Technical Report Documentation Page

1. Report No. FHWA/TX-00/1769-3	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle DESIGN FACTORS THAT AFFECT DRIVER SPEED ON SUBURBAN ARTERIALS		5. Report Date June 2000
		6. Performing Organization Code
7. Author(s) Kay Fitzpatrick, Paul J. Carlson, Mark D. Wooldridge, and Marcus A. Brewer		8. Performing Organization Report No. Report 1769-3
9. Performing Organization Name and Address Texas Transportation Institute The Texas A&M University System College Station, Texas 77843-3135		10. Work Unit No. (TRAIS)
		11. Contract or Grant No. Project No. 0-1769
12. Sponsoring Agency Name and Address Texas Department of Transportation Research and Technology Transfer Section, Construction Division P.O. Box 5080 Austin, Texas 78763-5080		13. Type of Report and Period Covered Research: September 1997 – August 1999
		14. Sponsoring Agency Code

15. Supplementary Notes

Research performed in cooperation with the Texas Department of Transportation and the U.S. Department of Transportation, Federal Highway Administration.
Research Project Title: Identify Design Factors That Affect Driver Speed and Behavior

16. Abstract

Driver behavior is affected by many roadway factors. This project investigated which geometric, roadside, and traffic control device variables have an effect on driver behavior on major suburban arterials. Traffic signals and traffic volume were considered within the study site selection and data collection criteria and, therefore, are not included in the analysis. Regression techniques were used to determine how selected variables affect speed at the midpoints of straight sections and horizontal curves. When all variables are considered, the only significant variable for straight sections was posted speed limit. In addition to posted speed, deflection angle and access density classes influence speed on curve sections. Because 85th percentile speed is frequently used to set the posted speed limit, one may expect that one value would be able to predict the other, as is shown in this analysis. Another series of analyses was performed without using posted speed limit so as to provide information on predicting operating speed when not considering posted speed limit. Without speed limit, only lane width is a significant variable for straight sections. For curve sites without speed limit, the impact of median presence now becomes significant along with roadside development.

17. Key Words Operating Speed, 85th Percentile Speed, Posted Speed Limit, Suburban Arterials, Curves, Straight Sections		18. Distribution Statement No restrictions. This document is available to the public through NTIS: National Technical Information Service 5285 Port Royal Road Springfield, Virginia 22161	
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 164	22. Price

Form DOT F 1700.7 (8-72)

DESIGN FACTORS THAT AFFECT DRIVER SPEED ON SUBURBAN ARTERIALS

by

Kay Fitzpatrick, P.E.
Research Engineer
Texas Transportation Institute

Paul J. Carlson, P.E.
Assistant Research Engineer
Texas Transportation Institute

Mark D. Wooldridge, P.E.
Associate Research Engineer
Texas Transportation Institute

and

Marcus A. Brewer
Graduate Assistant Researcher
Texas Transportation Institute

Report 1769-3
Project Number 0-1769
Research Project Title: Identify Design Factors That Affect Driver Speed and Behavior

Sponsored by the
Texas Department of Transportation
In Cooperation with the
U.S. Department of Transportation
Federal Highway Administration

June 2000

TEXAS TRANSPORTATION INSTITUTE
The Texas A&M University System
College Station, Texas 77843-3135

DISCLAIMER

The contents of this report reflect the views of the authors, who are responsible for the facts and accuracy of the data presented herein. The contents do not necessarily reflect the official views 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, P.E. (TX-86762), Paul J. Carlson, P.E. (TX-85402), Mark D. Wooldridge, P.E. (TX-65791), and Marcus A. Brewer.

ACKNOWLEDGMENTS

The project team recognizes Aurora (Rory) Meza, project director; Rick Collins, program coordinator; and technical panel members Larry Blackburn and Gilbert Gavia for their time in providing direction and comments for this study. Research was performed in cooperation with the Texas Department of Transportation and the U.S. Department of Transportation, Federal Highway Administration.

The authors would also like to recognize the following persons for helping with report preparation efforts and data collection:

- Report Preparation: Maria Medrano, Crystal Garza;
- Site Selection Assistance: Larry Colclasure (Waco District), Wes McClure (Tyler District), Terry Sams (Dallas District), David V. Seiler (City of Corpus Christi), Robert Benz (TTI Houston), Marc Jacobson (former TTI employee), Jon Collins (former TTI employee);
- Data Collection: TTI Technicians; Rhett Gordon, Dan Walker; and
- Data Reduction: Terri Arendale, Mike Davis, Brian DeLatte, Mark Harris, Kevin Herren, Chad Kopecki, Kimberly Murphy, Stephen Pate, Kollan Pillay.

TABLE OF CONTENTS

TABLE OF CONTENTS (CON'T)

TABLE OF CONTENTS (CON'T)

TABLE OF CONTENTS (CON'T)

LIST OF FIGURES

LIST OF FIGURES (CON'T)

LIST OF FIGURES (CON'T)

LIST OF TABLES

LIST OF TABLES (CON'T)

CHAPTER 1

INTRODUCTION

Driver behavior is affected by many roadway factors. Particularly in suburban or urban networks, drivers are besieged by sensations that are likely to influence behavior. The degree to which geometric elements and other driving environmental factors affect driver behavior on rural and low-speed urban roadways has been researched recently. The influence of these factors on major suburban arterial drivers, however, is essentially unknown. If factors providing major driver behavioral influences can be identified, and if cause and effect relationships can be developed, this knowledge can yield designs creating desired driver behavior that will probably result in a facility that is safer and more efficient. The measure most frequently used to describe driver behavior on a roadway is operating speed. Operating speed is easy to record and is the most common measure used to evaluate the quality of service present on the roadway.

While operating speed is used in evaluating an existing roadway, the anticipated operating speed is not explicitly used when designing a roadway. The selection of design speed and the values for the different geometric elements are made with little empirical data on their influences on drivers' speed choice. Research is needed to provide a fundamental step in understanding the relationship between drivers' choice of speed and geometric design decisions for major suburban arterials.

With a better understanding of how geometric design elements affect operating speeds, designers will be able to make more effective design decisions for major arterials. Better design decisions should lead to an actual operating speed more closely approximating the intended operating speed of these facilities, and consequently, the posted speed limit. When operating speed matches the designer's intended speed, the facility design should also be more consistent with driver expectancy. The convergence of design speed, operating speed, and posted speed limit will have an inherent improvement on safety and operations for these facilities.

OBJECTIVES

The objectives of this project were to identify those factors that affect speed on suburban arterials and to determine the range of the influence. The findings from this research can provide planners and designers with knowledge on how selected elements affect operating speed. The research project will help answer the following questions:

- Do roadway variables affect speed on suburban arterials?
- Which alignment, cross section, roadside, or traffic control devices variables affect operating speed?
- For a variable that affects speed, what is the design value range that is influential?

If significant statistical relationships exist between geometric, roadside, and traffic control device elements and operating speed on major urban arterials, this "basic research" project can provide base data for the eventual development of design criteria or design models to estimate operating speed.

ORGANIZATION OF REPORT

This report is divided into the following eight chapters:

- Chapter 1 contains background information concerning the project and presents the research objectives.
- Chapter 2 provides an overview of relevant literature on the influences of operating speed for different facilities.
- Chapter 3 introduces the study approach used during this project. Two pilot studies were performed as part of Phase I. The findings from those studies were used to develop the larger effort undertaken in Phase II.
- Chapter 4 presents the methodology and findings from the Individual Driver Pilot Study. Six volunteers drove through four sections of suburban arterial roadways while their speeds and positions on the roadway network were monitored.
- Chapter 5 presents the methodology from the Laser Pilot Study. Observations/ preliminary findings were developed from the data collected at six sites. In addition, these observations were used to develop recommendations for conducting Phase II of this study.
- Chapter 6 presents the methodology used to collect and reduce data for the Phase II Laser Gun Study. The findings and lessons learned from Phase I directed the Phase II study into two categories: horizontal curve sites and straight section sites.
- Chapter 7 presents the findings from the laser study at the horizontal curve sites.
- Chapter 8 presents the findings from the laser study at the straight section sites.
- Chapter 9 presents a summary of the project and discusses the conclusions and recommendations developed during this project.

CHAPTER 2

LITERATURE REVIEW

Speed has historically been the defining consideration in traffic operations and highway design. Several different speed terms have been used, including design speed, operating speed, posted speed, running speed, and others. The terms' definitions have changed over the years, and the relationship between the terms have also varied. For current applications, a common definition for operating speed is the observed 85th percentile speed at a point on a roadway. Following is a summary of the relationships between operating speed and other variables, as identified through the literature by functional classification.

TWO-LANE RURAL HIGHWAYS

1999 FHWA Study

In a recent Federal Highway Administration (FHWA) research project, several different efforts were undertaken to predict operating speed for different conditions, such as on horizontal and vertical curves, on tangent sections, and prior to or after a horizontal curve for two-lane rural highways.[1] Speed data were collected at over 200 two-lane rural highway sites for use in the project. Speed prediction equations were developed for passenger cars for most combinations of horizontal and vertical alignment. For some of the combinations, however, sample sizes were not large enough for the equations to be considered definitive, and engineering judgment was used. Table 2-1 lists the developed equations. The FHWA study also demonstrates that the predicted speed reduction on a horizontal curve relative to the preceding curve or tangent clearly has a strong and sensitive relationship to accident frequency. Following is a summary of the findings for different alignment conditions.

Horizontal Curves on Grades

Four different vertical grade conditions were considered in the evaluation of horizontal curves on grades: upgrades (0 to 4 percent), steep upgrades (greater than 4 percent), downgrades (-4 to 0 percent), and steep downgrades (less than 4 percent). Figure 2-1 shows that as R increases from 0 to 400 m (0 to 1312.3 ft), the 85th percentile speeds increase notably for all study locations. For radii greater than 400 m (1312.3 ft), the increase in speed is not as dramatic. The inverse of the radius was the variable most highly correlated to the 85th percentile speed of all the variables included within the correlation matrix (see Figure 2-2). The regression model developed to fit the data for horizontal curves on grades included the single independent variable 1/R.

Three of the four speed prediction equations have intercept values greater than the 97.9 km/h recommended by Krammes et al. on "long" tangents.[2] Long tangents were defined as tangents where drivers can reach their desired speed for the roadway. Therefore, in certain situations, the equations would predict speeds higher than the assumed speed on a long tangent. Observed speeds on long tangents ranged from 93 to 104 km/h (57.8 to 64.6 mph) (average 85th percentile speed, by state). Based on the data and engineering judgment, the maximum operating speed on horizontal curves and tangents could be rounded to 100 km/h (62.1 mph). Thus, operating speeds on large radius horizontal curves should be truncated to 100 km/h (62 mph) (or to another desired operating speed) when the predicted speed exceeds this value.

Table 2-1. Speed Prediction Equations for Passenger Vehicles.[1]

AC EQ (See note 1)	Alignment Condition	Equation (see note 2)	Num. Obser.	R^2	MSE
1.	Horizontal Curve on Grade: $-9\% \le G < -4\%$	$V_{85} = 102.10 - \frac{3077.13}{R}$	21	0.58	51.95
2.	Horizontal Curve on Grade: $-4\% \le G < 0\%$	$V_{85} = 105.98 - \frac{3709.90}{R}$	25	0.76	28.46
3.	Horizontal Curve on Grade: $0\% \le G < 4\%$	$V_{85} = 104.82 - \frac{3574.51}{R}$	25	0.76	24.34
4.	Horizontal Curve on Grade: $4\% \le G < 9\%$	$V_{85} = 96.61 - \frac{2752.19}{R}$	23	0.53	52.54
5.	Horizontal Curve Combined with Sag Vertical Curve	$V_{85} = 105.32 - \frac{3438.19}{R}$	25	0.92	10.47
6.	Horizontal Curve Combined with Non-Limited Sight Distance Crest Vertical Curve	(see note 3)	13	n/a	n/a
7.	Horizontal Curve Combined with Limited Sight Distance Crest Vertical Curve (i.e., $K \le 43$ m/%)	$V_{85} = 103.24 - \frac{3576.51}{R}$ (see note 4)	22	0.74	20.06
8.	Sag Vertical Curve on Horizontal Tangent	V_{85} = *assumed desired speed*	7	n/a	n/a
9.	Vertical Crest Curve with Non-Limited Sight Distance (i.e., $K > 43$ m/%) on Horizontal Tangent	V_{85} = *assumed desired speed*	6	n/a	n/a
10.	Vertical Crest Curve with Limited Sight Distance (i.e., $K \le 43$ m/%) on Horizontal Tangent	$V_{85} = 105.08 - \frac{149.69}{K}$	9	0.60	31.10

NOTES:
1. AC EQ = Alignment Condition Equation Number
2. Where: V_{85} = 85th percentile speed of passenger cars (km/h); K = rate of vertical curvature; R = radius of curvature (m); G = grade (%)
3. Use lowest speed of the speeds predicted from AC EQ 1 or 2 (for the downgrade) and AC EQ 3 or 4 (for the upgrade).
4. In addition, check the speeds predicted from AC EQ 1 or 2 (for the downgrade) and AC EQ 3 or 4 (for the upgrade) and use the lowest speed. This will ensure that the speed predicted along the combined curve will not be better than if just the horizontal curve was present (i.e., that the inclusion of a limited sight distance crest vertical curve results in a higher speed).

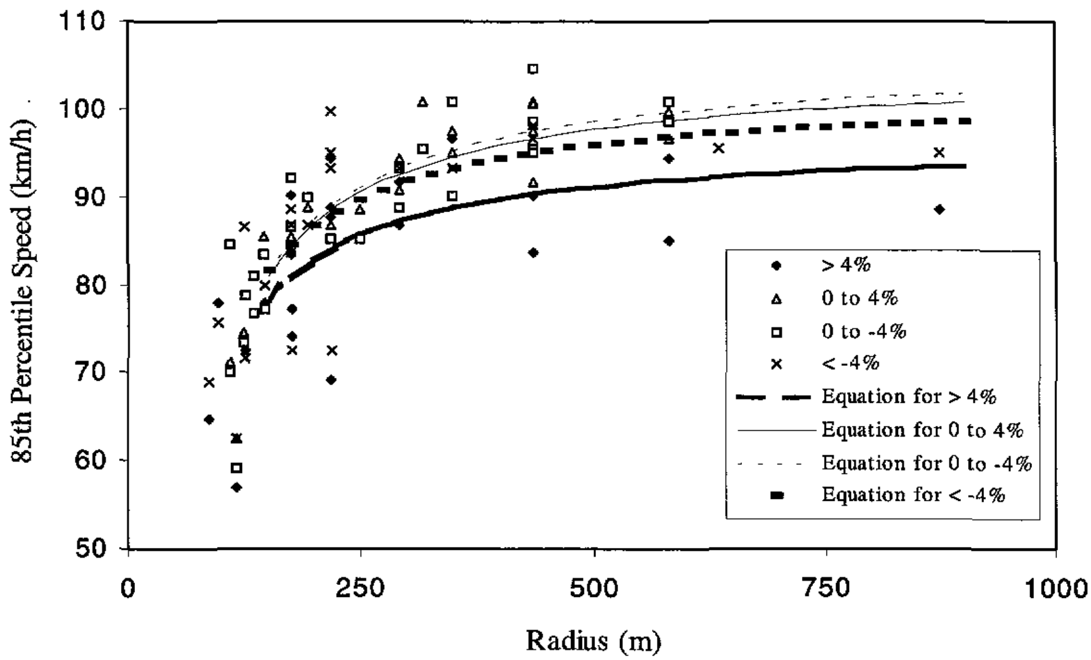


Figure 2-1. Horizontal Curves on Grades: V_{85} Versus R. [1]

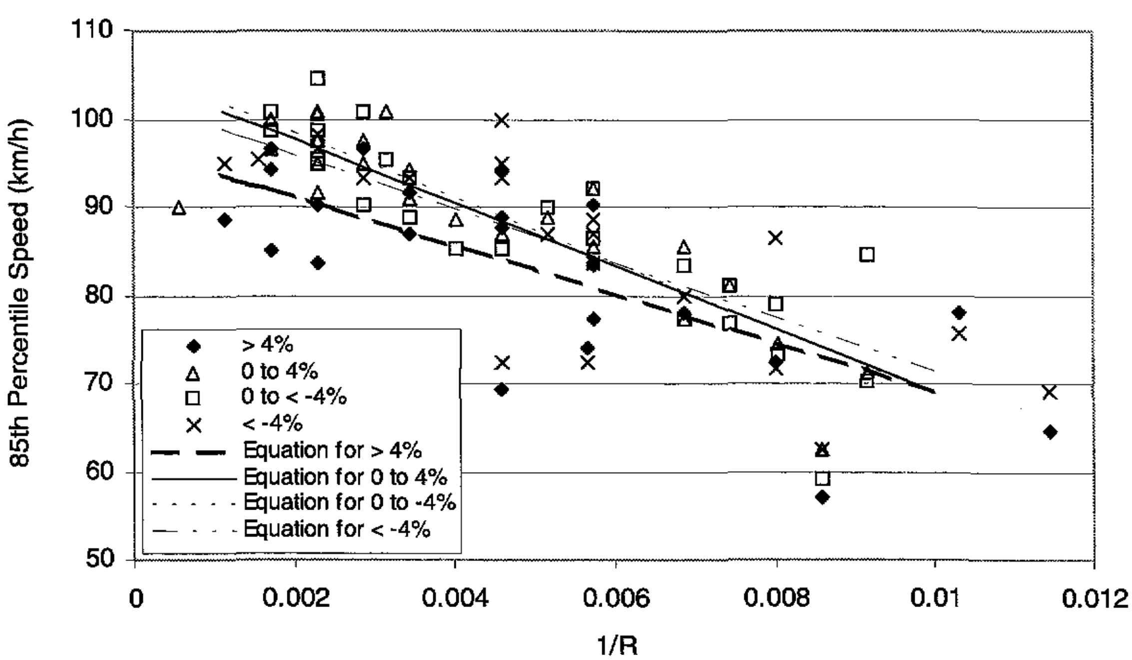


Figure 2-2. Horizontal Curves on Grades: V_{85} Versus 1/R. [1]

Vertical Curves on Horizontal Tangents

Vertical curves on horizontal tangents were divided into three categories: non-limited sight distance (NLSD) crest curves; limited sight distance (LSD) crest curves; and sag curves. A combined total of 21 study sites was collected for the vertical curves on tangents; two for NLSD crest curves; 10 for LSD crest curves; and nine for sag curves. The independent variables considered included K and 1/K (see Figures 2-3 and 2-4, respectively).

Of the independent variables, 1/K was most highly correlated to the 85th percentile speeds, even though the correlation was low for some conditions. The relationship between 85th percentile speed and 1/K is shown in Figure 2-4. Also included on these figures are the data from the NCHRP Stopping Sight Distance (SSD) study [3] and the plot of the selected regression equation for the limited sight distance condition.

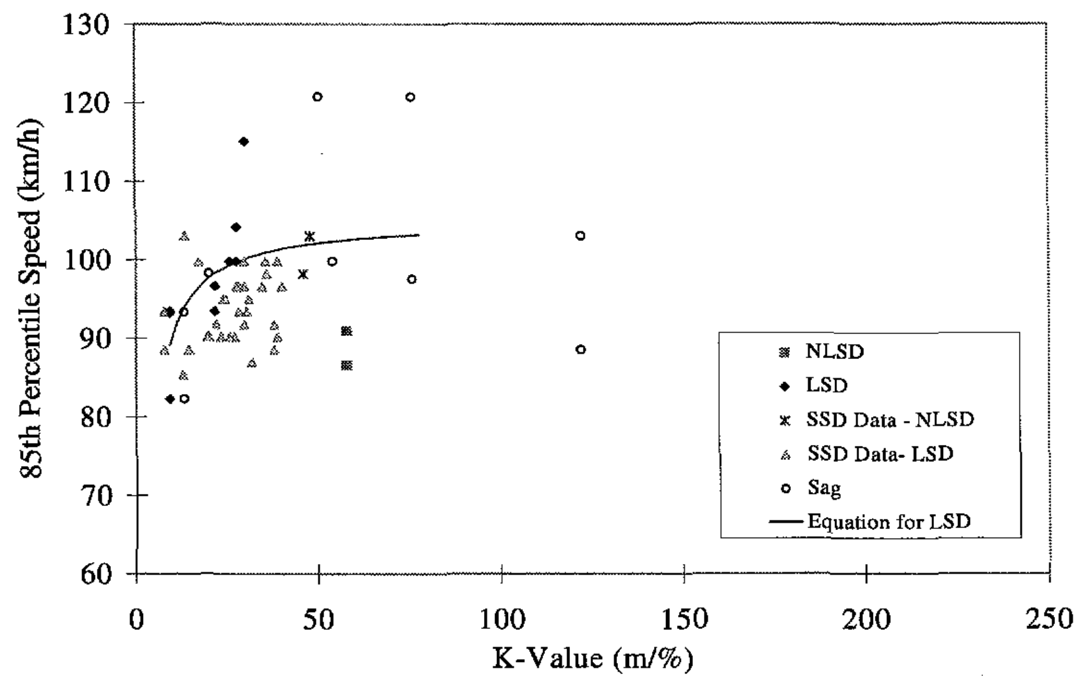


Figure 2-3. Vertical Curves on Horizontal Tangents: V_{85} Versus K. [1]

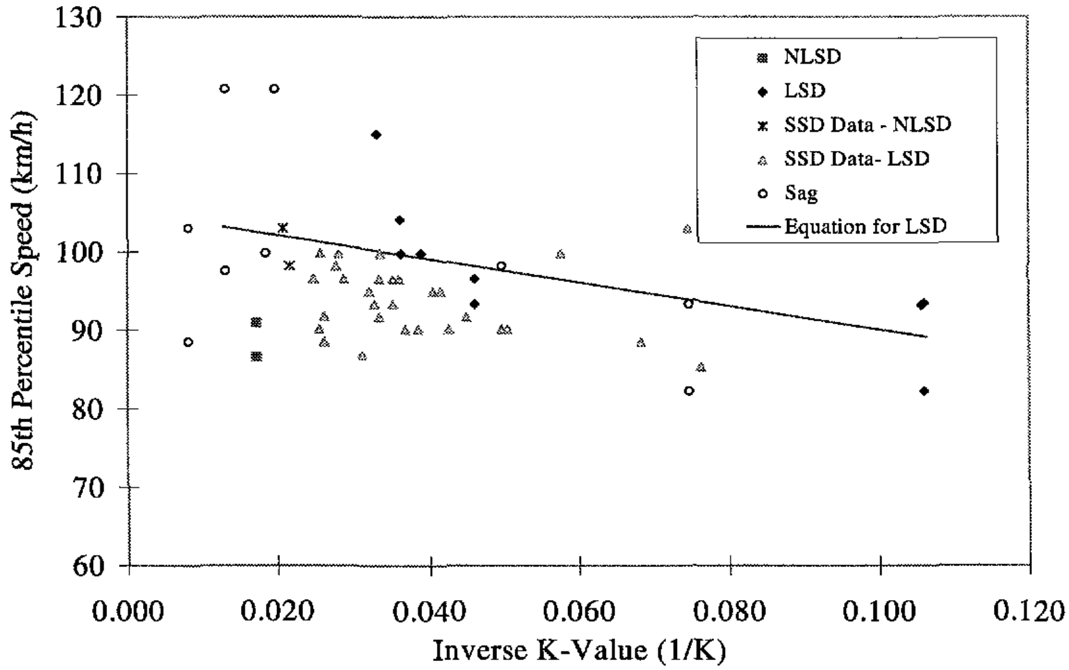


Figure 2-4. Vertical Curves on Horizontal Tangents: V_{85} Versus 1/K.[1]

No statistically significant regression equation was found for NLSD curves on horizontal tangents; therefore, the desired speed for long tangents is assumed for this condition. This recommendation is based on the graphical representation of the four sites and engineering judgment.

A total of nine sag curves on horizontal tangents sites was available for the analysis. As with the crest curves, the scatter plot does not show a clear relationship between the variables (see Figure 2-4). Therefore, based on the plots and attempts at developing a regression equation, it was recommended that the desired speed on long tangents be used for this alignment condition. Extreme sag vertical curves where the K-value is less than 15 may result in reduced operating speeds; however, the available data are too sparse to make a definitive conclusion on the issue.

Combination of Horizontal and Vertical Curves

The analysis of the combination curves (i.e., sites with both a horizontal curve and a vertical curve) began with plotting the speed data versus R, 1/R, K, and 1/K. Plots for R and K are shown in Figures 2-5 and 2-6, respectively. Initial evaluation of the plots indicated that both R and K could influence the speed along the combination of curves.

A statistically significant regression equation was not found for non-limited sight distance crest vertical curves in combination with horizontal curves. One of the reasons was that the data used in the analyses were for larger radii curves. Drivers on a combination of large horizontal radii and non-limited sight distance crest curves may not feel the need to reduce their speed in response to the geometry. The inclusion of all available data from this study also did not identify a regression equation with significant variables. All tested models that used variations of R and K had both insignificant variables and very low R^2 values. Therefore, engineering judgment must be used to determine the predicted speed for a horizontal curve combined with a nonlimited sight distance crest vertical curve. Based upon a review of the data available for this condition and for similar conditions, the lowest speed predicted using the equation developed for the following conditions is recommended:

- assumed maximum desired speed on long tangents,
- predicted speed using the horizontal curve radius equation for the upgrade, and
- predicted speed using the horizontal curve radius equation for the downgrade.

Using the lowest predicted speed will ensure that the speed predicted along the combined vertical and horizontal curve will not be better than if just the horizontal curve was present.

Limited sight distance crest curves combined with horizontal curves were evaluated using the 22 study sites available. Regression analysis compared the influences of 1/K, 1/R, and an interaction term. The analysis demonstrated that only 1/R was significant in predicting 85th percentile speeds.

The equation developed for the combination of sag vertical curves and horizontal curves had data from the 25 sites. It revealed that 1/R was the only significant independent variable.

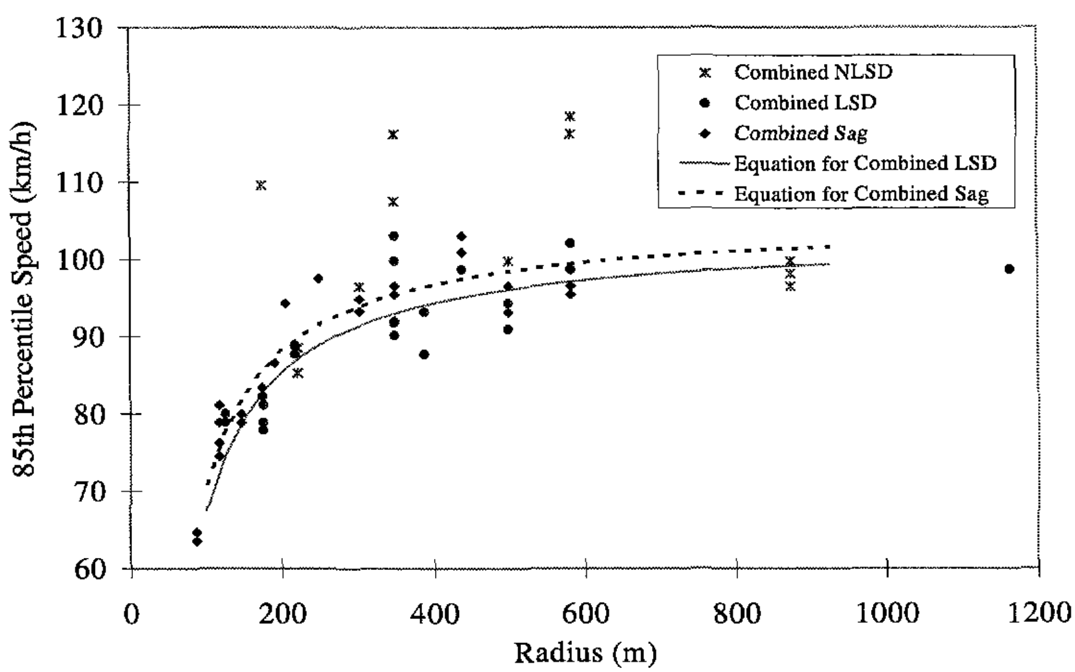


Figure 2-5. Combination Curves: V_{85} Versus R.[1]

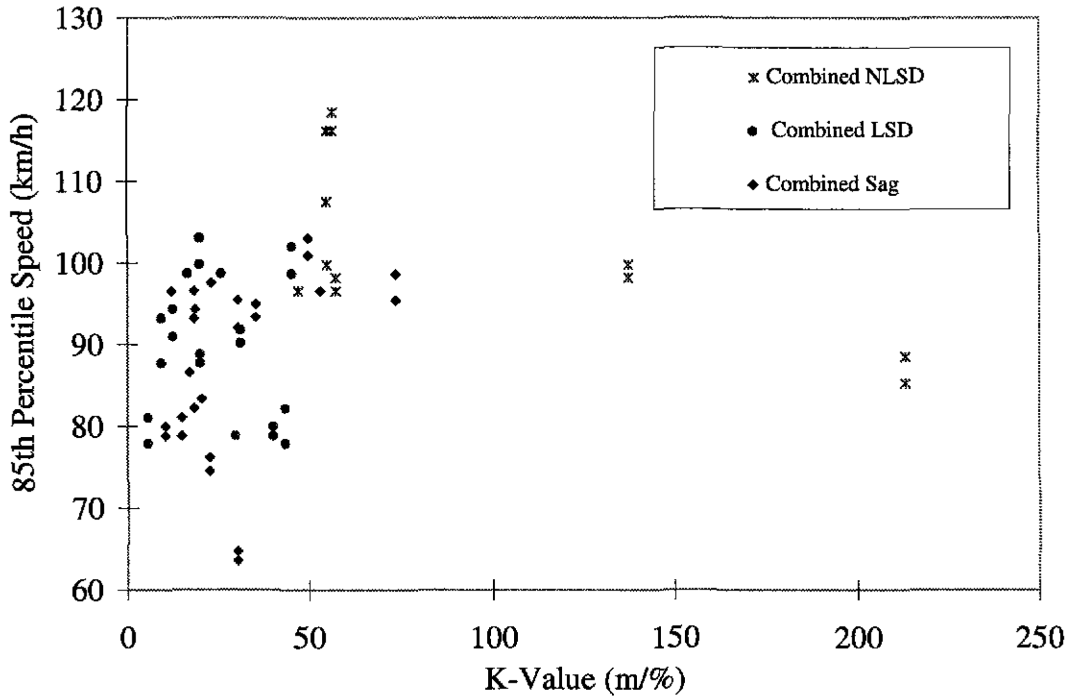


Figure 2-6. Combination Curves: V_{85} Versus K.[1]

Tangents

Part of the FHWA study was to evaluate the applicability of alignment indices as estimators of 85th percentile speeds on long tangents of two-lane rural highways. Alignment indices use the geometric characteristics of the roadway to provide quantitative measures of the general character of a roadway's alignment. Researchers hypothesized that the previous geometry of the roadway influences the subsequent speed expectations and desires of motorists. Therefore, these indices, which are based on the upstream alignment, can possibly reflect the expectancy of motorists when estimating their desired speeds on long tangents. The findings indicated that combinations of alignment indices and other geometric variables were not able to significantly predict the 85th percentile speeds of motorists on long tangents of two-lane rural highways. The 85th percentile tangent speeds on two-lane rural highways were determined to be affected by the region of the country and the vertical grade of the tangent.

Previous Studies

Recent studies have demonstrated that a noticeable disparity exists between design and operating speeds on two-lane rural highways. In a 1991 *Public Roads* article on advisory speed setting criteria, Chowdhury et al.[4] reported on speed data for 28 horizontal curves in three states (Maryland, Virginia, and West Virginia). They measured the 85th percentile speed and determined 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

(50.3 mph) or less had 85th percentile speeds that exceeded the design speed. Only on the single 97 km/h (60.3 mph) design speed curve was the observed 85th percentile speed less than the design speed.

In a previous FHWA study, speed data were collected at 138 horizontal curves on 29 rural two-lane highways in five states (New York, Oregon, Pennsylvania, Texas, and Washington) in three geographic regions.(2) Inferred design speed was determined from the standard superelevation equation given the degree of curvature and measured superelevation rate near the midpoint of the curve, and assuming that the AASHTO maximum coefficient of side friction was not exceeded. The data, shown in Figure 2-7, indicate that the 85th percentile speed exceeded the inferred design speed on all but two curves with design speeds of 80 km/h (49.7 mph) or less. In contrast, the 85th percentile speed was less than the inferred design speed for all curves with design speeds of 110 km/h (68.4 mph) or more. For the curves with 100 km/h (62.1 mph) design speeds, an almost equal number had 85th percentile speeds greater than and less than the inferred design speed. The disparity between the 85th percentile speeds and inferred design speeds is greatest for the lowest design speeds. The data in these studies clearly show that the radius of the horizontal curve affects operating speed.

The recent NCHRP study on stopping sight distance measured operating speed on limited sight distance crest vertical curves.(3) Figure 2-8 shows the measured speeds versus inferred design speed. The plot indicates that as the inferred design speed increases (i.e., greater available sight distance), operating speeds are higher. The reduction in speed between a control location and crest vertical curve was also determined in the study. The data indicated that available sight distance appears to influence mean reductions. Specifically, the mean reductions in speed between the control and crest sections tend to increase as available sight distance is decreased; however, the reduction in speed is less than that suggested by the current AASHTO criteria.

McLean(5,6) 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 (55.9 mph) had 85th percentile speeds that were consistently faster than the design speed; whereas curves with design speeds greater than 90 km/h (55.9 mph) 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.

Predicting Tangent Speeds

The estimation of speeds on curves may be easier than the prediction of speeds on tangent sections because of the strong correlation of speeds on a few defined and limiting variables, such as curvature, superelevation, and the side-friction coefficients between road surface and tires. On tangent sections, however, the speed of vehicles is dependent on a wide-array of roadway characteristics, such as the length of the tangent section, the radius of the curve prior to and after the section, cross-section elements, vertical alignment, general terrain, and available sight distance. Few studies have dealt with this issue to date because a considerable database is necessary to identify any significant trends, and a substantial modeling effort is required. An attempt was made using operating speeds on 162 tangent sections of two-lane rural highways.(7) The work developed models for speed prediction based on the geometric characteristics available.

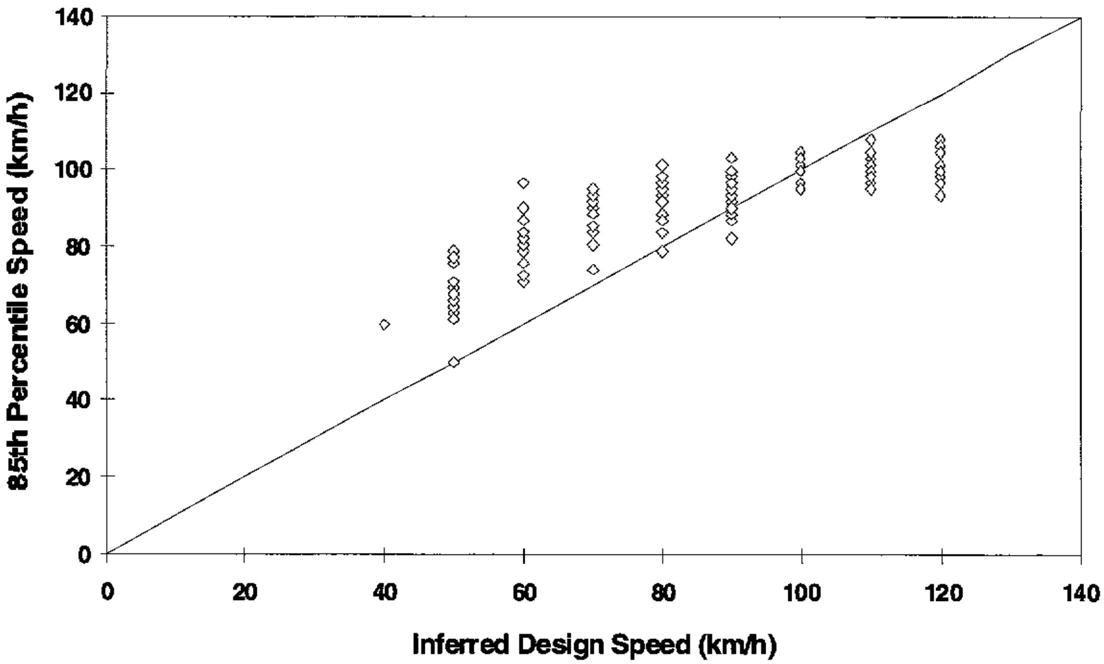


Figure 2-7. 85th Percentile Speed Versus Inferred Design Speed for 138 Rural Horizontal Curves.(2)

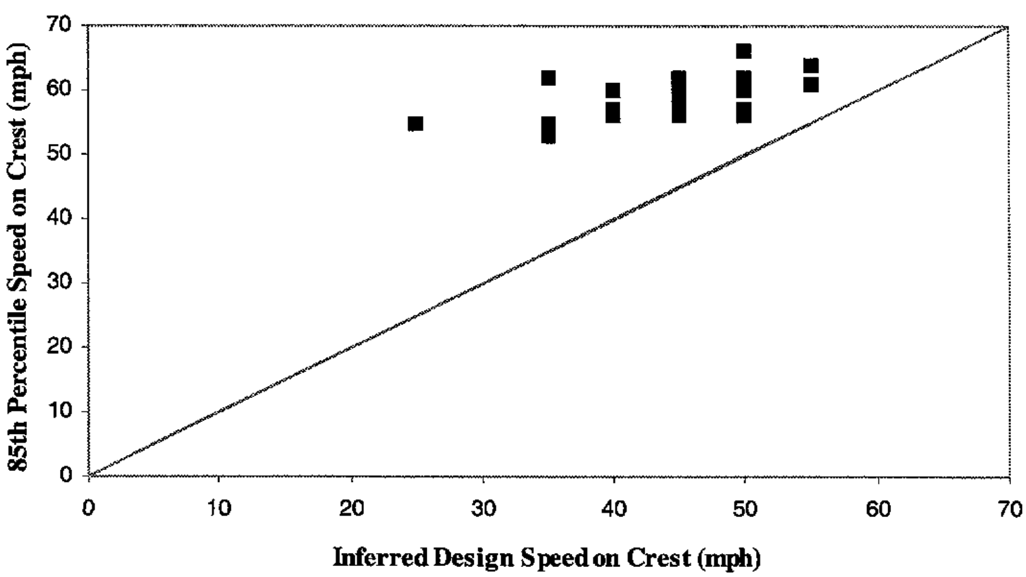


Figure 2-8. 85th Percentile Speed Versus Inferred Design Speed for Limited Sight Distance Crest Vertical Curves. (3)

Initially, a one-model approach was used; however, because of the low R^2 value, a family of models was developed that better predicted operating speeds.

The analyses showed that when determining 85th percentile speeds in the middle of a tangent section, it is necessary to observe a longer section—one that includes the preceding and succeeding curves — since these constitute the primary variables affecting speed. The influence of other, secondary geometric variables was investigated and found to not impact speed as much as the primary variables. Several geometric measures characterizing the geometry of the entire section (the tangent and attached curves) were developed, and the best measure was adopted for the development of the prediction models.

After considerable examination of the 162 sites, it was decided to assemble the data into four groups of similar characteristics. Separate prediction models for the 85th percentile speed were developed for each of the four groups and are listed in Table 2-2. The models for Groups 1 and 2 provided a good fit to the data and could be adapted for prediction purposes during the planning process for new two-lane highways. The models for Groups 3 and 4 were preliminary and clearly need additional data. Further research was also suggested on the impact of some secondary variables, such as the cross-section elements (lane width and roadside characteristics) and the longitudinal slope on the 85th percentile speed on two-lane rural highways.

Table 2-2. Models to Predict Speeds on Two-Lane Rural Highways Tangent Sections.[7]

Group	Description	Model	R^2
1	small radii (≤250 m [819.7 ft]) small tangent lengths (< 150 m [491.8 ft])	SP = 101.11 - 3420/GMs $GMs = (R_1 + R_2)/2$	0.553
2	small radii (≤250 m [819.7 ft]) intermediate tangent length (150 to 1000 m [491.8 to 3278.7 ft])	$SP = 105.00 - 28.107/e^{(0.00108 \times GML)}$ $GML = [TL \times (R_1 + R_2)^{1/2}]/100$	0.742
3	intermediate radii (> 250 m [819.7 ft]) intermediate tangent length (150 to 1000 m [491.8 to 3278.7 ft]) GML (1500 to 7500)	SP = 97.73 + 0.00067 GML $GML = [TL \times (R_1 + R_2)^{1/2}]/100$	0.200
4	large tangent length (> 1000 m [3278.7 ft]) "reasonable" radii (i.e., does not violate the minimum-radius criterion for assumed design speed of road)	$SP = 105.00 - 22.953/e^{(0.00012 \times GML)}$ $GML = [TL \times (R_1 + R_2)^{1/2}]/100$ (Note: only based on 6 points; considered a preliminary model)	0.838

Where: R_1 = Upstream radius (m)
R_2 = Downstream radius (m)
TL = Tangent length (m)

LOW-SPEED URBAN STREETS

AASHTO has separate design procedures for low-speed urban streets. The following points summarize the AASHTO[8] philosophy behind low-speed urban street design:

- On low-speed horizontal curves, drivers have developed a higher threshold of discomfort.
- When using the low-speed method of distributing superelevation and side friction factor, none of the lateral acceleration is typically counteracted by superelevation, unless the maximum side friction factor is obtained.
- For sharp curves, the side friction factor remains at maximum, while the superelevation is used in direct proportion to the continued increase in curvature, until superelevation reaches the maximum.
- The 1994 AASHTO Design Policy presents specific tables and figures for the design of low-speed urban streets (see Figures III-18 and III-19 and Table III-16). These tables present minimum curve-radii for the design of low-speed urban horizontal curves.

Researchers[9] examined the relationship between vehicle operating speeds and geometric design elements in the low-speed urban street environment. Low-speed was defined as below 64 km/h (40 mph). The objective of the research was to identify the geometric roadway elements (horizontal alignment, vertical alignment, and cross section), land-use characteristics, traffic engineering elements, and driver/vehicle characteristics that affected drivers' choice of operating speed. Data were collected at 27 sites within central Pennsylvania. The site selection was conducted to provide sites with variability in horizontal alignment, vertical alignment, and cross section.

One objective of the study was to develop a speed-estimation model for low-speed urban streets. The following variables were found to significantly affect operating speed in the low-speed urban environment: critical design speed (similar to 'inferred design speed' referenced in other reports); degree of curve; available stopping sight distance; available decision sight distance; absolute value of grade; road configuration (i.e., two-lane vs. two-lane with two-way, left-turn lane [TWLTL]); lane width; superelevation; type of curb; road surface; hazard rating; distance to and severity of lateral obstructions; land use; number of driveways; number of intersections; and proximity to the Central Business District.

The 85^{th} percentile speeds observed at the central Pennsylvania sites are shown in Figure 2-9. There are several interesting trends in these data:

- For study segments with low critical design speed (points to the left of Figure 2-9), curve radius controls the design speed. The 85^{th} percentile operating speed is above the critical design speed for nearly all these segments of streets.
- Although 85^{th} percentile operating speed exceeds the critical design speed in the lower range, there is a strong linear relationship between operating speed and horizontal alignment (this is shown in Figure 2-9 by the clustering of data paralleling the line for where 85^{th} percentile operating speed equals critical design speed).

- As critical design speed increases beyond 90 km/h (55 mph), the 85th percentile speeds are significantly lower than the critical design speed. In this range there is little relationship between operating speed and critical design speed. However, other variables apparently have an influence on drivers' choice of operating speed because the speeds do not increase beyond 90 km/h (55 mph).

In the statistical analysis of this study, it was shown that the use of 85th percentile speed masks the true variability of the observed operating speed. The aggregation of the data for analysis can lead to two false conclusions about the speed relationships of geometric elements. First, the analysis may overstate statistical significance of a variable. Second, some variables may not show statistical significance when a statistically significant relationship does exist. Because of these findings it is important to not only look at the relationship of the 85th percentile speeds but also the variability of the individual speed observations.

A more sophisticated analysis of the data was recently completed [10] using a mixed model statistical approach with repeated measures. Mixed models are a technique used in many other

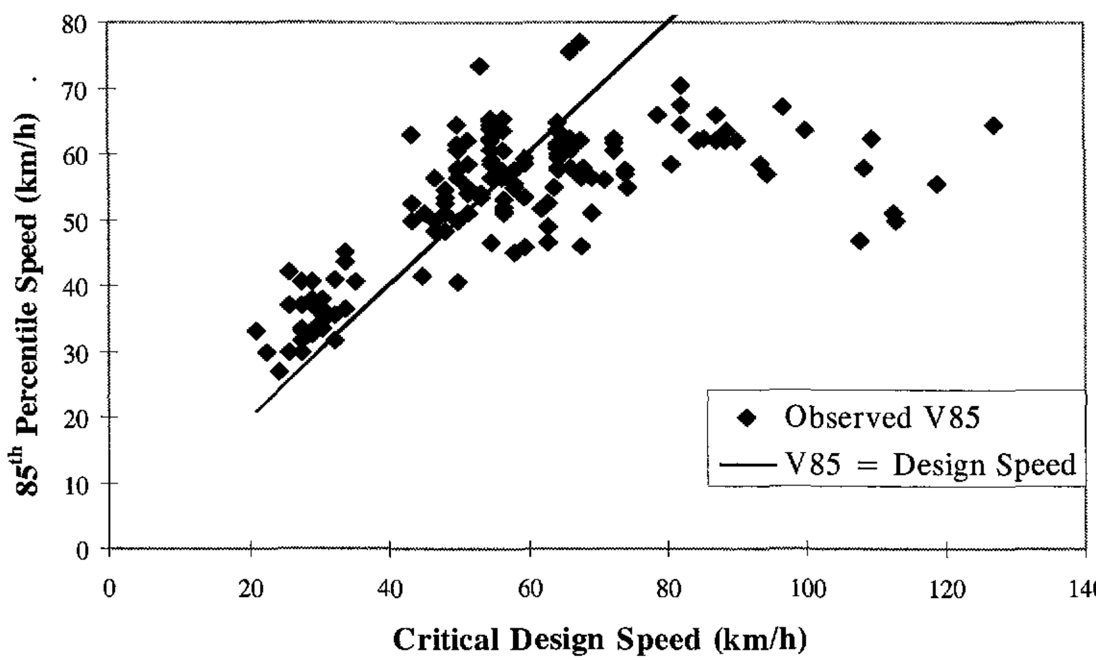


Figure 2-9. 85th Percentile Speeds on Low-Speed Facilities. [9]

disciplines, including the areas of travel behavior in transportation. The data collected on individual vehicle speeds tracked through a study site allow this technique to be applied to the operational effects of geometrics. The power of a mixed model approach is that it accounts for the random effect in the database (such as the data collection sites themselves) with modeling the fixed geometric effects. Because data were collected at several points along each roadway, the analysis also applies a repeated measures approach that addresses the effect caused by the same subjects traversing a roadway. The assumptions for the standard linear model of independent error terms and constant variance can be relaxed because the variance and within-subject correlation can be directly modeled.

The following items were identified from the mixed model analysis of vehicle operating speeds on low-speed urban streets:

- The mixed modeling approach provides a more appropriate method of analyzing vehicle speed observations at multiple sites and sensors with varying geometric characteristics.
- Modeling the speeds at the midpoint of the curve found that the following three geometric variables help explain the variability in speed: degree of curvature, lane width, and hazard rating. These variables indicate that the horizontal curve along with some cross section variables have an influence on drivers' selection of speed.
- When the analysis is conducted at sites other than the midpoint of the curve, the site variable explains more variability, and the geometric fixed effects are smaller.
- A multi-point analysis was performed using the data from sensors located 45.7 m (150 ft) before the curve and at the PC, midpoint, and PT of the curve. The mixed model approach appropriately described the data and influence of site, sensor, and geometric fixed effects; however, the variability across these sites and sensors is not well explained by the geometric fixed effects.

An Arkansas study examined the relationship among urban street function (i.e., arterial versus local traffic), width, and resulting speed.[11] Crash data from the roadways studied also were considered. The objective was to determine if the wider streets did in fact have more objectionable traits (e.g., higher speeds or crash rates) than did the narrower streets, taking street function into account. Six two-lane streets in a small city were considered; the predominate focus of the study was an old neighborhood with streets in a grid layout. For the streets having more local street characteristics (such as shorter length), the data did show a statistically significant difference between the mean speeds on wider and narrower street segments. When adjusted by eliminating vehicles that turned onto or off of the street in midsegment, the magnitudes of the differences were less than 7 km/h (4.3 mph), for the most part. Both mean and 85th percentile speeds trended downward with narrower widths. The findings suggest that street width may play a small role in vehicle speed, but other factors such as trip function may be more significant determinants of the average and 85th percentile through vehicle speeds.

SUBURBAN ARTERIALS

A recent TxDOT project examined the relationship between design speed, operating speed, and posted speed limit.[12] During the 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. In other words, inferred design speed (for drivers at vertical curves) and curve radius (for drivers at horizontal curves) influence the speed of drivers. Figure 2-10 illustrates the 85th percentile speed measured on horizontal curves by curve radius. The regression results are consistent with other research on horizontal curves that suggest 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 2-11 shows the relationship between inferred design speed and 85th percentile speed on vertical curves. Two interpretations exist, depending upon whether data from one site is included. The inferred design speed of the vertical curves had minimal influence on 85th percentile speed when Site VC-6 data are included. However, when the data from Site VC-6 were excluded, the relationship between inferred design speed and 85th percentile speed became more pronounced. Therefore, additional data are needed to determine which theory is valid.

The effects of other variables were controlled by specifying site selection criteria that limited the range of values of those variables. The study also attempted to determine whether access density has an effect on driver speed. Access density is defined as the frequency of all approaches (i.e., driveways and intersections) within the roadway section. It is expressed on a per kilometer basis. The results from the study were mixed. Access density appeared to influence speed at horizontal curves when very low densities exist. It did not influence speed at the vertical curve sites and the horizontal curve sites with higher approach density values (greater than three approaches per km).

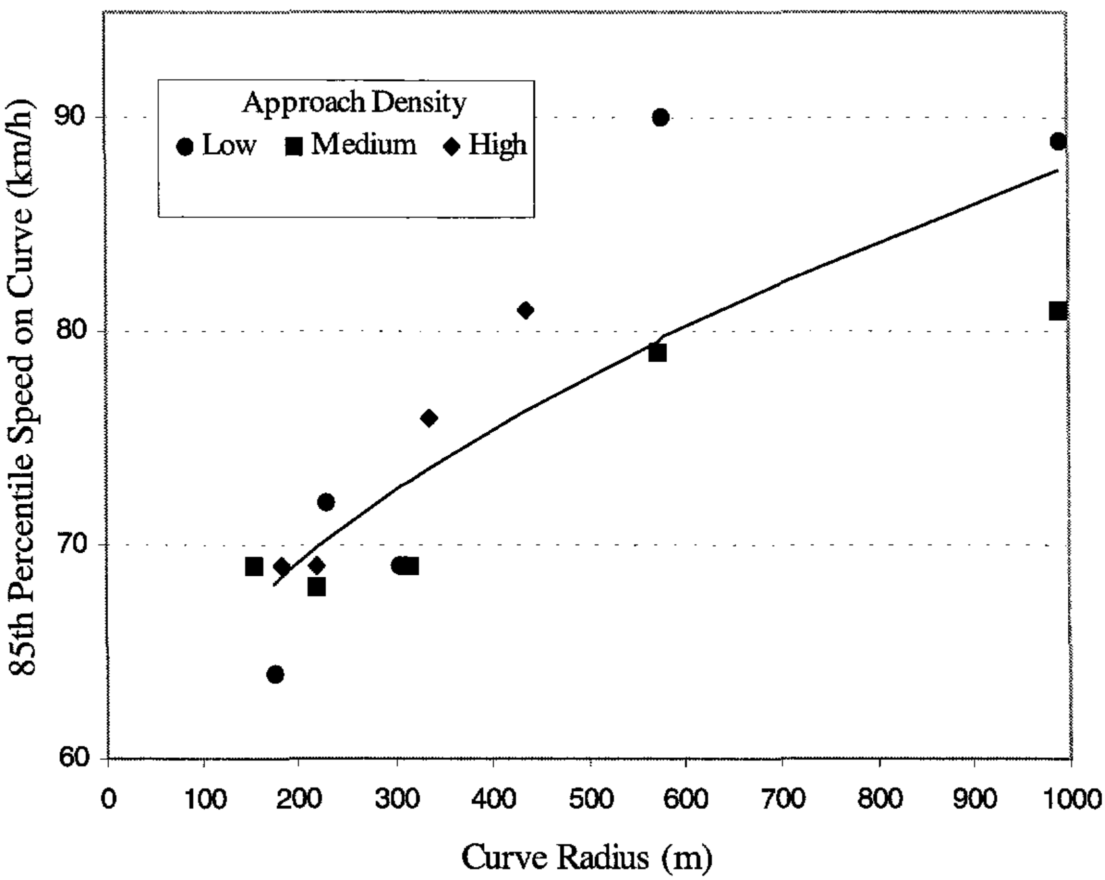


Figure 2-10. 85th Percentile Speed on Suburban Horizontal Curves Versus Curve Radius and Approach Density. [12]

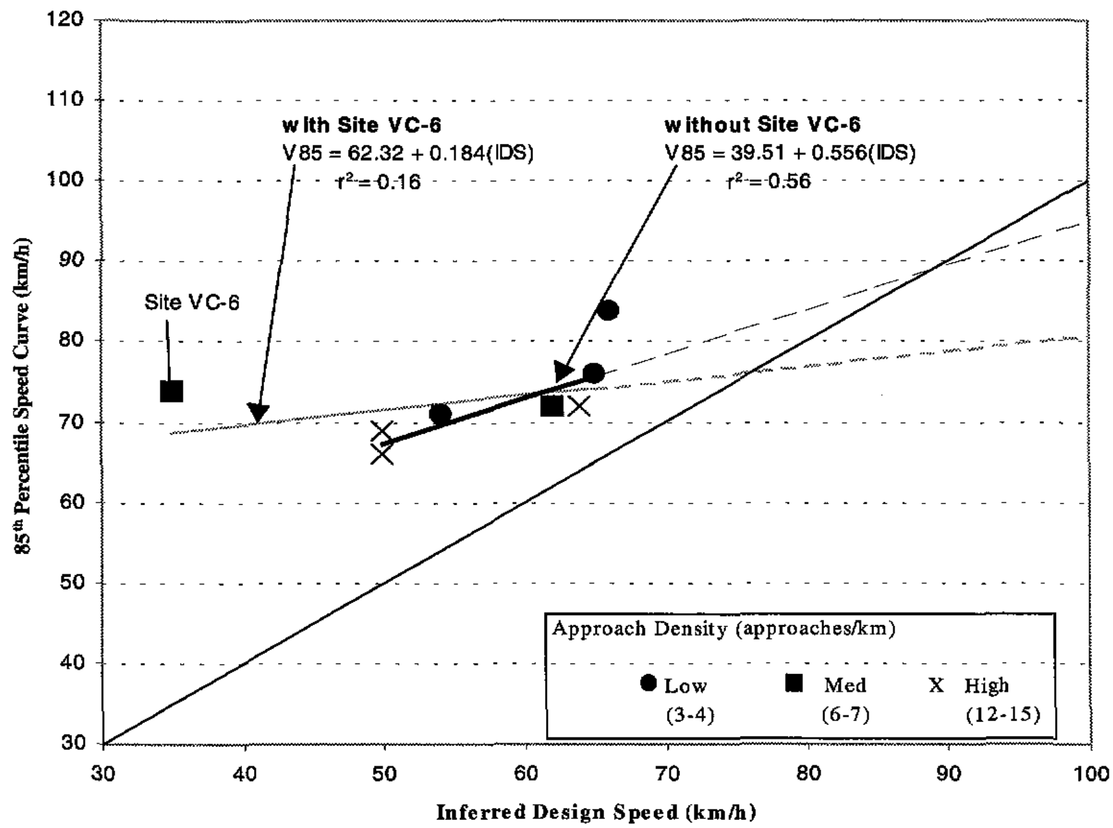


Figure 2-11. Regression Analysis Results for 85th Percentile Speed and Inferred Design Speed. [12]

FRONTAGE ROADS

The effects of access density on speeds on frontage roads were also examined in a TxDOT project that developed level of service techniques for frontage road evaluations.[13] Travel time, volume, and access density data were collected for 20 one-way frontage road sites and nine two-way frontage road sites. A distance measuring device was used to collect the travel time/distance data for approximately eight to 10 runs along each site. Note that the data are not free flow data; in other words, the speeds recorded are influenced not only by the geometry of the roadways but also by other vehicles. The data could show both the influence of the roadway environment and traffic considerations. Figure 2-12 shows an example of the speed data by distance for one of the sites. The site diagram on Figure 2-12 demonstrates the location of the ramps and intersections. This plot, as well as all the plots from the study, clearly demonstrates the effect of signals on the operations along a suburban roadway.

The collected data were divided into links, which were defined as the roadway between intersections and/or ramps (e.g., the roadway between an intersection and an entrance ramp, an entrance ramp to a exit ramp, etc.). Figure 2-13 illustrates the relationships between average speed and access density (called in this study as accesses per kilometer, acs/km) for each link included in the 20 one-way frontage road field sites that had speed limits of 72 km/h (44.7 mph) and greater. Observing this figure shows highly variable speeds at low ranges of access density; however, the variability decreases with increasing access density. The data also show that speed is slower for high access density. A critical access density value exists at approximately 20 acs/km (32.2 acs/mi). For example, below 20 acs/km (32.2 acs/mi), maximum speeds around 90 km/h (55.9 mph) are observed. For access densities above 20 acs/km (32.2 acs/mi), most of the speeds observed do not exceed 72 km/h (44.7 mph). At 20 acs/km (32.2 acs/mi), access points (i.e., driveways and unsignalized intersections) are spaced at an average of 50 m (164 ft) apart.

These observations support the hypothesis that access density influences driver behavior. Based on the findings from the frontage road study, the number (or spacing) of driveways and unsignalized intersections affect drivers' speeds when a threshold value is exceeded. Below that critical number of driveways/unsignalized intersections, drivers' speeds do not appear to be influenced.

The findings for the two-way frontage road sites were similar to the findings for the one-way frontage road sites. Figure 2-14 illustrates the relationship between average speed and link access density for two-way frontage roads. The critical access density occurs at approximately 16 acs/km (25.8 acs/mi). Therefore, two-way frontage road operations are noticeably influenced when densities are above approximately 16 acs/km (25.8 acs/mi). Increases in travel time of about 10 to 15 percent may exist for access densities above this critical value.

Volume also affected speeds on the two-way frontage roads. Figure 2-15 shows the relationship between average speed and volume per lane for each link on the nine study sites. As shown in this figure, speeds are highly variable at low volumes, and the variability decreases with increasing volume. In addition, the maximum speeds begin to drop above approximately 400 vehicles per hour per lane (vphpl). Below 400 vphpl, maximum speeds of 90 km/h (55.9 mph) are observed, while above 400 vphpl, most speeds are below 72 km/h (44.7 mph). For example, the maximum speeds for Site 27 exceed 89 km/h (55.3 mph) for volumes below 400 vphpl but do not exceed 64 km/h (39.8 mph) for volumes above 400 vphpl. Therefore, for the two-way frontage road sites studied, a critical volume of approximately 400 vphpl existed above which traffic operations began to break down. Above 400 vphpl, travel times may increase by as much as 10 to 15 percent.

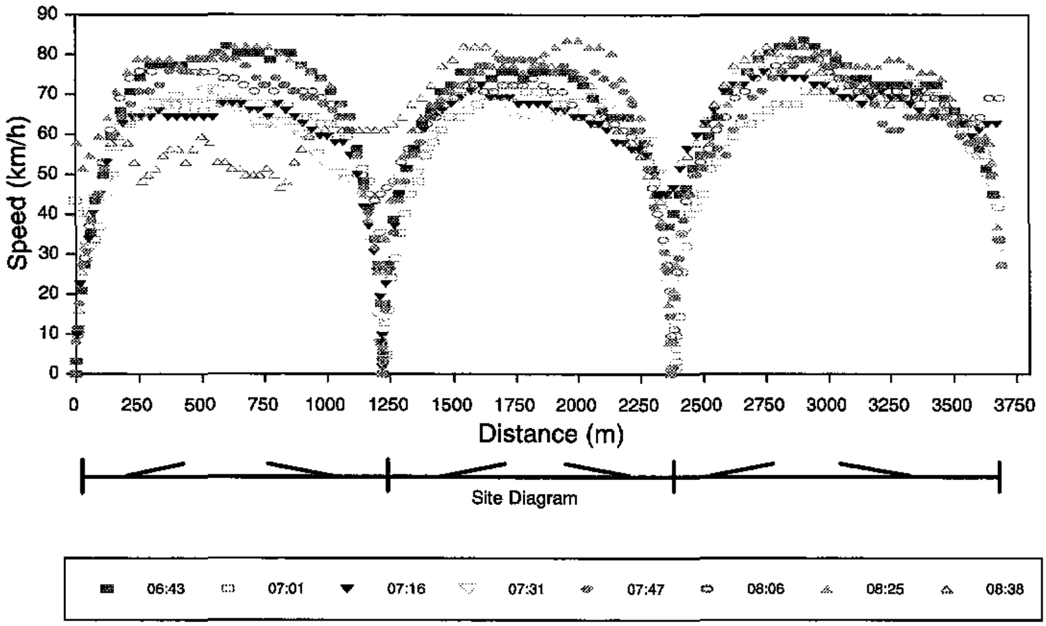


Figure 2-12. Speed Versus Cumulative Distance for One-Way Frontage Road Site.[13]

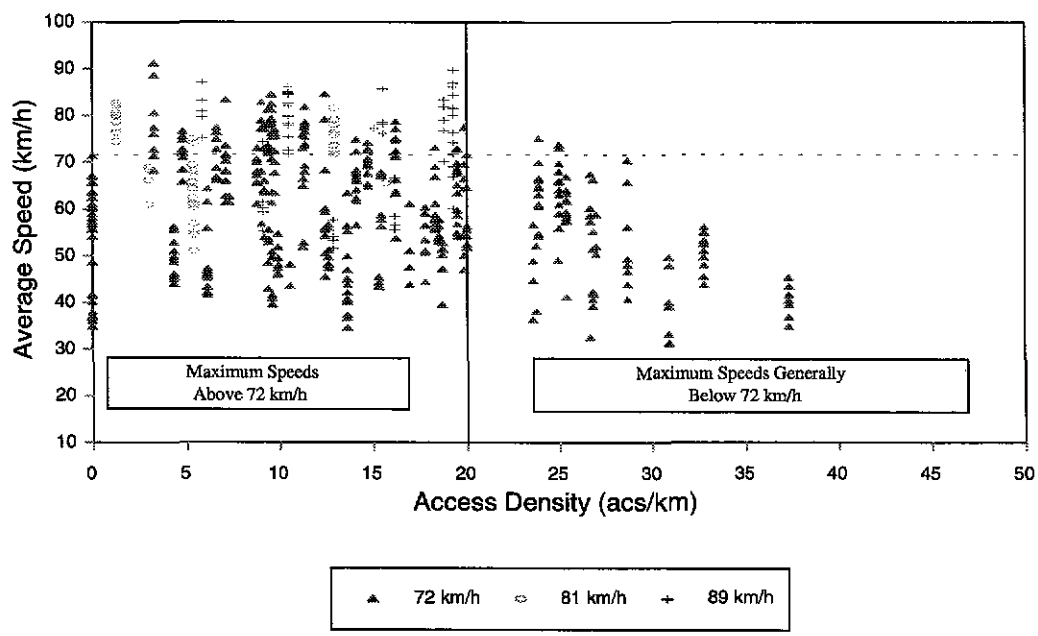


Figure 2-13. Average Speed Versus Access Density for Speed Limits of 72, 81, and 89 km/h on One-Way Frontage Roads.[13]

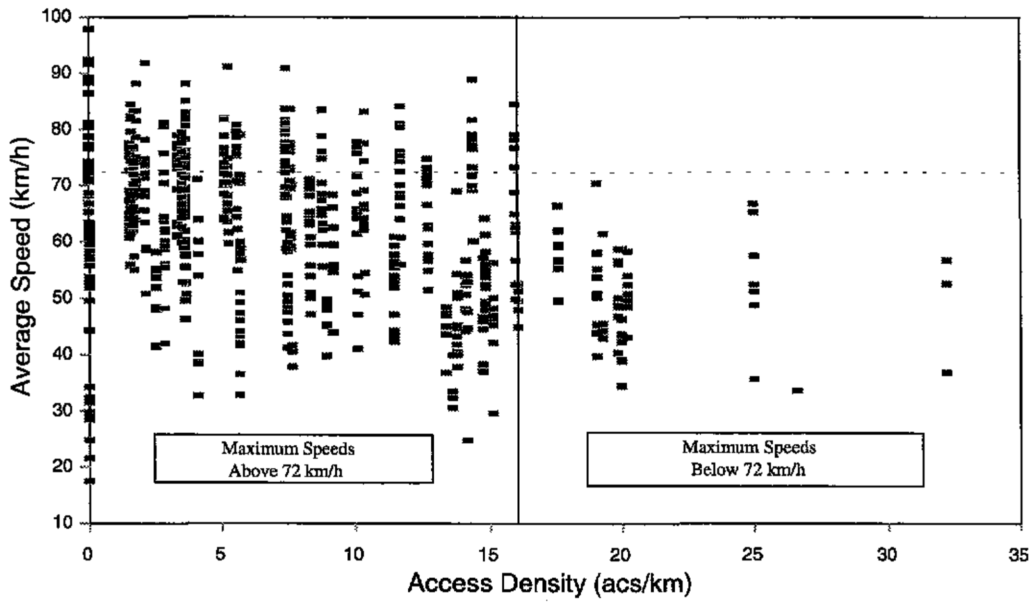


Figure 2-14. Average Speed Versus Access Density for Two-Way Frontage Roads.[13]

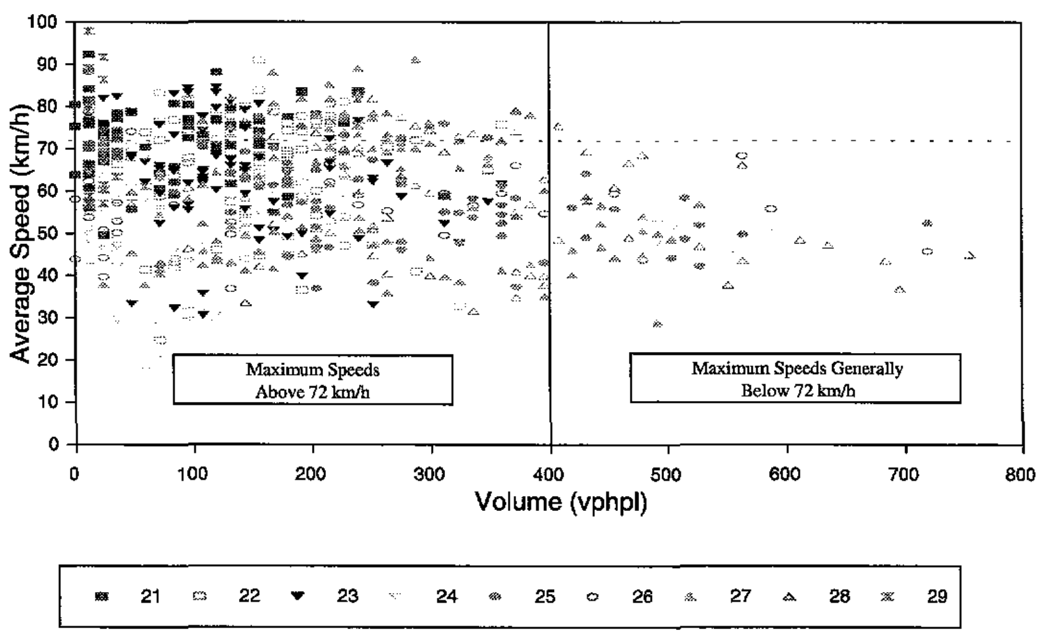


Figure 2-15. Average Speed Versus Volume for Two-Way Frontage Roads.[13]

FREEWAYS

A case study was conducted on the effects of visibility and other environmental factors on driver speed on a 161 km (100-mile) stretch of Interstate 84 in southeast Idaho and northwest Utah.[14] Sensors measured three types of data: traffic, visibility, and weather. During normal conditions (i.e., sunny, clear days, without wind, with very high visibility), the vehicles' speeds were fairly uniform and nearly always between 97 and 113 km/h (60 and 70 mph). The speed limit during data collection was 89 km/h (55 mph), and the average daily traffic was 4,500 vehicles, which was considered too low to be a factor affecting vehicle speeds. Results from multiple regression analyses found that the following affected driver speed:

- visibility affects speed according to a logarithmic relationship;
- speeds during daylight are about 1.6 km/h (1 mph) higher than during nighttime;
- speeds during colder temperatures (below freezing) are from 1.6 to 3.2 km/h (1 to 2 mph) lower than during higher temperatures; and
- speeds are lower by 1.1 km/h (0.7 mph) for each 1.6 km (1 mi) that wind speed is above 1.6 to 3.2 km/h (25 mph).

The data presented show that the drivers at the site respond to poor environmental conditions by reducing their speeds. The mean speed reduction for all vehicles was 8 km/h (5 mph) during the two fog events and 19 km/h (11.9 mph) during the 11 snow events. Consistent reductions were shown for both passenger cars and trucks. This response was based solely on the drivers' perceptions of what is safe, with no external information or warning signs. Although drivers do reduce their speeds during poor environmental conditions, this reduction is accompanied by a higher variation in speeds.

URBAN ROADWAYS

In a 1962 study on operating speeds within the urban environment, Rowan et al. 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 an influence on speed reduction.[15] Lateral restrictions (trees and shrubbery) were found to be a greater influence on speed-reduction than development density.

MULTIPLE ROADWAY TYPES

In 1966, Oppenlander reviewed the literature to identify variables influencing spot speed. The variables were organized into driver, vehicle type, roadway, traffic, and environment categories (see Table 2-3).[16] 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.

Table 2-3. Variables Whose Effect on Spot Speeds Has Been Studied.[16]

Variable Group				
Driver	**Vehicle**	**Roadway**	**Traffic**	**Environment**
Age Gender Residence Familiarity Trip distance Ownership of vehicle Passengers' occupation Trip purpose	Type Weight Horsepower Vehicle age	Functional classification Vertical grade Sight distance Number of lanes Direction of travel Lane width Shoulder width & type Presence of curb Presence of median Lateral clearance Road surface condition Roadside development Approach density	Volume Density Headway Traffic signals Traffic signs Pavement Markings Speed zoning	Day vs. night Inclement weather Wet/icy surface Visibility

In 1989, Garber and Gadiraju examined speed variances on 36 roadway locations including interstates, arterials, and rural collectors.[17] Analysis of variance tests were used to determine which traffic characteristics (design speed, highway type, year in which data were obtained, and traffic volume) had a significant effect on average speed and speed variance at the 5 percent significance level. Design speed and highway types were significant, while time and traffic volumes were not significant.[17]

In the Garber and Gadiraju study [17] of 36 roadway locations that included interstates, arterials, and rural collectors sites, and where design speed was used as a surrogate for geometric characteristics, the following were concluded:

- Speed variance on a highway segment tends to be 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 (24.8 and 70.2 mph), speed variance decreases with increasing average speed.
- The difference between the design speed and the posted speed limit has a statistically significant effect on the speed variance.
- Drivers tend to drive at increasing speeds as the roadway geometric characteristics improve, regardless of 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.

In order to reduce speed-related accidents, the authors recommended speed limits for different design speeds, as shown in Table 2-4.

Table 2-4. Recommended Speed Limits to Reduce Speed-Related Accidents.[17]

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)

SUMMARY

Horizontal curves appear to be the most researched design element related to operating speed. As evidenced by the vast amount of studies available on the topic, a definite relationship exists between operating speed and horizontal curvature. In general, as the radii of the curve decreases or the degree of the curve increases, the operating speed decreases. Several models have been developed to predict the operating speed in the curve. Table 2-5 summarizes a sample of these models that predict speed at the midpoint of a horizontal curve.

Table 2-5. Variables Influencing Mid-Point Horizontal Curve Operating Speed.

Influencing Roadway or Roadside Variable	Origin/Author (year)											
	Tarigan (1954)[18]	Dept. of Main Roads, New South Wales (1969)[18]	Emmerson (1969)[18]	McLean (1979)[6]	Glennon (1983)[9]	Lamm (1988)[9]	Krammes et al. (1993)[2]	Islam et al. (1994)[9]	Fitzpatrick et al. (1995)[13]	Poe et al. (1996)[9]	Fitzpatrick et al. (1999)[1]	Poe and Mason (1999)[10]
Degree of Curve	X				X	X	X	X		X		X
Radius		X	X	X					X		X	
Length of Curve							X					
Deflection Angle							X					
Inferred Speed				X						X		
Sight Distance										X		
Grade										X		
Roadside Configuration										X		
Lane Width										X		X
Curbs										X		
Road Surface										X		
Superelevation										X		
Hazard Rating										X		X
Land Use										X		
Access Density										X		
Speed Limit										X		
Centerline										X		
Warning Signs										X		
R-Squared	74	83	n/a	92	84	79	82	98	72	75	53-76	n/a

CHAPTER 3

STUDY APPROACH

This chapter introduces the research study approach used in the project. The objectives of this project were to identify which suburban arterial roadway variables affect speeds and the magnitude of that effect. Several approaches are available for measuring speed. A frequently used method is to record speed at spot locations along an alignment, for example prior to and at the center of a horizontal curve, using pavement sensors and roadway counters. Another method is to continuously record speed. The continuous recording can be made in an instrumented vehicle, using a radar/laser gun connected to a laptop computer, or with video. Because many of the approaches are experimental and no one approach provides all the advantages for achieving the objectives of this research, this research project was split into two phases.

Phase I examined alternative techniques available for collecting the speed and geometric data needed to identify how roadway and/or roadside variables affect speeds on suburban arterials. Two techniques were selected as the most promising and were examined in pilot studies. The results of the pilot studies would direct the larger research effort to be achieved in Phase II.

The two techniques selected and tested in Phase I were termed the Laser Pilot Study and the Individual Driver Pilot Study. This chapter presents an overview for each pilot study, discusses how the roadway variables were selected, and presents how the potential study sites were identified and chosen. The concluding efforts of the pilot studies were to determine which approach would provide the better data sets with consideration of data accuracy and quantity, desired regional representation for the sites, and available financial resources. Another goal of Phase I was to provide guidance on the variables that should be the focus of Phase II.

Phase II refined the better method identified at the conclusion of Phase I to maximize the likelihood of identifying variables that affect speed on suburban arterials. The conclusion of the pilot studies was that the laser approach was the better method. This method was expanded and refined to the larger scale needed for use in Phase II. This chapter presents a brief overview of the approach used in Phase II. Additional details on how the sites were identified and selected and how the data were collected and reduced are contained in Chapter 6.

PILOT STUDIES

Based upon a review of previous research efforts and the research team's current experiences with identifying the relationship between speed and roadway features, the research team selected two pilot studies: Laser and Individual Driver. An overview of these studies follows. Each technique has advantages and disadvantages. Table 3-1 presents the advantages and disadvantages for the two techniques that were selected for this research effort.

Table 3-1. Advantages and Disadvantages for Data Collection Techniques.

Advantages	**Disadvantages**
Continuous speed measurements at a specific site (Laser Gun). Speeds are continuously measured along a section of roadway using laser guns. Potential alternatives to the laser guns are video, radar guns, or pavement sensors connected to traffic counters.	
• Can provide a complete speed profile for a section of roadway for multiple drivers. • Can collect data for multiple vehicles relatively quickly as compared to drivers in an instrumented vehicle. • The speed profile can show the locations where drivers are accelerating or decelerating within the study section.	• Drivers may change speed pattern because they have a radar/laser detector or may notice the data collectors on the roadside. The disadvantage is greater when multiple data collection technicians are present. • Challenge to track vehicles through a very sharp curve when there are many roadside features that may interrupt the tracking process. • The data reduction efforts are greater when the quantity of data collected for each vehicle is larger, for example, when more guns are used or the length of the segment is long.
Continuous speed measurements for a roadway (Individual Driver). Speeds are continuously measured for a driver along a roadway using an instrumented vehicle.	
• Can provide a complete speed profile for a roadway or series of roadways. • Precise speed measurements can be obtained, up to and including detailed speed profiles obtained while traversing features of interest. • Can be used to measure the speed selected for different conditions for a given driver. • Potential to study individual driver characteristics.	• Subjects know that they are part of a study. • Numbers of sites studied are limited by the reasonable amount of time that a subject can be asked to drive before fatigue becomes a factor. • Significant time (and cost) is associated with gathering data for just one subject.

Laser Pilot Study

In the laser pilot study laser guns are used to collect the speed of free-flowing vehicles as they approach the study site, traverse through the study site, and depart the site. Three laser guns were employed at six study sites to obtain comprehensive speed profiles for the horizontal curve and its approaches. The laser guns were wired to laptop computers that recorded data three times per second when the gun was activated. The speed profile was superimposed on the measurements made of the roadway and roadside elements.

Individual Driver Pilot Study

In the individual driver pilot study, six drivers drove through several arterial roadway sections while their speeds and positions on the roadway network were monitored. The drivers were selected from volunteers recruited from TTI. The use of this pool of volunteers permitted greater flexibility in scheduling and provided a cost-effective method to enlist subjects. Researchers selected subjects that represented a variety of demographic groups so as to reduce potential bias in the results.

Following a familiarization period in the vehicle, each subject drove a pre-determined route along several urban arterial roadways in a passenger car provided by the research team. Speeds in test segments were continuously measured and recorded using an on-board laptop computer and distance meter. Subjects were not informed regarding the beginning and end of the test segments to ensure more representative responses. The subjects were instructed regarding the proposed route and shown a map of the route prior to the test, although the accompanying on-board researcher provided appropriate cues regarding the route during the test. The researcher had the means of indicating time periods when the driver was hampered by other traffic or circumstances. The primary measures used to quantify driver performance were speed and speed variation.

IDENTIFICATION AND SELECTION OF VARIABLES

Many factors influence drivers' speed behavior along roadways, including the following:

- vertical curvature,
- grade,
- horizontal curvature,
- number of lanes,
- lane width,
- surface condition,
- curb and gutter/shoulder type,
- shoulder width,
- median type,
- median width,
- lateral clearance,
- roadside development,
- access density,
- stopping sight distance,
- intersection sight distance,
- volume,
- headway,
- posted speed,
- traffic signs,
- traffic signals,
- pavement markings,
- age,
- gender,
- passengers in vehicle,
- vehicle type,
- enforcement practices,
- trip type, and
- speed/behavior of other vehicles.

Factors that traffic engineers can influence include roadway and roadside features. Chapter 2 reviewed the pertinent literature and demonstrated the range of roadway and roadside features that have been found to influence speed. Based upon that review as well as an internal TTI survey, several variables were selected for testing in this study. Following are a summary of the internal TTI survey and the discussion on the variables selected for each pilot study.

Internal TTI Survey

The critical review of the literature shows that horizontal curve has been the most prominent roadway or roadside feature that has been shown to influence speed. Of all the models appearing in Table 2-2, horizontal curve is the only factor that is common. The models were developed from various data and cannot be directly applied to suburban arterials; however, they do provide a good starting point.

A survey was conducted early in this project to help identify the most promising factors to consider during the pilot studies. It was sent to 18 individuals within TTI who are knowledgeable on the subject. A copy of the survey is shown in Figure 3-1. Fourteen surveys were returned. The survey responses were highly varied, but several overall results could be realized. For instance, horizontal curve, number of lanes, lane width, surface condition, lateral clearance, roadside development, access density, volume, posted speed, and vehicle type were factors that all respondents indicated influenced speed at some level. Ranking the responses resulted in the following three most influential factors (appearing in order from most influential to least): horizontal curvature, access density, and posted speed.

Selection of Variables

As a team, the researchers selected horizontal curvature and access density as the key independent variables for the laser pilot study. Ranges for each variable needed to be set to result in sites with varying radii and access density values. For rural two-lane highways, speed is influenced by the radius of a curve when the radius is less than 800 m (2624.7 ft); however, the effect is minimal between 400 and 800 m (1312.3 to 2624.7 ft).[1] Given that speeds are generally lower on suburban arterial than rural roadways, smaller radii were selected. The following categories were chosen for radius: greater than 400 m (1312.3 ft), between 400 and 200 m (1312.3 and 656.2 ft), and less than 200 m (656.2 ft). A study on frontage roads found that access densities greater than 16 access points per kilometer (acc/km) influence speeds on two-lane, two-way frontage roads.[13] The range for access density for this study was set at less than 10 (16.1), between 11 and 20 (17.7 and 32.2), and greater than 20 access points per kilometer (pts/km) (32.2 pts/mi). A site that satisfied each possible combination was sought during the site selection efforts.

Based on findings in the literature and the survey of TTI researchers, four factors were initially selected for examination in the individual driver pilot study: median type, lateral clearance, roadside development, and access density. Roadside development was later dropped from consideration because of concerns about confounding. Specifically, researchers found that access density and roadside development generally varied in a paired fashion; that is, when access density was high, commercial development tended to be high; and when access density was low, commercial development tended to be low. Although this confounding obviously does not occur everywhere, it was a strong enough relationship that it would be difficult to differentiate between the effects of the two factors.

Using the results of the critical literature review and previous experience, the research team set site selection controls and criteria. The goal was to limit the effects of the variables not

FACTORS AFFECTING OPERATING SPEED ON URBAN ARTERIALS

Variable Class	Variable	Classification[A] (circle one)			If a Study Factor (SF) please rank[B]
Roadway	Vertical Curvature	SF	CF	NS	
	Grade	SF	CF	NS	
	Horizontal Curvature	SF	CF	NS	
	Number of Lanes	SF	CF	NS	
	Lane Width	SF	CF	NS	
	Surface Condition	SF	CF	NS	
	Curb & Gutter/Shoulder Type	SF	CF	NS	
	Shoulder Width	SF	CF	NS	
	Median Type	SF	CF	NS	
	Median Width	SF	CF	NS	
	Lateral Clearance	SF	CF	NS	
	Roadside Development	SF	CF	NS	
	Access Density	SF	CF	NS	
	Stopping Sight Distance	SF	CF	NS	
	Intersection Sight Distance	SF	CF	NS	
Traffic	Volume	SF	CF	NS	
	Headway	SF	CF	NS	
	Posted Speed	SF	CF	NS	
	Traffic Signs	SF	CF	NS	
	Traffic Signals	SF	CF	NS	
	Pavement Markings	SF	CF	NS	
Driver	Age	SF	CF	NS	
	Gender	SF	CF	NS	
	Passengers in Vehicle	SF	CF	NS	
Vehicle	Type	SF	CF	NS	
		SF	CF	NS	
Other		SF	CF	NS	

[A] *Study Factor* - a variable affecting operating speed that should be studied because it may influence operating speed significantly

Control Factor - a variable possibly affecting operating speed but one that should be a focus of the study

Non-Significant - a variable that in your opinion does not affect operating speed

[B] Use a 1 for the most significant study factor, a 2 for the second-most, and so on

Figure 3-1. Internal TTI Survey.

selected for study. For example, lane width was controlled by selecting sites with only 3.05 to 3.66 m (10 to 12 ft) lanes. Table 3-2 summarizes the site selection and criteria used to limit the effect of factors not varied in the pilot study.

Table 3-2. Site Selection Variables and Controls.

Variables	Controls
Area Type	Urban to Suburban
Grade	-4 to +4
Number of Lanes	4
Lane Width	3.05 to 3.66 m (10 to 12 ft)
Surface Condition	Fair to good
Curb & Gutter Presence	Curb & gutter only
Stopping Sight Distance	Adequate
Intersection Sight Distance	Adequate
Headway	≥5 second headway and tailway
Posted Speed	56 to 88 km/h (35 to 55 mph)
Vehicle Type	Passenger car
Distance from/to Signal or Stop Sign	> 300 m (984.3 ft)
Distance from Another Curve	> 200 m (656.2 ft)
Lateral Clearance	Very restricted to sparse
Roadside Development	Residential, commercial, industrial, or park
Median Type	Raised, TWLTL, none

SITE SELECTION

For the pilot studies, potential sites were identified only in the Bryan/College Station area (Phase II efforts would include sites located throughout Texas). Testing in this area provided the researchers with a reasonably diverse set of roadways for testing, while remaining close to support facilities for modifying equipment or procedures. Plan and profile sheets were obtained from either TxDOT, the City of Bryan, the City of College Station, or Texas A&M University (depending on the jurisdiction of the potential study site). Field visits were then conducted to evaluate the feasibility of the potential study sites.

Laser Pilot Study

Table 3-3 summarizes the findings of the efforts for the laser pilot study. Each row in Table 3-3 represents a separate horizontal curve initially believed to be a potential study site. Because a curve can have significantly different access density values on each side, a curve essentially represents two potential study sites. Therefore, a total of 34 potential study sites were

Table 3-3. Potential Study Sites for the Laser Study.

Site Number	Street Name	Direction	Access Density (per km)	Radii (m)	Curve Length (m)	Distance Before		Distance After	
						TCD	Curve	TCD	Curve
1a	Jon Kimbrough	WB	5	152	193	837			234
		EB	5	152	193		234	837	
1b	Jon Kimbrough	WB	6	122	177		234		486
		EB	6	122	177		486		234
1c	Jon Kimbrough	WB	7	167	258		486	690	
		EB	7	124	190	690			486
2a	Briarcrest	WB	6	388	207		17	242	
		EB	1	388	207	242			17
2b	Briarcrest	WB	1	437	560	29			17
		EB	3	437	560		17	29	
3a	East Villa Maria	WB	0	303	177		120	71	
		EB	3	303	177	71			120
3b	East Villa Maria	WB	3	286	255		143		120
		EB	2	286	255		120		143
3c	East Villa Maria	WB	2	371	289	81			143
		EB	3	371	289		143	81	
4a	West Villa Maria	WB	6	583	333	317			533
		EB	3	583	333	2374			200
4b	West Villa Maria	WB	5	583	249		533		200
		EB	3	583	249		200		533
4c	West Villa Maria	WB	3	565	246		200	2374	
		EB	7	535	216		533	317	
5	S. College	NB	30	125	64	939		321	
		SB	28	125	64	321		939	
6	FM 2818	WB	10	305	394	421		354	
		EB	9	305	394	354		421	
7a	Rock Prairie	WB	4	299	110	299			149
		EB	8	299	110		149	299	
7b	Rock Prairie	WB	4	305	99		149	2500	
		EB	9	305	99	2500			149
8	East 29th	NB	17	159	59	617		901	
		SB	13	159	59	901		617	
9	Texas Ave	NB	18	87	61	363		1046	
		SB	14	87	61	1046		363	

identified and visited. The initial field visits were focused on determining the feasibility of collecting data at the sites. Several key features were identified through these visits, such as:

- validation of the plan and profile information (several plan and profile sheets were very dated);
- measurements not obtained from the plan and profile sheets;
- pavement condition;
- roadside development;
- lateral clearance;
- sight distance adequacy; and
- posted speed.

Desirably, the selected study sites should represent a range of values for the chosen variables. To assist with selecting the study sites, Figure 3-2 was created to illustrate the data shown in Table 3-3. Few of the study sites available have the combination of high access density and long radius. High access density is more commonly associated with older roadways that have smaller radii or with developed areas that would have high signal density. Sites with closely spaced signals would have been eliminated as potential study sites because the signals' influence on driver speed choice could mask or confound the influence of the roadway geometry or roadside characteristic.

Using Figure 3-2 and the study site matrix developed earlier, six sites were chosen for the laser pilot study. The sites chosen are summarized in Table 3-4 and shown highlighted in Figure 3-3. From Figure 3-3, it is evident that the extreme ranges of access density and horizontal curvature were studied. By being able to achieve this, the results should indicate whether or not we should continue with the study of access density and horizontal curvature or focus our efforts on some other potential factors.

Individual Driver Pilot Study

Table 3-5 lists the data collected on potential study sites for the individual driver study. Each row represents a section of roadway that was considered for the study. Field visits to each site provided the information presented in the table and also provided estimates of the travel time between sites. Desirably, participants should spend no more than one hour to one-and-a-half hours driving. Fatigue could become an issue if a participant is spending more than an hour driving.

Geometric variables studied in the individual driver pilot study included:

- median type (none, two way left turn lane (twltl), and raised),
- lateral clearance, and
- access density.

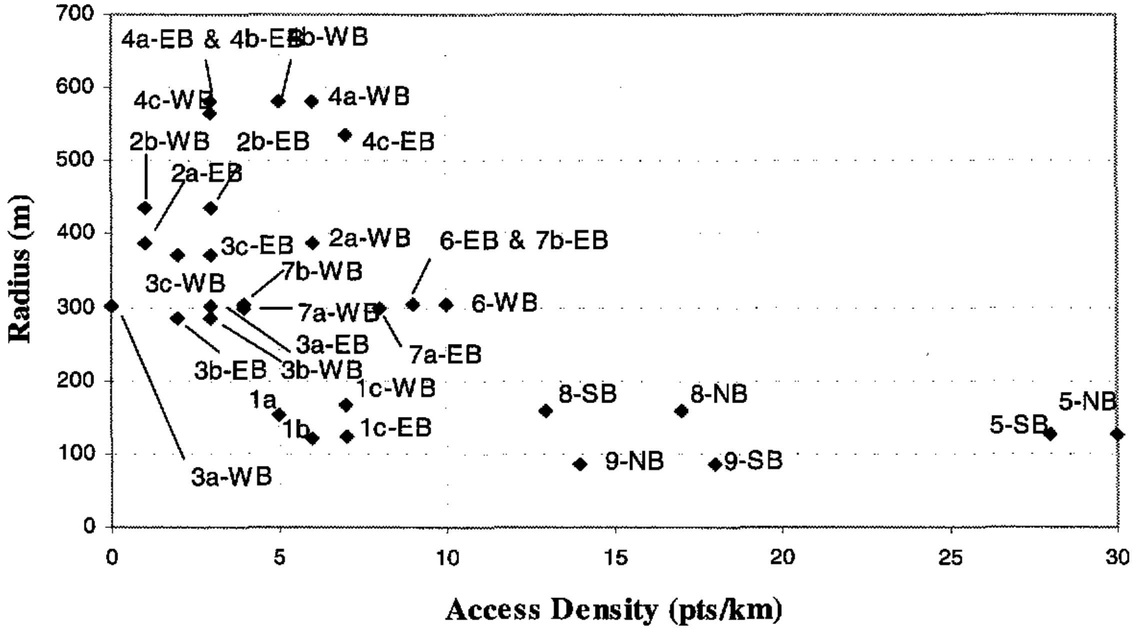


Figure 3-2. Access Density Versus Radius.

Table 3-4. Selected Study Sites for Laser Pilot Study.

Street Name	Direction	Access Density (per km)	Radii (m)	Curve Length (m)	Posted Speed (km/h)	Median Type
Jon Kimbrough	EB	5	152	193	48	Raised
Villa Maria	WB	5	583	249	72	TWLTL
S. College	SB	28	125	64	64	none
29th Street	NB	17	159	59	56	none
	SB	13	159	59	56	none
Texas Ave.	SB	14	87	61	64	TWLTL

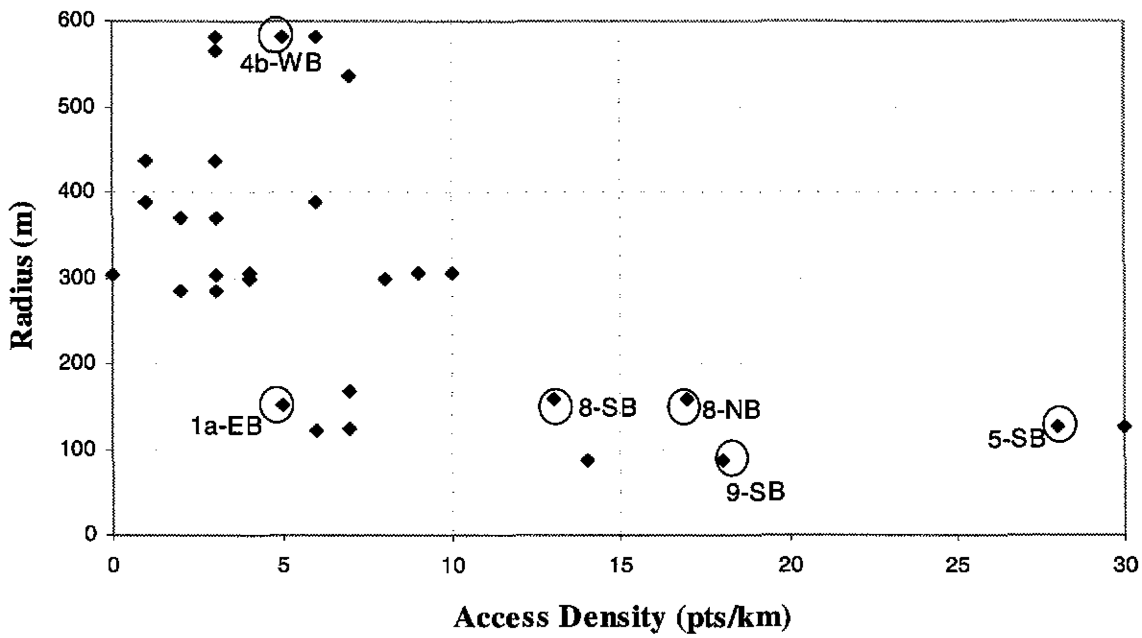


Figure 3-3. Selected Study Sites for Laser Pilot Study.

Although many possible combinations of these factors are possible, only a limited number of combinations could be studied in this pilot effort. The roadways selected for study represented a compromise between obtaining variation between median type, lateral clearance, and access density, and the driving time limitation. Table 3-6 lists the general characteristics of the selected sites.

DATA COLLECTION PLAN FOR PHASE II

While each of the pilot studies provided insight into the effects of roadway/roadside elements on speed, the laser gun study provided data at more sites with a greater variety of test conditions for less cost than the individual driver study. The individual driver study technique was a sound approach; however, it requires extensive resources (both time and funds) to obtain sufficient data to determine which factors influence driver speed. The reasonable maximum time for driving by a participant and the distance between potential study sites are two of the limitations of the technique.

Table 3-5. Potential Study Sites for the Individual Driver Study.

Site	Street Name (boundaries)	Median Type	Radius	Lateral Clearance	Roadside Development	Access Density
1	Villa Maria (Wellborn to FM 2818)	TWLTL	~200 m	6-9 m gen, posts at 1 m	Residential, apartments	Low
3	University (Agronomy to FM 2818)	TWLTL	Tangent	4-6 m South, 2 m North	Texas A&M University	Low
4	University (29th to Spring Loop)	TWLTL	Slight	2 m lightposts, 9-12 m gen	Apartments, commercial, empty	Low
5	University (Spring Loop to SH 6)	TWLTL	Slight	2-3 m light-posts, 9-12 m gen	Apartments, commercial	Low
7	George Bush Drive (FM 2818 and Wellborn)	Raised median	Tangent	5-9 m	Texas A&M University	Low
9	Rock Prairie Road	Raised (4-5 m)	2-300 m slight	3 m poles, 6 m trees	Residential, school, park	Low
10W	29th Street (Coulter and St. Joseph's hospital)	None	Medium	2-3 m	Commercial, residential	Med
10E	29th Street (Briarcrest and Texas)	TWLTL	Medium	2-3 m	Commercial	Med
12	FM 2818 (Hwy 6 and the Bypass)	TWLTL	300	4-9 m	Residential	Low
15	Jon Kimbrough (Research Park to Rec Center)	Raised	150-200 m	6 m	Texas A&M University	Low
16E	Wm. J. Bryan (East of Texas Ave)	pair of 1-way roads	Medium	2-3 m posts	Residential, school	Med
18	College Ave (Downtown and Villa Maria)	N/A	Medium	2 m utility poles	Commercial, residential	Low
19	Finfeather	N/A	Tangent	2 m utility poles, 9 m gen	Commercial, residential	Low
20	Villa Maria (West of FM 2818)	TWLTL	Medium	2 m utility poles, 9 m gen	Residential, empty	Low
21	Briarcrest (east of the Bypass)	TWLTL	Medium	9 m plus	Commercial, empty	Low

Table 3-6. Site Characteristics for Selected Study Sites Used in the Individual Driver Study.

Site	Median Type	Access Density	Lateral Clearance
South College Ave	None	High	Restricted
Finfeather Road	None	Low	Unrestricted
University Drive	TWLTL	Low	Unrestricted
Jon Kimbrough	Raised	Moderate	Restricted

The data collection and reduction methodology to be used in Phase II was similar to the methodology used in the pilot effort. Laser guns were used to collect the speed of free-flowing vehicles through the study sites. A few improvements were made to the process. For example, an additional laser gun was added on extremely sharp curves to minimize the gaps in the collected data. Criteria used to define free-flowing vehicles were also modified. Based on the pilot effort, approximate values of 5 and 3 seconds were used for headway and tailways, respectively, in the Phase II effort. Furthermore, engineering judgement was used in regards to vehicle lane changing and its effect on speed. In the pilot effort, if a vehicle changed lanes while traversing the study site, the data were discarded. In Phase II, engineering judgement was used to determine if the vehicle was impeded in some manner or was simply changing lanes arbitrarily and doing so under free-flow conditions.

The two pilot studies indicated that all of the variables examined (horizontal curvature, access density, lateral clearance, and median type) could have an influence on operating speeds. To allow for a more comprehensive study on the selected variables, the number of variables should be restricted to two or three. In addition, the efforts should be split between examining the geometric variables influencing speeds on horizontal curves and on straight sections. Preliminary findings from this study, as well as previous research, indicate that horizontal curvature has the greatest influence on speed for all roadway classifications. The question then becomes, which, if any, variables affect speed on straight alignments? Speed and geometric data should be collected away from the influence of horizontal curves (and traffic control devices) to be able to answer that question.

The pilot studies demonstrated that horizontal curvature and access density may have the greatest influence on speed. Horizontal curves are measured in meters (or feet), and access density is the number of access points per unit distance and is expressed as pts/km (pts/mi). Of the suggested variables, designers generally have control or influence over the type of median selected for a roadway. Therefore, the following elements and ranges were selected for the horizontal curve sites for Phase II efforts:

- horizontal curvature (less than or equal to 200 m [656.2 ft] and greater than 200 m [656.2 ft]),

- access density (less than 10 pts/km [16.1 pts/mi] and greater than or equal to 10 pts/km [16.1 pts/mi]), and
- median design (TWLTL, raised, and none).

The elements and ranges selected for the straight section sites were:

- access density (less than 10 pts/km [16.1 pts/mi] and greater than or equal to 10 pts/km [16.1 pts/mi]),
- median design (TWLTL, raised, and none), and
- posted speed limit (48 to 56 km/h [30 to 35 mph], 64 to 72 km/h [40 to 45 mph], and 80 to 88 km/h [50 to 55 mph]).

Lateral clearance was measured and evaluated during the study, along with other variables such as speed limit (for curve sections) and lane width. The goal during the project was to collect data at two sites for each potential combination. For example, two sites would have a horizontal curvature of less than 100 m (328 ft) with low access density, and a TWLTL median design. Although it was not possible to fill every possible combination of given ranges for the above variables, researchers focused on achieving a broad range of coverage of each of the study variables. Based upon the goal of two sites per combination, researchers attempted to collect data at a total of 24 horizontal curve sites and 36 tangent sites. Potential study sites were identified in the major urban areas of Texas, such as Houston, Dallas/Ft. Worth, San Antonio, Austin, and others. A similar technique as used in Phase I was used in Phase II for identifying sites; contacts were made at the local TxDOT districts, TTI urban offices, and local agencies for suggestions or recommendations of potential study sites.

Additional information on the individual driver pilot study and the laser pilot study is contained in Chapters 4 and 5, respectively. Details on the data collection and reduction of the Phase II data are contained in Chapter 6. The methodology for analyzing the data was based on developing speed prediction equations for the different conditions. The speed prediction equations used regression to model the relationship between operating speed and the variables (e.g., horizontal curvature, access density, and/or median type). The results of the regression analysis illustrate the magnitude of the effect that each variable has on the speed on a suburban arterial. The approach used and the findings from the analyses are contained in Chapter 7 for the horizontal curve sites and Chapter 8 for the straight section sites.

CHAPTER 4

INDIVIDUAL DRIVER PILOT STUDY

The objective of the individual driver pilot study was to determine whether a study could be efficiently conducted using individual drivers in an instrumented vehicle. The study would need to identify those factors that affect speed on suburban arterials and to determine the nature of that influence. The findings from the pilot study could then be used to guide further research efforts.

DATA COLLECTION

Data collection for the individual driver pilot study centered around the use of a test vehicle that researchers had equipped with recording devices to monitor speed. Subjects drove a Ford Taurus station wagon on open roadways selected to provide a variety of designs and environments.

Drivers

Six subject drivers were drawn from among this agency's employees. Both research and administrative staff were part of the pool of available volunteers. All drivers were required to have a valid U.S. driver's license at the time of the testing. Because of the large number of potential drivers, it was possible to select from among the volunteers such that a relatively diverse group of drivers actually performed the testing. Researchers recruited drivers that represented a relatively wide age range, with equal representation of males and females (see Table 4-1).

It was also considered desirable to provide as diverse an education level as possible considering the available subject pool. The drivers used in the study included a wide range of education levels, as shown in Table 4-1. Additional information obtained from the drivers was the approximate number of miles driven annually and where those miles were driven most.

Testing Equipment

A 1991 Ford Taurus station wagon was used for the study (Figure 4-1). The use of a station wagon provided ample room for instrumentation and a comfortable vehicle for the test drivers. During the testing, the speed in km/h and the location of the vehicle relative to control locations on each roadway were recorded using a laptop computer and data acquisition unit in the rear passenger area of the vehicle (Figure 4-2). Speeds were recorded every 0.3 seconds as the subjects drove through the test roadways. The control program permitted the recording interval to be set by the experimenter (between 0.001 and 2 seconds). The computer created a data file that recorded speed, the time and location associated with each measured speed, the test roadway, and the driver identification number.

Distance and velocity were sensed by means of a Datron electronic (no contact) fifth wheel suspended from the back of the vehicle. Times when the driver was impeded by the presence of other vehicles within an estimated 5 second headway or tailway were denoted by an input to the data file (in the "event" column). The view from a forward-looking video camera from behind the rear-view mirror was recorded on a video cassette recorder. The videotape, used for confirmation of the data, included an imprint of the driver number, run, test roadway, and the running distance and time. The test drivers were aware of the recording being made and were shown the location and orientation of the camera; the drivers did not appear in the videotapes.

Additional data that was recorded during each test run included whether a vehicle was present in driveways or intersections passed on the right side, whether the driver made a right or left lane change, and whether a slow or stopped vehicle was passed.

Table 4-1. Demographic Characteristics of Drivers.

Age (years)	18-24	2
	25-54	3
	55+	1
Gender	Male	3
	Female	3
Education Level	GED or High School Diploma	—
	Some College	3
	Associate Degree	—
	Bachelors Degree	—
	Masters Degree	2
	Doctoral Degree	1
Annual Mileage Driven	0-5,000	1
	5,001-10,000	2
	10,001-15,000	1
	15,001-20,000	2
	Over 20,000	—
Location of Most Driving	Urban Areas	1
	Suburban Areas	2
	Rural Areas	1
	Mix of All Areas	2

Study Sites

Four separate roadways were selected for testing. Pictures of the selected roadways are shown in Figure 4-3. They represent a variety of driving environments. A constraint that weighed in the selection process was that the roadways had to be reasonably close together. Testing of the drivers had to be accomplished within a relatively short time period (one to one-and-a-half hours) to prevent fatigue effects from biasing the data. Other consideration included having a variety of median types, lateral clearances, and access density. Figure 4-4 illustrates the location of the study sites in the cities. Table 4-2 lists the characteristics at each site.

Although clearly the factors shown in Table 4-2 are not all-encompassing descriptions of the test sites, one additional non-geometry based factor is also listed: speed limit. Speed limit is an interesting characteristic to study. Because speed limits are frequently based on measurements of actual speeds at sites (specifically, the 85^{th} percentile speed), speed limits as an influence on speed represent a circular reasoning problem. Are speeds low because of a low speed limit, or are they low because site characteristics dictate that drivers maintain low speeds (and thus, coincidentally, resulting in a low speed limit)?

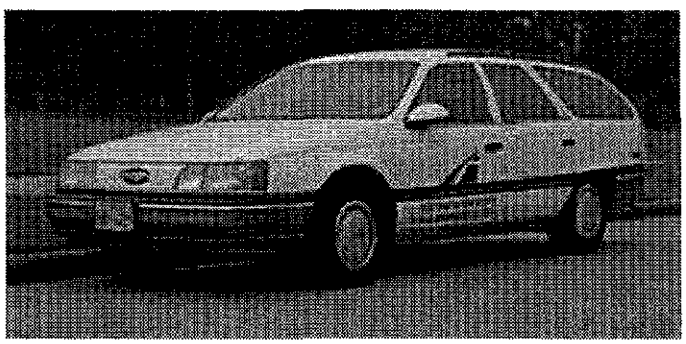
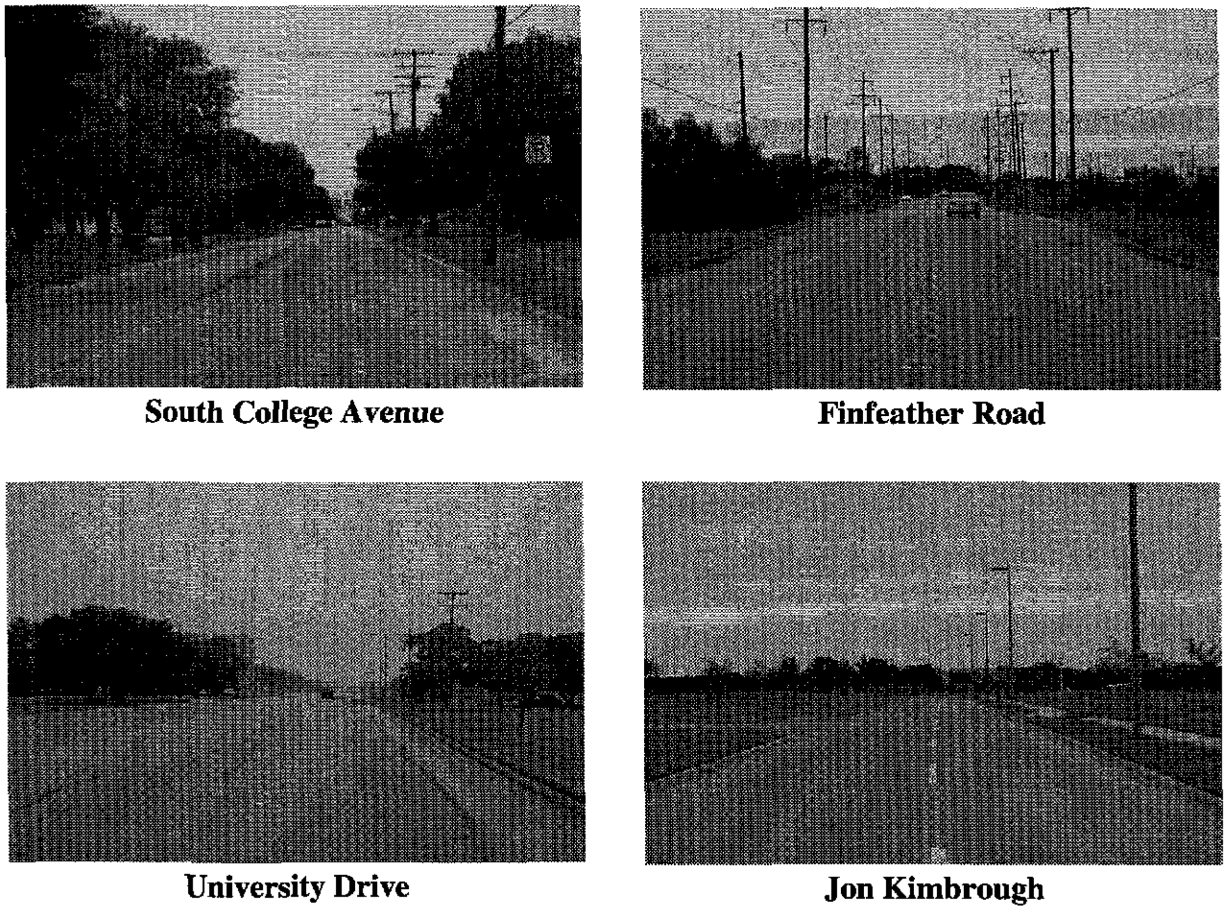


Figure 4-1. 1991 Ford Taurus Station Wagon Used for Testing.

Figure 4-2. In-Vehicle Instrumentation.

Table 4-2. Site Characteristics for Individual Driver Study.

Site	Median Type	Access Density	Lateral Clearance	Speed Limit km/h (mph)
South College Ave.	None	High	Restricted	64 (40)
Finfeather Road	None	Low	Unrestricted	72 (45)
University Drive	Divided (TWLTL)	Low	Unrestricted	64 (40)
Jon Kimbrough	Divided (Raised)	Moderate	Restricted	48 (30)



South College Avenue · Finfeather Road · University Drive · Jon Kimbrough

Figure 4-3. Test Roadways.

A key to the research effort is to be able to associate a speed with a geometric feature. Researchers mapped the roadway features of interest (driveways, streets, median openings, median type changes, and rigid and yielding objects) using coded keyboard inputs to the laptop computer during mapping runs in the test vehicle. This coding allowed graphical representations to be prepared for comparison to measured speeds obtained during driver testing.

Procedure

After showing the drivers a map of the course to be followed, drivers were provided verbal instructions about the experimental task and what they could expect to occur. They were told that during the test they would be accompanied by the researcher and that they would be asked to:

- drive "normally"--i.e., the way they would drive on a typical trip,
- generally drive in the right lane, although if a stalled/slower/stopped vehicle is in the lane they could pass it,
- expect directions in advance of intersections where the driver would be expected to turn, and
- expect that some parts of the route would be driven several times.

After asking for and responding to any questions, the drivers were asked to sign informed consent documents allowing them to participate in the research program.

The drivers then proceeded to drive to the various test roadways. Because of their proximity to each other, South College Avenue and Finfeather Road (referring to Figures 4-3 and 4-4) were paired, as were Jon Kimbrough and University Drive. The drivers drove through a roadway pair four times before proceeding to the next pair, thus completing four repetitions of driving each roadway. To eliminate practice and/or fatigue effects from influencing the results of the study, initial roadway starting points were assigned at random to the six drivers (counterbalancing).

DATA REDUCTION

The data reduction effort for the individual driver pilot study was relatively modest. The various data files for each of the four test roadways were combined to form a complete set of data. Because each line of data contained a single data record and included information regarding the subject, test run, test roadway, the distance associated with the data point, the measured speed, whether the driver was impeded at that point, and any special codes entered by the experimenter during the test, the records could be assembled readily into a larger database without losing accountability regarding the individual data points. Computer files were next prepared that contained both the site mapping data and the speed data. This facilitated the preparation of speed plots and representations of the physical characteristics of the test sites.

FINDINGS

Average measured speeds varied between 50 and 75 km/h (31.1 and 46.6 mph) on the four test sites. Figures 4-5 through 4-8 provide graphic representations of speed measurements and geometric variations observed at the four sites. The plots contain the individual speed measurements in relation to the geometric feature present at the location. Features shown include intersections (heavy vertical lines), driveways (light vertical lines), roadside objects that would yield if struck (plus symbols), and rigid objects on the roadside (triangles). The rigid and yielding objects were classified as adjacent to the roadway (less than 2 m [6.6 ft] from the curb face) or near the roadway (2 to 5 m [6.6 to 16.4 ft] from the curb face).

Per Site Findings

The University Drive test section (Figure 4-5) is a relatively wide-open roadway with a two-way left turn lane (TWLTL) and few access points or roadside obstacles. Speeds were relatively constant through the test section after steady speeds were reached.

The Jon Kimbrough test section (Figure 4-6) is a more constrained roadway with a raised median, few access points, and higher numbers of roadside obstacles. Speed decreases were observed at some of the horizontal curves encountered.

The South College test section (Figure 4-7) is an undivided roadway with high numbers of access points and higher numbers of roadside obstacles. Similarly to University Drive, the test drivers drove at a relatively constant speed after initial acceleration.

The Finfeather test section (Figure 4-8) was undivided and had few access points or roadside obstacles. A noticeable decrease in speed was observed at this site near the former railroad crossing, which remains elevated when compared to the remainder of the roadway.

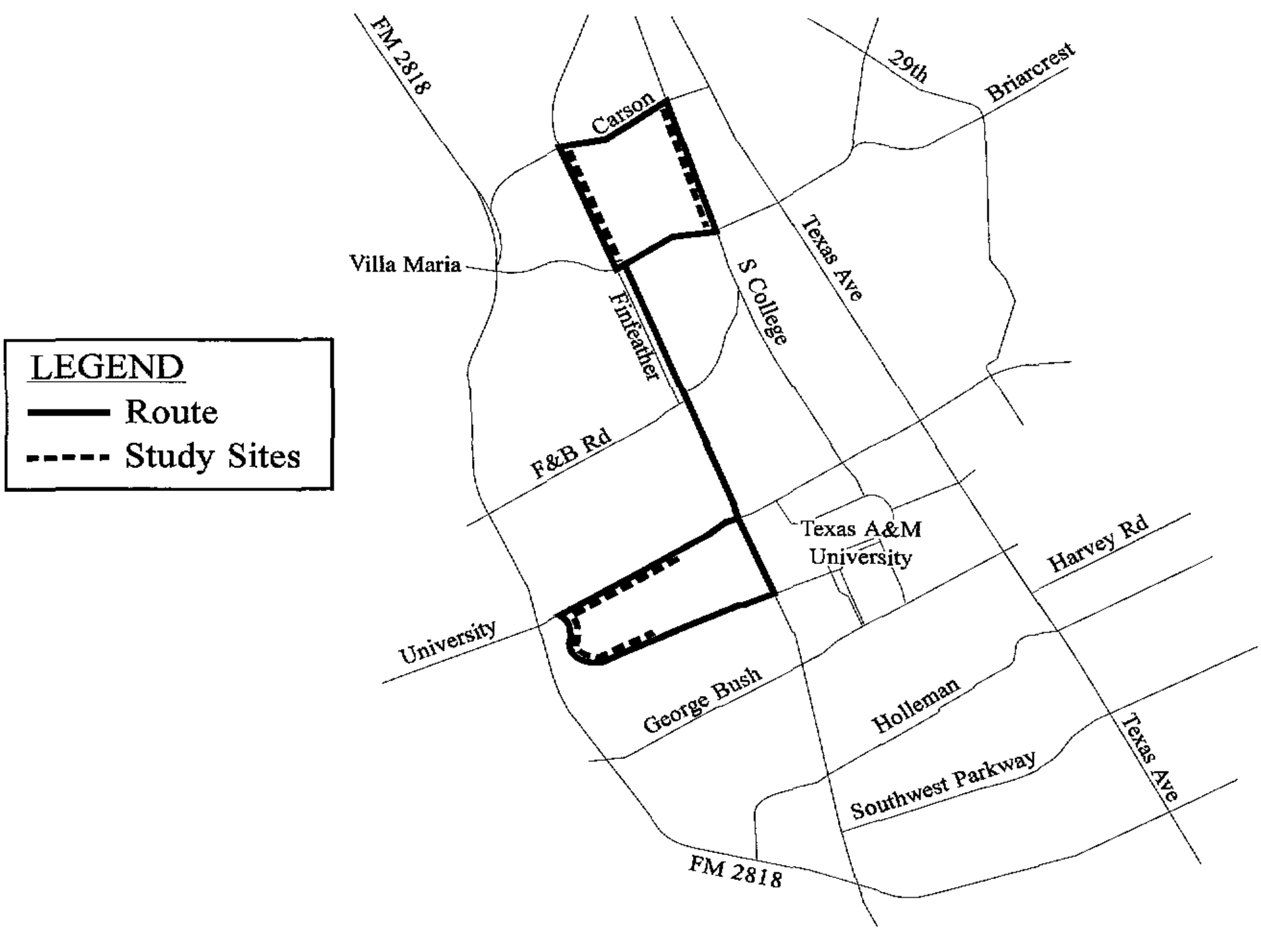


Figure 4-4. Study Site Locations

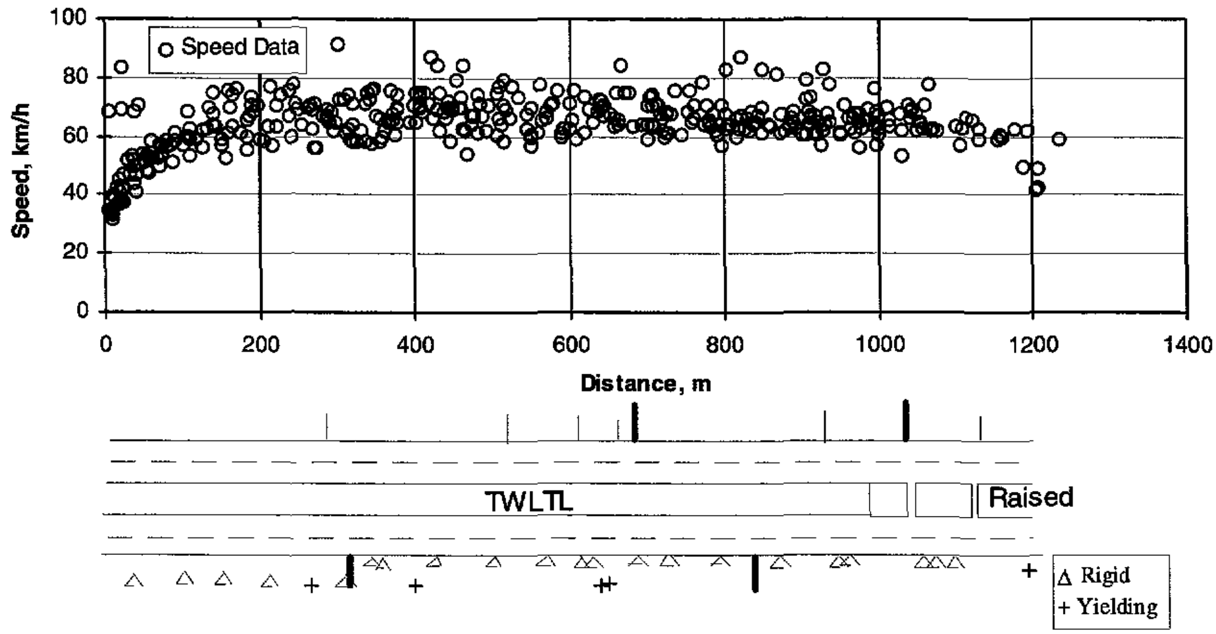


Figure 4-5. University – Speed Measurements and Geometric Variations.

Comparison of Site Findings

A number of plots were made comparing average speeds on 400 m tangents in the four test sections. The plot comparing access level and its potential influence on average speed (Figure 4-9) does not indicate a clear effect. A similar plot comparing median type and average speed (Figure 4-10) also does not indicate a clear effect. A plot comparing the number of obstacles and average speed does, however, appear to indicate a relationship between the two variables (Figure 4-11). When a low number of obstacles are present, speeds are higher.

Next, a plot was prepared that compared speed limit and average speed (Figure 4-12). In this plot, a 45 degree line was placed to provide a visual reference point — if the average speed equaled the speed limit the data point would lie on the line. As shown in the figure, a positive relationship appears to be indicated between speed limit and average speed. Further examining Figure 4-12, those sites with divided medians had average speeds that were higher than the speed limit, while sites without medians had average speeds lower than the speed limit.

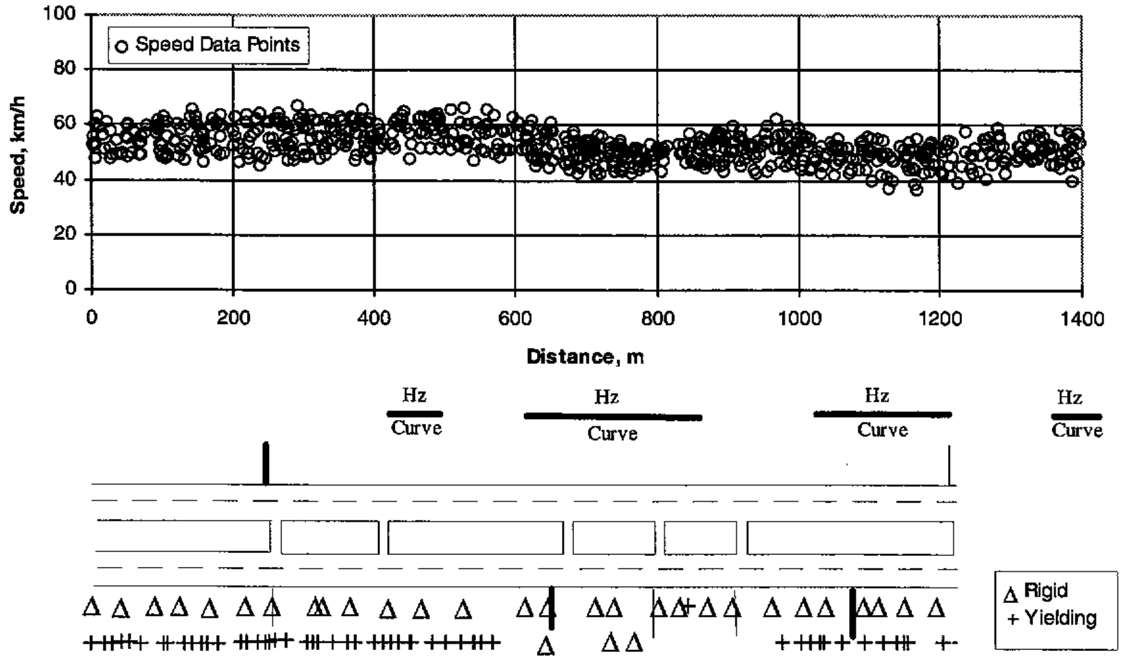


Figure 4-6. Jon Kimbrough – Speed Measurements and Geometric Variations.

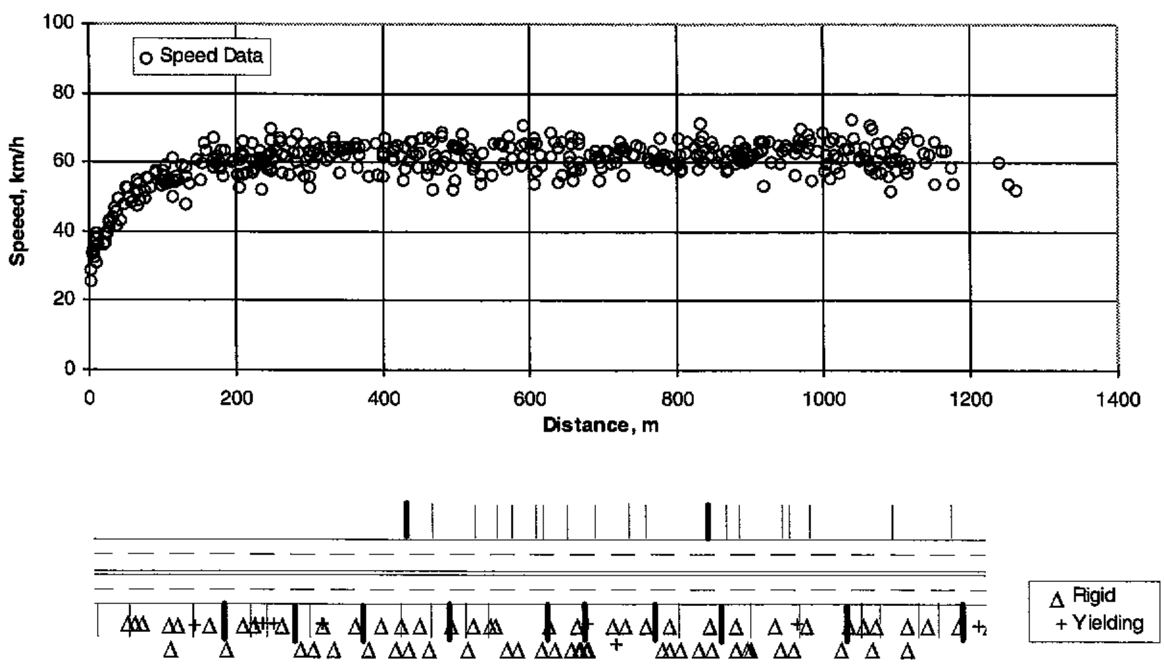


Figure 4-7. South College – Speed Measurements and Geometric Variations.

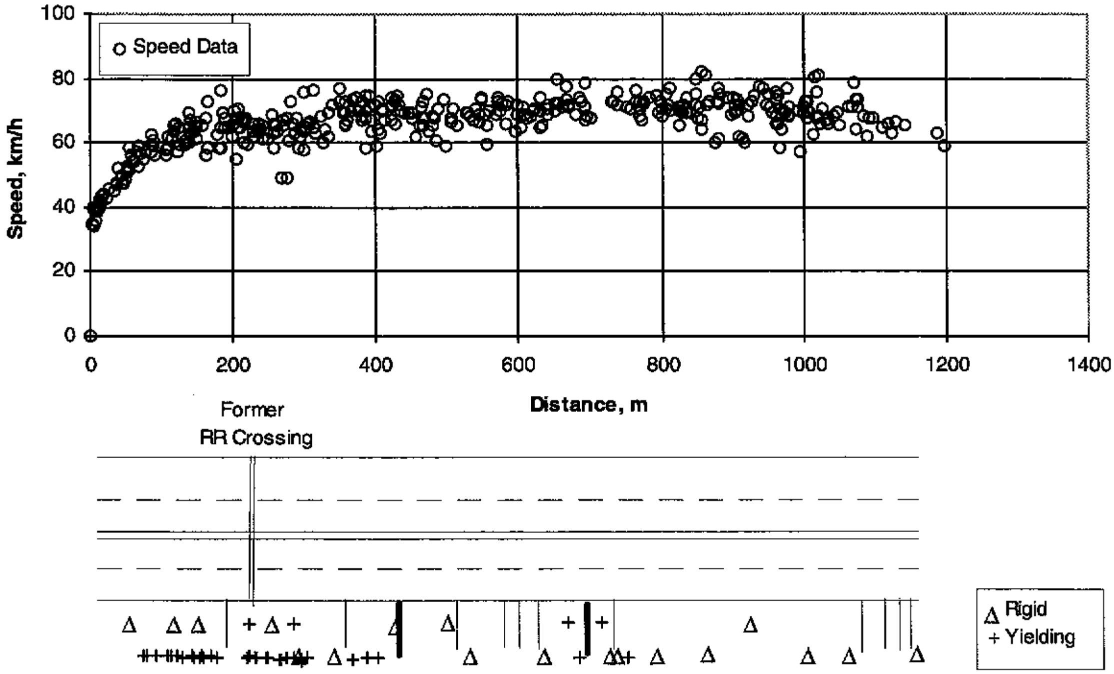


Figure 4-8. Finfeather – Speed Measurements and Geometric Variations.

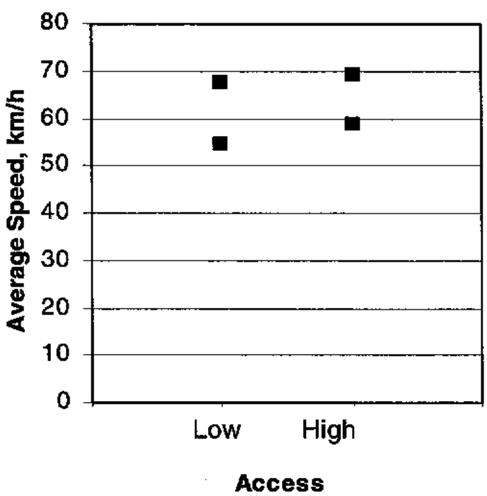


Figure 4-9. Access Density.

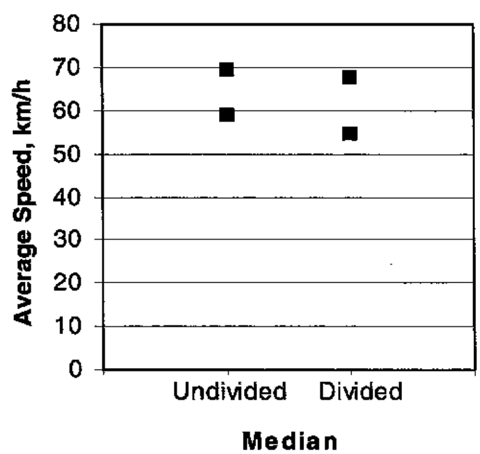


Figure 4-10. Median Type.

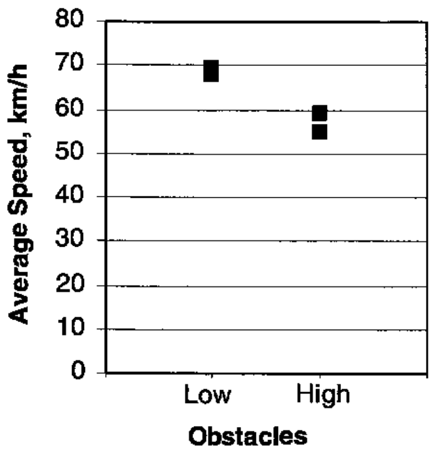


Figure 4-11. Obstacles.

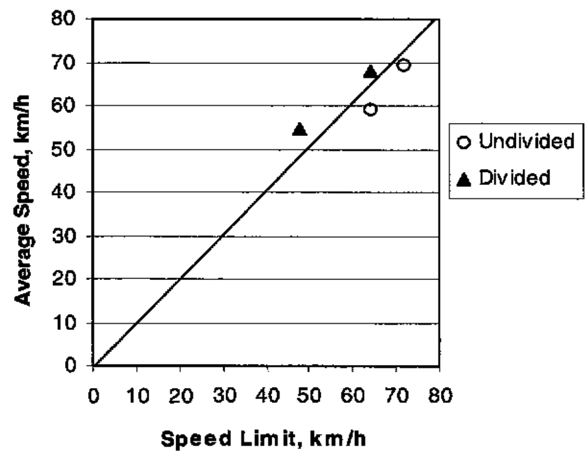


Figure 4-12. Speed Limit and Median Type.

LESSONS LEARNED

Confounding geometric variables and the low number of test sites and drivers restrict both the certainty and range of any conclusions regarding these speed measurements. That is, were the speeds low at South College Avenue and Jon Kimbrough because they had relatively restricted lateral clearance, high access density, or low speed limits? Did Jon Kimbrough have the lowest speeds because of the high number of obstacles? It is not possible to answer these questions with the limited amount of data available at this time because sufficient information is not available to distinguish the different possible influences present.

Although absolute answers regarding variables influencing speed cannot be provided at this time, it does seem apparent that the variables studied appear to be associated with speeds that differ markedly. That is, we cannot answer precisely which variable or combination of variables is influencing the observed speeds, although differences that could be associated with the various site characteristics were apparent.

Median type, access density, and lateral clearance appear to be promising variables for further study. Based on observations made by the research team during the selection of test sites, it appears likely that considerable confounding is present between access density and lateral clearance. That is, when access density is high, lateral clearance tends to be restricted; when access density is low, lateral clearance tends to be unrestricted. Confounding between median type and access density also appears to be likely because TWLTLs are frequently utilized in areas of high access density to provide the means of access for left-turning motorists. If these combinations of characteristics are found to be representative of test sites in general it will be difficult to distinguish the actual cause of observed speed variations. On the other hand, it may not be necessary to absolutely distinguish the cause if a set of characteristics can be defined rather than one individual factor.

One of the restrictions on a study using test drivers is that of maintaining a reasonable assurance that fatigue effects do not influence the results. This concern generally dictates that study sessions take no longer than one to one-and-one-half hours. Because driving time between test sites in the pilot stage is expected to be representative of that encountered in any future tests, this factor becomes problematic.

The strength of a repeated-measures study using test drivers is based on analyses that look at variations within the individual drivers. By accounting for variation between drivers and primarily examining differences in speeds at the different test sites or within the test sites, very strong statistical comparisons can be made. This strength, however, is negated when adequate numbers of test sites cannot be used in the study. As shown in Figure 4-13, individual drivers' speeds can be monitored as they traverse features on the test sites. In this figure, drivers' speeds are monitored as they approached, traversed, and departed a horizontal curve. Acceleration rates, speed changes, and speed profiles can be developed to provide detailed information that cannot generally be determined using conventional speed collection techniques. Given sufficient time and resources, the use of individual drivers in instrumented vehicles could be a very effective approach to study effects on speed.

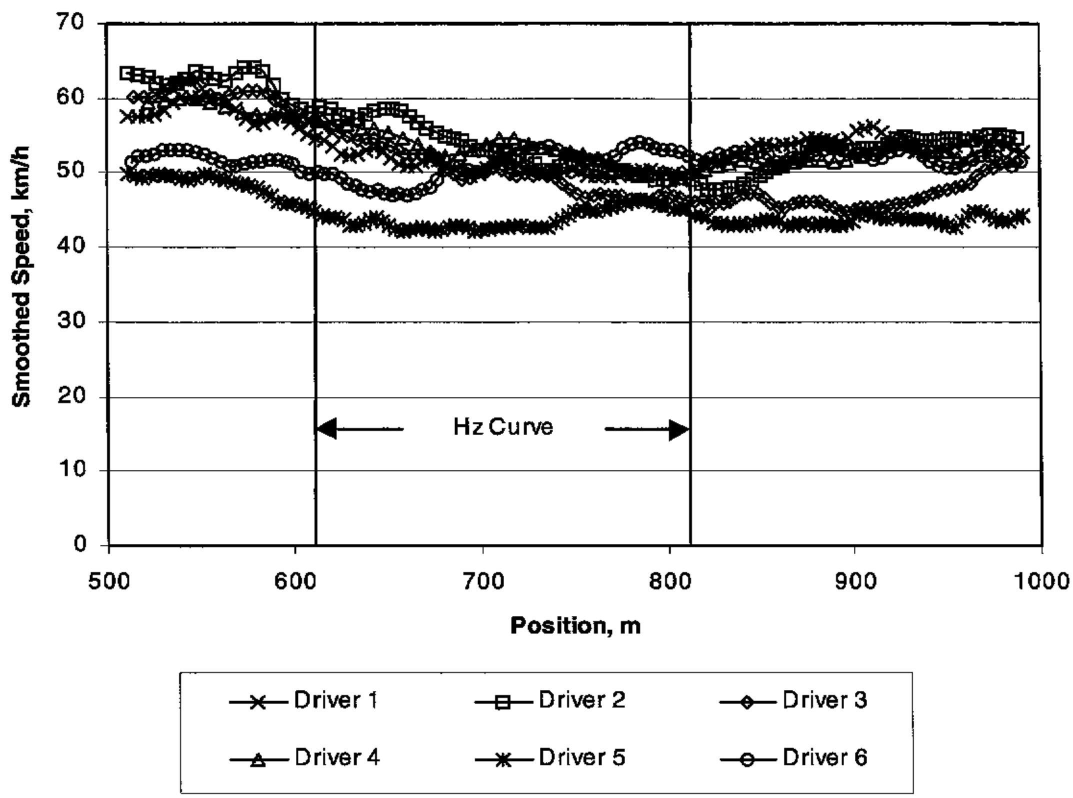


Figure 4-13. Speeds of Individual Drivers for a Single Run.

CHAPTER 5

LASER PILOT STUDY

This chapter discusses the data collection efforts and findings from the laser pilot study. The pilot study recorded speed profiles of vehicles as they passed through selected study locations. The suburban arterial locations were selected based on access density and horizontal curvature features. The intent of the pilot study was twofold: (1) to determine the feasibility of using the laser guns in a full-scale effort and (2) to assist in selecting variables and their ranges for a full-scale effort.

DATA COLLECTION

The first step in the data collection effort was to map each potential site so that locations of roadway and roadside features were known in reference to the stationing of the roadway. Specifically, access points (including driveways and intersections), traffic signals, stop signs, and other information were recorded while driving through the study site. This recording was done with a distance measuring instrument (DMI) linked to a noncontact fifth wheel and a laptop computer. In advance of the study site, the equipment was readied, and data acquisition began. Using an interval of 0.1 seconds, the computer recorded the distance traveled, elapsed time, speed, and any key strokes that may have been pressed on the computer. Before beginning this step of the data collection process, certain key strokes were assigned to indicate driveway to the left, driveway to the right, intersection to the left, intersection to the right, stop sign, traffic signal, and so on. Once completing the run, the data were downloaded from the computer and superimposed with the information from the plan and profile sheets as well as information obtained through the initial study site visits. Upon completion of this task, profiles of the study sites were created using a typical spreadsheet package. The profiles include recordings upstream and downstream of the study site limits in order to gain an appreciation of the general "feel" of the roadway and to better quantify approach and departure characteristics.

The next step in the collection effort was to collect the speed profiles. Lidar (Light Detection and Ranging) guns were used to accomplish this task. (Lidar guns are more commonly referred to as laser guns.) The use of laser guns in speed data collection has two major advantages over radar. First, the laser guns can measure distance to a vehicle as well as the speed of that vehicle, while the radar guns only measure speed. To measure speed and distance, hundreds of invisible infrared light pulses are released from the gun every second. As each pulse is transmitted, a time is started. When the energy of the light pulse is received by the device, the time is stopped. Based on elapsed time, the distance is calculated using the known speed of light through the atmosphere. An algorithm is used to derive the speed of the target from a successive number of range calculations.

The second advantage of laser over radar is that the signal transmitted travels in a straight line whereas the radar transmission is conically shaped. The narrower beam has at least two distinct advantages associated with it; it is harder to detect with conventional radar and laser detectors, and it allows for more precise measurements of individual speeds. An off-the-shelf device frequently employed by law enforcement personnel for speed enforcement was used in this data collection effort. It has the capability of continuously tracking a vehicle's speed through a section of the roadway.

Data were only collected during dry pavement conditions during daylight hours, usually between 7:00 am and 6:00 pm. The data were only collected during the weekdays. A typical set-up included two power sources. A gas-powered generator and portable 12-volt batteries were used to power one set-up location. The other two locations were typically powered through 12-volt power supply from a vehicle. For these two set-ups, a 12-volt Y-adaptor was used in conjunction with an AC-DC power converter for the computer.

The speed profiles were obtained by strategically positioning the laser guns throughout each site. The laser guns were positioned in a manner that made them and their operator as inconspicuous as possible to the target vehicles while recording speeds upstream of the curve, through the curve, and downstream of the curve, to the maximum extent possible. Every attempt possible was made to provide a continuous speed profile rather than one with gaps. The positioning of the laser guns was also controlled by an attempt to minimize the cosine error associated with collecting speeds using such devices. Although each site presented its own challenges that created slightly different setup locations, Figure 5-1 shows how the laser guns were generally positioned along the curves.

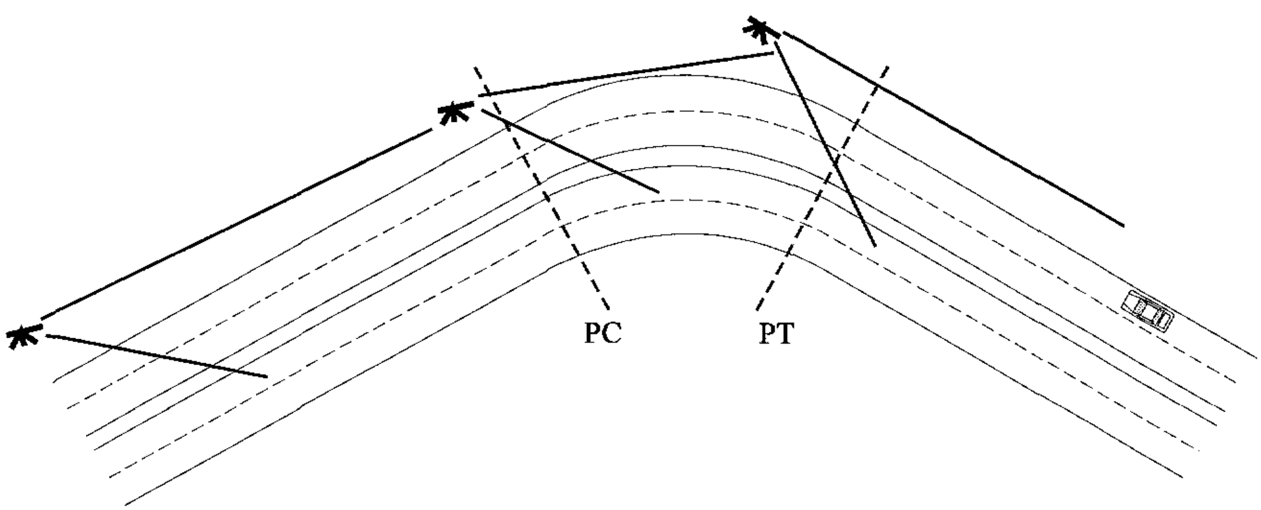


Figure 5-1. Typical Laser Gun Positions.

Where data could not be collected as vehicles were approaching the technicians, or where no relatively inconspicuous locations were located in the immediate area, a blind was built for the technician to hide behind. The blind was constructed so that a pick-up truck could be parked near the edge of the roadway and face the approaching vehicles. The technician would sit in the bed of the truck and measure the speed of vehicles traveling away. This set-up appeared to work well when no other alternative was available. Figures 5-2 and 5-3 show a mock set-up of the blind and how it was used. A nice feature of the blind was that it could be used on either side of the truck depending on the site specific needs.

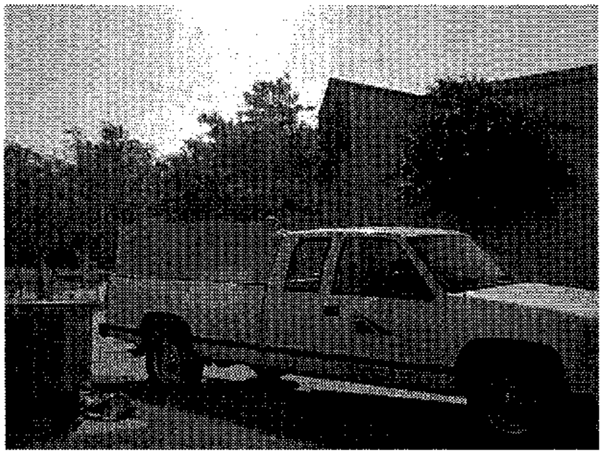


Figure 5-2. Speed Blind from Driver's Point of View.

Figure 5-3. Speed Blind with Laser Gun Operator.

To ensure that only free-flowing vehicles were recorded, several cautions were taken. First, the technicians only measured vehicles with at least a five second headway and tailway. This was estimated in the field as the vehicles were approaching. If a vehicle was impeded in any manner, the data for that vehicle were tagged and discarded. Also, if the vehicle changed lanes, the data were tagged and later discarded. Finally, using their own judgment, if the technicians believed they were spotted by the driver of the target vehicle, then a note was made and the data were later analyzed to determine the feasibility of using that particular vehicle's data (the technicians were instructed to note severe braking for no apparent reason other than the driver spotting the technician and fearing a speeding citation).

The laser guns used in this study are specially adapted for continuous speed and distance measurements. They are supplemented with laptop computers that are linked to the guns. A software program was developed within TTI to transmit the speed, time, and distance from the laser gun to a laptop computer. The transfer of data occurs at a rate of approximately three times per second. A sample of the data retrieved using this method is shown in Table 5-1.

Table 5-1. Sample of Laser Data.

Comment	Time	Speed (mph)	Distance (ft)
DAT	15:57.3	26	107
DAT	15:57.6	26	96
DAT	15:57.9	26	85
DAT	15:58.2	26	73
DAT	15:58.5	26	62
DAT	15:58.8	26	52
REM	grn car 1		

The data supplied were in U.S. Customary units and were later converted to metric units using a spreadsheet. Each time a vehicle's speed was recorded by each data collector, the software prompted for a remark concerning the latest data string. The field technicians input the color of the vehicle, the type, and which lane the vehicle was in. If, at any time during the collection of data for a single vehicle, the vehicle turned, was impeded by another vehicle or pedestrian, or impeded in any other way, the technicians entered "no good" in the remark field.

After the data collection efforts at the first two sites were completed and all the major problems resolved in the procedure, the remaining sites experienced few problems. One of the problems experienced was with the developed software. Until the bugs were completely worked out of the software, data collection efforts were constantly being interrupted by one of the three technicians needing to reboot a computer. Weather also played a role, as dry pavement conditions were required. Another factor that hindered the data collection efforts was high traffic generators located within the study sites. The first attempt at collecting data reveals an important consideration in site selection — do not collect data if a major traffic generator is located within the study site. The study requires vehicles operating under free-flow conditions; however, near major traffic generators, a free-flow vehicle is very likely to either enter the high traffic generator or be impeded by a vehicle turning from the high traffic generator or waiting to turn into the site.

Communication between technicians was accomplished through the use of walkie-talkies. The technician operating furthest upstream would provide a description of the approaching target vehicle. The description included color, type, and lane position. The second and third technicians would then watch for this vehicle. The system worked well except that when the button is pressed to speak into the walkie talkie, the laser gun shows an error and will not collect speed or distance data. After releasing the walkie-talkie button, it takes about 0.5 seconds for the laser gun to clear from its error mode. While this time lapse may seem insignificant, the effect on the technician furthest upstream is crucial because the vehicle is closing rapidly. Optimally, at the point when the technician decides that the vehicle is free-flowing and can determine the color, data collection should begin. However, since the laser guns and walkie-talkies do not operate simultaneously, the technician has to announce the target vehicle and wait for the gun to clear from error mode before data collection can begin. Assuming this takes 3 seconds and the vehicle is traveling at 70 km/h (43.5 mph), the vehicle has traveled almost 60 m (196.9 ft) from the point of ideal data collection commencement to the point of real data collection.

The goal was to record speeds of at least 100 free-flowing vehicles per site. Technicians spent at least a day at each site and at one site spent two days; however, the goal was met only once. This situation will be discussed further in the data analysis section.

STUDY SITES

Figures 5-4 through 5-9 show pictures taken of each pilot study site. Following are discussions pertaining to the general characteristics of each pilot study site. Roadway profiles are also included with each discussion to provide an overview for the site being studied. The profiles were generated from the data collected during the site selection efforts. The vertical lines represent access points according to the following scale:

0.5 or -0.5 Median Opening
2.0 or -2.0 Driveways
3.0 or -3.0 Intersections

The horizontal curves are shown as solid horizontal bars in the center of the plot.

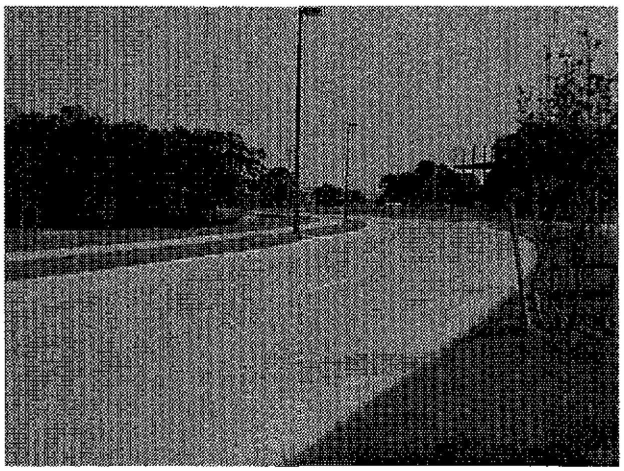


Figure 5-4. Jon Kimbrough.

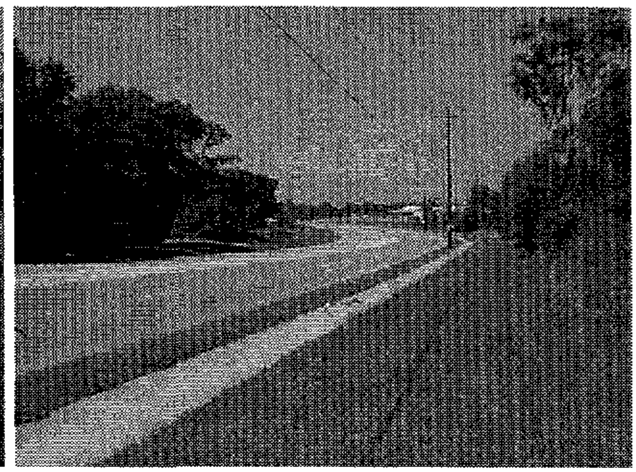


Figure 5-5. Villa Maria.

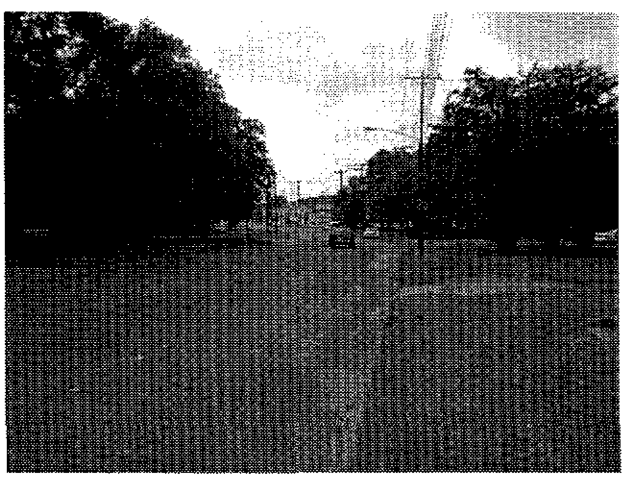


Figure 5-6. South College.

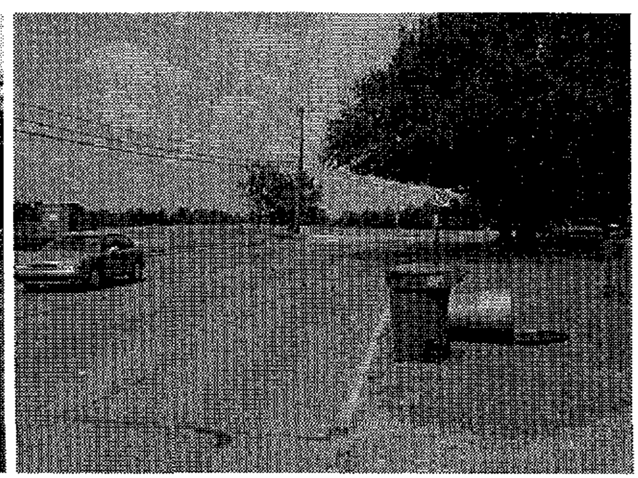


Figure 5-7. NB 29th Street.

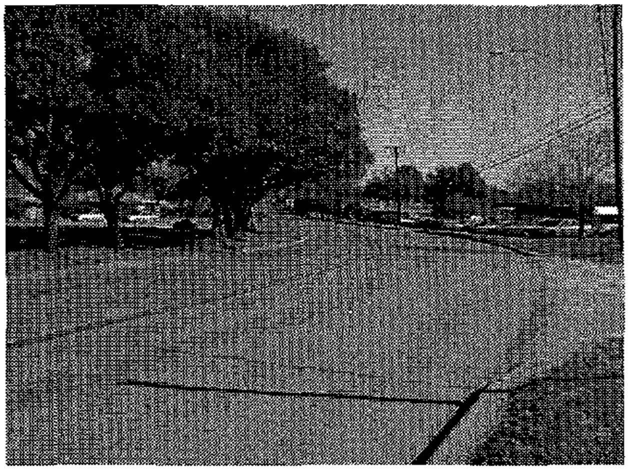


Figure 5-8. SB 29th Street.

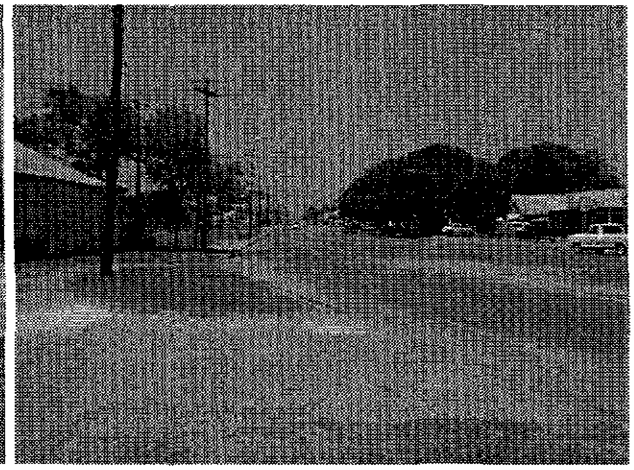


Figure 5-9. Texas Avenue.

Jon Kimbrough

The construction of Jon Kimbrough was finished in the summer of 1997. The roadway meanders through the west side of Texas A&M University (TAMU), which has yet to be developed. Access points have been sparsely provided along the road and most currently lead to empty fields where buildings are planned. Median openings are provided in the raised median wherever an access point is located. The lane widths are 3.66 m (12 ft), while the lateral clearance ranges from restrictive to wide open. Traffic volume is extremely light on Jon Kimbrough. In fact, when a vehicle finally entered the study site during data collection, it was either a University Police vehicle (UPD just moved to west campus), a TAMU bus, or a free-flowing passenger car. Figure 5-10 shows the roadway profile for Jon Kimbrough.

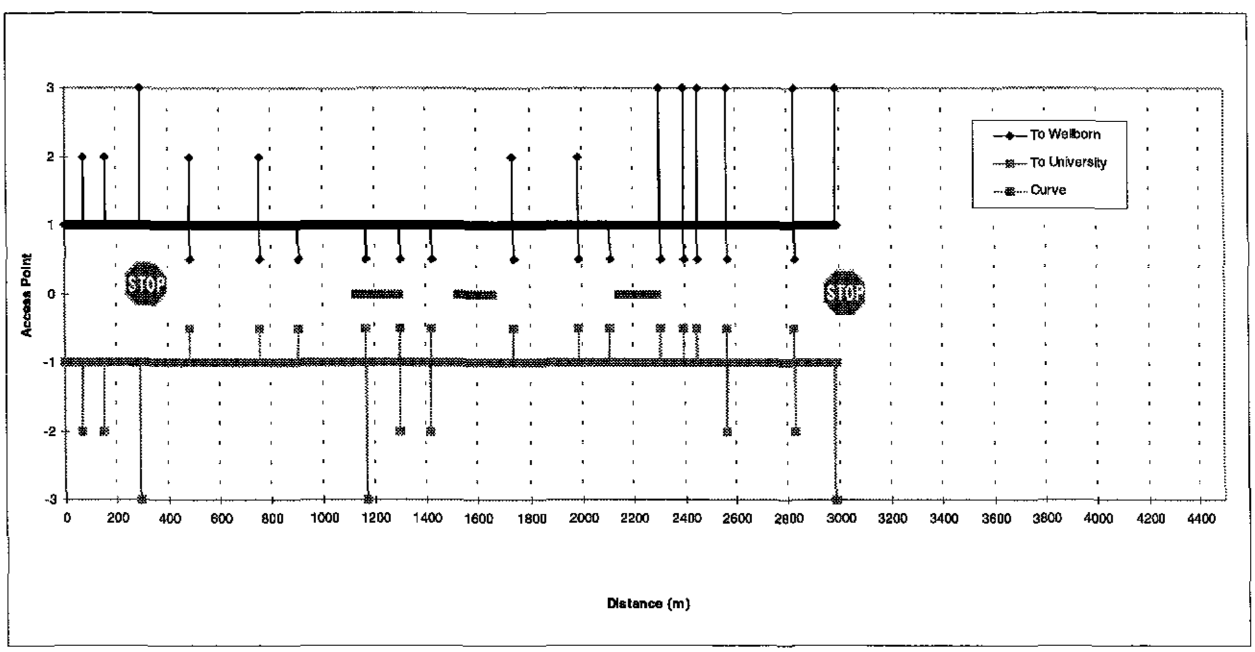


Figure 5-10. Jon Kimbrough Roadway Profile. (1 m = 3.28 ft)

Villa Maria

Villa Maria (also FM 1179) provides the region of Bryan/College Station one of the most direct east/west routes. The portion of Villa Maria studied is located in an area that is changing from urban arterial (with commercial development) to rural highway. This study site had the highest posted speed of all six pilot sites (72 km/h [45 mph]). Roadside clearance is moderate with telephone poles placed about 3 m (9.8 ft) off the face of the curb. However, other than the telephone poles, no rigid obstacles are within 5 m (16.4 ft) of the roadway. This section of Villa Maria features a TWLTL and lane widths of 3.66 m (12 ft). Traffic volumes are moderate, and arrival patterns are mostly random with some platooning (caused by a signal approximately 1 km upstream). The roadway is shown in Figure 5-11.

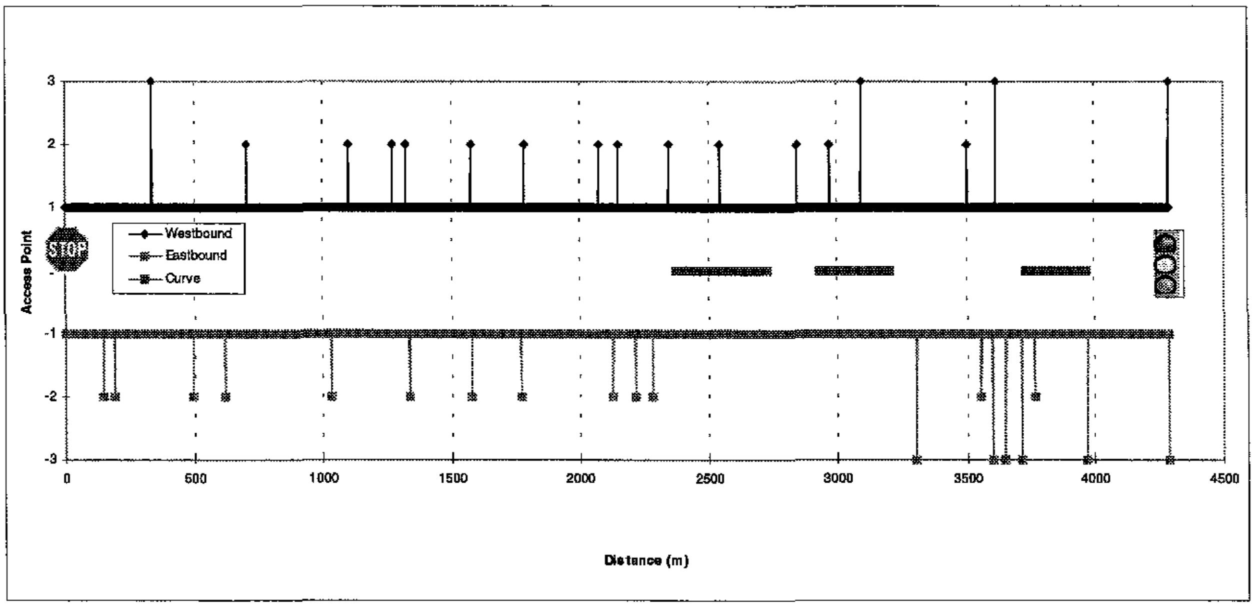


Figure 5-11. Villa Maria Roadway Profile. (1 m = 3.28 ft)

South College

South College Avenue is an older roadway with deteriorating pavement conditions. Access density is high and consists of a mix of residential to commercial roadside developments. The lateral clearance is very restrictive, with lateral clearance of less than 0.6 m (2.0 ft) in some areas, and the lane widths range from 3.05 to 3.35 m (10 to 11 ft). Approximately 300 m (984.3 ft) upstream of the PC of the horizontal curve of interest is a traffic signal. Figure 5-12 shows the roadway profile.

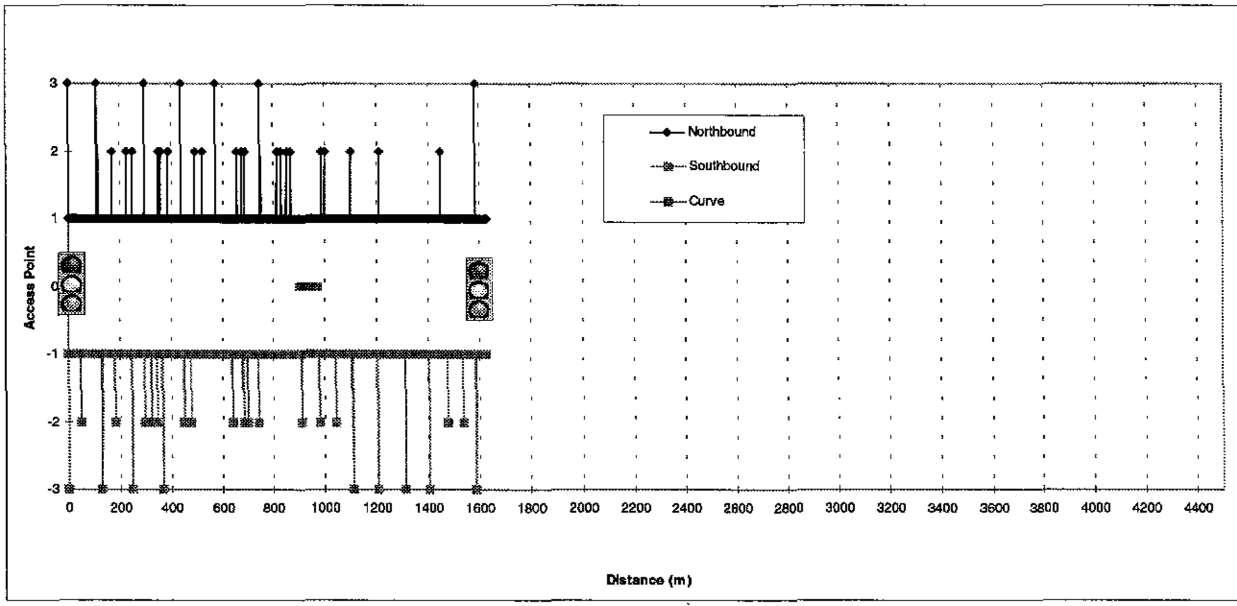


Figure 5-12. South College Roadway Profile. (1 m = 3.28 ft)

29th Street

29th Street was the only site where both directions of travel were studied. 29th Street is an older street that serves as a main artery from the Bryan CBD to a hospital and also continues through Bryan into College Station thus providing continuous access from one city to the next. The street is fairly old and includes less than desirable geometric and roadside features. For instance, the inside of the study site curve is lined with large live oak trees just a few meters from the edge of the travel way. Furthermore, the pavement width transitions from 3.5 to 4.2 m (11.5 to 13.8 ft) in the curve. Roadside development along the study site is mostly commercial, while it varies to residential just outside the study limits. Figure 5-13 shows the section of 29th Street.

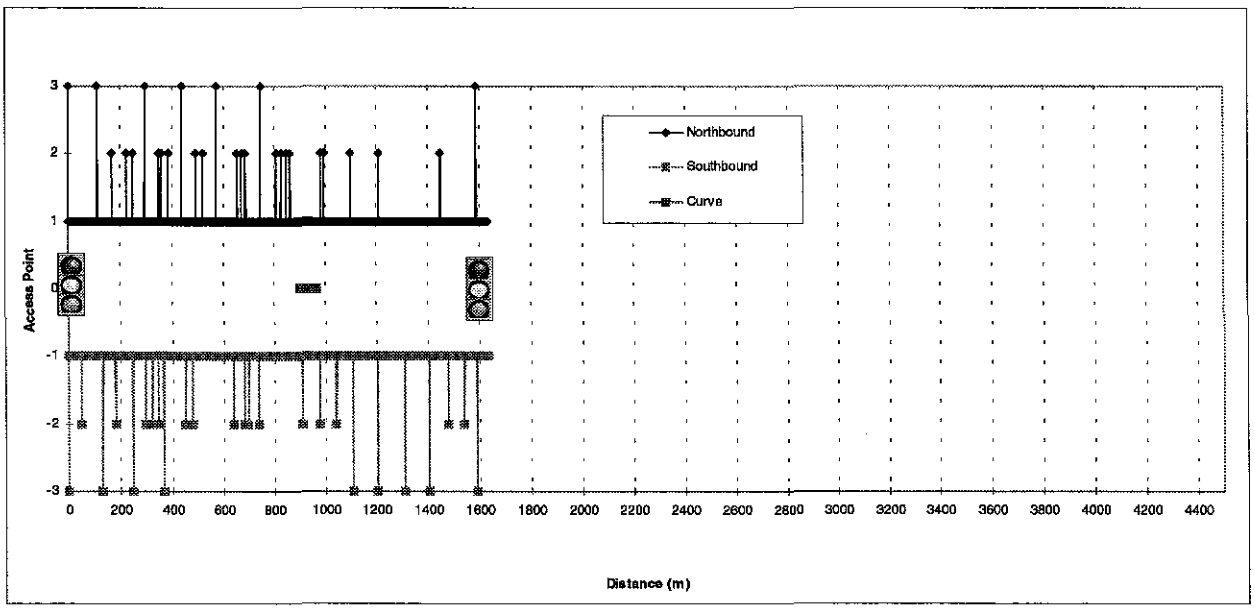


Figure 5-13. 29th Street Roadway Profile. (1 m = 3.28 ft)

Texas Avenue

Texas Avenue is the primary north-south arterial for the Bryan and College Station area. It has a wide range of characteristics, but near the study site it is mostly commercial with fairly restrictive lateral clearance, lane widths of 3.66 m (12 ft), and a TWLTL. The posted speed is 64 km/h (40 mph), and the pavement condition is good. The traffic volume is high, and even though signals are prevalent along this section, random arrivals continuously occur. Figure 5-14 shows the high access density through this section of the arterial.

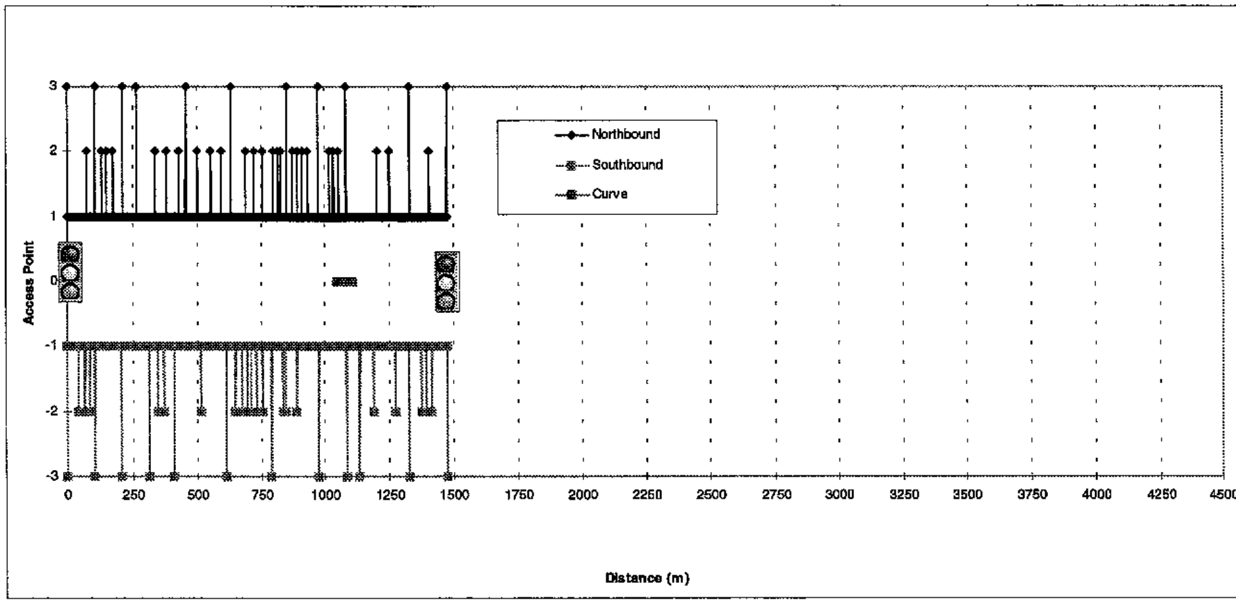


Figure 5-14. Texas Avenue Roadway Profile. (1 m = 3.28 ft)

DATA REDUCTION

The data collection efforts at one site produced three separate files (one for each technician). After the data were collected, a student worker would join the files, matching each string of speeds using the times (the times on all three laptops were synchronized before data collection commenced) and the descriptions of the vehicles. Strings of data marked "no good" were discarded as well as other data that appeared to have been influenced. This resulted in one concatenated file from the three previous files for each study site.

Another key element in the process was precise measurement of the location of each laser gun with respect to features available on the plan and profile sheets. Before leaving each site, the technicians measured distances to at least two features on the plan and profile sheets. This was done in order to locate the exact placement of the laser guns with respect to the roadway. This was crucial in matching the speed measurements to the roadway positioning.

With the profiles obtained with the DMI, the speeds and distances obtained with the laser guns, and the exact location of the laser guns with respect to the roadway, the roadway profile files and the speed files were matched. Special care was taken to ensure that appropriate speed corrections were made due to the angles created between the laser gun's laser vector and the instantaneous velocity vector of the vehicles. The need for these corrections had to be evaluated for each speed measurement taken due to the continuous distance differences between the laser gun and the target vehicle. Also, if a vehicle was traversing a horizontal curve while being tracked with the laser gun, then the vehicle's velocity vector was constantly changing as well. The corrections were made using an arbitrary *x-y* coordinate system to position key features of the roadway and a three-dimensional spreadsheet.

The data reduction process proved tedious and time consuming. The time required to concatenate the three files per site into one file depended on the quality of the data collection procedure. The laptops used for this study had highly varied hardware components. While one was quite dated, the others were more modern. The times the machines kept varied significantly over time, and if they were not synchronized immediately before collecting data, then the times stored and used to concatenate the files were less useful. Also, if great care was taken to provide descriptive notes pertaining to each vehicle, then the concatenating procedure went more smoothly, although the time involved in providing descriptive notes could cause a missed opportunity to collect speeds of a following vehicle.

Once the concatenated speed files were matched with the roadway profile files, the size of the files became a concern. File sizes varied from 3 megabytes to over 12. The number of vehicles that were recorded, the amount of speed data for those vehicles, and the length of the roadway profile were the main factors that caused the file sizes to grow so rapidly.

DATA ANALYSIS

The data analysis focused on two main issues:

1. determining the feasibility of using the laser gun to collect speed profiles, and

2. selecting variables and their ranges for a full scale effort.

Addressing both issues simultaneously, plots were generated showing the average measured speed plotted above the roadway profile. Mean speed and mean speed plus/minus two standard deviations are shown in kilometers per hour. Mean speed for each meter interval where at least two speeds were recorded are shown as circles. Mean speed plus two standard deviations are indicated with a "+" sign. Mean speed minus two standard deviations are shown with a "-" sign.

Jon Kimbrough

At Jon Kimbrough, the locations of the laser guns were not optimally positioned, as is evident from the gap in the speed profile (see Figure 5-15). Methods to minimize gaps in the data were developed and used in Phase II. Even with the large gap in the speed profile, the speed profile reveals some general characteristics about the curve. First, the average speeds throughout the curve appear to be about 50 km/h (31.1 mph) or just slightly above 50 km/h (31.1 mph). Data were not collected prior to the curve; therefore, the data set does not show whether the vehicles were slowing as they approached the curve. The laser guns were better positioned in the remaining study sites. There appears to be a decelerating trend in the data from 1075 to 975 m (3526.9 to 3198.8 ft), which could be caused by a four-way stop that lies approximately 600 m (1968.5 ft) upstream of that area.

The speed variance through the curve also appears to remain fairly constant. However, during the deceleration trend shown in the right half of Figure 5-15, it appears that the variance is reduced slightly. It should be noted that while there is a median opening at the beginning and the three-quarter point of the curve, there is only one intersecting roadway within the curve. The speeds on Jon Kimbrough do not appear to have been affected by the access points. Sight distance to each of the access points is generous.

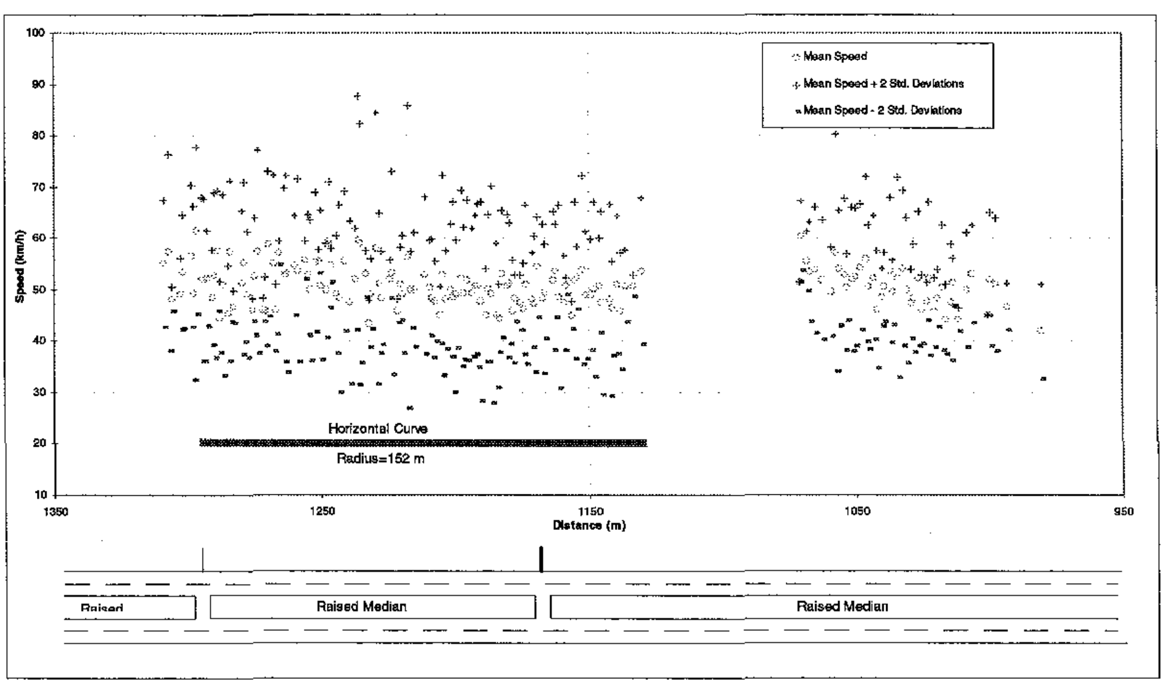


Figure 5-15. Jon Kimbrough Speed Profile. (1 m = 3.28 ft)

South College

The locations chosen for the laser guns at South College resulted in no gaps in the speed profile and reasonable overlaps (see Figure 5-16). Speeds for vehicles in the outer lanes of the curve were collected.

Once free-flow speeds were achieved (at about 2350 m [7710 ft]), the speed through the corridor did not change significantly. It appears that it may have decreased slightly around the PT of the curve but then quickly rebounded back to free-flow speeds. The dip is difficult to explain and may be just an artifact of this set of data. The free-flow average speed is around 60 km/h (37 mph), which is slightly below the posted speed of 64 km/h (40 mph). The free-flow average speed may be affected by the combination of the deteriorating condition of the pavement, the restricted lateral clearance, the narrow lanes, and the high access density. An important item from this data is that the presence of the horizontal curve did not appear to affect driver speed choice at this one site.

A signal is located near the 2500 m (8202 ft) point. The acceleration profile from the signal can be seen on Figure 5-16. Note that the 300 m (984 ft) distance required from a signal or stop sign to study site limit (see Table 3-1) appears appropriate. At about 250 m (820 ft) from the signal, vehicles are at a steady state.

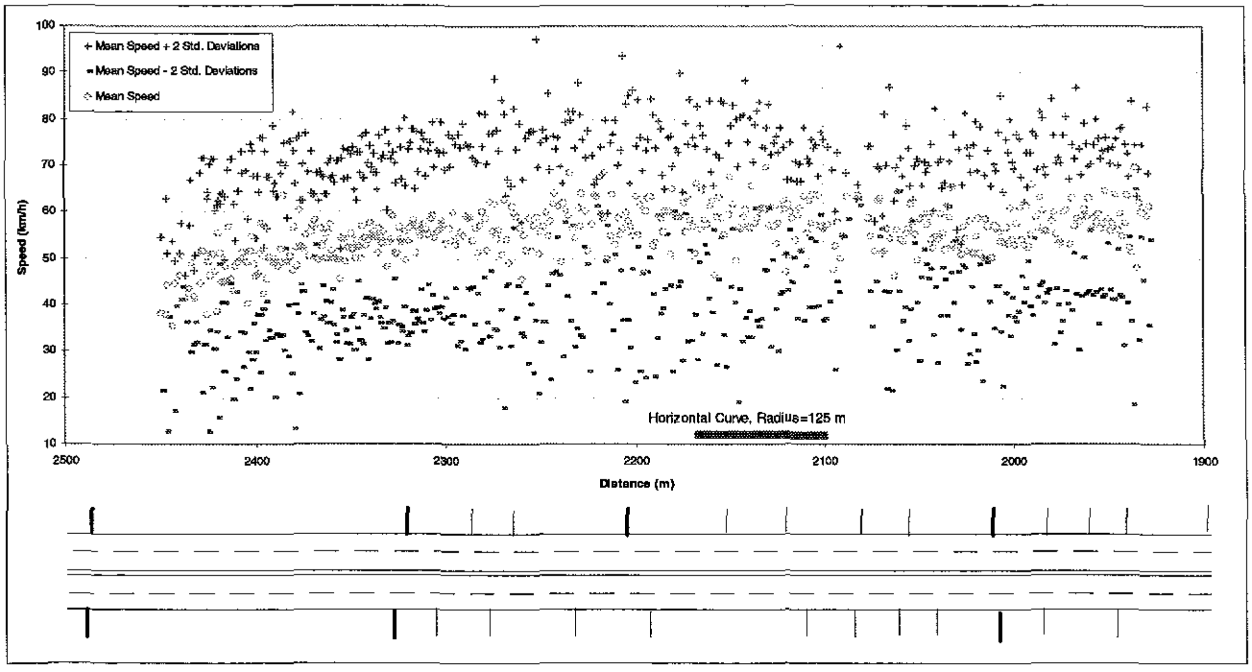


Figure 5-16. South College Speed Profile. (1 m = 3.28 ft)

Villa Maria

Villa Maria was selected as a "control" site for comparisons to other sites. It has a large radius compared to the other pilot sites (583 m [1912.7 ft] versus a range of 87 to 159 m [285.4 to 521.7 ft]). Based on the review of the literature, the geometrics (i.e., horizontal curvature) should not affect the average speeds at this site while they may at the other five pilot sites. As believed, the geometrics did not influence speed at this site (see Figure 5-17). As shown in Figure 5-17, the free-flow average speeds were approximately 72 km/h (44.7 mph) and did not change while approaching or traversing the curve. The acceleration shown in the beginning of the speed profile is likely caused by vehicles leaving a more developed area and entering a more sparsely developed area. The deceleration at the end of the speed profile was likely caused by utility work that was being conducted. The utility work was being conducted in the right-of-way but far enough from the roadside that a decision was made to proceed with the data collection upon arriving at the site and finding the work crew there. An elementary school is also present at the end of the curve. The two driveways shown on the figure (at 2980 and 2840 m [9777 and 9318 ft]) are the access points for the school. Although school was not in session when the data were collected at this site, the familiarity of the area may also have caused some deceleration.

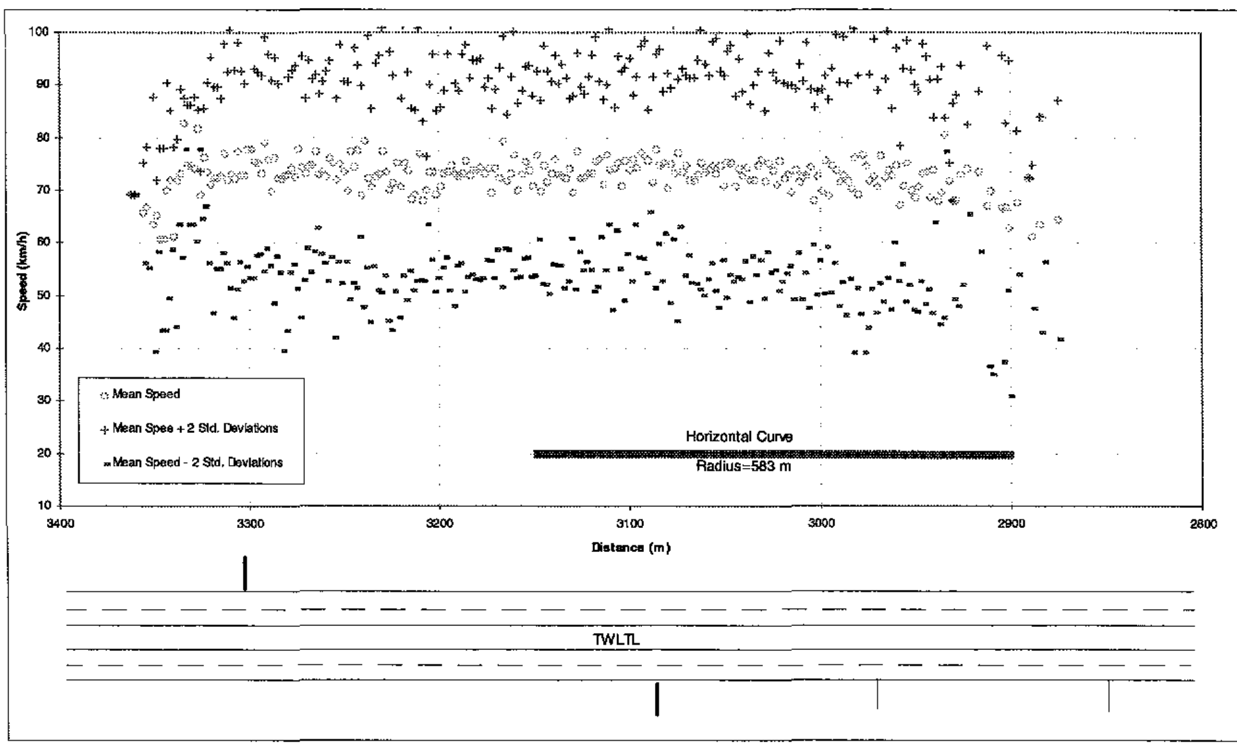


Figure 5-17. Villa Maria Speed Profile. (1 m = 3.28 ft)

Northbound 29th Street

One of the reasons that the northbound direction of 29th Street was studied was to compare the operation of the laser guns on the outside lanes of a curve versus the inside lanes. The outside lanes provide inconspicuous locations for operating laser guns. These locations also allow for long shots, especially along the approaches. The inside of the curve, however, presents several challenges. Locations along the inside of a curve do not provide the nice long shots. When the technicians are located along the outside of the curve, the guns have to shoot across the opposing direction of traffic. When data collection is interrupted by another vehicle, sign post, or other obstacle, the gun stops sending data and does not begin again for approximately one second (assuming precise aiming of the gun). If this occurs more than once for a given vehicle, the total amount of data collected for that vehicle is significantly reduced.

On 29th Street, the pavement width transitions from 3.5 to 4.2 m (11.5 to 13.8 ft) in the horizontal curve; however, the pavement width change does not appear to affect the speed within the study section (see Figure 5-18). Speeds appear to be increasing from about 200 m (656 ft) before the PC to the midpoint of the curve. From there until just after the PT, the average speeds remain constant at about 55 km/h (34 mph). A gap appears in the data from about 870 to 850 m (2854 to 2789 ft). During this gap, the speeds decreased about 5 km/h (3.1 mph). This decrease may be an adjustment period to the narrower pavement but more likely is an artifact of the data.

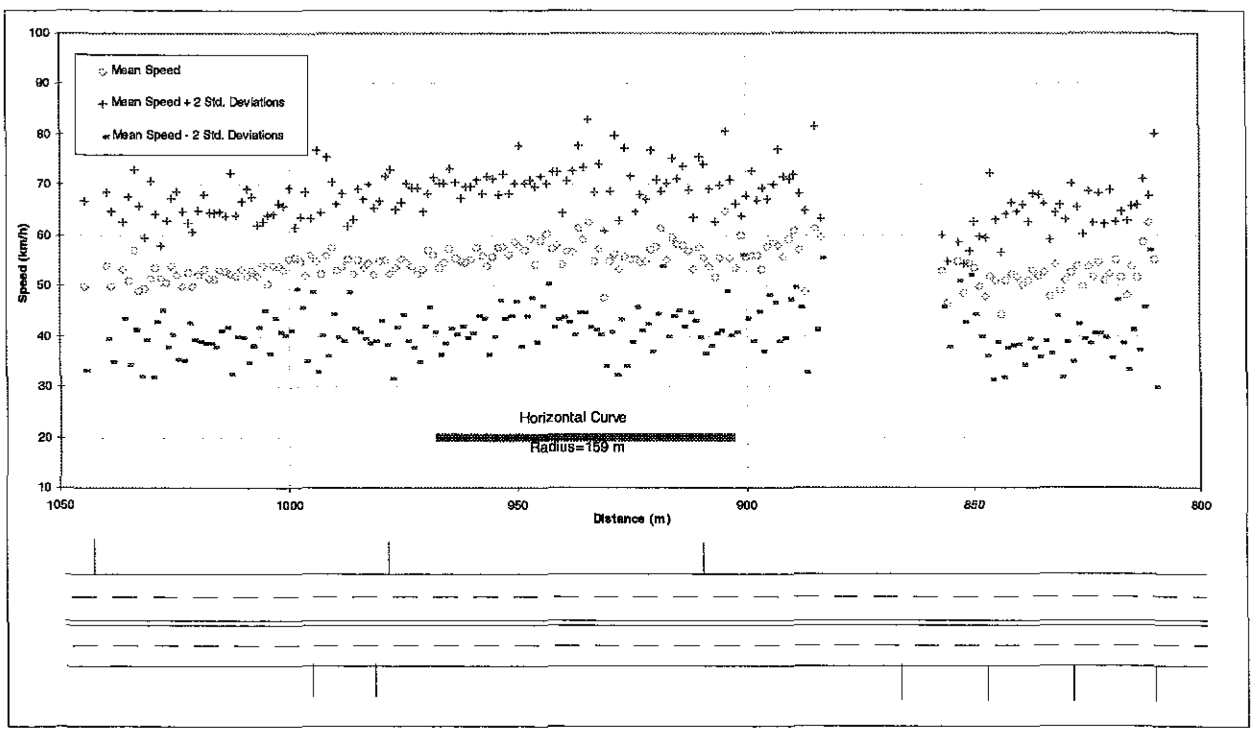


Figure 5-18. Northbound 29th Street Speed Profile. (1 m = 3.28 ft)

Southbound 29th Street

The positioning of the laser guns at the 29th Street southbound location provided a continuous speed profile (see Figure 5-19). It is interesting to observe in Figure 5-19 that the free-flow average speed of the vehicles increased throughout the approach to the curve. Average speeds started at about 55 km/h (34 mph) and increased to about 60 km/h (37 mph) (the posted speed is 56 km/h [35 mph]). Within the horizontal curve, the pavement width transitions from 3.5 to 4.2 m (11.5 to 13.8 ft). Both (or either) the widening of the lanes and the horizontal curve with a fairly tight radius of 159 m (521 ft) seem to have an effect on speeds. The variance of the speeds is also very interesting. From the start of the recordings (at about 733 m [2404 ft]) to just through the curve, the variance is fairly constant and tight. However, as the pavement widens, the variance increases.

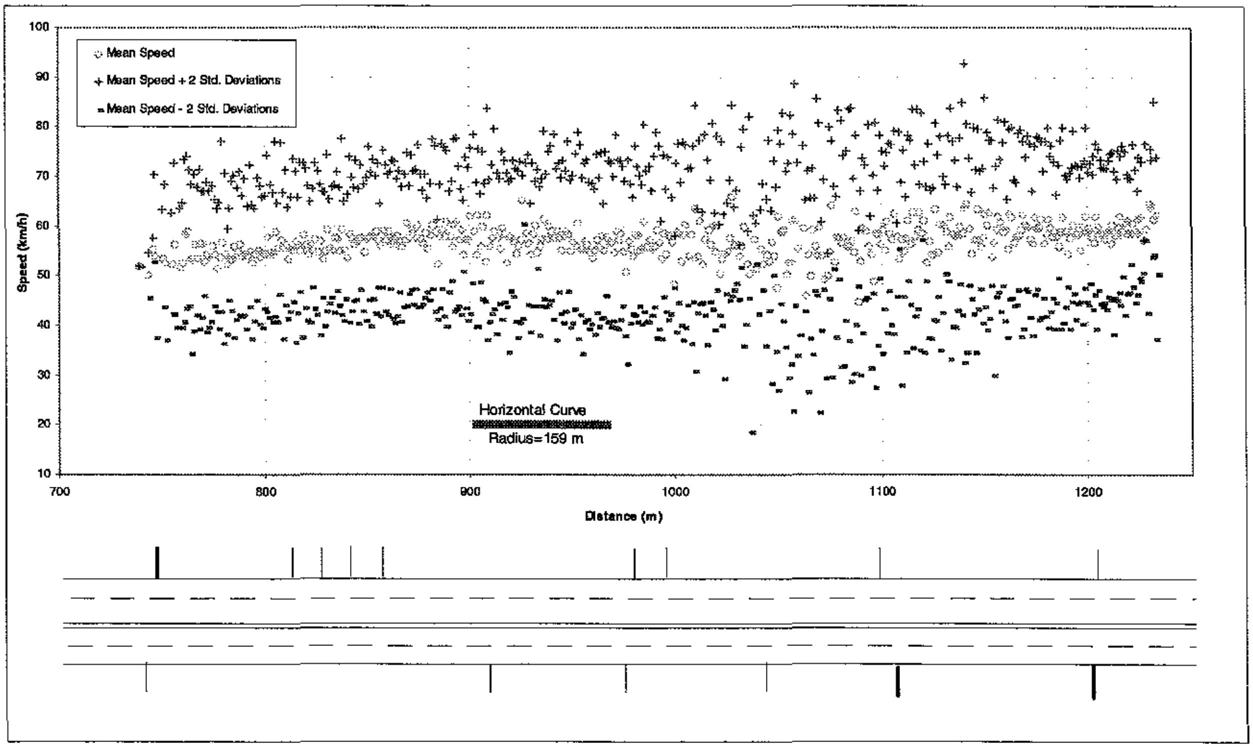


Figure 5-19. Southbound 29th Street Speed Profile. (1 m = 3.28 ft)

Texas Avenue

The curve studied on Texas Avenue has a radius of only 87 m (285 ft), which is the sharpest curve studied in the pilot effort. Initially, it was believed that this would be a good site to study because of the sharp curve; however, unexpected problems were created by the sharpness of the curve—as is evident from the large gap in the data (see Figure 5-20). There are several possible reasons for the gap. First, and probably least likely, was that the laser gun locations were not optimally chosen. Although this problem occurred at other study sites (see Jon Kimbrough, for example), another reason was believed to have caused the gap at this site.

The cause of the gap shown in Figure 5-20 was a function of the sensitivity associated with taking measurements using laser guns. When the gun is first activated and the target is within the cross-hairs of the gun, it may take up to one second for the gun to begin reading speed and distance. When any interruption of the laser beam occurs, the gun loses the target vehicle, and one must wait approximately another second for the readings to begin recording again. An interruption can be caused by another moving car, a pedestrian, or swinging the gun across a telephone pole or a sign post. While the transmission of a beam of light is advantageous in that it allows precise aiming of the gun, it also has an inherent drawback. The laser gun, to work properly, must be shot at a fairly reflective object. License plates, windshields, and headlights work well for this. When a vehicle is approaching on a tangent, it is not difficult to maintain accurate aim of the gun. However, when the vehicles are traversing a horizontal curve and the horizontal angle needed to maintain constant tracking of the vehicle increases, then there is a greater chance of losing the tracking. Once the tracking is lost, accurate aim for up to about one second is needed to regain speed and distance data. Furthermore, when speeds are relatively high, such as the case on Texas Avenue, the angle changes even faster, and the chance of losing the tracking becomes that much greater. This last problem probably accounts for the gap more

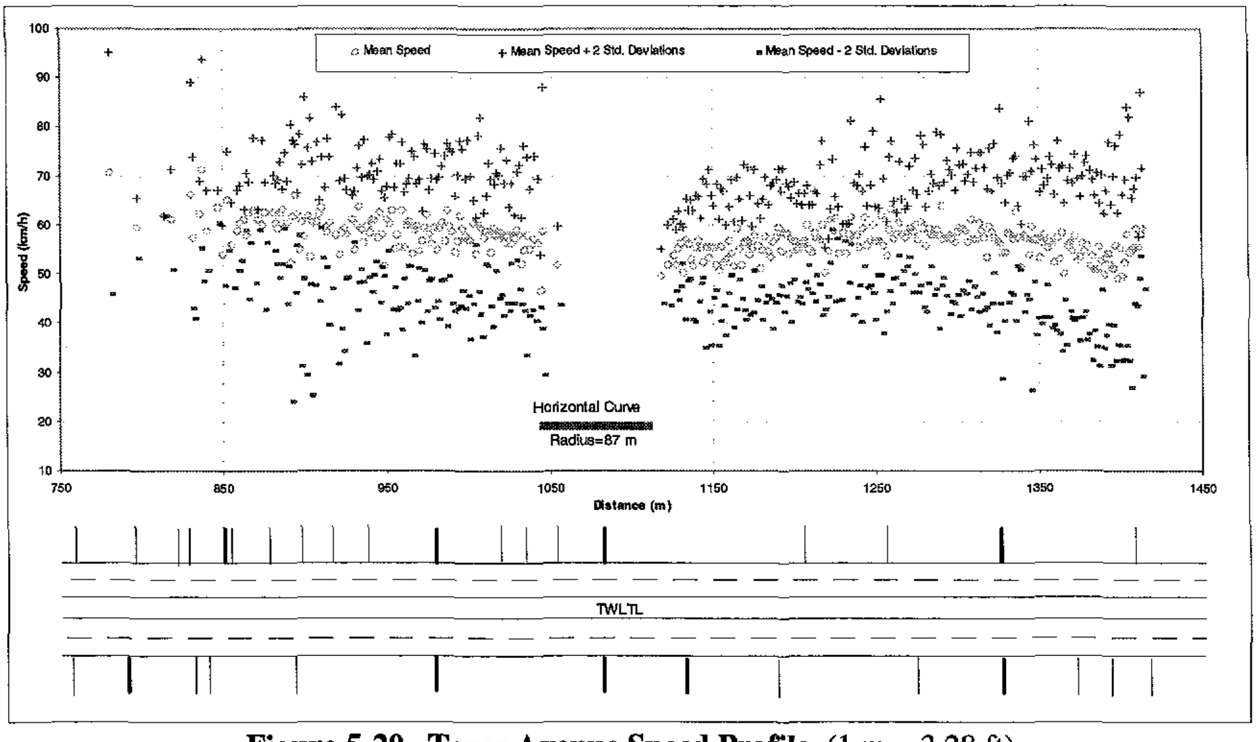


Figure 5-20. Texas Avenue Speed Profile. (1 m = 3.28 ft)

than any other reason. The curve on Texas Avenue is sharp, with many sign posts and telephone poles to interrupt the laser beam tracking, and the speeds are relatively high.

Even without the speed data for the length of the curve, it is evident from the figure that the speeds generally decreased after the curve was traversed compared to speeds upstream of the curve. The tail end of the distribution (near the 1350 to 1425 m [4429 to 4675 ft] locations) shows a drop in speeds. This could be due to a traffic signal located at the 1500 m (4921 ft) mark (not shown on the figure). The average speeds before the curve were approximately 65 km/h (40 mph), while after the curve they dropped to about 60 km/h (37 mph). These average speeds are similar with the posted speed of 64 km/h (40 mph).

FINDINGS

The results of the data collection effort are summarized in Table 5-2. Length of site reflects the approximate length of roadway where speed profiles were obtained. The next column indicates whether the speeds were measured for vehicles traveling on the inside edge of the curve or the outside edge of the curve. Number of good vehicles indicates the number of free-flow vehicles collected. In other words, these vehicles experienced no interaction from other vehicles, pedestrians, or other external sources. Furthermore, no braking occurred for these vehicles as they traversed the study site limits, and all can be classified as either passenger cars, sport utility vehicles, or pick-up trucks. Also, none of these vehicles changed lanes while traversing the study site limits. Summing over all six sites, a total of 395 speed profiles were obtained. This resulted in almost 20,000 individual speed and distance recordings.

Table 5-2. Data Summary.

Site	Length of Site (m)	Inside or Outside Curve	Number of Good Vehicles	Number of Speed Measurements
Jon Kimbrough	275	0	23	983
West Villa Maria	475	0	60	3585
South College	525	0	43	2922
29th Street (NB)	200	I	97	2935
29th Street (SB)	525	0	87	5568
Texas Avenue	625	0	85	3753
Total	n.a.	n.a.	**395**	**19746**

An evaluation of the six speed profiles (see Figures 5-15 to 5-20) lends to useful observations concerning the effects of individual site characteristics on the speed profile and on data collection procedures. Each speed figure is discussed previously with respect to the two aforementioned issues. However, to determine how the study variables (i.e., horizontal curvature and access density) influenced speed across the six study sites, an additional figure was created, summarizing the speeds of all six sites at several key locations along the study limits. Figure 5-21 contains this summary.

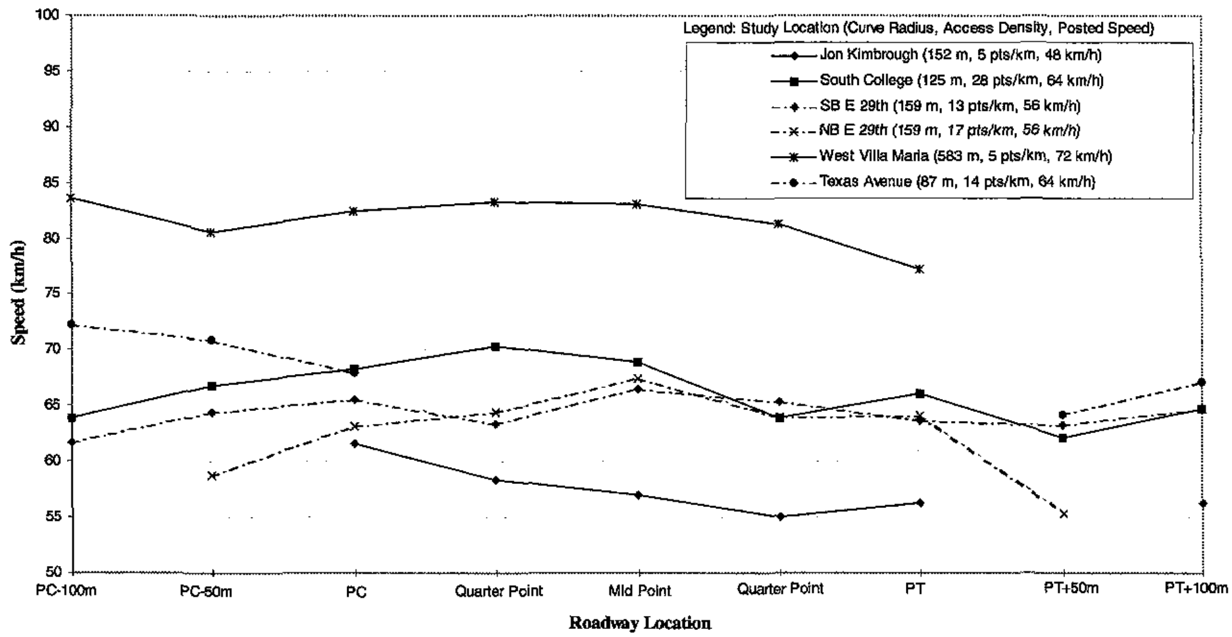


Figure 5-21. 85th Percentile Speeds at Key Roadway Locations.

Speeds shown in Figure 5-21 were determined using the speeds that occurred within 5 m (16 ft) around the point of interest. For instance, if the PC of the Jon Kimbrough site occurred at 1290 m (4232 ft), then speeds from 1288 to 1292 m (4225 to 4238 ft) were used to obtain the 85th percentile speed shown. This method was done to minimize the effects of speed variances caused by the measuring device. As evident in the speed profile figures, the average speed for each meter spacing can deviate anywhere from 0 to 5 or more km/h (3 mph). Because some speed profiles were incomplete (i.e., had gaps in the profiles) and others did not capture speeds far enough in advance of or after the curve, most of the summary speed profiles shown are incomplete. The legend in Figure 5-21 includes numbers in parentheses after each site name. These numbers are the horizontal curve radius, the average access density, and the posted speed at each site.

The relationships that can be loosely derived from the limited amount of information in Figure 5-21 are by no means conclusive. With only six study sites and in some cases incomplete data available per site, only tentative conclusions can be made. With that stated, Figure 5-21 indicates that, for these six sites, access density does not appear to influence speed or that other variables are having a greater influence. The sites with the fastest and slowest speeds had access density measurements of 5 pts/km (8 pts/mi), while those in between ranged from 13 to 28 pts/km (20 to 45 pts/mi).

The effect of horizontal curvature on acceleration/deceleration is debatable. Deviations from approach speed to speed at the midpoint (MP) of the curve are only available for five of the study sites. Of these five, one deviation is practically unmeasurable, three indicate a slight increase in speed, and one shows a slight decrease in speed. Speed deviations from the PC to the PT are available for five of the six sites. Results show a significant decrease in speed for one site, a slight decrease in speed for two sites, a slight increase in speed for another site, and finally, a negligible difference in speeds for the last site.

A noteworthy observation is that the posted speed limits do coincide well with the 85^{th} percentile speeds shown. If ordered based on speed at each site, the order would coincide with the order of the sites if listed in ascending order based on posted speed.

LESSONS LEARNED

Combining the information from the data collection discussion, the data reduction discussion, and the findings, the following observations have been reached concerning the feasibility of using laser guns in Phase II. The observations are split between data collection methodology and the relationship between speed and the variables studied.

Data Collection Methodology

- Identification of potential study sites is a time consuming task that can only be expedited by a rather detailed database or a knowledgeable individual familiar with the roadways in a certain area.
- Once sites have been identified, obtaining plan and profile sheets can be quite time consuming. Depending on the agency involved and their operations concerning locations of the plan profile sheets, the time involved can vary significantly. Of the four agencies used to obtain plan and profile sheets for the six pilot studies, three different procedures were utilized. First was where the agency directed a person to a room and basically said "good luck." Then there was the agency who asked specifics about what we were interested in and then said they would call when the plan profile sheets were located. Finally, and probably the best case scenario, was when an appointment was made with a person within the agency familiar with the plan and profile sheets. Together, the team identified and copied the pertinent sheets. Regardless of the procedure, however, all involve significant amounts of time and should be considered during Phase II.
- When obtaining the speed profiles of the vehicles, a five-second headway and tailway are too restrictive. Many free-flowing vehicles were not measured because of this criteria.
- The locations of the laser guns play a crucial role in obtaining constant speed profiles.
- The exact locations of the laser guns must be known with respect to some element contained on the plan and profile sheets. This is to be able to link the speeds of the vehicles to the exact position on the roadway.
- Where extremely sharp curves exist combined with high speeds and considerable amount of roadside obstructions such as sign posts and telephone poles, the tracking distance of the vehicles through the curve is severely limited.

- Where signals are in close proximity to the upstream study limit, vehicles tend to arrive in platoons. Because of the five-second headway and tailway constraints, no vehicles traveling in platoons can be considered free-flowing. This limits the number of vehicles that can be collected at such sites and essentially eliminates these sites from possible contention. However, because of the nature of this project and its focus on suburban arterial streets, a dilemma is created. Many suburban arterials have signals with a fairly close spacing.
- Data reduction is extremely time consuming and creates file sizes in excess of what older computers can handle.

Speed Relationship with Variables

- For the six sites studied herein, access density did not appear to influence speed. However, based on previous work and common knowledge concerning the relationship between access density and speed, more research is needed to reach a definitive conclusion.
- Horizontal curvature may influence speed slightly, but conclusive evidence cannot be realized from the limited data available in this study. Studies on high speed roadways show that the threshold for where geometrics (i.e., horizontal curvature) control speed is about a radius of 400 m (1312 ft). Any radii over 400 m (1312 ft) has minimal effect on operator speed choice, while radii under 400 m (1312 ft) do influence speed selection. This being the case, perhaps on lower speed roadways the threshold value for where speeds are influenced by radii on suburban arterials is much lower since motorists have a preconceived maximum speed associated with suburban arterials that is much lower than that for high speed roadways.
- Posted speed and free-flowing average speed coincided for the six study sites.

CHAPTER 6

DATA COLLECTION AND REDUCTION FOR LASER STUDY

This chapter describes the site selection, data collection, and data reduction methodology used in Phase II of the project. It also presents initial observations on the speeds recorded at the study sites. The data collection had two main components: recording the characteristics of the site and collecting the speed data. These components were merged during the data reduction efforts. Because the techniques used for site selection and data collection in Phase II were similar to the approaches used in the pilot study, the repetitive information is not included in this chapter. The reader is directed to Chapter 5 for additional details on site selection and data collection.

SITE SELECTION

Data were collected at both horizontal curve and straight section sites. The general criteria used to select study sites are summarized in Table 6-1. The criteria are very similar to those used in the pilot study, with a few refinements reflecting the lessons learned as part of the Phase I efforts. These criteria were selected to provide a degree of uniformity and minimize the effects of elements not under consideration in this study. A similar procedure as used during Phase I was employed on site identification and selection (see Chapters 3 and 5). TxDOT, TTI urban offices, and/or city representatives were contacted to assist in identifying potential study sites. In addition to the criteria listed in Table 6-1, a goal was to select sites from different regions of Texas.

To focus the site selection process, key variables were selected for emphasis in the Phase II effort. Based on the findings from the pilot studies, the following variables and ranges were selected for the horizontal curve sites:

- horizontal curvature (less than 200 m [656 ft] and greater than or equal to 200 m [656 ft]),
- access density (less than 10 pts/km [16.1 pts/mi] and greater than or equal to 10 pts/km [16.1 pts/mi]), and
- median design (TWLTL, raised, and none).

The variables and ranges selected for the straight section sites were:

- access density (less than 10 pts/km [16.1 pts/mi] and greater than or equal to 10 pts/km [16.1 pts/mi]),
- median design (TWLTL, raised, and none), and
- posted speed limit (48 to 56 km/h [30 to 35 mph], 64 to 72 km/h [40 to 45 mph], and 80 to 88 km/h [50 to 55 mph]).

In order to organize the site selection procedure, a matrix was developed to reflect all possible combinations of the selected variables for the horizontal curve sites and the straight section sites. Curve sites were divided into 12 categories based on the two ranges of access density, the three median types, and the two ranges of centerline radius. Straight section sites were divided into 18 categories based on the two ranges of access density, the three median types, and the three groups of posted speed limits. The goal was to identify two sites per cell. Therefore, a total of 24 horizontal curve sites and 36 straight section sites were desired.

Similar to the findings from the pilot study, certain combinations are rare, for example, high access density sites with high speed limits (80 to 88 km/h [50 to 55 mph] range). High access density is generally associated with lower speed facilities. While finding two valid sites for each cell was not feasible, the goal of the total number of sites was achieved. These sites were distributed across the range of variables as evenly as possible given the inherent limitations of identifying and selecting existing sites. Table 6-2 shows the different combinations of the study variables (i.e., TWLTL with low access density and small horizontal curve radius) and the number of study sites where data were collected for each possible combination for the curve sites. Table 6-3 shows similar data for the straight section sites. Figures 6-1 and 6-2 illustrate the data in graphic format.

Curve site data were collected in five regions and/or metropolitan areas in the state of Texas: Bryan-College Station, Dallas-Fort Worth Metroplex, Houston, San Antonio, and South Texas (Harlingen and Brownsville). There were 27 curve sites selected for data collection, and data from 23 of those sites were complete enough for use in the study. Straight section site data were also collected in five areas of Texas: Bryan-College Station, Waco, Houston, San Antonio, and Corpus Christi. A total of 36 straight section sites were used in the study.

Table 6-1. Site Selection Criteria.

Control	Criteria
Area Type	Urban/Suburban
Number of Lanes	Four Lanes
Grade	+4% to -4%
Terrain	Level to Rolling
Posted Speed Limit	48 to 88 km/h (30 to 55 mph)
Surface Condition	Fair to Good
Edge Control	Curb and Gutter only
Sight Distance	Adequate
Headway/Tailway	5/3 seconds
Distance from Adjacent Horizontal Curve	200 m (656 ft)
Distance from Adjacent Signal or STOP Sign	300 m (984 ft)

Table 6-2. Number of Curve Sites.

Access Density	Median Type	Radius, m (ft)	
		< 200 (656)	> 200 (656)
Low 0-10 pts/km (0-16.1 pts/mi)	None	1	2
	Raised	2	5
	TWLTL	0	0
High >10 pts/km (16.1 pts/mi)	None	2	1
	Raised	1	3
	TWLTL	4	2

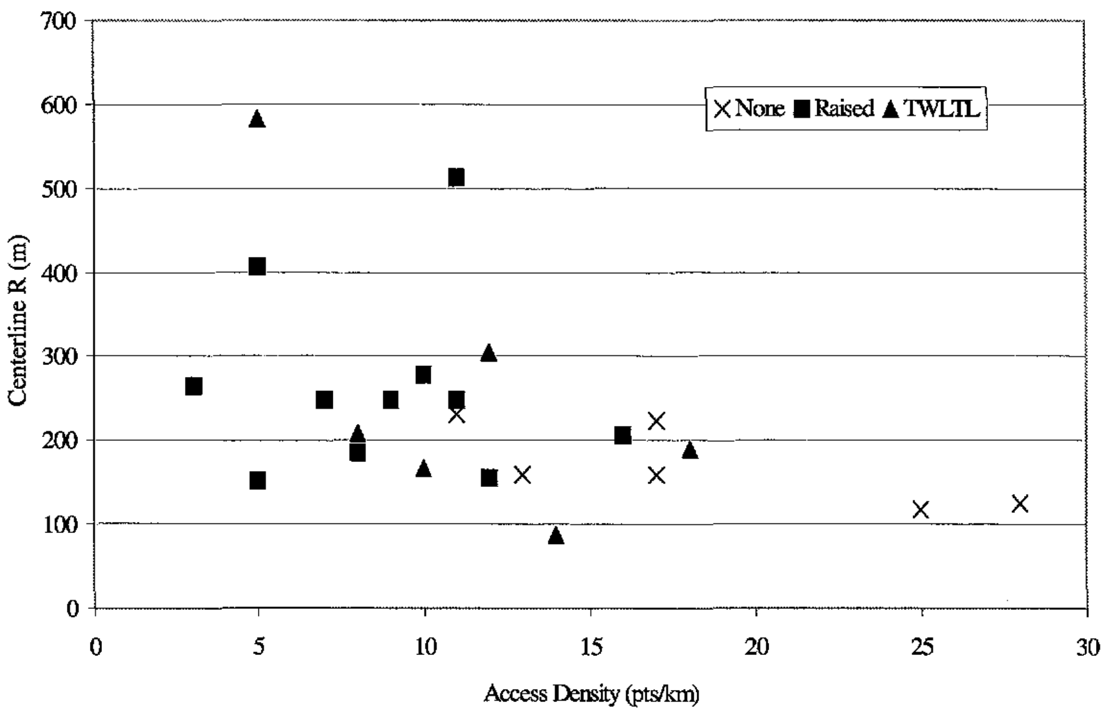


Figure 6-1. Distribution of Curve Sites.

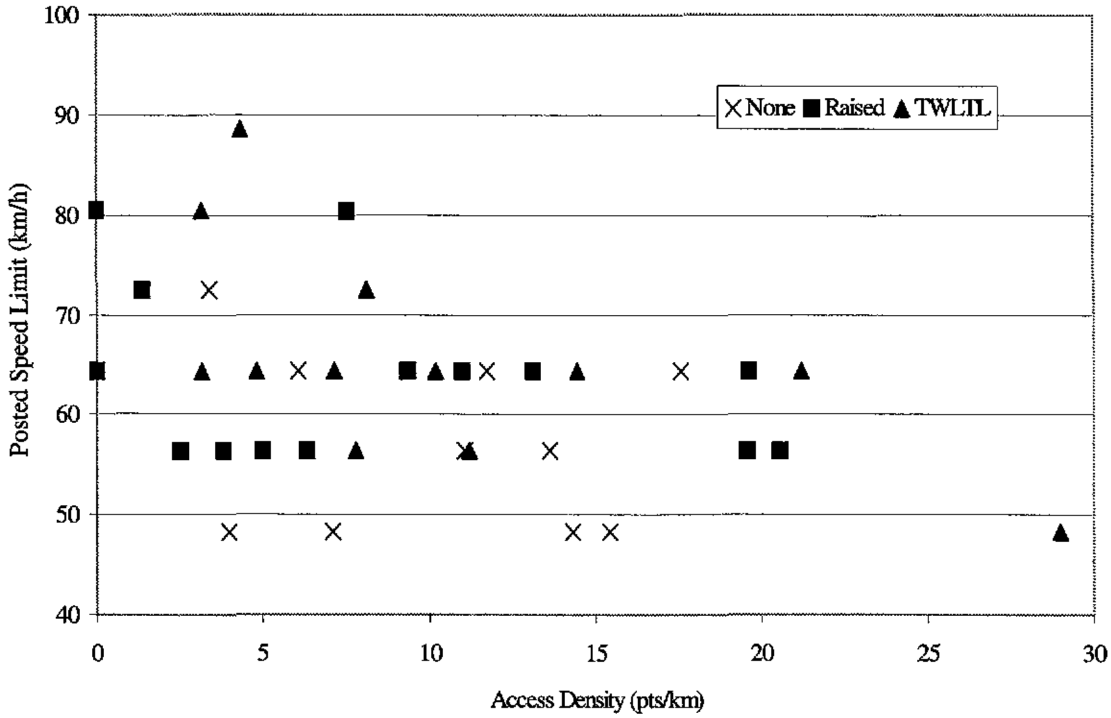


Figure 6-2. Distribution of Straight Section Sites.

Table 6-3. Number of Straight Sites.

Access Density	Median Type	Posted Speed Limit, km/h (mph)		
		48-56 (30-35)	64-72 (40-45)	80-88 (50-55)
Low 0-10 pts/km (0-16.1 pts/mi)	None	2	2	0
	Raised	4	3	3
	TWLTL	1	4	2
High >10 pts/km (16.1 pts/mi)	None	3	2	0
	Raised	2	3	0
	TWLTL	2	3	0

DATA COLLECTION

The data collection effort included obtaining both the characteristics of the site and the speed data of vehicles at a site. Generally, a single day was needed to set up, record speeds, and take down the equipment at the curve sites. Because fewer laser guns were needed at the straight section sites, speed data at two sites in a one-day period could be recorded on some occasions. The characteristics of the sites were either measured before or after the speed data were collected, or the information for several nearby sites would be obtained at the end of a data collection trip. The collection of both the site characteristics and the speed data generally occurred during the mid part of a day when volumes were typically lower to maximize the opportunity to capture the greatest number of free-flow vehicles.

Site Characteristics

A variety of site characteristic data were collected at each study site. Data for the curve sites were based on the study curve, the section of roadway immediately upstream, and the section of roadway immediately downstream. Site characteristic data for the straight section sites were confined to the area between the upstream and downstream controls of the study site. The site characteristic data collected are listed in Table 6-4.

Table 6-4. Site Characteristics Data Collected at Each Study Site.

Alignment • Curve radius (horizontal curve sites) • Curve length (horizontal curve sites) • Deflection angle (horizontal curve sites) • Length of straight section (straight sites) • Potential controlling feature upstream and downstream of site • Distance to potential controlling features	**Cross Section** • Lane width • Superelevation (horizontal curve sites) • Parking • Bike lane • Median type and width
Roadside • Roadside development • Access density • Roadside environment • Pedestrian activity	**Traffic Control Devices** • Signals per kilometer • Posted speed limit • Presence of curve/turn warning signs (horizontal curve sites) • Presence (and value) of advisory speed signs (horizontal curve sites)

The alignment data included specific characteristics of the horizontal curve (for the horizontal curve sites only) and features upstream and downstream that could affect the speed along the study section. Curve radius and curve length were measured in the field, and using these data, curve deflection angle was calculated in the office. Curve radius was estimated by anchoring the ends of a 33 m (100 ft) length of twine within the study curve so that both end points were within the curve, and the chord length was stretched taut. The distance between the chord and curb (normal to the chord length) was then measured at the chord midpoint. An empirical formula was then used to convert this value to an approximate radius. Depending on the lane widths and median presence/width, the approximate radius was converted to a centerline radius. This procedure was developed to replace the Phase I procedure, which included obtaining the plan/profile sheets from the various agencies. The field method saved many hours of interactions with various agencies and office work. The length of the curve was measured using a DMI.

The nearest feature that could affect speed was identified for both upstream and downstream of the study site. The feature was either a traffic control device (i.e., signal or stop-control on the study roadway) or a horizontal curve with a radius ≤ 500 m (1640 ft). In a few cases for the straight section sites, the feature was a bridge or a t-intersection. The distance to these features was measured using a DMI.

The cross section features were measured and recorded in the field. The presence of the following features were recorded: bike lane, on-street parking, and type of median. A measuring wheel was used to obtain the width of each lane, median, and bike lane, if present. The superelevation of the horizontal curve was estimated using a 1.3 m (4 ft) level and measuring the vertical offset at one end while the opposite end was held in contact with the pavement. Several measurements were made to reduce the chance of influence from rutting. An average was taken, and the value was converted to a percentage.

Recording the characteristics of the roadside features for a site was more involved than collecting the data for the other site variables. Measurements were made for some of the features and then were converted into a rating scale in the office. Determination of pedestrian and roadside characteristics was based on measurements and observations made at the study sites, and observations from pictures and video taken at the sites. Only characteristics within the limits of the study site were examined. Roadside development was recorded as being school, residential, commercial, mix of commercial and residential, or park. Access density, which is the number of access points per unit distance, was measured for 1 km (0.6 mi) in either direction from the center of the horizontal curve or along the straight section.

The pedestrian activity rating was based on the number of pedestrians observed during the study period and the presence and position of a sidewalk. The pedestrian activity rating was assigned a score from one to five according to the criteria described in Table 6-5. A site was considered to have a low presence of pedestrians if there was no sidewalk and no pedestrians were observed during the study period. Medium pedestrian presence was assigned to a site with a sidewalk or pedestrian path and no pedestrians observed during the study period. High pedestrian presence was assigned to a site with a sidewalk or path where pedestrians were observed during the study period. A buffer was considered to be a physical separation between the edge of the curb and the sidewalk of greater than 0.3 m (1.0 ft), but generally, more distance separated the sidewalk and travel lane. Based on these characteristics, each site was assigned a pedestrian activity rating using the values shown in Table 6-5.

Table 6-5. Values for Pedestrian Activity Rating.

Presence of Pedestrians	Buffer	No Buffer
Low	1	1
Medium	2	3
High	4	5

The roadside environment rating accounted for the presence and types of lateral restrictions at the study sites. Initially, attempts were made to utilize rating systems developed in other research efforts; however, those ratings did not adequately describe the characteristics of the sites in this study. For example, the rating system developed by Poe, et al. was examined; in this system, a rating of zero to four was assigned according to the following scale:[9]

0 = clear with no fixed objects
1 = yielding objects only
2 = combination of yielding and isolated rigid objects
3 = isolated rigid objects only
4 = numerous or continuous rigid objects

Because every site in this study contained at least one rigid object, application of this scale resulted in a rating of three or four at every site.

To obtain a more detailed description of the roadside environment of the study sites, a rating scale was developed that considered the frequency of the rigid objects and the distance between the objects and the roadway. Each of these criteria was assigned a score from one to five. The total rating for a site, based on a scale from two to ten, was obtained from the sum of the two scores for the individual criteria. Score values for these criteria are given in Table 6-6.

Table 6-6. Values for Roadside Environment Ratings.

Descriptor	Score
Frequency of Object	
Intermittent	1
Regular	3
Continuous	5
Distance of Rigid Object from Roadway	
≥ 3.0 m	1
1.5 m to 3.0 m	2
0.3 m to 1.5 m	3
≤ 0.3 m	5

Object frequency was divided into three categories: continuous, regular, and intermittent. Continuous objects were objects that had little to no space between them, such as guardrails or tree lines. Objects were considered to be placed at regular intervals if the spacing between them was less than 60 m (196.9 ft). Intermittent, or isolated, objects had a spacing of at least 61 m

(200 ft). Based on these definitions, an object frequency score (1, 3, or 5) was assigned to each site.

Rigidity of an object was primarily determined based on the definition provided in the *Roadside Design Guide*, which states that "a single tree with a trunk diameter greater than 150 mm is considered a fixed object." [19] Objects such as trees or utility poles that had diameters greater than 150 mm (6 in) were considered to be rigid. Distance from the roadway to these objects was divided into the four categories listed in Table 6-6 and a distance score (1, 2, 3, or 5) was assigned accordingly.

The data associated with the characteristics of traffic control devices located near or at the site included the posted speed limit value, the presence of warning signs such as curve/turn or advisory speed, and the number of signals per kilometer (the number of signals measured for one km distance upstream and downstream of the center of the horizontal curve or along the entire length of the straight section).

Tables 6-7 and 6-8 summarize the site characteristics for each curve and straight section site, respectively.

Table 6-7. Site Characteristics for Curve Sites.

	Alignment					Cross Section					
Site Number	**Radius (m)**	**Length (m)**	**Deflection Angle (deg)**	**Control Upstream (Distance, m)***	**Control Downstream (Distance, m)***	**Lane Width, Average (m)**	**Superelevation, (Average) (m/m)**	**Parking**	**Bike Lane**	**Median Type**	**Median Width (m)**
C1	87	61	40.2	sig (1000)	sig (312)	3.66	2.1	No	No	TWLTL	3.66
C2	117	114	70.5	sig (513)	cur (187)	3.66	2.1	No	No	None	---
C3	125	64	29.3	sig (256)	sig (749)	3.13	1.4	No	No	None	---
C4	152	193	72.8	cur (170)	stop (808)	3.43	1.2	No	Yes	Raised	3.05
C5	156	69	25.4	cur (629)	sig (658)	3.58	1.8	No	No	Raised	10.37
C6	159	59	21.3	cur (751)	sig (582)	3.13	0.1	No	No	None	---
C7	159	59	21.3	sig (582)	cur (751)	3.13	2.3	No	No	None	---
C8	167	100	34.4	cur (455)	sig (484)	3.66	1.3	No	No	TWLTL	5.18
C9	186	87	26.8	sig (359)	cur (1051)	3.66	1.3	No	No	Raised	9.76
C10	190	190	57.3	sig (692)	sig (345)	3.66	1.3	No	No	TWLTL	5.18
C11	206	177	49.3	cur (203)	sig (1162)	3.66	1.7	No	No	Raised	6.71
C12	209	188	51.5	sig (444)	stop (367)	3.58	2.6	No	No	TWLTL	4.88
C13	224	142	36.4	sig (1098)	sig (326)	3.66	-1.8	No	No	None	---
C14	231	196	48.7	cur (274)	sig (300)	3.35	-0.8	No	No	None	---
C15	247	115	26.7	cur (252)	cur (281)	3.58	0.3	No	No	Raised	9.45
C16	247	154	35.7	sig (448)	sig (245)	3.66	-2.1	No	No	Raised	7.18
C17	248	209	48.3	sig (755)	stop (473)	3.66	2.1	No	No	Raised	6.04
C18	266	224	48.3	cur (138)	cur (197)	3.54	-3.5	No	No	Raised	4.34
C19	278	193	39.8	cur (256)	sig (331)	3.66	1.8	No	No	Raised	10.06
C20	305	177	33.2	sig (1170)	sig (1479)	3.96	-3.6	No	No	TWLTL	5.03
C21	406	301	42.5	sig (341)	sig (1000)	3.66	2.1	No	No	Raised	9.76
C22	513	194	21.7	sig (371)	sig (652)	3.66	1.7	No	No	Raised	9.15
C23	583	249	24.5	cur (507)	cur (258)	3.89	4.8	No	No	TWLTL	4.73

* cur = Horizontal curve
sig = Traffic signal

Table 6-7. Site Characteristics for Curve Sites (continued).

	Roadside				Traffic Control Device				
Site Number	**Development**	**Access Density (pts/km)**	**Environment**	**Pedestrian Activity**	**Signal Spacing (sig/km)**	**Posted Speed (km/h)**	**Curve Sign**	**Turn Sign**	**Advisory Speed (km/h)**
C1	Comm	14	5	3	1	64	No	Yes	48
C2	Resid	25	5	2	1	64	Yes	No	---
C3	Comm	28	6	1	1	64	No	No	---
C4	Park	5	6	2	0.5	48	No	No	---
C5	Resid	12	5	2	1	64	Yes	No	48
C6	Comm	13	6	1	1.5	56	No	No	---
C7	Comm	17	10	1	1.5	56	Yes	No	---
C8	Comm	10	6	2	0.5	72	No	No	---
C9	Resid	8	6	1	0.5	64	Yes	No	48
C10	Comm	18	8	2	0.5	72	Yes	No	---
C11	School	16	5	2	0.5	64	Yes	No	---
C12	Resid	8	5	2	0.5	48	No	No	---
C13	Resid	17	7	2	1	48	Yes	No	32
C14	Resid	11	7	2	1	48	No	No	---
C15	Resid	7	7	5	1	64	No	No	---
C16	Resid	11	6	2	1	64	No	No	---
C17	Comm	9	8	2	1	72	Yes	No	---
C18	Park	3	8	5	0	48	Yes	No	---
C19	Resid	10	8	5	1	64	Yes	No	64
C20	Comm	12	2	1	0.3	72	No	No	---
C21	Resid	5	7	1	1	72	No	No	---
C22	Resid	11	8	1	1	56	Yes	No	---
C23	School	5	6	2	0.5	72	No	No	---

Table 6-8. Site Characteristics for Straight Section Sites.

	Alignment			Cross Section					Roadside				Traffic Ctrl.	
Site Number	Length (m)	Control Upstream (Distance, m)	Control Downstream (Distance, m)	Lane Width, Average (m)	Parking	Bike Lanes	Median Type	Median Width (m)	Development	Pedestrian Activity	Access Density (pts/km)	Environment	Signal/km	Posted Speed (km/h)
T1	149	stop (375)	stop (374)	3.26	No	No	None	---	Res	4	4.0	5	0.0	48
T2	799	t-int (700)	stop (699)	3.20	No	No	None	---	Res	2	7.1	8	0.0	48
T3	799	stop (700)	t-int (699)	3.30	No	No	None	---	Res	4	6.4	5	0.0	48
T4	436	stop (518)	sig (518)	3.05	No	No	None	---	Res	2	15.4	8	1.0	48
T5	401	sig (500)	sig (500)	3.21	No	No	TWLTL	3.05	Com	2	29.0	6	2.0	48
T6	186	sig (393)	stop (393)	3.63	No	No	Raised	7.32	Res	1	2.5	7	1.3	56
T7	186	stop (393)	sig (393)	3.63	No	No	Raised	7.32	Res	1	3.8	6	1.3	56
T8	1398	sig (999)	stop (999)	3.66	No	No	Raised	7.32	Res	1	5.0	6	0.5	56
T9	343	sig (472)	sig (471)	3.52	No	No	Raised	9.70	Com	2	6.4	5	2.1	56
T10	294	sig (447)	stop (447)	3.16	No	No	TWLTL	3.68	Res	4	7.8	8	1.1	56
T11	756	sig (678)	sig (678)	3.51	No	No	None	---	Res	5	11.1	8	1.5	56
T12	294	stop (447)	sig (447)	3.18	No	No	TWLTL	3.68	Res	4	11.2	8	1.1	56
T13	421	sig (511)	sig (510)	3.94	No	No	Raised	3.86	Res	4	19.6	7	2.0	56
T14	421	sig (511)	sig (510)	4.00	No	No	Raised	3.86	Res	4	20.6	7	2.0	56
T15	494	sig (547)	sig (547)	3.66	No	No	Raised	24.38	Res	2	0.0	7	1.8	64
T16	656	sig (628)	sig (628)	3.96	No	No	TWLTL	4.42	Res	5	3.2	8	1.6	64
T17	747	cur (574)	sig (673)	3.81	No	No	TWLTL	4.57	Mix	5	4.8	8	0.8	64
T18	554	sig (577)	stop (577)	3.72	No	No	None	---	Res	1	6.1	6	0.9	64
T19	656	sig (628)	sig (628)	3.96	No	No	TWLTL	4.42	Res	5	7.2	8	1.6	64
T20	578	sig (589)	sig (589)	3.62	No	No	Raised	9.14	Res	4	9.3	6	1.7	64
T21	872	sig (736)	sig (736)	3.85	No	No	TWLTL	4.17	Com	5	10.2	4	1.4	64
T22	677	sig (639)	sig (639)	3.66	No	No	Raised	3.05	Com	4	11.0	6	1.6	64
T23	596	sig (598)	sig (598)	3.21	No	No	None	---	Com	2	11.7	5	1.7	64
T24	700	sig (650)	t-int (650)	3.18	No	Yes	Raised	2.44	Res	2	13.1	8	0.8	64
T25	747	sig (674)	cur (573)	3.81	No	No	TWLTL	4.57	Mix	5	14.4	8	0.8	64
T26	596	sig (598)	sig (598)	3.21	No	No	None	---	Com	2	17.6	7	1.7	64
T27	216	sig (408)	sig (408)	4.27	No	Yes	Raised	2.74	Res	5	19.6	8	2.5	64
T28	295	sig (448)	sig (447)	3.51	No	No	TWLTL	3.66	Com	2	21.2	3	2.2	64
T29	973	cur (687)	sig (786)	3.52	No	No	Raised	9.45	Res	2	1.4	7	0.7	72
T30	575	sig (588)	sig (587)	3.66	No	No	None	---	Res	4	3.4	8	1.7	72
T31	872	sig (736)	sig (736)	4.19	No	No	TWLTL	4.27	Res	1	8.2	6	1.4	72
T32	536	bdg (568)	sig (568)	4.11	No	No	Raised	4.88	Res	2	0.0	6	0.9	80
T33	536	sig (568)	bdg (568)	4.11	No	No	Raised	4.88	Res	2	0.0	6	0.9	80
T34	668	stop (634)	sig (634)	3.53	No	No	TWLTL	3.66	Com	4	3.2	6	0.8	80
T35	458	sig (529)	sig (529)	3.96	No	No	Raised	4.88	Res	5	7.6	6	1.9	80
T36	1008	sig (804)	sig (804)	3.78	No	No	TWLTL	4.27	Res	2	4.4	6	1.2	88

Speed Data

The speed data were collected between April 1998 and June 1999 during daylight, off-peak periods, and under dry weather conditions. Speed profiles for approximately 100 free-flowing vehicles were taken at each site. Vehicle type was identified by observation. The speed profiles were collected using laser guns positioned on the side of the roadway. Figure 6-3 shows a close-up of a laser gun. Techniques used to hide the technicians from passing motorists include the truck blind (as discussed in Chapter 5) and locating behind a tree or bushes as shown in Figures 6-4 and 6-5. Additional details on how the data were collected with the laser guns are included in Chapter 5.

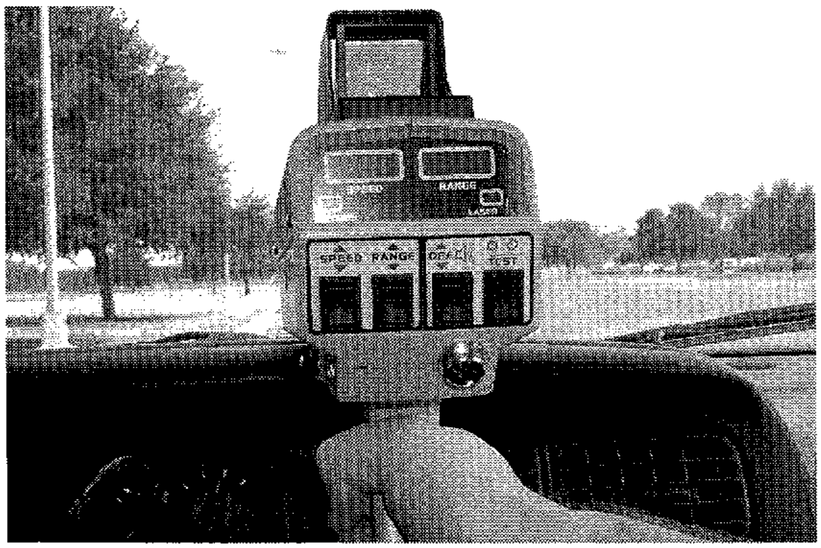


Figure 6-3. Example of Laser Gun.

Figure 6-4. Example of Technician Placement in Field (from back side).

Figure 6-5. Example of Technician Placement in Field, Driver's View.

For the collection of curve speed data, between two and four laser guns were used. These guns were strategically positioned through the length of the study curve. The laser guns and their operators were positioned as inconspicuously as possible while enabling the recording of speeds upstream of the curve, through the curve, and downstream of the curve, to the maximum extent possible. Every attempt was made to record a continuous speed profile rather than one with gaps.

For the collection of straight section speed data, one laser gun was used at most sites; the remaining straight section sites were studied using two guns. As with the curve sites, the laser guns were positioned inconspicuously.

Vehicles had to meet certain criteria to be included in this study. To ensure that only free-flowing vehicles were recorded, laser gun operators focused on vehicles with headways and tailways greater than 5 or 3 seconds, respectively. The use of 3 seconds as the limit for tailways was a recommended change from the pilot study's use of a 5 second tailway. The times were estimated in the field as the target vehicles approached. If a vehicle was impeded in any manner, the data for that vehicle were tagged and later discarded. Additionally, a vehicle had to remain on the study site for the entire length of the curve or straight section; if a vehicle turned off, its data were tagged and discarded. Finally, if the technicians judged that their presence was an influence on the speed of the target vehicle, a note was made, and the data were later reviewed for acceptability.

DATA REDUCTION

The speed and distance data measured by the laser guns are in U.S. Customary units. Each measurement or row of data consists of four columns of data: a comment column (i.e., "data" or "remark"), the time the speed was recorded, the vehicle speed in miles per hour, and the distance away from the gun to the vehicle in feet. A data file would include several rows of data: one row for each speed/distance measurement recorded. The measurements for different vehicles would be divided by a row that would contain a "remark," such as the color and type of the vehicle. The data file created by the laser gun and stored on a computer would be imported into a spreadsheet for evaluation during the data reduction effort. Data for vehicles that were tagged as unusable (based on comments made in the "remark" row) were noted by highlighting appropriate data cells in the spreadsheet.

In cases where more than one gun were used at a site, the individual spreadsheet data files for each gun were concatenated into one "combined" spreadsheet file. The vehicles recorded by each gun were matched based on the remark field and time stamp. The spreadsheet was sorted so that all speed measurements associated with a given vehicle were together. If a vehicle was noted as being unusable in an individual spreadsheet, then the data for that vehicle were deleted from the combined spreadsheet. A column was also added to the combined spreadsheet to indicate which gun recorded the data. Table 6-9 is an example of a partial spreadsheet for one vehicle with speed/distance measurements from two laser guns.

Table 6-9. Sample of Laser Data in a Combined Spreadsheet.

Gun #	Comment	Time	Speed (mph)	Distance (ft)
1	DAT	15:57.3	26	107
1	DAT	15:57.6	26	96
1	DAT	15:56.9	26	85
1	DAT	15:58.2	26	73
1	DAT	15:58.5	26	62
1	DAT	15:58.8	26	52
1	REM	grn car 1		
2	DAT	15:59.4	26	352
2	DAT	15:59.7	27	341
2	DAT	16:00.0	27	329
2	DAT	16:00.3	27	317
2	DAT	16:00.6	26	305
:	:	:	:	:
2	DAT	16:07.8	26	65
2	DAT	16:08.1	26	54
2	REM	grn car 1		

The next step of the process was to create the "statistical" spreadsheet. The data were converted from U.S. Customary units to metric units. After unit conversion, cosine error corrections were made to modify the speed data where needed. Afterwards, descriptive statistics were calculated, such as minimum and maximum recorded speeds, position on the roadway relative to the upstream control, and minimum and maximum recorded distances. Also, the time, speed, and acceleration differences between readings were recorded for each successive reading. Table 6-10 is an example of a sample of data contained in a statistical spreadsheet. The total number of vehicles and the total number of individual readings in the sample were recorded for reference.

Table 6-10. Sample of Data in Statistical Spreadsheet.

Time	Speed (mph)	Dist (ft)	Speed (km/h)	Dist (m)	Road loc (m)	Time diff (sec)	Speed diff (m/s)	Accel diff (m/s²)
11:44.1	-33	150	53.10	45.72	394.72	-	-	-
11:44.5	-33	164	53.10	49.99	398.98	0.33	0.00	0.00
11:44.7	-33	179	53.10	54.56	403.56	0.27	0.00	0.00
11:45.0	-33	189	53.10	57.61	406.60	0.28	0.00	0.00
11:46.2	-34	253	54.71	77.11	426.11	1.21	0.45	0.37
11:46.6	-34	267	54.71	81.38	430.38	0.33	0.00	0.00
11:46.8	-34	281	54.71	85.65	434.64	0.27	0.00	0.00
11:47.1	-33	296	53.10	90.22	439.22	0.27	-0.45	-1.66
11:47.4	-33	310	53.10	94.49	443.48	0.33	0.00	0.00

Once all of these statistics were calculated, another spreadsheet was created to determine average recorded speed at each point on the roadway. All of the individual speeds recorded at each meter of roadway were totaled, and an average was taken, along with a standard deviation and a count of readings at that meter. This process generated an average speed profile for the entire study site, which was depicted graphically on an X-Y graph. Figures 5-15 to 5-20 are examples of the plots that were generated during this step of the data reduction effort.

After the data were combined and plotted, it was apparent that additional efforts were needed to filter the data for motorists who apparently spotted the researchers collecting speed data. Although every effort was made to be as inconspicuous in the field as possible, some motorists did see the researchers and slowed considerably. This deceleration was usually obvious in the field, and after the speed profile for such a vehicle was recorded, it was tagged and later discarded. However, not all decelerations due to the presence of the technician were obvious.

Figure 6-6 illustrates five vehicle speed profiles along a study section. The speed limit of this site was 64 km/h (40 mph). This site has a relatively tight radius of 156 m (511.8 ft); therefore, drivers tend to slow for the curve. For this reason, technicians were sometimes reluctant to tag a vehicle for future discarding when drivers might be decelerating for the curve instead of decelerating because they spotted the data collectors. A good example of a speeding motorist slowing for the curve is Car 1, which decelerates about 5 km/h (3.1 mph) to enter the curve. Once through the curve the motorist has accelerated to the same speed value as used prior to the curve. Car 2 also decelerated just prior to the PC of the study curve. However, in this case the deceleration is much more severe and levels out near the speed limit. Additionally, a data collector was located in this region, which prompted the belief that this motorist spotted the data collector and quickly decelerated to the speed limit to avoid a speeding citation. In other words, the speed profile for Car 2 does not represent a free-flow speed.

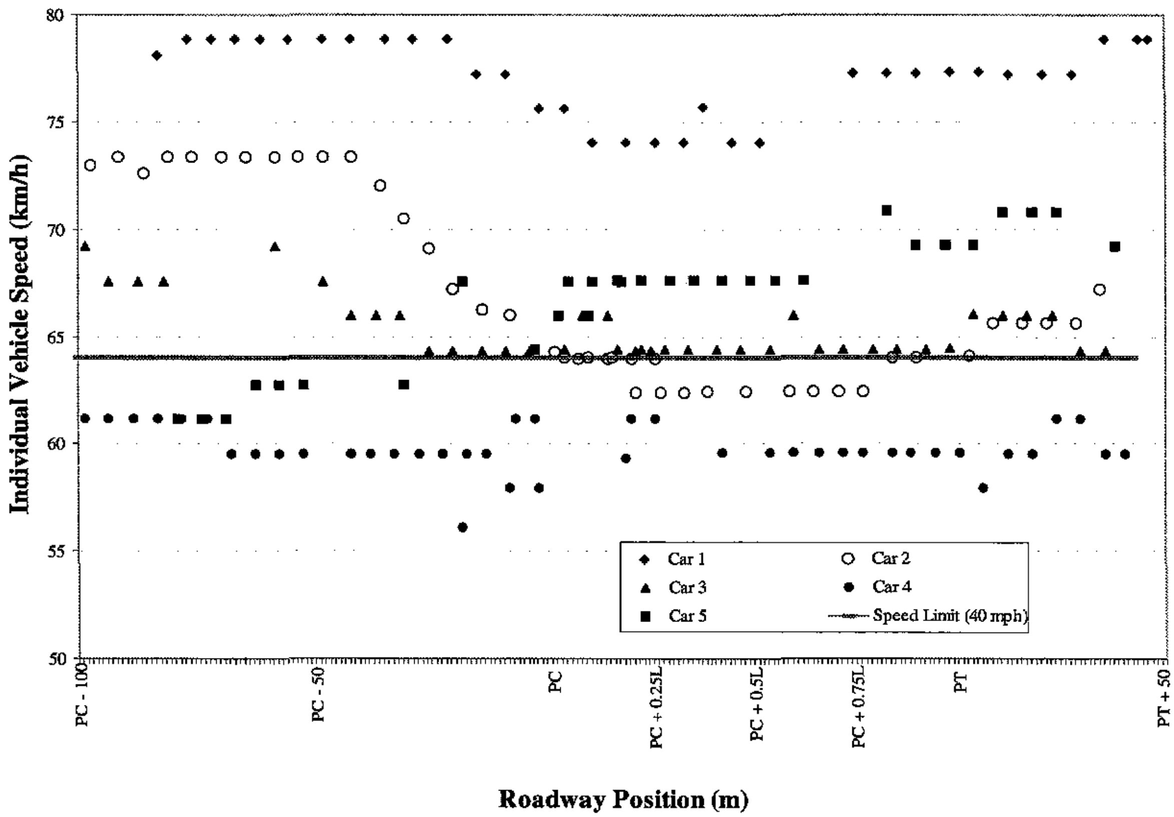


Figure 6-6. Filter Process to Eliminate Vehicles with Deceleration Rates Such as Car 2.

In order to identify this type of behavior, the researchers developed a filtering process for the data in which deceleration rates over 0.2 g were flagged for additional analysis. This procedure accounted for variations in the original laser gun readings by considering deceleration rates over a range of different intervals. Intervals examined included 1, 3, 5, and 7 meters. The data causing deceleration rates greater than 0.2 g were flagged and then analyzed to determine the cause of the large deceleration rates. Positions of the data collectors with respect to the roadway were known; therefore, a comparison could be made between the vehicle deceleration position and the data collector position. Data were discarded if it was believed that the motorist decelerated sharply because of the presence of the technician (presumably because the motorist believed that there was a significant risk of being issued a speeding citation). Table 6-11 summarizes the impact this procedure had on the curve data.

Table 6-11. Final Number of Speed Measurements Used in Analysis of Curve Sites.

Site	Total		Filtered Readings
	Vehicles	Readings	
C1	68	1955	1263
C2	91	4481	3812
C3	42	2573	1834
C4	22	678	818
C5	88	2896	2314
C6	86	4657	3830
C7	95	2227	1711
C8	83	4082	3471
C9	97	3857	3220
C10	82	5361	4409
C11	79	3233	2352
C12	72	4165	3462
C13	91	3499	2827
C14	75	3481	2876
C15	32	1464	580
C16	96	4848	3664
C17	61	3001	2578
C18	93	4321	3518
C19	72	4363	3614
C20	92	3852	3196
C21	94	6573	5395
C22	98	5363	4492
C23	54	2844	2433
Sum	1850	83774	67669
Average	77	3642	2942
Measurements Retained			81%

Effects of the filtering process on the straight section data were less severe, in terms of the number of vehicles and measurements removed. Unfiltered data contained 177,328 measurements from 3,628 vehicles, averaging 4,923 measurements per site. The filtering process retained 92 percent of the measurements, resulting in 161,811 measurements from 3,351 vehicles, averaging 4,495 measurements per site.

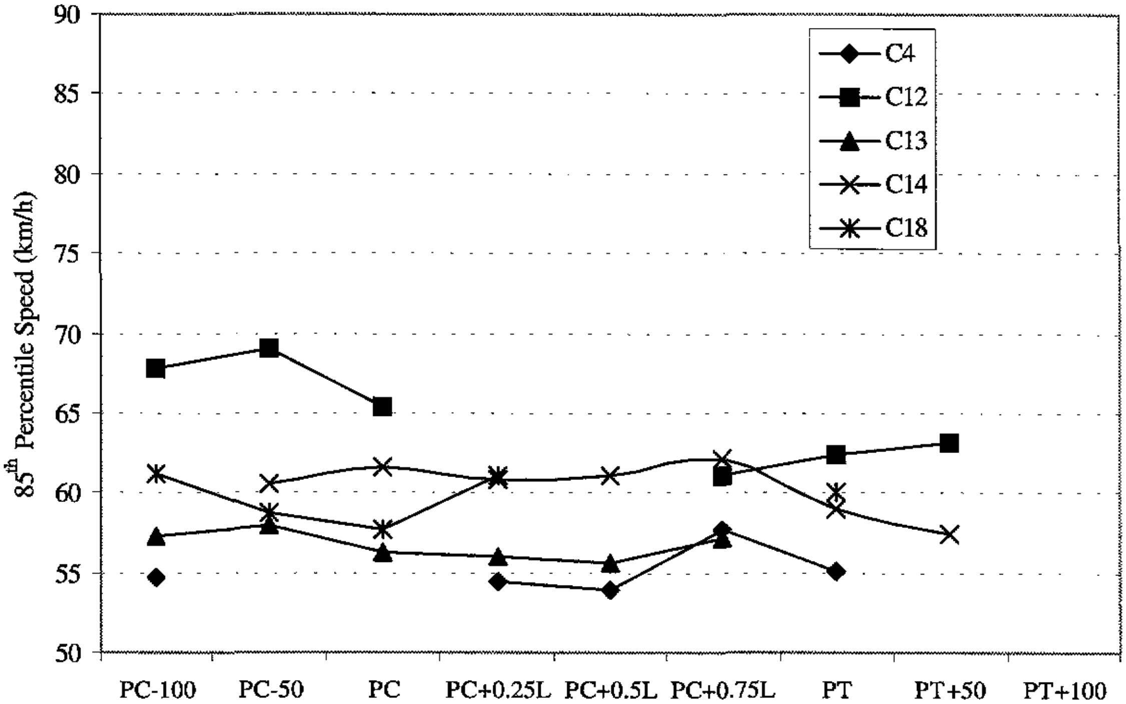
OBSERVATIONS/PRELIMINARY FINDINGS

The profiles of speeds at each site can provide an appreciation for the changes in speed along an alignment. Following are the profiles for the curves and straight sections, subdivided by different groups.

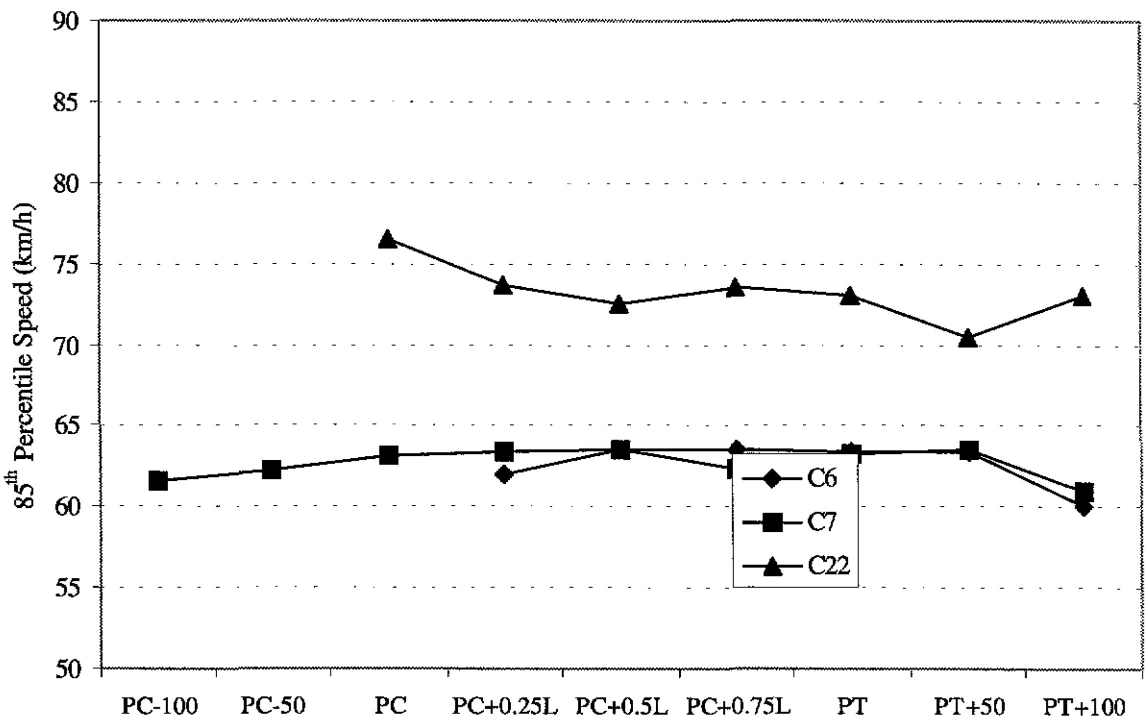
Curve Sites

A review of the speed profiles for the sites can provide insight into how drivers perform prior to, on, and after horizontal curves. Because of the number of sites and amount of data, placing all the speed profiles from the 23 sites onto one figure would result in a graphic that is difficult to read or interpret. Therefore, the sites were split using two characteristics: speed limit and radius. Figure 6-7 shows the speed profiles divided into four speed limit values, while Figure 6-8 shows the speed profiles divided into four radius ranges. The speeds shown in Figures 6-7 and 6-8 were determined using the speeds that occurred within 5 m (16.4 ft) of the point of interest to minimize the effects of speed variances caused by the measuring device. When available, the speed profile reflected drivers' performance from 100 m (328.1 ft) upstream of the horizontal curve to 100 m (328.1 ft) downstream of the horizontal curve. In most cases, a complete data set could not be collected at each site, and the speed profile shows "gaps" in the profile where data were not recorded.

When comparing the profiles for different speed limit groups (Figure 6-7), a very obvious observation is that as speed limits increase, the speeds within the profile are also higher. It appears that greater deceleration may be occurring prior to the PC and PC+0.25L points for the roadways with higher speed limits. Drivers may be in a position where they need greater reductions in speeds to comfortably negotiate the horizontal curve when starting from a higher speed. Observations on the speed profiles when subdivided by radius groups are not as obvious. A general belief is that drivers decelerate on the approach to or within a horizontal curve that has a radius of a certain value. The plots in Figure 6-8 show that the speed profile patterns were not similar for all sites or even for sites within a radius group. The location and quantity of deceleration on the approach to or within the start of a curve varies. In some radius groups, deceleration, minimal speed change, or limited acceleration were observed. Another observation is that the group with the largest radii has the site with the highest speeds (as expected). Unexpected is that the group with the largest radii also had the site with the lowest speed. This finding indicates that radius is probably not the only variable that influences the speed choice of drivers along suburban arterial horizontal curves.

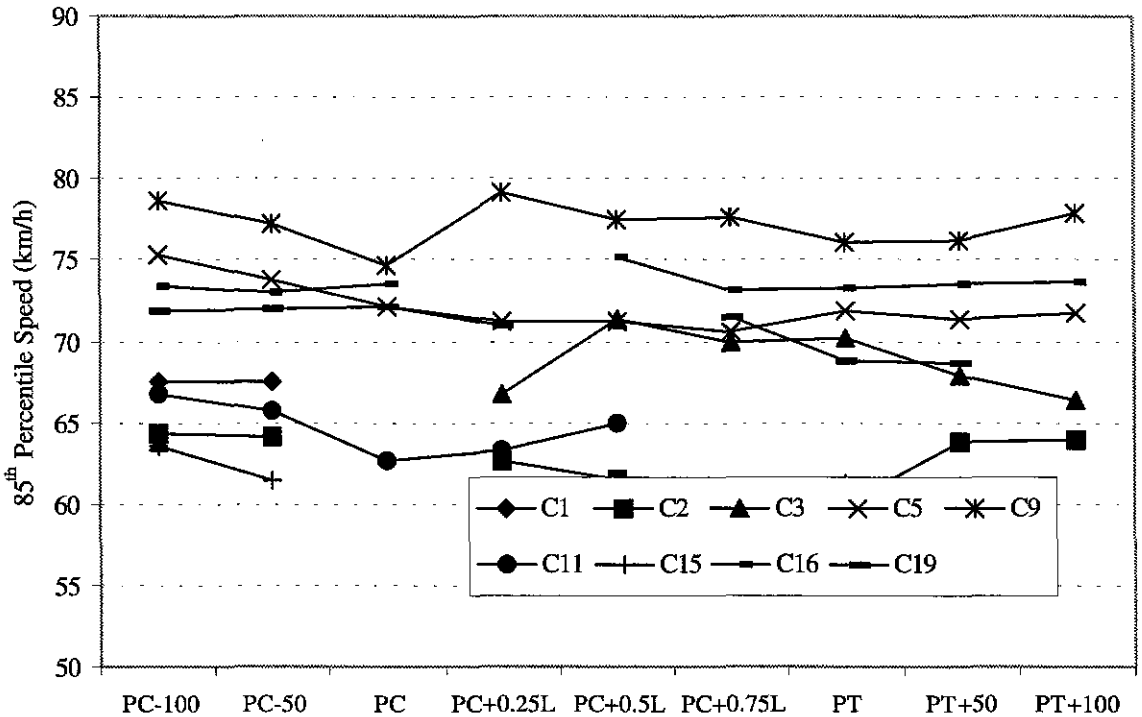


(a) Speed Limit = 48 km/h

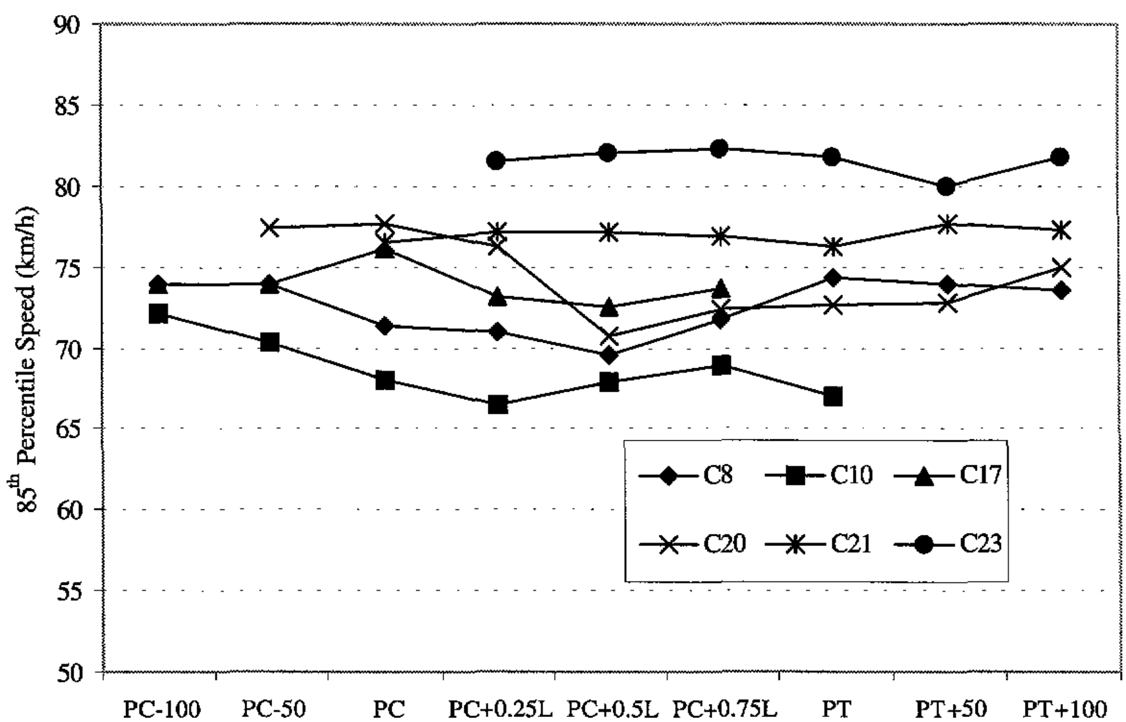


(b) Speed Limit = 56 km/h

Figure 6-7. Speed Profiles for Curve Sites (by Speed Limit Groups).

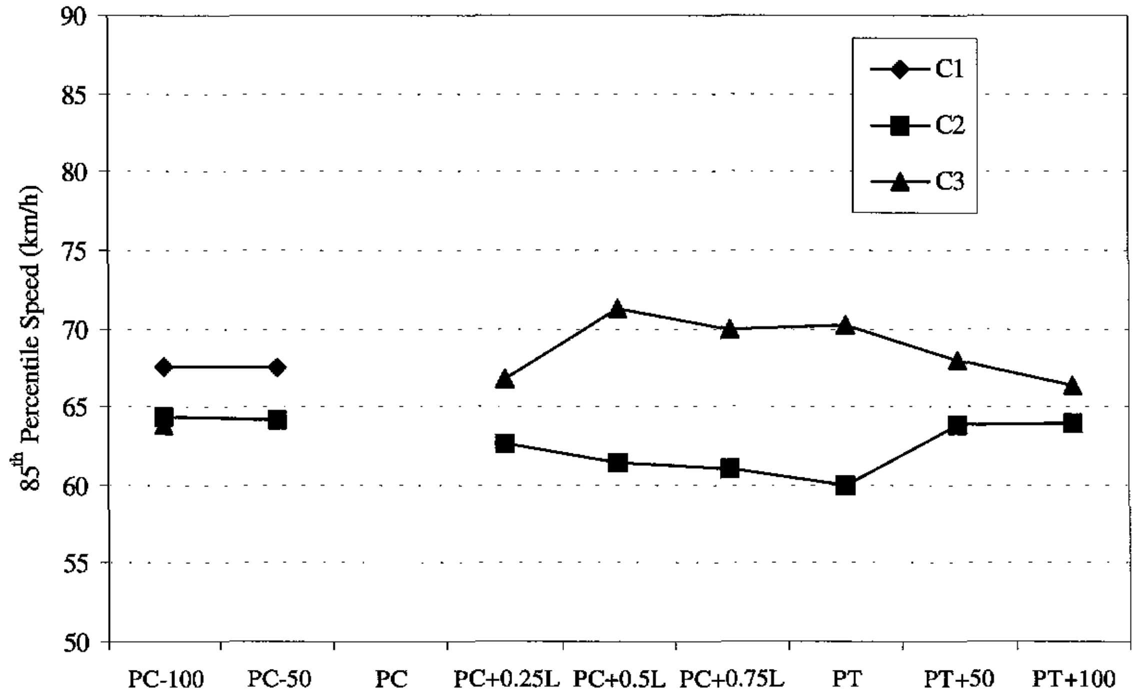


(c) Speed Limit = 64 km/h

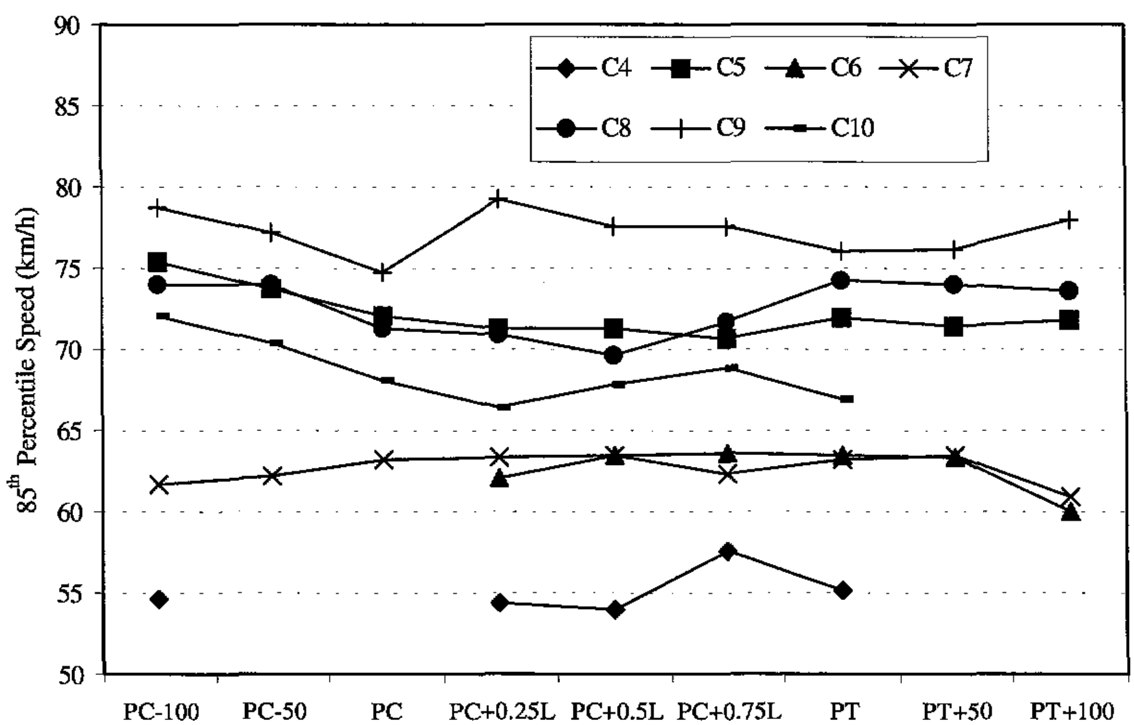


(d) Speed Limit = 72 km/h

Figure 6-7. Speed Profiles for Curve Sites (by Speed Limit Groups) (continued).

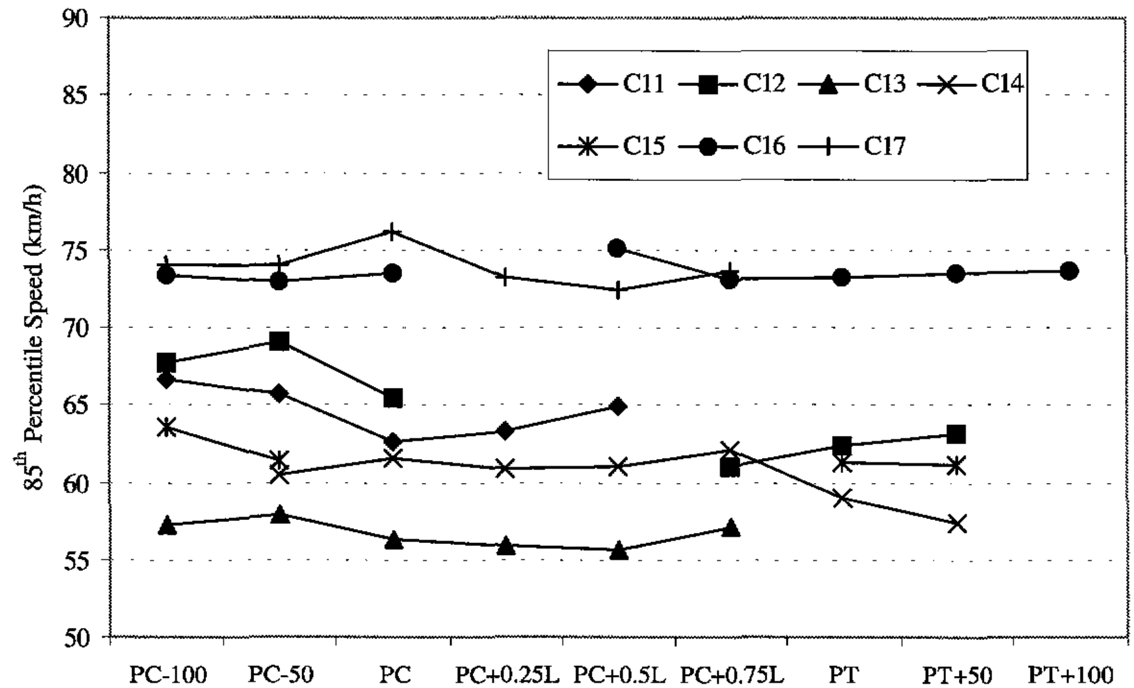


(a) Radius ≤ 150 m

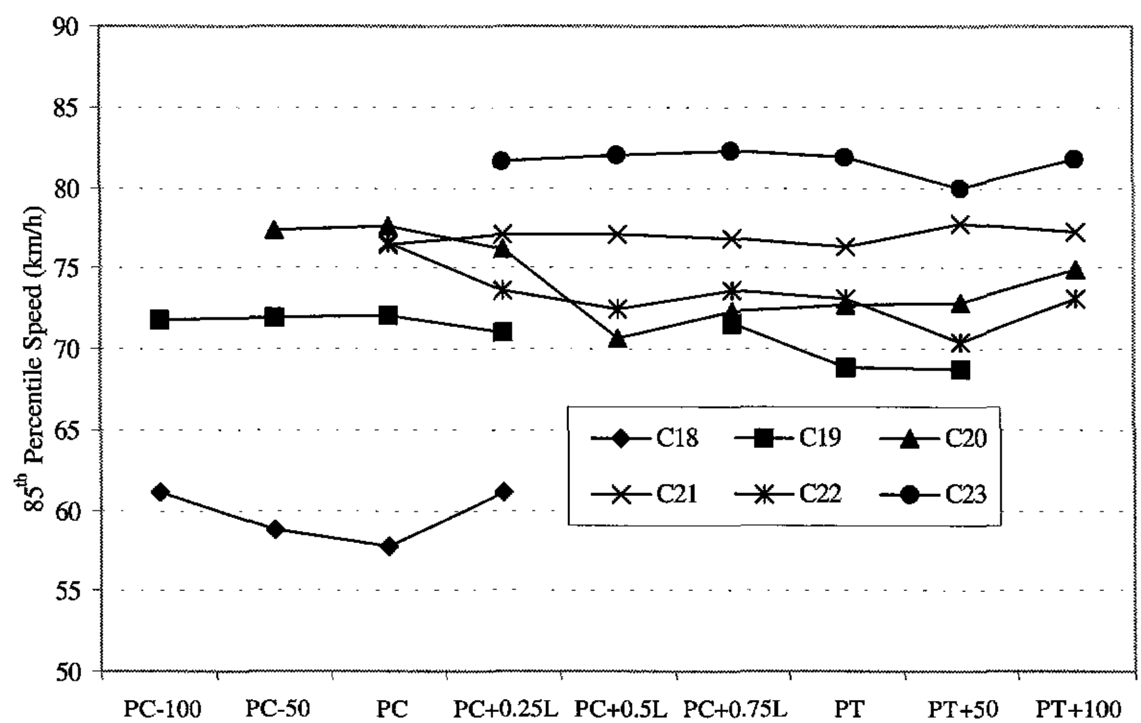


(b) 150 m < Radius ≤ 200 m

Figure 6-8. Speed Profiles for Curve Sites (by Radius Groups).



(c) 200 m < Radius ≤ 250 m



(d) Radius > 250 m

Figure 6-8. Speed Profiles for Curve Sites (by Radius Groups) (continued).

The key variables selected for the curve sites included horizontal curve radius, access density, and median type. Figures 6-9 and 6-10 show the measured 85th percentile speed at the midpoint of the curve versus radius and access density, respectively, with the data indicating the median type. A common transformation of radius used in other studies is inverse radius, shown in Figure 6-11. The midpoint of the curve was selected for these graphs because of the typical assumption that speeds are the lowest (and most influenced) at this point. The plots for radius and inverse radius show that there could be a relationship between those variables and the measured 85th percentile speed; however, a high amount of variability in the speed data for radii less than 250 m (820.2 ft) was observed. The access density plot also shows a high degree of variability for the speeds across the density range examined. The sites with no median generally had lower speeds; all but one site had speeds below 65 km/h (40.4 mph).

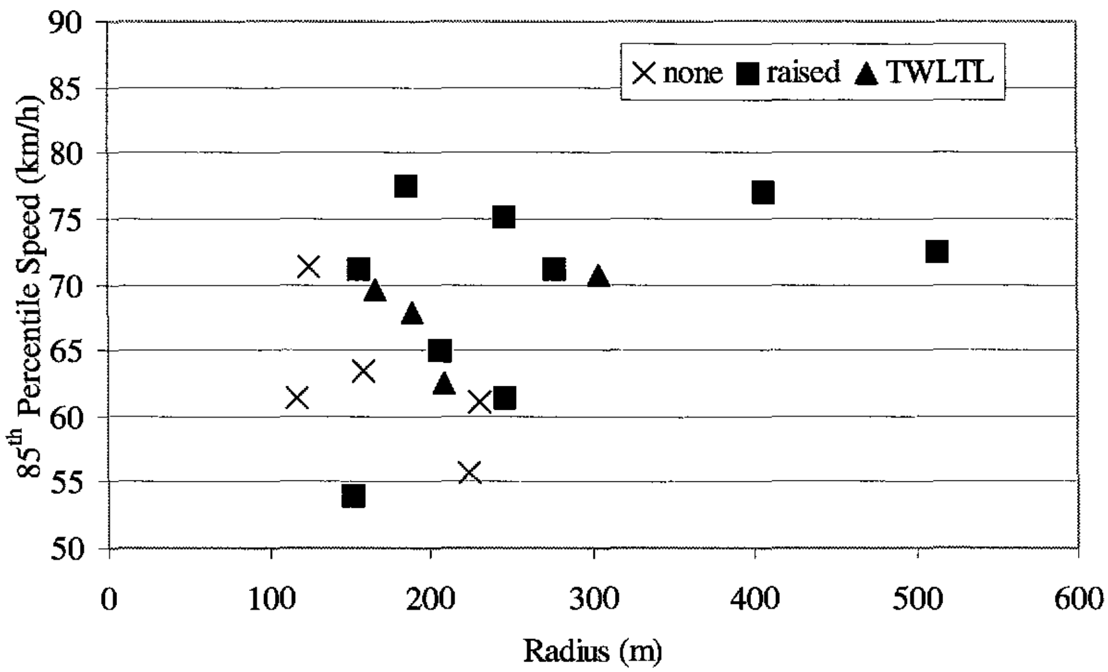


Figure 6-9. 85th Percentile Curve Speed (Midpoint) Versus Radius.

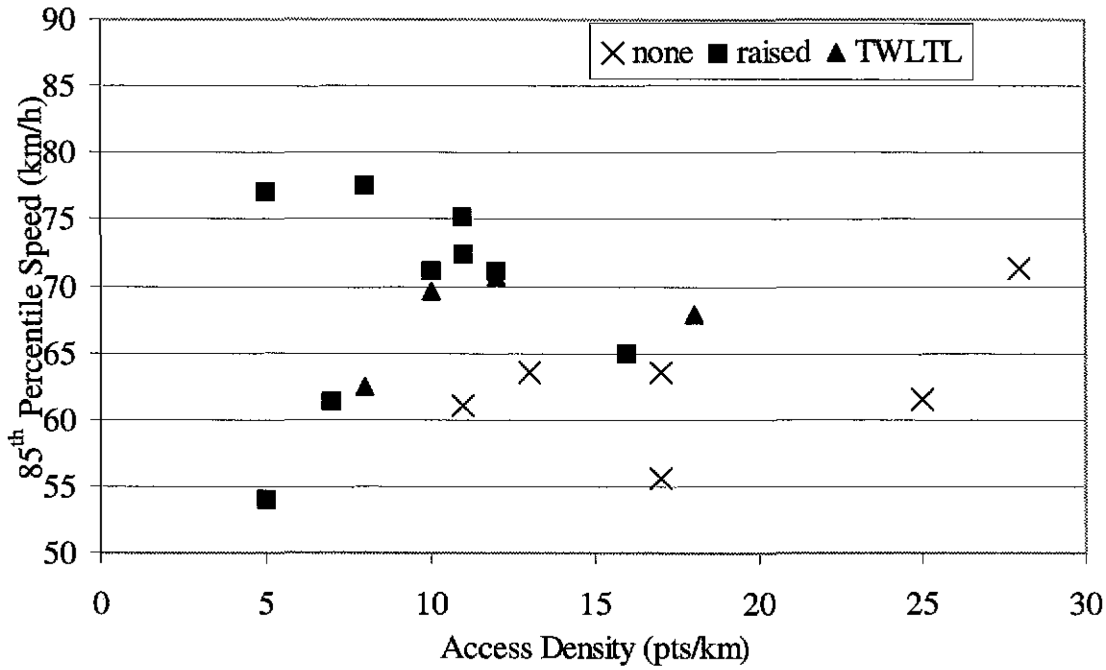


Figure 6-10. 85th Percentile Curve Speed (Midpoint) Versus Access Density.

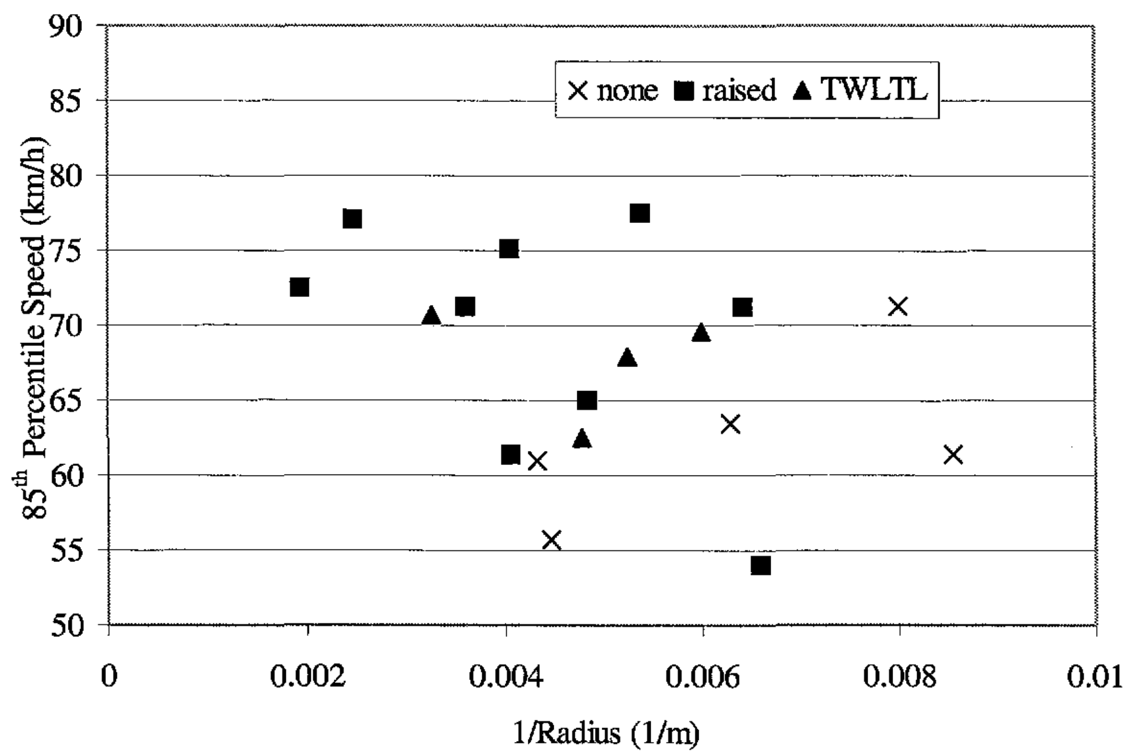
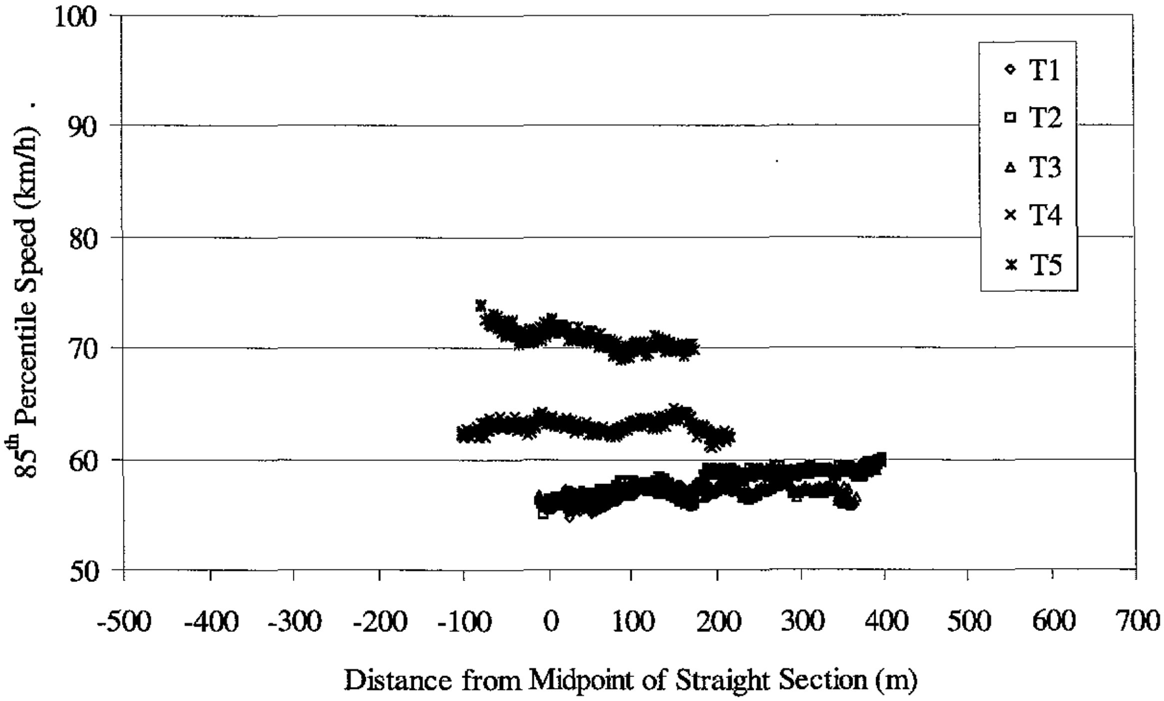


Figure 6-11. 85th Percentile Curve Speed (Midpoint) Versus Inverse Radius.

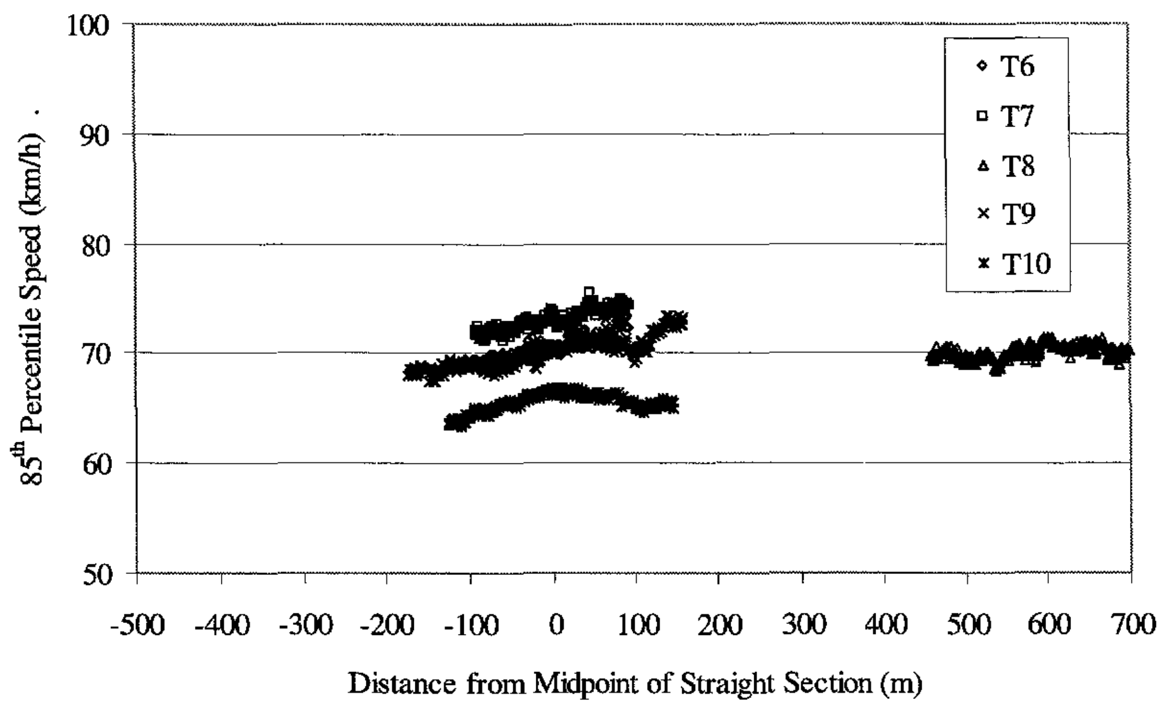
Straight Section Sites

Speed data along a straight section site were collected between two features that could control the speed on the roadway. These features included signalized intersections, stop-controlled intersections, and horizontal curves. While each site was on the tangent portion of a roadway (i.e., between two horizontal curves), the section used for the study was actually more restricted because the controls include not only horizontal curves but also intersections with signals or stop signs on the major roadway. Therefore the term "straight section" rather than tangent was selected for use within this project. When a section was bordered by a traffic control device (e.g., signal or stop sign), then the straight section began 300 m (984 ft) beyond the device. When a horizontal curve was the controlling feature, the section began 200 m (656 ft) before or after the curve. The technicians would generally set up near one end of the section and record speeds along the roadway for the limit of the laser gun. Although in some situations the accelerations or decelerations associated with a controlling feature were recorded, the data within 300 or 200 m (984 or 656 ft) of a traffic control device or horizontal curve, respectively, were deleted.

Figure 6-12 illustrates the speed profiles for the straight section sites divided into six plots. The divisions selected were based on speed limits and the desire to have eight or less sites represented on one plot. Even with only showing the profile for eight or less sites, there are several overlapping sections between the profiles. The plots are intended to provide a general appreciation of the speeds along a straight section rather than providing specific information for any one site. The profile starts for each site beyond the assumed influence of the upstream control. Some of the profiles are longer than others because the available straight section was longer, or the technicians were able to collect data farther along the site due to an advantageous set-up location. The speeds shown in Figure 6-12 were determined using the speeds that occurred within 7 m (23 ft) around the point of interest. Similar to the findings from the horizontal curve sites, the speeds are higher for those sites with the higher speed limits. In most cases, the speeds along a straight section are fairly constant. There were only a few sites where the speeds appeared to vary noticeably within the study segment.

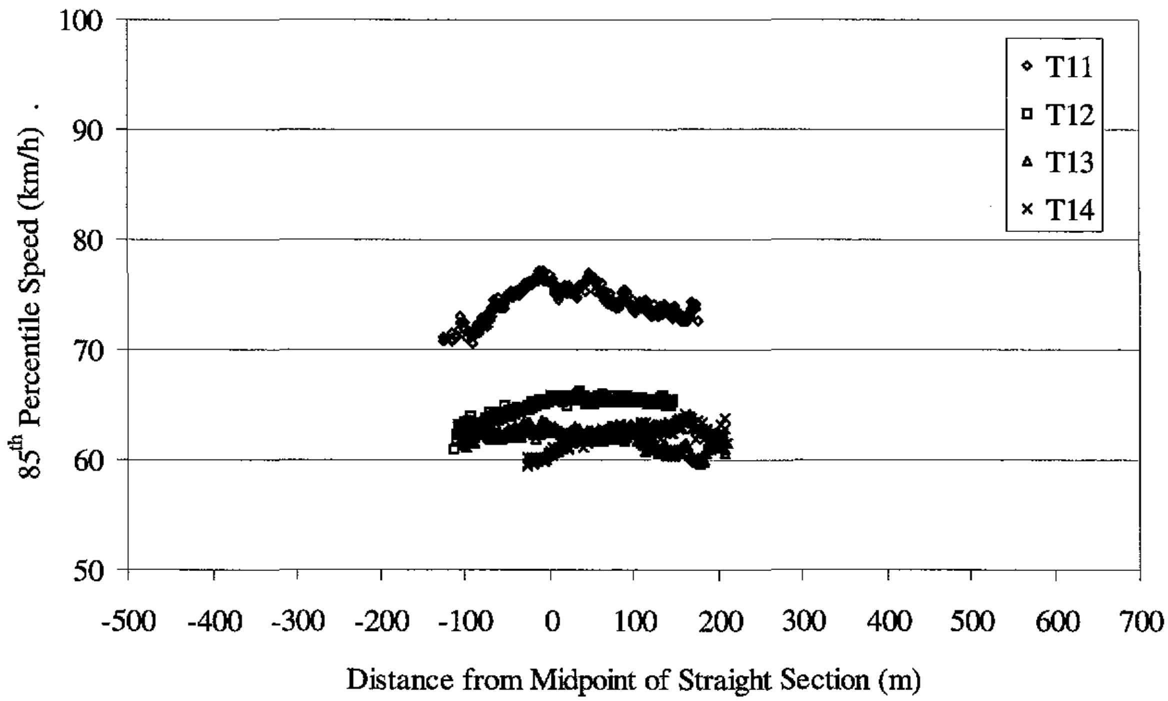


(a) Speed Limit = 48 km/h

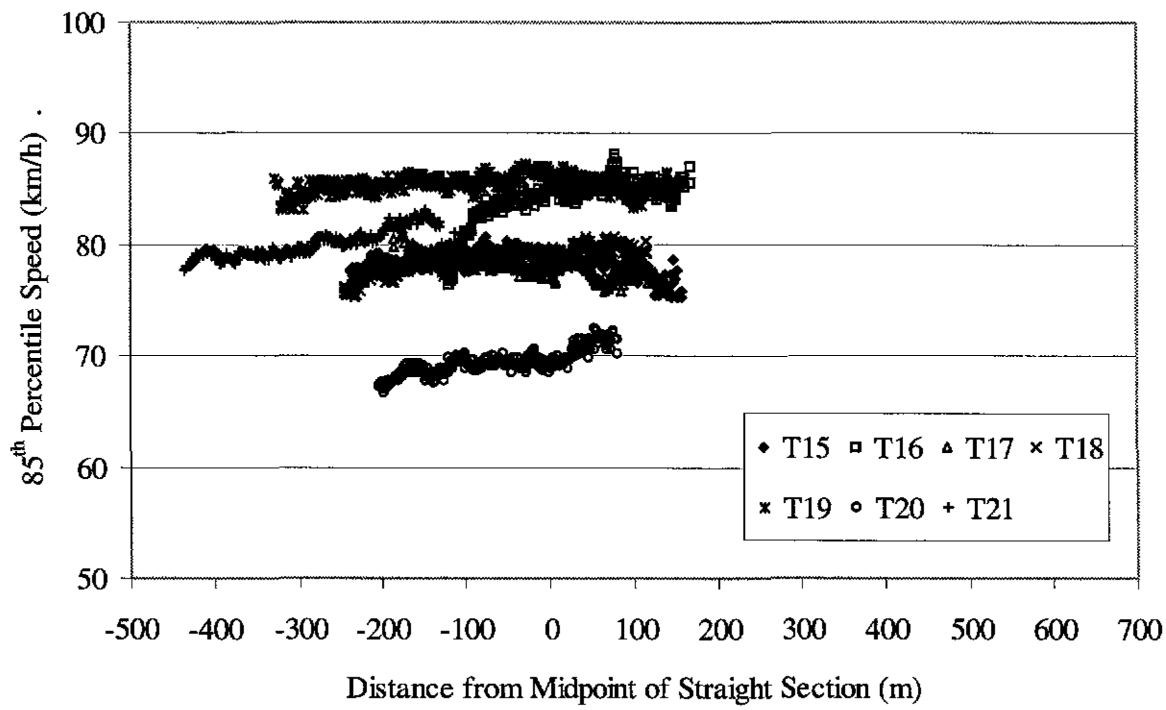


(b) Speed Limit = 56 km/h

Figure 6-12. Speed Profiles for Straight Section Sites (by Speed Limit Groups).

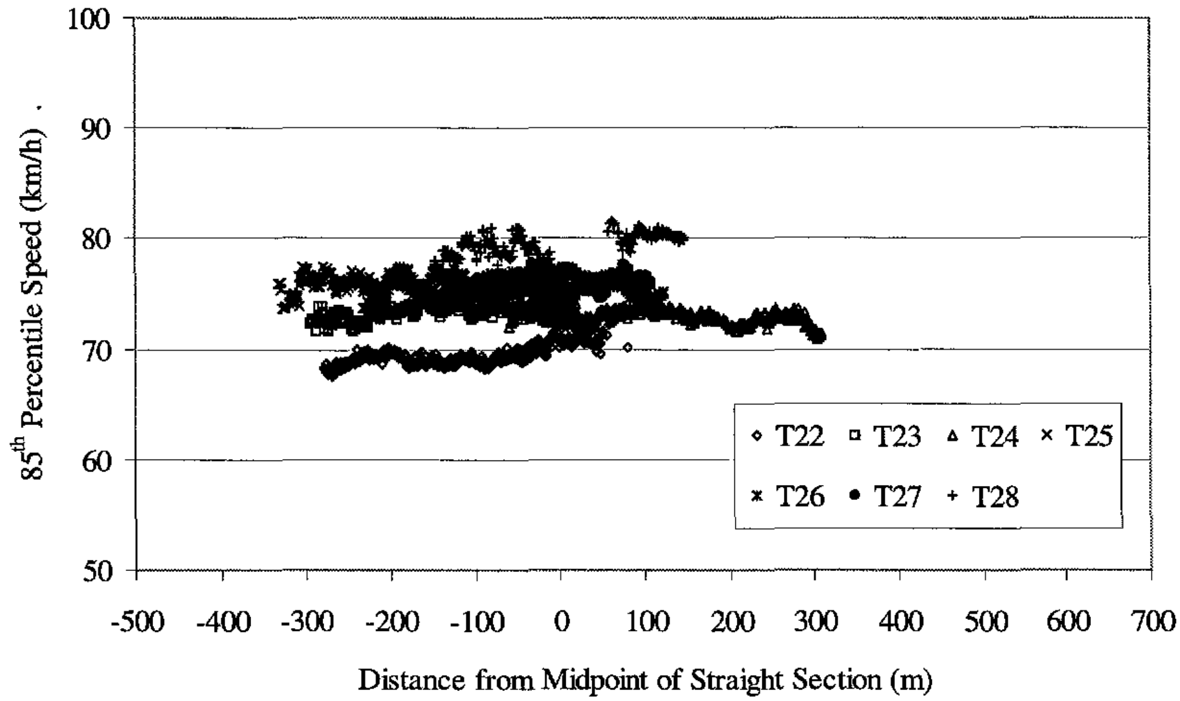


(c) Speed Limit = 56 km/h

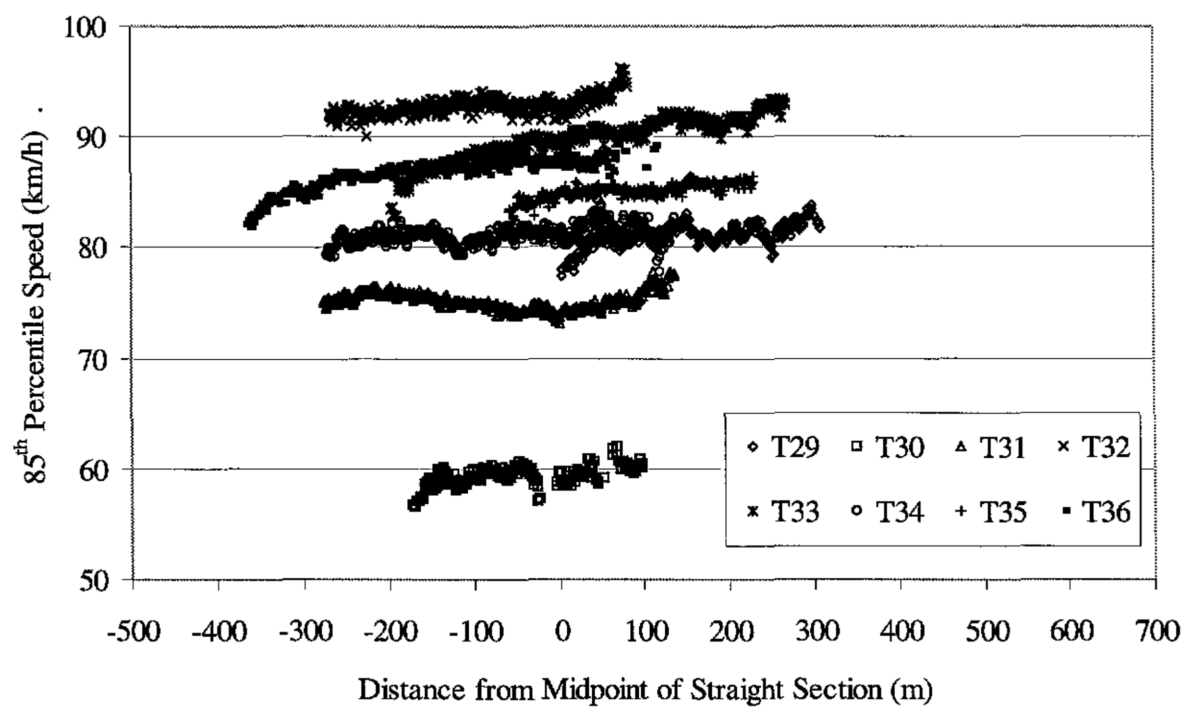


(d) Speed Limit = 64 km/h

Figure 6-12. Speed Profiles for Straight Section Sites (by Speed Limit Groups) (continued).



(e) Speed Limit = 64 km/h



(f) Speed Limit = 72-88 km/h

Figure 6-12. Speed Profiles for Straight Section Sites (by Speed Limit Groups) (continued).

CHAPTER 7

ANALYSIS AND FINDINGS FOR HORIZONTAL CURVE STUDY

This chapter identifies the variables that affect speed on suburban arterial horizontal curves. To begin the effort, the first decision to be made was where to focus the efforts for the curve analyses. Previous studies have generally assumed that the midpoint of the horizontal curve is the location where the speeds are the lowest and/or most affected. The data collection technique used in this study, however, allows the determination of this point rather than using an assumed location. Next, the speed data for this location were stratified using various methods to assist in identifying potential relationships. Finally, regression analyses were performed using the speed data for the key location and the models proposed from examining the stratified data.

SELECTION OF LOCATION FOR EVALUATION

The first step in the process was to determine where the speeds were most influenced. Once this point could be defined, extensive analyses could be performed using the questions presented in Chapter 1 as a map to guide the analyses. A summary of the mean speeds by site and by reference point is provided in Table 7-1 as an initial review of the data. The reference points were selected to provide a consistent location for comparisons between different sites both before and after the curve and within the curve. Set increments of distance (50 and 100 m [164 and 328 ft]) were selected for use before and after the curve. Within the curve, set percentages (25, 50, or 75) of the curve length were used. While a set increment of distance was considered within a curve (e.g., every 50 m [164 ft]), using a set increment would result in an uneven number of reference points for curves of different lengths. The longer curves would have several more reference points than the shorter curves. In addition, that approach would not allow a comparison of the speeds at the middle of the curve, a desirable reference point.

The speeds at each reference point were determined using a process where 3 m (9.8 ft) of data on either side of the reference point were averaged to determine the speed at that point. Therefore, each speed listed in Table 7-1 represents all readings that occurred within a 7 m (23.0 ft) section. This process helped capture a better representation of the vehicles because speeds were not available for every meter along the roadway. Speeds were measured approximately three times per second, so, depending on the speed of the vehicle, the distance between speed readings varied from about 5 m (16.4 ft) for the slower vehicles to about 8 m (26.2 ft) for the faster vehicles. This rate minimized using multiple readings from slower vehicles while maximizing the probability of capturing the faster vehicles, allowing a more representative analysis.

Table 7-1 demonstrates that gaps exist in the speed profiles. It does not, however, provide a good indication of where the curve analyses should be focused, so the research team developed a two-pronged approach to address this issue. The first approach was to conduct preliminary regression analyses on the alignment data at the reference points. Using the adjusted-R^2 statistic as a preliminary indication of where factors might be used to explain speed, preliminary analyses were performed. The results are illustrated in Figure 7-1. The last point, PT + 100 m, was not analyzed because data were recorded at only half of the sites. The plot indicates that the variation in mean speeds can be better explained in the curve as compared to the tangent section. Additionally, the area between the midpoint of the curve and the curve's PT shows the most promise for further consideration. To validate these findings, another approach was tried.

In this second approach, the research team used minimum speed as the criteria. Because the accuracy of the laser guns was 1.6 km/h (1 mph), speed profiles for each site were searched for the absolute minimum speed; then, any speed within 1.6 km/h (1 mph) within that speed was identified. Figure 7-2 illustrates the results using 5 percent increments of the curve lengths.

Table 7-1. Summary of Mean Speed by Location (km/h).

Site Number	PC-100	PC-50	PC	PC+0.25L	PC+0.5L	PC+0.75L	PT	PT+50	PT+100
C1	64.4	63.4						59.4	61.1
C2	60.6	57.8		55.9	54.8	54.7	54.5	56.8	58.5
C3	57.0	54.7		58.5	61.4	59.0	59.0	59.3	59.1
C4	48.3			48.5	49.6	52.0	50.1		
C5		68.6	65.5	65.7	65.7	65.3	66.6	66.3	
C6	54.7	55.8	58.0	57.9	57.6	56.6	57.2	54.9	57.4
C7		51.9	57.7	56.6	58.3	58.1	58.2	53.0	
C8	67.9	68.1	67.8	67.2	67.4	65.2	66.5	67.0	
C9	72.4	74.0	68.8	73.0	71.4	71.5	70.8	72.4	72.6
C10	68.1	65.7	63.1	61.8	63.2	63.3	62.7		
C11	59.6	58.7	55.7	57.2	57.5				
C12	61.8	62.8	59.6			56.0	56.6	57.4	
C13		52.8	51.5	51.1	50.4	52.8			
C14		56.2	56.3	56.4	56.1	55.5	54.6	53.3	55.3
C15		58.8					55.0	57.3	
C16	66.0	65.2	65.5		65.4	65.6	65.7	67.1	64.4
C17	62.4	66.2	68.4	65.4	65.2	65.7			
C18	54.7	53.1	52.5	56.0			54.7		
C19	65.2	65.5	65.6	65.1		64.2	62.8	63.8	
C20		71.3	69.9	68.7	64.2	65.2	65.9	67.0	67.6
C21			70.7	71.3	71.9	72.0	71.5	72.8	73.2
C22			70.9	67.7	65.9	66.5	65.6	63.8	66.9
C23				73.6	74.5	75.8	74.4	73.9	74.9
Avg	64.4	63.4	68.2	73.6	74.5	75.8	74.4	66.7	68.0

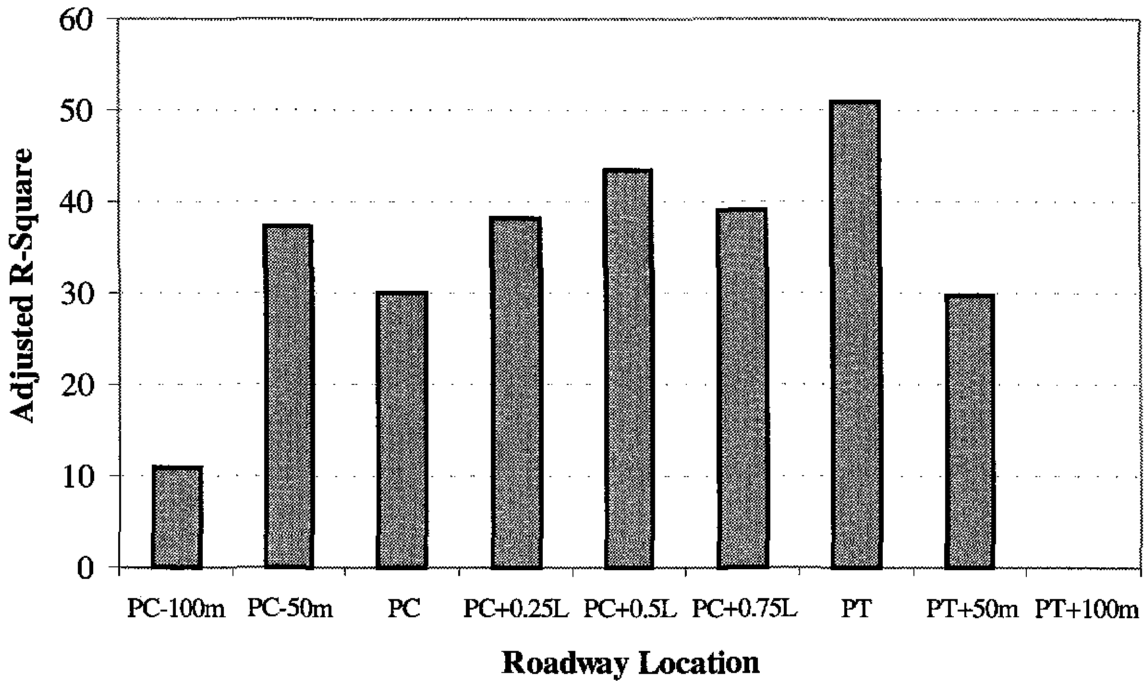


Figure 7-1. Summary of Preliminary Analyses.

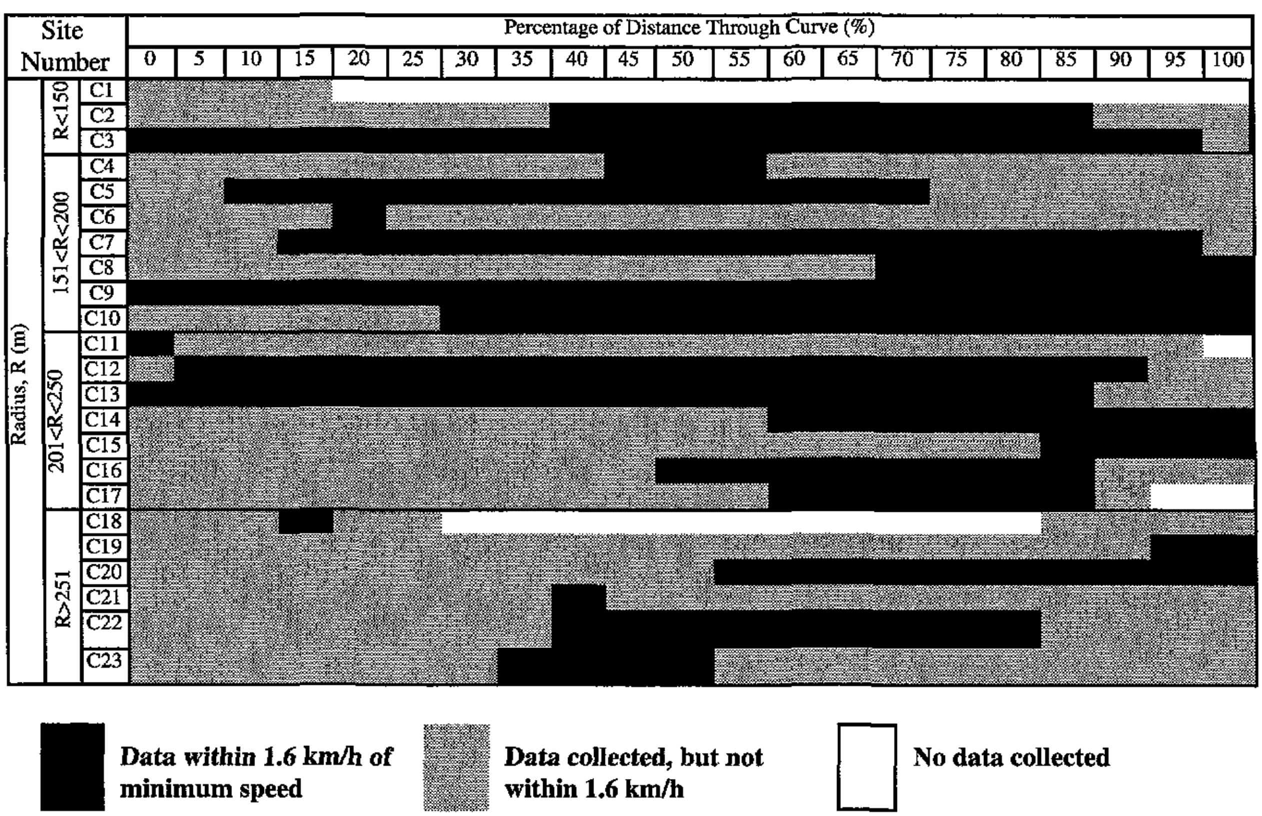


Figure 7-2. Summary of Minimum Speed Ranges.

A visual inspection shows that the range where speeds are most frequently at a minimum value occurs between the mid and three-quarter point of the curve. This finding is fairly consistent throughout the range of radii shown (although for the larger radius curves, the amount of minimum speeds found in the curve decreases). This finding is similar to the trend revealed in Figure 7-1. Consequently, the focus of the remainder of the curve data analysis is on the speeds measured between the mid and three-quarter point of the curve. This range is referred to as the "third quarter range" throughout the remainder of this report.

Box plots were developed to illustrate the distribution of the speed data in the third quarter range for the individual sites. Figure 7-3 includes box plots for each site. A box plot consists of a box, whiskers, and the average. The solid line inside the box represents the median. The top and bottom of the box reflects the third and first quartile, respectively. The whiskers are the lines that extend from the top and bottom of the box to the lowest and highest observations.

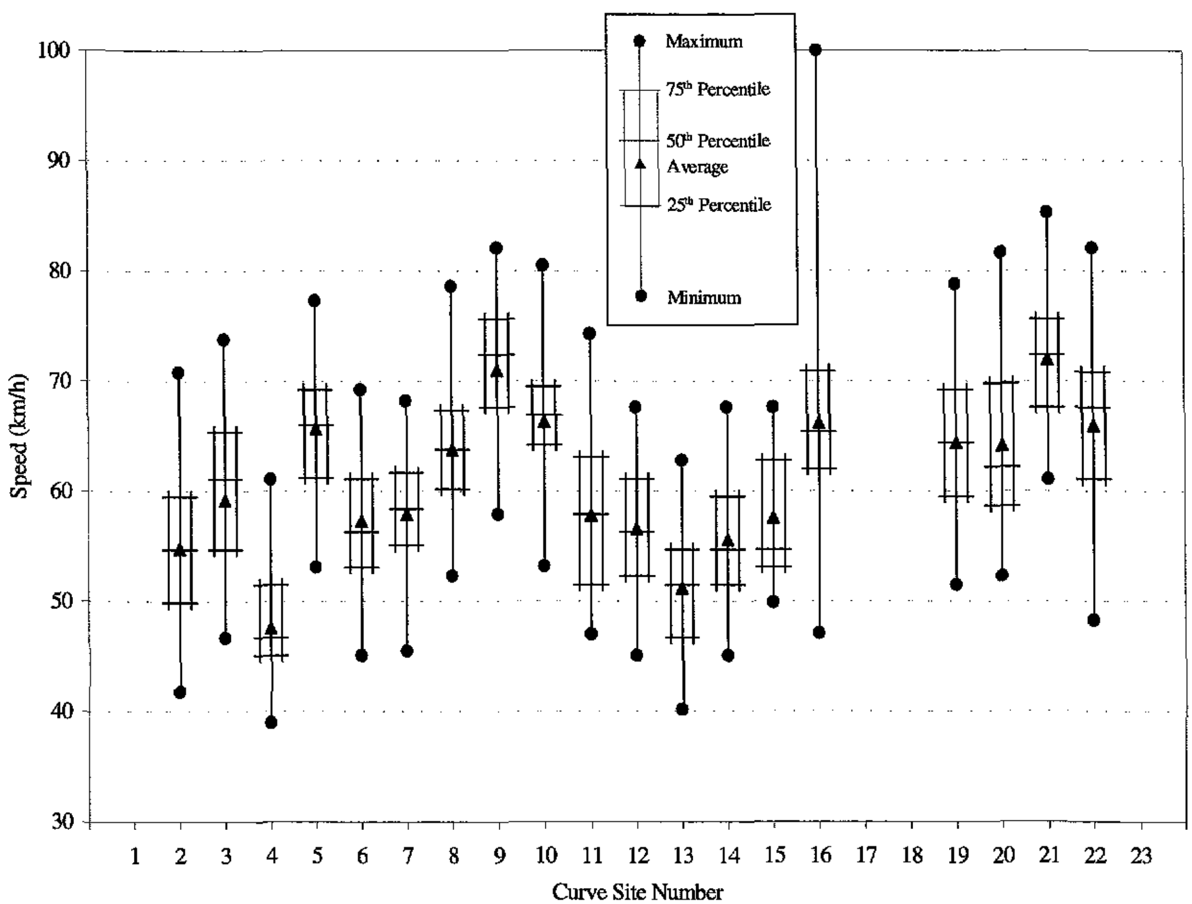


Figure 7-3. Speed Data from All Qualifying Sites

Because data were not available within the third quarter range for sites C1, C17, C18, and C23, those sites were not included in subsequent analyses. If a site contained data in only part of the third quarter range, the available data were used to represent the third quarter range of the curve. This procedure resulted in 19 sites available for use in the final analyses. To determine the 85th percentile speeds at these 19 sites, the first speed of each vehicle within the third quarter range was used. The first speed of each vehicle was used to avoid over-sampling slower vehicles and under-sampling of faster vehicles. Table 7-2 summarizes the calculated data.

Table 7-2. Summary of Speed Data in Third Quarter Range.

Site	85th Percentile Speeds (km/h)	Number of Speed Observations
C2	62.4	77
C3	70.0	31
C4	53.8	18
C5	72.0	68
C6	63.1	59
C7	64.5	68
C8	71.5	62
C9	78.0	76
C10	69.9	63
C11	66.8	63
C12	62.4	56
C13	56.2	75
C14	62.7	67
C15	65.8	26
C16	76.6	71
C19	71.7	54
C20	72.4	76
C21	77.5	64
C22	74.4	85

DESCRIPTIVE STATISTICS

This section presents descriptive statistics for the variables measured at the curve sites. For the variables with logical breakpoints within the data set, the mean speed and standard deviations (within the third quarter range) were calculated to provide a preliminary appreciation for how speed changes as the variable changes. Plots were also used to identify potential trends in the data, although, due to the large number of plots generated, they are not included in this report. The data are presented using the four major categories (alignment, cross section, roadside, and traffic control device) examined in the data analysis.

Alignment Variables

Table 7-3 lists the average, minimum, and maximum values for each alignment variable, and Table 7-4 provides the third quarter range data for selected alignment variables. Each alignment variable appears to have a reasonable range of values. Expected speed changes can be seen in Table 7-4. For example, as curve radius increases, speed increases, and as deflection angle increases, speed decreases. Some results are not as easily explained, however. For instance, both low and high values of curve length have higher speeds when compared to mid-range values.

Table 7-3. Average, Minimum, and Maximum Values for Alignment Variables.

Variable	Freq.	Average	Minimum	Maximum
Curve Radius, m (ft)	All sites	225 (737.7)	177 (580.3)	513 (1,682.0)
Curve Length, m (ft)	All sites	154 (504.9)	59 (193.4)	301 (986.9)
Deflection Angle	All sites	39°	21°	72°
Upstream Control and Distance to Control, m (ft)				
Traffic Signal	11	642 (2104.9)	256 (839.3)	1170 (3,836.1)
Stop Sign	0	0 (0)	0 (0)	0 (0)
Horizontal Curve	8	425 (1393.4)	170 (557.4)	751 (2462.3)
Downstream Control and Distance to Control, m (ft)				
Traffic Signal	13	639 (2095.1)	245 (803.3)	1479 (4849.2)
Stop Sign	2	588 (1927.9)	367 (1203.3)	808 (2649.2)
Horizontal Curve	4	668 (2190.2)	187 (613.1)	1051 (3445.9)

Table 7-4. Third Quarter Range Speed Data for Selected Alignment Variables.

Variable	Potential Ranges for Variable	Freq.	Mean Speed km/h (mph)	Standard Deviation km/h (mph)
Curve Radius	Less than 200 m (656 ft)	8	61 (38)	8 (5)
	Greater than 200 m (656 ft)	11	63 (39)	10 (6)
Curve Length	Less than 125 m (381 ft)	7	64 (40)	10 (6)
	125 to 191 m (381 to 582 ft)	7	59 (37)	9 (6)
	Greater than 191 m (582 ft)	5	65 (40)	10 (6)
Deflection Angle	Less than 25°	3	64 (40)	8 (5)
	25° to 35°	6	65 (40)	7 (4)
	35° to 45°	4	65 (40)	10 (6)
	Greater than 45°	6	57 (35)	8 (5)

Cross Section Variables

Average, minimum, and maximum values for each cross section variable are listed in Table 7-5. Third quarter range speed data for selected cross section variables are shown in Table 7-6. Lane width and superelevation were measured for each lane of the study direction. During this review, averaging the two superelevation values and the two lane width values was also considered. Table 7-6 demonstrates that even though the range of lane widths is not very large, speeds tend to be lower for narrower lanes. The presence of a median (i.e., either a raised or a two-way left turn lane) was associated with higher speeds when compared to sites with no median.

Although parking was recorded, none of the study sites permitted on-street parking, so this variable was not included in the evaluation. Similarly, the presence and width of bike lanes was recorded, but since only one site included bike lanes these variables were not included in the evaluation. Superelevation and lane width data were measured and are reported in Tables 7-5 and 7-6.

Table 7-5. Average, Minimum, and Maximum Values for Cross Section Variables.

Variable	Freq.	Average	Minimum	Maximum
Lane width - outside, m (ft)	All sites	3.64 (11.9)	3.20 (10.5)	4.27 (14.0)
Lane width - inside, m (ft)	All sites	3.50 (11.5)	3.05 (10.0)	3.96 (13.0)
Lane width - average, m (ft)	All sites	3.59 (11.8)	3.13 (10.3)	3.96 (13.0)
Superelevation - outside	All sites	0.928	-3.65	3.91
Superelevation - inside	All sites	0.987	-3.91	5.73
Superelevation - average	All sites	0.833	-3.65	4.82
Median type and width, m (ft)				
Raised	9	8.39 (27.5)	3.05 (10.0)	10.37 (34.0)
Two-Way Left Turn Lane	4	5.07 (16.6)	4.88 (16.0)	5.18 (17.0)
None	6	N/A	N/A	N/A
Parking (on-street)	All sites had no on-street parking			
Bike Lane	Only one site had a bike lane (1.52 m [5.0 ft])			

Table 7-6. Third Quarter Range Speed Data for Selected Cross Section Variables.

Category	Potential Ranges for Variables	Freq.	Mean Speed km/h (mph)	Standard Deviation km/h (mph)
Lane Width - Inside	Less than 3.6 m (11.8 ft)	5	57 (35)	6 (4)
	3.6 to 3.7 m (11.8 to 12.1 ft)	12	64 (40)	6 (4)
	Greater than 3.7 m (12.1 ft)	2	65 (40)	7 (4)
Lane Width - Outside	Less than 3.6 m (11.8 ft)	5	54 (34)	7 (4)
	3.6 to 3.7 m (11.8 to 12.1 ft)	12	64 (40)	9 (6)
	Greater than 3.7 m (12.1 ft)	2	58 (36)	9 (6)
Median Type	Raised	9	64 (40)	7 (4)
	Two-Way Left Turn Lane	4	67 (42)	5 (3)
	None	6	59 (37)	6 (4)
Superelevation	Inside - < 0%	5	59 (37)	9 (6)
	Inside - 0 to 2%	11	63 (39)	9 (6)
	Inside - > 2%	3	64 (40)	9 (6)
	Outside - < 0%	4	59 (37)	9 (6)
	Outside - 0 to 2%	11	63 (39)	8 (5)
	Outside - > 2%	4	64 (40)	10 (7)

Roadside Variables

The ranges for the roadside variables are listed in Table 7-7, while Table 7-8 shows their third quarter range speed values. Higher values for roadside environment (which indicates more rigid objects closer to the road) were associated with slightly higher speeds, an unexpected trend. Mean speed had an inverse relationship to the access density, as expected. When more access points were present, speeds were lower. Residential and commercial developments appeared to be associated with higher speeds than school and park developments. The speed trend for the pedestrian levels available in this data set was unclear.

Table 7-7. Average, Minimum, and Maximum Values for Continuous Roadside Variables.

Variable	Average	Minimum	Maximum
Roadside Development	described as either residential, commercial, park, or school		
Access Density, pts/km (pts/mi)	12.8 (20.6)	5 pts/km (8.1)	28 pts/km (45.1)
Roadside Environment	6.5	2	10
Pedestrians	1.9	1	5

Table 7-8. Third Quarter Range Speed Data for Roadside Variables.

Category	Potential Ranges for Variables	Freq.	Mean Speed km/h (mph)	Standard Deviation km/h (mph)
Roadside Environment	2-5 6-10	5 14	59 (37) 63 (39)	8 (5) 9 (6)
Access Density	0 to 10 pts/km (16.1 pts/mi) Greater than 10 pts/km (16.1 pts/mi)	7 12	66 (41) 60 (37)	10 (6) 8 (5)
Roadside Development	Residential School Park Commercial	11 1 1 6	62 (39) 58 (36) 48 (30) 63 (39)	9 (6) 7 (4) 4 (2) 6 (4)
Pedestrian Level	1 2 3 4 5	7 10 0 0 2	67 (42) 58 (36) 0 0 63 (39)	8 (5) 9 (6) 0 0 7 (4)

Traffic Control Device Variables

Table 7-9 lists the average, minimum, and maximum values for the traffic variables. Third quarter range speed data are provided for speed limit and signal spacing in Table 7-10. Speeds increased as the posted speed limit increased. Also, mean speeds were higher than the posted speed limit for limits of 64 km/h (40 mph) and lower. Table 7-10 did not reveal a clear trend between signal spacing and mean speed.

Table 7-9. Average, Minimum, and Maximum Values for Traffic Control Device Variables.

Variable	Average	Minimum	Maximum
Signals, sig/km (sig/mi)	0.86 (1.4)	0.33 (0.5)	1.5 (2.4)
Posted Speed Limit, km/h (mph)	61.2 (38)	48 (30)	72 (45)
Presence of Curve Sign	9 - yes 10 - no		
Presence of Turn Warning Sign	1- yes 18 - no		
Presence of Advisory Speed Sign	4 - yes 15 - no		

Table 7-10. Third Quarter Range Speed Range Data for Selected Traffic Control Device Variables.

Variable	Potential Ranges for Variables	Freq.	Mean Speed km/h (mph)	Standard Deviation km/h (mph)
Speed Limit	48 km/h (30 mph)	4	52 (32)	5 (3)
	56 km/h (35 mph)	3	61 (38)	6 (4)
	64 km/h (40 mph)	8	63 (39)	8 (5)
	72 km/h (45 mph)	4	68 (42)	6 (3)
Signal Spacing	0.33 sig/km	1	64 (40)	7 (4)
	0.5 sig/km	6	61 (38)	9 (6)
	1.0 sig/km	10	63 (39)	10 (6)
	1.5 sig/km	2	58 (36)	6 (4)

Potential Models

The evaluation began with identifying the amount each category of variables affects speed. In other words, do roadside variables have a greater effect on speed than cross section variables? Then all potential variables within these categories were used to identify the strongest relationship. Based upon the review of the variables as presented previously, the variables listed in Table 7-11 were included in the initial analyses.

Table 7-11. Variables Used in Analyses.

Category	Variables	
Alignment	Curve radius Curve length Deflection angle Upstream control type	Distance to upstream control Downstream control type Distance to downstream control
Cross Section	Lane width - outside Superelevation - outside Median type	Lane width - inside Superelevation - inside Median width
Roadside	Roadside development Access density	Roadside environment Pedestrian activity
Traffic Control Device	Signal spacing Posted speed limit	Presence of curve or turn signs Presence (and value) of advisory

ANALYSIS

The multivariate analysis used to meet the objectives of this project was ordinary least squares multiple regression. As demonstrated in the literature review (Chapter 2), previous research has focused on the prediction of an aggregate speed. The majority of this work uses operating speed in the form of 85th percentile speeds. The analysis technique used aggregated speeds into 85th percentile speeds, permitting easier comparison of the results to previous work. Additionally, 85th percentile speed is widely accepted as a quantifiable definition of operating speed.

Multicollinearity

By focusing exclusively on urban and suburban arterials with curb and gutter, some variables have a limited range of values. Because of this limited range, some variables appear to be correlated with others. There are circumstances where this correlation can be explained and was expected. However, there are other circumstances where the limited range in certain variables creates an apparent relationship. The problem is that these types of relationships can significantly affect the results of the regression analyses. They need to be identified and addressed in order to develop valid statistical results. Using SAS™ and the proc CORR command, those variable pairs with multicollinearity problems were identified. Table 7-12 summarizes the relationships that were found to be significant at $\alpha = 0.05$.

Table 7-12. Correlation Coefficients of Significance.

Variable	Variable	Corr Coeff	p-value
Curve radius	Curve length	0.62688	0.0041
Curve length	Deflection angle	0.52490	0.0210
	Outside lane width	0.50118	0.0288
	Inside lane width	0.45854	0.0483
Deflection angle	Inside lane width	0.52490	0.0210
Outside lane width	Inside lane width	0.79745	0.0001
Outside lane super	Inside lane super	0.94264	0.0001

To minimize the effects of multicollinearity, inside and outside lane widths were averaged to create a one lane width variable defining the average lane width. Similarly, inside and outside superelevation rates were averaged to create one average superelevation for the curve. Because curve length was related to many other factors, including curve radius (a variable that was judged likely to be significant), it was omitted from further analyses. While these modifications did not completely eliminate the multicollinearity problems, they greatly reduced the impact multicollinearity could have had on the results of the regression analyses. Final models were checked for collinearity problems after the significant variables were identified.

Variable Transformations

Previous studies have determined that transformations on certain variables can improve their statistical power for identifying possible relationships. Typically, curve radius and grade are the variables that are the focus of these transformations. During the site selection effort, an attempt was made to keep all grades within a range between +4 and -4 percent. Grades were essentially flat and constant among all sites and were not considered to be a factor. Consequently, the only variable considered for transformation in this study was the curve radius. Two commonly used transformations were attempted, and Table 7-13 lists the correlation coefficients with respect to 85th percentile speed. The results indicate that radius and the square root of radius are almost identically correlated with 85th percentile speeds, although radius had a slightly better relationship. The inverse of the radius shows the weakest relationship.

Table 7-13. Transformation of Curve Radius.

Variable	Variable	Corr Coeff	p-value
85th percentile speed	Radius	0.44636	0.0554
	$(\text{Radius})^{-1}$	-0.39869	0.0909
	$(\text{Radius})^{0.5}$	0.44493	0.0563

Variable Types

There are generally two variable types describing data. Class variables are those variables such as roadside development that are not assigned a numeric value. Based on the development adjacent to the study sites, roadside development was assigned to one of four classes: park, school, residential, or commercial. Because of the classification of the data, variables such as roadside development and median type (none, raised, or TWLTL) are called class variables. Continuous variables, on the other hand, can take any reasonable value. For instance, curve radius is a continuous variable. Although it cannot have a negative number and there is a reasonable minimum radius that can be found on suburban arterials, it could have any value above approximately 75 m (246 ft). Class variables are usually assigned a value based on qualitative assessments of the site's characteristics, while continuous variables are the quantifiable measures of certain characteristics.

Generally, once a variable is assigned as a class variable, it cannot be changed to a continuous variable. It can, however, be reclassified into other classificatory schemes. For instance, median type was classified using three classes: none, raised, and TWLTL. One could then classify median type by presence of median. Under this new classificatory scheme, a new variable, "median presence," is created and assigned a value of "yes" if the median type is raised or TWLTL. Median presence is assigned a value of "no" if median type is none.

On the other hand, a continuous variable may be changed to a class variable depending on the circumstances. For instance, if there is a good reason to believe that there is a break point within the range of the continuous data where speed changes significantly, then it may be desirable to classify the continuous data into classes of low and high. This procedure is essentially creating a step function. If there were multiple break points within the continuous range of data, then the number of classes would increase, and a multi-step function would result. The number of classes is theoretically unlimited, although if too many are introduced the analyses will become unstable. Consequently, engineering judgement and knowledge must be used to create such classes.

During the data analyses, several modifications of various variables were attempted. For instance, access density was originally a continuous variable ranging from 5 to 28 pts/km (8 to 45 pts/mi). Analyses showed that access density in the continuous form was not significant. However, previous research, preliminary plots, and Table 7-8 led the researchers to investigate further. A breakpoint of 12 pts/km (19 pts/mi) was identified as a reasonable breakpoint, and the continuous variable access density was changed to a class variable. The values assigned to the class variable of access density were "low" for values less than or equal to 12 pts/km (19 pts/mi) and "high" when values were greater than 12 pts/km (19 pts/mi). Another modification included changing median type from three classes to two classes based on the presence of a median. Various other modifications were also examined.

Statistics

The process for identifying those variables that influence speed began with an overview of how different categories of the data can be associated to speed. Multiple regression techniques from SAS ™ (proc REG and proc GLM) were used to determine how the variables within each category of data affect speed. Table 7-14 summarizes these findings. Most of the categories only explain about 25 percent of the variation in the speed data. The traffic category explained as much as 49 percent of the variation. While a first impression may lead to reservations regarding the findings, these levels of R^2 values are frequently judged favorably in accident analyses and human factor studies.

Of the alignment variables examined, curve radius and deflection angle were the only significant variables. Curve radius has been found in other studies to affect driver speed on low-speed residential streets and on two-lane rural highways. The presence of a median (rather than type of median) was found to be significant among the variables in the cross section category. This finding agrees with other research that has indicated that lower speeds are associated with undivided roadways. Access density and roadside development were the roadside variables that were found to be significant. Access density is a class variable, where the value is 0 when access density is less than or equal to 12 pts/km (19 pts/mi) and 1 when the value is above 12 pts/km (19 pts/km). Roadside development is also a class variable consisting of four classes: park, school, residential, and commercial. Posted speed was the variable from the traffic control device category that was significant, explaining a large portion of the variation of the data (49.3 percent). The findings shown in Table 7-14 indicate that driver speed behavior on suburban arterials are influenced by more than one category.

After the analyses associated with each category were complete, all significant variables were combined, and a final series of analyses was conducted to determine the variables that, when all variables are considered, affect speeds in the third quarter range of horizontal curves. The findings are shown in Table 7-14 in the "All" category. Once all the variables are considered, cross section variables do not significantly impact operating speeds on horizontal curves on suburban arterials with curb and gutter. The significant variables include posted speed limit, deflection angle, and access density. A closer look at the variables that were found to best explain the variation associated with 85th percentile speed is shown in Table 7-15. The variation inflation factors shown in the rightmost column are indications of multicollinearity concerns. Values near or above 10 indicate problems. The values indicate that multicollinearity among the variables was not of concern.

Table 7-14. Summary of Regression Analyses.

Category	Adjusted R^2	p-value	Significant Variables
Alignment	21.1	0.0480	1. Curve radius 2. Deflection angle
Cross Section	24.2	0.0320	1. Median presence
Roadside	39.8	0.0228	1. Access density (low ≤ 12 pts/km [19.3 pts/mi], high > 12 pts/km [19.3 pts/mi]) 2. Roadside development
Traffic Control Device	49.3	0.0005	1. Posted speed limit
All	70.5	0.0001	1. Posted speed limit 2. Deflection angle 3. Access density (low ≤ 12 pts/km [19.3 pts/mi], high > 12 pts/km [19.3 pts/mi])

Table 7-15. Final Analysis with Speed Limit.

Variables	Parameter Estimate	p-value	Variation Inflation Factor
Intercept	42.916	0.0001	0.000
Speed Limit (km/h)	0.523	0.0001	1.021
Deflection Angle (deg)	-0.150	0.0183	1.025
Access Density (if below 12 pts/km [19.3 pts/mi] then 1, otherwise 0)	4.402	0.0262	1.007
R^2 = 75.2% Adjusted R^2 = 70.5%	F-statistic = 15.341 p-value = 0.0001		

Another check of a regression model is to inspect each variable to determine if the sign and/or value of the parameter estimate are reasonable. Stated another way, does the sign of the coefficient agree with expected behavior at horizontal curves? For the model listed in Table 7-15, higher posted speed limits result in higher speeds, while higher deflection angles result in lower 85th percentile speeds. Both of these results are expected along a suburban arterial: higher speed limits reflect high operating speeds (or vice versa) and larger deflection angles would be associated with slower speeds. When the access density is greater than 12 pts/km (19.3 pts/mi), the predicted speed will be 4.4 km/h (2.7 mph) slower. The influence of access density is nominal until it reaches a critical value. After that critical value, speeds are lower. For the data in this study, that value was 12 pts/km (19.3 pts/mi). A previous TxDOT study found values of 20 pts/km (32.2 pts/mi) for one-way frontage roads and 16 pts/km (25.8 pts/mi) for two lane, two-way frontage roads.[13] Therefore, each sign and parameter estimate are generally performing as one would expect.

Other Attempts to Explain Variation in Speeds

Posted Speed Limit

One potential area of concern with the findings from this analysis is that the variable "posted speed limit" is included as a significant variable. In fact, Table 7-14 shows that posted speed limit is the variable that is most related to 85th percentile operating speed. However, one school of thought says that because posted speed limits are based on 85th percentile speeds, then the two variables should be significantly correlated and, therefore, not considered for inclusion in such an analysis. While this may be the case with the data herein, other studies have included posted speed limit in their list of potential variables, and it has been shown to be insignificant. In addition, a recent ITE survey on speed zoning found that over half of the speed zoning recommendations from studies provided to the committee were for speeds that were not supported by the 85th percentile speed.[20] In summary, past research findings have been inconclusive in determining whether posted speed and operating speed are indeed causally related.

To provide findings for both situations, another series of analyses were performed without using posted speed limit. Statistics of the best model are summarized in Table 7-16. These results show the significance of speed limit. With speed limit in the model, the adjusted R^2 and model F-statistic both indicated stronger relationships. Without speed limit, the impact of median presence now becomes significant along with roadside development. The confounding (as measured by the variation inflation factor) among these variables is low, and the signs of the coefficients are as expected.

Table 7-16. Final Analysis without Speed Limit.

Variables	Parameter Estimate	p-value	Variation Inflation Factor
Intercept	44.538	0.0001	0.000
Median Presence (if Raised or TWLTL then 1, otherwise 0)	9.238	0.0023	1.115
Roadside: if School then 1 otherwise 0	13.029	0.0733	1.894
Roadside: if Residential then 1, otherwise 0	17.813	0.0032	5.146
Roadside: if Commercial then 1, otherwise 0	19.439	0.0025	5.068
R^2 = 62.3% Adjusted R^2 = 52.0%	F-statistic = 15.265 p-value = 0.0001		

Radius

Almost every previous study of speeds on horizontal curves, regardless of the functional classification of the roadway, has identified horizontal curve radius as a key variable for explaining the variation of speeds on curves. Preliminary observations of speed versus radius (see Figure 6-9 and Table 7-4) and speed versus inverse radius (see Figure 6-11) indicated that a similar trend may be present in the data for suburban arterials. The statistical evaluation, however, demonstrated that deflection angle is the horizontal curve variable that best contributes to explaining the variation in speeds on a horizontal curve when speed limit is included in the model.

Additional evaluations were conducted with various forms of radius while excluding deflection angle to illustrate the influence of radius if deflection angle was not included. Using this approach, the models listed in Table 7-17 resulted. The adjusted R^2 decreased, and the results even indicated that both access density and radius should not be included because their p values exceeded the 0.05 limit. When the same attempt was made using inverse radius, an even poorer model resulted (adjusted R^2 value of 61.2 percent). Another transformation tried was to change the continuous variable radius into a class variable. The data were split into those sites with a radius of 250 m (820 ft) or less and those sites with a radius greater than 250 m (820 ft). Table 7-18 lists the findings. Both the radius class variable and deflection angle would be included (if the α level is relaxed from 0.05 to 0.07), and the lower R^2 value is acceptable. Speed limit was not a potential variable in this model.

In summary, for the data collected in this project, other variables are better at explaining the variation in operating speeds on horizontal curves than the radius of the curve. A previous study on suburban arterials, however, did find a strong relationship between radius and speed.[12]

A reason that deflection angle may be stronger than radius is that drivers on suburban arterials may be more sensitive to how the curve looks (as represented by deflection angle) rather than driver comfort (as represented by radius). Curves on multilane roadways with large deflection angles may appear to be more severe, causing drivers to slow more. A study where people were asked to estimate speeds by looking at roadway scenes found that they were much more influenced by the curve angle rather than the radius in estimating the appropriate speed.[21]

An example of a study site with a large deflection angle (49.3 deg) and a midrange radius (206 m [675.9 ft]) is shown in Figure 7-4. In this photograph of the Site C-11 curve, the view of the roadway beyond the curve appears limited. The speed profile for this site (shown in Figure 6-8) supports the observation that a driver's view may be limited upstream of the curve. Drivers slowed from more than 66 km/h (41.0 mph) at 100 m (328.1 ft) upstream of the curve to about 62 km/h (38.5 mph) at the PC of the curve. Site C-12, which has a similar deflection angle and radius value, also shows deceleration after the PC-50 point to the PC of the curve.

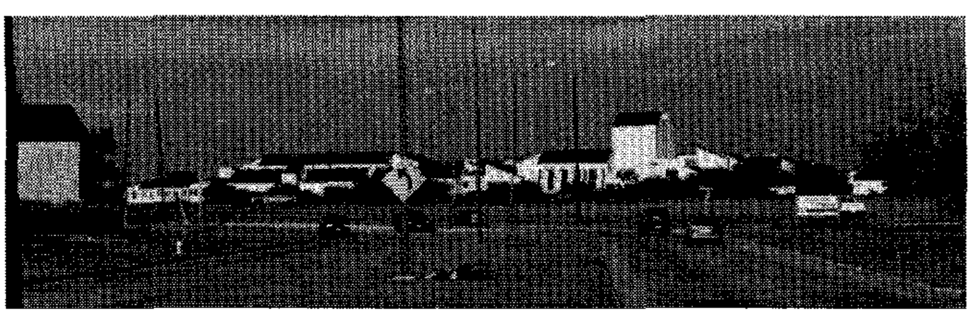


Figure 7-4. Photograph of Site C-11 (Deflection Angle of 49.3 Deg and Radius of 206 m).

To investigate whether the combination of deflection angle and curve radius would be better at explaining the variability of the data, a new variable (raddef) was created in this study. Raddef was defined as being equal to 100 times the deflection divided by the radius. By combining deflection angle and radius, the driver's perception of the horizontal curve may be captured in one variable. Table 7-19 shows the calculations for raddef. When raddef is included in the model (and deflection angle and radius are excluded), the values listed in Table 7-20 result. The model is slightly better at explaining the speed variance than other models, although it is still not superior to the model that only uses deflection angle.

Table 7-17. Analysis with Including Radius and Excluding Deflection Angle.

Variables	Parameter Estimate	p-value	Variation Inflation Factor
Including Speed Limit as a Variable			
Intercept	27.755	0.0015	0.000
Access Density (if below 12 pts/km [19.3 pts/mi] then 1, otherwise 0)	3.023	0.1874	1.257
Radius (m)	0.020	0.0983	1.267
Speed Limit (km/h)	0.552	0.0002	1.010
R^2 = 70.1% Adjusted R^2 = 64.2%	F-statistic = 11.74 p-value = 0.0003		
Excluding Speed Limit as a Variable			
Intercept	43.799	0.0001	0.000
Radius (m)	0.011	0.4523	1.422
Presence of Median (if raised or TWLTL then 1, otherwise 0)	8.348	0.0099	1.347
Roadside: if School then 1 otherwise 0	12.452	0.0929	1.918
Roadside: if Residential then 1, otherwise 0	16.459	0.0091	5.754
Roadside: if Commercial then 1, otherwise 0	18.648	0.0045	5.251
R^2 = 64.3% Adjusted R^2 = 50.6%	F-statistic = 4.691 p-value = 0.0114		

Table 7-18. Analysis with Radius as a Class Variable.

Variables	Parameter Estimate	p-value	Variation Inflation Factor
Intercept	73.374	0.0001	0.000
Radius, Class (if radius is less than 250 m [820 ft] then 1, otherwise 0)	6.558	0.0649	1.028
Deflection Angle (deg)	-0.172	0.0689	1.028
R^2 = 36.7% Adjusted R^2 = 28.8%	F-statistic = 4.63 p-value= 0.0259		
Speed limit was not considered for this model			

Table 7-19. Computation of Raddef.

Perceived Difficulty of the Curve from Drivers' Perspective	Deflection Angle	Radius	Raddef
Low	21	513	4.1
Medium	21	117	17.9
Medium	39	225	17.3
Medium	72	513	14.0
High	72	117	61.5
NOTE: The values of deflection angle and radius represent the minimum, maximum, and average values for the sites evaluated herein.			

Range of Influence of Variables

Previous studies have demonstrated that certain variables can be very influential on speeds but only within certain ranges. In other words, beyond a given value, the variable no longer influences speed. An objective of this research project was to identify the ranges of variables found to significantly influence speed. The best model for the data collected in this study found the following three variables to influence speed: speed limit, deflection angle, and access density (above 12 pts/km [19.3 pts/mi]). When speed limit was omitted from the analysis, median type and roadside development also influenced speed.

For speed limits typically used on suburban arterials (e.g., 48 to 72 km/h [30 to 45 mph]), all speed limit values influence operating speed. Figure 7-5 shows a plot of the regression equation for the range of speed limits studied. Deflection angle was held constant at its average value of 39 deg. Similar to posted speed, the entire range of deflection angles studied in this project (21 to 72 deg) also influenced speed, as shown in Figure 7-6. As always, caution must be used in extrapolating findings beyond the limits of the study data.

Table 7-20. Analysis with Including Raddef and Excluding Deflection Angle and Radius.

Variables	Parameter Estimate	p-value	Variation Inflation Factor
Including Speed Limit as a Variable			
Intercept	39.929	0.0001	0.000
Raddef	-0.224	0.0053	1.019
Speed Limit (km/h)	0.534	0.0002	1.019
R^2 = 70.1% Adjusted R^2 = 67.3%	F-statistic = 19.548 p-value= 0.0001		
Excluding Speed Limit as a Variable			
Intercept	63.021	0.0001	0.000
Raddef	0.020	0.9595	1.267
Presence of Median (if raised or TWLTL then 1, otherwise 0)	16.101	0.0015	3.501
Raddef × Presence of Median	-0.482	0.0091	3.782
R^2 = 64.4% Adjusted R^2 = 57.2%	F-statistic = 9.036 p-value = 0.0012		

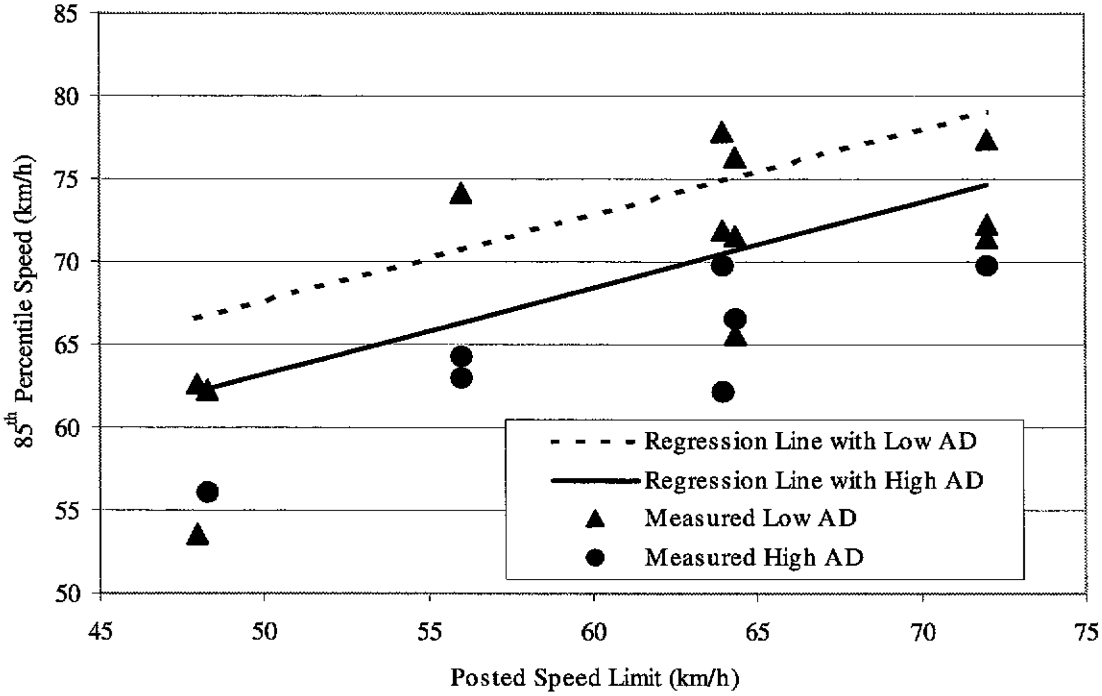


Figure 7-5. Posted Speed Limit Versus 85th Percentile Speed.

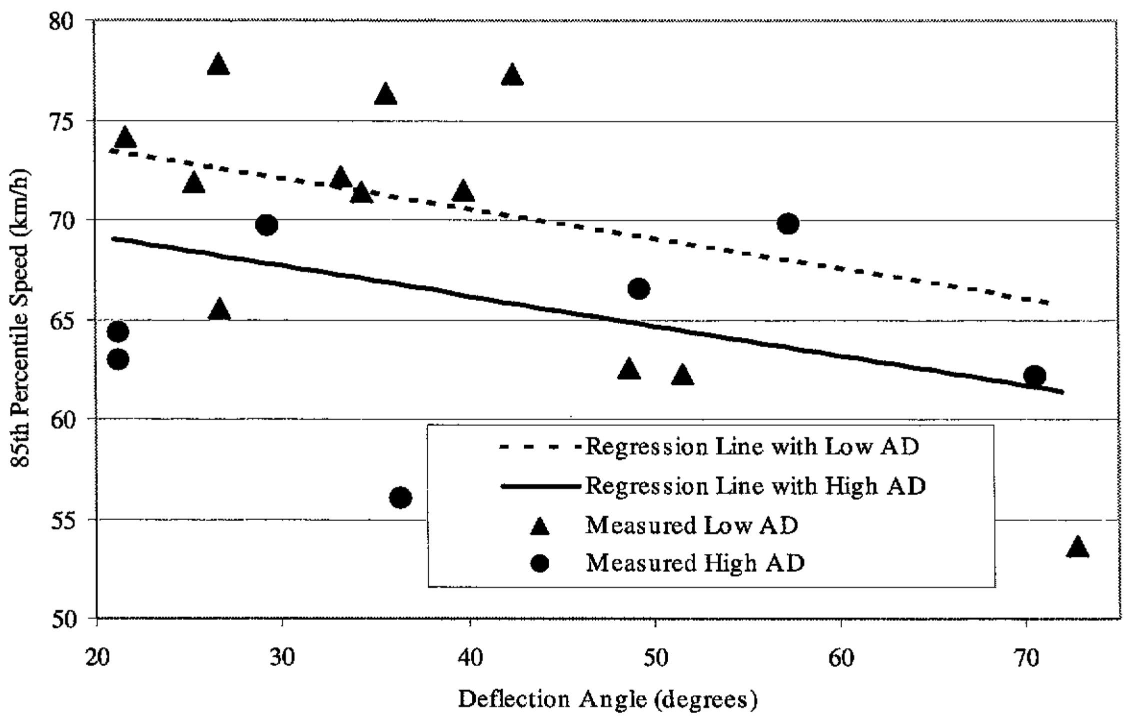


Figure 7-6. Deflection Angle Versus 85th Percentile Speed.

The findings for access density and median type provided the clearest examples of variables that only influence speeds in a certain range. When access density was a continuous variable, it did not significantly contribute to explaining the variation in speed. When converted to a class variable, access density influenced speed when more than 12 pts/km [19.3 pts/mi] were present. Fewer driveways and intersections within the 2 km (1.2 mi) section around the midpoint of the horizontal curve did not have an influence on the speed within the curve. When a median was present, higher speed resulted than when a median was not present. The analysis demonstrated that the type of median present (e.g., raised versus two-way left turn lane) was not significant for the data available, but the presence of a separation between lanes will result in higher speeds. Note that other studies have demonstrated that the type of median does have an effect on operations and safety; therefore, it is important to not assume that a raised median will perform similar to a two-way left turn lane in all situations. The selection of the type of median best suited for a given roadway is a complex decision that is beyond the scope of this study. This study does demonstrate that the designer should expect higher speeds when a median is used than when a median is not present, however.

Because so many studies have included radius or inverse radius as a variable in their model, the variable was examined further. Figure 7-7 shows the plot of models that included radius or inverse radius (and excluded deflection angle) for this study and two previous studies. The plot of the data and the models from this study show that high variability was present when the radius of the curve was less than approximately 250 m (820 ft). This pattern is very similar to the pattern found in the recent FHWA study on two-lane rural highways.[1] As shown in Figure 2-1 and reproduced as part of Figure 7-7, higher variability in speeds exists for sites with horizontal curve radii less than 250 m (820 ft).

A stronger relationship between speed and horizontal curve radius was found in the FHWA study[1] (R^2 between 53 and 76 percent, depending upon the grade of the site) and in a 1995 TxDOT study[12] (R^2 of 72 percent) than in this study. There are several potential reasons for the difference, including the observation that overall speeds were higher on the two-lane rural highways. Another item that could have contributed to the stronger relationships is the amount of data available for curves with radii larger than 250 m (820 ft) in the two-lane rural highway study and the 1995 TxDOT study. Only four data points are available above 250 m (820 ft) for this TxDOT study. The small number of sites above 250 m (820 ft) as compared to less than 250 m (820 ft) may not have been enough to statistically determine a relationship.

For two-lane rural highways, radii greater than 400 m (1312 ft) have been assumed to be the limiting value for radius' influence on speed. For suburban arterials, the hypothesis was that a radius above 200 m (656 ft) was the value when the radius has minimal influence on speed. Based upon the statistical findings and the plots of the data, it appears that if a speed-radius relationship similar to a two-lane rural highway is to be found for suburban arterials, the value would probably be higher, say approximately 300 m (984 ft) (the inverse radius model becomes relatively level at about 72 to 73 km/h [44.7 to 45.3 mph] and a curve radius of 300 m [984.3 ft]). Additional data would be needed to test this hypothesis, however.

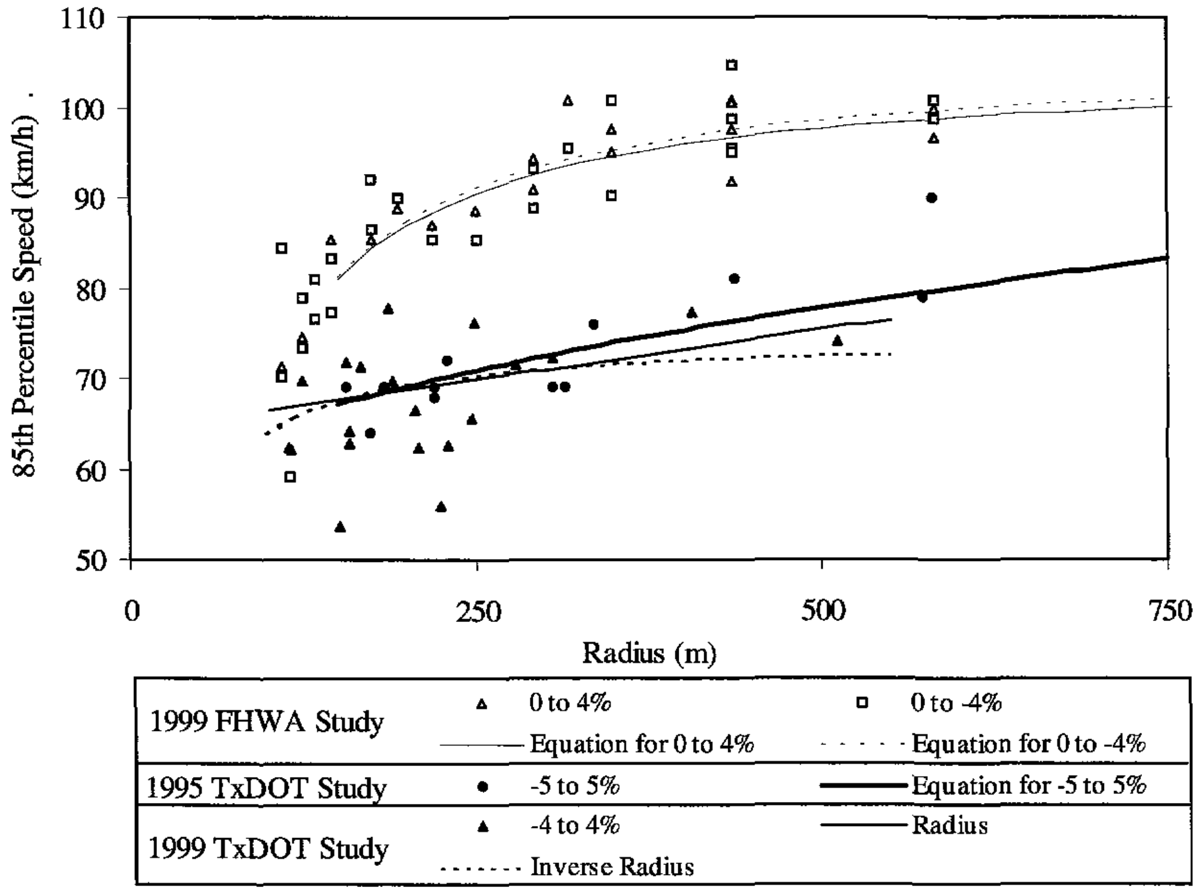


Figure 7-7. Plots of Radius Versus 85th Percentile Speed for Two-Lane Rural Highways and Suburban Arterials.

CHAPTER 8

ANALYSIS AND FINDINGS FOR STRAIGHT SECTION STUDY

This chapter identifies the geometric, roadside, or traffic control device variables affect on speed on suburban arterial straight sections. The operations at traffic signals and the influence of other vehicles were considered within the study site selection criteria and, therefore, are not included in the analysis. As with the curve analysis, the first decision made was where to focus the efforts for the analyses. Next, the speed data for this location were stratified using various methods to assist in identifying potential relationships. Finally, regression analyses were performed using the speed data for the key location and the models proposed from examining the stratified data.

SELECTION OF LOCATION FOR EVALUATION

The first step in the process was to decide how to calculate the speeds that should be used in the analysis. Once this was determined, extensive analyses could be performed using the questions presented in Chapter 1. A summary of potential speed values for each site is provided in Table 8-1 as an initial review of the data. This summary illustrates some of the various methods of determining a speed to represent a site. The "All Data" variable averaged the 85th percentile speeds calculated at each meter over the entire portion of the straight section where data were available. The "Midpoint 85th" variable is the 85th percentile speed recorded at the midpoint of the straight section at each site; for sites where speeds were not recorded at the midpoint, this column contains the speed recorded nearest to the midpoint. The "Mid 50% 85th" variable is the average of the 85th percentile speeds for the middle 50 percent of the straight section (i.e., 0.25 L to 0.75 L) at each site. The "Highest 85th" variable is the highest, or maximum, 85th percentile speed recorded in the straight section of each site.

The speeds for the midpoint 85th and highest 85th values were determined using a process where 3 m (9.8 ft) of data on either side of the reference point were averaged to determine the speed at that point. Therefore, the "Midpoint 85th" and "Highest 85th" speeds listed in Table 8-1 represent all readings that occurred within a 7 m (23.0 ft) section. This process helped capture a better representation of the vehicles because speeds were not available for every meter along the roadway. Table 8-1 also lists the number of observations that were used to determine the 85th percentile speed at the midpoint of the straight section (midpoint 85th).

Table 8-1. Summary of 85th Percentile Speed Calculations.

Site Number	Highest 85th (km/h)	All Data (km/h)	Mid 50% 85th (km/h)	Midpoint 85th (km/h)	Observations for Midpoint Speed
T1	56.3	55.7	55.5	55.2	213
T2	60.1	58.0	57.1	56.3	284
T3	58.0	57.0	56.9	56.3	271
T4	64.6	62.9	62.9	63.6	359
T5	74.3	70.9	71.2	71.9	235
T6	73.9	70.9	70.0	69.8	272
T7	75.6	73.1	73.1	73.9	310
T8	71.4	69.9	—	66.1	179
T9	73.7	70.1	70.0	70.0	337
T10	66.9	65.5	66.0	66.2	416
T11	77.2	74.1	74.1	76.0	221
T12	66.2	64.8	65.1	65.5	351
T13	63.5	61.9	62.4	62.7	366
T14	64.2	62.1	61.6	60.7	365
T15	80.7	78.4	78.7	79.2	262
T16	88.2	84.4	84.2	85.9	246
T17	82.6	78.3	78.3	78.1	345
T18	80.8	78.5	79.1	79.0	194
T19	87.3	85.5	85.4	86.3	290
T20	73.2	69.4	69.7	68.6	215
T21	83.2	80.1	81.5	81.0	134
T22	72.8	69.5	69.8	70.8	140
T23	74.8	73.2	73.3	72.3	306
T24	74.8	73.4	73.4	72.8	305
T25	77.4	75.5	75.4	75.0	268
T26	77.8	76.1	76.2	76.9	257
T27	77.9	75.9	75.8	75.2	258
T28	81.6	79.4	79.2	78.7	50
T29	86.2	81.1	79.8	74.3	69
T30	62.0	59.2	59.4	59.5	115
T31	77.8	75.1	75.1	73.7	301
T32	100.0	92.9	93.3	93.0	242
T33	93.5	89.8	89.6	89.2	261
T34	84.3	81.1	81.2	81.0	229
T35	86.5	85.1	84.8	84.8	261
T36	89.9	86.7	87.4	87.8	205
Avg	76.1	73.5	73.6	73.3	254.0

Table 8-1 demonstrates that there are a number of ways to represent the speed at a site. A comparison of the speeds in Table 8-1 indicates that, with only a few exceptions, the speed values calculated (other than the highest 85th percentile speed) are within 1.6 km/h (1 mph) of one another. Because this is the accuracy level of the laser guns used in this study, these speeds are essentially equivalent. Therefore, this comparison alone does not provide a good indication of where the analyses should be focused. To further address this problem, the research team developed an approach similar to that used for the curve data. Using maximum speed as the criterion, speed profiles for each site were searched for the maximum speed shown in Table 8-1; then, any speed within 1.6 km/h (1 mph) of that speed was identified. Figure 8-1 illustrates the results using 5 percent increments of the straight section lengths.

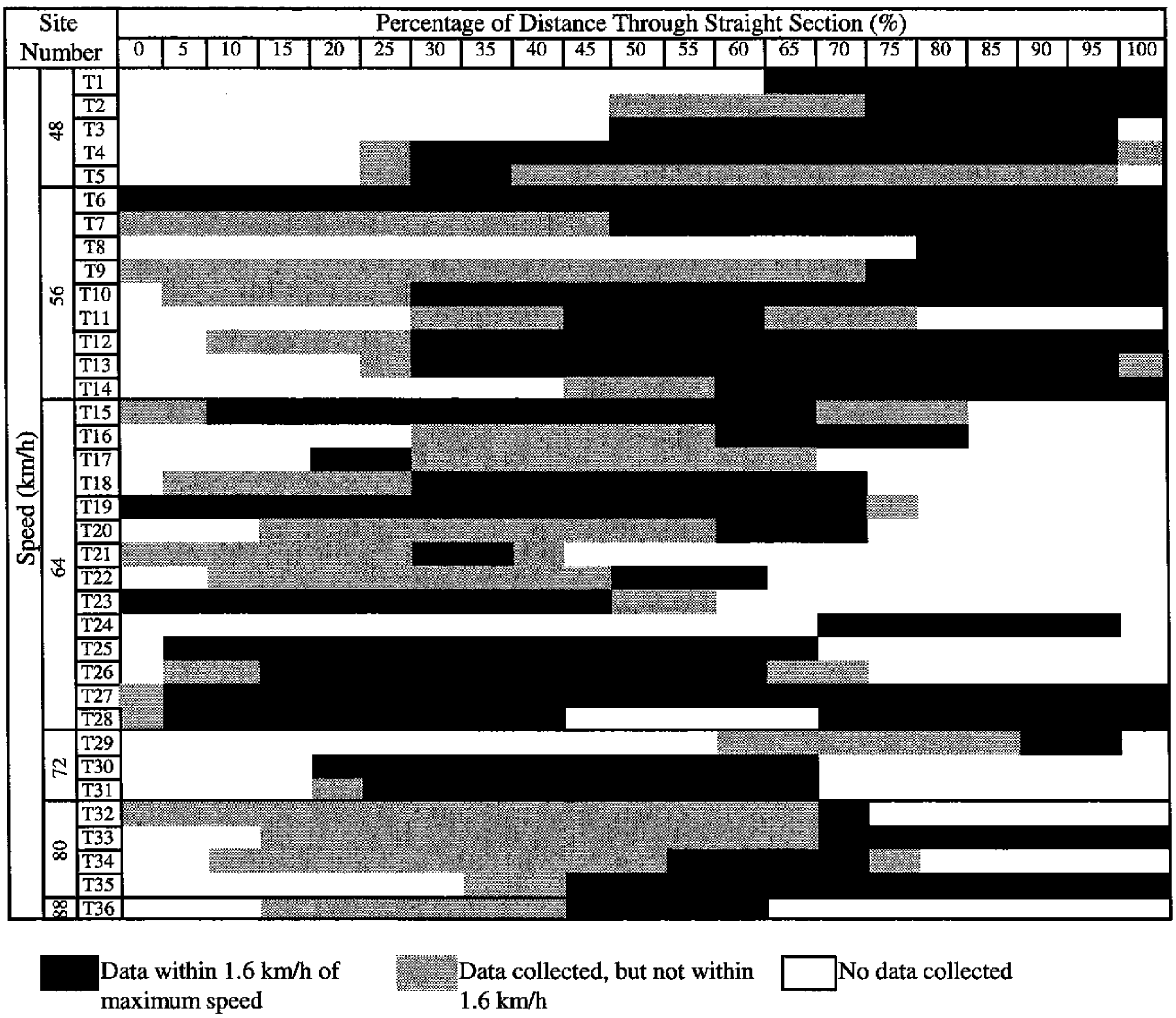


Figure 8-1. Summary of Maximum Speed Ranges.

A visual inspection of Figure 8-1 shows that the range where speeds are within 1.6 km/h (1 mph) of the maximum speed (i.e., where the graph is shaded solid black) appears to be random. Speeds within 1.6 km/h (1 mph) of the maximum speed occur at the beginning of the straight section, in the middle, and at the end. When the number of sites with a maximum speed at a specific distance is counted, the highest number of sites occurs between the midpoint and the third-quarter point range. Between 19 and 23 of the 36 sites have speeds within 1.6 km/h (1 mph) of the maximum speed within that range. Because the midpoint of the straight section should be the point least influenced by the upstream and downstream traffic controls, and because of the high number of sites with a maximum speed at that location, the focus of the remainder of the straight section data analysis is on the speeds measured at the midpoint of the straight section.

DESCRIPTIVE STATISTICS

This section summarizes descriptive statistics for the variables measured at the straight section sites. For the variables with logical breakpoints within the data set, the mean speed and standard deviations were calculated to provide a preliminary appreciation for how speed changes as the variable changes. Plots were also used to identify potential trends in the data; however, due to the large number of plots generated, only a selection of these plots are included with this report. The data are presented in the four major categories (alignment, cross section, roadside, and traffic control device) used during the data analysis efforts.

Alignment Variables

Table 8-2 lists the average, minimum, and maximum values for each alignment variable, and Table 8-3 provides the mean speed and standard deviations for the alignment variables. Figures 8-2 and 8-3 illustrate the relationships between 85th percentile speed and the straight section length and distance to downstream control, respectively. These figures illustrate that a minor relationship between speed and straight section length or distance to downstream control may exist. Speeds associated with the type of downstream and upstream controls are listed in Table 8-3; for example, mean speeds are lower for sites controlled with stop signs.

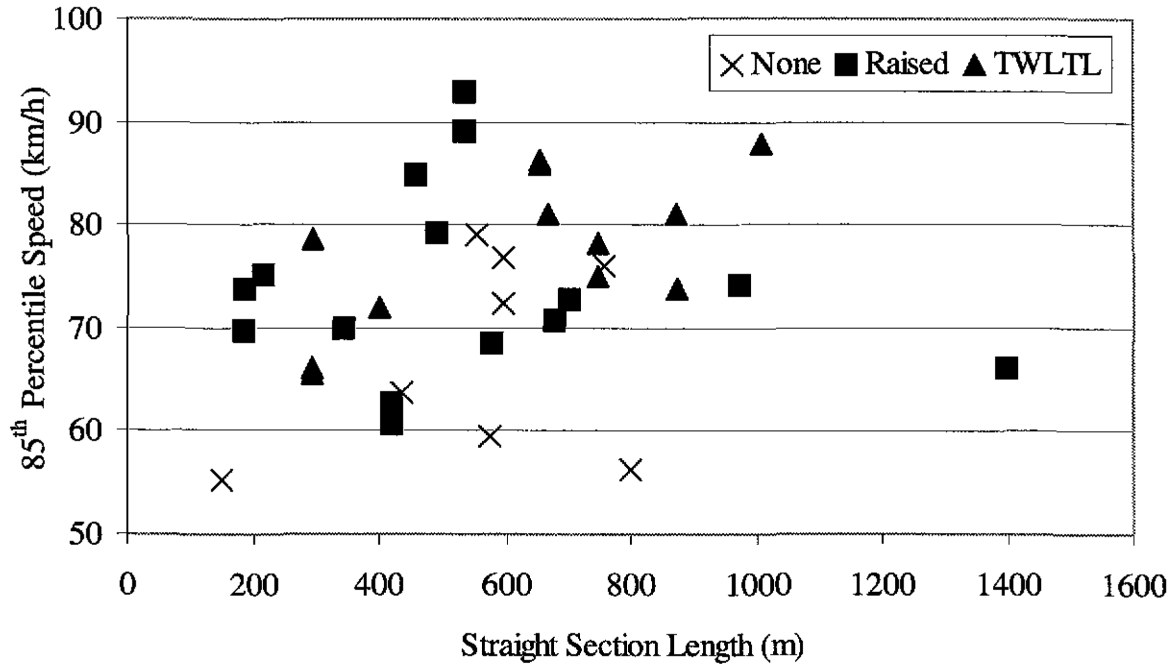


Figure 8-2. 85th Percentile Speed at Midpoint of the Straight Section Versus Straight Section Length.

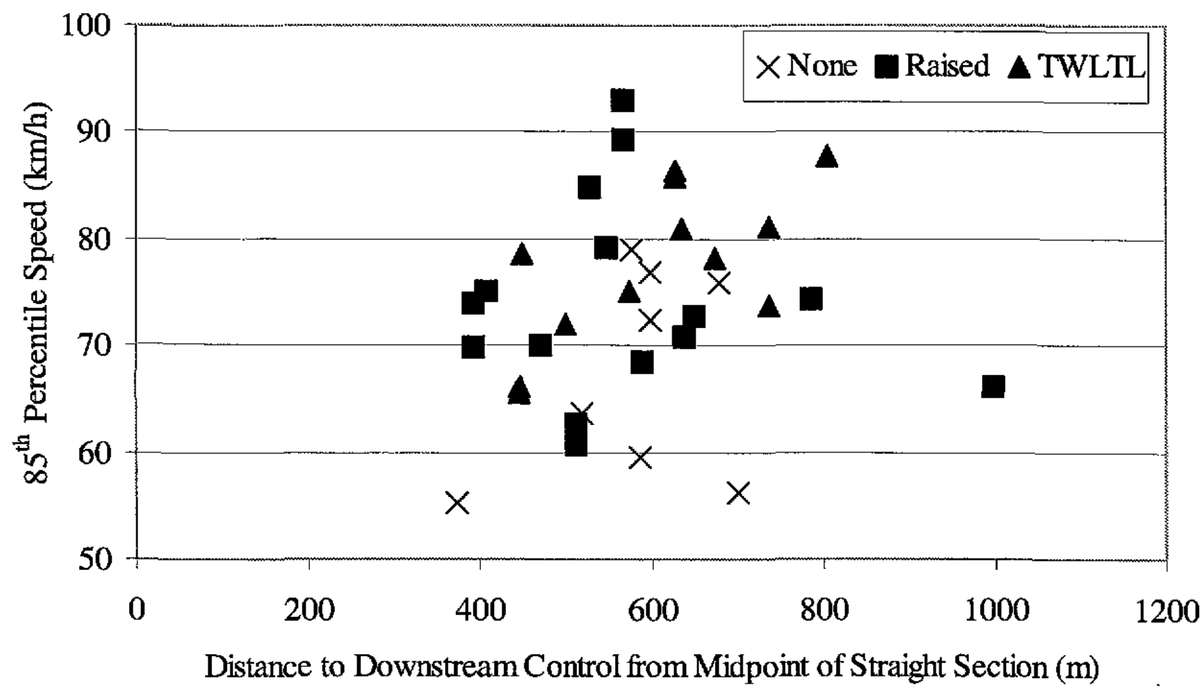


Figure 8-3. 85th Percentile Speed at Midpoint of the Straight Section Versus Distance to Downstream Control.

Table 8-2. Average, Minimum, and Maximum Values for Alignment Variables.

Variable	Freq.	Average	Minimum	Maximum
Straight Section Length, m (ft)	All sites	580 (1901.6)	149 (488.5)	1398 (4583.6)
Upstream Control and Distance to Control, m (ft)				
Traffic Signal	26	594 (1947.5)	393 (1288.5)	998 (3272.1)
Stop Sign	6	511 (1675.4)	375 (1229.5)	700 (2295.1)
Other (Curve, T, Bridge)	4	632 (2072.1)	568 (1862.3)	700 (2295.1)
Downstream Control and Distance to Control, m (ft)				
Traffic Signal	26	576 (1887.2)	393 (1288.5)	804 (2636.1)
Stop Sign	6	582 (1908.2)	375 (1229.5)	998 (3272.1)
Other (Curve, T, Bridge)	4	648 (2124.6)	568 (1862.3)	700 (2295.1)

Table 8-3. Midpoint Speed Data for Alignment Variables.

Variable	Potential Ranges for Variable	Freq.	Mean Speed km/h (mph)	Standard Deviation km/h (mph)
Upstream Control	Traffic Signal	26	68 (42)	8 (5)
	Stop Sign	6	60 (37)	8 (5)
	Other	4	69 (43)	13 (8)
Downstream Control	Traffic Signal	26	68 (42)	8 (5)
	Stop Sign	6	60 (37)	8 (5)
	Other	4	67 (42)	12 (7)

Cross Section Variables

Average, minimum, and maximum values for each cross section variable are listed in Table 8-4. Midpoint speed data for selected cross section variables are shown in Table 8-5. Lane widths were measured for each lane of the study direction. During this review, averaging the two lane width values was also considered. Table 8-5 demonstrates that, despite the relatively small range of lane widths, speeds tend to be lower for narrower lanes. The presence of a median (i.e., either a raised or a two-way left turn lane) indicated higher speeds than when no median was present. Both of these observations are similar to the curve analysis findings.

Parking was measured; however, because none of the study sites permitted on-street parking, this variable was not included in the evaluation. Similarly, the presence and width of bike lanes were initially considered; however, because only two sites included bike lanes, these variables were not included in the evaluation.

Table 8-4. Average, Minimum, and Maximum Values for Cross Section Variables.

Variable	Freq.	Average	Minimum	Maximum
Lane Width - Outside, m (ft)	All sites	3.65 (12.0)	2.95 (9.7)	4.57 (15.0)
Lane Width - Inside, m(ft)	All sites	3.59 (11.8)	3.05 (10.0)	4.17 (13.7)
Lane Width - Average, m (ft)	All sites	3.62 (11.9)	3.05 (10.0)	4.27 (14.0)
Median Type and Width, m (ft)				
Raised	15	7.01 (23.0)	2.44 (8.0)	4.38 (14.4)
Two-Way Left Turn Lane	12	4.03 (13.2)	3.05 (10.0)	4.57 (15.0)
None	9	N/A	N/A	N/A
Parking (on-street)	All sites had no on-street parking			
Bike Lane	Only two sites had bike lanes (2.13 m)			

Table 8-5. Midpoint Speed Data for Selected Cross Section Variables.

Category	Potential Ranges for Variables	Freq.	Mean Speed km/h (mph)	Standard Deviation km/h (mph)
Lane Width - Inside	Less than 3.5 m (11.5 ft)	12	61 (38)	6 (4)
	3.5 to 3.7 m (11.5 to 12.1 ft)	16	67 (42)	7 (4)
	Greater than 3.7 m (12.1 ft)	8	73 (46)	10 (6)
Lane Width - Outside	Less than 3.5 m (11.5 ft)	11	61 (38)	7 (4)
	3.5 to 3.7 m (11.5 to 12.1 ft)	11	65 (41)	6 (4)
	Greater than 3.7 m (12.1 ft)	14	71 (44)	9 (6)
Median Type	Raised	15	67 (42)	8 (5)
	Two-Way Left Turn Lane	12	70 (44)	7 (4)
	None	9	60 (38)	9 (6)

Roadside Variables

The ranges for the roadside variables are listed in Table 8-6, while Table 8-7 shows their midpoint speed values. Data in Table 8-7 indicates some expected relationships between roadside variables and mean speed. Higher values for roadside environment (indicating more rigid objects closer to the road) are associated with slightly lower speeds; a similar result can be found for increases in access density (see Figure 8-4). Similar to the findings for the horizontal curve sites, the 85th percentile speed versus access density plot (Figure 8-4) shows a high variability in speeds for a given access density. In addition, the highest speeds for access densities above about 11 pts/km (17.7 pts/mi) are approximately 10 km/h (6.2 mph) lower than the highest speeds for access densities below 11 pts/km (17.7 pts/mi). Commercial and mixed developments appear to have slightly higher speeds than residential developments, but a specific relationship between development and speed is not apparent from this data. The speed trend indicated for the pedestrian levels with this data set is also unclear.

Table 8-6. Average, Minimum, and Maximum Values for Continuous Roadside Variables.

Variable	Average	Minimum	Maximum
Roadside Development	described as either residential, commercial, or mixed		
Access Density, pts/km (pts/mi)	9.4 (15.1)	0 (0)	29 (46.7)
Roadside Environment	6.6	2	10
Pedestrian Level (scale of 1 to 5)	3.1	1	5

Table 8-7. Midpoint Speed Data for Roadside Variables.

Category	Potential Ranges for Variables	Freq.	Mean Speed km/h (mph)	Standard Deviation km/h (mph)
Roadside Environment	2-6 7-10	17 19	68 (42) 65 (40)	9 (6) 8 (5)
Access Density	0 to 10 pts/km (16.1 pts/mi) Greater than 10 pts/km (16.1 pts/mi)	21 15	68 (42) 64 (40)	10 (6) 6 (4)
Roadside Development	Residential Commercial Mixed	26 8 2	66 (41) 68 (42) 69 (43)	10 (6) 4 (3) 2 (1)
Pedestrian Level	1 2 3 4 5	5 13 0 10 8	66 (41) 69 (43) 0 59 (37) 73 (45)	5 (3) 9 (6) 0 6 (4) 5 (3)

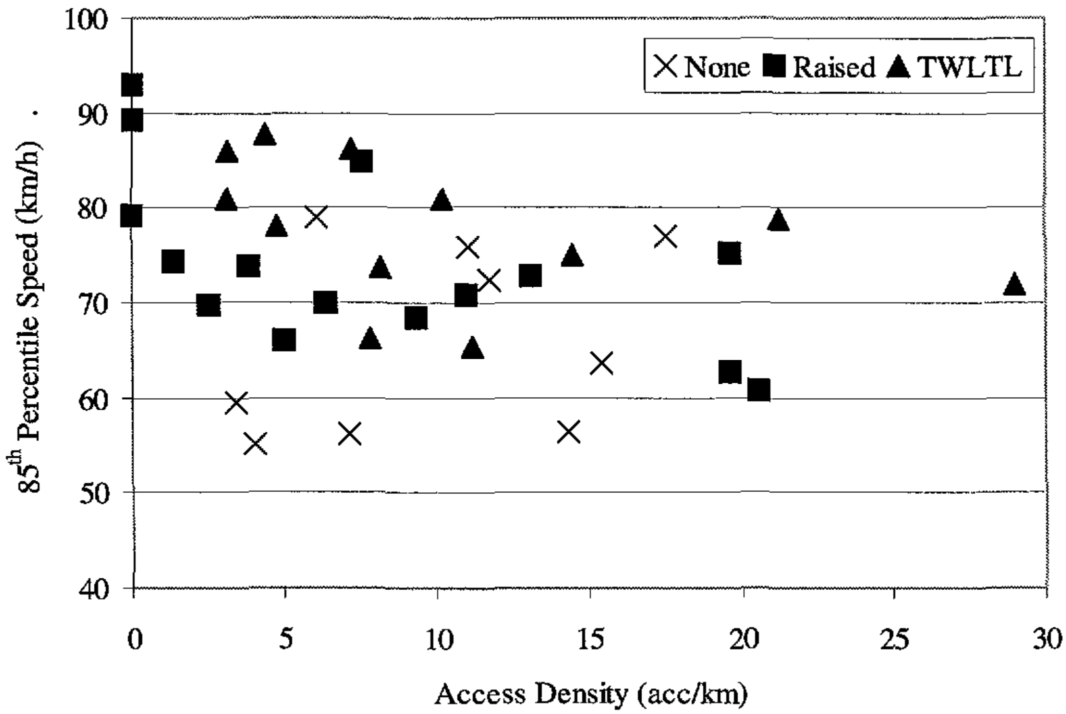


Figure 8-4. 85th Percentile Straight Section Speed (Midpoint) Versus Access Density.

Traffic Control Device Variables

Table 8-8 lists the average, minimum, and maximum values for the traffic control device variables. Midpoint speed data are provided for speed limit and signal spacing in Table 8-9. The plot of speed limit versus 85th percentile speed is shown in Figure 8-5. The figure illustrates that the measured 85th percentile speed exceeded the posted speed limit at almost every site and that operating speeds are higher for roads with higher posted speeds. Table 8-9 also shows that a clear trend between signal spacing and mean speed does not exist for this data set. Note, however, that the values for signal spacing are generally very small, with a relatively large distance between signals. The *Highway Capacity Manual*[22] does not consider a suburban arterial a moderate density design until signal spacing is over 2.5 sig/km (4.0 sig/mi). Therefore, this data set cannot be used to reach a conclusion on how signal spacing affects free flow speeds on a suburban arterial straight section.

Table 8-8. Average, Minimum, and Maximum Values for Traffic Control Device Variables.

Variable	Average	Minimum	Maximum
Signals, sig/km (sig/mi)	1.28 (2.1)	0.0 (0.0)	2.5 (4.0)
Posted Speed Limit, km/h (mph)	63.1 (39.2)	48 (30)	88 (55)

Table 8-9. Midpoint Speed Data for Selected Traffic Control Device Variables.

Variable	Potential Ranges for Variables	Freq.	Mean Speed km/h (mph)	Standard Deviation km/h (mph)
Signal Spacing	Less than 1.0 sig/km (1.6 sig/mi)	12	67 (41)	11 (7)
	1.0 to 1.5 sig/km (1.6 to 2.4 sig/mi)	9	66 (41)	7 (4)
	Greater than 1.5 sig/km (2.4 sig/mi)	15	66 (41)	8 (5)
Speed Limit	48 km/h (30 mph)	5	56 (35)	6 (4)
	56 km/h (35 mph)	9	62 (38)	4 (2.5)
	64 km/h (40 mph)	14	70 (43)	5 (3)
	72-88 km/h (45-55 mph)	8	73 (45)	10 (6)

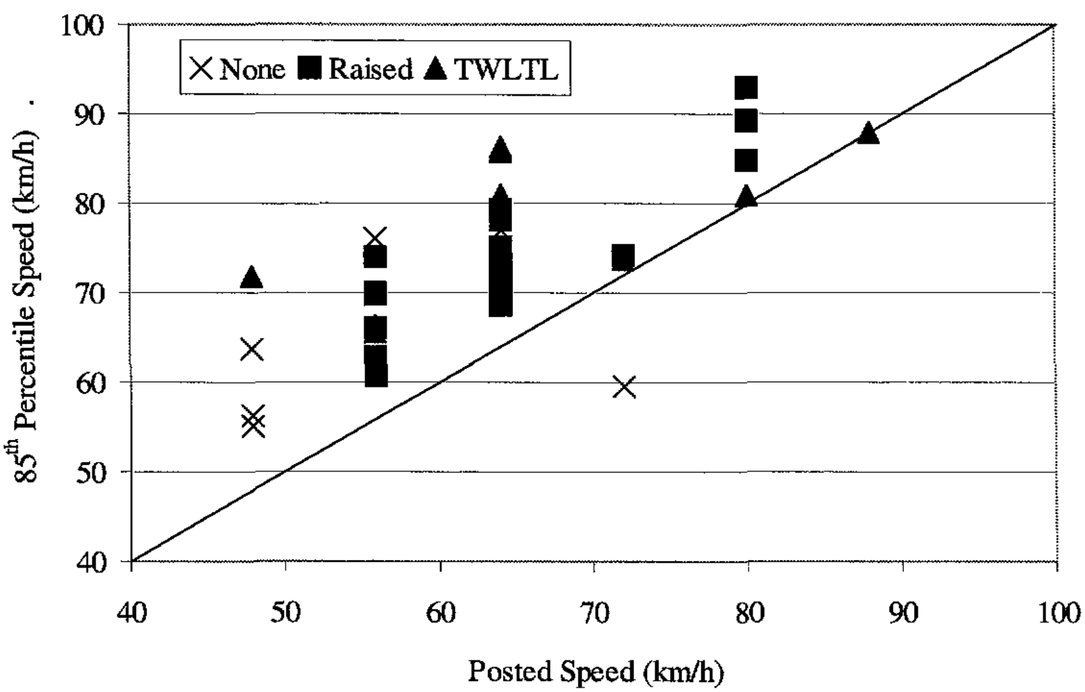


Figure 8-5. 85th Percentile Straight Section Speed (Midpoint) Versus Posted Speed.

Potential Models

The evaluation began in a similar manner to that used in the curve evaluation. The first step was aimed at determining how each category of variables affects speed. For those categories that have an effect, the variables responsible for the relation were identified. Then all potential variables were used to identify the strongest relationships. Based upon the review of the variables presented previously, the variables listed in Table 8-10 were included in the initial analysis.

Table 8-10. Variables Used in Analyses.

Category	Variables	
Alignment	Straight section length Upstream control type Distance to upstream control	Downstream control type Distance to downstream control
Cross Section	Lane width - outside Median type	Lane width - inside Median width
Roadside	Roadside development Access density	Roadside environment Pedestrian activity
Traffic Control Device	Signal spacing	Posted speed limit

ANALYSIS

Similar to the curve analysis, the method used to evaluate the straight sections was based on 85th percentile speed and ordinary least squares multiple regression. This decision permits easier comparison of the results to the curve findings and to other previous work. Additionally, 85th percentile speed is widely accepted as a quantifiable definition of operating speed.

Multicollinearity

Table 8-11 lists the correlation coefficients of significance for the straight sections. SAS™ and the proc CORR command were used to identify those variable pairs with multicollinearity problems. A value for α of 0.05 was used. The only modifications made at this point in the analysis were averaging the inside and outside lane widths and testing for the inclusion of correlated variables listed in Table 8-11 in a specific model. These combinations were not present in any of the final models.

Table 8-11. Correlation Coefficients of Significance.

Variable	Variable	Corr Coeff	p-value
Straight Section Length	Upstream Distance	0.66708	0.0001
	Downstream Distance	0.49360	0.0022
	Signals/km	-0.37551	0.0240
Lane Width Average	Speed Limit	0.54109	0.0007
Access Density	Signals/km	0.41352	0.0122

Variable Types

During the data analyses, several modifications of various variables were attempted. For instance, access density was originally recorded as a continuous variable. In the curve analyses, it was shown that a breakpoint of 12 pts/km (19 pts/mi) was identified as reasonable, and the continuous variable access density was changed to a class variable. This procedure was attempted for the straight section data, but the results indicated that the continuous form of the variable was better, although not significant, at explaining speed variance. Other modifications included changes to median type (from a three-class scheme to a two-class variable defining the presence of a median) and reclassifying the pedestrian variable into a three-class scheme (low, medium, and high). Unfortunately, these modifications did not help explain the variability in speed.

Statistics

The process for identifying those variables that influence speed began with an overview of how different categories of the data can be associated to speed. Multiple regression techniques from SAS™ (proc REG and proc GLM) were used to determine how the variables within each category of data affect speed. Table 8-12 summarizes these findings. Similar to the findings for the curve sites, the alignment and cross section categories only explain less than 25 percent of the variation in the speed data. The traffic category explained as much as 53 percent of the variation. As noted in the curve analysis, these levels of R^2 values are frequently judged favorably for accident analysis and human factors studies.

Of the alignment variables examined, the distance to the downstream control was the significant variable. Lane width was found to be significant among the variables in the cross section category. None of the roadside variables were found to be significant. Again, posted speed was the variable from the traffic control device category that was significant, and it explained a large portion of the variation of the data (53 percent). After the analyses associated with each category were complete, all significant variables were combined, and a final series of analyses were conducted to determine the variables that, when all variables are considered, affect speeds at the midpoint of the straight section. The findings are listed in Table 8-12 in the "All" category. Once all the variables are considered, the only significant variable was posted speed limit. A closer look at the variable that was found to best explain the variation associated with 85th percentile speed at the midpoint of a straight section is shown in Table 8-13. Similar to the curve analysis, higher posted speed limit values are associated with higher 85th percentile speeds.

Table 8-12. Summary of Regression Analyses.

Category	Adjusted R^2	p-value	Significant Variables
Alignment	17.3	0.0068	Downstream distance to control
Cross Section	24.9	0.0012	Lane width (average)
Roadside	n/a	n/a	No variables found significant
Traffic Control Device	53.0	0.0001	Posted speed limit
All	53.0	0.0001	Posted speed limit

Table 8-13. Final Analysis with Speed Limit.

Variables	Parameter Estimate	p-value
Intercept	29.180	0.0002
Speed Limit (km/h)	0.701	0.0001
R^2 = 54.3% Adjusted R^2 = 53.0%	F-statistic = 40.503 p-value = 0.0001	

Because 85th percentile speed is frequently used to set the posted speed limit, one would expect that one value would be able to predict the other, as is shown in this analysis. As discussed in the curve analysis section (see Chapter 7), other studies have included posted speed limit in their list of potential variables and it has been shown to be insignificant. Other studies have questioned the assumed strong relationship between 85th percentile speed and posted speed limit. Another series of analyses was performed without using posted speed limit so as to provide information on predicting operating speed when not considering posted speed limit. Statistics of the final model are summarized in Table 8-14. These results show the significance of speed limit. With speed limit in the model, the adjusted R^2 and model F-statistic both indicated stronger relationships. Without speed limit, only lane width is a significant variable, explaining about 25 percent of the variability of the speeds. The sign of the coefficient is as expected—as the width of the lane increases the speed on the roadway increases. Figure 8-5 shows the plot of the model and data points for lane width versus 85th percentile speed. When lane widths are 1 m (0.6 ft) greater, speeds are predicted to be 15 km/h (9.4 mph) faster.

Table 8-14. Final Analysis without Speed Limit.

Variables	Parameter Estimate	p-value
Intercept	18.688	0.2345
Average Lane Width (m)	15.050	0.0012
$R^2 = 27.0\%$ Adjusted $R^2 = 24.9\%$	F-statistic = 12.594 p-value = 0.0012	

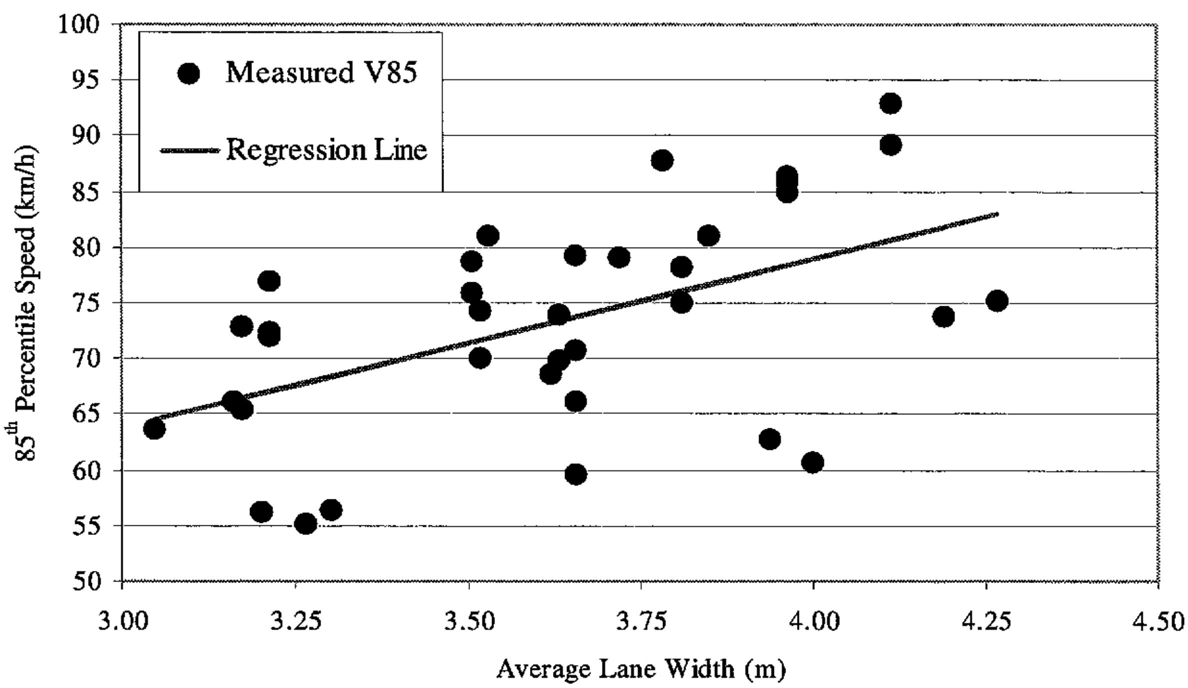


Figure 8-6. Average Lane Width Versus 85th Percentile Speed.

CHAPTER 9

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

This chapter provides a summary of the research project. In addition, it provides the conclusions and recommendations developed based upon the findings from the project.

SUMMARY

Driver behavior is affected by many roadway factors. Particularly in suburban networks, drivers are besieged by sensations that likely influence behavior. This project investigated geometric, roadside, and traffic control device variables that have an effect on driver behavior on major suburban arterials. Traffic signals and the influence of other vehicles were considered within the study site selection and data collection criteria and, therefore, are not included in the analysis. The goal was to identify cause and effect relationships so that the knowledge can be used to develop designs that result in desired driver behavior. When the operating speed matches the designer's intended speed, the facility design should be more consistent with driver expectancy. The convergence of design speed, operating speed, and posted speed limit should have an inherent improvement on safety and operations for these facilities.

Data Collection Methodology

The project was subdivided into two phases. Phase I investigated potential data collection techniques, preliminary analysis techniques, and experimental designs. Its goal was to identify the best data collection method, balancing the need of a large database of study sites (to expand the possibility of finding variables that affect speed) with the need for high quality of data (to expand the possibility of finding statistically valid results). After reviewing several different techniques, two were selected as the most promising. These two techniques were examined in pilot studies called the Laser Pilot Study and the Individual Driver Pilot Study. The lessons learned from these two pilot studies were used to develop the data collection methodology for Phase II of the project.

In the Laser Pilot Study, laser guns were used to collect the speed of free-flowing vehicles as they approached, traversed, and departed the study site. Three laser guns were employed at six study sites to obtain a comprehensive speed profile for the horizontal curve and its approaches. The laser guns were wired to laptop computers that recorded data three times per second when the gun was activated. The speed profile was superimposed on the measurements made of the roadway and roadside elements.

The Individual Driver Pilot Study used individual drivers in an instrumented test vehicle. Six drivers drove through several arterial sections while their speeds and positions on the roadway network were monitored. The drivers were selected from volunteers recruited from TTI. The use of this pool of volunteers permitted greater flexibility in scheduling and provided a cost-effective method to enlist drivers. Researchers selected drivers who represented a variety of demographic groups so as to reduce potential bias in the results.

While each of the pilot studies provided insight into the effects of roadway, roadside, and traffic control device elements on speed, the laser pilot study provided data at more sites with a greater variety of test conditions for less cost than the individual driver study. The individual driver study technique was a sound approach; however, it requires extensive resources (both time and funds) to obtain sufficient data to determine which factors influence driver speed. While the technique is limited because of sample size requirements and the time required to collect data for each individual, strong statistical comparisons could be made using this type of data if sufficient resources were available.

The data collection and reduction methodology used in Phase II was similar to the methodology used in the pilot effort. Laser guns were used to collect the speed of free-flowing vehicles through the study sites. A few improvements were made to the process, such as including the use of another laser gun on extremely sharp curves to minimize the gaps in the collected data.

The pilot studies demonstrated that horizontal curvature and access density may have the greatest influence on speed. In addition, variables that influence speed on curves may be different than the variables that influence speeds on sections of roadways between horizontal curves or traffic control devices (called "straight sections" in this project). Of the suggested additional variables, it was recognized that designers generally have control or influence over the type of median selected for a roadway. Therefore, the following variables and ranges were selected for the horizontal curve sites for Phase II efforts:

- horizontal curvature (less than 200 m [656 ft] and greater than or equal to 200 m [656 ft]),
- access density (less than 10 pts/km [16.1 pts/mi] and greater than or equal to 10 pts/km [16.1 pts/mi]), and
- median design (TWLTL, raised, and none).

The variables and ranges selected for the straight section sites were:

- access density (less than 10 pts/km [16.1 pts/mi] and greater than or equal to 10 pts/km [16.1 pts/mi]),
- median design (TWLTL, raised, and none), and
- posted speed limit (48-56 km/h [30-35 mph], 64-72 km/h [40-45 mph], and 80-88 km/h [50-55 mph]).

Roadside environment was measured and evaluated during the study, along with other variables such as speed limit and lane width.

A goal during the project was to collect data at two sites for each potential combination. For example, two sites would have a horizontal curvature of less than 200 m [656 ft] with low access density and a TWLTL median design. Although it was not possible to fill every possible combination of given ranges for the above variables, researchers focused on achieving a broad range of coverage of each of the study variables. Based upon the goal of two sites per combination, researchers collected data at a total of 24 horizontal curve sites and 36 straight section sites. Study sites were identified in several areas of Texas, including Houston, Dallas/Ft. Worth, San Antonio, Waco, and others. Although data were collected at more sites than initially planned, difficulties with equipment and/or the need to have speeds measured in a specific location resulted in having 19 horizontal curve sites and 36 straight section sites used in the analysis.

Selection of Location for Evaluation

The first step in the analysis process was to decide where the speeds were most influenced within the curve or along the straight section. Set increments of distance (50 and 100 m [164 and 328 ft]) were selected before and after a curve, while set percentages of the curve or straight section length (e.g. 25, 50, or 75 percent) were used within those elements. For curves, minimum speed was used as the criteria, while the highest speed was used for straight sections. In theory, the lowest speed within the curve would be the speed most influenced by the characteristics of the curve. The highest speed on a straight section is assumed to be the speed drivers would prefer to drive and, therefore, is the best reflection of the characteristics of the roadway. Because the accuracy of the laser guns was 1.6 km/h (1 mph), speed profiles for each site were searched for the absolute minimum or maximum speed, and any speed within 1.6 km/h (1 mph) within that speed was identified.

A visual inspection was used to reveal where speeds were most influenced. For horizontal curves, the minimum values occurred between the mid and three-quarter point of the curve. For straight sections, the area of maximum speed was not as evident. Most of the highest speeds occurred within the 30 to 70 percent range, although a few of the highest speeds extended to the end of the defined straight section. The speed at the middle of the straight section was selected for investigation.

Variables That Influence Speed

The analyses used 85^{th} percentile speeds and ordinary least squares multiple regression. This decision permitted easier comparison of the results between the curve and straight sections and to other previous work. Additionally, 85^{th} percentile speed is widely accepted as a quantifiable definition of operating speed. The correlation coefficients of significance for the curve and straight section variables were determined. This effort identified pairs of variables that were correlated and, therefore, should be eliminated or used cautiously. During the data analyses, several transformations of variables were attempted. For example, access density was originally recorded as a continuous variable. In the analyses, it was examined as a two-class variable with the break point at 12 pts/km (19 pts/mi) for the curve sites and at 10 to 12 pts/km (16.1 to 19.3 pts/mi) for the straight section sites. Other transformations included changes to median type (from a three-class scheme to a two-class variable defining the presence of a median) and reclassifying the pedestrian variable into a three-class scheme (low, medium, and high).

The process for identifying those variables that influence speed began with an overview of how different categories of the data can be associated to speed. Multiple regression techniques using SAS™ were performed to determine how the variables within each category affect speed. Table 9-1 summarizes the findings for the curves and straight sections. The alignment and cross section categories explain about 25 percent of the variation in the speed data for both the curve sections and the straight sections. The variables included in the roadside category were not significant for straight sections and explained about 40 percent of the variation in speed for the curve sections. The traffic control device category explained as much as 53 percent of the speed variation.

After the analyses associated with each category were complete, all significant variables were combined, and a final series of analyses was performed to determine the variables that affect speeds at the midpoint of the horizontal curve and the midpoint of the straight section. The findings are listed in Table 9-1 in the "All" category. Once all the variables were considered, the only significant variable for straight sections was posted speed limit. In addition to posted speed, deflection angle and access density classes influence speed on curve sections.

Table 9-1. Summary of Regression Analyses.

Category	Curve Sections			Straight Sections		
	Adjusted R^2 (%)	Prob > F	Significant Variables	Adjusted R^2 (%)	Prob > F	Significant Variables
Alignment	21.1	0.0480	1. curve radius 2. deflection angle	17.3	0.0068	downstream distance to control
Cross Section	24.2	0.0320	median presence	24.9	0.0012	average lane width
Roadside	39.8	0.0228	1. access density 2. roadside development	n/a	n/a	no variables found significant
Traffic Control Device	49.3	0.0005	posted speed limit	53.0	0.0001	posted speed limit
All	70.5	0.0001	1. posted speed limit 2. deflection angle 3. access density	53.0	0.0001	posted speed limit

Because 85th percentile speed is frequently used to set the posted speed limit, one may expect that one value could be used to predict the other, as shown in this analysis. Other studies have included posted speed limit in their list of potential variables; however, it has been shown to be insignificant, and other studies have questioned the assumed strong relationship between 85th percentile speed and posted speed limit. Therefore, another series of analyses was performed without using posted speed limit. Statistics of these models are summarized in Table 9-2. These results show the significance of speed limit. With speed limit in the model, the adjusted R^2 and model F-statistic both indicated stronger relationships. Without speed limit, only lane width is a significant variable for straight sections, explaining about 25 percent of the variability of the speeds. For curve sites, the impact of median presence now becomes significant, together with roadside development.

Table 9-2. Final Analysis without Speed Limit.

Variables	Parameter Estimate	p-value
Curve Sections		
Intercept	44.538	0.0001
Median Presence (if Raised or TWLTL then 1, otherwise 0)	9.238	0.0023
Roadside (if School then 1 otherwise 0)	13.029	0.0733
Roadside (if Residential then 1, otherwise 0)	17.813	0.0032
Roadside (if Commercial then 1, otherwise 0)	19.439	0.0025
R^2 = 62.3% Adjusted R^2 = 52.0%	F-statistic = 15.265 p-value = 0.0001	
Straight Sections		
Intercept	18.688	0.2345
Average Lane Width (m)	15.050	0.0012
R^2 = 27.0% Adjusted R^2 = 24.9%	F-statistic = 12.594 p-value = 0.0012	

Almost every previous study of speeds on horizontal curves, regardless of the functional classification of the roadway, have identified horizontal curve radius or degree of curvature as a key variable for explaining the variation of speeds on a curve. Preliminary observations of speed versus radius and speed versus inverse radius indicated that a similar trend may be present in the data for suburban arterials. The statistical evaluation, however, demonstrated that deflection angle is the horizontal curve variable that best contributes to explaining the variation in speeds on a horizontal curve when speed limit is included in the model. A reason that deflection angle may be stronger than radius is that drivers on suburban arterials may be more sensitive to how the curve looks (as represented by deflection angle) rather than driver comfort (as represented by radius). Another item that could have contributed to the stronger relationship found on two-lane rural highways is the amount of data available for curves with radii larger than 250 m (820 ft). Only four data points are available above 250 m (820 ft) for this study. The small number of sites above 250 m (820 ft) as compared to less than 250 m (820 ft) may not have been enough to statistically determine a relationship.

CONCLUSIONS

Selection of Location for Evaluation

- Speeds measured within the third quarter range of a curve (i.e., starting with the midpoint of the curve and extending to the 3/4 point of the curve) generally represented the minimum speeds measured in the horizontal curves. This range was selected as the location for additional analysis.

- Speeds measured at the midpoint of the straight section were used in the analysis. Speeds within 1.6 km/h (1 mph) of the highest speed measured occurred for long portions of the straight sections including being frequently present at the straight section's midpoint. Several locations could have been justified for the analysis; however, the ease of finding the midpoint of the straight section along with its high representation of having the highest speed present encouraged its selection.

Variables that Influence Speed

- Roadway variables can be used to explain the variation in speed on suburban arterials.

- The variables that influence speed on suburban arterial curves and straight sections are listed in Table 9-3. These variables are from the models with the strongest R^2 values.

- Because radius is predominate in other studies that investigated the relationship of speed to geometric variables, it was further investigated in this study. When a form of radius was forced into the model, lower R^2 values resulted. A potential reason for the poor performance of radius in this data set could be the limited number of sites with radius values above 250 m (820 ft). Another reason that deflection angle may be a stronger variable than radius is that drivers on suburban arterials may be more sensitive to how the curve looks (as represented by deflection angle) rather than driver comfort (as represented by curve radius).

Table 9-3. Variables That Influence Speed on Suburban Arterials.

	Curve Sections	Straight Sections
With speed limit considered	Speed limit (km/h) Deflection angle (deg) Access Density (class variable with split at 12 pts/km [19.3 pts/mi])	Speed limit (km/h)
With speed limit not considered	Median Presence (class variable with split between no median and a median present—TWLTL or raised) Roadside Development (class variable with split between commercial, residential, school, and park)	Average lane width (m)

RECOMMENDATIONS

The following recommendations were developed based upon the findings and conclusions made within this study.

- The following key findings could be included in future editions of TxDOT's design manual and appropriate training courses:

  - On suburban arterial horizontal curves, higher speeds should be expected when the access density is less than 12 pts/km (19.3 pts/mi) and when a median (e.g., TWLTL or raised) is used. In addition, high deflection angle values are associated with lower speeds, and higher speeds are associated with higher posted speed limit values.

  - On suburban arterial straight sections away from a traffic signal, higher speeds should be expected with wider lane widths.

- Very recently, other statistical techniques have been proposed and used to evaluate speeds on roadways. For example, a mixed model approach was used on low-speed residential streets.[10] That approach could also be used on the data collected for this project to account for the randomness of study sites as compared to the geometric and traffic control device variables.

- An advantage of having nearly continuous speed profiles for roadway curves is that the deceleration and acceleration patterns into and out of a curve can be investigated. The data collected in this project could be used in a future project to identify relationships between curve characteristics and the deceleration and acceleration patterns.

- Using speed profiles, researchers were able to verify that the midpoint of a horizontal curve is where speeds are most influenced. This should help other researchers collecting data using spot speed methods.

- A finding from this project is that the way a curve appears to a driver (as represented by the deflection angle or a combination of deflection angle/radius/length) may have an effect on the speed a driver selects prior to and within the beginning of a horizontal curve. Additional research is needed to develop a better understanding of how the appearance of the curve affects speed.

- This project focused on determining which unique variables influence speeds on a suburban arterial. While individual variables have an influence, the combination of several variables may also form <u>an environment</u> that has a significant influence on drivers. For example, the characteristics associated with an Interstate freeway communicates to the driver that higher speeds are acceptable. Limited access points, wide medians, non-narrow lanes, few trees along the roadside, and other characteristics <u>in combination</u> encourage the higher speeds. Any one of these variables could be present along another roadway type and not encourage similar higher speed. Therefore, additional research could examine what combination of variables and their dimensions would encourage speeds within a given range. In the *Highway Capacity Manual*, suburban arterials are split into three speed limit ranges: 40 to 56 km/h (25 to 35 mph), 48 to 64 km/h (30 to 40 mph), and 64 to 72 km/h (40 to 45 mph). What combination of variables would encourage speeds between 40 to 56 km/h (25 to 35 mph) rather than speeds between 64 to 72 km/h (40 to 45 mph)?

- The operations at traffic signals can have a very significant impact on the speeds along a suburban arterial. In addition, the amount of traffic on the roadway can also result in decreased travel speeds. The influences of these variables were minimized in this study by selecting sites away from signals and selecting free-flow vehicles only. By minimizing these variables, the influence of the geometric variables and/or traffic control devices (such as signs) could be examined. Another study could include consideration of these other, highly influential, variables on driver speeds on suburban arterials.

REFERENCES

1. K. Fitzpatrick, L. Elefteriadou, D. Harwood, J. Collins, J. McFadden, I.B. Anderson, R.A. Krammes, N. Irizarry, K. Parma, K. Bauer, and K. Passetti. *Speed Prediction for Two-Lane Rural Highways.* Report FHWA-RD-98-171. June 1999.
2. R.A. Krammes, R.Q. Brackett, M.A. Shafer, J.L. Ottesen, I.B. Anderson, K.L. Fink, K.M. Collins, O.J. Pendleton, and C.J. Messer. *Horizontal Alignment Design Consistency for Rural Two-Lane Highways.* Report FHWA-RD-94-034. 1994.
3. D.B. Fambro, K. Fitzpatrick, and R. Koppa. *Determination of Stopping Sight Distance.* NCHRP Report 400. 1997.
4. M.A. Chowdhury, D.L. Warren, and H. Bissell. "Analysis of Advisory Speed Setting Criteria." *Public Roads*, Vol. 55, No. 3, December 1991, pp. 65–71.
5. J.R. McLean. *Speeds, Friction Factors, and Alignment Design Standards.* Research Report ARR 154. Australian Road Research Board, Victoria, 1988.
6. J. McLean. "An Alternative to the Design Speed Concept for Low Speed Alignment Design." *Transportation Research Record 702.* National Research Council, Washington, D.C., 1979, pp. 55–63.
7. A. Polus, K. Fitzpatrick, and D. Famboro. "Predicting Operating Speeds on Tangent Sections of Two-Lane Rural Highways." Paper submitted to Transportation Research Board, 79th Annual Meeting, January 2000.
8. American Association of State Highway and Transportation Officials. *A Policy on Geometric Design of Highways and Streets*, 1994.
9. C.M. Poe, J.P. Tarris, and J.M. Mason, Jr. *Relationship of Operating Speed to Roadway Geometric Design Speed*, Pennsylvania Transportation Institute, Report Number PTI 9606, December 1996.
10. C.M. Poe, and J.M Mason. "A Mixed Model Approach to Analyzing the Influence of Geometric Design on Operating Speeds Along Low-Speed Urban Streets." Paper submitted to the Transportation Research Board 79th Annual Meeting, January 2000.
11. J.L. Gattis and A. Watts. "Urban Street Speed Related to Width and Functional Class." *Journal of Transportation Engineering*, Vol. 125, No. 3, May/June 1999.
12. K. Fitzpatrick, J.D. Blaschke, C.B. Shamburger, R.A. Krammes, and D.B. Fambro. *Compatibility of Design Speed, Operating Speed, and Posted Speed.* Final Report FHWA/TX-95/1465-2F. October 1995.
13. K. Fitzpatrick, L. Nowlin, and A. Parham. *Development of Level-of-Service Analysis Procedure for Frontage Roads.* Report FHWA/TX-97/1393-3. August 1996.
14. F. Kitchener, M. Kyte, W. L. Liang, and P. Shannon. " Effect of Environmental Factors on Driver Speed: A Case Study." *Transportation Research Record 1635.* National Research Council, Washington, D.C. 1998.
15. J. Rowan and C.J. Keese. "A Study of Factors Influencing Traffic Speed." *HRB Bulletin 341*, Highway Research Board, Washington, D.C., 1962.
16. C. Oppenlander. "Variables Influencing Spot-Speed Characteristics—Review of the Literature." *Special Report 89*, Highway Research Board, Washington, D.C., 1966.
17. N.J. Garber and R. Gadiraju. "Factors Affecting Speed Variance and Its Influence on Accidents." *Transportation Research Record 1213*, National Research Council, Washington, D.C., pp. 64–71, 1989.

18. M.S. Good. "Road Curve Geometry and Driver Behavior." *ARRB Special Report No. 15*, May 1978.
19. *Roadside Design Guide*. American Association of State Highway and Transportation Officials. Washington, D.C. 1996.
20. ITE TENC Committee 97-12, *Survey of Speed Zoning Practices*, Draft Information Report, August 1999.
21. B.N. Fildes and T.J. Triggs. "Effect of Changes in Curve Geometry at Magnitude Estimates of Road Like Perspective Curvature." *Perception and Psychophysics*, 37, pp 218–224. 1985.
22. *Highway Capacity Manual*. Special Report 209. 3rd Edition. Transportation Research Board. 1994.