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**COMPARISON OF DAY AND NIGHT VEHICULAR  
SPEEDS ON HORIZONTAL CURVES ON  
RURAL TWO-LANE HIGHWAYS**

**RESEARCH REPORT 04690-5**

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

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16. Abstract  <p>This thesis documents the research comparing day and night vehicular speeds on horizontal curves on rural, two-lane highways. For each selected curve, daytime and nighttime operating speeds were measured using piezoelectric sensors. Speed data was collected in each direction at the midpoint of the approach tangent and at the midpoint of the curve. A vehicle's speed reduction was then calculated as the difference between the speed at the midpoint of the tangent and the speed at the midpoint of the curve. Hypothesis tests of daytime and nighttime speeds at the midpoint of the approach tangents resulted in the conclusion that a small percentage of curves exhibited a difference between daytime and nighttime speeds. However, no discernible pattern for the results could be found. Hypothesis tests of daytime and nighttime speeds at the midpoint of horizontal curves showed that over half the curves tested had daytime speeds that were significantly different from nighttime speeds. Even though a large percentage of statistically significant differences in mean speeds at the midpoint of curves were observed, no discernible pattern was evident. Statistical tests of the daytime and nighttime speed reduction from the approach tangent to the midpoint of the curve showed that five out of 16 curves had a significantly higher speed reduction at night than during the day.</p> <p>The results of this research indicate that there are some differences between daytime and nighttime speeds on rural, two-lane highways. However, because the magnitude of the difference between daytime and nighttime speeds is small for all degrees of curvature, a variable accounting for light condition is not needed for operating-speed-based profile modeling for horizontal alignment design consistency evaluation.</p>					
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# SI\* (MODERN METRIC) CONVERSION FACTORS

## APPROXIMATE CONVERSIONS TO SI UNITS

## APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
<b>LENGTH</b>				
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
<b>AREA</b>				
in <sup>2</sup>	square inches	645.2	square millimeters	mm <sup>2</sup>
ft <sup>2</sup>	square feet	0.093	square meters	m <sup>2</sup>
yd <sup>2</sup>	square yards	0.836	square meters	m <sup>2</sup>
ac	acres	0.405	hectares	ha
mi <sup>2</sup>	square miles	2.59	square kilometers	km <sup>2</sup>
<b>VOLUME</b>				
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft <sup>3</sup>	cubic feet	0.028	cubic meters	m <sup>3</sup>
yd <sup>3</sup>	cubic yards	0.765	cubic meters	m <sup>3</sup>
NOTE: Volumes greater than 1000 l shall be shown in m <sup>3</sup> .				
<b>MASS</b>				
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")
<b>TEMPERATURE (exact)</b>				
°F	Fahrenheit temperature	5(F-32)/9 or (F-32)/1.8	Celcius temperature	°C
<b>ILLUMINATION</b>				
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m <sup>2</sup>	cd/m <sup>2</sup>
<b>FORCE and PRESSURE or STRESS</b>				
lbf	poundforce	4.45	newtons	N
lbf/in <sup>2</sup>	poundforce per square inch	6.89	kilopascals	kPa

Symbol	When You Know	Multiply By	To Find	Symbol
<b>LENGTH</b>				
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
<b>AREA</b>				
mm <sup>2</sup>	square millimeters	0.0016	square inches	in <sup>2</sup>
m <sup>2</sup>	square meters	10.764	square feet	ft <sup>2</sup>
m <sup>2</sup>	square meters	1.195	square yards	yd <sup>2</sup>
ha	hectares	2.47	acres	ac
km <sup>2</sup>	square kilometers	0.386	square miles	mi <sup>2</sup>
<b>VOLUME</b>				
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m <sup>3</sup>	cubic meters	35.71	cubic feet	ft <sup>3</sup>
m <sup>3</sup>	cubic meters	1.307	cubic yards	yd <sup>3</sup>
<b>MASS</b>				
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
<b>TEMPERATURE (exact)</b>				
°C	Celcius temperature	1.8C + 32	Fahrenheit temperature	°F
<b>ILLUMINATION</b>				
lx	lux	0.0929	foot-candles	fc
cd/m <sup>2</sup>	candela/m <sup>2</sup>	0.2919	foot-Lamberts	fl
<b>FORCE and PRESSURE or STRESS</b>				
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in <sup>2</sup>

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

## TABLE OF CONTENTS

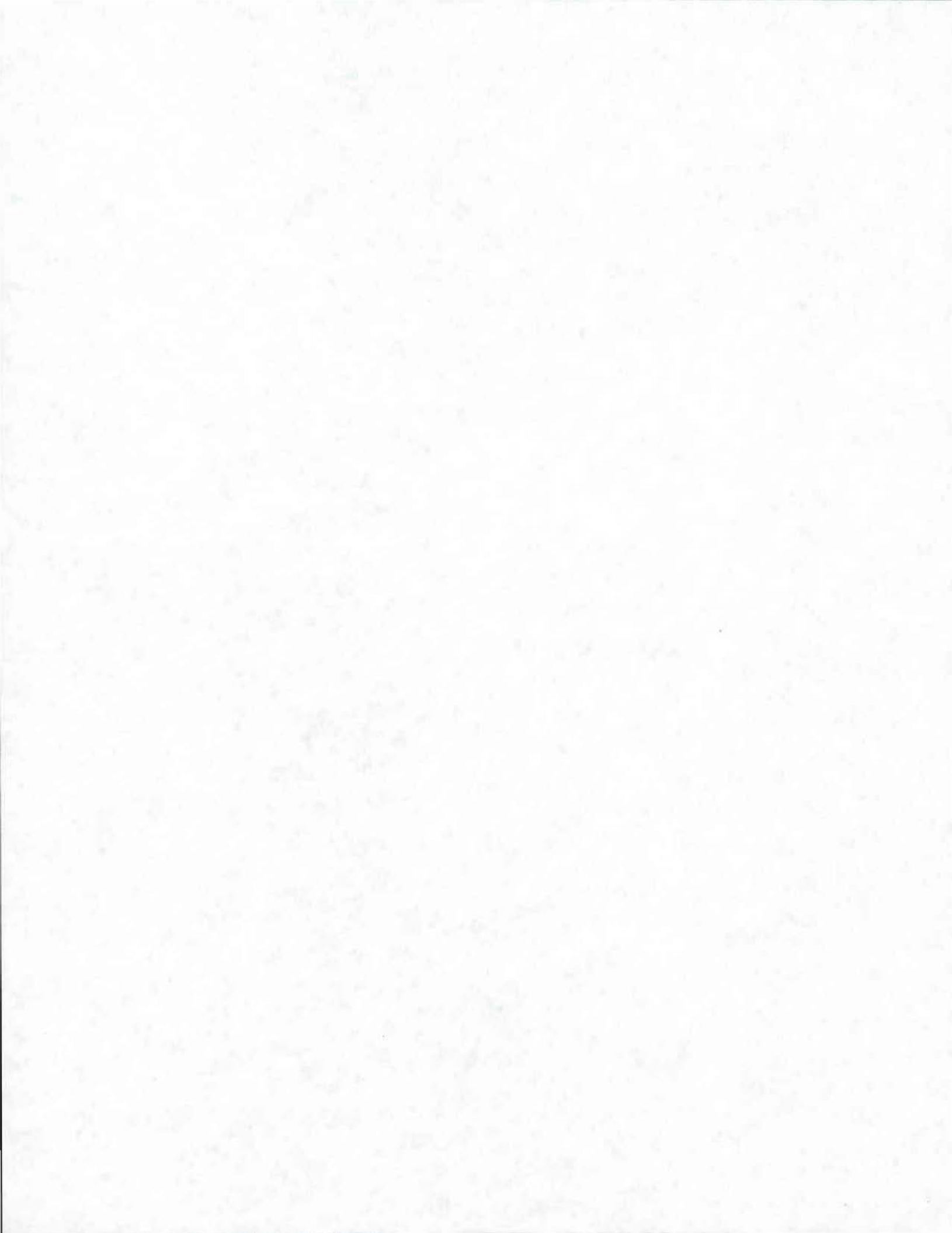
	Page
1. INTRODUCTION .....	1
DESIGN CONSISTENCY AND NIGHTTIME CONDITIONS .....	1
PROBLEM STATEMENT .....	2
SCOPE AND OBJECTIVES .....	2
THESIS ORGANIZATION .....	3
2. LITERATURE REVIEW .....	4
CURRENT U.S. RURAL ALIGNMENT DESIGN POLICY .....	4
PROPOSED U.S. DESIGN CONSISTENCY EVALUATION PROCEDURES .....	5
PREVIOUS RESEARCH ON DRIVER SPEED BEHAVIOR .....	5
OVERVIEW OF NIGHTTIME AND ROADWAY DELINEATION RESEARCH .....	7
DETAILED SPEED DATA COLLECTION .....	9
LITERATURE REVIEW SUMMARY .....	10
3. STUDY METHODOLOGY .....	12
STUDY DESIGN .....	12
DATA REDUCTION AND ANALYSIS .....	15
4. RESULTS .....	19
SAMPLE SIZES .....	19
ANOVA RESULTS: SITE, LIGHT CONDITION, LANE .....	19
COMPARISON OF DAYTIME AND NIGHTTIME MEAN OPERATING SPEEDS .....	22
Speed at the Midpoint of Approach Tangents .....	23
Speed at the Midpoint of Curves .....	26
Speed Reduction from the Midpoint of the Tangent to the Midpoint of the Curve .....	28
Summary .....	33
5. SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS .....	34
SUMMARY .....	34
CONCLUSIONS .....	35
RECOMMENDATIONS .....	35
REFERENCES .....	36
APPENDIX .....	39

## LIST OF FIGURES

<u>FIGURE</u>		<u>Page</u>
1	General Site Layout and Speed Measurement Locations .....	12
2	Mean Speed at Midpoint of Tangent--Outside Lane .....	24
3	Standard Deviation at Midpoint of Tangent--Outside Lane .....	24
4	Mean Speed at Midpoint of Tangent--Inside Lane .....	25
5	Standard Deviation at Midpoint of Tangent--Inside Lane .....	25
6	Mean Speed at Midpoint of Curve--Outside Lane .....	27
7	Standard Deviation at Midpoint of Curve--Outside Lane .....	27
8	Mean Speed at Midpoint of Curve--Inside Lane .....	29
9	Standard Deviation at Midpoint of Curve--Inside Lane .....	29
10	Mean Speed Reduction--Outside Lane .....	30
11	Standard Deviation of Speed Reductions--Outside Lane .....	30
12	Mean Speed Reduction--Inside Lane .....	32
13	Standard Deviation of Speed Reductions--Inside Lane .....	32

## LIST OF TABLES

<u>TABLES</u>		<u>Page</u>
1	Number of Curves Selected by Degree of Curvature .....	13
2	Site Selection Controls and Criteria .....	14
3	Curve Geometry .....	16
4	Sample Sizes After Screening by Degree of Curvature .....	19
5	Sample Sizes After Screening by Site .....	20
6	Summary of ANOVA Results--Significant Variables .....	20
7	Duncan's Multiple Range Tests .....	21
8	Significant Differences at the Midpoint of the Approach Tangent .....	23
9	Significant Differences at the Midpoint of the Curve .....	26
10	Significant Differences in Speed Reduction From Midpoint of Approach Tangent to Midpoint of Curve .....	31



## 1. INTRODUCTION

In March 1988, the Federal Highway Administration (FHWA) designated Highway Safety Design Practices and Criteria as a high-priority research and development area. With this designation, the wheels were put in motion for developing an integrated design process that systematically considers both the roadway and the roadside in evaluating highway design alternatives. Using this process, highway engineers will be able to assess alternatives from a safety standpoint

This integrated design process is now known as the Interactive Highway Safety Design Model. The most recent version of the Model consists of six modules: accident analysis, consistency, driver, policy review, traffic, and vehicle dynamic (1). Of particular interest to this thesis is the consistency module which will be based on speed profiles, since large changes in speed between successive roadway sections are believed to contribute to accidents (2).

The objective of alignment consistency is to allow most drivers to operate safely at their desired speed along the entire alignment of a roadway. U.S. policy for the design of rural alignments is stated in *A Policy on Geometric Design of Highways and Streets* by the American Association of State Highway and Transportation Officials (AASHTO). AASHTO's current document focuses on the use of the design-speed concept to ensure highway alignment consistency. AASHTO defines design speed as "the maximum safe speed that can be maintained over a specified section of highway when conditions are so favorable that the design features of the highway govern" (3). The design-speed concept presumes that a design will be consistent if the individual alignment features share the same design speed and the design speed reflects the uniform speed at which a high percentage of drivers desire to operate. Unfortunately, research in the United States and abroad has shown that there is a disparity between design speeds and drivers' desired operating speeds (4).

Alignments where most drivers are required to decelerate from their desired speed in order to safely traverse certain alignment elements are termed inconsistent. Today, many of the older alignments in current use have horizontal curves whose design speeds are lower than the desired speeds of the majority of today's drivers, which results in operating-speed inconsistencies (5). With newer alignments, inconsistencies occur when the designer or design policy underestimates or disregards driver speed preferences. Designers underestimating driver speed preferences is a growing concern because the U.S. design-speed-based alignment policy only ensures a consistent alignment to drivers whose desired speeds do not exceed the design speed. However, drivers typically select their speeds on tangents oblivious to the design speeds on downstream horizontal curves. The results are large speed reductions when approaching and entering curves, curve operating speeds in excess of curve design speeds, and curve-related accidents.

### DESIGN CONSISTENCY AND NIGHTTIME CONDITIONS

U.S. policy for designing rural horizontal alignments relies on the selection and application of design speeds to achieve consistency, which is an important policy objective. In order to achieve this objective all driving conditions must be studied, including nighttime conditions. In the past, however, design consistency research has focused on daytime conditions. This focus is probably

because the effect of environmental variables, such as nighttime conditions, are often difficult to predict, control, and/or express in terms of quantitative measures. Therefore, to truly guarantee a consistent design, designers must consider both daytime and nighttime speed behavior on rural horizontal alignments.

The selection of speeds is dependent on drivers being able to view the road (3). During daytime conditions, drivers have an abundance of visual information. Drivers can also use many different objects for assistance in road guidance. At night, however, a driver's primary means of guidance is the roadway and its delineation. A driver's sight distance is reduced to a vehicle's headlight illumination distance. Street lighting may improve the safety of a highway and the ease and comfort thereon, however, it is the general consensus that the lighting of rural highways seldom is justified except at certain critical locations, such as interchanges, intersections, railroad crossings, narrow or long bridges, tunnels, sharp curves, and areas where roadside interference is a factor (3).

Drivers must see the road directly in front of their vehicles and far enough in advance to predict with a high degree of accuracy the alignment, grade, width, and other related aspects of the roadway (3). Therefore, due to the differences in the driving task caused by the different light conditions, a consistent design for daytime travel may not be a consistent design for nighttime travel.

## **PROBLEM STATEMENT**

Two-lane rural highway safety is an issue of pressing national concern. It has been identified as one of the highest priority research needs by the Transportation Research Board's Committee on Geometric Design. Consequently, much research has been initiated on the topic of consistency. In addition to this recent research, many previous studies have also focused on the topic of consistency. None of these studies, however, have addressed the issue of horizontal consistency of rural two-lane roads at night. In order to be truly effective, U.S. policy must ensure consistency both during daytime and nighttime conditions. Research is needed to determine what, if any, differences exist between daytime and nighttime operating speeds on horizontal curves on rural two-lane roadways. With better knowledge of these differences, recommendations on whether to incorporate a variable accounting for daytime and nighttime driving habits into consistency-based design and/or operating-speed-based profile models can be made.

## **SCOPE AND OBJECTIVES**

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

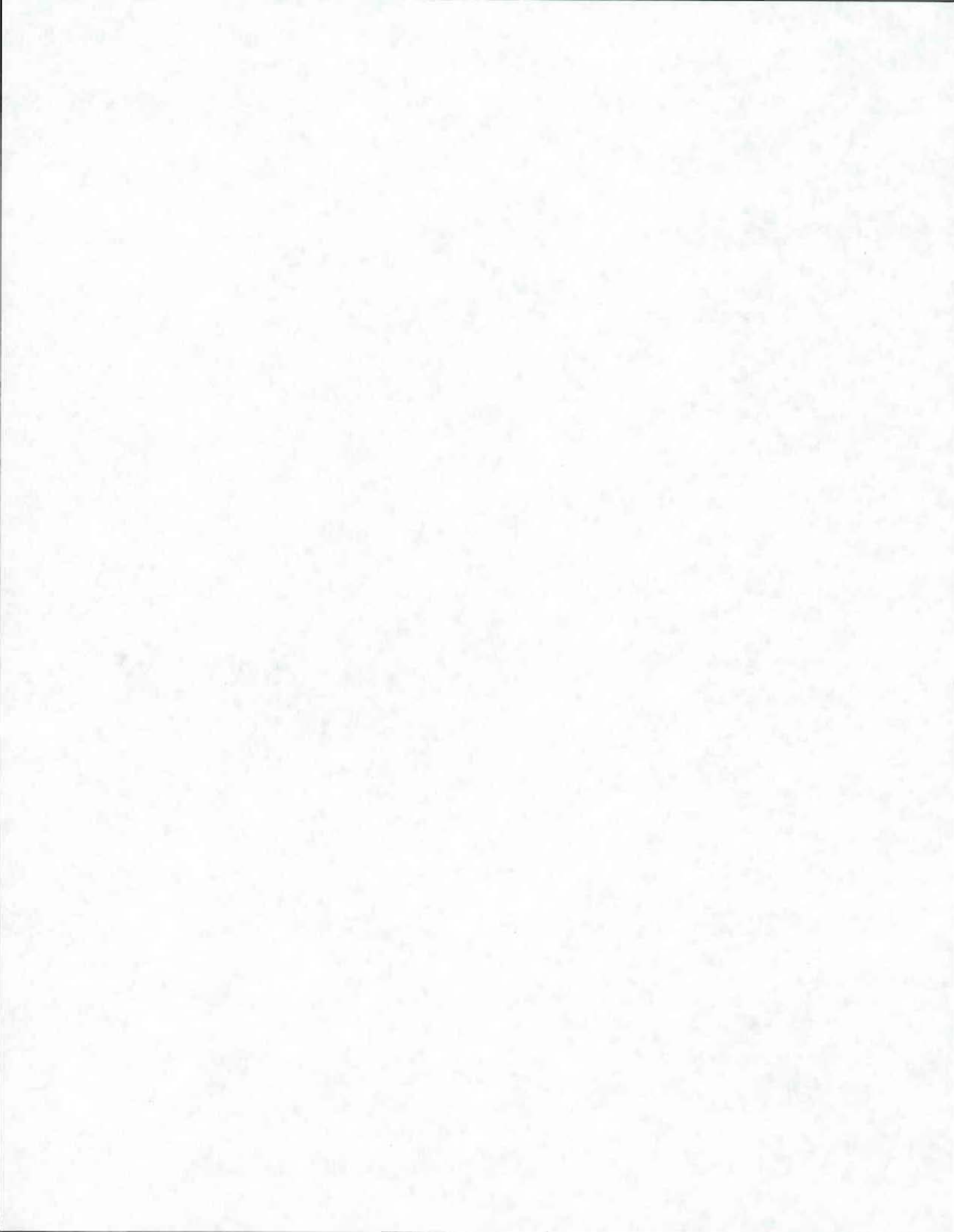
- Determine if a statistically significant difference exists between daytime and nighttime operating speeds at the midpoint of the approach tangents to curves with a degree of curvature between 3 and 12 degrees;
- Determine if a statistically significant difference exists between daytime and nighttime operating speeds at the midpoint of horizontal curves, for curves with a degree of curvature between 3 and 12 degrees; and

- Determine if a statistically significant difference exists between the daytime and nighttime speed change that occurs between the midpoint of the approach tangents and the midpoint of horizontal curves, for curves with a degree of curvature between 3 and 12 degrees.

The scope of this thesis is limited to independent horizontal curves on rural, two-lane highways in level and rolling terrain in Texas with preceding tangents longer than 800 feet. Superelevation and design speed at the midpoint of the curves were not controlled.

## **THESIS ORGANIZATION**

This thesis is divided into five chapters. This introductory chapter provides a brief background and describes the research scope and objectives. Chapter 2 is a review of the current U.S. design policy related to horizontal alignment design consistency and previous research on horizontal alignment design consistency. The second chapter also reviews previous research where nighttime speed behavior has been documented. Chapter 3 describes the methodology used in the study design, data collection, data reduction, and data analysis. Chapter 4 presents the results of the data analysis. Chapter 5 summarizes the findings, conclusions, and recommendations on how light conditions should be treated in alignment consistency evaluations.



## 2. LITERATURE REVIEW

Chapter 1 identified two-lane rural highway safety as a high priority research need. Secondly, it established the need for research addressing the issue of horizontal alignment consistency on rural two-lane highways during nighttime conditions. This chapter, Chapter 2, begins with a review of the current U.S. design policy related to the horizontal alignment and design consistency of roadways. This section is followed with a review of two proposed U.S. operating-speed-based consistency evaluation procedures and a review of recent research addressing driver speed behavior on rural two-lane roads. The next section reviews nighttime and roadway delineation studies. These studies provide vital information on the nighttime speed behavior of drivers and the effects of roadway delineation on speeds. Lastly, the study designs of previous daytime and/or nighttime spot speed studies are reviewed since the collection of daytime and nighttime spot speed data was necessary for this study.

### CURRENT U.S. RURAL ALIGNMENT DESIGN POLICY

The current U.S. rural alignment design policy is based on a design-speed concept. Design speed is defined by AASHTO to be “the maximum safe speed that can be maintained over a specified section of highway when conditions are so favorable that the design features of the highway govern” (3). The design-speed concept relies on the selection and application of design speeds to achieve consistency. According to AASHTO, the design speed should:

- Be related to all pertinent features to obtain a balanced design;
- Be consistent with the speed a driver is likely to expect;
- Be logical with respect to the topography, land use, and the functional classification of the highway;
- Consider the average trip length; and
- Fit the travel desires and habits of nearly all the drivers.

AASHTO also states that “every effort should be made to use as high a design speed as practicable to attain a desired degree of safety, mobility, and efficiency while under the constraints of environmental quality, economics, aesthetics, and social or political impacts” (3).

Unfortunately, even with these guidelines, geometric inconsistencies still exist. Experience shows that in many instances, geometric features or combinations of adjacent features have such an unexpectedly high driver workload that motorists may be surprised and drive in an unsafe manner (7). In other instances, especially on low-design-speed highways, operating speeds simply exceed the design speed. In cases such as these, AASHTO uses the application of superelevation to horizontal curves to provide a balanced design and a smooth transition from one curve to the next. The policy for distributing superelevation on curves, however, is dependent on state policy. Therefore, curves with the same degree of curvature may have different design speeds. This further complicates a driver’s ability of selecting an appropriate speed for a curve (4).

Growing numbers of geometric design researchers and practitioners recognize the fact that the design-speed concept as applied in the United States can only offer a consistent alignment to drivers whose desired speeds do not exceed the design speed.

## **PROPOSED U.S. DESIGN CONSISTENCY EVALUATION PROCEDURES**

Realizing the shortcomings of the design-speed concept, several countries have revised their design policies to address alignment consistency more explicitly. The U.S., however, continues to apply the design-speed concept as stated in AASHTO. Attempting to develop methods to ensure design consistency in the U.S., Leisch and Leisch (8) and Lamm, Choueiri, Hayward, and Paluri (9), both developed procedures for measuring the consistency of horizontal design using operating-speed-based evaluation methods.

Leisch and Leisch presented “a new concept in the definition and application of design speed . . . The overall object (of the design-speed concept) is to meet driver expectations and to comply with his or her inherent characteristics to achieve operational consistency and improve driving comfort and safety.” With this in mind, Leisch and Leisch recommended an updated design speed approach using a three-part 15-km/h (10 mph) rule:

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

Lamm, Choueiri, Hayward, and Paluri adapted a German horizontal design method for use in the United States. Lamm et al. recommended an alignment consistency evaluation method where successive horizontal features (tangent-to-curve or successive horizontal curves) are given a rating based on the change in degree of curvature ( $\Delta D$ ) and/or the change in 85th percentile speed ( $\Delta V_{85}$ ). Using the Lamm et al. model, horizontal alignments are rated on the following rating criteria:

- Good:  $\Delta D \leq 5^\circ$  or  $\Delta V_{85} \leq 9.7$  km/h (6 mph)
- Fair:  $9.7$  km/h (6 mph)  $< \Delta V_{85} \leq 19.3$  km/h (12 mph) or  $5^\circ < \Delta D \leq 10^\circ$
- Poor:  $\Delta D > 10^\circ$  or  $\Delta V_{85} > 19.3$  km/h (12 mph)

While both methods appear to pinpoint inconsistencies in an alignment, neither method was adopted by the U.S. due to data limitations.

## **PREVIOUS RESEARCH ON DRIVER SPEED BEHAVIOR**

Recent horizontal alignment design consistency studies have addressed various aspects of design consistency. These studies have found several interrelationships between design speed, operating speed, and design consistency.

Messer, Mounce, and Brackett reported that more than half of the drivers exceeded the design speed on 80.5 km/h (50 mph) design speed highways, and that only 5 percent of drivers exceeded the design speed on highways with a 112.7 km/h (70mph) design speed (10). For 96.9 km/h (60 mph) design speed highways, 96.9 km/h only represented the average operating speed (10). In a similar study, the 85th percentile speed exceeded the design speed on a majority of curves in each 10-km/h (6.2-mph) design-speed increment less than or equal to 100 km/h (62.1 mph); and the 85th percentile speed was less than the design speed for all curves whose design speed was 110 km/h (68.3 mph) or higher (4). Chowdhury, Warren, and Bissell (11) and McLean (12) in Australia also found similar results.

In a study entitled *Horizontal Alignment Design Consistency for Two-Lane Highways*, Krammes et al. presented empirical evidence that operating speeds on horizontal curves frequently exceed design speeds (4). Krammes also reported the following: (1) AASHTO recommended minimum design speeds do not reflect the desired speeds of today's drivers, (2) current AASHTO policy on the application of the selected design speed cannot guarantee that alignments with design speeds less than 60 mph will promote uniform operating speed profiles, (3) drivers have difficulty judging curvature and appropriate speeds from the approach tangent to a horizontal curve, and (4) the current curve warning and advisory speed signing system is not accurate, uniform, or effective (4). In that same study, Krammes et al. also stated that "the principal operating-speed-based measure of alignment consistency is the change in 85th percentile speed from an approach tangent to a horizontal curve" (4). In a review of U.S. and foreign research and design practices, Krammes et al. stated that two approaches are being used to estimate operating-speed reductions from a tangent to a horizontal curve:

- Estimating operating speed reduction as a function of the degree of curvature of the curve.
- Estimating operating speeds on the horizontal curve and on the approach tangent and computing the speed reduction as the difference between these two speed estimates.

The second approach is the preferred method because the first approach is limited by the fact that it does not explicitly account for factors that may affect speeds on the approach tangent (4).

In research focusing on design consistency, Krammes et al. also found that the mean 85th percentile speeds on tangents at least 244 m (800 ft) long, was 97.9 km/h (60.8 mph) (4). Krammes et al. also developed many equations for predicting 85th percentile speeds on horizontal curves. For each of the equation forms, the same independent variables were statistically significant: degree of curvature, length of curve, and deflection angle.

Among those equations developed were a linear and multiple-linear model. The linear model contained degree of curvature as the independent variable and 85th percentile operating speed as the dependent variable. The linear model had an  $R^2$  of 0.80. The multiple-linear model contained degree of curvature, length of curve, and deflection angle as the independent variables and 85th percentile operating speed as the dependent variable. The multiple-linear model had an  $R^2$ -value of 0.82. The linear equation was deemed the preferred form due to its simplicity (4).

Using 97.9 km/h as the mean 85th percentile speed on tangents and the linear model for estimating speeds on horizontal curves, Krammes et al. developed a speed-profile model for estimating the reduction in 85th percentile speeds from an approach tangent to a horizontal curve. A preliminary validation of the speed-profile model found that the majority, 79 percent, of the 78 approach tangent-curve pairs were within 5 km/h (3.1 mph) of the measured speed reduction (4). Though the preliminary validation study results were promising, the findings must be viewed with caution because the actual speed reductions were based upon the same data used to calibrate the speed-profile model from which the estimated speed reductions were obtained (4).

In follow-up research, Voigt determined that a statistically significant relationship existed between 85th percentile vehicle operating speed at the midpoint of curves and superelevation (13). This conclusion was reached by including superelevation as an independent variable in the linear and multiple-linear models developed by Krammes et al. However, even though Voigt found superelevation to be statistically significant, it was only a minor effect in terms of accounting for the variance in speeds. With superelevation included as an independent variable in the linear model, the  $R^2$  increased from the original value of 0.80 to 0.81 (13). With superelevation included as an independent variable in the multiple-linear model, the  $R^2$  increased from the original value of 0.82 to 0.84 (13). The Voigt multiple-linear model, with superelevation included, only improves on the Krammes linear model by four percentage points (13).

Based on the research by Krammes et al., Collins attempted to validate the following two elements of the Krammes speed-profile model: (1) the speed reduction estimation ability of the model, and (2) the assumptions about acceleration and deceleration behavior of drivers approaching and departing horizontal curves (14). Collins found that the current speed-profile model fit the observed data reasonably well, and that the assumption of equal acceleration and deceleration rates at  $0.85 \text{ m/s}^2$  were reasonable for the purposes of this model. This model and others developed by Krammes et al. will be considered for incorporation into the consistency module of the Interactive Highway Safety Design Model once the validation process is complete.

## **OVERVIEW OF NIGHTTIME AND ROADWAY DELINEATION RESEARCH**

Though the primary focus of nighttime research is often on roadway delineation, many studies have used speed as a measure of effectiveness for safety and operational evaluations of delineation treatments. Several studies have also tried to determine the relationship between speed behavior and various types of delineation treatments, such as post mounted delineators (PMDs), raised pavement markers (RPMs), lane striping, and supplemental signs. Based on this previous research, some insight into the visual needs of drivers negotiating rural curves at night can be gained.

On German autobahns, traffic volumes strongly influence the average speed. However, Brilon and Ponzlet examined typical fluctuations of average speeds on 4-lane and 6-lane autobahns which were not due to traffic volumes (15). The study showed that darkness caused an average reduction of velocities by about 5 km/h at the 15 test sites.

Stimpson observed that the mean speeds on tangent sections for day and night conditions were not statistically different (16). Stimpson also studied a 20 degree horizontal curve and nine

other horizontal curves ranging in degree of curvature from  $3\frac{1}{2}$  to  $8\frac{1}{2}$  degrees. Speeds were measured at three different locations along each curve's alignment. The first location was 500 feet in front of the curve. The second location was the point of curvature, and the last location was the midpoint of the curve. On horizontal curves, 20 percent of the location differences were statistically significant, for both light conditions (day and night) and direction of travel (inside and outside lane), with a majority of these occurring between the first two locations (16). In 72 percent of the day/night comparisons, day speeds were higher than night speeds but not statistically significant (16).

Stimpson also states that the reduction in speed between the first two locations appears to be related to degree of curvature. In addition, speeds at the midpoints of the curves revealed that vehicles on the outside lane traveled at the same speed as vehicles on the inside lane of the curve.

Pagano collected data during daytime and nighttime hours. Even though statistically significant differences in the mean speeds did occur, no discernible pattern was evident (17). The test site was approximately 3,000 feet in length, consisting of a tangent section with a slight crest vertical curve at one end.

Capelle observed on two straight segments that a tree-lined road elicited slower speeds than an open road (18). The average speed of each of five test drivers was seven miles faster on the unbordered open road, supporting a hypothesis that peripheral structured patterns enhance speed perception and increase drivers' estimation of their velocity (18).

Krammes, Tyler, Middleton, and Feldman observed that the mean speeds in the outside lane at the midpoint of the curves were consistently 1-3 mph higher with newly installed RPMs and than with the existing PMDs (19). Krammes et al. also observed that when comparing RPMs and PMDs the mean speed change from the beginning to the midpoint of the curve did not differ significantly (19). Data were collected only at night and at seven curves ranging in degree of curvature from 3 to 5 degrees. The statistical analysis for this study focused primarily on the effects of different delineation treatments. The effects of degree of curvature on speed behavior were not examined.

David observed that the mean vehicular speeds were essentially the same for all patterns of roadway delineation treatments tested on two horizontal curves (17). The study was divided into two phases. In the first phase, six patterns of post delineators and a null case were tested. In the second phase, two patterns of RPMs, one pattern of PMDs, and a freshly painted centerline were compared. Because the objective of this study was to compare the effects of delineation treatments on traffic behavior, only nighttime data were collected.

According to Hultman and McGee there was a tendency for speeds to be lower within the curve when raised pavement markers were present (17). The data, however, are not conclusive, because only a single horizontal curve with a degree of curvature of  $20^\circ$  was selected as the test site. In a comparison between treatments, significant changes in the mean for speeds taken at the approaches to the curves occurred in only a few instances. Even though light conditions (day and night) and direction of travel (right and left) were considered in this study, statistical tests were only performed between the different delineation treatments.

Zador et al. compared the operational effects of chevrons, PMDs, and RPMs at horizontal curves on two-lane highways. They found that the estimated mean approach speeds were increased by about 1.1 ft/sec with raised pavement markers, increased by about 2.3 ft/sec with post-mounted delineators, and reduced by about 0.5 ft/sec at one site and increased by 3 ft/sec at another with chevrons (20).

Lastly, several articles on highway travel characteristics indicate that average spot speeds in the daytime are about 1 mph higher in urban areas than the corresponding nighttime speed values (21). In rural areas, daytime speeds, depending on the particular roadway facility, are 2 to 8 mph higher than the corresponding nighttime speed values (21). The research documented in this section clearly shows the different and often conflicting findings that result when daytime speeds are compared to nighttime speeds. More research is clearly needed in this area especially since speed profiles are the basis for the Federal Highway Administration's Interactive Highway Safety Design Model consistency module.

## **DETAILED SPEED DATA COLLECTION**

In order to achieve the objectives of this thesis, it was necessary to collect the spot speeds of vehicles at the midpoint of horizontal curves and at the midpoint of the approach tangents to the curves. The following section documents the data collection methodologies of previous studies.

Stimpson (16) used pairs of resistance-based electrical tapeswitches for his data collection. The tapeswitches were secured to the road with two-sided adhesive tape and covered by dull gray duct tape. The data collected at each pair of tapeswitches were stored using a Vehicle Placement and Event Monitor. On tangent sections, two traps were installed 600 ft (183 m) apart. Each trap was at least 1,500 ft (457 m) from the nearest curve. On horizontal curve sections, six traps (three per lane) were installed. The traps were installed at three points along an alignment:

- At the curve warning sign or 750 feet (229 meters) before point of curvature or at the maximum extension of equipment;
- At the point of curvature; and
- At the midpoint of curve.

Rockwell and Hungerford (22) collected speeds using hand-held radar and tapeswitches. The hand-held radar was used from a vehicle parked in a driveway off the road. Five radar measurements from the approach tangent to the point of curvature were recorded for every car. The tapeswitches were mounted on 10 feet long metal strips backed with rubber. The switches were secured to the road with nails at the midpoint of the curve in a Z-configuration.

Glennon, Neuman, and Leisch (23) 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.

David (17) used a series of light source/photoelectric detector pairs as the major component of the speed profile data acquisition system. Pairs 1 through 9 were spaced at 100-ft intervals and

were used to record the vehicle's successive arrival times through the trap. Pairs 0 and 10 were used to trigger the recorder when a vehicle was about to enter the test section. Only free-flowing, two-axle vehicles were recorded. For speed data purposes, a free-flowing vehicle was defined as one that, upon entering the test section was following another vehicle in the same direction by a headway of less than 7.5 seconds, and did not meet an oncoming vehicle in the middle 400 ft of the test section. Data were collected only on weekday nights (Monday through Thursday).

Hultman and McGee (17) used radar meters to collect speed data. Approach speeds were taken before the driver was influenced by the coming curve. Curve speeds were measured near the apex of the curve. Only free flow vehicles not influenced by other vehicles were included in the sample.

Similarly, Pagano (17) used radar speed meters to collect spot speed data. Data were collected at both the point of curvature and the midpoint of the curve. Only free-flowing vehicles, vehicles not following another vehicle in the same direction by less than 5 seconds or encountering an oncoming vehicle within 5 seconds before or 5 seconds after crossing the spot where the speed was taken, were used for analysis. Only nighttime data were collected and only on weekday nights.

Krammes, Tyer, Middleton, and Feldman (19) used tapeswitches and Golden River Environmental Computers to collect vehicle spot speed data. The tapeswitches were placed on the roadway using a nylon mesh protective mat material with a bitumen backing. The tapeswitches were arranged in a double Z-configuration that allows data to be collected in both directions at each location. For each curve, the traps were placed: (1) 300-800 ft from the end of the curve on the approach tangent, (2) at the point of curvature, (3) at the midpoint of the curve, (4) at the point of tangency, and (5) 300-800 ft from the end of the curve on the departure tangent.

Collins (14) used infrared photoelectric sensors for the collection of speed data. Similar to pneumatic road tubes or piezoelectric sensors, two individual speed sensors were placed 1 meter apart at each speed measurement location and connected to a microprocessor. At each pair of sensors, once a vehicle passed through the infrared beams, speed was calculated based on the time difference between the actuations. Collins recorded speeds at the point of curvature, quarter point, and midpoint of each curve. In addition, 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.

Reviewing the data collection methodologies of these studies provided valuable information on the placement of data collection equipment for speed studies. It is apparent from these studies that placement of equipment is subject to the objective(s) of the study and equipment constraints.

## **LITERATURE REVIEW SUMMARY**

The idea of alignment consistency originated in the 1930's with the design-speed concept, however, U.S. design policy still cannot guarantee a consistent alignment in the 1990's. Even though the evaluation of design consistency has been a topic of research for nearly two decades, only Leisch and Leisch and Lamm et al. have proposed design procedures for promoting design consistency in

highway geometric design on two-lane rural roads. However, AASHTO, which states the U.S. policy for the design of rural alignments, has not adopted either procedure.

Recently, Krammes et al. developed a speed-profile model for predicting speeds given the geometric features of the road. However, because most design consistency studies has been limited to daytime conditions, a variable accounting for the effects of light condition in the speed-profile model has not been researched. This is due to the fact that most nighttime research has primarily focused on the effects of roadway delineation. In cases where daytime and nighttime speeds have been collected, design consistency was not the objective. Therefore, their applicability to highway design consistency research or speed-profile modeling is very limited.

Therefore, this thesis compares the daytime and nighttime speeds at eight curves over a range of four degrees-of-curvature with a focus on horizontal design consistency and speed-profile modeling.

### 3. STUDY METHODOLOGY

Chapters 1 and 2 have established the need for research that examines the speed behavior of drivers during daytime and nighttime conditions. The following sections document the work plan followed for this study: study design, data collection, data reduction, and data analysis.

#### STUDY DESIGN

The primary objective of this research was to determine whether differences exist between daytime and nighttime operating speeds on rural, two-lane highways that should be reflected in operating-speed-based design consistency evaluation models. In order to accomplish this objective, speed data were collected on the approach tangents and at the midpoints of selected horizontal curves. The speed data were collected by using a total of four speed measurement locations, two per direction, for each selected curve. As shown in Figure 1, data were collected on the approach tangent and at the midpoint of each curve on each lane such that each lane would comprise a curve-tangent section. Then, from these two measurements, the speed change from the approach tangent to the midpoint of the curve was calculated by subtracting a vehicle's speed at the midpoint of the curve from its speed on the approach tangent.

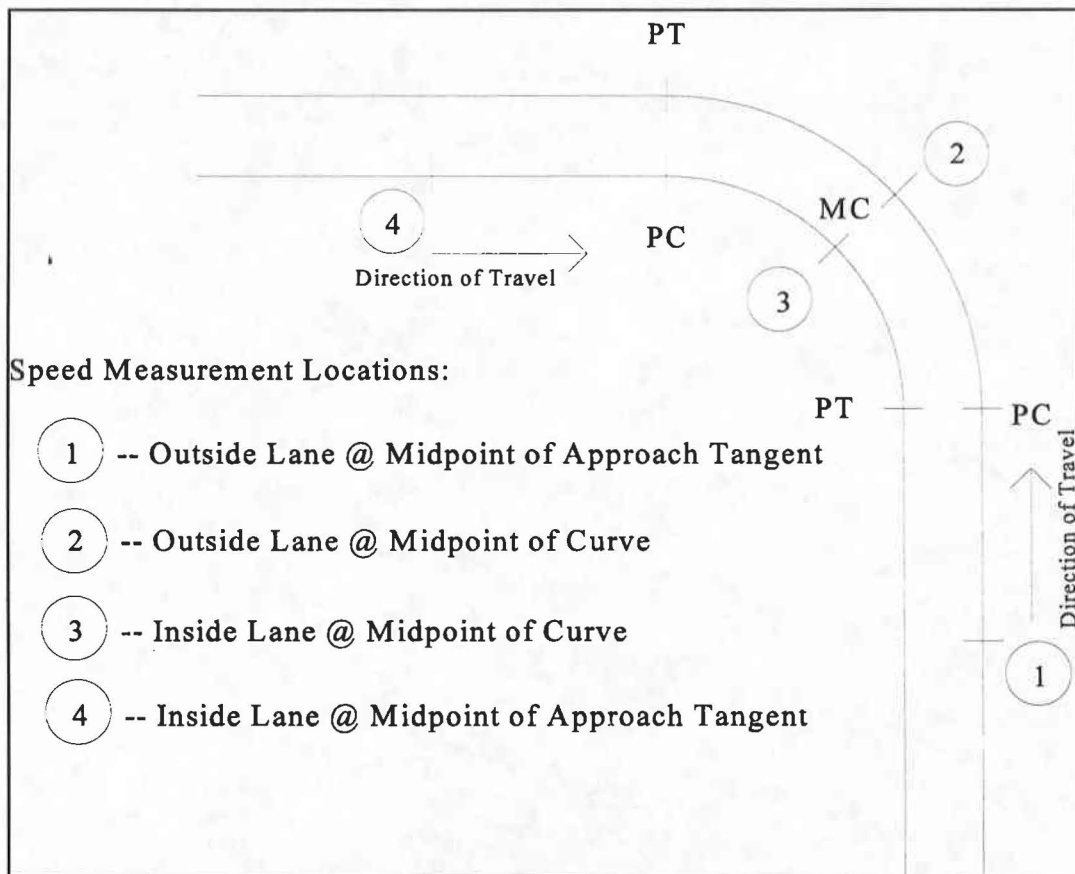


FIGURE 1 General Site Layout and Speed Measurement Locations

For most vehicles, this calculation resulted in a positive value which indicated that the vehicles decelerated from the midpoint of the approach tangent to the midpoint of the curve. However, for some vehicles, this calculation resulted in a negative value which indicated that the vehicles accelerated from the midpoint of the approach tangent to the midpoint of the curve.

Data were collected 24 hours a day under clear, dry weather conditions until sufficient speed measurements were obtained. The number of vehicles using the roadway at night, which is directly related to each roadway's average daily traffic (ADT), was the primary factor used to estimate the length of time required to collect data. At some sites, data were collected on both weekdays and weekends for logistical reasons, but only weekday data were used in the analysis.

To facilitate data analysis and to test across a range of degree of curvature, data were collected at ten horizontal curves. However, data collected at a 6° curve on FM 980 and a 12° curve on FM 831 were dropped from the database leaving only eight curves for the analysis. The curve on FM 980 was not used because speeds at the site were affected by a state prison driveway. When the site was chosen, it was believed that the driveway was far enough downstream from the curve to not affect speeds on the curve. The curve on FM 831 was not used due to an extremely small nighttime sample size on the outside lane resulting from an equipment failure. The nighttime sample size on the outside lane consisted of only five vehicles.

Degree of curvature was the main control used to select study sites for this study because it is a good predictor of speeds on curves. Krammes et al. found that a simple linear equation consisting of only one independent variable, degree of curvature, explained a large percentage of the variation in 85th percentile speeds ( $R^2 = 0.80$ ) on horizontal curves (4). Adding length of curve, deflection angle, and superelevation rate to this model increased the  $R^2$  to 0.84 (13). Therefore, these other variables were not controlled because their contribution to explaining the variation in 85th percentile speeds on horizontal curves was very small.

In order to test across a range of degree of curvature, eight horizontal curves over a range of four degrees of curvature were used for data analysis. Table 1 shows the curves by degree of curvature, and Table 2 summarizes the site selection criteria used for each data collection site. The site selection controls listed are the same as those used in previous design consistency research by Krammes et al. (4). Every attempt was made to control factors related to the geometry and roadside environment.

TABLE 1 Number of Curves Selected by Degree of Curvature

Degree of Curvature	# of Curve Selected
3 °	3
6 °	2
10 °	2
12 °	1

TABLE 2 Site Selection Controls and Criteria

Control	Criteria
Area Type	Rural
Administrative Classification	State
Functional Classification	Collector or Arterial
Design Classification	Two-Lane
Design Speed	≤ 88.6 km/h
Posted Speed Limit	≤ 88.6 km/h
Terrain	Level to Rolling
Grade	< 5 percent
Traffic Volumes	400-4000 vpd
Lane Widths	3.05-3.66 m
Shoulder Widths	0-2.44 m
Plan-Profile Sheets	Available
Length of Route	≥ 4.03 km
Distance from a Town	≥ 0.81 km
Distance from End of Roadway	≥ 0.81 km
Intersecting Roadways	None

When a vehicle passed over the sensors, electronic impulses were generated for each axle and transmitted to the counter. Knowing the spacing of the sensors, ten feet for this study, and the time difference between impulses for each axle, operating speed was calculated. In addition to operating speed, the counter also recorded the following information: (1) time of actuation (time stamp), (2) number of axles, and (3) spacing between axles. The time stamp was vital for distinguishing between daytime and nighttime vehicles. However, all data were used to track vehicles from the midpoint of the approach tangent to the midpoint of the curve.

Even though data collected using this system is believed to be quite accurate, the principal source of error is the improper placement of sensors. Sensors must be placed perpendicular to a vehicle's direction of travel, and a 0.1 ft error in placement results in a 1 mph error in speed (19).

The Series R piezo polymer traffic sensors which were used for this study are designed for short-term traffic monitoring. They are extruded encapsulations on piezo cable, with a high impact plastic housing for the lead attachment (24). When the cable is compressed or stretched, a charge is generated signifying the presence of a vehicle.

The bituthane tape used to cover the sensors was black in color and blended well with the color of the roadway surface. The piezo sensors were approximately 1/4 inch high when placed on

the roadway. When covered with the protective bituthane tape, a barely audible rumble is heard within vehicles passing over the sensors. The observation of drivers passing over similar tapeswitches in a previous study showed no noticeable effect on driver behavior (25).

Two different types of traffic counter/classifiers were used for this study. Traffic counters convert electronic pulses into usable data and store it on an IBM compatible microcomputer for later processing. Initially, International Road Dynamics Counter/Classifiers were the only counters being used for the study. However, due to equipment conflicts with another study, it became necessary to use four newly acquired Traffic Tally Phoenix Counter/Classifiers during the latter portion of the data collection. Both counters operated similarly in all respects.

TRAFMAN was the software used to export the data to a laptop computer as ASCII text files. The text files were then imported into Microsoft Excel where the data was reduced and organized into columns. The data was then converted back into ASCII text files for analysis using Statistical Analysis Software (SAS).

The curve geometry data for each study site were obtained from plan and profile sheets and from field measurements. The data collected from the plan and profile sheets included the following: county, station, degree of curvature, length of curve, preceding tangent, and preceding curve. The data collected from field measurements included the following: total width of roadway, lane width, superelevation, type or presence of shoulder, background, curve advisory speeds, delineation, and any additional signing. Roadway volume data were obtained from the 1993 Texas Department of Transportation (TxDOT) District Highway Traffic Maps. In addition, the inferred design speed for each of the curves was calculated and based on the limiting values of superelevation and side friction listed in AASHTO's green book (3). All of these variables were considered as possible explanations for the variability in the results.

The curve geometry data for the eight horizontal curves used for data analysis in this study are listed in Table 3. Several sites were selected from an existing collection of plan and profile sheets for Texas Farm-to-Market Highways. The remainder of the sites were selected after reviewing plan and profile sheets at TxDOT's Bryan District Office.

In addition to the site selection controls and criteria used by Krammes et al. to select study sites, curves for this study were also selected on the basis of background, delineation, and roadway cross-section. For example, each of the sites had trees in the background throughout most of the alignment, and each site used RPMs as a supplemental form of delineation. In terms of roadway cross-section, two sites, both on the same roadway, had 3-foot shoulders with edgelines, two sites just had edgelines, and five sites had neither shoulders nor edgelines.

## **DATA REDUCTION AND ANALYSIS**

Speed data were collected at the locations shown in Figure 1 and described earlier in this chapter. Directional data were collected for two reasons. First, directional data were collected since driver behavior on the inside lane may be different from that of the of the outside lane. Secondly,

TABLE 3 Curve Geometry

Curve #	FM Road	County	Station at PI of Curve	Degree of Curvature	Length (feet)	Total Width (feet)	Lane Width (feet)	1993 ADT	Superelevation at Midpoint of Curve	Inferred Design Speed (mph)
1	FM 974	Brazos	292+57.1	12	528	21.08	9.67	800	0.06	30
2	FM 831	Leon	207+49	12	567	18.83	9.00	260	0.07	40
3	FM 969	Travis	648+15.0	10	804	24.50	10.33	2200	0.11	40
4	FM 969	Bastrop	906+60.4	10	894	22.33	11.75	2200	0.12	40
5	FM 305	Burleson	180+04.16	6	1015	24.25	11.33	900	0.08	50
6	FM 244	Grimes	253+21	6	995	19.58	9.00	730	0.07	55
7	FM 117	Brazos	214+98.2	3	573	22.00	10.92	3700	0.04	65
8	FM 487	Milam	343+95.8	3	673	23.67	12.08	370	0.05	65
9	FM 305	Burleson	262+45.97	3	848	24.17	11.83	900	0.08	70

Curve #	FM Road	Direction of Curve	Preceding Tangent (feet)	Preceding Curve (degrees)	Background	Edgelines and Shoulders	Supplemental Delineation & Signing	Advisory Speed (mph)
1	FM 974	I	586	2	Trees @ MC	Edgelines	Rt. Ang. Sign, Chevrons, RPMs, Directional arrows	30
		O	1687	5		No Shoulders		
2	FM 831	I	854	8	Trees Throughout, No Trees on Inside of Curve	No Edgelines	Curve Signs, PMDs, & RPMs	35
		O	106	2		No Shoulders		
3	FM 969	I	965	1.75	Trees @ MC & Inside Lane Approach	No Edgelines	Grooved Pavement (O), RPMs, & Curve Signs	40
		O	1591	7		No Shoulders		
4	FM 969	I	1760	7.5	Small Trees Throughout	No Edgelines	Narrow Bridge, RPMs, & Curve Signs	45
		O	881	1		No Shoulders		
5	FM 305	I	1578	5	Trees @ MC & Outside Lane Approach	3 ft Shoulder w/ Edgelines	Curve Sign, PMDs, & RPMs	55
		O	2157	2		No Shoulders		
6	FM 244	I	772	1.75	Tree-Lined	No Edgelines	Curve Signs & RPMs	45(I) & 50(O)
		O	1781	1.5		No Shoulders		
7	FM 117	I	1467	3	Tree-Lined	Edgelines	RPMs	--
		O	990	1		No Shoulders		
8	FM 487	I	3546	3	Trees @ MC & on Inside of Curve	No Edgelines	Curve Signs & RPMs	--
		O	2942	2		No Shoulders		
9	FM 305	I	790	3	Tree-Lined	3 ft Shoulder w/ Edgelines	RPMs	--
		O	4805	5		No Shoulders		

Note: (I)--Inside, (O)--Outside, & (MC)--Midpoint of Curve

directional data were needed to ensure that vehicles were not influenced by other vehicles, either oncoming or in the same direction.

The midpoint of the approach tangent was selected as a speed data collection point because by the midpoint of the tangent most drivers have reached their maximum speed both approaching and departing the curve. From the point of tangency of the preceding curve to the midpoint of the approach tangent, it was assumed that most drivers accelerate as they come out of the preceding curve and reach a maximum speed by the midpoint of the approach tangent. Beyond the midpoint of the approach tangent it was assumed that most drivers begin reducing their speed before entering the upcoming horizontal curve.

The midpoint of the curve was selected as the second speed data collection point under the assumption that this point coincides with the minimum speed that most drivers will reach on a tangent-curve section. From the point of curvature to the midpoint of the curve, it was assumed that most drivers decelerate and reach a minimum speed by the midpoint of the curve. After the midpoint of the curve, it was assumed that most drivers begin accelerating as they leave the curve. Also, and more importantly, the midpoint is where previous speed/consistency studies measured speeds on curves.

The raw data collected at each of the eight study sites were carefully screened. First, to keep the characteristics of the driving population similar, only data from midnight Monday mornings to sunrise Friday morning were used. Initially, only data collected on weekdays and weekday nights were to be used in the analysis. This decision was based on several studies including those of David (17) and Pagano (17) where only data collected on weekdays and weekday nights were used for analysis. However, due to the limited number of nighttime vehicles, Monday mornings and Friday mornings were included in the analysis.

Second, any vehicle whose operation might have been affected by other vehicles or whose operation could not be tracked through both speed traps was eliminated. Only those vehicles that could be tracked from the midpoint of the approach tangent to the midpoint of the curve were used in the analysis. This decision was made on the basis that speed reduction is computed as the difference between the operating speed at the midpoint of the approach tangent and the midpoint of the curve (4). The primary variables used for tracking vehicles through the study site were time of actuation and direction of travel. Vehicle lengths and speeds were used when necessary to track a vehicle from one sensor to the next. Vehicles that could not be tracked included vehicles that left the roadway at personal driveways within the study sections, vehicles that did not hit both sensors at any of the data collection points, or vehicles that did not get processed correctly due to equipment error.

Based on previous studies, vehicles were considered to be unaffected by other vehicles in the same direction if there was at least a 10-second headway between vehicles. A vehicle following another vehicle with a headway less than 10 seconds was considered to be following too closely for this study. Drivers closely following another vehicle in their lane have visual cues from the leading

vehicle as well as from the roadway delineation to guide them through a curve (19). Drivers closely following another vehicle may also not be able to attain their desired speeds

Vehicles were also considered to be affected by other vehicles if they were within the curve during the same time as vehicles in the opposing lane. Illumination from the headlights of oncoming vehicles affects driver behavior through curves (19). In cases where vehicles were within the curve during the same time as vehicles in the opposing lane, both vehicles were removed from the data set. For this study, this determination was made by examining the time actuations of vehicles in both directions at the midpoint of the curve. For this study, a vehicle was considered to be within the curve at the same time if it crossed the midpoint of the curve at the same time or within 10 seconds of a vehicle in the opposing direction.

The desired sample size for each curve-tangent section was 100 vehicles. This sample size was selected based on a previous study where it was estimated that a sample size of approximately 50 vehicles would be required with each treatment at each site in order to detect a 2-mph difference in mean speeds with 95 percent confidence (19). In several instances, the desired sample size of screened vehicles was not collected for each curve-tangent section for either one or both light conditions. This was often a result of:

- Logistical constraints;
- Equipment failure/vandalism; and
- Low ADTs at night.

A 0.05 significance level was selected for all statistical tests. The significance level is the probability that the differences observed are due to the natural variability among the vehicles observed and are not the result of real differences. If the probability is greater than 0.05, then the data does not provide sufficient evidence to conclude that there is a statistically significant difference between the conditions tested. SAS was the primary tool used for statistical analysis. Specifically, analysis of variance and t-tests were selected as the primary statistical tests.

Analysis of variance (ANOVA) was used to test three main effects: site, light condition, and direction of travel. Main effects used as independent variables test the hypothesis that the mean of the dependent variable (speed at the midpoint of the approach tangent, speed at the midpoint of the curve, and the speed change from the midpoint of the approach tangent to the midpoint of the curve) is the same for each level of the factor in question, ignoring the other independent variables in the model (26). The ANOVA also considered interaction terms. Interaction terms in a model test the hypothesis that the effect of a factor does not depend on the levels of the other factors in the interaction (26). In addition to the ANOVA, two-sample, two-tailed pooled t-tests were used to compare the daytime and nighttime mean operating speeds at the midpoint of the approach tangents and at the midpoint of the curves by direction of travel on a site-by-site basis. The mean daytime and nighttime speed changes were also compared in the same manner. Each t-test was also used to determine whether the daytime and nighttime means came from populations with equal variances. After a determination was made, the appropriate t-value and p-value for each comparison were selected.



## 4. RESULTS

This chapter is divided into four sections. The first section reports the speed data sample sizes used at each site. The second section documents the results of several analysis of variance tests where the effects of site, light condition, and direction of travel were considered. The third section compares daytime and nighttime mean operating speeds by lane and by site.

### SAMPLE SIZES

This section summarizes the vehicle sample sizes used in the analysis. The sample sizes are shown in Table 4 by degree of curvature, and in Table 5 by farm-to-market road. Due to extensive data screening, the vehicle sample sizes shown are considerably less than those actually collected. It should also be noted that only 2-axle vehicles were included in the database for analysis.

TABLE 4 Sample Sizes After Screening by Degree of Curvature

Degree of Curvature	Total Vehicles	Day Vehicles	Night Vehicles	Inside Lane Vehicles	Outside Lane Vehicles
3	1772	900	872	899	873
6	1082	682	400	554	528
10	969	494	475	479	490
12	598	333	265	266	332

### ANOVA RESULTS: SITE, LIGHT CONDITION, LANE

Analysis of variance tests (ANOVA) were performed using SAS procedure PROC GLM to model the speed at the midpoint of the approach tangent, the speed at the midpoint of the curve, and the speed change between the two locations in terms of three variables: site, light condition, and lane. The tests were conducted to examine whether the differences in mean speed for the eight sites, the two light conditions (day and night), and the two lanes of approach (inside lane and outside lane) were significantly different. A three-way ANOVA with interactions was performed for each of the three speed measurements. Table 6 below shows the variables and interaction terms that were significant. The f-statistics and p-values for the variables and interaction terms of the three ANOVA tests are shown in Table A-1 of the appendix.

Site was selected as one of the main effects so that all of the study sites could be analyzed together without prematurely grouping any of the curves based on geometric features. This is especially important since degree of curvature was the main control when selecting curves. Light condition was selected as a main effect because it is the objective of this thesis to determine if there is a difference between daytime and nighttime speeds. Lastly, lane was selected as a main effect to determine if each curve should be evaluated as two independent tangent-curve sections. The decision to use lane as a main effect was based on the study of Collins (14) where each direction of travel was treated as a separate site and the findings of Stimpson (16) where 20 percent of the location differences were statistically significant for both light condition and direction of travel.

TABLE 5 Sample Sizes After Screening by Site

Site	Total (veh)	Day (veh)	Night (veh)	Inside (veh)	Outside (veh)	Day & Inside (veh)	Day & Outside (veh)	Night & Inside (veh)	Night & Outside (veh)
FM 1179--3°	754	325	429	390	364	195	130	195	234
FM 3058--3°	508	284	224	255	253	124	160	131	93
FM 487--3°	510	291	219	254	256	149	142	105	114
FM 244--6°	497	275	222	259	238	132	143	127	95
FM 3058--6°	585	407	178	295	290	209	198	86	92
FM 969(B)--10°	441	210	231	215	226	101	109	114	117
FM 969(T)--10°	528	284	244	264	264	125	159	139	105
FM 974--12°	598	333	265	266	332	108	225	158	107

(B)--Bastrop County; (T)--Travis County

TABLE 6 Summary of ANOVA Results--Significant Variables

Variables & Interaction Terms	Midpoint of Approach Tangent	Midpoint of Curve	Speed Change
Site	X	X	X
Lane (Inside, Outside)	X	X	
Site*Lane	X	X	X
Light Condition (Day, Night)		X	X
Site*Light	X	X	
Lane*Light			
Site*Lane*Light	X	X	X

As can be seen in Table 6, site was statistically significant for all three speed measurements. Based on the results of the Duncan post-hoc test, shown in Table 7, there is no obvious pattern that explains the statistically significant differences at the midpoint of the approach tangent.

TABLE 7 Duncan's Multiple Range Tests

Duncan Grouping for Speed at Midpoint of Approach Tangent					Duncan Grouping for Speed at Midpoint of Curve				Duncan Grouping for Speed Change From Tangent to Curve			
Duncan Grouping	Mean	Site	Degree of Curvature	Duncan Grouping	Mean	Site	Degree of Curvature	Duncan Grouping	Mean	Site	Degree of Curvature	
	A	61.95	FM 3058	3	A	61.17	FM 3058	3	A	9.72	FM 3058	12
	B	60.88	FM 3058	6	B	57.05	FM 3058	6	B	8.84	FM 3058	10
	C	58.34	FM 244	6	C	54.44	FM 1179	3	C	6.38	FM 244	10
D	C	57.47	FM 969(T)	10	D	52.89	FM 244	6	D	5.46	FM 969(T)	6
D	E	56.56	FM 487	3	D	52.83	FM 487	3	E	3.83	FM 487	6
D	E	56.54	FM 969(B)	10	E	50.16	FM 969(B)	10	E	3.73	FM 969(B)	3
D	E	56.27	FM 1179	3	F	48.64	FM 969(T)	10	F	1.84	FM 1179	3
	F	53.12	FM 974	12	G	43.40	FM 974	12	G	0.78	FM 974	3

(B)--Bastrop County; (T)--Travis County

At the midpoint of the curve, however, there appears to be a threshold between the 3° and 6° curves and the 10° and 12° curves. For the speed change from the midpoint of the approach tangent to the midpoint of the curve, the Duncan post-hoc test indicates that the larger speed reductions are associated with the sharper curves. In addition the curves are perfectly ordered by degree of curvature, with the 12° curve having the largest speed reduction.

Table 6 also shows that site and the three interaction terms where site is a variable were significant at the midpoint of the approach tangent, and at the midpoint of the curve. For speed change, site and two interaction terms were significant: site\*lane and site\*lane\*light condition.

In addition to the significance of site, the main effect of lane was significant at the midpoint of the approach tangent and at the midpoint of the curve. The main effect of light condition was significant at the midpoint of the curve and for the speed change from tangent to curve.

Therefore, based on the significance of all three main effects, especially site, and the objective of this thesis which is to compare daytime and nighttime speeds, the next section of this chapter describes the results of a site-by-site analysis where daytime and nighttime speeds were compared by lane. This site-by-site analysis serves to explain the results of the ANOVA.

## **COMPARISON OF DAYTIME AND NIGHTTIME MEAN OPERATING SPEEDS**

As stated before, the objectives of this thesis were to determine if a statistically significant difference existed between:

- Daytime and nighttime operating speeds at the midpoint of the approach tangents to curves with a degree of curvature between 3° and 12°;
- Daytime and nighttime operating speeds at the midpoint of horizontal curves, for curves with a degree of curvature between 3° and 12°; and
- Daytime and nighttime speed change between the midpoint of the approach tangents and the midpoint of horizontal curves, for curves with a degree of curvature between 3° and 12°.

In order to compare daytime values to nighttime values, statistical hypothesis testing was performed. First, mean speeds and standard deviations were calculated. The mean speeds and standard deviations are shown in tabular form by site, lane, and light condition in Tables A-2 and A-4 of the appendix, respectively. Next, the daytime and nighttime mean operating speeds and speed reductions were compared using two-sample, two-tailed pooled t-tests. The null hypothesis for each of the t-tests was that the difference between the mean daytime operating speed and mean nighttime operating speed was equal to zero. The alternative hypothesis was that the differences were not equal to zero. For each t-test, SAS generated t-statistics and p-values for samples with equal and unequal variances. Therefore, the F-statistic was used to determine whether the daytime and nighttime means came from populations with equal or unequal variances. The appropriate t-statistic and p-value for each sample are shown in Table A-3 of the appendix. The F-statistics and p-values are shown in Table A-5 of the appendix. Following are the results of the analysis.

### Speed at the Midpoint of the Approach Tangents

Figures 2 and 3 illustrate the daytime and nighttime means and standard deviations of operating speeds in the outside lane at the midpoint of the approach tangents. The mean nighttime operating speed was higher at four sites, where as the mean daytime operating speed was higher at the remaining four sites. However, the results of the t-tests indicate that the differences between the mean daytime and mean nighttime speeds were statistically significant at only two sites: FM 969 (Travis Co.), and FM 974. The mean daytime speed was higher at both sites. A summary of the significant differences found between daytime and nighttime speeds are shown in Table 8.

TABLE 8 Significant Differences at the Midpoint of the Approach Tangent

Site	Degree of Curvature	MEAN		STANDARD DEVIATION	
		Outside Lane	Inside Lane	Outside Lane	Inside Lane
FM 1179	3			D	
FM 3058	3		N		
FM 487	3		D	D	
FM 244	6				
FM 3058	6		N		D
FM 969 (B)	10		D	D	
FM 969 (T)	10	D			
FM 974	12	D			

N--Nighttime Speed Higher; D--Daytime Speed Higher; B--Bastrop County; T--Travis County;  $\alpha = 0.05$ .

The average difference in speed between the mean daytime speed and the mean nighttime speed at the two sites was 2.5 mph. No relationship between these tangent locations could be found.

The daytime and nighttime standard deviation of speeds at the midpoint of the approach tangents to curves in the outside lane were compared using F-tests. The results of the F-tests indicate that there was significantly more variability during the day than at night at three sites: FM 1179, FM 487, and FM 969 (B).

Figures 4 and 5 illustrate the daytime and nighttime means and standard deviations of operating speeds in the inside lane at the midpoint of the approach tangents. The mean nighttime operating speed was higher at three of the eight sites, while the mean daytime operating speed was higher at the remaining five sites. However, results of the t-tests indicate that the differences between the mean daytime and mean nighttime speeds were only statistically significant at FM 3058 (3°), FM 487, FM 3058 (6°), and FM 969 (B). Of these four sites, half exhibited a higher mean nighttime operating speed and half exhibited a higher mean daytime operating speed. The differences between the two speeds for these four sites ranged from 3.8 mph to 1.8 mph.

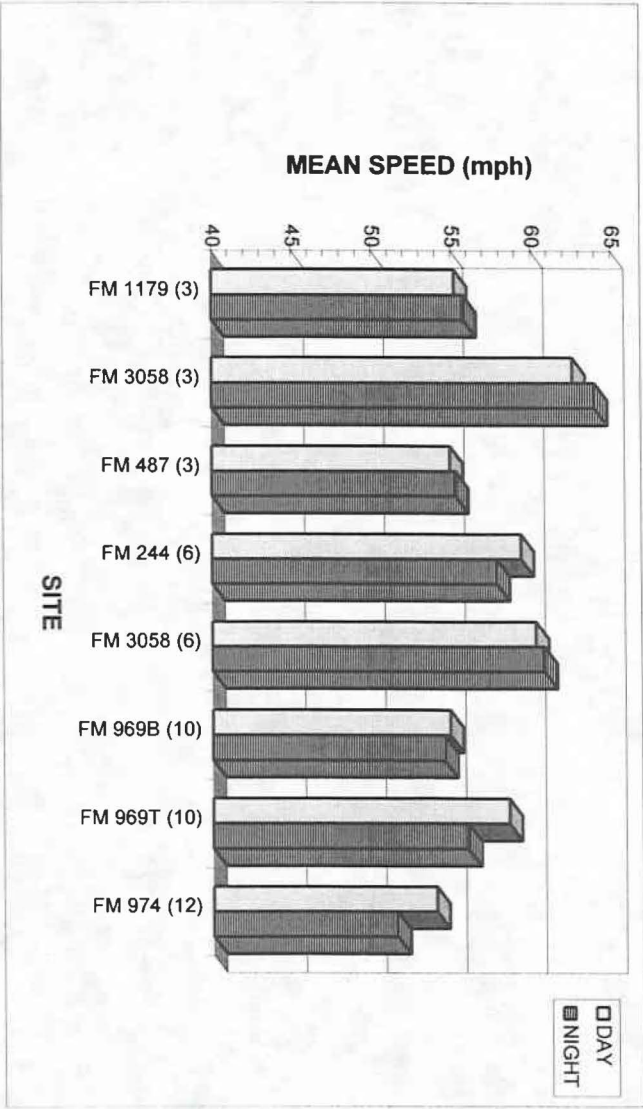


FIGURE 2 Mean Speed at Midpoint of Tangent--Outside Lane

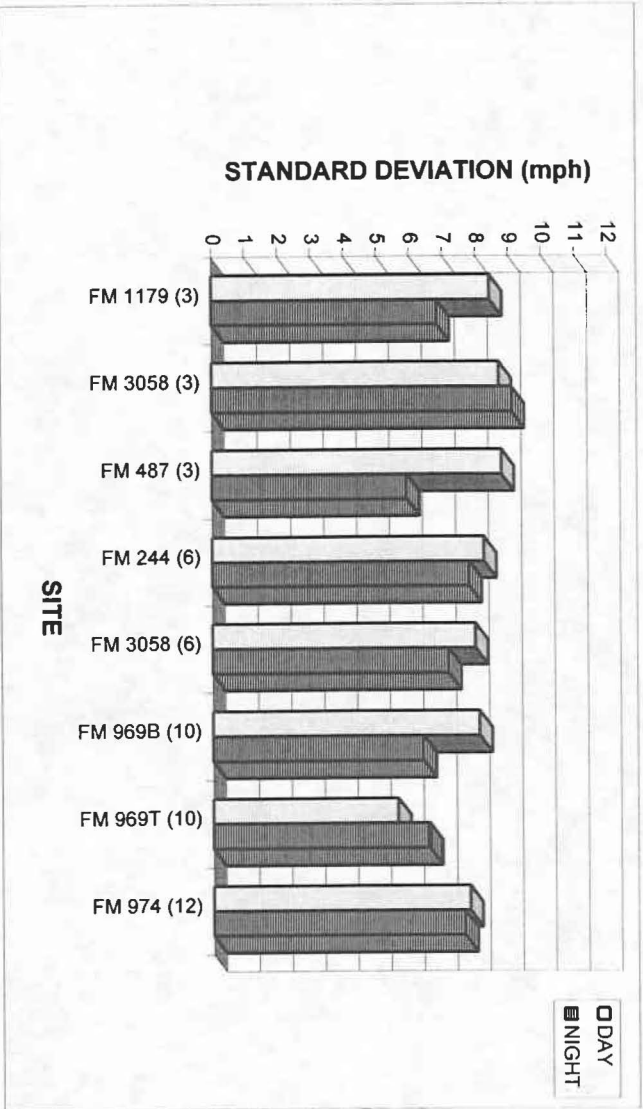


FIGURE 3 Standard Deviation at Midpoint of Tangent--Outside Lane

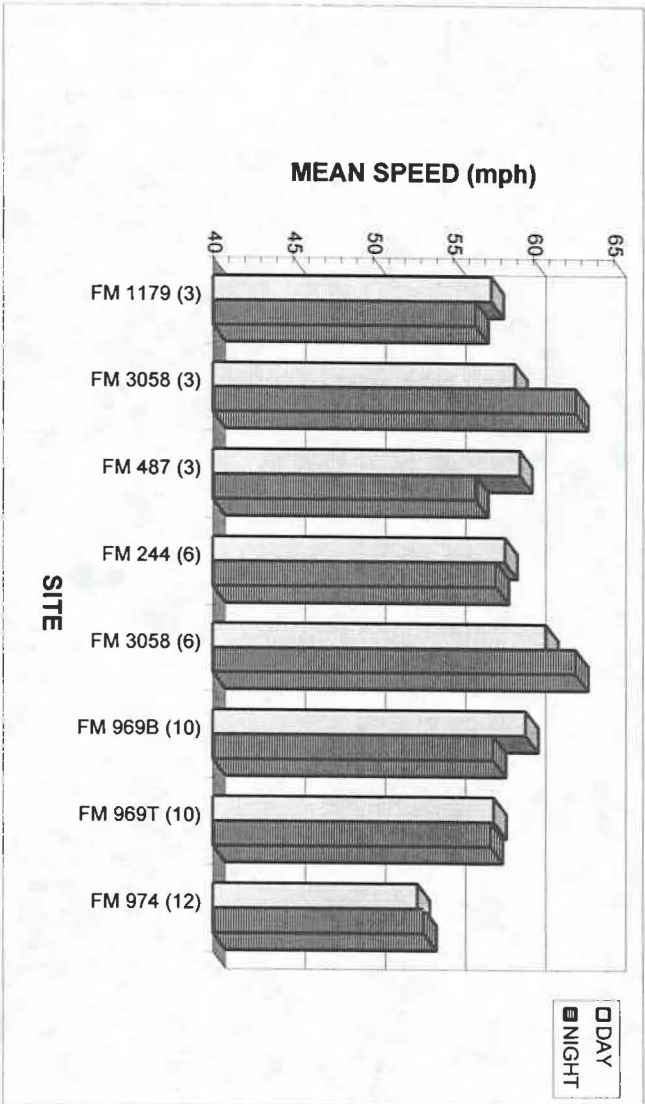


FIGURE 4 Mean Speed at Midpoint of Tangent--Inside Lane

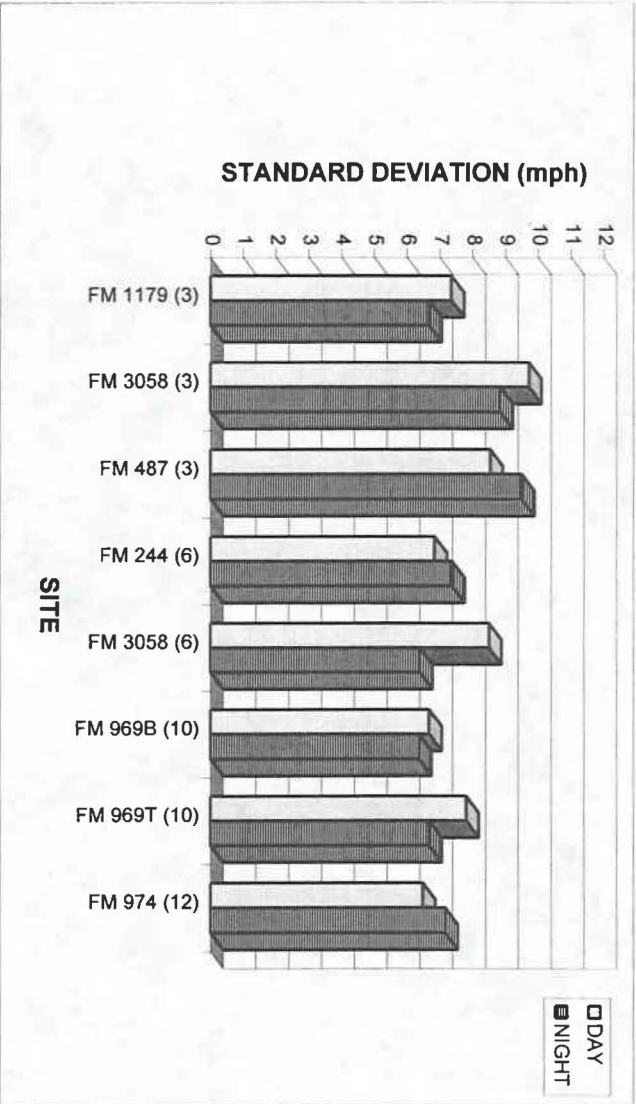


FIGURE 5 Standard Deviation at Midpoint of Tangent--Inside Lane

The only pattern that could be found is the fact that both curves on FM 3058, the only sites with shoulders, had mean speeds at the tangent that were higher at night than during the day. Also of interest is the fact that for each FM road, daytime and nighttime mean tangent speeds were either not significant, significant only on the outside lane, or significant only on the inside lane.

The results of the F-tests used to compare the daytime and nighttime standard deviation of speeds at the midpoint of the approach tangents to curves in the inside lane indicate that there was significantly more variability during the day than at night only at the site on FM 3058 (6°).

### Speed at the Midpoint of the Curves

Figures 6 and 7 illustrate the daytime and nighttime means and standard deviations of operating speeds in the outside lane at the midpoint of curve. The mean nighttime operating speed was higher at three of the eight sites, whereas the mean daytime operating speed was higher at the remaining five sites. However, the results of the t-tests indicate that the differences between the mean daytime and mean nighttime speeds were statistically significant at only four sites. These results and a summary of the significant differences found between daytime and nighttime speeds at the midpoint of the curve are shown in Table 9.

Significant differences at the midpoint of the curve on the outside lane were found at FM 244, FM 969 (B), FM 969 (T), and FM 974. In all four cases, the daytime speed was higher than the nighttime speed. In addition, these four sites include the three sharpest curves with all four curves having a degree of curvature of at least 6°. A possible explanation for the differences between the means is that drivers might have had difficulty seeing enough of the road in front of them at night. AASHTO states “drivers must see the road directly in front of their vehicles and far enough in advance to predict with a high degree of accuracy the alignment, grade, width, and other related aspects of the roadway.”

TABLE 9 Significant Differences at the Midpoint of the Curve

Site	Degree of Curvature	MEAN		STANDARD DEVIATION	
		Outside Lane	Inside Lane	Outside Lane	Inside Lane
FM 1179	3			D	D
FM 3058	3		N		
FM 487	3		D		N
FM 244	6	D		N	
FM 3058	6		N		D
FM 969 (B)	10	D	D		
FM 969 (T)	10	D			
FM 974	12	D	D		

N--Nighttime Speed Higher; D--Daytime Speed Higher; B--Bastrop County; T--Travis County;  $\alpha=0.05$ .

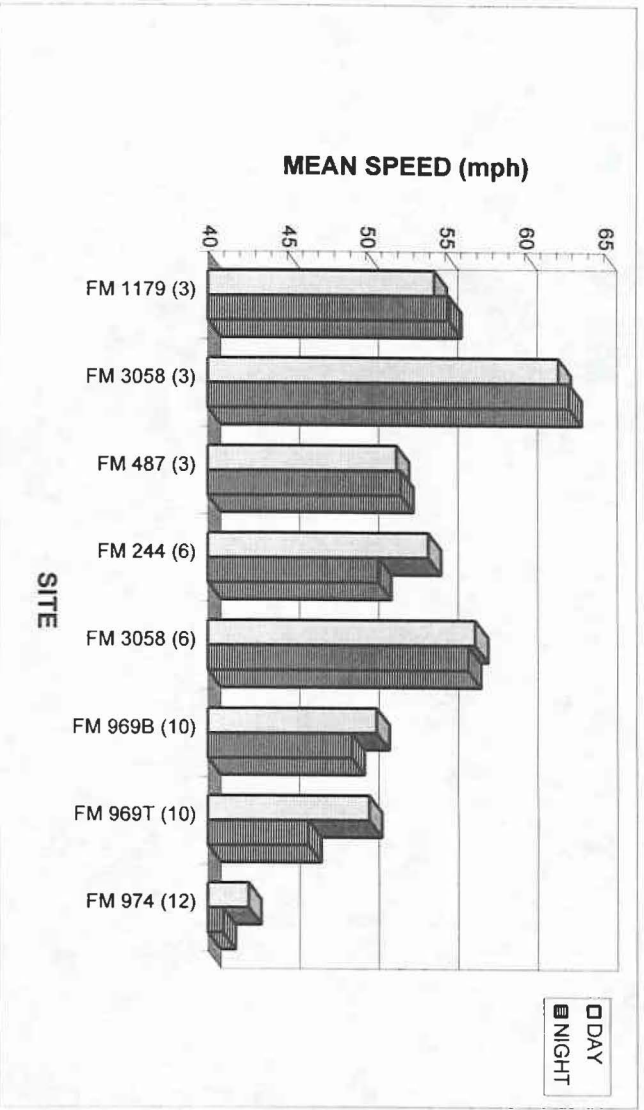


FIGURE 6 Mean Speed at Midpoint of Curve--Outside Lane

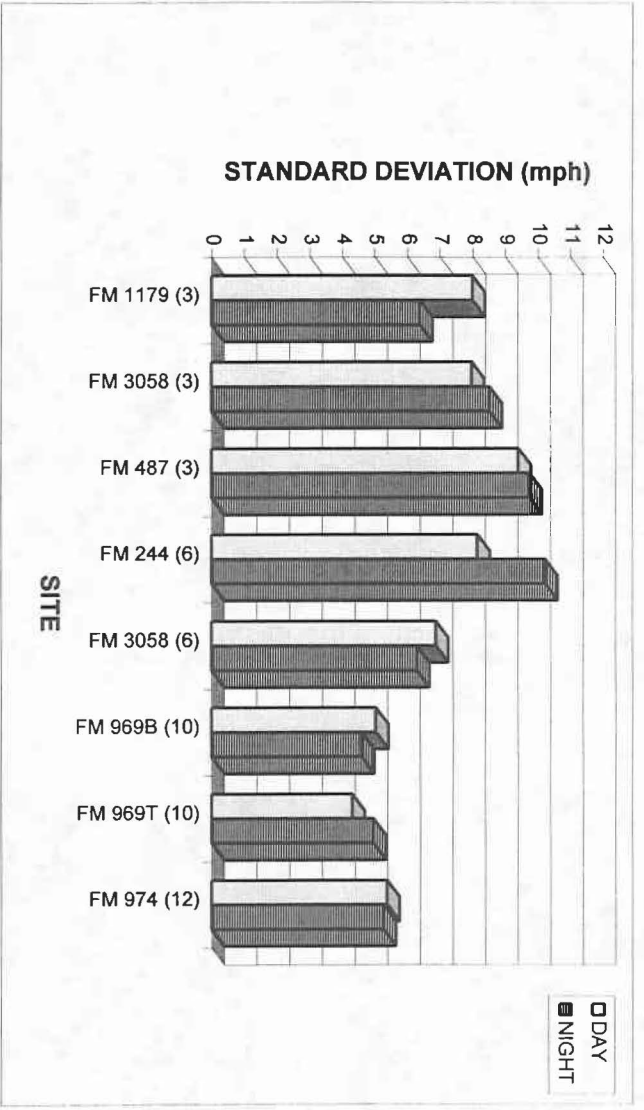


FIGURE 7 Standard Deviation at Midpoint of Curve--Outside Lane

The daytime and nighttime standard deviation of speeds at the midpoint of curves indicated that there were significant differences only at FM 1179 and FM 244. On FM 1179 the greater variability in speeds occurred during the day. On FM 244 there was greater variability in speeds at night.

Figures 8 and 9 illustrate the daytime and nighttime means and standard deviations of operating speeds in the inside lane at the midpoint of the curve. The results of the t-tests indicate that the difference between the mean daytime and mean nighttime speed was statistically significant at five sites: FM 3058 (3°), FM 487, FM 3058 (6°), FM 969 (B), and FM 974. These five sites represent all four degree of curvature categories. At FM 487, FM 969 (B) and FM 974 the daytime mean speed on the inside lane was significantly higher than the nighttime mean speed. FM 969 (B) and FM 974 also had a mean daytime speed that was statistically higher on the outside lane. As noted before, this may be due to drivers' difficulty in assessing the alignment at these two curves at night. At both curves on FM 3058, the only sites with shoulders, the nighttime mean speed on the outside lane was significantly higher than the daytime mean speed.

The results of the F-tests used to compare the daytime and nighttime standard deviation of the speeds at the midpoint of the curve in the inside lane indicate that there was significantly more variability during the day than at night at only two sites: FM 1179 and FM 3058 (6°). On FM 487 there was more variability at night.

### **Speed Reduction from the Midpoint of the Tangent to the Midpoint of the Curve**

Figures 10 and 11 illustrate the daytime and nighttime means and standard deviations of speed reductions that occurred from the midpoint of the approach tangent to the midpoint of the curve in the outside lane. The mean nighttime speed reduction was greater at six of the eight sites, where as the mean daytime operating speed was higher only at two sites. However, the results of the t-tests indicate that the differences between the mean daytime and mean nighttime speeds were statistically significant at only three sites. These results and a summary of the significant differences found between the daytime and nighttime speed reductions from the midpoint of the approach tangent to the midpoint of the curve are shown below in Table 10.

Significant differences between the mean daytime and nighttime speed change on the outside lane occurred at the following sites: FM 3058 (3°), FM 3058 (6°), and FM 969 (T). At all three of these sites, the mean nighttime speed reduction was greater than the mean daytime speed reduction. The differences between the daytime and nighttime speed reductions (nighttime speed reduction minus daytime speed reduction) were 0.7 m.p.h., 1.0 m.p.h., and 1.3 m.p.h, respectively. The only pattern that is evident is the fact the nighttime speed reduction was significantly higher for the only two curves with shoulders.

The standard deviations of the mean daytime and nighttime speed reductions showed significant differences at six sites: FM 3058 (3°), FM 487, FM 244, FM 3058 (6°), FM 969 (B), and FM 969 (T).

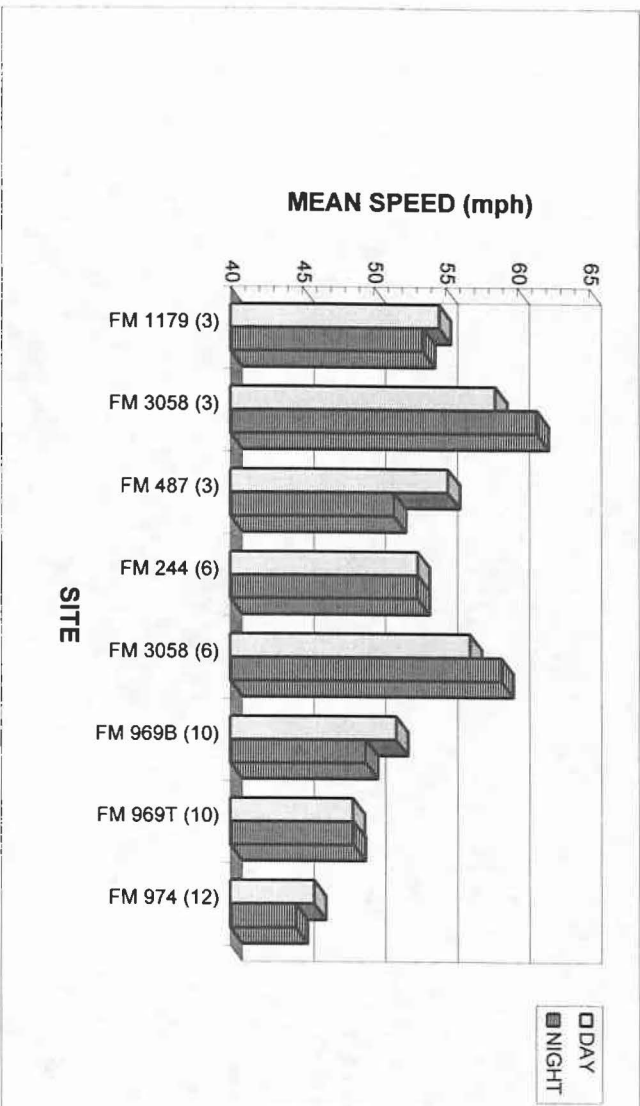


FIGURE 8 Mean Speed at Midpoint of Curve--Inside Lane

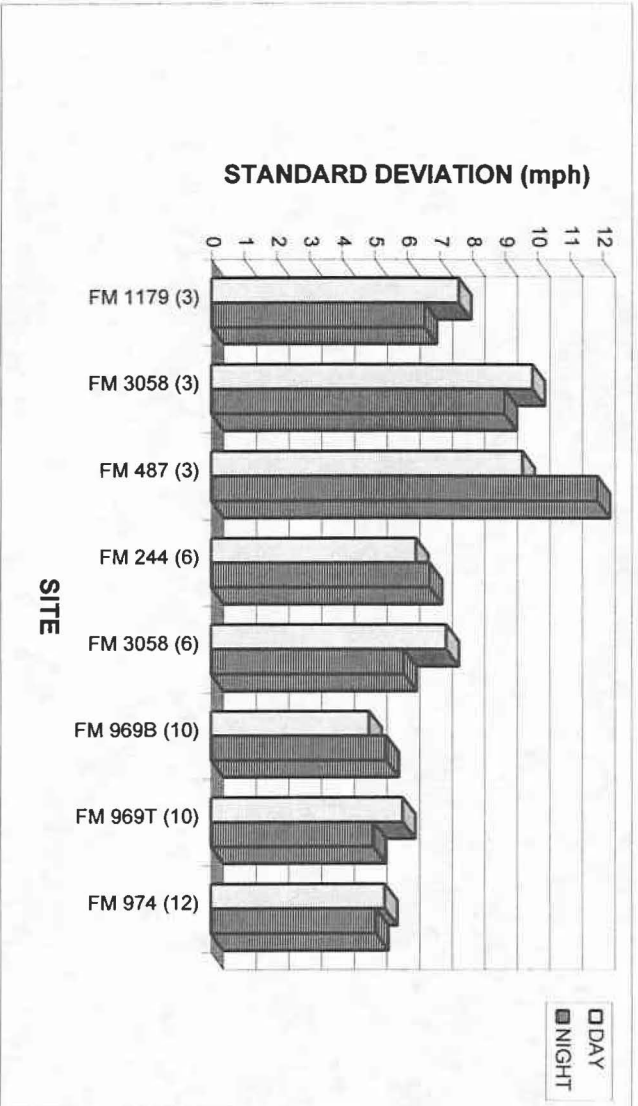


FIGURE 9 Standard Deviation at Midpoint of Curve--Inside Lane

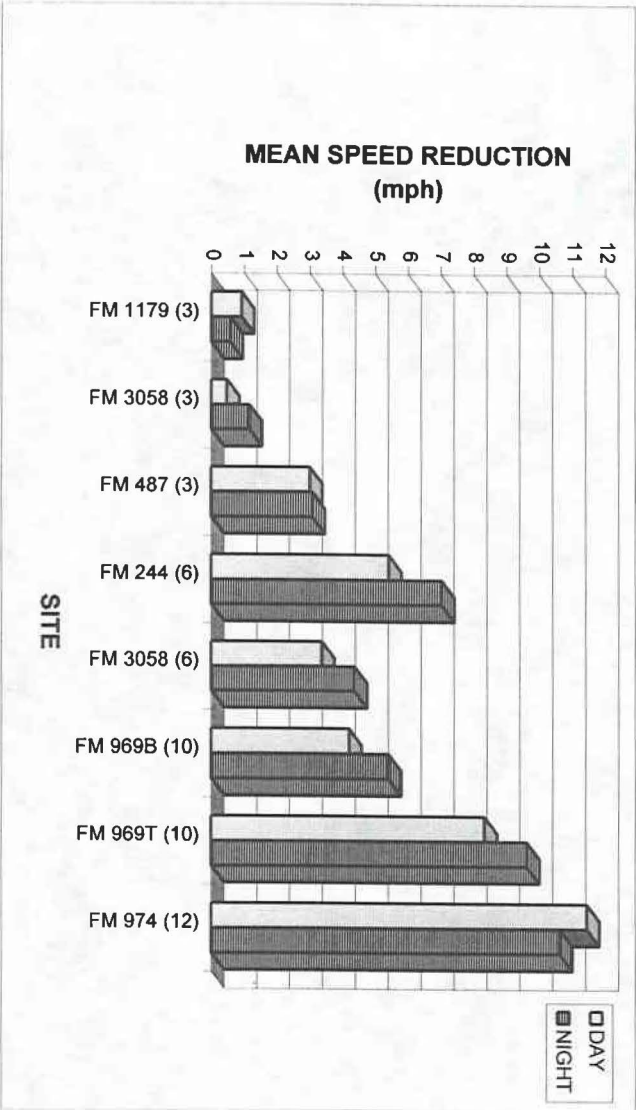


FIGURE 10 Mean Speed Reduction--Outside Lane

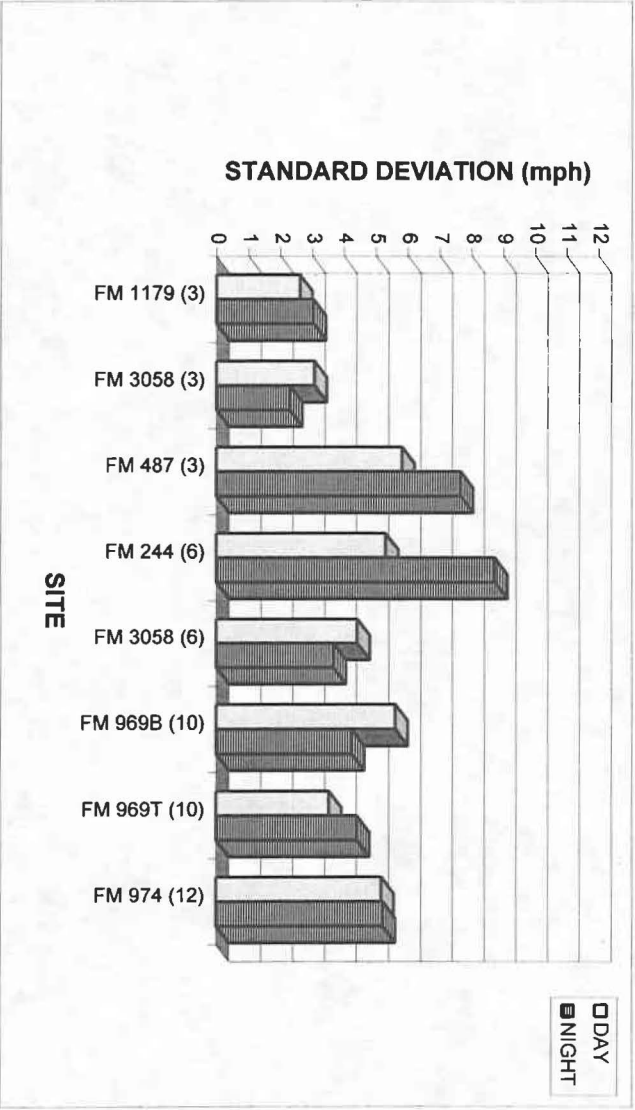


FIGURE 11 Standard Deviation of Speed Reductions--Outside Lane

TABLE 10 Significant Differences in Speed Reduction From Midpoint of Approach Tangent to Midpoint of Curve

Site	Degree of Curvature	MEAN		STANDARD DEVIATION	
		Outside Lane	Inside Lane	Outside Lane	Inside Lane
FM 1179	3				N
FM 3058	3	N	N	D	
FM 487	3			N	N
FM 244	6			N	
FM 3058	6	N		D	D
FM 969 (B)	10			D	
FM 969 (T)	10	N		N	
FM 974	12		N		

N--Nighttime Speed Higher; D--Daytime Speed Higher; B--Bastrop County; T--Travis County;  $\alpha = 0.05$ .

Half of these sites exhibited a larger variability at night, and half exhibited a larger variability during the day. Breaking this down further, there were two curves for each degree of curvature represented (3°, 6°, and 10°); and for each degree of curvature, one curve had a higher variability in speed reduction during the day and the other curve had a higher variability in speed reduction at night.

Figures 12 and 13 illustrate the daytime and nighttime means and standard deviations of speed reductions that occurred from the midpoint of the approach tangent to the midpoint of the curve in the inside lane. The mean nighttime speed reduction was greater at five of the eight sites, while the mean daytime operating speed was higher at three sites. However, the results of the t-tests indicate that the difference between the mean daytime and mean nighttime speed were statistically significant at only two sites: FM 3058 (3°), and FM 974. Both sites had a larger mean speed reduction at night. The differences between the nighttime and daytime mean speed reductions (nighttime speed reduction minus daytime speed reduction) were 0.9 m.p.h. and 1.7 m.p.h., respectively. Once again one of the two curves is on FM 3058, the only roadway with shoulders.

The standard deviations of the mean daytime and nighttime speed reductions were significantly different at FM 1179, FM 487, and FM 3058 (6°). FM 1179 and FM 487 exhibited a larger variability at night, and FM 3058 exhibited a larger variability during the day.

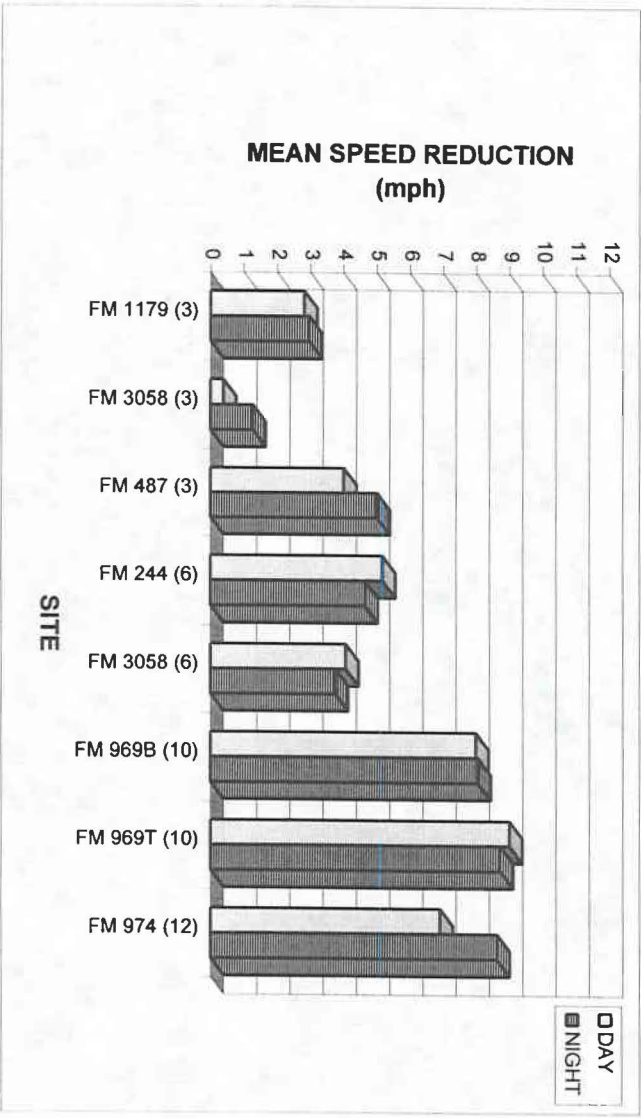


FIGURE 12 Mean Speed Reduction--Inside Lane

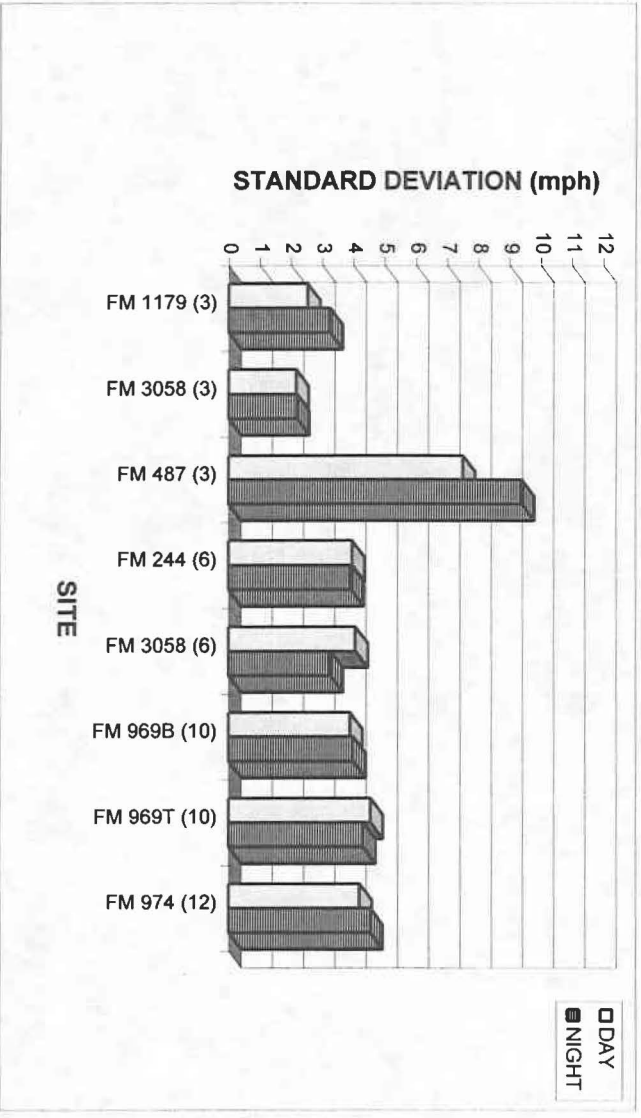


FIGURE 13 Standard Deviation of Speed Reductions--Inside Lane

## Summary

Findings regarding the comparison of daytime and nighttime mean speeds at the midpoint of approach tangent to curves for curves with a degree of curvature between 3° and 12° are as follows:

- 37 percent (6 of 16) of the tangent-curve sections exhibited a statistically significant difference.
- Of the six tangent-curve sections with statistically significant differences, two had a higher nighttime mean speed, and four had a higher daytime mean speed.
- Of the six tangent-curve sections with statistically significant differences, two occurred on the outside lane, and four occurred on the inside lane.
- Even though all four degrees of curvature were represented by the six tangent-curve sections, no discernible pattern for the results could be found

Findings regarding the comparison of daytime and nighttime mean speeds at the midpoint of curves for curves with a degree of curvature between 3° and 12° are as follows:

- 56 percent (9 of 16) of the tangent-curve sections had a mean daytime speed that differed from the mean nighttime speed.
- Of the nine tangent-curve sections with statistically significant differences, two had a higher nighttime mean speed, and seven had a higher daytime mean speed.
- Of the nine tangent-curve sections with statistically significant differences, four occurred on the outside lane, and five occurred on the inside lane.
- Of the four tangent-curve sections with statistically significant differences on the inside lane, all had a higher daytime speed. No other discernible patterns for the results could be found.

Findings regarding the comparison of the daytime and nighttime speed reduction from the midpoint of the approach tangent to the midpoint of the curve for curves with a degree of curvature between 3° and 12° are as follows:

- 31 percent (5 of 16) of the tangent-curve sections had a mean daytime speed reduction that differed from the mean nighttime speed reduction.
- All five tangent-curve sections with statistically significant differences had a larger speed reduction at night. For these five curves, the difference between the nighttime and daytime speed reduction ranged from 0.7 to 1.7 mph and averaged 1.1 mph.
- Of the five tangent-curve sections with statistically significant differences, three occurred on the outside lane, and two occurred on the inside lane.
- All four degrees of curvature were represented by the five tangent-curve sections.
- 3 of the 5 tangent-curve sections were on FM 3058, the only roadway where data were collected that had a shoulder.



## 5. SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

In 1988, the Federal Highway Administration designated Highway Safety Design Practices and Criteria as a high-priority research and development area. With this designation, the Interactive Highway Safety Design Model was begun. The most recent version of the Model consists of a consistency module which will be based on speed profiles, since large changes in speed between successive roadway sections are believed to contribute to accidents (2).

In order to guarantee a consistent design, designers must consider both daytime and nighttime speed behavior on rural horizontal alignments. Previous consistency studies, however, only focused on daytime conditions. Therefore, this study focused on both daytime and nighttime conditions.

This study was designed to determine if a statistically significant difference exists between: (1) daytime and nighttime operating speeds at the midpoint of the approach tangents to curves, (2) daytime and nighttime operating speeds at the midpoint of horizontal curves, and (3) daytime and nighttime speed reductions that occur from the midpoint of the approach tangents to the midpoint of horizontal curves.

### SUMMARY

Vehicle spot speed data were collected at a sample of nine horizontal curves and their approach tangents on rural two-lane highways in the U.S. Vehicle speed measurements were made using piezoelectric sensors at the midpoint of each approach tangent and at the midpoint of each curve for both approaches. A time stamp was recorded for each vehicle passing through the sensors as well as number of axles, spacing between axles, and direction of travel. Vehicles were tracked from the midpoint of the approach tangent to the midpoint of the curve. From these measurements, speed change was calculated by subtracting each vehicle's speed at the midpoint of the curve from its speed on the approach tangent. Only free-flow, 2-axle vehicles that did not encounter an oncoming vehicle within the test section and whose speeds were recorded at both locations were included in the database for analysis.

Hypothesis tests were performed in an effort to compare daytime and nighttime speeds. Plots of mean speed and standard deviation comparing daytime and nighttime speeds by lane at the midpoint of the approach tangent, and at the midpoint of the curve were generated for each tangent-curve section. Plots comparing the mean daytime and nighttime speed reduction and standard deviation by lane were also generated for each tangent-curve section.

Results were mixed and varied by site. Significant differences were found at some sites, but not at other sites. However, no trend in roadway geometry was found between those tangent-curve sections that had daytime and nighttime speeds that were statistically significant and those that were not statistically significant. Thirty-seven percent of the 16 daytime and nighttime mean speed comparisons at the midpoint of the approach tangent were statistically significant. Fifty-six percent of the 16 daytime and nighttime mean speed comparisons at the midpoint of the curve were statistically significant. Thirty-one percent of the 16 daytime and nighttime mean speed reduction

comparisons were statistically significant. In all cases the magnitude of the differences between the daytime and nighttime speeds were small.

## CONCLUSIONS

Based on the findings of this research, the following conclusions have been drawn:

- T-tests comparing daytime and nighttime means showed that 20 of the 48 comparisons, 42 percent, were significantly different. Nine out of the twenty instances where there were significant differences occurred at the midpoint of the curves.
- F-tests comparing the variability between all 48 daytime and nighttime speed pairs showed that most of the differences in variability occurred at 3° and 6° curves. Out of the 20 instances where there were significant differences, 75 percent (15 of 20) occurred at 3° and 6° curves.
- No trend in roadway geometry was found between those tangent-curve sections that had daytime and nighttime speeds that were statistically significant and those that were not statistically significant.

## RECOMMENDATIONS

It is the recommendation of this study that a variable accounting for daytime and nighttime driving habits is not needed for operating-speed-based profile modeling for horizontal alignment design consistency evaluation. This recommendation is based on the following facts:

1. Differences at the midpoint of the approach tangent for tangent-curve sections where the mean daytime and nighttime speeds were statistically significant ranged in value from -3.8 mph to 2.7 mph. (Negative values indicate higher nighttime speed). The average of the magnitudes of the significant differences was 2.6 mph.
4. Differences at the midpoint of the curve for tangent-curve sections where the mean daytime and nighttime speeds were statistically significant ranged in value from -2.9 mph to 3.8 mph. The average of the magnitudes of the differences was 2.5 mph.
3. Differences in speed reduction where the mean daytime and nighttime speed values were statistically significant ranged in value from -1.7 mph to -0.7 mph. The average of the magnitudes of the differences was 1.1 mph.

As can be clearly seen by points 1 through 3, the magnitude of the difference between daytime and nighttime speeds is small for all degrees of curvature and does not warrant adding an additional variable to operating-speed-based profile models.

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**APPENDIX**  
**STATISTICAL ANALYSIS OUTPUT**

TABLE A-1. F-Statistics &amp; P-Values from ANOVA

Variable	Midpoint of Tangent		Midpoint of Curve		Speed Reduction	
	F-Statistic	P-Value	F-Statistic	P-Value	F-Statistic	P-Value
Site	74.84	0.0001	295.22	0.0001	241.81	0.0001
Lane	11.42	0.0007	5.52	0.0188	3.75	0.0529
Site*Lane	7.95	0.0001	7.71	0.0001	25.12	0.0001
Light Condition	1.37	0.2424	10.99	0.0009	10.14	0.0015
Site*Light Condition	4.30	0.0001	4.86	0.0001	0.50	0.8377
Lane*Light Condition	0.91	0.3393	2.49	0.1149	0.73	0.3914
Site*Lane*Light Condition	2.82	0.0063	4.89	0.0001	3.66	0.0006

TABLE A-2. Mean Speeds

Site	Degree of Curvature	Inferred Design Speed at Midpoint of Curve (mph)	Lane	Mean Speeds at Midpoint of Tangent			Mean Speeds at Midpoint of Curve			Mean Speed Reductions		
				Day (mph)	Night (mph)	Day-Night (mph)	Day (mph)	Night (mph)	Day-Night (mph)	Day (mph)	Night (mph)	Day-Night (mph)
1179	3	65	Inside	57.38	56.43	0.95	54.56	53.46	1.10	2.82	2.97	-0.15
			Outside	55.24	55.80	-0.56	54.32	55.22	-0.90	0.92	0.57	0.35
3058	3	70	Inside	58.87	62.64	3.77 **	58.48	61.37	-2.89 **	0.39	1.27	-0.88 **
			Outside	62.60	63.97	-1.37	62.13	62.81	-0.68	0.47	1.16	-0.69 **
487	3	65	Inside	59.18	56.44	2.74 **	55.17	51.42	3.75 **	4.01	5.01	-1.00
			Outside	54.93	55.28	-0.35	51.93	52.20	-0.27	3.00	3.08	-0.08
244	6	55	Inside	58.25	57.72	0.53	53.08	53.08	0.00	5.17	4.64	0.53
			Outside	59.34	57.82	1.52	53.93	50.80	3.13 **	5.41	7.02	-1.61
3058	6	50	Inside	60.80	62.65	1.85 **	56.72	58.89	-2.17 **	4.07	3.76	0.31
			Outside	60.24	60.78	-0.54	56.88	56.43	0.45	3.37	4.36	-0.99 **
969-B	10	40	Inside	59.55	57.53	2.02 **	51.57	49.48	2.09 **	7.98	8.05	-0.07
			Outside	54.87	54.52	0.35	50.66	49.11	1.55 **	4.20	5.40	-1.20
969-T	10	40	Inside	57.55	57.34	0.21	48.56	48.61	-0.05	8.99	8.72	0.27
			Outside	58.52	55.97	2.55 **	50.20	46.38	3.82 **	8.32	9.60	-1.28 **
974	12	30	Inside	52.77	53.19	-0.42	45.86	44.58	1.28 **	6.90	8.61	-1.71 **
			Outside	53.98	51.53	2.45 **	42.56	40.93	1.63 **	11.42	10.60	0.82

TABLE A-3. T-Statistics &amp; P-Values for Mean Speeds

Site	Degree of Curvature	Lane	Midpoint of Tangent		Midpoint of Curve		Speed Reductions	
			T-statistic	P-value	T-statistic	P-value	T-statistic	P-value
1179	3	Inside	1.34	0.1809	1.53	0.1258	-0.50	0.6196
		Outside	-0.65	0.5175	-1.11	0.2689	1.09	0.2772
3058	3	Inside	-3.24	0.0013	-2.45	0.0149	-3.22	0.0014
		Outside	-1.19	0.2363	-0.64	0.5260	-2.05	0.0417
487	3	Inside	2.40	0.0169	2.68	0.0079	-0.91	0.3646
		Outside	-0.37	0.7101	-0.22	0.8247	-0.09	0.9294
244	6	Inside	0.60	0.5505	0.00	1.0000	1.08	0.2819
		Outside	1.42	0.1568	2.61	0.0134	-1.76	0.1101
3058	6	Inside	-2.04	0.0420	-2.68	0.0081	0.69	0.4882
		Outside	-0.55	0.5796	0.54	0.5924	-2.01	0.0460
969-B	10	Inside	2.27	0.0240	2.98	0.0033	-0.12	0.9052
		Outside	0.36	0.7192	2.42	0.0163	-1.80	0.0725
969-T	10	Inside	0.24	0.8128	-0.08	0.9369	0.48	0.6277
		Outside	3.37	0.0009	6.66	0.0000	-2.49	0.0136
974	12	Inside	-0.49	0.6227	2.00	0.0468	-3.12	0.0020
		Outside	2.70	0.0074	2.60	0.0098	1.35	0.1784

TABLE A-4. Standard Deviations

Site	Degree of Curvature	Lane	Standard Deviation at Midpoint of Tangent		Standard Deviation at Midpoint of Curve		Standard Deviation of Speed Reductions	
			Day (mph)	Night (mph)	Day (mph)	Night (mph)	Day (mph)	Night (mph)
1179	3	Inside	7.35	6.67	7.58	6.53	2.53	3.25
		Outside	8.44	6.84	7.99	6.38	2.61	3.03
3058	3	Inside	9.72	8.84	9.85	8.99	2.16	2.19
		Outside	8.72	9.10	7.97	8.51	3.06	2.29
487	3	Inside	8.54	9.50	9.54	11.85	7.50	9.39
		Outside	8.79	5.92	9.40	9.74	5.81	7.66
244	6	Inside	6.84	7.37	6.27	6.70	3.96	3.92
		Outside	8.24	7.79	8.14	10.22	5.30	8.73
3058	6	Inside	8.50	6.39	7.21	5.91	4.06	3.26
		Outside	7.97	7.15	6.87	6.28	4.42	3.66
969-B	10	Inside	6.67	6.36	4.84	5.37	3.88	3.99
		Outside	8.09	6.39	5.03	4.60	5.60	4.24
969-T	10	Inside	7.80	6.67	5.87	4.98	4.54	4.30
		Outside	5.62	6.57	4.30	4.95	3.53	4.40
974	12	Inside	6.48	7.16	5.32	5.05	4.18	4.53
		Outside	7.78	7.62	5.37	5.26	5.16	5.20

TABLE A-5. F-Statistics & P-Values for Standard Deviations

Site	Degree of Curvature	Lane	Midpoint of Tangent		Midpoint of Curve		Speed Reductions	
			F-statistic	P-value	F-statistic	P-value	F-statistic	P-value
1179	3	Inside	1.21	0.1811	1.35	0.0378	1.65	0.0006
	3	Outside	1.52	0.0056	1.57	0.0030	1.35	0.0604
3058	3	Inside	1.21	0.2861	1.20	0.3070	1.03	0.8865
	3	Outside	1.09	0.6309	1.14	0.4630	1.79	0.0026
487	3	Inside	1.24	0.2371	1.54	0.0152	1.57	0.0120
	3	Outside	2.20	0.0000	1.07	0.6876	1.74	0.0019
244	6	Inside	1.16	0.3993	1.14	0.4521	1.02	0.9169
	6	Outside	1.12	0.5567	1.57	0.0144	2.71	0.0000
3058	6	Inside	1.77	0.0030	1.49	0.0371	1.55	0.0214
	6	Outside	1.24	0.2381	1.20	0.3316	1.45	0.0456
969-B	10	Inside	1.10	0.6239	1.23	0.2907	1.06	0.7761
	10	Outside	1.60	0.0126	1.20	0.3387	1.74	0.0035
969-T	10	Inside	1.37	0.0743	1.39	0.0605	1.12	0.5263
	10	Outside	1.37	0.0770	1.33	0.1080	1.56	0.0117
974	12	Inside	1.22	0.2755	1.11	0.5521	1.17	0.3794
	12	Outside	1.04	0.8120	1.04	0.8118	1.01	0.9222