify the relationship between design and operating speed for horizontal and crest vertical curves with limited sight distance on suburban highways.

CONCLUSIONS

Specific conclusions from the research include the following:

- More than 75 percent of the respondents to the mail-out survey agreed with the comment that anticipated operating speed should be considered when selecting the design speed of a roadway. Other factors, such as urban versus rural and functional class, however, were identified more often than anticipated operating speed.

- Several mail-out survey respondents expressed a desire for an improved advisory speed selection process.

- The surveys and interviews revealed that documentation is needed that explains why posting a speed limit that is above a design speed is reasonable.

- The AASHTO definition for design speed does not accurately reflect current conditions and should be changed. The term "maximum safe speed" is the most objectionable portion of the current definition.

- A large majority of those interviewed agreed that posting speed limits higher than the road's design speed is appropriate and that roadway traffic conditions are safe if speed limits are posted based on 85th percentile speeds regardless of the roadway's design speed.

- The participants in the interviews commented on liability concerns associated with the situation where 85th percentile speed is higher than the inferred design speed; however, the number of cases involving the specific issue was very low among those interviewed.

- The field studies at the horizontal curve sites on suburban roadways found the following:
  - At the horizontal curve sites studied, the 85th percentile speeds on the tangents decreased as approach density increased.
  - The 85th percentile driver exceeded the design speed and corresponding side-friction factor on curves with inferred design speeds less than 70 km/h (43.5 mph).
  - Regression analyses suggested that curve radius is a good predictor of 85th percentile speed on suburban highway horizontal curves. For the curves examined, the 85th percentile speed on curves increased as curve radii increased.
  - Previous research suggests that mean speed reductions decrease as curve radius increases. The general trend in the data supports this theory, but the trend is not statistically significant.

- The field studies at the vertical curve sites on suburban roadways found the following:
  - Design speed is a moderately good predictor of 85th percentile crest speeds while posted speed is not.

- For design speeds less than 90 km/h, the regression equation predicts 85th percentile speeds that are greater than the design speed of the curve. This finding is consistent with findings from other studies.
- Whether driveway density causes a speed reduction between a control section and a limited sight distance crest vertical curve section was inconclusive based on the data collected during this study.

RECOMMENDATIONS

Two documents were prepared as part of the research efforts. The first, "Suggested Guidelines—Design Speed and Operating Concepts" (which is included in this report as Appendix A), contains specific recommendations on selecting posted and design speeds. It also addresses the liability issue that arises when posted speed is greater than an inferred design speed for a vertical or horizontal curve. The other document developed was published as a separate report (FHWA/TX-95/1465-1). It was developed to explain the design/operating/posted speed concepts to individuals who do not have an engineering background.

Other recommendations identified from the research include:

- The current definition of design speed in the AASHTO *Green Book* needs to be revised. As a minimum, the term "maximum safe" should be eliminated. Preferably the entire definition should be rewritten to reflect the current usage of the concept. One suggested definition is "a selected speed used to determine various geometric design features of a roadway, including the horizontal and vertical alignments, curb-and-gutter sections, curb offsets, and roadside clearances that will correspond with the functional usage of the roadway."

- Because of the focus on designing a roadway primarily to serve a functional role, the term "design speed" is not really necessary. It could be replaced with "functional design features" or some similar terminology that bases the design of a roadway on its anticipated functional usage and operational speed.

- Research should be conducted to develop a new procedure or refine the existing procedure for selecting advisory speeds at horizontal curves.

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APPENDIX A

SUGGESTED GUIDELINES—DESIGN SPEED AND OPERATING SPEED CONCEPTS

KEYWORD DEFINITIONS

For the purpose of these guidelines, the following keyword definitions should be understood.

Operating Speed- the speed at which drivers are observed operating their vehicles during free flow conditions. The 85th percentile of the distribution of observed speeds is the most frequently used descriptive statistic for the operating speed associated with a particular location or geometric feature.

85th Percentile Speed- the speed below which 85 percent of motorists travel. It is frequently used to set speed limits.

Posted Speed- the maximum speed limit posted on a facility, as established by the appropriate public entity.

Advisory Speed- the suggested speed for a specific condition (such as a horizontal curve) on a highway.

Design Speed- a selected speed used to determine various geometric design features of a roadway, including the horizontal and vertical alignments, curb-and-gutter sections, curb offsets, and roadside clearances.

SELECTING POSTED SPEEDS

It is a well-known traffic engineering principle that motorists drive at speeds at which they feel comfortable. For example, the legislated 55 mph speed limit on Interstate Highways was largely ignored by the motoring public because the speed was considered too slow for the type of roadway provided. Arbitrarily setting lower speed limits in order to reduce traffic speeds is ineffective unless the speed selected is consistent with the speeds driven by the motoring public.

For more than 50 years, traffic engineers have been using the 85th percentile speed to help select the posted speed limit. Other factors like access locations, type and amount of development, and vehicle mix may influence the selection of the posted speed. Because drivers as a group tend to travel at speeds appropriate for the roadway conditions, significant variation from the 85th percentile speed is not recommended unless it exceeds the legal maximum speed limit.

DESIGN SPEED CONCEPT

The concept of design speed was introduced into the highway design profession in the 1930s. The purpose of the design speed concept was to identify design criteria to be used in the design of a new roadway. The roadway's design speed was assumed to be that speed adopted by the faster group of drivers, but not drivers who traveled at reckless speeds. After a design speed was selected, appropriate geometric features were incorporated in the design to provide a comfortable driving environment and sufficient stopping sight distances. Many older roadways were designed with minimum geometric features for the selected design speed.

Since the 1930s, roadway design criteria has been modified to reflect changes in the design coefficients of friction, driver eye height, and object height in the roadway. Hence, longer stopping sight distances are now recommended compared to those suggested many years ago.

Very old roadways (pre-1940s) were designed (or simply evolved) without considering design speeds. Some roadways designed in the 1940 to 1970 period and based on AASHO criteria relevant to that period have geometric features that would not meet the minimum values used today for similar design speeds. Often these older roadways are compared with newer roadways and the evaluation may be that the older roadway "has a lower design speed" than when it was first designed; however, a more correct statement would be that the older roadway may have a lower inferred design speed. In reality, recommended design criteria have changed but the older roadway's actual design speed was not altered.

POSTED SPEED GREATER THAN INFERRED DESIGN SPEED

If a roadway segment has a limited stopping sight distance with respect to the posted speed limit *and* a safety concern exists at the location, then some type of warning or informational sign should be provided to the motoring public. For example, relatively sharp horizontal curves are frequently provided with a Turn or Curve warning sign and an advisory speed plate. Properly marked horizontal curves provide adequate information to drivers such that they can adapt to the downstream curve radius.

If a vertical curve has a limited stopping sight distance *and* a safety concern exists at the location, then appropriate warning or informational signs should be provided. Warning signs (Intersection Ahead, Prepare to Stop, Stop Ahead, or similar type of signs) can be placed with an appropriate advisory speed plate to advise the motoring public of the suggested speed for the available sight distance. Posting a lower speed limit at such locations cannot be viewed as appropriate because arbitrarily lowering speed limits does not guarantee slower speeds. If limited stopping sight distance is present and appropriate information is provided, drivers can adjust to the condition.

SELECTING DESIGN SPEED

If new roadways are designed (or older roadways are designed for reconstruction), then the basic elements of design should be considered. First, the function of the roadway should be clearly identified. Second, the highest anticipated 85th percentile speed on the facility (either original or future) should be used to determine stopping sight distances and clear zone features. Third, other features such as curbs, merging areas, lighting, and safety features should be determined, bearing in mind the anticipated operating speeds and roadway function.

As an example, if a city is building a major urban arterial street for the future but is expecting to use the roadway temporarily as a suburban arterial roadway with high operating speeds, then the design features should be based on the higher-speed conditions. Similarly, if a frontage road of a freeway is constructed initially and is expected to function temporarily at high speeds, then the frontage road should be designed and constructed to accommodate the high-speed operation, the initial function of the frontage road. This practice would be considered good engineering judgment. If lower speed operating conditions evolve over time, then changes to the geometrics of the roadway (primarily cross-sectional modifications) could be made at that time. The speed limits posted on these temporary roadways should be based on spot speed studies and the 85th percentile speeds. This practice is also considered good engineering judgment.

SUMMARY

In summary, the following guidelines should be followed.

1. Speed limits on all roadways should be set by an engineer based on spot speed studies and the 85th percentile operating speed. Legal minimum and maximum speeds should establish the boundaries of the speed limits. If an existing roadway section's

posted speed limit is to be raised, the engineer should examine the roadway's roadside features to determine if modifications may be necessary to maintain roadside safety.

2. The 85th percentile speed is considered to be the appropriate posted speed limit even for those sections of roadway that have an inferred design speed less than the 85th percentile speed. Posting a roadway's speed limit based on its 85th percentile speed is considered good and typical engineering practice. This practice remains valid even where the inferred design speed is less than the resulting posted speed limit. In such situations, the posted speed limit would not be considered excessive or unsafe.

3. Arbitrarily setting lower speed limits at point locations due to a perceived less than desirable stopping sight distance is neither effective nor good engineering practice.

4. If a section of roadway has (or is expected to have) a posted speed in excess of the roadway's inferred design speed and a safety concern exists at the location, then appropriate warning or informational signs should be installed to warn or inform drivers of the condition. Slightly less than desirable stopping sight distances do not present an unsafe operating condition because of the conservative assumptions made in establishing desirable stopping sight distances. It is important to remember that any sign is a roadside object and that it should be installed only when its need is clearly demonstrated.

5. New or reconstructed roadways (and roadway sections) should be designed to accommodate operating speeds consistent with the roadway's highest anticipated posted speed limit based on the roadway's initial or ultimate function.