TEXAS TRANSPORTATION INSTITUTE

VALIDATION OF AND ENHANCEMENTS TO AN OPERATING-SPEED-BASED GEOMETRIC DESIGN CONSISTENCY EVALUATION MODEL

RESEARCH REPORT 04690-4

TEXAS TRANSPORTATION INSTITUTE
THE TEXAS A&M UNIVERSITY SYSTEM
COLLEGE STATION, TEXAS

DISCLAIMER

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
TTI-04690-4		

4. Title and Subtitle	5. Report Date
PRELIMINARY VALIDATION OF A SPEED-PROFILE MODEL FOR DESIGN CONSISTENCY EVALUATION	August 1996
	6. Performing Organization Code
7. Author(s) K. Collins	8. Performing Organization Report No. 04690-4
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. DTFH61-92-x-00019
12. Sponsoring Agency Name and Address Federal Highway Administration U.S. Department of Transportation 6300 Georgetown Pike McLean, VA 22101-2296	13. Type of Report and Period Covered Jan. 1994 - May 1995
	14. Sponsoring Agency Code

15. Supplementary Notes
Agreement Officer's Technical Representative (AOTR): Jeffrey F. Paniati, HSR-20

16. Abstract

The objectives of this study were to test the validity of a speed-profile model for design consistency evaluation, including: (1) the speed reduction estimation ability of the model, and (2) assumptions about deceleration and acceleration characteristics approaching and departing horizontal curves. Detailed speed data were collected at a sample of ten horizontal tangent-curve sections on two-lane rural highways in Texas.

The results indicated that the model provides a reasonable, albeit simplified, representation of speed profiles on horizontal alignments consisting of long tangents and isolated curves. The model provides reasonable estimates of speed reductions from long approach tangents to curves, with the caveat that the model does not account for the effect of nearby intersections on speeds.

The results further indicate that the assumed 0.85 m/s^2 value (taken from Lamm, et al.) is reasonable for deceleration rates approaching curves that require speed reductions, but that it may overestimate acceleration rates departing curves. The model's assumptions that deceleration occurs entirely on the approach tangent and that speeds are constant throughout a curve were not confirmed by observed speed behavior. The observations that deceleration continues after entering a curve and that speed adjustments occur throughout a curve are indicators of the difficulty drivers experience in judging appropriate speeds through curves.

17. Key Words	18. Distribution Statement
Design Consistency Superelevation Highway Accidents	No restrictions. This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161

19. Security Classif.(of this report)	20. Security Classif.(of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	53	

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
	LENGTH			
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
	AREA			
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yards	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
	VOLUME			
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3

NOTE: Volumes greater than 1000 l shall be shown in m^3.

Symbol	When You Know	Multiply By	To Find	Symbol
	MASS			
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
	TEMPERATURE (exact)			
°F	Fahrenheit temperature	5(F-32)/9 or (F-32)/1.8	Celcius temperature	°C
	ILLUMINATION			
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
	FORCE and PRESSURE or STRESS			
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
	LENGTH			
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
	AREA			
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
	VOLUME			
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.71	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3

Symbol	When You Know	Multiply By	To Find	Symbol
	MASS			
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
	TEMPERATURE (exact)			
°C	Celcius temperature	1.8C + 32	Fahrenheit temperature	°F
	ILLUMINATION			
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
	FORCE and PRESSURE or STRESS			
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

* SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.

(Revised September 1993)

TABLE OF CONTENTS

Page

1. INTRODUCTION 1
   - DESIGN CONSISTENCY AND SAFETY 1
   - PROBLEM STATEMENT 2
   - SCOPE AND OBJECTIVES 2
   - STUDY ORGANIZATION 3

2. LITERATURE REVIEW 4
   - OPERATING-SPEED-BASED DESIGN CONSISTENCY EVALUATION 4
     - Leisch and Leisch 4
     - Lamm et al. 5
     - Ottesen and Krammes 5
   - DETAILED SPEED DATA COLLECTION AND SPEED TRANSITION 9
   - LITERATURE REVIEW SUMMARY 10

3. STUDY METHODOLOGY 11
   - STUDY DESIGN 11
   - DATA COLLECTION 13
     - Curve Geometry 13
     - Speed Data 13
     - Data Collection Equipment 15
   - VARIABLE ESTIMATION 15
     - Speed Reduction 15
     - Acceleration and Deceleration Characteristics 17
   - DATA REDUCTION AND ANALYSIS 18

4. RESULTS 19
   - SAMPLE SIZES 19
   - VALIDATION OF SPEED REDUCTION ESTIMATION PROCEDURE 20
     - Current Speed Reduction Estimation Procedure 20
     - Comparison of Observed and Estimated Speed Reduction 20
     - Summary 24
   - VALIDATION OF ACCELERATION AND DECELERATION RATES 24
     - Operating-Speed Profiles 24
     - Calculated 85th Percentile Rates 30
     - Implied Rates 34
     - Rate Estimation and Comparison 35
     - Summary 41

5. SUMMARY, FINDINGS, CONCLUSIONS AND RECOMMENDATIONS 43
   - SUMMARY 43
   - FINDINGS 43
   - CONCLUSIONS 44

LIST OF FIGURES

Figure		Page
1	Speed Profile Model	8
2	Simple Site Layout Schematic	16
3	Observed and Estimated Speed Reduction by Degree of Curvature Category	23
4	Speed Profiles for Low Degree of Curvature Category	27
5	Speed Profiles for Middle Degree of Curvature Category	28
6	Speed Profiles for High Degree of Curvature Category	29
7	Observed 85th Percentile Rates for Low Degree of Curvature Category	31
8	Observed 85th Percentile Rates for Middle Degree of Curvature Category	32
9	Observed 85th Percentile Rates for High Degree of Curvature Category	33
10	Implied Rates for Low Degree of Curvature Category	36
11	Implied Rates for Middle Degree of Curvature Category	37
12	Implied Rates for High Degree of Curvature Category	38

LIST OF TABLES

Table		Page
1	Equations for Constructing the Estimated Operating-Speed Profile	7
2	Site Selection Controls and Criteria	12
3	Controls on Degree of Curvature and Length of Curve	13
4	Curve Geometry	14
5	Sample Sizes Before and After Screening	19
6	Observed and Calculated Reduction in 85th Percentile Speeds	21
7	Test of Means for Samples: Reduction in 85th Percentile Speed	22
8	Test of Mean 85th Percentile Speeds on Tangents	30
9	Average Implied Acceleration and Deceleration Rates	39
10	Tests of Acceleration and Deceleration Means	40

1. INTRODUCTION

It has long been recognized that the likelihood of accidents is higher on curved highway sections than on tangents. In the past several years, much research has been conducted to examine the relationship between accident experience and horizontal curves. Several studies have investigated possible surrogate measures of accident experience on horizontal curves. The variables investigated include degree of curvature, length of curve, tangent length, sight distance, and speed reduction from the tangent to the curve.[1] The results of these studies have prompted ongoing research focusing on current highway design practices.

Design procedures currently employed in the U.S. are based on the design-speed concept. The process bases the design of the horizontal alignment solely on design speed. A problem with this design policy is that the design speed of a roadway section is defined as the design speed of the most restrictive geometric element within the section.[2] Therefore, drivers may be able to drive at speeds higher than the design speed throughout much of the roadway. If the design speed of the most restrictive element, generally a horizontal curve, is lower than the desired speed of the driver, speed reductions may be necessary in order to safely traverse the element. An alignment that requires the driver to adjust speed in this manner is termed an inconsistent alignment, whereas a consistent alignment would allow the driver to operate at a uniform desired speed throughout the highway section.[1] Thus, for an inconsistent alignment, a driver must be able to either recognize and drive at the selected design speed of the alignment, or drive at the desired speed on each element of the alignment and reduce speed where required. The goal of the designer is alignment consistency.

Originally, the design-speed concept was intended to ensure that: (1) all curves along a highway alignment have the same design speed, and (2) the design speed reflects the speed at which a high percentage of drivers operate. Gradual diversion from the second concept has resulted in inconsistent geometric design. One question that is raised when dealing with design consistency is how the design speed should be selected. Current practice is selection of design speed based on AASHTO definitions.[2] This procedure has resulted in increasing disparities between driver operating speeds and design speeds.

DESIGN CONSISTENCY AND SAFETY

Previous studies have revealed two primary measures of design consistency: operating speed, and driver mental workload.[1, 3] Operating speed is defined herein as the 85th percentile speed of drivers along an alignment. With respect to design consistency, the operating speed is examined in the context of operating-speed reductions or changes. Driver mental workload is defined as "the time rate at which drivers must perform a given amount of work or driving task." [3] Again, change or fluctuation in driver mental workload would be the indicator of inconsistency.

Ottesen and Krammes established a model for predicting the operating speed along a given tangent-curve section based on the geometry of the curve, assumptions about where and at what rate acceleration and deceleration occur and basic kinematic equations.[4] The study

resulted in development of an operating-speed-profile model having three main components. First, a regression equation for predicting operating speeds at the midpoint of a horizontal curve based on the geometry of the curve was developed. Second, the operating speed on a tangent was calibrated and defined as the mean observed 85th percentile speed on long tangents. Finally, assumptions about where and at what rate acceleration and deceleration occur were based on previous work, but were not calibrated.[1] Using the operating-speed model, an alignment could be evaluated based on changes in speed through the section. Given guidelines as to acceptable speed reductions along an alignment, a designer could then evaluate the consistency of the horizontal alignment.

Anderson and Krammes examined operating-speed reduction as a surrogate measure for accident experience on horizontal curves.[5] Operating-speed reduction is defined as the difference between the 85th percentile speed on the tangent and the 85th percentile speed on a horizontal curve. Utilizing the operating-speed model developed by Krammes and Ottesen, the study determined that there was a significant relationship between accident rates on horizontal curves and the reduction in 85th percentile speeds. The results of the study support the idea that design consistency is critical to safe design of rural highways.

PROBLEM STATEMENT

As established by Krammes et al. design consistency in rural alignment is an important concept from a driver safety standpoint.[1] Further, the consistency of the design can be evaluated based on an operating-speed-profile model. Two components of the model (curve and tangent speeds) have been validated, but the third component (acceleration and deceleration characteristics) have not. Research is needed to validate the current assumptions about acceleration and deceleration characteristics of drivers on two-lane rural highways. Given validated acceleration and deceleration characteristics, design decisions based on the operating-speed-based design consistency evaluation model may be made with greater confidence, with better understanding of driver behavior near horizontal curves.

SCOPE AND OBJECTIVES

The objectives of this research are to collect detailed speed data at a sample of horizontal curves and tangents on rural, two-lane highways and:

- Test the speed change predicting ability of the previously established operating-speed-profile model.
- Test the assumptions regarding acceleration and deceleration rates and points where acceleration and deceleration begin and end.
- If deemed necessary, make recommendations pertaining to acceleration and deceleration characteristics to enhance the current speed-profile model.

The scope of this study is limited to independent horizontal curves with preceding tangents longer than 800 feet on rural, two-lane highways in level and rolling terrain in Texas.

STUDY ORGANIZATION

This report is divided into five chapters. The first chapter is this introductory chapter. Chapter 2 reviews literature relevant to the operating-speed-profile model, driver acceleration and deceleration behavior near horizontal curves, and detailed speed data collection efforts. Chapter 3 details the study design and data collection, reduction and analysis methodology. Chapter 4 presents results from the analysis performed to test: (1) the speed-reduction predicting ability of the current operating-speed-profile model, and (2) the acceleration and deceleration characteristics of drivers on and adjacent to horizontal curves. Chapter 5 presents a summary of the analysis and results, conclusions from the research, and recommendations regarding application of the results and additional research.

2. LITERATURE REVIEW

Chapter one established first that accident experience is higher on horizontal curves than on tangent sections, demonstrating the need for the current research in horizontal curve design. Second, descriptions of research into surrogate measures for accident experience were provided. The examples established the need for an operating-speed-profile model for estimating speed reduction through tangent-curve sections. Additionally, the introduction identified some of the unvalidated assumptions made during development of the current model. Chapter two focuses on previous research which resulted in operating-speed models to evaluate the design consistency of a roadway alignment. Specifically, the acceleration and deceleration characteristics used in the models are detailed. Finally, since collection of detailed speed and acceleration data was required for this study, the literature review briefly examines study designs of past research that required detailed speed data collection and summarizes findings relevant to acceleration and deceleration characteristics on horizontal curves.

OPERATING-SPEED-BASED DESIGN CONSISTENCY EVALUATION

Leisch and Leisch

One of the earliest design-speed evaluation procedures was developed by Leisch and Leisch.[6] The model produced by Leisch and Leisch considered the effect of both horizontal and vertical alignment features, whereas most procedures focus on horizontal curvature alone. Additionally, the model estimated speeds for both passenger cars and trucks. The model recommended a 10-mph rule to evaluate consistent design as summarized by the following three guidelines:[6]

- Within a given design speed, the potential average automobile speeds should not vary by more than 15 km/h (10 mph).
- When a reduction in design speed is necessary it should normally be no more than 15 km/h (10 mph).
- On common lanes, potential average truck speeds should generally be no more than 15 km/h (10 mph) lower than average automobile speeds.

The Leisch model had provisions for estimating separate deceleration and acceleration distances for vehicles entering and departing a curve. This feature differs from other models which assume equal acceleration and deceleration rates. The procedure estimates deceleration rates dependent on approach tangent speed and required speed reduction. Acceleration rates for departing vehicles are estimated as a function of approach speed reduction, speed on the curve and average grade beyond the curve. Hence, Leisch and Leisch established the possibility that acceleration and deceleration rates may vary from curve to curve and may not be equal. The model developed by Leisch and Leisch was based on values from the 1965 and 1972 AASHO design manuals and, therefore, may not reflect current driver behavior.

Lamm et al.

A more recent study into design-consistency evaluation was performed by Lamm et al.[7] The procedure categorized horizontal curve-tangent sections based on whether the tangent is independent or non-independent. A tangent is independent if its length is sufficient for drivers to reach their desired speed. A model was developed to estimate the change in 85th percentile speed from tangent to curve or between successive horizontal curves. A consistency rating is then assigned based on change in degree of curvature and change in 85th percentile speed between successive horizontal curves. Based on the Lamm model, a roadway alignment can be rated as either good, fair or poor.

The speed-profile model developed by Lamm for purposes of estimating operating speed reduction is partially based on information about where and at what rate acceleration and deceleration occur relative to the horizontal curve. It is assumed that speeds are constant within the limits of the horizontal curve, acceleration and deceleration occur only on tangent sections, and the acceleration and deceleration rates are equal.

Lamm et al. collected detailed speed data in New York State using a "car-following" technique.[8] After fitting second-order polynomial equations to their speed data, they determined that average acceleration and deceleration rates were equal at a rate of 0.85 m/s^2 (2.8 ft/s^2). This value is almost equal to 0.8 m/s^2 (2.6 ft/s^2), which is used in Swiss design procedures.[1]

The model form reported by Lamm et al. was based on data collected on 261 horizontal curves in New York State. The reported acceleration and deceleration characteristics were based on data collected on six horizontal curves in the same state. Due to data limitations, neither the Leisch and Leisch nor the Lamm et al. models has been adopted as part of U.S. design procedure.

Ottesen and Krammes

Based upon a review of U.S. and foreign research and practice, Ottesen and Krammes determined that the Lamm et al. model was an appropriate basis for further development of a procedure for use in U.S. design practice.[4] Three elements of the model needed calibration:

- Estimated speeds on curves,
- Estimated desired speeds on tangents, and
- Acceleration and deceleration characteristics.

Budget limitations permitted calibration of only the first two elements. The third element was adopted from Lamm et al. without validation.

Ottesen and Krammes recommended use of a multiple-linear regression equation to estimate speeds on curves.[4] The multiple-linear equation was presented as follows:

$$V85 = 102.45 - 1.57D + 0.0037L - 0.10I \quad (1)$$

where:

	$V85$	= 85th percentile speed on the curve (km/h) [1 km/h = 0.621 mph]
	D	= degree of curvature (°)
	L	= length of curve (m) [1 m = 3.28 ft]
	I	= deflection angle (°) [=D x L_{ft} ÷ 100]
	L_{ft}	= length of curve (ft)

One problem identified with the equation was that by simply treating a tangent as a zero degree curve, operating speeds on tangents were overestimated. Therefore, for use with the operating-speed-profile model, the desired speed on tangents was taken as the mean observed 85th percentile speed on long tangents, 97.9 km/h (60.8 mph). The desired speed on the curve was defined as the 85th percentile speed on the curve calculated using the multiple-linear equation.

Several assumptions were made toward the development of the model. First, the assumption is made that speed is constant throughout the horizontal curve. In other words, all acceleration or deceleration occurs on the approach or departing tangents. Second, the model assumes that acceleration and deceleration rates are equal and constant at 0.85 m/s^2 (2.8 ft/s^2). The assumptions were based on the Lamm et al. study and are similar to those used in Swiss design guidelines.[1]

The operating-speed-profile model is divided into three cases based on whether the approach tangent length is sufficient for drivers to reach their desired speed. The length required for a driver to depart a given horizontal curve, achieve their desired speed on the tangent, and then decelerate to a safe speed on the following horizontal curve is defined as the critical tangent length. The equation for critical tangent length is given as follows:

$$TL_c = \frac{2V_f^2 - V85_1^2 - V85_2^2}{25.92a} \quad (2)$$

where:

	TL_c	= Critical tangent length (m)
	V_f	= Desired speed on tangent (=97.9 km/h)
	$V85_n$	= 85th percentile speed on curve n (km/h)
	a	= Acceleration/deceleration rate (=0.85 m/s^2)

The remainder of the operating-speed-profile model is given in table 1. Figure 1 depicts the speed profile model plotted against an alignment for each of the three cases. Note that the transition from tangent to curve is defined solely by the assumed acceleration and deceleration behavior.

The equations developed to estimate operating speeds on curves and tangents were calibrated using an extensive database of curve speeds collected in the U. S. However, the

TABLE 1 Equations for Constructing the Estimated Operating-Speed Profile [4]

Case	Condition	Equation
1	TL = X_1	$X_1 = \frac{V85_1^2 - V85_2^2}{25.92a}$
2.1	TL < TL_c	$X_{2d} = \frac{V85_1^2 - V85_2^2}{25.92a}$ $Max(V85)^*_{Tan} = V85_1 + \Delta V85_{Tan}$ $\Delta V85_{Tan} = \frac{2V85_1 + [4V85_1^2 + 44.06(TL - X_{2d})]^{\frac{1}{2}}}{2}$ Note: when calculating $Max(V85)_{Tan}$ lower degree curve must be selected.
2.2	TL = TL_c	$X_{2a} = X_{3a} = \frac{V_f^2 - V85_1^2}{25.92a}$
3	TL > TL_c	$X_{3a} = \frac{V_f^2 - V85_1^2}{25.92a}$ $X_{3d} = \frac{V_f^2 - V85_2^2}{25.92a}$

Where: $X_{n,(a,d)}$ = Distance traveled in meters for Case n during acceleration or deceleration
V85n = 85th percentile speed on curve n (km/h)
ΔV85 = difference between the 85th percentile speeds (km/h)
a = acceleration/deceleration rate (=0.85 m/s^2)
TL = transition length (tangent length) (m)

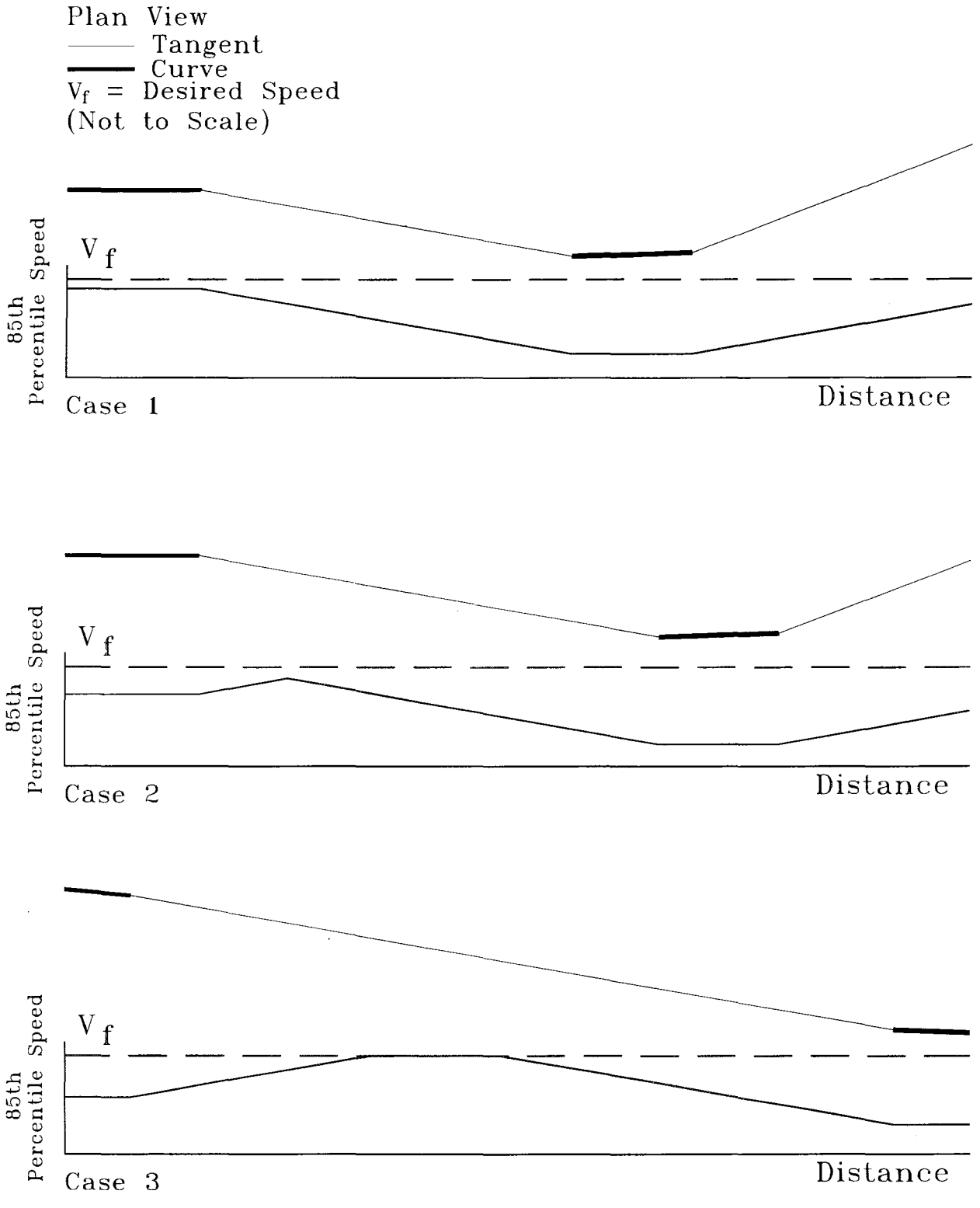

FIGURE 1 Speed Profile Model

assumptions regarding where and at what rate acceleration and deceleration take place have not been validated. It can be seen upon examination of the equations of the speed profile model that these assumptions are critical to the accurate estimation of speeds throughout a section of roadway, and more importantly of speed reductions from tangent to curve. Since the acceleration and deceleration rates are the transition portions of the speed-profile model, adjustment of the rates will change the estimation of speed reduction. Hence, it was recommended that validation of the acceleration and deceleration characteristics should be performed.[1]

DETAILED SPEED DATA COLLECTION AND SPEED TRANSITION

This study required collection of detailed speed data on tangent-curve sections on rural two-lane highways. The following section reviews the data collection methodology of other studies requiring detailed speed data. When available, the method of data collection and speed measurement locations are reported. In addition, findings pertaining to acceleration and deceleration transition points are summarized if available.

Glennon, Neuman and Leisch used radar meters to collect data at four points along an alignment: (1) 700-800 feet upstream of curve on approach tangent, (2) 200 feet prior to point of curvature on approach tangent, (3) at point of curvature, and (4) at midpoint of curve.[9] They report that drivers only begin adjusting speed as a curve becomes "imminent," with about one-half of the total reduction in speed taking place after the point of curvature. This research does not support the current assumption that speeds on curves are constant.

Lee used a video camera and markers placed at 10-meter intervals, starting 30 meters prior to point of curvature, continuing 10 meters beyond midpoint of curve for a total of 10 measurement locations.[10] Lee reports that the zone preceding the curve is the zone of speed reduction, the first 30 meters following the point of curvature is the zone of speed adjustment (to achieve a comfortable speed level) and the following 30 meters as the zone of comfortable driving. Again, this study does not support the assumption that speeds on curves are constant.

Mentsis used manual timing over 20-meter intervals at point of curvature, curve midpoint, and point of tangency and used radar meter to record speeds on approach tangent.[11] Mentsis reports that in all cases, continuous speed adjustment was observed throughout the horizontal curves. Mentsis cites several references which report findings pertaining to speed transition into and out of horizontal curves. The following references were cited. Taragin reports that speeds are essentially constant throughout length of horizontal curves.[12] Holmquist reports observed symmetrical speed behavior for vehicles entering and exiting horizontal curves with constant speed between.[13] Newhardt, Herrin and Rockwell report that vehicles decelerate through the approach half of the curve, reaching a minimum speed near the midpoint of the curve.[14] Thus it appears that the Mentsis study, along with the Taragin, Holmquist, and Newhardt et al. studies offer further evidence against the assumption of constant speeds on curves. However, they do tend to support the idea of symmetrical approach and departure behavior.

Reinfurt, Zegeer, Shelton and Neuman used radar meters to collect data at the midpoint of a curve and 250 feet prior to midpoint of a curve.[15] Segal and Banney used car-following technique to collect detailed speed data at three evenly-spaced intervals along a horizontal curve.[16] Datta et al. examined speeds 250 feet prior to the point of curvature, at the point of curvature and at the curve midpoint.[17] Terhune and Parker used radar meters placed 250 feet prior to point of curvature and at curve midpoint.[18]

These studies, as well as the studies into design consistency evaluation aided in establishing the data collection methodology and the placement of data collection equipment along the alignment. In addition, they provided evidence that some of the assumptions made in the current model are valid, while others warrant evaluation.

LITERATURE REVIEW SUMMARY

The importance of geometric design consistency has long been recognized. The evaluation of design consistency has been a topic of research for nearly two decades. Three of the benchmark studies in design consistency have been outlined in the previous paragraphs. The Leisch and Leisch model was developed in 1977 and was based on values provided in AASHO. The procedure considered both cars and trucks, both horizontal and vertical alignment, and allowed for varying acceleration and deceleration distances. The model concluded by providing evaluation guidelines using the 10 mph rule as a guide. The Leisch and Leisch study was of great importance in concept. However, due to data limitations, it was not adopted for U.S. design practice.

Lamm et al. produced a model to evaluate horizontal alignment alone. The Lamm model was developed using data collected in New York State. The model evaluates tangent-curve sections by grouping them into three categories based on tangent length and whether or not drivers are able to reach their desired speed. Acceleration and deceleration characteristics were established which compared favorably with Swiss guidelines. Again, data limitations discouraged adoption of the Lamm model for U.S. design practice.

The Ottesen and Krammes model was similar to the Lamm et al. model, yet was designed to be adopted as part of U.S. design procedure. First, equations were developed to estimate operating speeds on horizontal curves and their approach tangents. Then, assuming acceleration and deceleration characteristics based on studies by Lamm and the Swiss, a speed-profile model was developed for use in estimating speed reductions from tangent to curve. The speed reduction estimates are then used to evaluate the consistency of an alignment design.

Finally, several studies were reviewed as possible models for detailed speed data collection. Methodology, frequency and location of speed measurement varies widely from study to study. Some results support the assumptions made by the Ottesen and Krammes study, while other results do not.

3. STUDY METHODOLOGY

The need for further research into design consistency evaluation has been established. The following paragraphs detail the work plan followed during the study. Sections included are study design, data collection, and data reduction and analysis.

STUDY DESIGN

The study design for this project can best be described in terms of achieving the stated objectives. The first objective of the study was to validate speed reduction estimates produced by the current speed-profile model. In order to meet this objective, speeds were collected at selected locations on horizontal curves as well as points along their approach tangents. Then, 85th percentile speeds were calculated for all points along each study section where speed measurements were recorded. The 85th percentile speed reduction was then calculated as the maximum 85th percentile speed on the tangent minus the minimum 85th percentile speed on the curve. The model was then validated by comparing observed 85th percentile speed reductions to 85th percentile speed reductions predicted by the operating-speed-profile model.

The second objective of the research was to calibrate assumptions in the current model pertaining to acceleration and deceleration behavior. The first assumption made is that acceleration and deceleration rates are equal, and that the rate is 0.85 m/s^2 (2.8 ft/s^2). In order to test this assumption, it was necessary to collect detailed speed data on selected horizontal curves and both the approach and departure tangents. Directional data were collected on a tangent and one-half of a curve such that each lane would comprise a curve-tangent section: one being an approach tangent and entry half of the curve, and the other being the exit half of the curve and departure tangent. Detailed speed data were collected by using a total of seven speed measurement locations for each tangent-curve section. After determining 85th percentile speeds for each data measurement location, and determining reasonable intervals over which rates could be calculated, observed implied acceleration and deceleration rates for each tangent-curve section were calculated. The assumptions were then tested by comparing the observed implied acceleration and deceleration rates to each other and to the assumed rate for each section.

The second assumption made when developing the existing operating-speed-profile model is that acceleration and deceleration behavior is constant along a single tangent-curve section. To test this assumption, observed 85th percentile speed profiles were constructed for each of the study sites. These speed profiles were superimposed upon operating-speed profiles calculated using the current speed-profile model. The profiles were then compared to examine the assumption of constant acceleration and deceleration rate within a single tangent-curve section.

The final assumption states that the acceleration and deceleration behavior does not change with varying curve geometry. To test this assumption, a range of curves with different geometry were selected based on established criteria. First, the curves used for validation should have the same general characteristics as those used to calibrate the current model. Site selection controls and criteria were used to establish a database of roadways from which study sites could

be selected. These controls and criteria are presented in table 2 below. The controls listed are the same site selection controls used by Ottesen and Krammes.[4]

Two variables were identified as the primary independent variables to test for change in acceleration and deceleration behavior. The two variables, degree of curvature and length of curve, were selected based on the fact that variability in speed reduction across curve geometry may be partially explained by variability in acceleration and deceleration rates. It follows that if variability in speeds on tangents and curves, which define speed reduction, can be modeled by length of curvature and degree of curve, then acceleration and deceleration rates may vary with these two variables as well. To test across a range of length of curve and degree of curvature, additional site selection criteria were established. Directional speed data were collected at sites for each cell of the matrix as indicated in table 3 below. The original intent was to collect data at one site for each cell, however limited availability of sharp curves necessitated collection at two short, sharp curves. In addition, the curve selected for the high degree of curvature, high length of curve case had sufficiently long approach and departure tangents that data were collected on both ends of the curve. Visual inspection of the speed profiles was performed in an effort to establish trends across the two primary independent variables.

TABLE 2 Site Selection Controls and Criteria

Control	Criteria
Area Type	Rural
Administrative Classification	State
Functional Classification	Collector or Arterial
Design Classification	Two-Lane
Posted Speed Limit	≤88.6 km/h
Terrain	Level to Rolling
Maximum Grade	5 percent
Pavement	High Type
Traffic Volumes	400-3500 vpd
Lane Widths	3.1-3.7 m
Shoulder Widths	0-2.5 m
Plan-Profile Sheets	Available
Length of Route	≥ 4.0 km
Distance from a Town	≥ 0.8 km
Distance from End of Roadway	≥ 0.8 km

TABLE 3 Controls on Degree of Curvature and Length of Curve

Degree of Curvature Category	Length of Curvature Category (m)		
	91-152	152-213	213-274
4°-5°	1	1	1
7°-8°	1	1	1
10°-11°	2	0	2

DATA COLLECTION

Curve Geometry

Curve geometry data were extracted from plan and profile sheets and used to compile a geometry database. This database was used in the statistical analysis to provide data on the independent variables. Included in the database were data for the following variables: degree of curvature, length of curve, approach tangent length, departure tangent length, superelevation, and degree of curvature of preceding and following curves. In addition, roadway volume data were included in the database. Variables such as level of background delineation (trees, fences, heavy brush, etc.), approach lane (inside lane or outside lane), implied design speed and sight distance were examined as possible explanations for variability and are included in the database. Sites were selected from an existing collection of plan and profile sheets for Texas Farm-to-Market Highways. Table 4 provides a listing of curve geometry for each of the ten sites selected.

Speed Data

The layout of speed sensors was similar for each curve. Speeds were recorded at the point of curvature, quarter point, and midpoint of each curve. Additionally, sensors were placed on the tangent at 60 meter spacings, beginning at the point of tangency/curvature, and ending 240 meters upstream/downstream of the curve. The spacing was selected to ensure that vehicle desired speeds were recorded yet spaced closely enough to determine acceleration and deceleration rates and establish where acceleration begins, ends and changes as accurately as possible.

Directional data were collected since driver behavior entering and exiting a curve may be different. Due to the fact that directional data were collected, each curve could be evaluated as two separate sites; one comprised of an approach tangent and the first half of the curve, and the

TABLE 4 Curve Geometry

Site	Texas FM-Highway No.	Degree of Curvature	Curve Length (ft)	Curve Length (m)	Deflection Angle	Approach Tangent Length (m)	Departure Tangent Length (m)	Superelevation (m/m)
1	980	4.0	466	142	18.6	1393	1935	0.038
2	1179	4.0	543	166	21.7	365	189	0.026
3	3058	5.0	766	234	38.3	481	255	0.091
4	149	8.0	428	130	34.2	260	41	0.047
5	1818	8.0	501	153	40.1	770	202	0.068
6	969	7.0	792	241	55.4	483	116	0.103
7	1818	10.0	310	94	30.9	370	288	0.049
8	980	10.0	344	105	34.4	577	142	0.090
9	969	10.0	804	245	80.4	464	485	0.129
10	969	10.0	804	245	80.4	485	464	0.129

Site	Preceding Degree of Curvature	AADT vpd	Background Level	Approach Lane	Design Speed (kph)	Sample Sizes (Before/After Reduction)		Preceding Sight Distance (m)
						Approach	Departure	
1	2.0	1890	High	Inside	89	126/62	180/76	153
2	1.0	1310	Medium	Inside	89	125/88	97/35	503
3	6.0	930	Low	Inside	113	84/36	100/53	336
4	2.5	1170	High	Outside	73	122/35	174/45	336
5	6.0	1860	High	Outside	73	191/85	144/54	564
6	7.0	2370	Medium	Outside	81	108/33	174/45	549
7	7.0	900	High	Outside	64	96/59	127/77	336
8	1.0	4690	Medium	Outside	64	212/103	212/58	1525
9	1.7	1930	High	Inside	73	139/74	109/46	412
10	7.0	1930	High	Outside	73	94/57	131/26	580

other site being comprised of the second half of the curve and the departure tangent. Figure 2 is a simple schematic indicating the placement of speed recorders on each curve.

Several factors are present during collection of directional speed data which may render the data not usable. These factors include non-free-flow conditions (platooning), vehicle speeds influenced by some feature inside or outside of the study section such as a driveway or minor intersection, and vehicles passing in opposite directions at speed recorder locations. Additionally, since the same sample of vehicles is desired for all speed measurement locations, only vehicles that can be tracked through all speed measurement locations can be used. In an effort to collect sufficient data to account for these factors, it was determined that 125 vehicle speeds should be recorded in each direction.

Data Collection Equipment

The speed data collection for this research was performed using infrared photoelectric sensors. The theory is similar to other means of speed data collection such as pneumatic tubes or piezoelectric strips. Two individual sensors were spaced one meter apart at each speed measurement location. When a vehicle passed though the infrared beams, actuations were recorded. Knowing the spacing of the sensor heads (1 meter), and the time difference between actuations, the speed is calculated. Through the use of a microprocessor connected to the sensors, the direction of travel, length of vehicle, and speed were recorded. In addition, a time stamp was recorded for each vehicle which was used for vehicle tracking purposes. The data were stored in the microprocessor and downloaded to a laptop personal computer. ASCII text format is used for the data file.

VARIABLE ESTIMATION

Speed Reduction

The first objective of this study was to validate the speed reduction estimation ability of the current operating-speed-profile model. In order to perform this task, both estimated and observed operating-speed reductions were calculated. The estimated operating-speed reduction was calculated using the Ottesen and Krammes speed profile model.[4] Since all of the sites used for this study could be described as having independent tangents, the speed reduction calculation was reduced to the operating speed on the curve estimated by the multiple-linear regression equation subtracted from the desired speed on the tangent, 97.9 km/h (60.8 mph).

Calculation of the observed operating-speed reduction could have been performed in one of two ways. The first method would be to calculate observed speed reductions for each vehicle traversing the study section and then find the 85th percentile speed reduction from those values. The second option was to find the 85th percentile speed of all vehicles at each speed measurement location and then subtract the minimum 85th percentile speed on the curve from the maximum 85th percentile speed on the tangent.

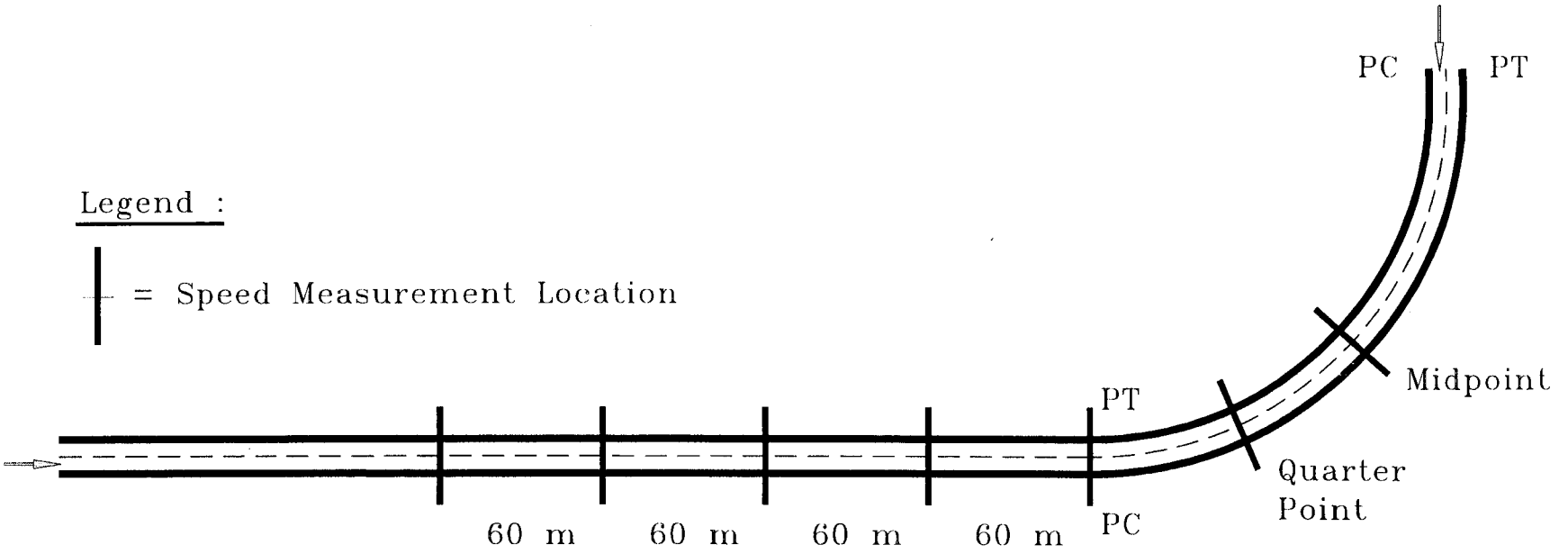

FIGURE 2 Simple Site Layout Schematic

The objective in calculating operating-speed reduction is to find the difference between the operating speed on the tangent and the operating speed on the curve. With this in mind, and given that operating speed is defined as the 85th percentile speed, the second option was selected. Further, had the first method been chosen, the operating-speed reduction, may not have corresponded to the 85th percentile vehicle since speed reduction for a single vehicle is dependent primarily on the change in speed, not on the magnitude of the speed. Thus, the 85th percentile speed reduction calculated may have actually been associated with a driver whose speed ranks somewhere other than the 85th percentile.

Acceleration and Deceleration Characteristics

As with the dependent variable operating-speed reduction, acceleration and deceleration could have been examined in one of two ways. The first method would be to determine the average acceleration and deceleration rate for each vehicle over each of the six speed measurement intervals. It follows that the 85th percentile acceleration and deceleration rates would be determined for each interval and used for analysis. This method would help in understanding acceleration and deceleration behavior along an alignment, but would not give values that correspond to the operating speed at points along the alignment.

The second option was to calculate the implied acceleration and deceleration rates based on the 85th percentile speed at each sensor location. Thus, the calculated acceleration and deceleration rates would correspond to the 85th percentile, or operating, speed profile.

While both methods of examining acceleration and deceleration were explored, the second option was selected for validating the assumptions regarding acceleration and deceleration behavior. Again, this is due to the fact that the model estimates operating speed. Therefore, the acceleration and deceleration characteristics, which serve as transitions in the profile model, should be calculated as transitions between the observed operating (85th percentile) speeds.

One final problem when dealing with transitions between operating speeds along an alignment is the determination of a single average acceleration or deceleration rate. Since rates vary between any given pair of speed measurement locations, a method of determining average rates over some interval was selected. First, appropriate intervals for both acceleration and deceleration were selected through inspection of the observed operating speed profiles. Then, implied rates were calculated using the 85th percentile speeds at the endpoints of the intervals and the length of the intervals. In order to compare the calculated average rates to each other and to the assumed rate, hypothesis testing was performed at a 0.05 significance level.

It should be noted that the first method of determining acceleration and deceleration characteristics was utilized to produce plots of 85th percentile acceleration and deceleration rates between each sensor interval for each site. These plots were helpful in gaining understanding of driver behavior approaching or departing a horizontal curve.

DATA REDUCTION AND ANALYSIS

In an effort to have a single sample of free-flow vehicle speeds at each site, extensive data reduction was performed prior to analysis efforts. The desired sample of vehicles for analysis purposes was a single sample of free-flowing passenger vehicles, recorded at each of seven measurement locations, whose paths did not cross within the study section. In order to establish a single sample of vehicles for which speeds were measured at each location, vehicles were tracked through the study section using the time of actuation and direction of travel as the primary tracking variables. Inspection of vehicle lengths and speeds was performed when necessary to track a vehicle from one sensor to the next. Non-free-flow vehicles were eliminated from the database according to a five-second headway criteria. Finally, any two vehicles passing in opposite direction within the study section were eliminated from the database. This screening process reduced sample sizes significantly. Larger raw data sample sizes should have been used to maintain the desired sample size of 125 vehicles.

Statistical analysis was performed using the speed and geometry data to test the validity of the current operating-speed-profile model. Specifically, hypothesis testing was utilized to validate the speed reduction estimation ability of the speed-profile model. The accuracy of the current assumptions regarding where and at what rate acceleration and deceleration occur relative to a horizontal curve were validated through single- and two-sample hypothesis testing. The assumption regarding equal acceleration and deceleration behavior across varying curve geometry was studied as well. Both SAS statistical analysis software and Microsoft Excel were used to perform the analysis. Through reduction and inspection of the data, simple calculations and hypothesis testing the current speed-profile model was validated to the extent possible for this research.

4. RESULTS

Efforts were made to validate the speed-reduction estimation ability of the current speed-profile model. The mean difference in observed speed reductions and speed reduction estimated by the model were found to be not statistically different across data for sites where no downstream intersections exist and thus the model is considered validated for continued use. Efforts to validate the assumptions concerning acceleration and deceleration characteristics were somewhat inconclusive. The results of this research indicate that use of the model should be continued, until further research proves more conclusively otherwise.

This chapter is divided into three main sections. First, speed data sample sizes before and after screening are reported. Second, the analysis of speed data to test the speed-reduction predicting ability of the current speed-profile model is presented. Finally, the analysis of the speed data to examine the acceleration and deceleration characteristics of drivers on horizontal curves on rural two-lane highways is reported.

SAMPLE SIZES

This first section provides a brief description of vehicle speed sample sizes used in the analysis. Due to extensive data screening, vehicle speed sample sizes for analysis purposes were reduced considerably. The sample sizes before and after screening are reported in table 5.

TABLE 5 Sample Sizes Before and After Screening

Site	Sample Size Before Screening (veh)		Sample Size After Screening (veh)	
	Approach	Departure	Approach	Departure
1	126	180	62	76
2	125	97	88	35
3	84	100	36	53
4	122	174	35	45
5	191	144	85	54
6	108	174	33	45
7	96	127	59	77
8	212	212	103	58
9	139	109	74	46
10	94	131	57	26

VALIDATION OF SPEED REDUCTION ESTIMATION PROCEDURE

Current Speed Reduction Estimation Procedure

In order to understand the analysis performed in an effort to validate the speed-reduction estimation ability of the current speed-profile model, it is necessary to briefly restate the current procedure. First, the speed-profile model developed by Ottesen and Krammes and described in Chapter 2 is used to estimate operating speeds along a curve-tangent-curve section. Second, the operating speed on the horizontal curve of interest is subtracted from the estimated maximum speed on its approach tangent. This estimated speed reduction is the focus of this validation effort.

Further discussion of exactly what the current model estimates is warranted here. The current model estimates the mean 85th percentile speed for a sample of curves with given geometry characteristics. It follows that the speed reduction estimated for a curve of given geometry is actually the expected (mean) speed reduction for a sample of curves of the same geometry. Hence, the procedure used to validate such a model should focus not on speed reduction of an individual curve, but on the mean speed reduction for a sample of curves. The following paragraphs present the methodology and results of this analysis.

Comparison of Observed and Estimated Speed Reduction

The procedure used to calculate the observed operating speed reduction from tangent to curve can be summarized by the following steps:

- For a given site, the 85th percentile speed of the sample of vehicles at each of the seven locations was calculated.
- The maximum 85th percentile speed of the four sensors positioned on the tangent was determined.
- The minimum 85th percentile speed of the three sensors positioned on the curve was determined.
- The minimum 85th percentile speed on the curve was subtracted from the maximum 85th percentile speed on the tangent to calculate the observed operating speed reduction for the site.

This procedure was repeated for each of the ten sites studied. Also, the operating speed-profile model was utilized to determine the mean operating speed reduction for each of the sites. These estimated values along with the observed values were used in the analysis. Table 6 is a listing of the observed operating-speed reduction, estimated mean reduction in operating speed and the difference between observed and estimated values for each of the ten sites. Figure 3 is an illustration of the observed and estimated values for each of the sites. Since the analysis entails splitting the sites into categories based on degree of curvature, table 5 and figure 3 are split into these categories as well.

TABLE 6 Observed and Calculated Reduction in 85th Percentile Speeds

Site	Degree of Curvature Category	Reduction in 85th Percentile Speed (km/h)		Difference (Observed-Calculated) (km/h)
		Observed	Calculated	
1	Low	13	3.1	9.9
2	Low	4	3.3	0.7
3	Low	4	6.3	-2.3
4	Middle	20	11.0	9.0
5	Middle	19	11.5	7.5
6	Middle	14	11.1	2.9
7	High	15	13.9	1.1
8	High	16	14.2	1.8
9	High	18	18.3	-0.3
10	High	23	18.3	4.7

Initial inspection of figure 3 illustrates the generally good estimation of the model as compared to the observed values for seven of the ten sites. Differences in observed and estimated values for sites two, three, and six through ten are small, ranging from 0 to 4.7 km/h (2.9 mph). Further, eliminating sites one, four and five, it appears that the model estimates speed reduction equally well across all degree of curvature categories.

Final analysis of figure 3, however, should address sites one, four and five. Upon examination of the observed and estimated speed reductions for these sites one notices significant disparities. Closer evaluation of these sites identified a common characteristic which accounts for the speed-profile model's underestimation of speed reductions. Each of these sites has an intersection a short distance from the point of tangency (downstream of the curve). In the case of site one, which exhibits the greatest disparity, this intersection was quite significant as it was the entrance to one unit of the Texas State Penitentiary. The intersections located on the other two sites were minor intersections, but nevertheless had a noticeable effect on the observed speeds on the curves. Though difficult to quantify in a model, these results may indicate the need for a provision within the speed profile model to account for downstream intersections.

While the plots contained in figure 3 are useful for understanding speed reduction behavior, examined alone they are not sufficient to validate the estimation capabilities of the current model. In an effort to quantify the comparison of the observed operating-speed reduction to the estimated operating-speed reduction, statistical hypothesis testing was performed. First,

the difference between the observed and estimated speed reduction for each of the ten sites was calculated. Then the mean of the sample of ten differences was compared to zero using a single-sample, two-tailed t-test. The null hypothesis for the test was that the mean difference between the observed and estimated speed reduction for the sample is equal to zero. The alternative hypothesis is that the difference is not equal to zero. The same procedure was performed for the sample of differences with sites one, four and five eliminated. Finally, the same procedure was followed to compare the mean difference for each degree of curvature category to zero. The results of these tests are reported in table 7.

It is first significant to note that the null hypothesis that the mean difference between the observed and estimated reduction in 85th percentile speed for the sample of ten sites was equal to zero was rejected. The conclusion in this case is that the mean difference is significantly different from zero at a 0.05 significance level. As discussed above, an explanation for the failure of the mean of the sample of ten curves is that there were intersections downstream of three of the curves which significantly influenced the minimum speed on the curve, and therefore the speed reduction. It should be noted that the p-value for this test was 0.03 so that the null hypothesis would not have been rejected at a 0.01 significance level despite the intersection influences.

TABLE 7 Test of Means for Samples: Reduction in 85th Percentile Speed

Sample	Mean (km/h)	S (km/h)	n	$t_{.025,n-1}$	t_{calc}	p-value	Reject H_o?
Entire	3.52	4.14	10	2.262	2.551	0.0312	Yes
Dclow	2.79	6.36	3	4.303	0.620	0.5985	No
DCmid	6.50	3.20	3	4.303	2.877	0.1026	No
DChigh	1.84	2.11	4	3.182	1.835	0.2286	No
No intersections	1.24	2.24	7	2.447	1.356	0.2238	No

H_o: Mean Difference in Observed and Predicted Reduction in 85th %ile Speed = 0
H_a: Mean Difference in Observed and Predicted Reduction in 85th %ile Speed $\neq$ 0

It is interesting to examine the results of the test of means for the three degree of curvature categories. In all cases, the null hypothesis that the mean difference in observed and estimated reduction in 85th percentile speed is equal to zero was not rejected. Hence, the

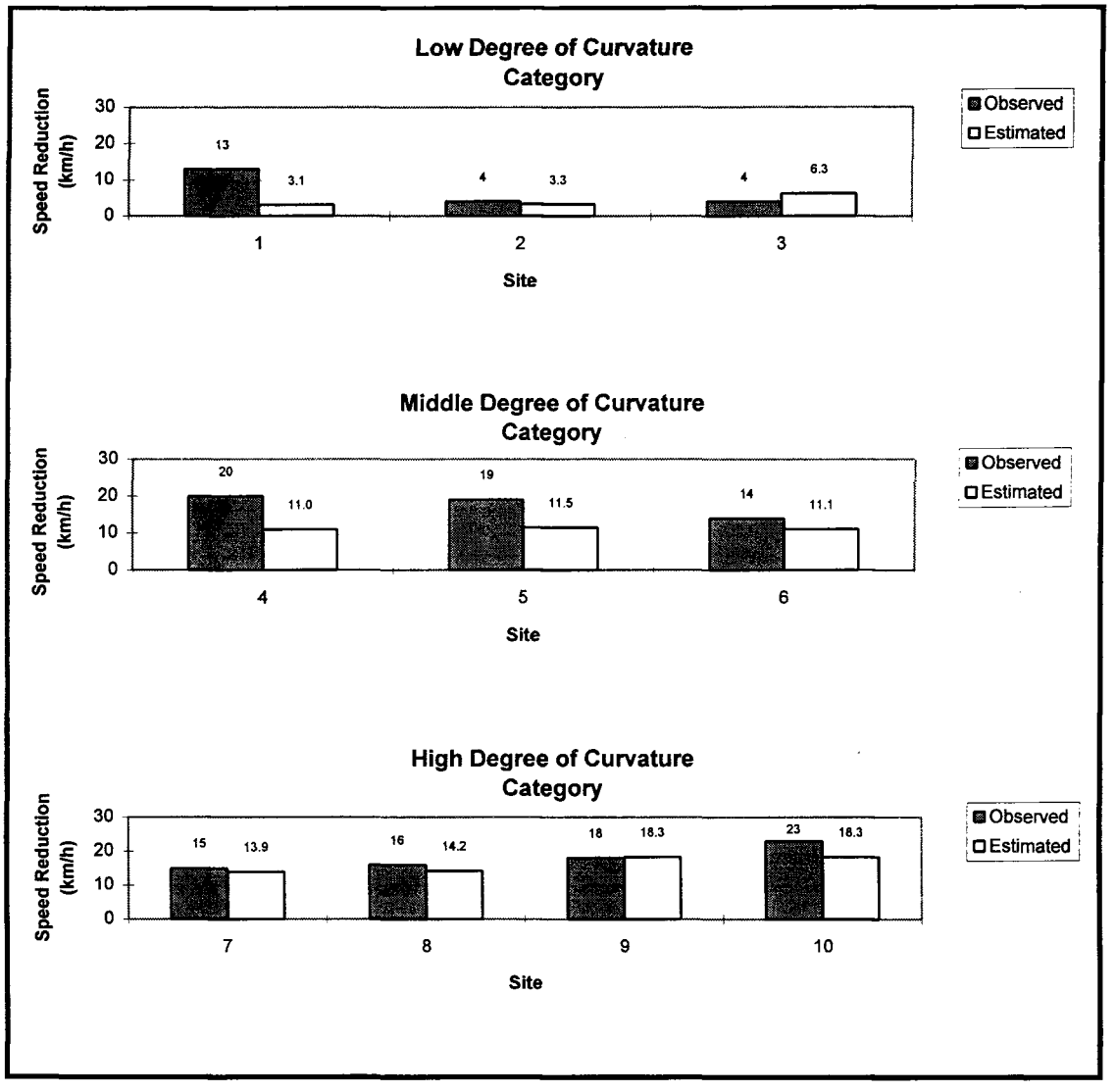

FIGURE 3 Observed and Estimated Speed Reduction by Degree of Curvature Categor

Perhaps the most significant test was a test of means for the difference between the observed and estimated reduction in 85th percentile speeds performed for the entire sample of curves without intersections downstream. Again, the null hypothesis that the differences are equal to zero was not rejected. Hence, for the sites without any downstream intersection influences, the mean difference between observed and estimated reduction in operating speed is not significantly different from zero at a 0.05 significance level.

Summary

The results of the analysis described above support the adequacy of the operating-speed-profile model to estimate reduction in 85th percentile speeds on tangent-curve sections on rural two-lane highways. The analysis indicates that in cases where nearby downstream influences such as intersections are present, the model should be used with caution. Tests of means with the null hypothesis that the mean difference in observed and estimated reduction in 85th percentile speeds is equal to zero was performed for the following five samples:

- Entire sample of curves for which data was collected (10).
- Sample of low degree of curvature curves (3).
- Sample of middle degree of curvature curves (3).
- Sample of high degree of curvature curves (4).
- Sample of curves with no downstream intersection (7).

The null hypothesis was not rejected in all but the first sample, which may be explained by the presence of downstream intersections in three of the curves. Perhaps most significant in terms of validating the model was the test for the sample of curves with no downstream intersections. The result of this test indicates that for curves with no downstream intersections, the mean difference between observed and estimated reduction in 85th percentile speeds is not significantly different from zero at a 0.05 significance level.

VALIDATION OF ACCELERATION AND DECELERATION RATES

The current assumptions regarding acceleration and deceleration characteristics can be summarized as follows:

- Acceleration and deceleration take place only on the tangent.
- Acceleration and deceleration rates are equal at 0.85 m/s^2 (2.8 fpss).
- The point along the alignment where deceleration or acceleration begin or end respectively is a function of the operating speeds on the tangent and curve and the assumed acceleration and deceleration rate.

The objective of this portion of the study was to test the validity of these assumptions using the detailed speed data.

- The point along the alignment where deceleration or acceleration begin or end respectively is a function of the operating speeds on the tangent and curve and the assumed acceleration and deceleration rate.

The objective of this portion of the study was to test the validity of these assumptions using the detailed speed data.

Operating-Speed Profiles

In an effort to understand driver behavior on the sites studied, observed 85th percentile speed profiles were plotted for each site. Included on each graph are 85th percentile values for vehicles approaching the curve and departing the curve. Superimposed on each graph is a profile of 85th percentile speeds estimated using the operating-speed-profile model. The vertical axis represents the 85th percentile speed of drivers, and the horizontal axis represents distance from the point of curvature. Positive values on the horizontal axis represent speed measurement locations on the tangent, and the negative values represent measurements made on the curve. The operating-speed profiles for the low, middle, and high degree of curvature categories are presented in figures 4-6.

One important observation can be made by initial observation of figures 4-6. In general, the operating-speed model estimates the actual 85th percentile speed profile reasonably well. This begins to confirm the reasonableness of the operating-speed-profile.model. However, it appears that some speed correction is taking place continuously along most of the alignments. These and other observations are discussed further in the following paragraphs.

Inspection of figure 4, which includes the low degree of curvature sites, must begin with the observation that the observed profiles very nearly follow the estimated profile. It is significant to note that the profiles for these sites are relatively flat, indicating little or no speed adjustment for these sites. This supports the current model which suggests that for flat curves drivers are able to drive very near their desired speed. Further inspection of figure 4 indicates a near mirror image for the approaching and departing vehicles.

An observation of the site one plot in figure 4 is that for approach vehicles, speeds tend to decrease significantly at the midpoint of the curve. This can be explained by the presence of an intersection downstream of the curve which may have influenced speeds on the back side of the curve.

One final observation of the curves in this category can be made of the site three plot in figure 4. It is apparent that while the shape of the observed profile fits the estimated profile, the model underestimated speeds at all points along the alignment. This underestimation may be explained by the fact that site three is on a high-type roadway, with four-foot paved shoulders, and the curve has an implied design speed of about 70 miles per hour. Thus, the safe design speed for this curve is higher than for the other sites; therefore, the speeds at which drivers operate are higher. The relationship may further indicate that the estimated desired speed on

tangents is a good estimate for roadways with a design of 60 mph or below, but may underestimate speeds for curves with higher design speeds.

Figure 5 illustrates 85th percentile speed profiles for the curves in the middle degree of curvature category. Inspection of this figure yields observations similar to those made of figure 4. First, although some variation exists, the operating-speed-profile model appears to estimate 85th percentile speeds on the curve reasonably well. Next, the magnitude of the speeds predicted match the observed operating speeds relatively well. This not only tends to validate the predicting ability of the speed profile model for curve speeds, but also supports the use of the current estimated desired speed on tangents. It is apparent in figure 5 that a breakpoint for approach speeds on curves is at the quarter point of the curve. It also appears that a breakpoint for approach speeds on tangents may fall between the point of curvature and the first sensor on the tangent. Similar breakpoints for departing vehicles appear to fall at the point of curvature and a point on the tangent approximately 120 meters from the point of tangency. These break points are not apparent in the first three sites because of the lack of speed change on flat curves. Perhaps the most significant feature of the three plots as a group is that the speed profile model does not accurately model driver speed behavior on curves. Although the average speed on the curve may be relatively close to the estimated speed on the curve, the model assumes that speeds on curves are constant. The observed speed profiles indicate that drivers adjust their speed throughout the length of the curve. It is again interesting to note the effect of the downstream intersection on approach speeds at the midpoint. This influence can be observed in the plots for both sites four and five, as speeds tend to drop throughout the curve.

Many of the observations made of the plots in figures 4 and 5 can be applied to the profiles in figure 6. This figure represent plots for observed 85th percentile speeds for the curves in the high degree of curvature category. Again, it is apparent that the estimated speed profile models the observed speeds relatively well. However, as was the case for the middle degree of curvature category, speeds on the curve are not modeled accurately. It appears that, although the relationship varies from curve to curve, some driver correction is taking place on the curve as opposed to the constant speed assumed by the model.

Close inspection of the curves in this category confirms the estimation of the approach breakpoint for speeds on the tangent at the first sensor on the tangent. This estimation, confirmed by the plots for the middle degree of curvature category, provided the interval over which deceleration rates were calculated for validation purposes. The breakpoints for acceleration again appear to be at the point of curvature and 120 meters out on the tangent.

One final observation which applies to all of the speed profile plots pertains to speeds on the tangents. It appears that drivers on tangents may not operate at a constant desired speed. The significance of this observation is tempered by the relatively minor adjustments which take place on the tangent. Explanations for these adjustments in speed may range from length of the tangent, sharpness of the preceding and approaching curves, or level of background delineation provided by brush, trees, etc. As stated earlier, the magnitude of the speeds on the tangent generally differ very little from the calibrated desired speed on the tangent. It should also be noted that speeds on tangents are difficult to model, and that the calibrated value is the product of

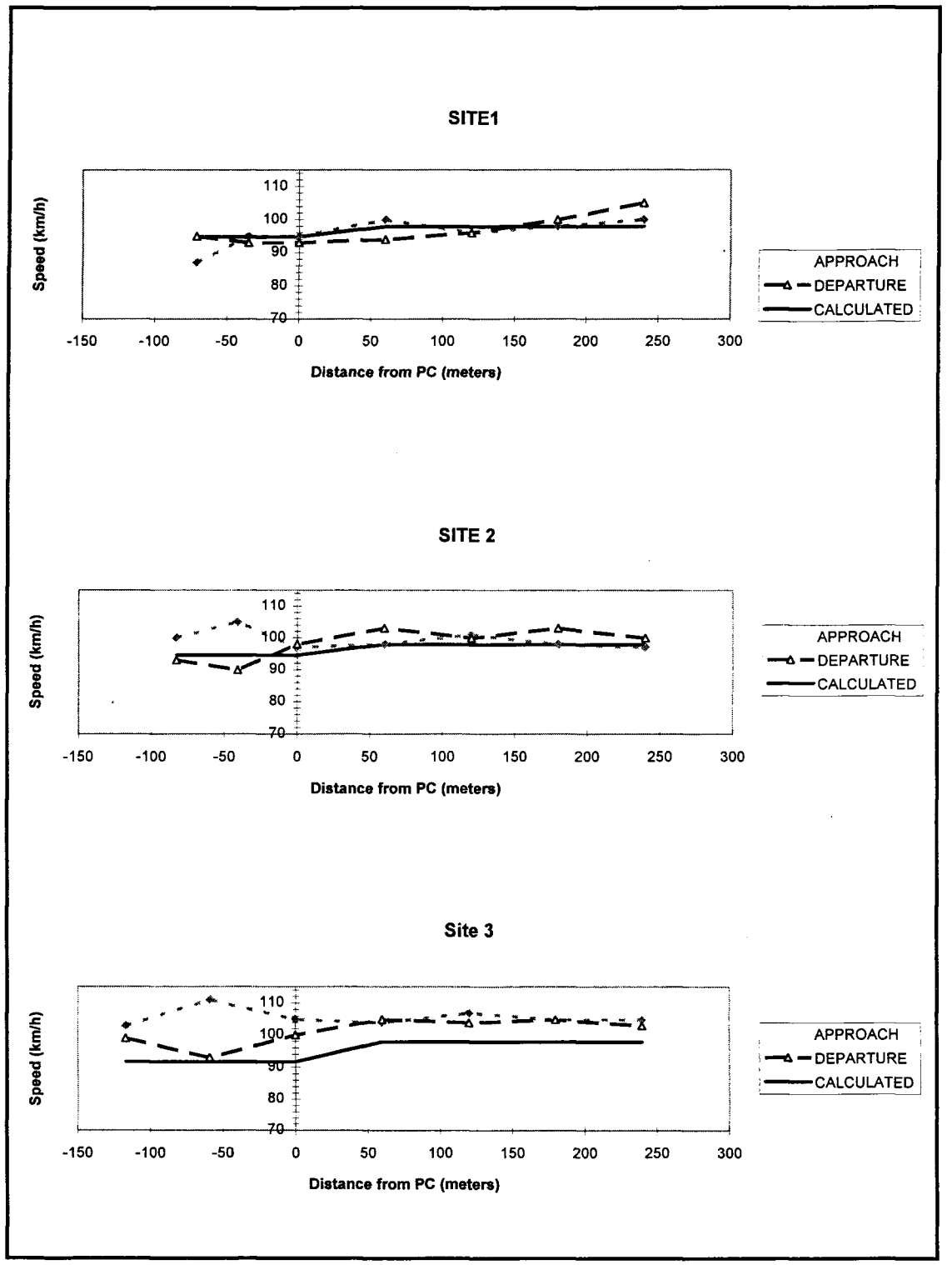

FIGURE 4 Speed Profiles for Low Degree of Curvature Category

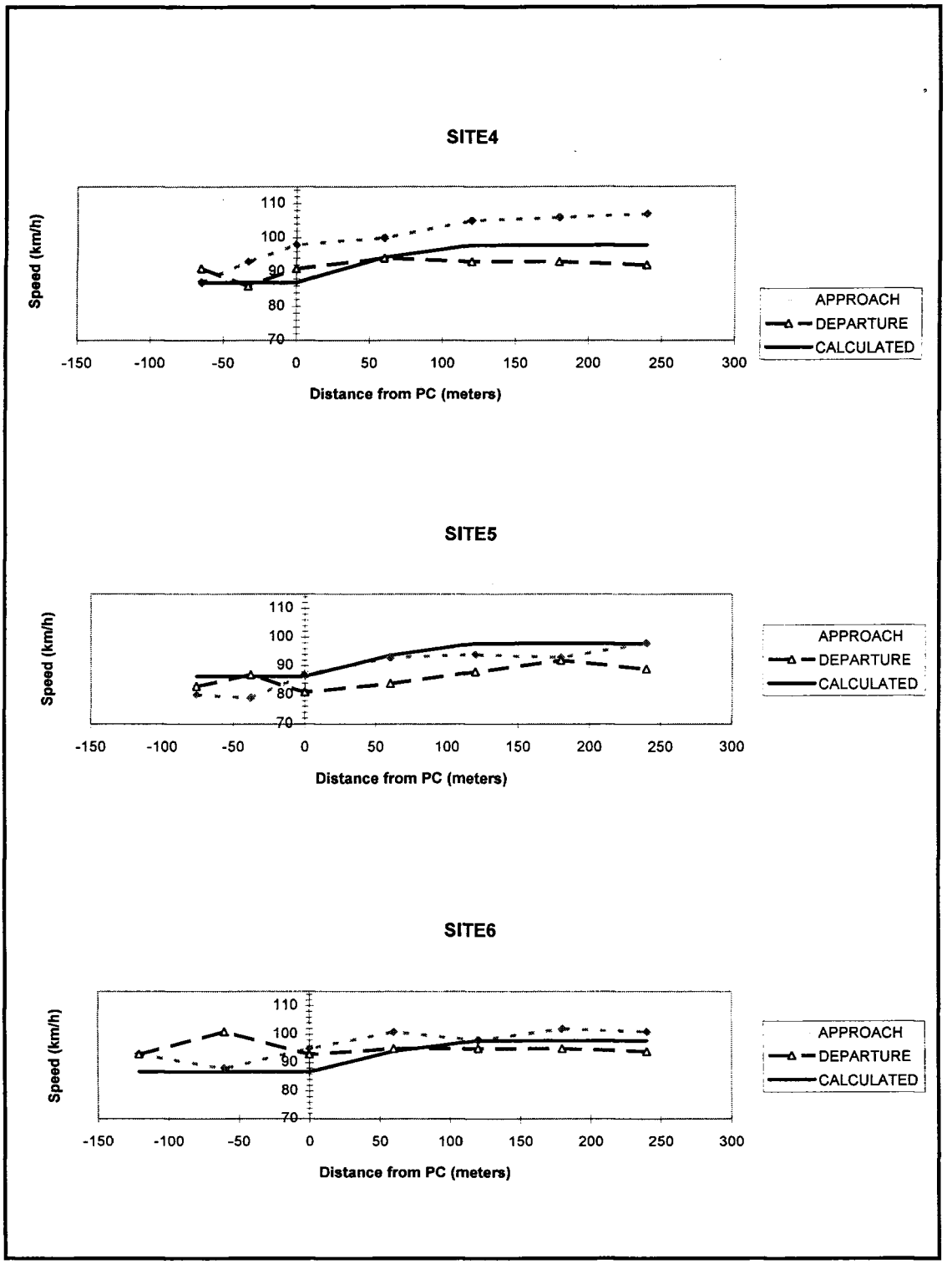

FIGURE 5 Speed Profiles for Middle Degree of Curvature Category

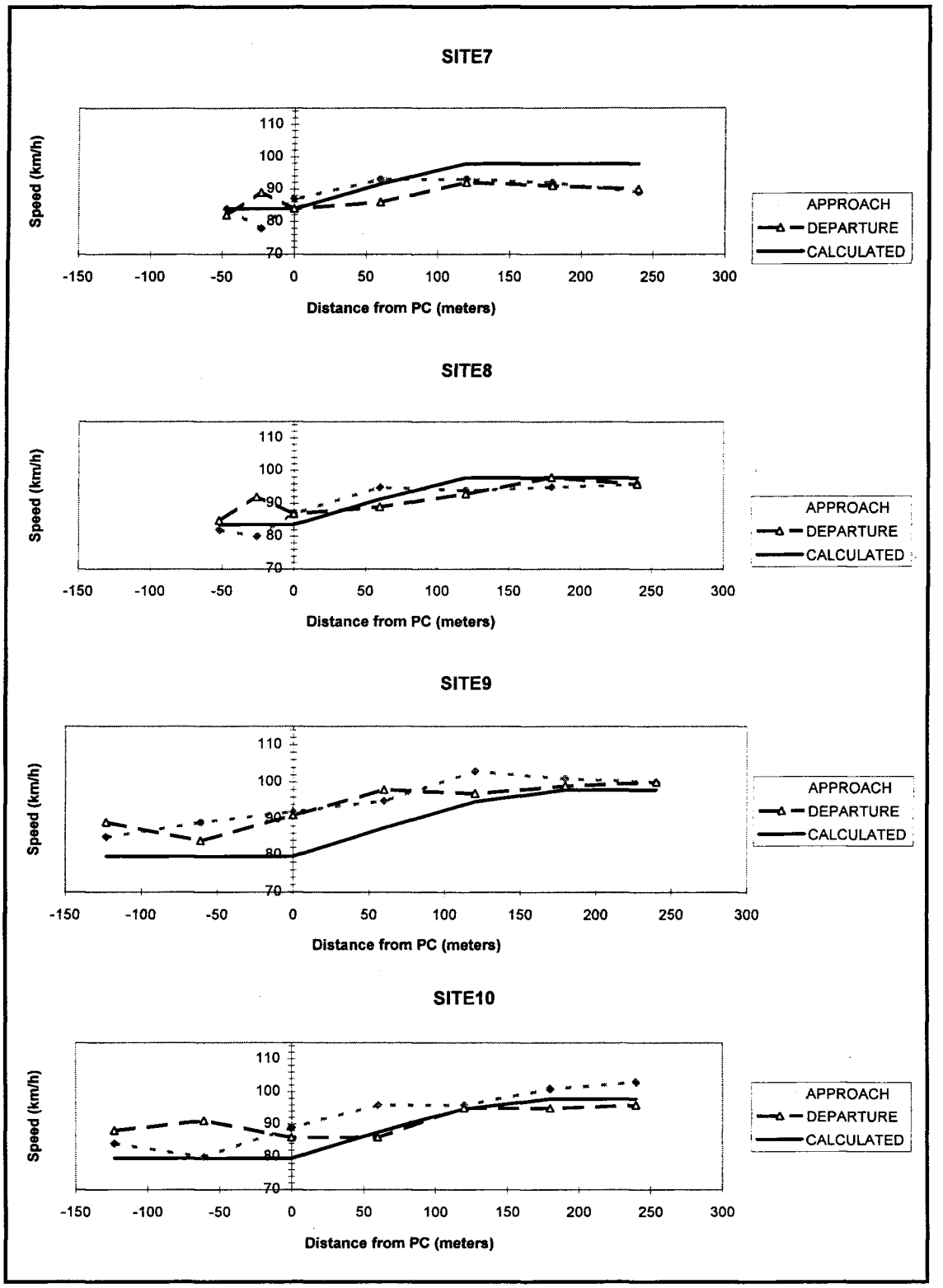

FIGURE 6 Speed Profiles for High Degree of Curvature Category

data collection on 78 tangents and should therefore represent a reasonable estimate of the 85th percentile speed on tangents. The observed speeds on tangents support this statement.

Given that there appears to be a desired speed that drivers attempt to reach and maintain on tangents, a test was performed to compare the current estimate of desired speed (97.9 km/h) to the observed speeds on tangents.
Since the current estimate was established as the mean 85th percentile of speeds measured on long tangents from the Ottesen and Krammes study, the tests performed compared 97.9 km/h to mean observed 85th percentile speeds on tangents. The sample used for the test was the sample of ten (one for each site) 85th percentile speeds collected 240 meters from the point of curvature on the tangent.

The test performed was a single-sample t-test with the null hypothesis that the mean 85th percentile speed on tangents is equal to 97.9 km/h. The test was performed by direction of travel at a 0.05 significance level. The results of the tests are summarized in table 8.

TABLE 8 Test of Mean 85th Percentile Speeds on Tangents

Direction of Travel	Mean 85th Percentile Speed (km/h)	n	Standard deviation (km/h)	t_{calc}	p-value
Approach	99.6	10	5.082	1.06	0.318
Departure	96.5	10	5.421	-0.82	0.435

The observations thus far have simply indicated that there is some speed on tangents at which drivers desire to drive. The results of this test support the current estimate that the desired speed is equal to 97.9 km/h.

Calculated 85th Percentile Rates

Initial attempts at quantifying acceleration and deceleration rates entailed calculation of average rates for each vehicle over the intervals between speed measurement locations. It was then deemed appropriate to find the 85th percentile rate for each interval. Plots of the observed 85th percentile rates are presented in figures 7-9. It should be noted prior to discussion of these plots that caution was taken when analyzing these profiles. Although calculated rates are sensitive to the magnitude of vehicle speed, an 85th percentile rate may not be associated with the 85th percentile driver in terms of operating speed. Thus these plots were used only to aid in understanding driver behavior, not in validating the assumed rate.

The current speed profile model assumes that the acceleration and deceleration rates are equal and constant. However, inspection of figures 7-9 indicates that these assumptions may not hold true. For instance, on all sites studied, calculated rates vary both on the curve and on the tangent. The assumption that acceleration and deceleration are mirror images appears to be

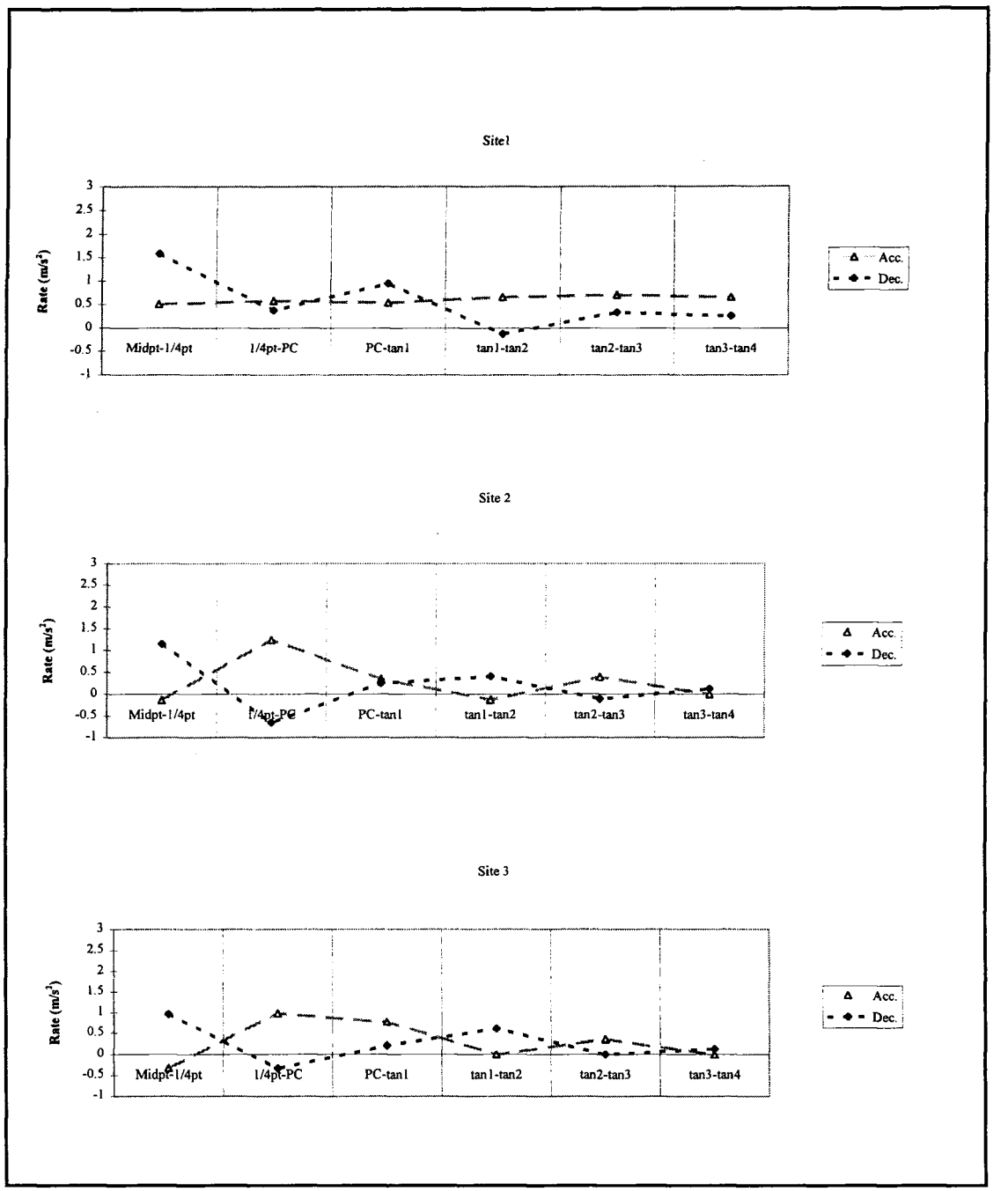

FIGURE 7 Observed 85th Percentile Rates for Low Degree of Curvature Category

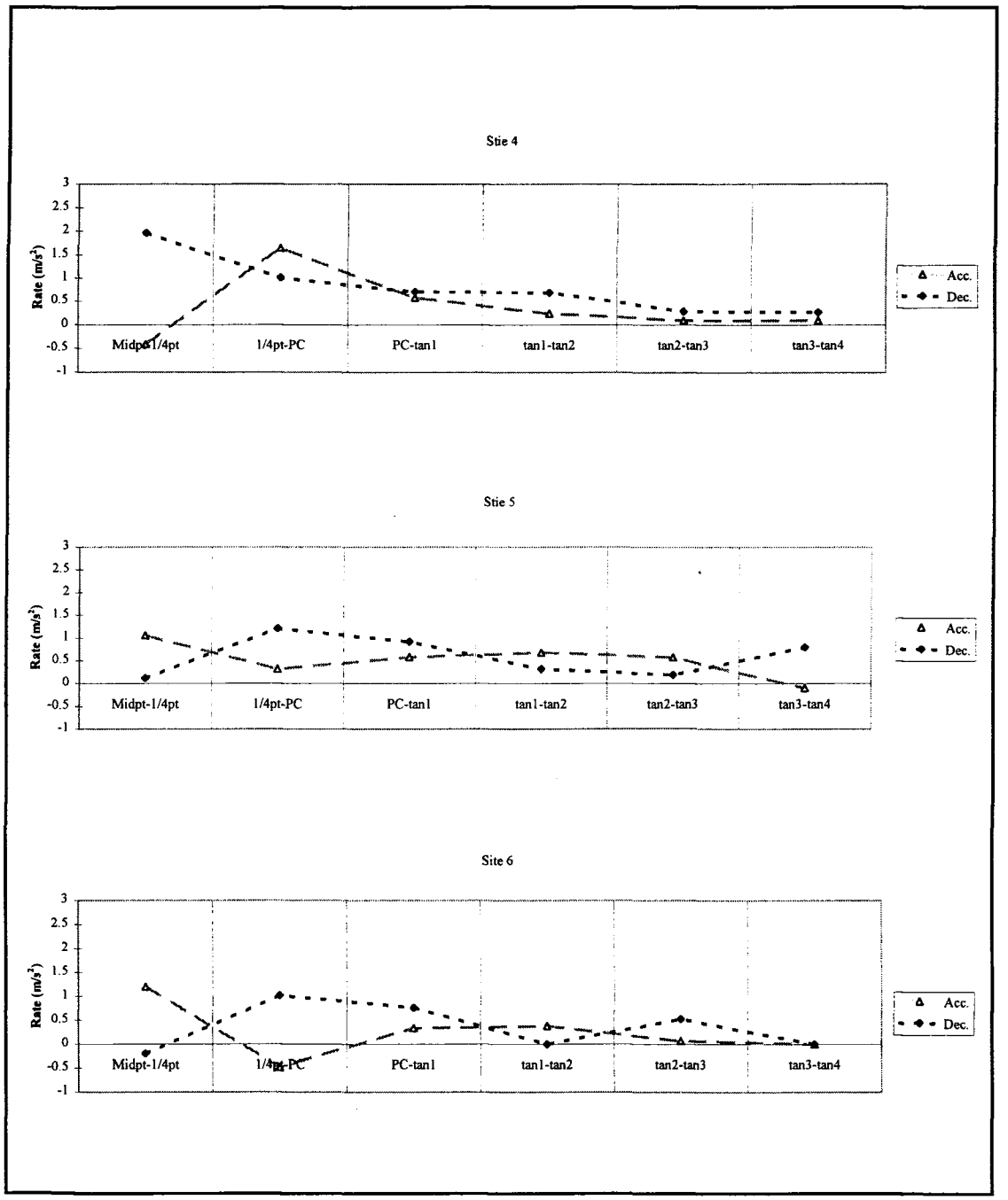

FIGURE 8 Observed 85th Percentile Rates for Middle Degree of Curvature Category

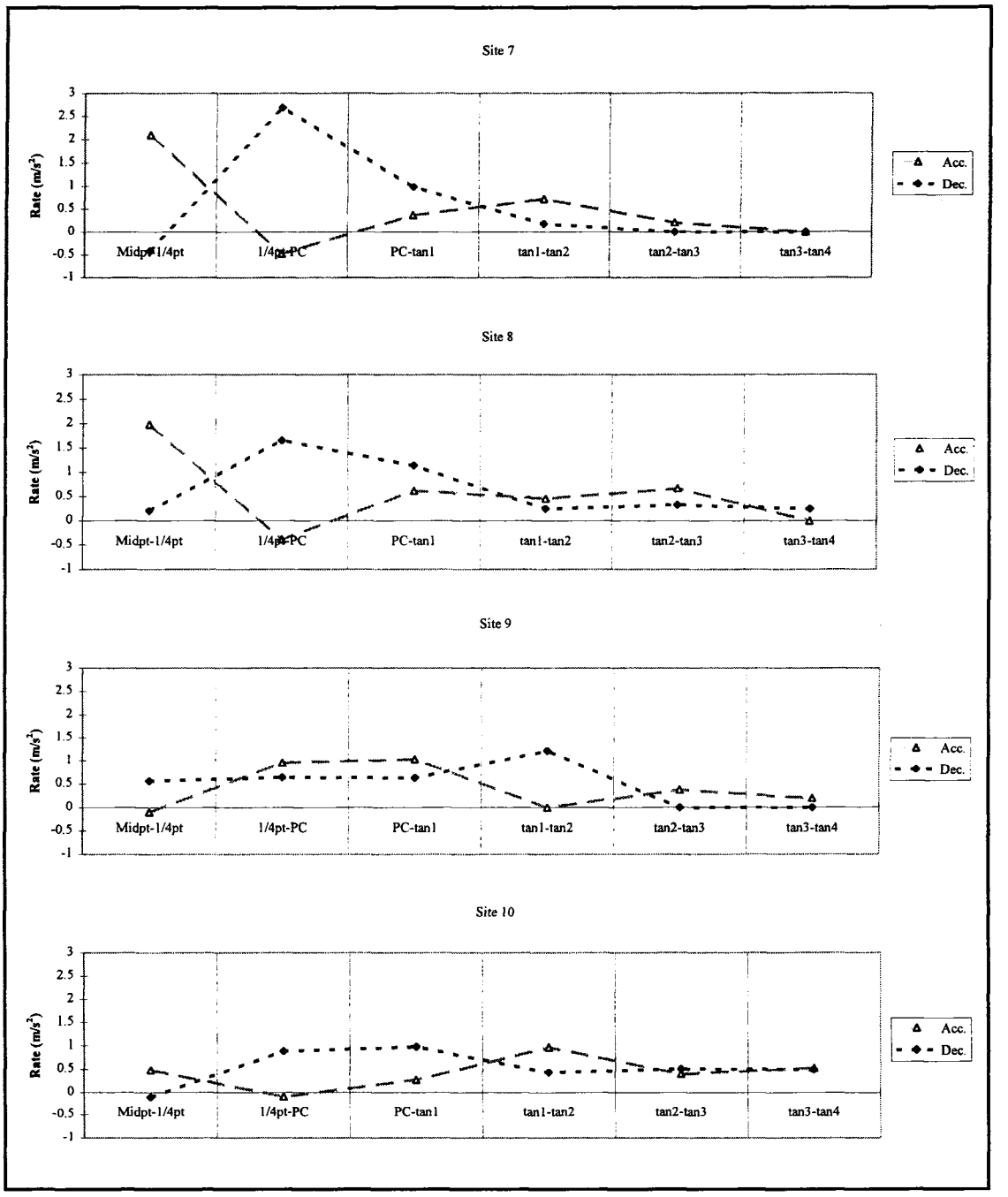

FIGURE 9 Observed 85th Percentile Rates for High Degree of Curvature Category

reasonable by inspection of the plots, although deceleration rates may be slightly higher than acceleration rates. This is not surprising as it is much more critical for approaching drivers to make a reduction in speed to safely traverse a curve than it is for departing drivers to reach their desired speed on the following tangent. It also appears that the points of inflection for acceleration occur near the point of curvature and around 120 meters out on the tangent, whereas they occur nearer to the quarter point of the curve and 60 meters out on the tangent for deceleration. In other words, deceleration begins about 60 meters from the point of curvature and ends around the quarter point while acceleration begins about the point of curvature and ends approximately 120 meters out on the tangent.

Another significant observation which supports the current model is the fact that rates approach zero and the magnitude of variation decreases on each tangent section. This supports the idea that drivers reach a desired speed on the tangent and through minor variations in acceleration and deceleration, attempt to maintain it until they begin reduction in speed for the next curve.

It is recognized that drivers must reduce their speed to traverse sharper curves. Associated with the overall speed reduction is a series of corrections as drivers attempt to estimate the appropriate speed on the upcoming curve. For instance, a driver may not be able to recognize the sharpness or length of a curve until beyond the point of curvature. This idea is supported by the increasing undulations in observed rates as drivers approach and depart curves. This relationship is obvious in all of the figures discussed here. The idea that sharper curves require more reduction, and thus require more corrections in speed is supported by inspection of the sharper curves as compared with the flatter ones. In general, as degree of curvature increases, so does the level of correction required as the driver nears the curve.

Generally, figures 7-9 support the components of the speed-profile model. The model estimates that a driver reaches a desired speed on a tangent, then attempts to maintain that speed until reduction in speed for the next curve begins. Also, the model estimates that the magnitude of speed reduction from tangent to curve increases with increasing degree of curvature. Both of these statements are supported by the relationships in figures 7-9. The assumptions that speeds on curves are constant, and that a single rate is used for both deceleration and acceleration are not supported by these plots. The model makes these simplifications in the interest of user-friendliness, but they are nevertheless not supported by these plots.

Implied Rates

The current methodology for evaluating the design consistency of a roadway uses operating speed measures (e.g. reduction in operating speed) to characterize driver behavior along an alignment. Therefore, the next logical step in the analysis process was to evaluate acceleration and deceleration characteristics based on measures implied by the observed 85th percentile speeds along each alignment. The measures studied were acceleration and deceleration rates and the points along the alignment where acceleration and deceleration begin and end. Figures 10-12 are graphical illustrations of the average acceleration and deceleration rates implied by the observed 85th percentile speeds.

The current operating-speed model assumes that drivers have a desired speed which they reach and maintain on long tangents. It is believed that associated with attempting to reach and maintain a desired speed over some distance are minor corrections in speed. Hence, as a driver is achieving and maintaining a desired speed, oscillations in acceleration take place. The oscillations which can be seen in figures 10-12 support this idea. Further, as drivers reach a portion of a tangent where they may drive at their desired speed, the magnitude of the oscillations should decrease. Again, inspection of the trends in figures 10-12 indicate that the magnitude of the oscillations is generally greater near the curve and decreases on the tangent. This is especially true for the sharper curves where greater adjustment in speed is required from tangent to curve and vice versa.

Two of the assumptions of the current model with respect to acceleration and deceleration characteristics may be addressed in reference to figures 10-12. First, the assumption is made that acceleration and deceleration characteristics are mirror images. The oscillations seen in figures 10-12 do not refute this assumption, although the relationship for acceleration seems to be shifted one interval toward the tangent. Second, the assumption is made that all acceleration or deceleration occurs on the tangent, with speeds on curves being constant. Although this assumption is made to simplify the model, the relationships in these figures indicate that this assumption should be investigated further. Figure 10-12, along with figures 4-9 indicate that drivers adjust their speed throughout the curve, with a breakpoint in speed occurring near the quarter point for deceleration and point of curvature for acceleration. One explanation for this may be that drivers approaching a curve may not recognize the sharpness of the curve, and thus are not able to estimate a safe speed for the curve until well into the curve. For drivers departing curves, it appears that acceleration may take place about the midpoint of the curve, followed by adjustment on the departure half of the curve in an effort to maintain a safe speed, finally accelerating at the point of curvature in an effort to reach their desired speed on the tangent.

Though these plots were originally developed in an effort to calibrate a rate for use in an enhanced model, limitations in sample sizes did not allow determination of any definitive rates. The analysis did, however, aid in establishing approximate breakpoints used to determine average acceleration and deceleration rates for the sample of curves. Discussion of estimate development and tests to determine if the rates are equal and how they compare with the assumed 0.85 m/s^2 follows.

Rate Estimation and Comparison

A combined examination of the plots discussed in the previous section was performed to estimate intervals over which average implied acceleration and deceleration rates could be calculated for comparison. The examination yielded two separate intervals for acceleration and deceleration. The interval selected for deceleration rate calculation begins at the quarter point of the curve and ends 60 meters from the point of curvature on the tangent. The interval used to calculate an average implied acceleration rate for each site begins at the point of curvature and ends 120 meters from the point of curvature on the tangent. These intervals are not definitive in each of the plots examined but they appeared to be reasonable intervals for the sample of sites as a whole.

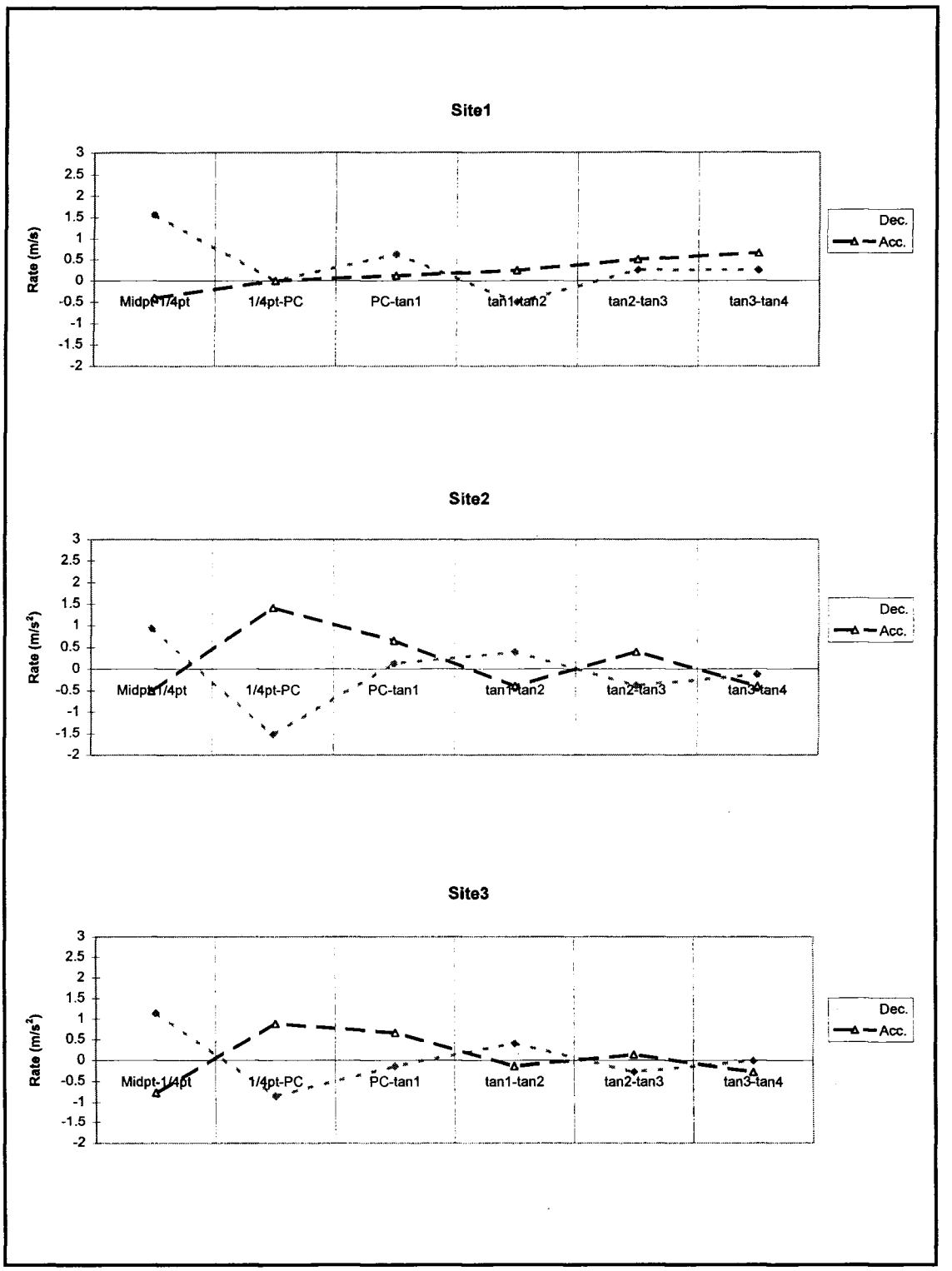

FIGURE 10 Implied Rates for Low Degree of Curvature Category

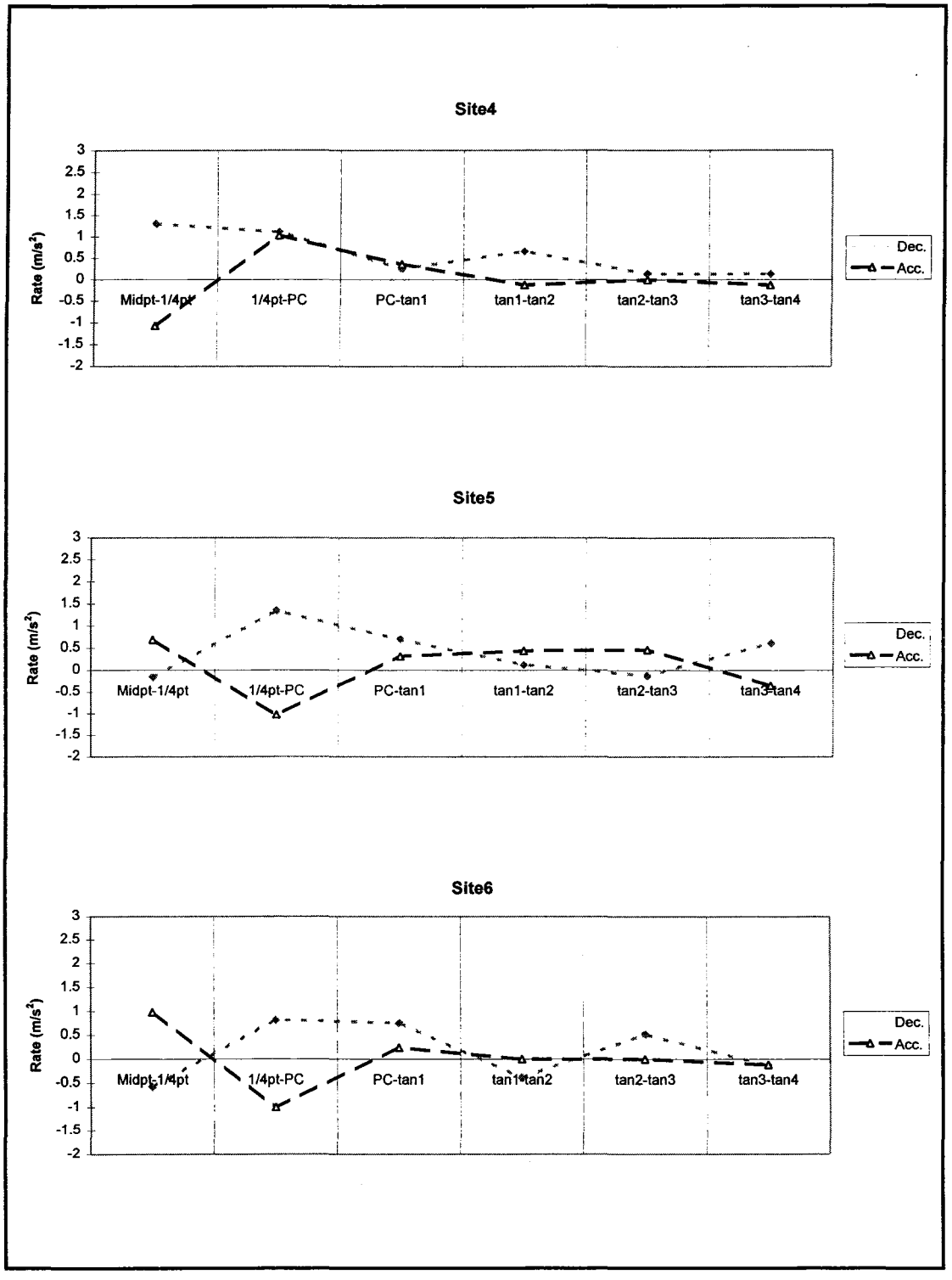

FIGURE 11 Implied Rates for Middle Degree of Curvature Category

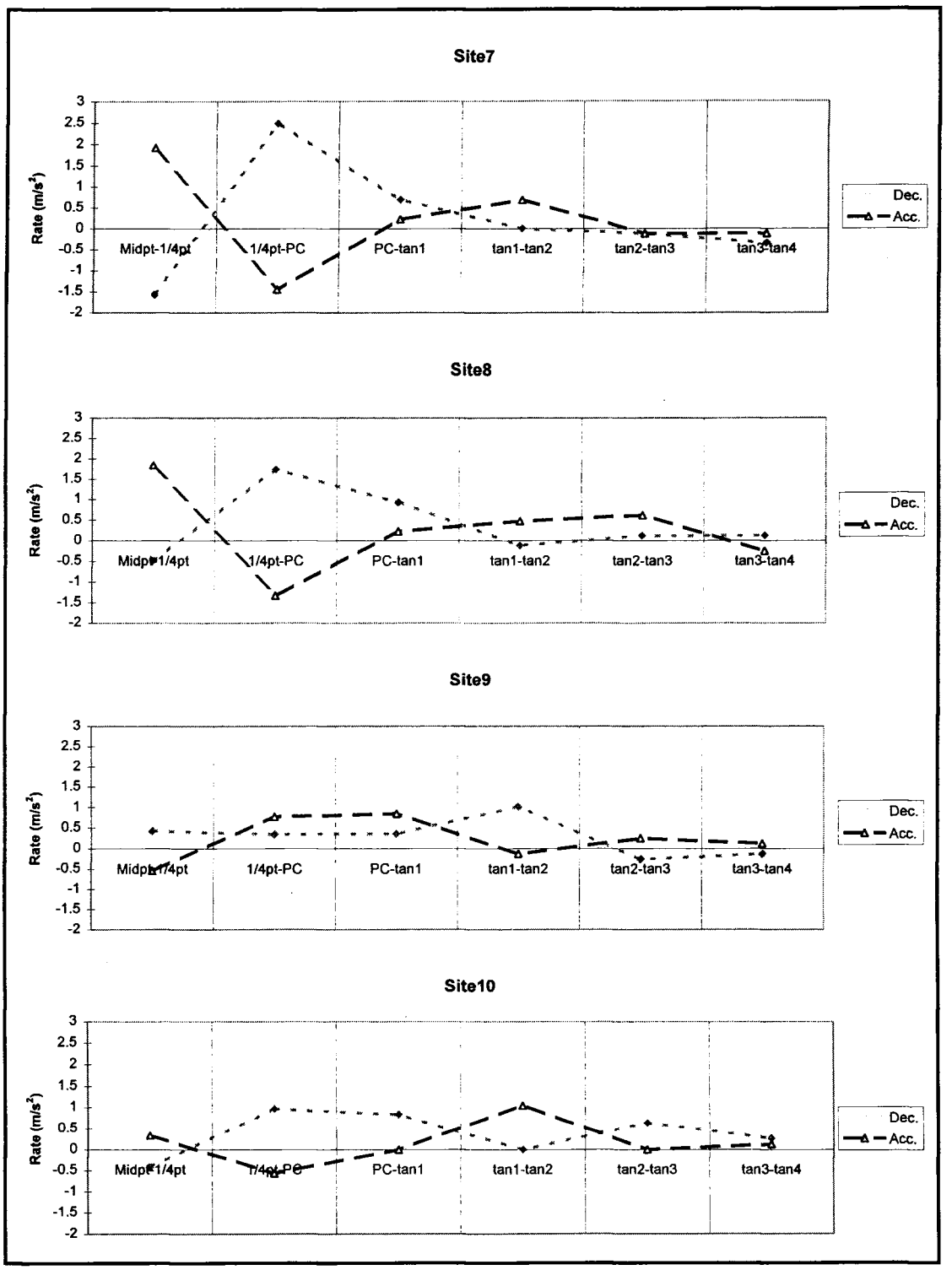

FIGURE 12 Implied Rates for High Degree of Curvature Category

Inherent in any attempt at estimating a single descriptor for a range of different sites is the fact that certain assumptions and generalizations must be made. The following are a few words of caution which apply to the rate calculation methodology:

- Due to a limited number of samples within each degree of curvature category, it was decided to generalize across all sites. In other words, the rates calculated were done so based on the same interval for each site.
- The spacing between data measurement locations prohibits a more precise estimate of where acceleration and deceleration begin. The rate calculation intervals, and thus the precision of the rates, were limited by this spacing.
- The methodology used to calculate a rate can only produce an approximation of acceleration and deceleration characteristics near the curve, and as such is a simplification of the actual behavior for comparison purposes.

The next step of the rate validation effort was to calculate implied acceleration and deceleration rates for each of the sites. This was done by using the observed 85th percentile speeds at each endpoint of the selected intervals (e.g. at point of curvature and 120 meters out on tangent for acceleration) as well as the length separating them to calculate the rates. Table 9 lists the average acceleration and deceleration rates implied by the observed 85th percentile speeds for each site.

The current model uses equal rates for acceleration and deceleration. The acceleration rates reported in table 9 indicate that average acceleration for vehicles departing a curve are consistently lower than the 0.85 m/s^2 currently used. Further, it appears that at least for sharper curves, acceleration rates tend to be somewhat lower than deceleration rates. This indicates that the assumption of equal rates across all curve geometry warrants further investigation.

TABLE 9 Average Implied Acceleration and Deceleration Rates

Site	Acceleration Rate (m/s^2)	Deceleration Rate (m/s^2)
1	0.18	0.40
2	0.13	-0.54
3	0.26	-0.49
4	0.12	0.56
5	0.38	0.95
6	0.12	0.79
7	0.45	1.19
8	0.35	1.18
9	0.36	0.35
10	0.52	0.90

As discussed earlier, it is believed that there is little or no speed reduction for flat curves, and speed reduction increases with increasing curve sharpness. The deceleration rates calculated tend to support this belief. For lower degrees of curvature, deceleration rates are either low or negative, indicating acceleration may be taking place as vehicles near the curve. As curve sharpness increases, rates tend to increase as well. So, while these results tend to support the overall driver behavior predicted by the model, they also support the idea that rates may vary with curve geometry. Again, further research should be performed before that conclusion can be made.

In an effort to validate the current assumptions about acceleration and deceleration, hypothesis tests were performed to test if the means of the calculated acceleration and deceleration were: (1) different from each other, and (2) different from the current rate of 0.85 m/s^2. The test between acceleration and deceleration means was first performed using the Smith-Satterthwaite two-sample t-test assuming unequal variance, tested at a 0.05 significance level. The two-sample t-test assumes independent samples. Since these samples may or may not be independent, a paired t-test was also performed to test the same hypothesis at the same significance level. To test both the acceleration and deceleration means against the current assumption, single-sample t-tests were performed with the hypothesized mean equal to 0.85 m/s^2. Again, the tests were performed at a 0.05 significance level. The results of these tests are reported in table 10.

TABLE 10 Tests of Acceleration and Deceleration Means

Null Hypothesis H_o:	mean		standard deviation		t_{calc}	t_{crit}	p-value	Reject H_o?
	a	d	a	d				
a=d (2-sample)	0.29	0.53	0.15	0.62	1.192	2.228	0.2609	No
a=d (paired)	0.29	0.53	0.15	0.62	1.359	2.262	0.2072	No
a=0.85 m/s^2	0.29		0.15		-11.468	2.262	1.13E-6	Yes
d=0.85 m/s^2		0.53		0.62	-1.553	2.262	0.1548	No

The current model assumes that acceleration and deceleration rates are equal. The results of the hypothesis tests indicates that the rates are not statistically different at a 0.05 significance level. The current model also assumes that the average rate is 0.85 m/s^2. The mean deceleration rate for the sample of ten sites was not statistically different from 0.85 m/s^2 at a 0.05 significance level. However, the mean acceleration was found to be statistically different from the assumed rate at a 0.05 significance level. These results tend to suggest that the model estimates behavior for drivers approaching curves better than for drivers departing them. Since the deceleration rate is used in the operating speed profile to predict speed reduction, these results help to support the speed reduction estimation ability of the model. However, given the sample sizes used for this

analysis, further data collection and analysis efforts should be undertaken to confirm these results.

Summary

Numerous plots were generated and examined to test the validity of the assumed acceleration and deceleration characteristics. Plots of observed 85th percentile speeds yielded observations which tend to support the current assumptions. For example, in most cases it appears that the observed operating speeds generally follow the model, the magnitude of observed operating speeds on tangents and curves closely match the estimated speeds and there is little difference in driver behavior for drivers approaching and departing curves. However, other observations made do not support the operating-speed model. The model assumes that speeds are constant on curves. The observed operating speed profiles indicate continued speed adjustment throughout the alignment, especially within the limits of the curves.

Next, plots of calculated 85th percentile rates and rates implied by the calculated 85th percentile speeds were examined. These analyses further supported the observations made of the speed profiles:

- Drivers adjust their speed continuously over an alignment.
- Drivers attempt to reach and maintain a desired speed on tangents.
- Speed variation, or change, is more severe for sharp curves than for flat curves.

In addition, examination of the rate profiles yielded observations specific to acceleration and deceleration. It appears that drivers approaching curves decelerate beyond the point of curvature, accelerate through the midpoint of the curve, then make appropriate adjustments to maintain a safe speed on the curve, finally accelerating again at the point of curvature to reach a desired speed on the following tangent. As a result of these observations, break points were estimated for determining average implied acceleration and deceleration rates for comparison purposes. The interval selected for deceleration begins 60 meters from the point of curvature on the tangent and continues to the quarter point of the curve. A similar interval for departing vehicles begins at the point of curvature and continues to a point 120 meters from the point of curvature on the tangent.

Hypothesis tests performed on the mean 85th percentile speeds on tangents for all ten sites indicates that the observed mean 85th percentile speeds are not significantly different from the current estimate of 97.9 km/h. These results support the continued use of the current estimate for purposes of consistency evaluation.

Results of hypothesis tests on the means for acceleration rates, deceleration rates, and the assumed rate of 0.85 m/s^2 yielded the following:

- The mean acceleration and deceleration rates were not statistically different at a 0.05 significance level.
- The mean deceleration rate was not statistically different from 0.85 m/s^2 at a 0.05 significance level.

- The mean acceleration rate was found to be statistically different from 0.85 m/s^2 at a 0.05 significance level.

On the whole, the results reported should be tempered by the limited sample size available for use in the tests. Further, based on the sample sizes reported, future studies which require detailed speed data should consider collection sample sizes on the order of three times the desired analysis sample size.

5. SUMMARY, FINDINGS, CONCLUSIONS AND RECOMMENDATIONS

Design consistency has long been recognized as an important characteristic of a safe roadway. Several studies have identified reduction in operating speed from tangent to curve as a good surrogate for accident experience and measure of design consistency. Thus, recent studies have focused on speed reduction as a surrogate measure upon which to base design consistency evaluation.

A procedure was recently developed which evaluates the design consistency of an alignment based on reduction in operating speed. The procedure utilizes an operating-speed-profile model to estimate reductions in speed from tangent to curve based on tangent length and curve geometry. In the model, the transition from tangent speed to curve speed is based on unvalidated assumptions about acceleration and deceleration characteristics. This research was designed to: (1) validate the speed-reduction estimation ability of the current model, and (2) validate the assumptions about acceleration and deceleration characteristics.

SUMMARY

Detailed speed data were collected at a sample of ten horizontal curves and their approach tangents on rural two-lane highways in the U.S. Vehicle speed measurements were made using infrared photoelectric sensors at seven locations along the approach tangent and curve. Directional speed measurements and a time stamp were recorded for each vehicle passing through a speed sensor. Vehicle speeds were then tracked through all seven speed measurement stations. Only free-flow passenger vehicles whose speeds were recorded at all seven locations and whose paths did not cross within the test section were included in the database for analysis purposes.

Plots of observed and estimated reduction in 85th percentile speed were generated and inspected. Additionally, hypothesis tests were performed in an effort to validate the speed reduction estimation ability of the existing operating-speed-profile model.

Plots of observed and estimated 85th percentile speed profiles, observed 85th percentile acceleration and deceleration rates, and acceleration and deceleration rates implied by the observed 85th percentile speeds were generated and inspected. Average implied acceleration and deceleration rates were calculated for comparison purposes. Hypothesis tests were then performed in an effort to test the validity of the current assumptions about acceleration and deceleration characteristics.

FINDINGS

Findings regarding validation of the speed reduction estimation ability of the model are as follows:

- The speed reduction estimation ability model has been validated based on the limited data collected for this study.

- Observed speed reductions for sites with downstream intersections were much greater than the speed reductions estimated with the model. Thus, the model should be used with caution to estimate speed reductions where intersections are present in the vicinity of the curve.
- It should be understood that the model predicts the expected (mean) reduction in operating speed for curves of given geometry. Thus, more data would be required for more conclusive validation.

Findings regarding validation of the current estimated acceleration and deceleration characteristics are as follows:

- In general, the model estimates operating speeds reasonably well.
- Corrections in speed, and thus oscillation in acceleration and deceleration takes place throughout the length of an alignment.
- Drivers attempt to reach and maintain a desired speed on tangents.
- The current estimate for desired speed of 97.9 km/h is valid based on data collected on ten long tangents.
- It appears that acceleration and deceleration behavior on curve-tangent sections can be modeled as being equal.
- Acceleration and deceleration take place within the limits of a curve, which warrants more detailed study on curve speed behavior.
- The approximate locations where acceleration and deceleration begin and end respectively may be different, with acceleration beginning around the point of curvature ending 120 meters from the point of curvature on the following tangent, and deceleration beginning at about 60 meters from the point of curvature on the tangent and ending at the quarter point of the curve.
- Although the current assumptions may overestimate acceleration rates, the assumed equal acceleration and deceleration rate at 0.85 m/s^2 is a reasonable approximation for the current model given that the model is intended for use in estimating reduction in speed.
- The speed sample sizes reported indicate that collection sample sizes for similar studies should be on the order of three times the desired analysis sample size.

CONCLUSIONS

The objectives of this study were to validate: (1) the speed reduction estimation ability of the current operating-speed-profile model, and (2) the assumed acceleration and deceleration characteristics used in the model. The following conclusions correspond to the stated objectives.

- The current operating-speed-profile model is appropriate for estimating speed reductions from tangent to curve on rural, two-lane highways, with design speed less than or equal to 97 km/h (60 mph), where no downstream intersections exist.
- The assumption that the deceleration rate is equal to 0.85 m/s^2 is appropriate for estimating speed reduction from tangent to curve.

- The assumption that the acceleration rate is equal to 0.85 m/s^2 needs refinement. The appropriate rate appears to be lower than the currently assumed rate.
- Given that the current model is intended for use to estimate speed reduction from tangent to curve, that the deceleration rate is the only rate used in that estimation, and the results of the hypothesis tests on the whole, the assumption of equal acceleration and deceleration characteristics (at 0.85 m/s^2) is not inappropriate for use in the operating-speed-based design consistency evaluation procedure.

RECOMMENDATIONS

The speed reduction ability of the current model was validated with certain reservations. The model appears to underestimate speed reduction for curves with nearby downstream intersections. Further research into the effects of intersections on operating speeds should be conducted in an effort to quantify these effects and possibly include them in the design consistency evaluation procedure.

The acceleration and deceleration characteristics currently assumed were partially validated. It appears that acceleration and deceleration rates can be modeled as being equal. However, more research of this type should be conducted to obtain larger sample sizes for the analysis. This research supports the assumption that drivers attempt to reach and maintain some desired speed on tangents. Research should be conducted with emphasis placed on collecting data to examine speed profiles on curves and acceleration and deceleration taking place on the tangent near the point of curvature. Perhaps by taking data measurements more frequently, at closer intervals, and most importantly at more sites, acceleration and deceleration characteristics could be calibrated with greater confidence and precision.

The results of this study raise questions about some of the assumptions made in the speed profile model. One important assumption which should be evaluated more extensively is the assumption that speeds are constant within the limits of curves. The analysis performed for this study indicates that drivers make speed adjustments continuously along an alignment, especially on curves. Research should be conducted to determine the magnitude and location of speed adjustments made within the limits of a curve.

The measure of consistency evaluated with the design consistency evaluation model is speed reduction. Having validated the speed reduction estimation ability of the model and considering the remainder of the results on the whole, the final recommendation is the continued use of the current model for design consistency evaluation on curves with long tangents on rural two-lane highways until further research can be conducted to refine the model.

REFERENCES

1. 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. FHWA, U.S. Department of Transportation, 1993.

2. *A Policy on Geometric Design of Highways and Streets.* Washington, D.C.: American Association of State Highway and Transportation Officials, 1990.

3. C. J. Messer, J. M. Mounce, and R. Q. Brackett. *Highway Geometric Design Consistency Related to Driver Expectancy. Volume III. Methodology for Evaluating Geometric Design Consistency.* Report FHWA/RD-81/037. FHWA, U.S. Department of Transportation, 1981.

4. J. L. Ottesen and R. A. Krammes. *Speed Profile Model for a U.S. Operating-Speed-Based Design Consistency Evaluation Procedure.* Paper 940995 Presented at the 73rd Annual Meeting of the Transportation Research Board, Washington, D.C., 1994.

5. I. B. Anderson and R. A. Krammes. *Speed Reduction as a Surrogate for Accident Experience at Horizontal Curves on Rural Two-Lane Highways.* Paper 940994 Presented at the 73rd Annual Meeting of the Transportation Research Board, Washington, D.C., 1994.

6. J. E. Leisch and J. P. Leisch. New Concepts in Design-Speed Application. In *Transportation Research Record* 631, TRB, National Research Council, Washington, D.C., 1977. pp. 5-14.

7. R. Lamm, E. M. Choueiri, and J. C. Hayward. Recommendations for Evaluating Horizontal Design Consistency Based on Investigation in the State of New York. In *Transportation Research Record* 1122, TRB, National Research Council, Washington, D.C., 1987. pp. 68-78.

8. E. M. Choueiri. *Statistical Analysis of Operating Speeds and Accident Rates on Two-Lane Rural Highways*. Ph.D. Dissertation, Clarkson Univeristy, Potsdam, N.Y., 1987.

9. J. C. Glennon, T. R. Neuman, and J. E. Leisch. *Safety and Operational Considerations for Design of Rural Highway Curves*. Report FHWA/RD-86/035. FHWA, U.S. Department of Transportation, 1985.

10. C. H. Lee. A Study Into Driver-Speed Behaviour on a Curve by Using Continuous Speed Measurement Method. *Proceedings 14th Annual Australian Road Research Board Conference*, Vermont South, Victoria, Australia, 1988.

11. G. Mintsis. Speed Distributions on Road Curves. *Public Roads*, January 1988, pp. 21-27.