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| 16. Abstract The objectives of the research were to evaluate the use of zero-length vertical curves with respect to TxDOT design practice, construction results, vehicle dynamics, and accident history, and to compare zero-length vertical curves to minimum design vertical curves (as specified by TxDOT). Researchers determined use of zero-length vertical curves using a questionnaire distributed to TxDOT personnel in all 25 districts. Seventy-one percent of the respondents had used zero-length vertical curves. In this study, 20 zero-length vertical curves and 15 minimum-length vertical curves were evaluated. Constraints limited grade change for the vertical curves to a maximum of two percent. Evaluation included surveying the roadway profile, measuring vertical acceleration, and investigating accident information. The results showed that: sight distance is not applicable to sag curves with grade changes below two percent and is applicable to crest curves with grade changes above 0.5 percent and design speeds over 100 km/h; below 0.5 percent grade change, comfort criteria for zero-length and minimum design vertical curves did not exhibit any practical difference; between 1.0 and 0.5 percent grade change, comfort criteria showed unacceptable performance for high speed tests; zero-length vertical curves were more likely to meet drainage grade requirements than were minimum design vertical curves; and accident studies did not reveal any apparent relationship to the type of vertical curve. | | | | | |
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EVALUATION OF ZERO-LENGTH VERTICAL CURVES

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Research Study Number 7-2975
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IMPLEMENTATION STATEMENT

Zero-length vertical curves are points of intersection without designed vertical curves. They have long been used by many TxDOT designers for minor changes in grade, although their use has been based on many different criteria. This research project evaluated the use and performance of zero-length vertical curves, comparing the performance of 20 zero-length vertical curves and 15 designed vertical curves. Comparisons were made with regard to safety, surveying accuracy, and comfort. The research found no significant or practical difference in curve performance when zero-length vertical curves were used in restricted circumstances, leading to the recommendation that their use is acceptable in appropriate situations. The findings of this research project should be included in future editions of the TxDOT Design Manual.

DISCLAIMER

The contents of this report reflect the views of the authors, who are responsible for the facts and accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Texas Department of Transportation (TxDOT) or the Federal Highway Administration (FHWA). This report does not constitute a standard, specification, or regulation, nor is it intended for construction, bidding, or permit purposes. This report was prepared by Mark D. Wooldridge (TX-65791), Angelia H. Parham (TN-100,307), and R. Lewis Nowlin.

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SUMMARY

This study evaluated the use of zero-length vertical curves with respect to TxDOT design practice, construction results, vehicle dynamics, and accident history. Additionally, zero-length vertical curves were evaluated and compared to minimum-length vertical curves.

TxDOT uses zero-length vertical curves in situations with small grade changes or where minimum design curves would overlap. A questionnaire distributed to TxDOT staff in all 25 TxDOT districts determined actual usage of vertical curves. Questionnaire results indicated that 71 percent of the respondents had used zero-length vertical curves.

To evaluate zero-length vertical curves and minimum-length vertical curves in the field, researchers studied 20 zero-length vertical curve sites and 15 minimum-length curve sites in five TxDOT districts (Amarillo, Bryan, Houston, Waco, and Yoakum). The sites covered a wide range of characteristics including: zero-length and designed vertical curves, rigid and flexible pavements, rural and urban environments, curb-and-gutter and ditch sections, intersections present and not present, grade changes between 0.1 and 1.5 percent, and design speeds ranging between 48 and 120 km/h.

Each curve was surveyed in the field and compared to the construction plans to determine accuracy of construction. Most zero-length curves were actually constructed with some length of vertical curve due to typical field construction practices. However, these curves were somewhat shorter and sharper than would have been specified as a minimum design curve. The only factor studied that had a significant effect on the length of constructed zero-length vertical curves was design speed: as design speed increased, the length of constructed curve increased. Also, for curb-and-gutter test sites, zero-length vertical curves were more likely to meet drainage grade requirements than were minimum design vertical curves.

The study team measured vertical acceleration on each curve using an accelerometer to examine comfort criteria. Each curve was driven at speeds of 30 to 120 km/h in 10 km/h increments, corresponding to the design speeds used by TxDOT designers. Where it was unsafe or above the posted speed limit, some curves were not driven at the highest speeds. Comparing measured vertical accelerations and accounting for pavement conditions, zero-length and designed vertical curves could not be reliably distinguished and exhibit approximately the same

performance under low-speed testing. High-speed testing could not distinguish performance changes in grades below 0.5 percent.

Accident data for each site indicated that there was no direct relationship between accidents and zero- or minimum-length vertical curves. Literature reviews did not reveal any studies indicating such a relationship for vertical curves comparable to those examined in this study.

Sight distance is generally the primary design criteria used for curve design, but it is not applicable to sag curves with grade changes below 2 percent and is applicable to crest curves with grade changes above 0.5 percent and design speeds over 100 km/h. Below 0.5 percent grade change, comfort criteria for zero-length and minimum design vertical curves did not exhibit any practical difference; between 1.0 and 0.5 percent grade change, comfort criteria showed unacceptable performance for high speed tests.

CHAPTER 1

INTRODUCTION

The Texas Department of Transportation (TxDOT) developed design procedures governing the design of vertical curves primarily with regard to sight distance and driver comfort (1). These procedures mandate that minimum-length vertical curves be utilized regardless of the magnitude of the change in grade. Previous research into vertical curve design has focused primarily on sight distance and has not addressed design criteria that might be applicable when the changes of grade in question are relatively small or even negligible.

Construction practices generally result in the construction of a vertical curve, even though design plans might not mandate its placement. Because of construction vehicles' long wheelbases and contractor and inspector "rideability" checks on roadway surfaces, vertical curves are typically constructed even when not required by construction plans. The characteristics of these vertical curves are generally unknown, although it appears likely that their performance is acceptable for very small changes in grade.

Actual roadway performance characteristics at locations where vertical points of intersection (PIs) have been placed without designed vertical curves have not been examined. This lack of information warranted a research project to examine the safety and operational effects of the design and placement of zero-length vertical curves.

OBJECTIVES

The objectives of this study were to evaluate the effects of and prepare guidelines for the use of zero-length vertical curves. In support of these objectives, researchers evaluated minimum-length vertical curves and zero-length vertical curves to compare their performance characteristics and construction accuracy. This report presents the findings from this study. A companion report (Report 2975-2) presents recommended guidelines.

ORGANIZATION

This report is divided into five chapters. Chapter 1 provides an introduction and states the project objectives. Chapter 2 summarizes previous research related to the use of zero-length vertical curves. Chapter 3 provides the results of a questionnaire completed by TxDOT engineers and designers regarding the use of zero-length vertical curves in the respective districts. Chapter 4 shows results of field studies including field surveys, acceleration studies, and accident data for both designed and zero-length vertical curves. Chapter 5 presents the summary and conclusions.

The appendices contain supporting materials. Appendix I includes the TxDOT questionnaire and a summary of results. Appendix II contains the field survey plots regarding roadway profiles. Appendix III includes the graphs illustrating acceleration data, and Appendix IV includes graphs illustrating sight distance requirements.

CHAPTER 2

LITERATURE REVIEW

A review of applicable vertical curve research was conducted using the Transportation Information Service (TRIS) database. Attention was placed primarily on the design and safety aspects of sag and crest vertical curves, particularly focusing on those aspects that govern design when relatively small changes in grade are encountered. The review provides an overview of design criteria used for sag and crest vertical curves, safety with respect to vertical curves, and the impact of drainage on vertical curve design.

CURRENT DESIGN CRITERIA

Sag Vertical Curves

A sag vertical curve is defined as an upwardly concave curve that is normally designed as a symmetrical parabola. Criteria used in the design of sag curves include sight distance, driver comfort, and appearance (2). Controls that affect these criteria include headlight height and divergence angle, stopping sight distance, and vertical acceleration. Another criterion used is that of a minimum-length vertical curve, applicable for small-approach grade differences. This limit is usually found by multiplying the design speed of the roadway in kilometers per hour by 0.6, providing a minimum length of curve in meters (2). A review of vertical curve design follows.

Sight Distance

One of the most important criteria governing the design of sag vertical curves is sight distance. In this case, sight distance is governed primarily by headlight characteristics. The characteristics used by American Association of State Highway and Transportation Officials (AASHTO) assume a one-degree upward divergence from the vehicle's headlights and a headlight height of 600 mm (2). Two equations are provided by AASHTO to calculate the

required length of a sag vertical curve. The first equation, used when sight distance is less than the length of vertical curve, is defined as:

$$L = \frac{AS^2}{120 + 3.5S} \quad (1)$$

where:

L = length of vertical curve (m)

A = change in grade (percent)

S = sight distance (m)

When sight distance is greater than the length of the vertical curve, another equation is utilized:

$$L = 2S - \frac{404}{A} \quad (2)$$

Figure 1 compares the sag vertical curve length required by sight distance and the length that results from the use of the desirable K-values, and Figure 2 compares these lengths using minimum K-values (2). For A-values less than four percent, the minimum-length vertical curves for each of the design speeds shown provide vertical curves that are much longer than required for stopping sight distance (SSD). Table 1 further clarifies this relationship, indicating the maximum change of grade that does not restrict sight distance if no curve is provided.

Vertical Acceleration

Another commonly cited criterion for the design of minimum-length sag vertical curves is comfort. The measure used for comfort in this instance is vertical acceleration. Although no experimental work was found on which to base a limiting value for vertical acceleration in roadways, a review of the literature by Gebhard revealed that elevator manufacturers generally design for acceleration rates of 0.16g to 0.22g, with a maximum comfort level of 0.30g (3). Although not strictly comparable, because elevator passengers are standing rather than sitting, these values do provide a level of comparison when examining recommendations presented by AASHTO (2).

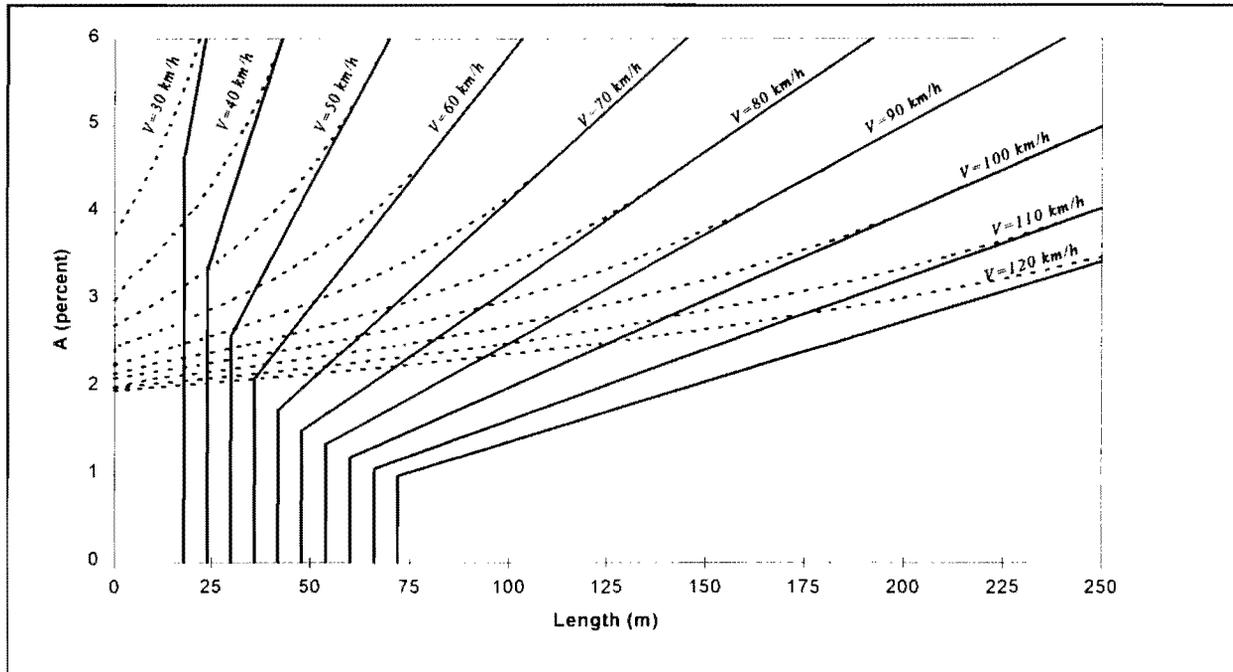


Figure 1. Length of Sag Vertical Curve Required by Sight Distance - Desirable Values.

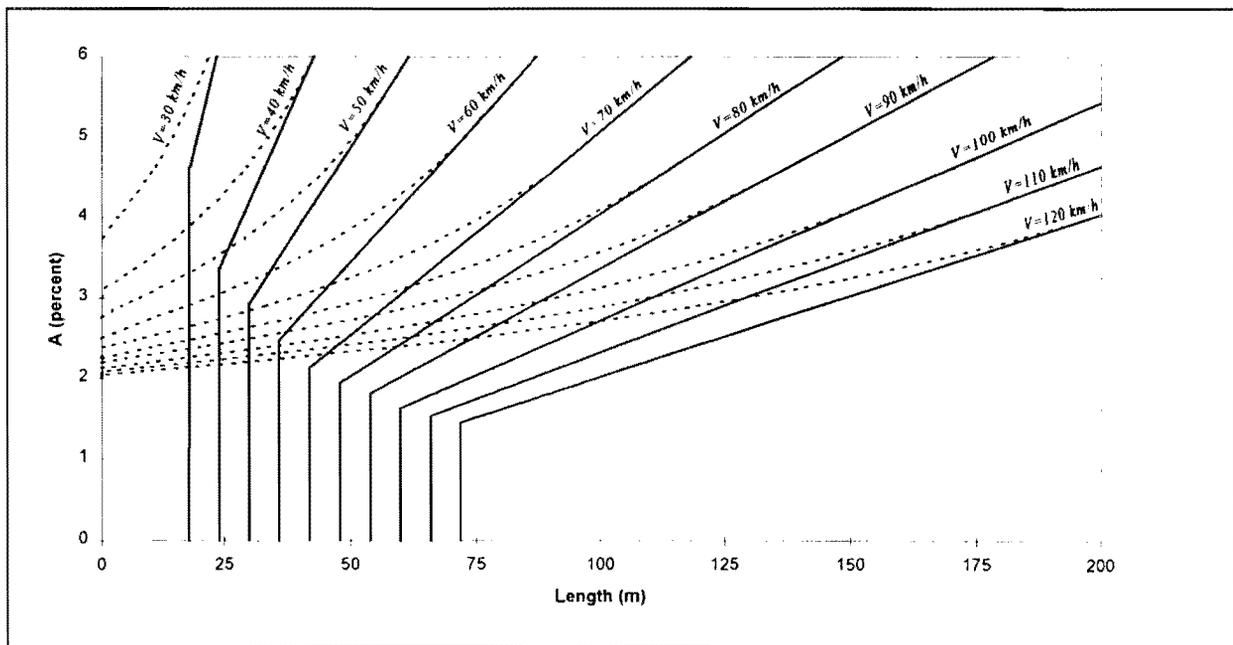


Figure 2. Length of Sag Vertical Curve Required by Sight Distance - Minimum Values.

Table 1. Maximum Difference in Grade for Unrestricted Sight Distance with Zero-Length Vertical Curve.

| Design Speed | A (percent) | |
|--------------|-----------------------|---------------------|
| | Crest Vertical Curves | Sag Vertical Curves |
| 30 | 6.8 | 3.8 |
| 70 | 1.8 | 2.3 |
| 120 | 0.7 | 2.0 |

The acceleration due to the traversal of a parabolic vertical curve is provided by (4):

$$a = \frac{v^2 A}{100L} = \frac{v^2}{100K} \quad (3)$$

where:

- a= vertical component of acceleration (m/s²)
- v= speed of the vehicle (m/sec)
- A= change in grade (percent)
- L= length of curve (m)
- K= L/A

AASHTO cites a criterion of a maximum centrifugal acceleration of 0.3 m/s² or 0.031g; this is particularly important for sag vertical curves because the centrifugal acceleration and gravitational acceleration are combining forces rather than opposing as in the case of the crest vertical curve (2). The equation used for curve length developed in response to this control is (2):

$$L = \frac{AV^2}{395} \quad (4)$$

where:

- L= length of curve (m)
- A= algebraic difference in grades (percent)
- V= design speed (km/h)

The use of this equation results in a curve length of approximately 50 percent of that used to satisfy stopping sight distance requirements, as shown in Figure 3.

By way of comparison, *AUSTROADS* has published recommendations for Australian designers to use 0.05g or 0.49 m/s² (4). A higher limit of 0.10g or 0.98 m/s² is recommended for low standard roadways and intersections. The Transportation Association of Canada recommends a value of 0.3 m/s², equal to that recommended by AASHTO (5).

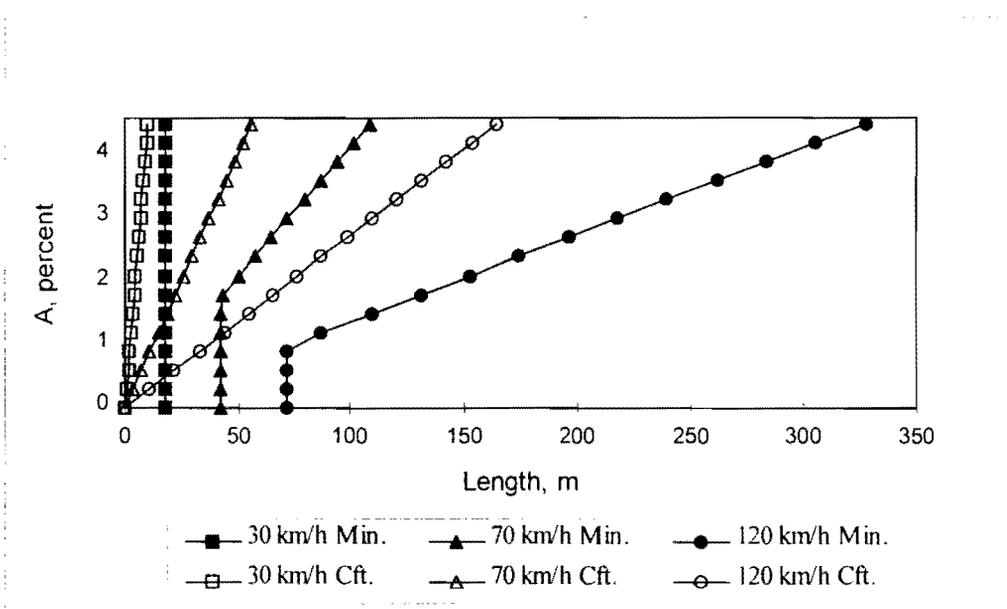


Figure 3. Length of Sag Vertical Curve Suggested by Comfort.

Appearance

Appearance is another criterion that has been utilized in Australia for the development of guidelines for conditions that do not require a vertical curve (4). The guidelines provided are contained in Table 2. The aim of the guidelines is to prevent an “awkward” alignment appearance. The guidelines cover both crest and sag vertical curves and establish a maximum grade change without using a vertical curve according to design speed.

Table 2. AUSTROADS Zero-Length Vertical Curve Guidelines (5).

| Design Speed (km/h) | Maximum Grade Change Without Vertical Curve (%)[†] | Minimum Length of Vertical Curve for Satisfactory Appearance (m) |
|--------------------------------|--|---|
| 40 | 1.0 | 20-30 |
| 60 | .8 | 40-50 |
| 80 | .6 | 60-80 |
| 100 | .4 | 80-100 |
| 120 | .2 | 100-150 |

[†] In practice vertical curves are frequently provided at all changes of grade.

AASHTO has not established comparable criteria; however, they mention that some engineers accept a maximum grade change of about 1 percent or less without the design of a vertical curve (2). Standard construction practices will normally result in the placement of a short vertical curve regardless of the formal design.

Crest Vertical Curves

Crest vertical curves are defined as downwardly concave curves and are also normally designed as symmetrical parabolas. Guidelines established by AASHTO base design primarily on sight distance (2), although appearance criteria have been established by *AUSTROADS* (4). Controls affecting these criteria include the height of the eye above the roadway surface and the height of the object sighted. A review of these criteria used to establish vertical curve length for crest vertical curves follows.

Sight Distance

Crest vertical curve design is based primarily on the provision of adequate stopping sight distance. AASHTO provides the equations to calculate curve length based on eye and object heights of 1070 mm and 150 mm, respectively (2). When sight distance is less than the length of the vertical curve, the following equation is used:

$$L = \frac{AS^2}{404} \quad (5)$$

where:

L= length of vertical curve (m)

A= change of grade (percent)

S= sight distance (m)

When sight distance is greater than the length of the vertical curve, a different equation is used:

$$L = 2S - \frac{404}{A} \quad (6)$$

As previously indicated for sag vertical curves, Figures 4 and 5 show that for crest curves with small A values, the minimum-length vertical curves recommended by AASHTO provide more sight distance than required for stopping sight distance (SSD) (2).

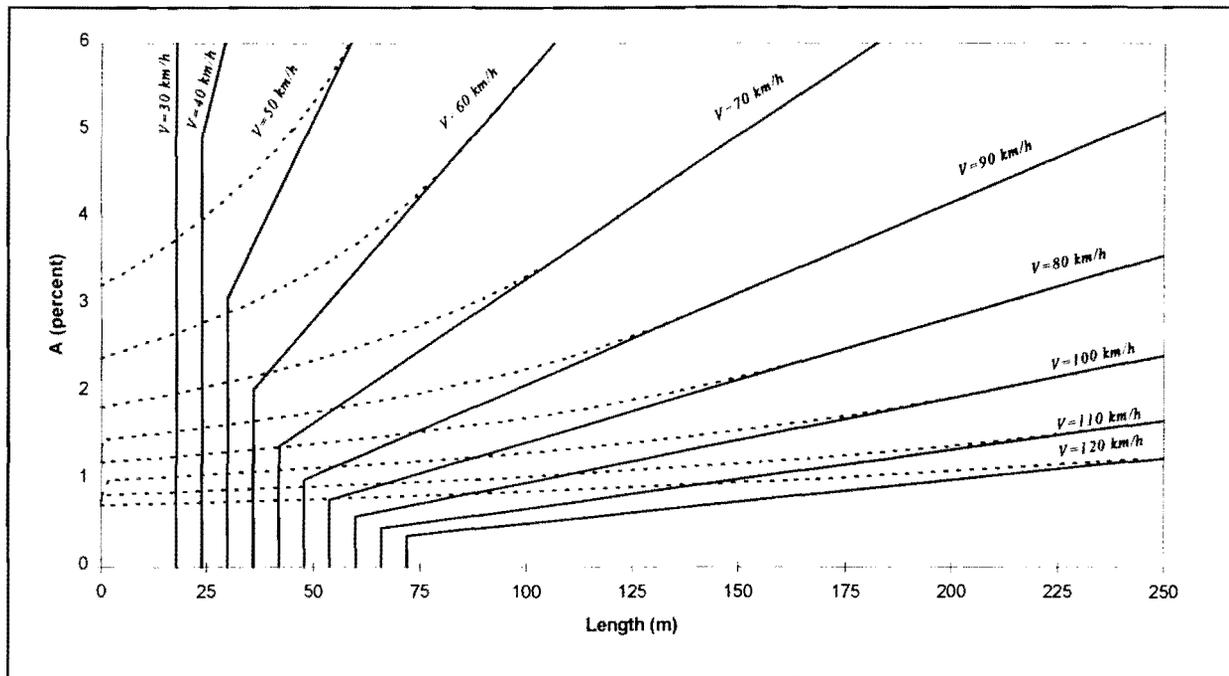


Figure 4. Length of Crest Vertical Curve Required by Sight Distance - Desirable Values.

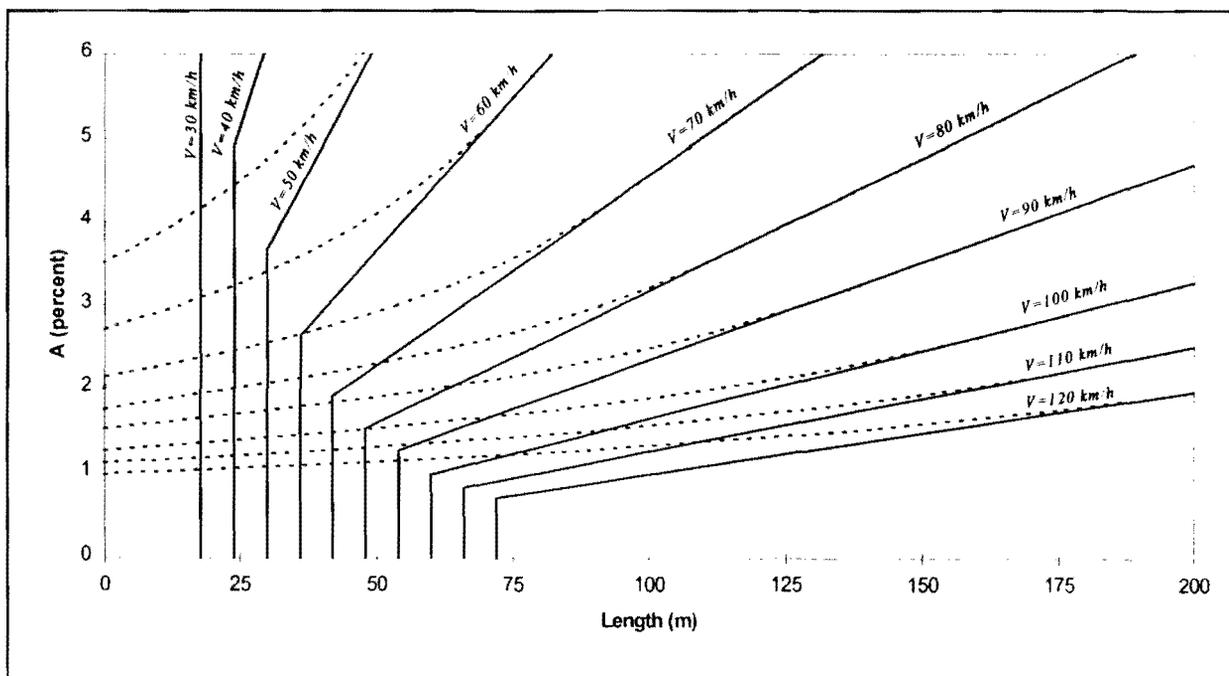


Figure 5. Length of Crest Vertical Curve Required by Sight Distance - Minimum Values.

Vertical Acceleration

AASHTO does not establish comfort criteria for crest vertical curves (2). Although *AUSTROADS* discusses comfort criteria in a general way with regard to all vertical curves (sag and crest), it also provides design criteria based on comfort only for sag vertical curves (5).

Appearance

The Australian guidelines established for visual appearance (shown previously in Table 1) also apply to crest vertical curves (4). Their intent is to permit the design of zero-length vertical curves when small differences in vertical grade are encountered.

SAFETY AND VERTICAL CURVATURE

Several studies analyze the effects of grade and stopping sight distance of accident rates on vertical curves. One of the latest studies was conducted at the Texas Transportation Institute (TTI) by Fambro, et al. (7). The objective of the study was to analyze the relationship between accident rates and limited sight distance on vertical curves. One of the first steps involved reviewing previous study efforts focused on investigating the relationships between accidents and vertical curves. In the review, Fambro, et.al. noted that the results from these previous studies are inconsistent. For example, a study conducted in Germany reported a direct relationship between accident rates and grades (8). Nevertheless, other studies revealed that the effect of grade alone on accident rate was insignificant (9,10). In addition, one study (11) stated that significantly fewer accidents occurred at sites where the available stopping sight distance met AASHTO standards; however, other studies (12,13) found no relationship between sight distance and accident rates.

Fambro, et.al. (7) offered several explanations for the inconsistencies in the findings from these previous studies. The greatest cause was associated with obtaining adequate data to evaluate the effects of vertical curves on accident rates. Because of the extreme variability in accident rates, it is very difficult to relate accidents to vertical curve geometry. For example, other features of the roadway, such as driveway location or the presence of a horizontal curve, may influence accident rates. Also, the locations of accidents are not typically recorded with

great precision. This further increases the difficulty in relating an accident to a specific location (such as a vertical curve).

After identifying these problems, Fambro, et al. (7) began their analysis. The researchers selected 222 field sites to be included in their study. All field sites were two-lane roadways with 88 km/h posted speeds and were located in central and east Texas. Each study segment was a minimum of 1.6 kilometers in length to account for the lack of precision in recording accident location. To minimize the effects of traffic signals, all sites excluded signalized intersections within 0.8 kilometers of the study area.

Each site was initially identified by using highway profiles and determining the K-value and the length of curve. Each site was then visited and videotaped. Accident data were obtained using the state of Texas accident database, maintained by TTI. In an attempt to achieve a normal distribution of accident rates, accident data were averaged over several years (1984 to 1987). This short time interval avoided the likelihood of road construction taking place during the study period. The computerized state roadway inventory files (RI) were used to estimate annual average daily traffic (AADT). Data from these sources were merged to create a data set for analysis.

The analysis consisted of employing multiple regression techniques to measure the effects of limited sight distance on accident rates. For each site, accident rates were adjusted to account for AADT. This was accomplished by first modeling the effects of AADT on accident rates before attempting to evaluate other potential effects.

Analysis results concluded that the relationship between available sight distance on crest vertical curves and accidents is difficult to quantify even when a large database is utilized. Accident rates appeared to be affected by the location of intersections and the existence of other geometric conditions (such as horizontal curves). For example, the results revealed that where intersections exist within the limited sight distance of crest vertical curves, there is a statistically significant increase in accident rates.

DRAINAGE AND VERTICAL CURVATURE

Drainage influences the design of a roadway's vertical alignment on curbed roadways because of minimum grade requirements that are necessary to ensure adequate removal of water from the pavement. Under these circumstances, AASHTO usually requires a minimum grade required of 0.5 percent, although 0.3 percent grades are permitted in some cases (2); TxDOT's design manual limits the minimum roadway grade to 0.35 percent (1). When relatively "flat" vertical curvature (i.e., K values greater than 51) is introduced on an alignment, the roadway may have unacceptably long sections of pavement that do not meet this requirement. It should be noted, however, that these drainage requirements influence the design of crest and sag vertical curves only when the approach and departure grades are opposite in sign (types I and III vertical curves in AASHTO's Figure III-38) (2), unless one or both of these grades are themselves below the minimum grade.

AASHTO has established that a vertical curve may have unacceptable drainage characteristics if a minimum grade of 0.30 percent is not reached within 15 m of the apex of the curve (2). Both AASHTO and TxDOT have established maximum K values to ensure adequate drainage on vertical curves. Because the provision of a maximum K value is counter to the normal minimum K values for sight distance and comfort requirements, a conflict may occur in the design of high speed roadways with curb and gutter. For roadways with "desirable" (TxDOT) or "upper range" (AASHTO) design speeds greater than approximately 80 km/h (crest vertical curves) or 100 km/h (sag vertical curves), the requirements are in apparent conflict on curbed roadways (1)(13). However, both AASHTO and TxDOT provide the designer with the option of flatter than minimum curves if drainage needs are carefully considered in the design.

CHAPTER 3

QUESTIONNAIRE

BACKGROUND

A questionnaire was developed to determine if and where zero-length vertical curves are used by TxDOT. The questionnaire was also used to determine current staking and construction accuracy practices. TTI employees pre-tested the questionnaire, and TxDOT project panel members reviewed the draft questionnaire. Revisions were made based upon panel member comments. Appendix I shows the questionnaire.

METHODOLOGY

Letters and four copies of the questionnaire were mailed to each of the 25 TxDOT district engineers. The district engineers were requested to distribute the questionnaires to the district design engineer, the district construction engineer, and two area engineers in their districts. A total of 100 surveys was distributed.

FINDINGS

One hundred percent of the districts was represented with 72 questionnaires (72 percent) returned. The number of respondents by group is shown in Figure 6. The questionnaire results are summarized in the following paragraphs and tables.

Seventy-one percent of the respondents reported that their districts have used zero-length vertical curves. The total percentage of respondents who would consider using vertical PIs in place of designed vertical curves for particular circumstances is shown in Table 3.

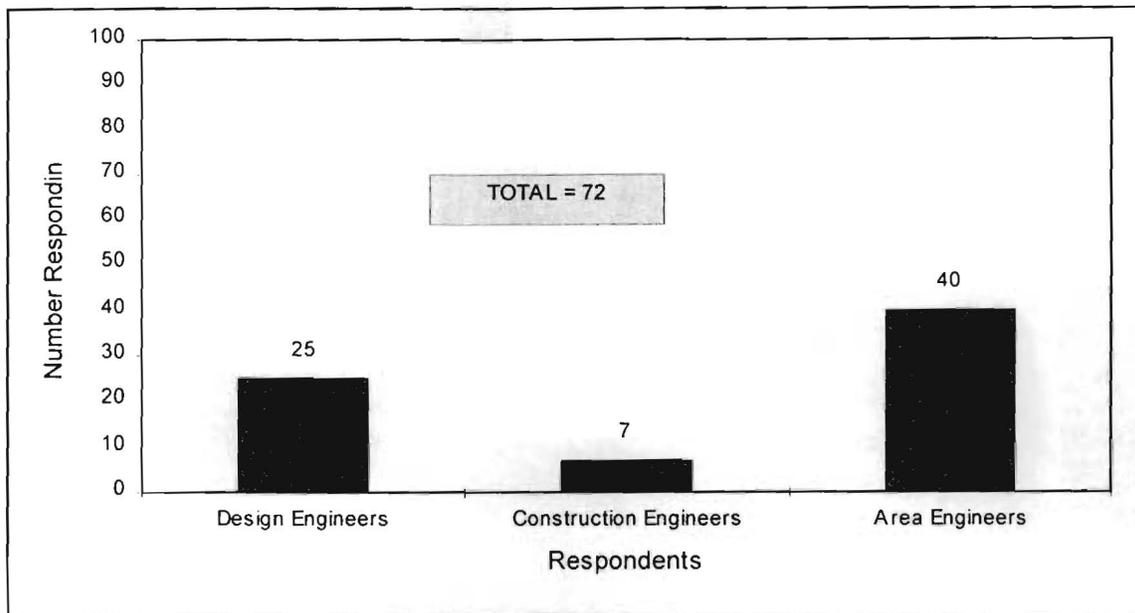


Figure 6. Number of Respondents by Group.

Table 3. Total Percentage of Respondents Who Would Consider Using Vertical PIs for These Circumstances.

| Roadway Class | | Pavement Type | | Drainage | | Type of Vertical Curve | |
|----------------|-----|---------------|-----|-----------------|-----|------------------------|-----|
| Freeway | 19% | Rigid | 31% | Ditch | 61% | Crest | 63% |
| Rural Highway | 58% | | | | | | |
| Urban Arterial | 47% | Flexible | 64% | Curb and Gutter | 51% | Sag | 61% |

Respondents noted that the maximum difference in grade used for a vertical PI with zero-length vertical curve ranged from 0.35 to 0.86 percent for high speeds and from 0.60 to 1.1 percent for low speeds.

General staking practices varied from district to district. The longitudinal distance between grade stakes varied from 19.0 m to 21.7 m, and the accuracy obtained for grade points that was judged acceptable in the field varied from 5.0 mm to 15.6 mm.

Sixty-five percent of the respondents had not added vertical curves at zero-length vertical curves in the field to improve ride quality. However, the 35 percent of respondents who had added vertical curves stated that the curves were constructed as follows: 21 percent were field adjustments by the contractor; 11 percent used other methods; 7 percent were designed by TxDOT staff; 6 percent used a rule of thumb method; and 4 percent had no comment.

Fifty-one percent of respondents had not encountered drainage problems when constructing designed vertical curves. However, 42 percent had problems with sag curves with flat-approach grades creating ponds. Also, 10 percent had problems with crest curves ponding water at the apex. Four percent noted experiencing unrelated design and construction problems.

Respondents indicated that they had used vertical PIs with zero-length vertical curves for the following reasons:

- because the grade change was so minor that it had no impact on ride quality;
- to tie into an existing pavement or structure;
- to improve pavement longitudinal drainage;
- to accommodate staking limitations; and
- to ensure accuracy in construction.

Two-thirds of respondents reported that their districts had not experienced any specific problems at intersections related to designed vertical curves or zero-length vertical curves. However, of the 33 percent of respondents indicating that they had experienced some problems at intersections, 22 percent stated they had problems maintaining cross slopes of main roadways with curves on side roads; 8 percent described problems with drainage; 3 percent noted other problems; and 1 percent needed a contour plot of the intersection.

When asked for additional comments regarding the design or construction of zero-length vertical curves or designed vertical curves, the responses were as shown in Table 4.

Table 4. Comments Regarding the Design or Construction of Vertical PIs or Vertical Curves.

| No Comment | Provided Heuristics Used for the Design and Use of Zero-Length Vertical Curves | Would like to Use Zero-Length Vertical Curves | Other | No Problems With Using Vertical Curves |
|-------------------|---|--|--------------|---|
| 54% | 15% | 16% | 11% | 4% |

CHAPTER 4

FIELD STUDIES

DATA COLLECTION

Thirty-seven study sites were selected based on TxDOT recommendations and included representation from five TxDOT districts: Amarillo, Bryan, Houston, Waco, and Yoakum. Two study sites were later eliminated due to the presence of superelevation run-off in the immediate vicinity of the vertical curves under study. The remaining thirty-five sites included locations with the following characteristics:

- designed and zero-length vertical curves;
- rigid and flexible pavements;
- rural and urban environments;
- curb-and-gutter and ditch sections;
- intersection present or not present;
- grade change between 0.1 and 1.5 percent; and
- design speeds ranging between 48 and 120 km/h.

The inclusion of sites with these wide-ranging characteristics was intended to provide researchers with the opportunity to examine the influence of these variables on construction practices and to provide a more robust experiment.

From the 35 field sites studied, 20 included zero-length vertical curves and 15 included designed vertical curves. Tables 5 and 6 provide descriptions of the field sites with zero-length and designed vertical curves, respectively.

Table 5. Description of Field Sites with Zero-Length Vertical Curves.

| Site | Roadway / TxDOT District | Rigid (R) or Flexible (F) Pavement | Sag (S) or Crest (C) | Δ Grade, percent | Design Speed, km/h | Curve Length, m | Curb & Gutter (C&G) or Ditch (D) |
|------|-----------------------------|--|-------------------------------|----------------------------|--------------------------|-----------------------|---|
| 1 | FM 107 / Waco | F | C | 0.915 | 50 | 0 | D |
| 2 | FM 107 / Waco | F | S | 0.658 | 50 | 0 | D |
| 3 | FM 1365 / Waco | F | S | 0.908 | 70 | 0 | D |
| 4 | FM 1365 / Waco | F | C | 0.364 | 70 | 0 | D |
| 5 | FM 3369 / Waco | F | C | 0.212 | 60 ^a | 0 | D |
| 6 | FM 2590 / Amarillo | F | S | 1.543 | 90 | 0 | D |
| 7 | SH 70 / Amarillo | F | C | 0.096 | 90 | 0 | D |
| 8 | SH 99 / Houston | R | C | 0.220 | 100 | 0 | D |
| 9 | US290 / Houston | R | C | 0.500 | 110 | 0 | D |
| 10 | SH 21 / Bryan | F | S | 0.444 | 70 | 0 | C&G |
| 11 | SH 36 / Bryan | F | S | 0.092 | 70 | 0 | C&G |
| 12 | US 77 / Yoakum | F | C | 0.383 | 75 | 0 | C&G |

^a Implied design speed.

Table 5. Description of Field Sites with Zero-Length Vertical Curves (continued).

| Site | Roadway / TxDOT District | Rigid (R) or Flexible (F) Pavement | Sag (S) or Crest (C) | Δ Grade, percent | Design Speed, km/h | Curve Length, m | Curb & Gutter (C&G) or Ditch (D) |
|------|-----------------------------|--|----------------------------|----------------------------|--------------------------|-----------------------|---|
| 13 | US 77 / Yoakum | F | S | 0.315 | 75 | 0 | C&G |
| 14 | Coulter Dr. / Amarillo | F | S | 1.00 | 100 | 0 | C&G |
| 15 | Coulter Dr. / Amarillo | F | C | 0.800 | 100 | 0 | C&G |
| 16 | Spur 261 / Houston | R | C | 0.700 | 60 | 0 | C&G |
| 17 | Spur 261 / Houston | R | S | 0.700 | 60 | 0 | C&G |
| 18 | Beltway 8 N / Houston | R | S | 0.600 | 75 | 0 | C&G |
| 19 | Beltway 8 N / Houston | R | C | 0.600 | 75 | 0 | C&G |
| 20 | SH 6 / Houston | R | C | 0.800 | 75 | 0 | C&G |

Table 6. Description of Field Sites with Designed Vertical Curves.

| Site | Roadway / TxDOT District | Rigid (R) or Flexible (F) Pavement | Sag (S) or Crest (C) | Δ Grade (A), percent | Design Speed, km/h | Curve Length, m | Curb & Gutter (C&G) or Ditch (D) |
|------|-----------------------------|--|----------------------------|--------------------------------|--------------------------|-----------------------|---|
| 21 | US 84 / Waco | F | C | 0.531 | 70 | 30 | C&G |
| 22 | FM 2063 / Waco | F | S | 0.925 | 50 | 30 | C&G |
| 23 | US 87 / Yoakum | F | C | 0.177 | 80 | 60 | C&G |
| 24 | US 87 / Yoakum | F | S | 0.372 | 80 | 60 | C&G |
| 25 | US 59 / Yoakum | F | C | 0.322 | 70 | 60 | C&G |
| 26 | US 59 / Yoakum | F | S | 0.632 | 70 | 60 | C&G |
| 27 | SH 273 / Amarillo | F | C | 0.590 | 70 | 30 | C&G |
| 28 | SH 273 / Amarillo | F | S | 0.760 | 70 | 30 | C&G |
| 29 | US 385 / Amarillo | F | S | 0.300 | 70 | 30 | C&G |
| 30 | US 385 / Amarillo | F | C | 0.400 | 70 | 30 | C&G |
| 31 | FM 1541 / Amarillo | F | S | 0.720 | 70 | 30 | C&G |
| 32 | FM 1541 / Amarillo | F | C | 0.724 | 70 | 30 | C&G |
| 33 | Beltway 8 E / Houston | R | S | 0.900 | 80 | 30 | C&G |
| 34 | Beltway 8 E / Houston | R | C | 1.00 | 80 | 45 | C&G |
| 35 | SH 6 / Houston | R | S | 0.800 | 75 | 45 | C&G |

FIELD SURVEYS

Background

Each field site was surveyed to measure the constructed vertical profiles. Figure 7 illustrates the measurement intervals used to survey the field sites. The sites were surveyed 150 m prior to and 150 m past the vertical point of intersection (VPI). Grade shots were taken at three-meter intervals for 45 m on each side of the VPI. From 45 m to 150 m from the VPI (a distance of 105 m), shots were taken every 7.5 m.

To illustrate the field survey results, plots were created for each site (see Appendix II). These plots show elevation versus distance from VPI. Only the data within 45 m of the VPI are shown on the plots. Because the actual elevations of the vertical curves were not determined in the field, an elevation of zero was assumed 45 m prior to the VPI.

For those sites with zero-length vertical curves, the following three data series are shown on each plot: survey, plan, and minimum design. "Survey" represents the results from the field survey and "planned" shows what was drawn on the plans. "Min design" represents what would have been built if the minimum length vertical curve had been used. The minimum length in meters was determined using AASHTO's policy of 0.6 times the design speed

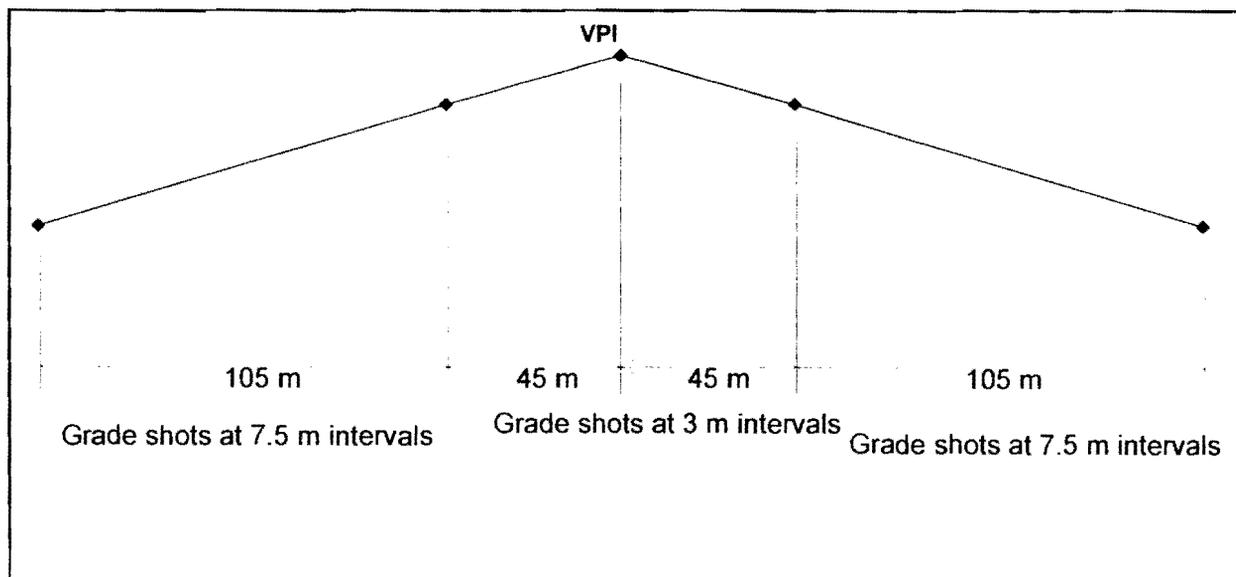


Figure 7. Measurement Intervals for Field Surveys.

(km/h). For those sites with designed vertical curves, only the plan and survey data are shown.

Findings

To analyze the results from the field survey, several factors were investigated, including length of curve, construction accuracy, measure of curvature (K), and drainage provisions (for sites with curb and gutter). For field sites with zero-length vertical curves, each of the above factors (except construction accuracy) was analyzed by comparing what was constructed in the field with what would have been built if the vertical curves had been designed with minimum design requirements. Construction accuracy for the field sites with zero-length vertical curves was compared to accuracy for those field sites with designed vertical curves. Results from the field survey are described in the sections below. Tables 7 and 8 summarize the results for the field sites with zero-length vertical curves and the field sites with minimum designed vertical curves, respectively.

Length of Curve

Because of typical construction practices, the majority of sites designed with zero-length vertical curves were actually built with some length of vertical curve. This is illustrated by the plots of the survey data (shown in Appendix II). These plots were used to estimate the actual length of vertical curve surveyed, which was then compared with the minimum design length (0.6 times design speed, km/h) for each site. The results are shown in Table 7. Figure 8 illustrates the relationship between design speed and length of vertical curve surveyed. The minimum design length is also shown for comparison. These results reveal that the length of vertical curve for the survey data is typically shorter than the minimum design length.

Table 7. Field Survey Results for Sites with Zero-Length Vertical Curves.

| Site | Length of Curve, m | | Construction Accuracy ^a (Plan-Survey), mm | | Drainage (C&G) ^b Length <0.3%, m | | K-Value | |
|------|-----------------------|-------------------|---|---------|--|-------------------|---------|-------------------|
| | Survey (Estimated) | Minimum Design | Max | Average | Survey | Minimum Design | Survey | Minimum Design |
| 1 | 18 | 27 | 30 | 9 | NA | NA | 58 | 67 |
| 2 | 12 | 27 | 23 | 11 | NA | NA | 144 | 93 |
| 3 | 24 | 41 | 70 | 40 | NA | NA | 67 | 91 |
| 4 | 18 | 41 | 10 | 7 | NA | NA | 182 | 226 |
| 5 | 15 | 36 | 50 | 23 | NA | NA | 438 | 392 |
| 6 | 24 | 50 | 140 | 18 | NA | NA | 56 | 65 |
| 7 | 52 | 50 | 29 | 10 | NA | NA | 263 | 1080 |
| 8 | 15 | 55 | 30 | 9 | NA | NA | 173 | 220 |
| 9 | 40 | 64 | 21 | 11 | NA | NA | 140 | 244 |
| 10 | 15 | 41 | 70 | 36 | 0 | 0 | 152 | 187 |
| 11 | 15 | 41 | 20 | 6 | 37 | 61 | 228 | 895 |
| 12 | 26 | 41 | 30 | 11 | 85 | 85 | 391 | 2546 |
| 13 | 27 | 41 | 30 | 13 | 61 | 91 | 517 | 278 |
| 14 | 15 | 55 | 15 | 4 | 3 | 30 | 169 | 137 |
| 15 | 43 | 55 | 76 | 38 | 21 | 40 | 58 | 110 |
| 16 | 15 | 32 | 20 | 8 | 27 | 24 | 66 | 87 |
| 17 | 21 | 32 | 10 | 5 | 6 | 21 | 56 | 87 |
| 18 | 15 | 41 | 20 | 9 | 21 | 46 | 109 | 142 |
| 19 | 20 | 41 | 20 | 5 | 15 | 70 | 80 | 142 |
| 20 | 12 | 41 | 20 | 7 | 9 | 52 | 67 | 103 |

^a Shading indicates that the average construction accuracy exceeded 10 mm.

^b Shading indicates that the grade was <0.3% for a distance greater than 30 m.

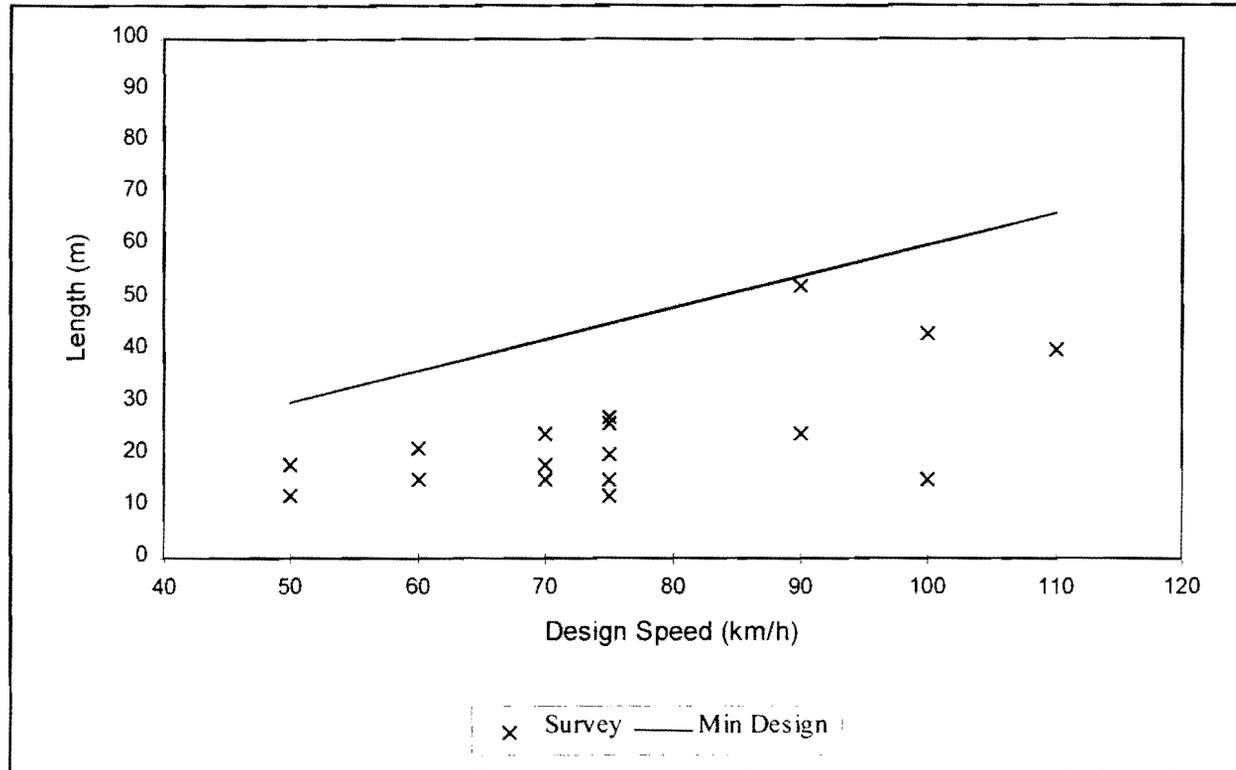


Figure 8. Length of Vertical Curve for Zero-Length Vertical Curve Sites.

A paired *t*-test was performed to determine whether statistically significant differences existed between the vertical curve lengths for the survey and minimum design data. The resulting *p*-value of 0.00 revealed that the average length for minimum design was higher than the average length for survey at a high confidence level (greater than 99 percent). In conclusion, the zero-length vertical curves constructed in the field typically have shorter lengths than those built with a minimum design length.

A stepwise regression analysis was performed to identify any independent variables that might be affecting the length of vertical curve constructed. The stepwise regression procedure involved adding various combinations of independent variables and computing a *p*-value for the *F* statistic. Those variable combinations with computed *p*-values above 0.1 were removed. The remaining independent variables were assumed to have a significant effect on the dependent variable if the computed *p*-value was below 0.05 (95 percent confidence level). The independent variables included the following site characteristics: pavement type (rigid/flexible), drainage type (ditch/curb and gutter), type of vertical curve (sag/crest), percent-grade

change, and design speed. The dependent variable was vertical curve length for the survey data.

The stepwise regression analysis revealed that the only variable significantly affecting the length of vertical curve surveyed was design speed (p -value = 0.013). This variable resulted in an R^2 -value of 0.256 (i.e., design speed explained 25.6 percent of the variability in the length of vertical curve). Therefore, the design speed of a roadway has some effect on the length of vertical curve constructed for zero-length vertical curves.

Construction Accuracy

The current TxDOT policy maintains that a roadway is to be constructed within 10 mm of the plan elevations (1). To estimate the construction accuracy for the field sites, the survey elevations were compared with plan elevations by taking the difference between the plan data and the survey data within 45 m of the VPI. Since actual elevations were not determined in the field, the researchers assumed that the survey data matched the plan data at 45 m prior to the VPI. The maximum and average differences for the zero-length curves are shown in Table 7, and the results for those sites with designed vertical curves are shown in Table 8.

Table 8. Field Survey Results for Sites with Designed Vertical Curves.

| Site | Length of Curve, m | Construction Accuracy ^a (Plan-Survey), mm | | Drainage (C&G) ^b Length < 0.3%, m |
|------|--------------------|---|---------|---|
| | | Max | Average | |
| 21 | 41 | 20 | 9 | 0 |
| 22 | 27 | 40 | 31 | 0 |
| 23 | 46 | 20 | 5 | 85 |
| 24 | 46 | 20 | 10 | 91 |
| 25 | 41 | 30 | 19 | 6 |
| 26 | 41 | 40 | 20 | 0 |
| 27 | 41 | 30 | 19 | 37 |
| 28 | 41 | 10 | 5 | 37 |
| 29 | 41 | 30 | 18 | 91 |
| 30 | 41 | 40 | 12 | 46 |
| 31 | 41 | 30 | 8 | 21 |
| 32 | 41 | 39 | 13 | 21 |
| 33 | 46 | 40 | 24 | 18 |
| 34 | 46 | 10 | 6 | 15 |
| 35 | 41 | 10 | 2 | 55 |

^a Shading indicates that the average construction accuracy exceeded 10 mm.

^b Shading indicates that the grade was < 0.3% for a distance greater than 30 m.

Figure 9 shows the construction accuracy obtained at each of the 35 field sites. The maximum construction accuracy maintained by TxDOT (10 mm) is shown for comparison. To compare the construction accuracy of sites with zero-length vertical curves to the construction accuracy of sites with designed vertical curves, a *t*-test was performed. The *t*-test revealed that the average construction accuracy for the designed vertical curves was not significantly different than the average construction accuracy for the zero-length vertical curves (13.4 mm compared to 14.0 mm) at a 95 percent confidence level (p -value = 0.43). Therefore, no significant difference in average construction accuracy existed for those sites with zero-length vertical curves and those sites with designed vertical curves.

Additional factors that could influence construction accuracy include type of pavement (rigid/flexible), type of drainage (ditch/curb and gutter), type of curve (crest/sag), and design speed. A stepwise regression analysis was performed to identify any variables that might have an effect on construction accuracy.

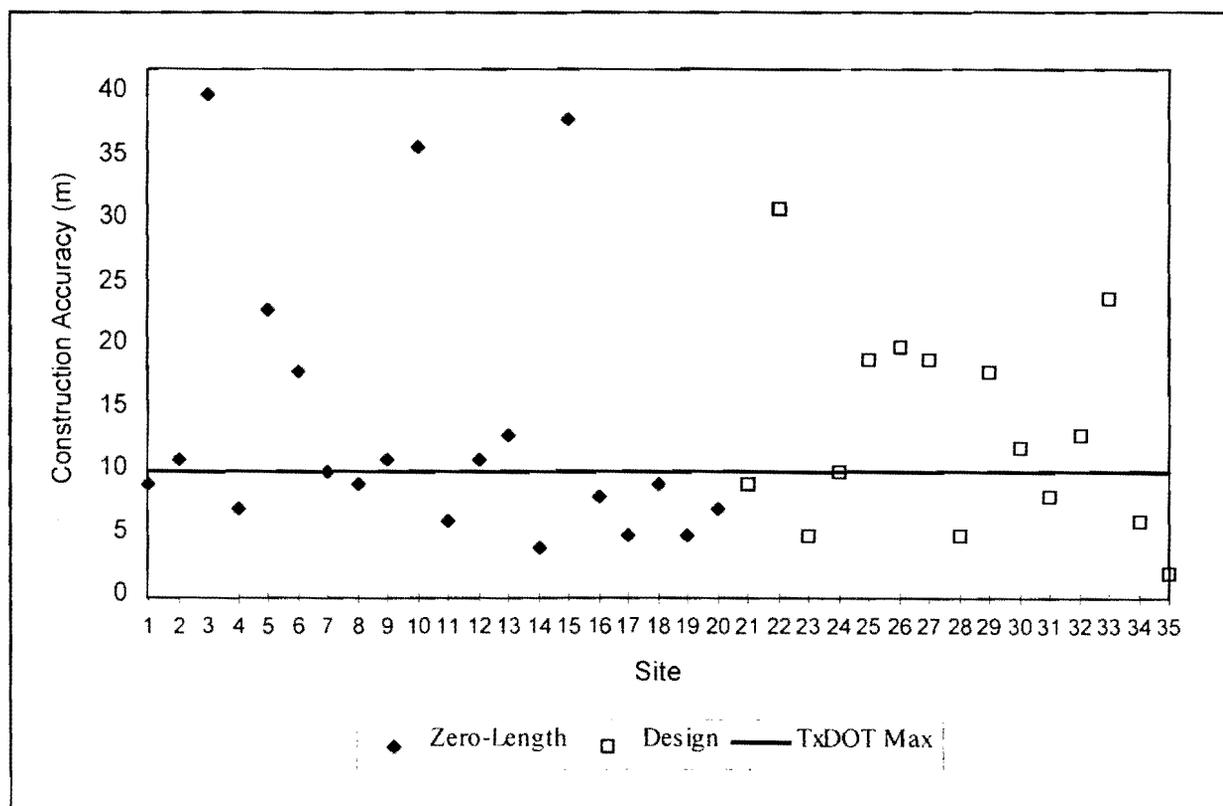


Figure 9. Construction Accuracy for Field Sites.

The stepwise regression analysis revealed that the only variable affecting construction accuracy was the type of pavement (rigid/flexible) (p -value = 0.05). Pavement type explained 8.3 percent of the variability in the data ($R^2 = 0.083$). Therefore, pavement type does have a small effect on construction accuracy.

Measure of Curvature (K)

A measure of curvature, K , is computed by dividing the length of vertical curve (L) by the algebraic difference in grade (14). AASHTO defines this value as “the horizontal distance...required to effect a 1 percent change in gradient” (2). The K -value represents how sharp or flat a vertical curve is—the higher the K -value, the flatter the curve.

In an effort to further compare the survey data with the minimum design data for the zero-length vertical curve sites, K -values were computed. The purpose was to determine how close the constructed vertical curves were to vertical curves designed with a minimum length. The K -values for the minimum design curves were computed using the equation L/A . The K -values for the survey curves were computed from the following parabolic equation for a vertical curve:

$$y = r/2 (X)^2 + g_1X \quad (7)$$

where:

y = elevation

X = station

r = rate of change in grade = $(g_2 - g_1) / L$, stations

g_1 = initial grade

By using regression to fit a second-order equation to the survey data, r in the above equation was computed for each survey curve. K was computed by taking the inverse of r and converting L from stations to meters.

The results of the comparison of K-values for the zero-length sites are shown in Table 7 and in Figure 10. As shown by the results, K for the survey data is typically lower than K for the minimum design. A paired *t*-test conducted on the data revealed that the K-values for the minimum design were higher than the K-values for the survey at a 94 percent confidence level (*p*-value = 0.06). Therefore, the zero-length vertical curves constructed in the field typically are shorter and sharper than they would be if they had been built with a minimum design length.

Drainage Provisions (Sites with Curb and Gutter)

For drainage purposes on roadways with curb and gutter, AASHTO recommends that a grade greater than 0.3 percent with 15 m from the PI of a vertical curve (2). In other words, a grade less than 0.3 percent is permitted only within 15 m of the VPI (for a total distance of 30 m). This guideline does not mean that curves cannot be constructed that exceed the recommendation, but drainage must be more carefully designed if this guideline cannot be met.

The survey data for the zero-length vertical curves were used to estimate the length of the constructed curve that was less than 0.3 percent. This length was compared to the length less than 0.3 percent for a minimum design curve. The results are shown in Table 7 and in Figure 11. These results show that a higher number of curves designed for minimum length (eight out of 11) exceed the AASHTO guidelines when compared with those curves designed for zero-lengths (three out of 11).

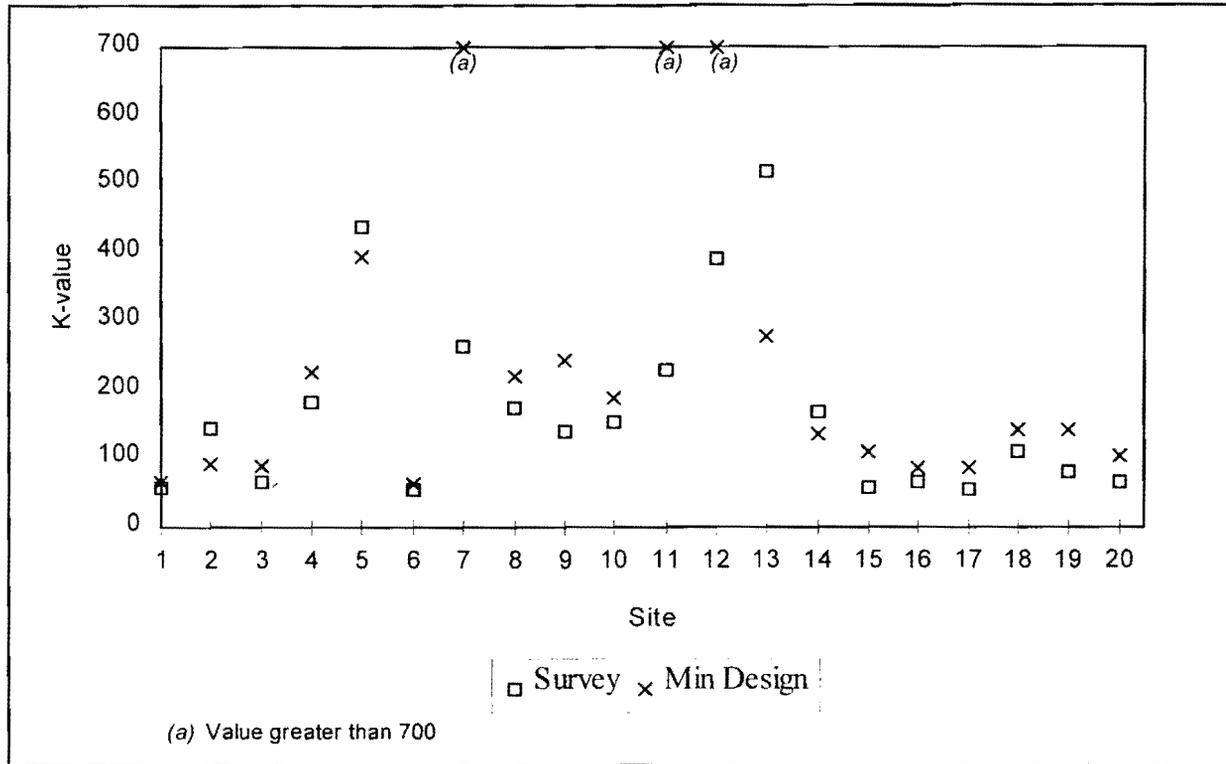


Figure 10. K-Values for Sites with Zero-Length Vertical Curves.

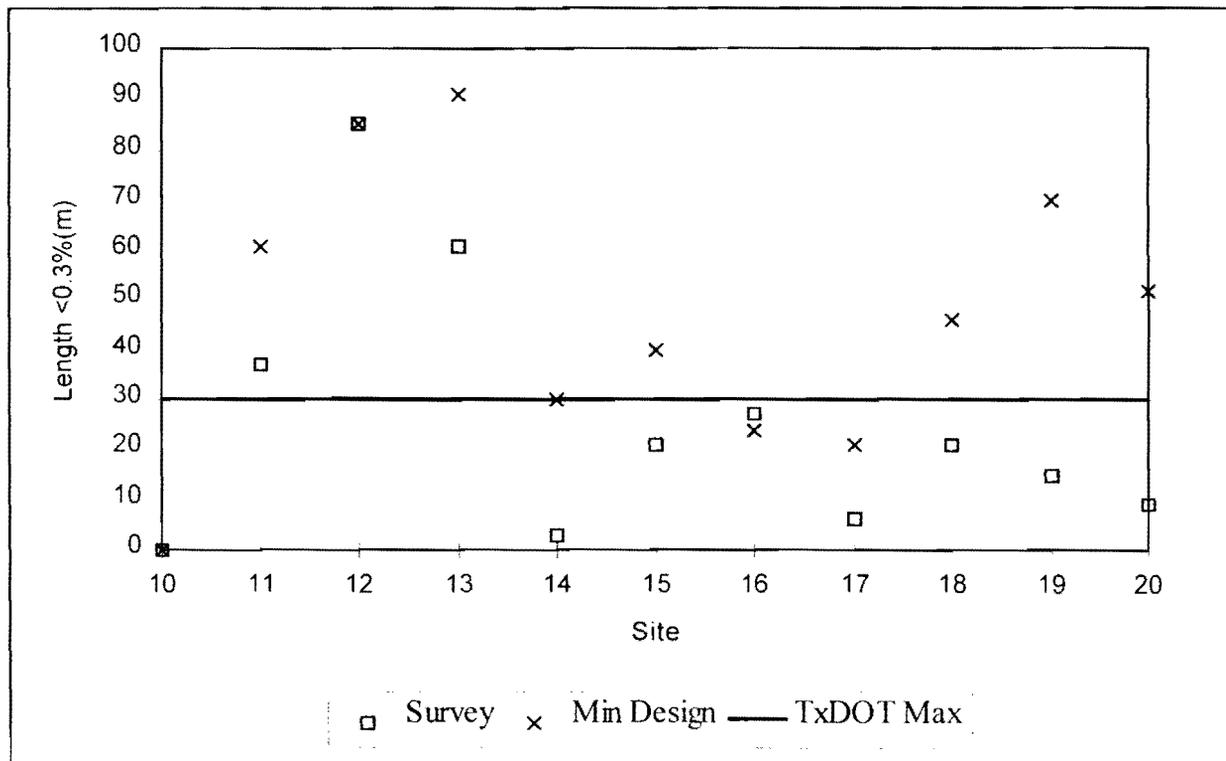


Figure 11. Drainage Provisions for Zero-Length Sites with Curb and Gutter.

A statistical *t*-test was performed to determine whether significant differences existed between the lengths below 0.3 percent for the survey and minimum design data. The results revealed that the lengths for minimum design were typically higher than the lengths for survey at greater than a 99 percent confidence level (p -value = 0.00). Therefore, the zero-length vertical curves constructed in the field typically have shorter segments with grades below 0.3 percent than they would if they had been built with a minimum design length. These results reveal that the minimum design curves would result in more roadway sections that do not meet AASHTO's requirements for drainage on roadways with curb and gutter than would the zero-length curves.

Table 8 shows lengths less than 0.3 percent for the designed vertical curves. Again, a high proportion of curves (7 out of 15) does not meet AASHTO's guidelines.

VEHICLE DYNAMICS

Background

The investigation of vehicle dynamics and zero-length vertical curves centered around the use of a vehicle-mounted accelerometer. The accelerometer measured acceleration on the vertical axis, providing an indication of the influence of the passage over a sag or crest-vertical curve. This indication was expressed using a standard unit, gravity (*g*). One *g* is equal to 9.81 m/s².

Vertical curves are usually designed as parabolas, thus yielding a theoretically constant vertical acceleration. This is the case only on a perfectly smooth roadway that conforms exactly to the designed gradeline. In practice, small variations in the pavement surface and deviations from the gradeline also contribute significantly to measured accelerations.

Methodology

The approach taken by the research team was to use a vehicle-mounted accelerometer to measure the influence of zero-length vertical curves on vertical acceleration. The choice of vehicle for the study was based on a decision to use a “worst-case” approach. A sport utility vehicle was chosen based on the stiff suspension and long-standing popularity in Texas. A four-wheel-drive 1996 Chevrolet Blazer was selected based on vehicle sales figures and availability. The test vehicle and accelerometer used are shown in Figure 12.

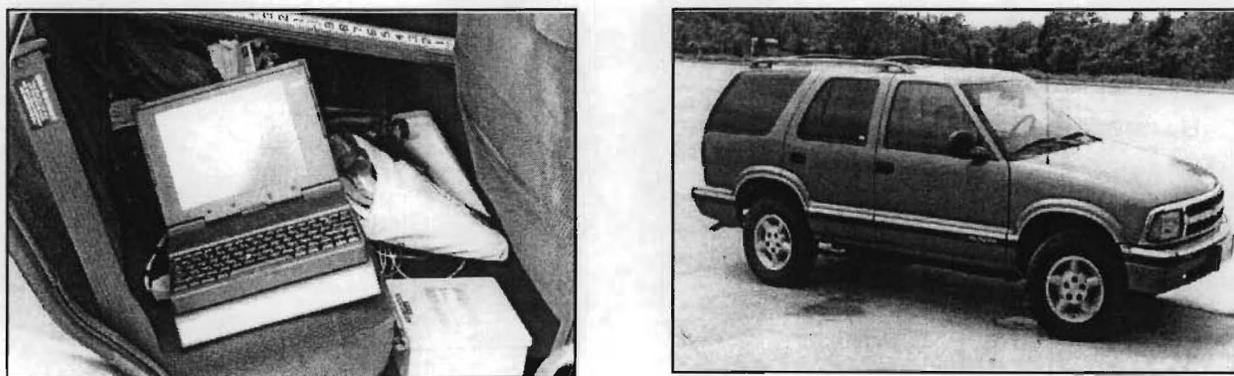


Figure 12. Accelerometer and Test Vehicle.

The accelerometer used in the study was a Sundstrand Data Control, Inc., Model 303B precision vertical accelerometer. This accelerometer is a force balance closed-loop instrument whose operation is based on measuring the current necessary to constrain a seismic element such that it will move with the accelerated case. The accelerometer consists essentially of an anodized aluminum case, a movable seismic element, a capacitive pick off, and a servo amplifier. Electrical power to the accelerometer was supplied by means of a regulated DC to DC converter using the vehicle power as an input. Linearity of the accelerometer is specified to be ± 0.05 percent full scale with hysteresis and repeatability of 0.0005 g.

An accelerometer was mounted in the rear floorboard of the vehicle. The output of the accelerometer was connected to an active, four pole, Butterworth, low pass filter with a -3 dB point of 8 Hz. This filter removed the high frequency vehicle vibrations while passing the

vertical acceleration rates of the vehicle body. Static calibration was accomplished by aligning the accelerometer sensitive axis coincident with the earth's gravity vector and digitizing the output. This procedure was repeated for 0 g, +1 g and -1 g. These values were stored in the computer program for later comparison with actual data to produce accurate g levels.

Acceleration measurements were recorded every 1/18-second during the traversal of the vertical curves.

The selected vertical curves were tested at speeds ranging from 30 km/h to 120 km/h in 10-km/h increments, corresponding to the design speeds utilized by TxDOT. Some sites were not tested at high speeds due to safety considerations. A typical acceleration "run" consisted of beginning from a stop condition 600 meters prior to the first PI of interest. The first two seconds were used to calibrate the accelerometer; after that time period the researcher accelerated to the speed of interest and drove over the section being studied. Where possible, researchers included a straight constant grade control section. The test curves and control section were located in areas unaffected by horizontal curvature to eliminate vertical accelerations induced by the introduction of superelevation or vehicle body-sway.

Findings

The goal of the data analysis effort was to determine whether zero-length vertical curves were associated with higher vertical accelerations than designed vertical curves. Measurements of maximum accelerations for both zero-length and designed vertical curves revealed that both were greater than AASHTO limits for comfort control (2). The maximum accelerations measured in the test curves ranged from .031 to .267 g, compared to an AASHTO limit of 0.031 g. As shown in the following paragraphs, much of the variation shown in the maximum acceleration appeared to be due to factors other than the presence of the vertical curve.

Maximum Acceleration

The first statistical analysis completed was to determine whether the presence or absence of a designed vertical curve influenced vertical acceleration. Data reduction efforts provided maximum accelerations measured within the bounds of the designed vertical curves; in the case of zero-length vertical curves, boundaries were set that matched the limits of the minimum-design vertical curve that applied to the site in question. All significance tests completed in the study used a test value of $\alpha=0.05$.

A box-plot showing the maximum accelerations measured at the test sites is shown in Figure 13. As shown in Figure 13, the effects of curve type appear to be slight with only modest differences detected in the testing. Detailed plots of accelerations measured for each test speed are contained in Appendix III.

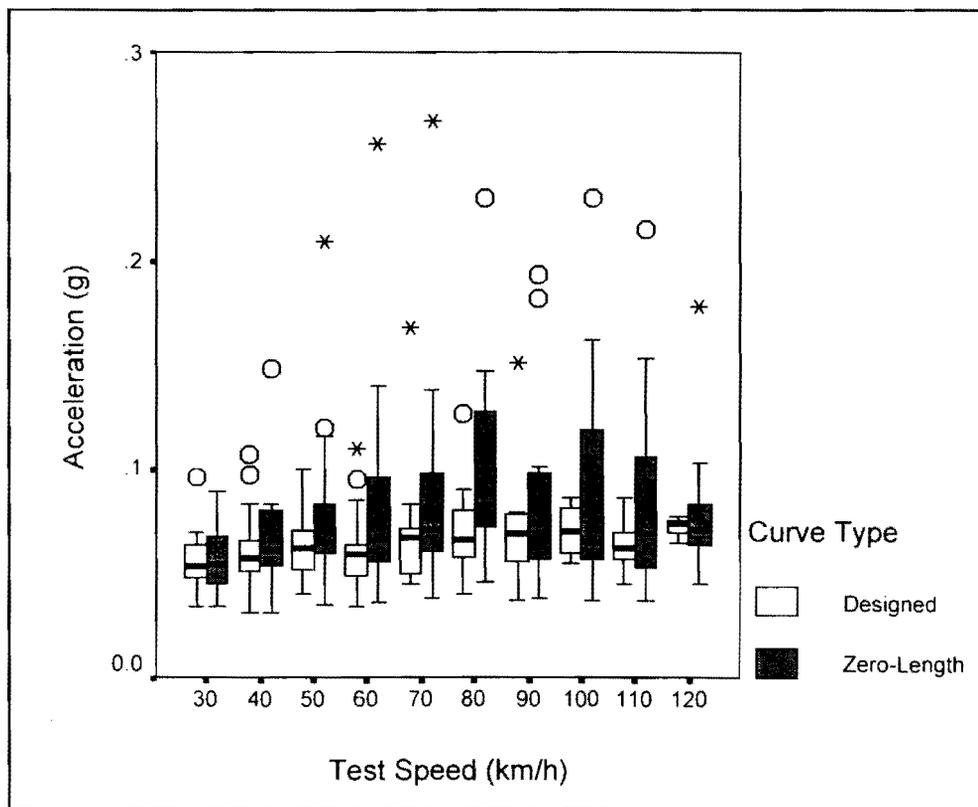


Figure 13. Maximum Acceleration.

Utilizing general linear model regression techniques in a repeated measures design, researchers found that vertical curve type (designed or zero-length), pavement type (rigid or flexible), and cross-section type (curb and gutter or ditch) were significantly related to the maximum acceleration measured in the curve sections. Rigid pavements, curb and gutter sections, and zero-length vertical curves were all associated with higher vertical accelerations, although the effects were relatively modest. The marginal effects revealed increases in acceleration with regard to these variables of 0.0018, 0.0017, and 0.0015 g, respectively.

Next, researchers examined whether the influence of the test speed affected the significance of the two variables. The data were separated into high-speed (80-120 km/h) and low-speed (30-70 km/h) test runs. These limits correspond to the limits used by AASHTO design speed guidelines separating high-speed and low-speed design, although 70 km/h can be included in either depending on site characteristics (2). Curve type and cross-section type were still significantly related to maximum measured acceleration for both data sets, although the pavement type was no longer significant for either.

Finally, comparisons were made between designed and zero-length vertical curves using a reduced data set that limited the range of change in grade. Type of vertical curve was not found to be significant if the data were limited to grade changes of 0.5 percent or less, but it was significant for curves with grade changes of greater than 0.5 percent. Interestingly, the data revealed that for grade changes of 0.5 percent or less, zero-length curves were associated with reduced acceleration; for grade changes of greater than 0.5 percent, zero-length curves were associated with increased acceleration.

Test section minus control section

In an attempt to gain a better understanding of the influence of zero-length vertical curves, researchers next utilized the data available from the control sections. Subtracting the maximum acceleration measured in the control section from the maximum acceleration measured in the corresponding test curve in an attempt to remove the influence of surface characteristics, comparisons were again made between designed and zero-length vertical curves. A box-plot of the differences in acceleration is shown in Figure 14.

Curve type was found to be a significant factor; pavement type and cross-section type were not found to be significant factors. The influence was again relatively modest with a difference in marginal effect of 0.0016 g. Splitting the data set into greater than 0.5 percent grade change and less than or equal to 0.5 percent grade change showed significant relationships with regard to acceleration, although again the direction of the effect was reversed. The data set containing measurements from sites with grade changes of greater than 0.5 percent had increased acceleration for zero-length vertical curves; the data set containing measurements from sites with grade changes of less than or equal to 0.5 percent had decreased acceleration for zero-length vertical curves.

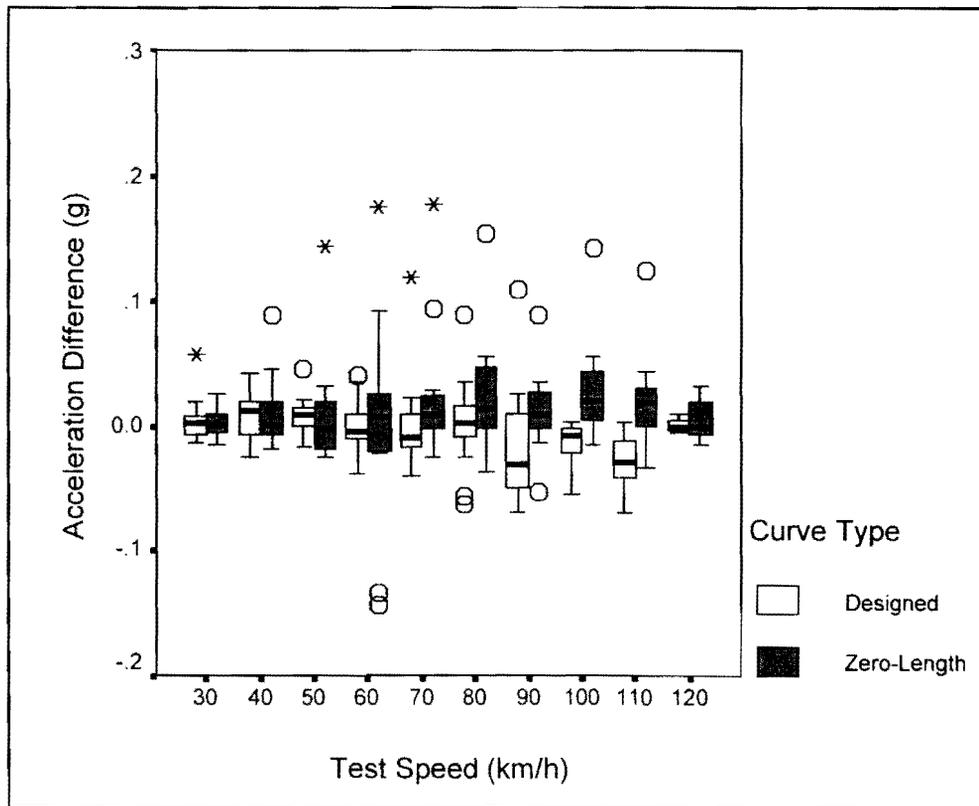


Figure 14. Acceleration Difference Using Control Section Effect.

Examining the influence of test speed, it was found that a significant effect existed for curve type when testing the high speed test runs; curve type was not significant for the low speed test runs. In an examination of the combined effects of test speed and grade change, results showed that when high test speeds (greater than 70 km/h) and high grade change (greater than 0.5 percent) were combined, significantly higher accelerations were measured. The combinations of high test speed and low grade change, and low test speed and high grade change, were not found to be significant; low test speed and low grade change was significant, but in this case zero-length vertical curves were associated with lower accelerations than those measured for designed vertical curves. These results are shown graphically in Figure 15. Measured accelerations were shown to be greater when zero-length curves, high grade changes (>0.5 to 1.0 percent), and high test speeds (80 to 120 km/h) were combined; this was confirmed by the three-way interaction term's significance at the 95 percent confidence level.

ACCIDENT ANALYSES

Background

One criterion for selecting roadways for this project was that the roadways were relatively new, or at a minimum, the pavement was in very good condition. For example, the study section of US 290 in the Houston district has been open to traffic only a few months. Therefore, accident data were limited, or even unavailable, on some recently constructed roadways.

Methodology

The researchers recognized that it would be difficult to correlate accidents with vertical curves having such small changes in grade. However, the research team felt that it was necessary to examine the accident data to ensure that accidents were not related to ponding water or ice on sag curves or to any alignment problems related to the design of the vertical curves.

When available, Texas Department of Public Safety (DPS) accident reports were obtained for the years 1993, 1994, and 1995 (1996 data were not available at the time of this report.) Criteria examined in the accident reports included: date, day of week, time of day, severity, weather, alignment, type of collision, objects struck, contributing factors, and other factors.

Findings

The analyses do not indicate direct relationships between vertical curve type (i.e., designed or zero-length) and traffic accidents. Most of the reports for accidents during inclement weather listed speeding, driving while intoxicated, driving under the influence of drugs, or disregarding traffic control devices as contributing factors for the accidents.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

Reviews of zero-length vertical curve design were made with respect to TxDOT design practices, construction results, vehicle dynamics, and accident history. Designers at TxDOT have a long history of using zero-length vertical curve designs with no reported problems. The curves have typically been used in situations with small changes in grade or where minimum design vertical curves would have overlapped.

Vertical curves are subject to several different requirements, and they must provide acceptable performance on all of them. Sight distance is generally the primary design criteria used for curve design, but it is largely inapplicable with respect to sag curves with less than a 2 percent change in grade and applicable to crest curves only under certain conditions (i.e., grade changes between 0.5 and 1 percent and design speeds over 100 km/h).

Comfort is another criteria that is used for curve design. Comparing measured vertical accelerations and accounting for pavement conditions, zero-length, and designed vertical curves in the range tested cannot reliably be distinguished and exhibit approximately the same performance under low-speed testing; high-speed testing revealed that the performance could not be distinguished for changes in grade below 0.5 percent.

Drainage characteristics also contribute to curve design. Zero-length vertical curves were found to be constructed in such a way as to be both shorter and sharper than minimum design vertical curves. For curb and gutter test sites, zero-length vertical curves were more likely to meet drainage grade requirements than were minimum design vertical curves.

Accidents have been reviewed at the sites under study and did not reveal any apparent relationship to the type of vertical curve present. Reviews of the literature did not reveal any studies that might have found such a relationship for vertical curves comparable to this study.

RECOMMENDATIONS

Based on these findings, the researchers recommend that design guidelines be prepared to provide TxDOT designers with information to guide the use of zero-length vertical curves.

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APPENDIX I
QUESTIONNAIRE

**QUESTIONNAIRE - USE OF VERTICAL POINTS OF INTERSECTION (PI) WITHOUT A VERTICAL CURVE
TxDOT Project 2975**

This survey is part of TxDOT Project 2975 whose purpose is to prepare guidelines for the use of vertical points of intersection (PI) in the place of designed vertical curves (i.e., zero-length vertical curves) for small changes in grade. Your response is essential to aid in the design of useful guidelines.

Please circle the appropriate answer and/or explain as necessary.

Yes No 1. Has your district used vertical PI with zero-length vertical curves? If yes, under which of the following circumstances would using vertical PI in the place of designed vertical curves be considered (please circle all that apply):

- Roadway Classification:** Freeway Rural Highway Urban Arterial
- Pavement Type:** Rigid Flexible
- Drainage Type:** Ditch Curb & Gutter
- Vertical Alignment:** Crest Sag

2. What is the maximum difference in grade that has been used for a vertical PI with zero-length vertical curve for: a) High speed _____ b) Low speed _____

3. What are the general staking practices (i.e., longitudinal distance between grade stakes, etc.) in your district? _____

4. What is the acceptable accuracy obtained for grade points in the field? _____

Yes No 5. Have calculated zero-length vertical curves ever been added in the field at a vertical PI to improve ride quality? If yes, how are they constructed? (Please circle one of the following.)

- A) A curve is designed by TxDOT staff
- B) A field adjustment is made by the contractor
- C) Rule of thumb is used (please specify) _____
- D) Other (please describe) _____

QUESTIONNAIRE

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Yes No 6. Has your district encountered drainage problems when constructing designed vertical curves?

If yes, please describe the circumstances. _____

7. If your district has used vertical PI with zero-length vertical curves, please describe why they were used (e.g., drainage problems, etc.) _____

Yes No 8. Has your district experienced any specific problems at intersections related to designed vertical curves or zero-length vertical curves? If yes, please describe the circumstances. _____

9. Please add any additional comments you have regarding the design or construction of vertical PI or vertical curves. _____

*Thanks for completing this survey.
Please return to:*

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Respondent Information:

Name _____
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APPENDIX II
FIELD SURVEY PLOTS

