EFFECT OF THE COMBINATION OF HORIZONTAL AND VERTICAL ALIGNMENTS ON ROAD SAFETY

by

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ABSTRACT

Current design practices are based on design guidelines considering the road alignment in two dimensions only. Those guidelines were developed without considering the 3D effect of the combined road alignment. As a result, the design process is oversimplified and does not ensure safety. The objective of this research is to investigate the effect that vertical curves have on horizontal curves and to assess the significance of different road design variables individually or in combination on collision occurrences. In addition, the effect of crest or sag curves on horizontal alignment and overall road safety is studied. As a quantitative measure of the combined effect of road alignment on safety is required, several collision prediction models are developed.

The study is conducted using the data of the Trans-Canada Highway for the section between Cache Creek and the Rockies. The Generalized Linear Regression Model (GLIM) was used for finding the significance of various variables and in developing 15 collision prediction models for different combination of horizontal and vertical alignments cases. The results of the study show that the most significant variables found were the exposure variables (traffic and horizontal curve length). Other significant variables found are the value of the horizontal curve radius, the algebraic difference in vertical gradients, the percentage of overlap between the vertical and horizontal curves, the location of the vertical intersection point with respect to the horizontal curve and the ratio between the horizontal curve radius and the vertical curve radius. Some of those variables have a positive relationship with collisions, such as the traffic volume, the curve length and the algebraic difference, and some have a negative relationship, such as the
horizontal curve radius, the percentage of overlap, and the distance of the vertical intersection point with respect to the horizontal curve. It has also been concluded that horizontal curves overlapping with crest curves are more prone to collisions than those overlapping with sag curves. Therefore, it is advised to avoid combining minimum horizontal curves with crest curves.
# Table of Contents

Abstract ................................................................................................. ii  
List of Tables ........................................................................................ vi  
List of Figures ....................................................................................... viii  
Acknowledgements .............................................................................. x  

1.0 INTRODUCTION ............................................................................. 1  
1.1 Background ................................................................................... 1  
1.2 Statement of the Problem ............................................................... 3  
1.3 Thesis Objectives .......................................................................... 4  
1.4 Thesis Structure ........................................................................... 5  

2.0 LITERATURE REVIEW .................................................................... 6  
2.1 The Geometric Design Process and Safety ..................................... 6  
2.2 The co-ordination of horizontal and vertical alignments .............. 8  
2.2.1. Road geometry and current design procedures ...................... 9  
2.2.2. Driver’s Behavior on Combined Alignments ......................... 12  
2.2.3. Cost .................................................................................. 20  
2.2.4. Sight Distance .................................................................. 21  
2.3 General Guidelines of Evaluation ................................................. 25  
2.3.1. Germany Guidelines .......................................................... 26  
2.3.2. United States Guidelines .................................................... 27  
2.3.3. Switzerland Guidelines ...................................................... 28  
2.3.4. Australia Guidelines .......................................................... 29  
2.4 Review Summary and Conclusions .............................................. 31  

3.0 DATA DESCRIPTION AND MODEL DEVELOPMENT .................. 32  
3.1 General ....................................................................................... 32  
3.2 Data Description .......................................................................... 32  
3.2.1. Geometric Characteristics of the Road ................................... 34  
3.2.2. Data Classification .............................................................. 36  
3.3 Methodology ............................................................................... 37  
3.3.1. Generalized Linear Interactive Modeling ............................... 37  
3.3.2. Significance Testing ............................................................. 39  
3.3.3. Model Structure ................................................................. 42
List of Tables

Table 3.1: Vertical Curves Overlap Percentages ......................................................... 35
Table 3.2: Summary of Road Element Characteristics ............................................. 35
Table 4.1: Developed Model Forms ........................................................................... 56
Table 4.2: Model Forms for the four cases ................................................................. 57
Table 4.3: Significance Results for Model 1 ................................................................. 59
Table 4.4: Significance Results for Model 2 ................................................................. 59
Table 4.5: Significance Results for Model 3 ................................................................. 60
Table 4.6: Significance Results for Model 4 ................................................................. 61
Table 4.7: Significance Results for Model 5 ................................................................. 61
Table 4.8: Significance Results for Model 6 ................................................................. 62
Table 4.9: Significance Results for Model 7 ................................................................. 63
Table 4.10: Significance Results for Model 8 ............................................................... 64
Table 4.11: Significance Results for Model 9 ............................................................... 64
Table 4.12: Significance Results for Model 10 .............................................................. 65
Table 4.13: Significance Results for Model 11 .............................................................. 65
Table 4.14: Significance Results for Model 12 ........................................66
Table 4.15: Significance Results for Model 13 ........................................67
Table 4.16: Significance Results for Model 14 ........................................67
Table 4.17: Significance Results for Model 15 ........................................68
Table 4.18: Comparison of models ..........................................................69
Table 4.19: Percentages of reduction and increase in collisions.................70
Table 4.20: Error Calculation .................................................................71
Table 4.21: T-ration of (Z) .................................................................72
List of Figures

Figure 2.1: Three-dimensional design elements .....................................................15

Figure 2.2: Different three-dimensional views .......................................................16

Figure 2.3: Design cases .........................................................................................19

Figure 3.1: Cook’s Distance Graph ........................................................................49

Figure 4.1: Cook’s Distance Graph and the Tabulation for Outlier Removal ...........55

Figure A-1: Cook’s Distance and tabulation for Model 1 ........................................101

Figure A-2: Cook’s Distance and tabulation for Model 2 ........................................102

Figure A-3: Cook’s Distance and tabulation for Model 3 ........................................103

Figure A-4: Cook’s Distance and tabulation for Model 4 ........................................104

Figure A-5: Cook’s Distance and tabulation for Model 5 ........................................105

Figure A-6: Cook’s Distance and tabulation for Model 6 ........................................106

Figure A-7: Cook’s Distance and tabulation for Model 7 ........................................107

Figure A-8: Cook’s Distance and tabulation for Model 8 ........................................108

Figure A-9: Cook’s Distance and tabulation for Model 9 ........................................109
Figure A-10: Cook’s Distance and tabulation for Model 10 ...........................................110

Figure A-11: Cook’s Distance and tabulation for Model 11 ...........................................111

Figure A-12: Cook’s Distance and tabulation for Model 12 ...........................................112

Figure A-13: Cook’s Distance and tabulation for Model 13 ...........................................113

Figure A-14: Cook’s Distance and tabulation for Model 14 ...........................................114

Figure A-15: Cook’s Distance and tabulation for Model 15 ...........................................115
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CHAPTER I

INTRODUCTION

1.1 Background

Highway Safety is a growing concern, as the number of collisions on the roads increases. Worldwide, more than 1 million people are killed annually in road collisions. In the US, more pre-retirement years of life are lost due to road collisions than from the combined effect of the two leading diseases: cancer and heart. According to Transport Canada, almost 200,000 people have died on Canadian roads in the last 50 years (Transport Canada, 2003). This figure exceeds the total number of Canadians killed in the two world wars. In British Columbia, the Insurance Corporation of British Columbia (ICBC, 2000) statistics reveal that the total number of collisions in the year 2000 was 42,603 and that the number of serious injuries and deaths was 30,307. That is an average of 3,550 collisions per month or 118 collisions per day. The number of licensed vehicles in 2000 was 3,326,423, which means that 1.28% of vehicles were engaged in collisions that year. Therefore, the importance of improving road safety and reducing the enormous social and economic costs of road collisions can not be overstated.

Traffic collisions are mainly caused by factors related to one or a combination of the three elements of a road system: the driver, the road and the vehicle. Human error is often
Chapter I: Introduction

cited as contributing to about 90% of traffic collisions (Sabey and Taylor, 1980, Evans, 1991). This statistic, however, can mislead one to believe that there is no road engineering solution to the traffic safety problem. Fortunately, engineers have come to realize that properly designed roads and vehicles can significantly reduce human errors and a significant number of collisions (Kanellaidis, 1996). Nonetheless, it is essential for safety professionals to understand and consider human factors when designing highways.

The highway design process includes several main stages, namely planning, geometric design, and structural design. The planning stage is an ongoing process of finding the best route selection. It defines the needs, constraints, and available technology that can be used according to a preset budget. The second stage, geometric design, is concerned with the horizontal and vertical geometry of the road and the cross section. This stage aims to create a safe and efficient highway by addressing the laws of motion, vehicle characteristics, and road users' behaviour. At this stage, most highway designers follow some design standards (e.g. American Association of State Highways and Officials (AASHTO) design guidelines or the Manual of Geometric Design Standards for Canadian Roads).

The problem addressed in this research is the co-ordination between the horizontal and vertical alignments and their effects on road safety. Design by objectives rather than by standards is emerging as a new approach to geometric design (Sayed and deLeur, 2003). This new approach calls on the assessment of objectives and one of the most important objectives is road safety. Therefore, there is a need to establish a quantitative relationship that best describes road safety, and enables the prediction of the degree of safety that can be achieved by making changes in road design. As such, collision prediction models are an essential tool for safety evaluation.
Chapter I: Introduction

There has been lately an increasing interest in developing collision prediction models to quantify impacts of geometric design elements on safety. However, one area that has not been adequately researched is the coordination between vertical and horizontal alignments. This issue is very important given that collision rates on horizontal curves are 1.5 to 4.0 times those of similar tangents (Zegeer et al., 1992, OECD, 1999).

1.2 Statement of the Problem

Traditionally, highway design is undertaken by first laying the horizontal alignment and then superimposing it onto the vertical profile or considering each design independently of the other. The interaction of the combined horizontal and vertical alignments is usually considered only for the calculation of the cost of earthworks quantities. Three-dimensional design is not used because of its complexity. As a result, the design process is oversimplified and does not ensure safety (Hassan et al., 1997a, 1998a). It has been observed by several studies that poorly designed horizontal and vertical alignment combinations can lead to poor safety performance and signify the design deficiencies (Hassan et al., 1998a, Lamm and Smith, 1999, Bidulka et al., 2002b). It has also been noted that the combination of the horizontal and vertical alignments affect drivers selection of speed (Lamm et al., 1999). Drivers tend to drive faster on horizontal curves in sag combinations and slower on horizontal curves in crest combinations. It is thus believed that the co-ordination of horizontal and vertical alignment has a great effect on the drivers’ decision making.

Horizontal and vertical elements of road design should also complement each other. The two designs must be fully co-ordinated. A good combination can increase efficiency and road safety, encourage consistent speed, and improve the appearance of roads at little
Chapter I: Introduction

cost. If this is not possible to achieve for some reason, then road marking, chevron signing, and speed calming measures can be used to help the driver to perceive the horizontal curve until a certain degree of safety can be accomplished. Several researchers and manuals stress that the co-ordination of horizontal and vertical alignments should start from the early stages of the highway design process, during which adjustments can be made easily (Hassan et al., 1997, Lamm and Smith, 1999, Bidulka et al., 2002a). The designer should study long, continuous stretches of a specific highway in both plan and profile as well as visualize the whole road section in three dimensions.

So far, there are many general guidelines and recommendations on how to coordinate horizontal and vertical alignments. However, these guidelines are subjective in nature and sound quantifiable criteria for the coordination of horizontal and vertical alignments have not been established. As well, there is very little statistical accident analysis research conducted with respect to this coordination.

1.3 Thesis Objectives

The main objectives of this thesis are to provide an improved understanding of the co-ordination between horizontal and vertical alignments and to assess the effect of this coordination on safety in terms of actual collision occurrence. The data used for the research include horizontal and vertical alignments of the Trans-Canada Highway between Cache Creek and the Rockies, together with its corresponding accident data for the period between 1991 and 1995. The significance of traffic and geometric variables on collision data is investigated. Several road geometry elements such as horizontal curves, length of horizontal curves, vertical curves gradients, percentages of overlap of the
vertical curves on horizontal curves, and the location of the vertical curve intersection point in relationship to the horizontal curve are evaluated. Also, their positive or negative effects on accident occurrences are determined.

In order to evaluate road safety and compare the significance of different road elements, collision prediction models are developed. By applying these models, a more quantitative understanding of the combination of both horizontal and vertical alignment and their effect on collisions is achieved. Also, road variables are investigated individually and in groups to find out the effect of vertical curves, on horizontal curvatures and safety. In addition, the effect of crest curves or sag curves on horizontal alignments and overall road safety is investigated.

1.4 Thesis Structure

This thesis consists of six chapters. Chapter One contains a background, a statement of the problem, thesis objectives and structure. Chapter Two contains a literature review of previous work with respect to the co-ordination between horizontal and vertical alignment. Chapter Three describes the data used as well as the methodology and the model development procedures adopted. The modeling results are presented in Chapter Four, followed by a discussion and analysis of the results in Chapter Five. Finally, Chapter Six contains the summary and conclusions of this research as well as recommendations for future research.
2.1 The Geometric Design Process and Safety

The main focus of geometric design before the Second World War was on the “trafficability” of roads which include the structure adequacy of pavements, drainage, grades and width. A rapid growth of road usage was experienced by developed countries after World War Two, which increased the need for a highway system that can support the efficient and safe transportation of people and goods. As a result, the focus of highway design shifted from “trafficability” to safety and efficiency and geometric design standards were established to ensure safety and the uniformity across jurisdictions. These standards were generally based on professional judgment, experience and some empirical research. However, in the 1970s, several factors led to the examination of the role of geometric design standards regarding road safety. These factors included shifting from using the standards for road building to road upgrading and the advances in technology and research. In the 1980s, design by objectives rather than by standards emerged as a new approach for geometric design. This new approach calls on assessment of objectives and one of the most important objectives is safety.

Highway design is a creative process that combines both technical guidance and engineering judgment, attempting to achieve a safe, efficient and reliable transportation system. Technical guidance used in highway design is available in various manuals.
(AASHTO, TAC) and is often presented in tabular format that is somewhat restrictive to the creative design process. As such, engineering judgment is often required when highway design problems are not adequately resolved by using the guidance that is available in the technical design manuals. Therefore, the success of any design decision is dependent on the quality and interpretation of the technical guidance and engineering judgment.

Hence, there is a potential that some of the objectives for a transportation system, such as road safety, may not be adequately realized (Sayed and de Leur, 2004). An important component of any design approach is the explicit evaluation of safety performance. An explicit safety evaluation facilitates the quantification of safety impacts resulting from changes in highway design parameters and safety associated with the level of highway design consistency. Quantifying these safety impacts can support the design process by allowing decision makers the opportunity to analyze the safety benefits in relation the cost of the highway improvement. This "trade-off" analysis allows for the justification and rationalization of highway infrastructure investment (Sayed and de Leur, 2004).

The ability to accurately quantify safety impacts is achieved by utilizing state of the art safety evaluation tools such as collision prediction models (CPMs), collision modification factors (CMFs) and measures of design consistency. Although described and available in the highway safety engineering research literature for some time, these safety evaluation tools are now becoming widely accepted, since their use responds to the need to quantify safety performance. This is in sharp contrast to many traditional highway safety assessments that often have relied solely on an "expert opinion" and thus have failed to adequately support difficult design decisions (Sayed and de Leur, 2004).
2.2 The co-ordination of horizontal and vertical alignments

Easa et al. (1999) and Lamm et al. (1999) stated that the accident rate for horizontal curves is much higher than road tangents. Horizontal curvatures have also a significant effect on changing the operating speed of vehicles (Lamm et al., 1999, Easa et al., 2001). Recently, some studies have observed that poor horizontal and vertical alignment co-ordination may violate driver expectations and lead to erroneous perception thus compromising safety. However, there are little statistical accident analysis researches conducted with respect to this subject. Accordingly, the issue of horizontal and vertical design co-ordination and its importance to road safety has become important.

Easa et al. (1999) found that highway design inconsistent with the driver’s performance increases driver errors and produces unsafe operations. In addition, locations with high driver workload or locations that do not coincide with the drivers’ expectations usually show poor design. On the other hand, it has been noticed that consistent design of highways is expected to affect the driver’s attitude positively and result in safe and efficient driving conditions. The use of 3D simulation models can also be very helpful in visualizing the final design of the road and designing parameters from the driver’s sight line.

General guidelines have been established and recommendations have been issued for designers in some countries (Lamm et al., 1999). Although these guidelines and recommendations are related to safety directly or indirectly, they do not establish quantitative relationships between collisions and the impact of the overlapping horizontal and vertical alignments. Recently, many design procedures have stressed the inclusion of the effect that horizontal and vertical alignments have on each other in combination (Hassan et al., 1997b, 1998a,b, Bidulka et al., 2002a). It has been observed that certain
combinations of horizontal and vertical alignments increase accident frequency and severity. However, again no real values concerning safety and collision occurrences are well known about such cases. The next section discusses some facts about both alignments in order to create a better understanding of their elements, their capabilities and limitations, and their effect on road safety.

2.2.1. Road geometry and current design procedures

The geometry of any road mainly consists of horizontal and vertical design. In many cases, those two elements are combined. The elements of horizontal alignment are horizontal curves, tangents and in some cases transition curves (spirals). The elements of vertical alignment are vertical crest and sag curves and a series of upgrade and downgrade tangents. As a vehicle travels on a horizontal curve, both the vehicle and the passengers are subjected to centrifugal forces acting on the outside of the curve (AASHTO, 1994). Those forces are balanced by a combination of forces generated by the side (lateral) friction between the road surface and the tires as well as a component of the vehicle weight caused by the superelevation of the road.

Designers should ensure that lateral forces are kept within a tolerable range for driver comfort and vehicle stability. Hassan et al. (2000) noted that the most used AASHTO procedure for calculating a vehicle’s moving forces by approximating the vehicle weight to a point mass, fails to consider the 3D nature of the highway, leading to an underestimation of the real driving conditions.
Lamm et al. (1999) and Easa et al. (1999) concluded that accident rates decrease with the increase in the radius of horizontal curve. Therefore, the degree of curvature and the length of curve were found to be of great importance to safety. The AASHTO design procedures were investigated in several studies, and their results and conditions were compared to real driving conditions. Lamm et al. (1999) concluded that radii greater than 400 metres and vertical grades of less than 5% have relatively little effect on accidents. For grades greater than 6% a sharp increase in accident rates and an increase in speed were noted. Lamm et al. (1999) also mentioned that for combined alignments, the ratio between the radius of horizontal curves (R) and the radius of sag vertical curves (Rs) should be as small as possible, ranging between 1/5 and 1/10.

Hassan and Easa (2000) found that the estimated horizontal elements' lengths used by the AASHTO procedures are not satisfying the sight distance requirements. This underestimation worsens as the radius of the horizontal curve decreases and/or as the superelevation rate increases. Accordingly, the perception of the horizontal curve when combined with the vertical curve affects driver behaviour and safety. As well, the AASHTO procedures overestimate the value of the radius when the horizontal curve is combined with a downgrade and underestimate the horizontal curve when combined with an upgrade. This is contradictory with the safety expectations of sag curves and crest curves. As will be illustrated later, sag curves are perceived by the driver as safer than crest curves due to lack of sight distance on crest curves.

Bonneson (1999) observed that drivers appear to reduce speed on horizontal curves out of desire to maintain an acceptable level of side friction demand. Moving in a circular path, a vehicle undergoes a centripetal acceleration that acts toward the center of curvature. This acceleration is sustained by the friction between the tire and the pavement, and by a
component of gravity in case the road is superelevated. The following equation describes the relationship between those components:

\[ f_D = \frac{\nu^2 - e}{gR} \]

where:

- \( f_D \) = side friction demand factor
- \( \nu \) = vehicle speed (m/s)
- \( g \) = gravitational acceleration (9.807 m/s\(^2\))
- \( R \) = radius of curve (m)
- \( e \) = superelevation rate (\%)

Bonneson (1999) also concluded that drivers do not slow to one common curve speed for a given radius. Easa et al. (2002) argued that AASHTO procedures are adequate for vehicles driving at a constant speed but are far from conservative when an emergency maneuver is performed on the curve.

Hassan et al. (1997a) observed that the higher the operating speed on the horizontal curve, the higher the effect of crest curves and the lower the effect of sag curves on collisions. This fact was further elaborated on by Hassan et al. (1998b), and it was proposed that sharp horizontal curvature should not be introduced at or near the top of a pronounced crest vertical curve. AASHTO suggested that the horizontal curve should lead the vertical curve or design values above the minimum for the design speed being used. Sharp left-hand curves and sharp downgrades have also been found to be common crash sites (Lamm et al., 1999).
Thus, the findings of previous studies vary, and it is difficult to determine the predictions for drivers' behavior on the roadway. Accordingly, it is difficult for designers to make decisions, because they have only the general design guidelines to follow, which in turn do not provide maximum safety.

### 2.2.2. Driver’s Behavior on Combined Alignments

The majority of studies dealing with the co-ordination of horizontal and vertical alignments and their effect on collisions focus on the driver's perception of the road. It has been observed that a driver can clearly see three-dimensionally only up to a certain distance. For longer distances, a person usually relies on experience. Therefore, when relating perception and behavior to road geometry, the two most intriguing elements are perceived radius and preview sight distance (Hassan et al., 1997b and 1998b, Bidulka et al., 2002b). The perceived radius explains the appearance of crest curves as more sharp and of sag curves as less sharp when combined with the horizontal curvature. The preview sight distance (PVSD) is the distance required to perceive and react to a road condition.

Drivers change their speed as soon as the horizontal curve in combination with the vertical curve becomes visible. When approaching a vertical crest curve, drivers perceive the horizontal curve as sharper. Subsequently, drivers tend to reduce their speed. On the other hand, when approaching a sag curve, the drivers perceive the horizontal curvature as less sharp and increase their speed. Hassan et al. (2003) explained that this phenomenon of misperception of the horizontal curvature relates to the fact that the way
drivers see and perceive the road determines the way they react to it, independently of speed signs or any other regulatory or warning signs on the road. It can thus be concluded that the value of the horizontal curvature radius appears to the driver as different from its actual value. This new perceived value is what influences driver behaviour.

The perceived horizontal radius as discussed in Bidulka et al. (2002b) depends on the radius of the horizontal curve and the type of vertical curve according to the following equation:

\[ R_p = -51.28 + 0.953R_a + 132.11V + 0.125R_aV \]  \hspace{1cm} (2.1),

where \((V)\) is equal to 0 for crest vertical curves, and equal to 1 for sag vertical curves (units are in meters). The model states that a horizontal curve radius \((R_p)\) would be perceived as sharper than the actual radius \((R_a)\) when it is overlapping with a crest vertical curve. Conversely, it would be perceived as flatter when it is overlapping with a sag vertical curve, leading to higher speeds and increasing accident risk.

Figures 2.1 and 2.2, as extracted from Lamm et al. (1998), show the different cases of geometric road alignment and their effects on the sight distance. Figure 2.1 presents six cases of combined alignment. The first three cases are the combination of a straight horizontal tangent with a vertical grade, a sag curve, and a crest curve. The three remaining cases are a horizontal curve combined with a vertical grade, a sag curve, and a crest curve. It can be observed from the figures that as long as there are no obstructions on the road, the driver has a full view in cases of vertical straight gradient line combinations and in cases of sag curve combinations. However, the issue is different in the case of the horizontal curve and the crest curve combination. In these cases, the
Chapter 2: Literature Review

driver’s sight distance is limited to the top of the crest curve. The driver does not see the other side of the road, which leads to a decrease in travel speed. On the other hand, when the driver has a full view of the road while traveling on a sag curve the driving speed increases.

Figure 2.2 presents the same six cases of road alignment but with the road divided into stretches of equal length. The 3D effect illustrates that the longest part of the road perceived by the driver is in the case of the vertical sag curve combination (case ‘c’ and case ‘f’) followed by the longitudinal straight line combination (case ‘a’ and case ‘d’) and the vertical crest curve combination (case ‘b’ and case ‘e’).

It can also be concluded from cases ‘b’ and ‘e’ that horizontal curves tend to elongate the sight distance line for crest curves more than horizontal tangents. In case of sag curves, although they are fully perceived when combined with tangents or horizontal curves, their sight distance seems larger when combined with horizontal curves.

Several studies recommend that wherever possible the vertical curves be contained within horizontal curves (Lamm et al., 1999, Hassan et al, 1997a). This would enhance the appearance of sag curves by reducing the three-dimensional rate of direction change and improve the safety of crest curves by indicating the direction of curvature before the road disappears over the crest.
**Chapter 2: Literature Review**

<table>
<thead>
<tr>
<th>Horizontal Design Element</th>
<th>Vertical Design Element</th>
<th>Three Dimensional Design Element</th>
</tr>
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<tbody>
<tr>
<td>Tangent</td>
<td>Tangent</td>
<td>Tangent with Constant Longitudinal Grade</td>
</tr>
<tr>
<td>Tangent</td>
<td>Curve</td>
<td>Straight Sag Vertical Curve</td>
</tr>
<tr>
<td>Tangent</td>
<td>Curve</td>
<td>Straight Crest Vertical Curve</td>
</tr>
<tr>
<td>Curve</td>
<td>Tangent</td>
<td>Curve with Constant Longitudinal Grade</td>
</tr>
<tr>
<td>Curve</td>
<td>Curve</td>
<td>Curved Sag Vertical Curve</td>
</tr>
<tr>
<td>Curve</td>
<td>Curve</td>
<td>Curved Crest Vertical Curve</td>
</tr>
</tbody>
</table>

(Source: Lamm, 1999)

**Figure 2.1**: Three-dimensional design elements created by superimposing tangents and curves
Chapter 2: Literature Review

Figure 2.2: Different three-dimensional views obtained by superimposing vertical and horizontal curves

(Source: Lamm, 1999)
Chapter 2: Literature Review

Lamm et al. (1987) observed that a short tangent between two succeeding sag vertical curves can give the impression of a crest vertical curve and that a short tangent between two succeeding crest vertical curves can give the impression of a sag vertical curve. Both situations should thus be avoided. Similarly, short circular curves between tangents appear as optical breaks and should be replaced by a long circular curve. Therefore, intersections should be located in sag curves, while horizontal and vertical curvatures should be as flat as permitted by the conditions. The study further emphasizes that the use of crest curves is critical when the curve length is short, because this can create insufficient sight distances.

Drivers also find long tangent sections very monotonous and fatiguing. Therefore, during the design stage it is better to avoid long horizontal tangents with constant vertical grades wherever possible (Easa et al., 1999). The German guidelines, for example, limit the maximum length of tangents in meters to 20 times the design speed in kilometers per hour. Long sag curves are encouraged in order to reduce the fatiguing effect on the driver.

Another concern of combined alignments is that the combination of superelevation and profile grades may cause distortion in the outer pavement edge, which could confuse drivers at night. In these situations the edge of the pavement profile should be plotted, and smooth curves should be introduced to eliminate any irregularities or distortion.

On highways in mountainous or rolling terrain, where horizontal and vertical curves are combined at a grade summit or sag, studies have proposed that the design speed of the horizontal curve be at least equal to that of the crest or sag and be not more than 15 km/h less than the measured or estimated running (85th percentile) speed of vehicles on the
approach roadway. (Lamm and Smith, 1999) Therefore, on long, open curves a uniform grade line should be used because a rolling profile results in a poor appearance.

In summary to the above discussion, Lamm et al. (1999) compiled driving conditions which should be avoided because they lead to critical driving maneuvers caused by visual misconceptions. Those conditions are presented in Figure 2.3 and described as follows:

- **Diving (Figure 2.3.d):** The partial disappearance of the road from the driver's view with reappearance in the extension of the just-passed roadway section.
- **Jumping (Figure 2.3.e):** Similar to diving but with displaced reappearance.
- **Fluttering (Figure 2.3.f):** Multiple driving or a rapidly rolling profile.
- **Broken-back vertical curve (Figure 2.3.a, 2.3.b and 2.3.c):** A short tangent section between two sag vertical curves.

Some studies have used simulation techniques to offer a better understanding of road aesthetics in the case of combined alignment (Hassan and Easa, 2000, 2002, Bidulka et al., 2002a). Road alignment is simulated by 3D computer models in order to predict how drivers will react to certain alignments. Necessary measures are then taken to improve maximum safety. By constructing a perspective view, the horizontal and vertical curves combine in one specific image curve, which results in a better evaluation. In addition, simulation ensures that road characteristics are not greatly changed over short roadway sections and that different sections are connected with gradual transitions. If these measures are used, the final road design has harmonized alignment and is consistent with driver expectations.
Chapter 2: Literature Review

Figure 2.3: Design cases

(Source: Lamm, 1999)
Chapter 2: Literature Review

Generally, the impact of driver misperception on safety has not been quantified in previous studies. Therefore, the only existing measure of enhancing road aesthetics is providing and using appropriate pavement markings, road signing, colored road textures, slopes, embankments, planting, directional signing, road lighting, traffic mirrors and roadside or median delineators. Pavement markings such as edge and center lines can also help control the driver's chosen speed by enabling the driver to evaluate available space.

2.2.3. Cost

Transportation cost consists of construction, operation, and maintenance costs. The highest of those costs is the operation cost, with nearly 65% of the total transportation cost (ICBC, 2000). Road construction and design are greatly affected by the nature of the terrain. Therefore, horizontal and vertical alignment should be consistent with area topography. They should also preserve the developed properties of the area and incorporate community values in order to minimize costs as much as possible. Superior alignments are those that follow the natural contours of the land and do not affect aesthetic, scenic, historic, and cultural resources along the way. As such, construction costs may be reduced when fewer earthwork is needed and when existing developments are preserved.

From the safety point of view, the only cost that can be minimized by using a well-studied alignment is the cost of collision avoidance when designing the road in a well-coordinated horizontal and vertical alignment. If a road is considered dangerous, the costs of reconstructing the section, insurance, and human life can be very high. If this cost is considered as part of the operating costs, money can be saved in the design stage.
Chapter 2: Literature Review

2.2.4. Sight Distance

Sight distance is important because of its close relation to operating speed, driver’s perception of the road, driver’s decision making and therefore safety (Urbanik et al., 1989). Due to topography constraints and alignment limitations, the driver’s sight line may be blocked by lateral or vertical obstruction, resulting in a limited sight distance. Accordingly, enough sight distance needs to be provided and visual breaks resulting from short horizontal curves, short vertical curves, or the combination of the two need to be avoided. A minimum Stopping Sight Distance (SSD) should be always provided along the length of the entire highway, so that drivers can stop before hitting an unexpected object. In addition, a sufficient Passing Sight Distance (PSD) allowing drivers on two-lane highways to pass slower vehicles should be provided frequently.

The minimum Stopping Sight Distance is the distance that a vehicle requires to come to a complete stop. This distance can be calculated by applying Equation 2.2 (AASHTO, 1994). Equation 2.2 shows that both horizontal and vertical alignments affect the Stopping Sight Distance and consequently the choice of operating speed. However, horizontal alignment is only presented by the coefficient of longitudinal friction, which presents the superelevation of the horizontal curve in an implicit way. Vertical alignment is only presented by the vertical gradient, neglecting the vertical curves in spite of their significance.

\[ S = 0.278PV + \frac{v^2}{254(f_i \pm G)} \]  

(2.2)
where
\( S = \) Stopping Sight Distance (m)
\( P = \) Perception reaction time (s)
\( V = \) Operating speed (km/h)
\( f_i = \) Coefficient of longitudinal friction
\( G = \) Highway longitudinal grade (m/m)

Stopping Sight Distance can be affected by the hour of the day. Nighttime sight distance is controlled by the height of the vehicle’s headlights (AASHTO, 1994). Also, a long sag curve gives the driver a longer lasting view than a crest curve (Hassan et al., 2003). Using Equation 2.2, the designer must ensure that the driver has an adequate signing and marking scheme, especially on combined horizontal and vertical sections.

Bidulka et al. (2002a) designated sight distance as a very significant factor in horizontal curve perception and consequently speed choice. It has been also observed that as drivers approach a horizontal curve they tend to reduce their speed from a relatively high tangent operating speed to a lower curve operating speed. The distance required to perceive the existence of a curve and to decelerate at a comfortable rate is called the Preview-Sight Distance (PVSD) (Gattis & Duncan, 1995). Gattis and Duncan (1995) also observed that as the radius of the horizontal curve increases, the required PVSD on the curve also increases.

The values of horizontal curve radii are generally determined from design guidelines. Hassan et al. (2000) noticed that design standards sometimes overestimate or underestimate the required horizontal curve radius in the case of cut sections. However, the 3D effect of the horizontal curve in combined alignments changes its value, as stated
in section 2.2.2 (Equation 2.1). Thus, 3D sight distances were studied, and elements such as horizontal and vertical alignments, cross sections, and road sideslope data were incorporated. 3D models for daytime and nighttime sight distance and vehicle stability were used to determine the maximum allowable speed. The percentage difference between the 2D and the 3D sight distances (\( \text{Diff} \)) was described by Hassan (1996) as follows:

\[
\text{Diff} = \frac{3D(SSD) - 2D(SSD)}{2D(SSD)} \times 100
\]  

The 2D value is taken as the reference value, as it is the most known value to designers. Thus, a negative value of the \( \text{Diff} \) means that the 2D value overestimates the design, while a positive value indicates that the 2D value underestimates the design. Positive values occur either at nighttime, when the sag vertical curve overlaps with the horizontal curve, or at daytime, when the crest vertical curve overlaps with the horizontal curve in a cut section. Negative values occur at daytime in cut sections or when a crest vertical curve overlaps with a horizontal curve in fill sections.

Hassan (1996) also concluded that a 3D analysis for both the Stopping Sight Distance and the operating speed models was essential because it could help in understanding, applying, and analyzing road consistency and safety. The study showed that the 3D value of the horizontal curve when combined with a crest or sag curve depended mainly on the algebraic difference of vertical grades (\( A \)) rather than on the length of horizontal curve. 3D sight distance on sag vertical curves is generally lower than the corresponding 2D value when the sag curve is overlapping with the horizontal curve. In addition, the overlapping of horizontal curves with crest vertical curves enhanced the 3D sight
distance. The difference between 2D and 3D sight distance values increased with a decrease in the horizontal curve radius and an increase in the pavement cross-slope.

Hassan (1996) stated that the percentage difference between 2D and 3D sight distances ranged from 27.72 to 29.13 for crest and from -54.56 to -39.17 for sag curves assuming a speed of 110 km/hr. This indicates that in design guidelines sag curves are overestimated, while crest curves are underestimated. For combined horizontal and vertical curves, the available sight distance calculated in 2D analyses ranges from 50% to 115% of the actual available sight distance calculated in 3D analyses.

The study also showed that as the horizontal curve radius \( R \) decreased, the effect of the combined alignment became more significant as a result of the decreasing Headlight Sight Distance (HLSD). As \( R \) approached infinity, the alignment corresponded to a 2D sag vertical curve. The 3D HLSD was also less than its 2D value for all values of \( R \).

Another study by Hassan et al. (1998b) introduced the expression of the red zones while studying the Preview Sight Distance. Red zones refer to locations where the available sight distance is less than the stopping sight distance or the preview sight distance. The PVSD is determined by checking the distance needed from the driver's eye of height (of 1 metre) to reach the road marking (which is of zero height).

The determination of red zone locations is undertaken using a 3D analysis for sight distance. Red zones are most critical for nighttime PVSD. The use of a spiral curve when added before the horizontal curve helps to reduce the range of red zones. The study showed that the range of red zones increased as the curve radius increased. Furthermore, it was found that the higher the superelevation rate, the shorter the range of the red zones. This case generally occurs when the radius of the horizontal curves decreases and when a
Chapter 2: Literature Review

higher superelevation rate is required to maintain the operating speed and the balance of forces of motion.

Easa et al. (1998) tried a different approach to improve sight distance. The Equal-Arc Unsymmetrical Vertical (EAU) curve was introduced. The EAU consisted of two unsymmetrical horizontal curves, with their Point of Compound Curvature (PCC) in the middle of the unsymmetrical vertical curve. The EAU curve increases vertical clearance, reduces curve length, and therefore enhances the sight distance. The length of an EAU curve required to satisfy a specific sight distance is shorter than that of a traditional curve. It was proven that by using an EAU vertical curve sight distance, highway aesthetics, and driver comfort could be enhanced. The EAU curve is to be used when the vertical curve is combined with a tangent or when there is a considerably flat curve in the horizontal alignment.

2.3 General Guidelines of Evaluation

This section is a summary of guidelines and recommendations that have been prepared for selected countries as a result of studies dealing with combination of horizontal and vertical alignment. The goal of these guidelines was to produce the best alignment possible, providing optimum safety and traffic quality. The guidelines generally agree that the use of well-balanced sections can minimize lack of safety and driver discomfort.

The guidelines for Germany, the United States, Switzerland, and Australia were extracted from Lamm et al. (1999). These guidelines are used in a comparison with the results of this study in Chapter 5.
2.3.1. Germany Guidelines

- In hilly topography, the radii of crest vertical curves should be larger than the radii of sag vertical curves in order to provide a longer sight distance for crest vertical curves and consequently a greater feeling of safety to the driver. \( R_{\text{crest}} > R_{\text{sag}} \)

- For smaller differences in the elevation of a roadway and on roadways with flat topography, the radii of sag vertical curves should be larger than those of crest vertical curves. \( R_{\text{sag}} > R_{\text{crest}} \)

- Quick sequences of short crest and sag vertical curves should be avoided.

- Long tangents with constant grades must be avoided, and the maximum length (in m) should be limited to 29 times the design speed (in km/h).

- When long tangents are used in a hilly topography, it is recommended to use a sag vertical curve with a long length and a large radius. \( 6V_{D} \leq L_{\text{max}} \leq 20V_{D} \), \( V_{D} \) is the design speed.

- When superimposing horizontal and vertical alignments, the ratio of \( R/R_{s} \) should be as small as possible, preferably 1/5 to 1/10 where \( R \) and \( R_{s} \) are the radii of the horizontal curve and the sag vertical curve, respectively.

- The flatter the topography, the larger should the radii of crest and sag vertical curves be with respect to the radii of horizontal curves.

- In hilly or mountainous topography, it is recommended to select a segment of constant grade between the ends of consecutive crest and sag vertical curves. The distortion point of the horizontal alignment in that case should be set near the beginning of the sag vertical curve.
2.3.2. United States Guidelines

- Curvature in the horizontal plane should be accompanied by comparable curvature in the vertical plane and vice versa. Thus, the gradeline for a long, flat horizontal curve should be smooth, flowing, and uninterrupted by short dips and humps.

- Awkward combinations of curves and tangents in both horizontal and vertical planes should be avoided. The most prominent of these combinations is the broken back gradeline, which consists of two sag curves going in the same direction connected by a short tangent. The use of longer vertical curves at each end of the short grade tangent or the elimination of the short tangent is recommended. The remedy for horizontal broken back curves is replacing the tangent with a flat curve or using a tangent of at least 500 metres between the two horizontal curves in the same direction.

- Horizontal and vertical curvatures should be co-ordinated to avoid combinations that appear awkward when viewed from a low angle. Ideally, the vertices of horizontal and vertical curves should coincide or at least to be apart by no more than one quarter of their length.

- Sharp horizontal curvatures should not be introduced at or near the top of a pronounced crest vertical curve, and the horizontal curve should be longer than the vertical curve, i.e. \( R_{\text{horizontal}} > R_{\text{vertical}} \). Design values above the minimum for the design speed are recommended.

- Sharp horizontal curvature should not be introduced at or near the low point of a pronounced sag vertical curve.

- The length of a highway that can be seen at one time by the motorist could be limited, but adequate sight distance should be preserved. There should be no more
than two course changes in the horizontal alignment or three breaks in the vertical gradeline in the driver’s view at any one point.

- Both horizontal and vertical should be longer than required by the minimum design standards when it comes to safety and operational ease, especially for sag curves which can appear as kinks. The length of a sag vertical curve should be about the same as the viewing sight distance from which the curve is first perceived by the driver, or as a minimum of 0.6 of the viewing sight distance. The length of the horizontal curves (in metres) should be at least 3 times the design speed (in km/h) and preferably twice the length.

- While designing a crest curve, it is recommended to use large crest radii to increase the driver’s feeling of safety, security, and view.

2.3.3. Switzerland Guidelines

In addition to the German Guidelines, which are also used in Switzerland, the Swiss standards add that the basis for a balanced alignment is a harmonious tuning of design elements and element sequences aimed to guarantee a well-perceived alignment and prevent abruptly changing road characteristics.

- Changes in vertical curvature should be limited as far as possible, especially in the case of a strong winding alignment. The curvatures in the vertical plane should agree with the curvatures in the horizontal plane. The length of the horizontal curve should approximately correspond to the length of the vertical curve.

- Small directional changes in the plan and small gradient changes in the profile should be improved by curves with large radii.
- A short interim tangent between two horizontal curves in the same direction should be replaced by a large horizontal curve. Short sections with constant grades between two sag vertical curves should be replaced by a long sag vertical curve.
- Directional changes hidden by a crest vertical curve should be avoided to improve safety.
- If a sag vertical curve follows a crest vertical curve, then the course of the roadway may disappear from the sight of the motorist and reappear after a certain distance. Sight losses are caused by diving and have an irritating effect on the driver. Sight losses should be avoided whenever they mask dangerous spots such as intersections or unexpected directional changes in the alignment.

2.3.4. Australia Guidelines

The Australian Guidelines deal with fitting the road to the terrain and combining horizontal and vertical alignment from an aesthetics point of view. The fact that speed conditions are influenced by the nature of the terrain and horizontal alignment was also investigated.

- Avoid excessive lengths of straight road. A gentle curvilinear design, especially in hilly terrain, always keeps the operating conditions under control and at the same time affords scope for a more sympathetic fitting of the road to the terrain.
- Arc lengths of at least 500 metres may be required to ensure that curves with small deflections angles do not appear as kinks.
- Independent tangents may be acceptable in flat terrains; isolated curves should be avoided in flat terrains.
- Several curves in succession from time to time eliminate the feeling of monotony; sound transitions between independent tangents and curves should be provided.
- Compound curves should be avoided unless the radii are large enough.
- In rolling terrain, reversed horizontal curvature fitting the terrain look good; they should be correctly related and sufficiently separated to allow warping of superelevation.
- Horizontal curves in the same direction joined by short tangents should be avoided.
- Vertical grading composed of long tangents and generous vertical curves should be adopted in preference to sections with numerous grade changes between short tangents. Hidden dips will thus be avoided as well.
- Road profiles should not include minor humps or hollows which curtail sight lines when the horizontal is adequate to provide overtaking sight distance.
- Broken back profiles consisting of two or more vertical curves in the same direction separated by short tangents should be avoided.
- Reversed vertical curves can be designed to have common vertical tangent points.
- Vertical curves should be contained within horizontal curves. This enhances the appearance of sag curves by reducing the three-dimensional rate of change of direction. It also improves the safety of crest curves by indicating the direction of curvature before the road disappears over the crest.
- Horizontal curves combined with crests have less influence on the appearance of a road than those combined with sags.
- Minimum radius horizontal curves should not be combined with crest vertical curves.
2.4 Review Summary and Conclusions

At all stages of design, the road should be considered as a three-dimensional structure which should be designed in a safe, functional, economical, and aesthetically pleasing manner. Although geometric design and computer-aided design programs have improved dramatically, designs are still not considering the 3D nature of the alignment. Design standards are mainly based on 2D separate horizontal and vertical alignments. This underestimates crest curves in some cases and overestimate sag curves in other cases, thus leading to an inconsistent and unsafe final alignment.

The literature review has also shown that the way a driver sees the road affects the speed. There exists an erroneous perception of horizontal curves when they overlapped with vertical curves. Sag curves appear flatter, while crest curves appear sharper and more dangerous. This leads the driver to decrease speed before crest curves and increase speed while approaching sag curves. As a result, the risk of collision is getting higher.

Most guidelines recommend containing vertical curves within horizontal curves, as this enhances the appearance in sag curves, improves the safety of crest curves, reduces the number of sight restrictions, and makes changes in profile less apparent. Most studies note that the main factors affecting road safety include the radius of horizontal curve and the type of vertical curve (crest or sag curve). Increasing the value of the horizontal radius was recommended by most guidelines. However, no quantitative safety measures exist. Since very few studies exist on 3D alignments, more research is required in this field.
3.1 General

This chapter is divided into two sections. The first section describes the data used for this research, while the second section presents the methodology adopted for conducting the analysis. The research is aimed at developing models for accident prediction and to estimate the impact of overlapping vertical alignments on the safety of horizontal curves.

3.2 Data Description

The road data used for the analysis consists of a section of the Trans-Canada Highway between Cache Creek and the Rockies. The horizontal and vertical alignments data has been used together with the related accident data covering the period between 1991 and 1995. This road is commercially important, transporting more than a million shipments per year. Also, it is highly used for tourism, which is clear from the amount of money spent by travelers on accommodation along its corridor every year (about $80 million). (Transport Canada, 2003) The Ministry of Transport is expecting tourism and truck traffic to increase over the next ten years on this road.
Chapter 3: Data Description and Model Development

The road stretches from Cache Creek in British Columbia to the Alberta border at the Rocky Mountains. This road section belongs to British Columbia's primary highway systems and Canada's national highway system. The highway is about 525 km long, with travel lanes varying between two, three, four and six in number. There are 14 signals and 50 intersections along the route. The route passes through national parks, as well as three provincial and five federal snow sheds. The average operating speed along the 525 kilometers section has been found fluctuating between 56.5 and 105.4 km/h.

In the past, this highway experienced problems such as accidents, extended travel time, fluctuating operating speeds, diminishing pavement life condition, and the average condition of bridges. Furthermore, in some locations poor reliability and high driver workload have also been documented. A number of studies identified locations with high accident severity and frequency, congestion areas, as well as some factors related to road conditions. These studies also evaluated the road's performance and identified possible solutions by looking into the benefit/cost ratio, community land use plans, social and environmental impact, economic development potential, and other factors that could help improve the highway. It is worth noting here that the cost of accidents alone on this highway was about $285 million for the period between 1993 and 1995. (Transport Canada, 2003)

One of the main objectives of the upgrading program was to provide safety and save half to one hour of commuter travel time (Transport Canada, 2003). This requires the upgrading of the road to an average operating speed of 95km/h, which is achieved by allowing a speed of 100km/h in rural sections and 70km/h in urban sections. Another goal was to provide a good return on investment by reducing travel time, improving pavement quality, improving the conditions of bridges, and improving the consistency and predictability of the highway.
3.2.1. Geometric Characteristics of the Road

In this study, the effect of overlapping horizontal and vertical curves on the safety of the road will be investigated. Therefore, data was collected only for the horizontal curves. Using vertical alignment data, traffic volume data, and available collision data, an analysis of the effect of the overlapping horizontal and vertical alignments was conducted. The first step in preparing the data was defining which geometric variables to select for inclusion in the data. In general, variables that are significant in estimating collisions were considered. In addition, the horizontal and vertical data of the road under study was retrieved, overlapping locations were determined, and the percentage of the vertical curves overlapping with the horizontal curves was calculated.

The following is a brief summary of the road data. The total number of horizontal curves was 366, their radius values ranging from 160 metres to 5730 metres. Of the curves, 40% had a radius between 250 metres and 500 metres, and 37% of the radii values were between 500 and 1,000 metres. The lengths of those horizontal curves ranged from 100 metres to 1,300 metres, with an average curve length of 287 metres. The Average Annual Daily Traffic (AADT) volume on these curves ranged from 3,865 to 30,110 vehicles. The majority of the curves had the AADT value ranging from 5,000 to 6,000. The number of horizontal curves overlapping with crest curves was found to be 112, and the number of the horizontal curves overlapping with sag curves was 132. The gradients of vertical curves ranged from 0% to 8.4%, with the algebraic difference (A) ranging between 0.1 and 14. About 47% of those gradients had values of less than 1%. Thus, the change in gradient for most of the road section was considered to be mild. The (K) value ranged from 0 metres to 2,500 metres.
Chapter 3: Data Description and Model Development

The data for the overlap of vertical curve locations with horizontal curves is as shown in Table 3.1. As shown in the table, about 66.7% of horizontal curves were co-ordinated with vertical curves, and that the majority of those curves have a 50% to 100% overlap.

<table>
<thead>
<tr>
<th>Overlap Percentages</th>
<th>Number of Horizontal Curves</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 %</td>
<td>122</td>
</tr>
<tr>
<td>&gt;0 to 50 %</td>
<td>116</td>
</tr>
<tr>
<td>&gt;50 to &lt;100 %</td>
<td>88</td>
</tr>
<tr>
<td>100 %</td>
<td>40</td>
</tr>
</tbody>
</table>

Table 3.1: Vertical Curves Overlap Percentages

Table 3.2 summarizes the characteristics of road elements as described above.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Minimum value</th>
<th>Maximum value</th>
<th>Mean value</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radius of horizontal curve (m)</td>
<td>160</td>
<td>5730</td>
<td>696.7</td>
<td>560.4</td>
</tr>
<tr>
<td>Length of horizontal curve (m)</td>
<td>100</td>
<td>1300</td>
<td>286.8</td>
<td>166.3</td>
</tr>
<tr>
<td>AADT</td>
<td>3865</td>
<td>30110</td>
<td>5817.8</td>
<td>2943.1</td>
</tr>
<tr>
<td>Vertical grade (%)</td>
<td>0.0</td>
<td>8.4</td>
<td>0.3</td>
<td>2.8</td>
</tr>
<tr>
<td>Algebraic difference in grades (%)</td>
<td>0.0</td>
<td>14.0</td>
<td>2.23</td>
<td>2.58</td>
</tr>
<tr>
<td>K- value (m)</td>
<td>0.0</td>
<td>2500</td>
<td>150</td>
<td>241.7</td>
</tr>
<tr>
<td>Percentage of overlap (%)</td>
<td>0.0</td>
<td>100.00</td>
<td>37</td>
<td>36.15</td>
</tr>
<tr>
<td>Total Accidents (#)</td>
<td>0.0</td>
<td>16</td>
<td>1.27</td>
<td>1.84</td>
</tr>
</tbody>
</table>

Table 3.2: Summary of Road Element Characteristics
3.2.2. Data Classification

The data for this research has been split into four groups in order to investigate various combinations of horizontal and vertical data independently and to study the effect of sag and crest curves on road safety. Those four groups are as follows:

1- Group 1 - No vertical curves: In this group, only the horizontal curves not overlapped with vertical curves are taken into consideration. The total sample size of horizontal curves is 122.

2- Group 2 - Horizontal curves overlapped with crest curves: In this case, only the horizontal curves overlapped with crest vertical curves are considered. The total sample size of horizontal curves is 112.

3- Group 3 - Horizontal curves overlapped with sag curves: In this group, only the horizontal curves overlapped with sag vertical curves are considered. The total sample size of horizontal curves is 132.

4- Group 4 - All Horizontal Curves: In this group, all horizontal curves belonging to groups 1, 2, and 3 above are included. The total sample size of horizontal curves is 366.
3.3 Methodology

The methodology followed in this study is based on the development of collision prediction models (CPM) to estimate the impact of overlapping vertical alignments (crest and sag curves) on the safety of horizontal curves. The type of CPM used in this study relates accidents frequency to exposure (both traffic volume and length) raised to the power of estimated model variables. As well, other explanatory variables are added to the models in an exponential term.

The Generalized Linear Interactive Model (GLIM 4) has been used for the development of collision prediction models. The GLIM model was developed by the Numerical Algorithms Group (NAG, 1994), and it is commonly applied in similar traffic studies. The developed model was checked and any misleading data (outliers) was removed. This process was repeated for the four groups of data under study. Finally, a comparison of all groups was done to quantify the enhancement or decrease in road safety.

The following sections provide a general discussion on the use of collision prediction models, followed by the specifics of their application in this study.

3.3.1. Generalized Linear Interactive Modeling

The GLIM model is a program specifically designed to facilitate the fitting of generalized linear models. It simplifies model specification and model fitting procedures. The GLIM approach assumes a non-normal error structure (usually a Poisson or a Negative Binomial distribution). Thus, it overcomes the shortcomings of the conventional regression
approach in modeling accidents which are random, discrete, non-negative, and typically sporadic events. Conventional linear regression models can also predict negative values for accidents, which is unrealistic. This is also why logarithmic link functions are usually used.

Previous research and studies have found that using the Binomial distribution to describe collision occurrence is more realistic than the Poisson distribution. This is because most collisions data is likely to be overdispersed and to have a variance greater than the mean, thus leading to an underestimation of the variances of the estimated model coefficients and an overestimation of the significance of these coefficients. Overdispersion is mostly due to the fact that no accident prediction model can contain all the variables that explain accident occurrence. Other factors include the uncertainties in vehicle exposure data, traffic variables, and the fact that some accident data comes from a non-homogenous roadway environment. Therefore, Binomial distribution error structure was adopted for the evaluation of results in this research.

The conventional linear regression model has the form presented in Equation 3.1. This form can only be used if the model is linear. In other words, all error terms must be normally distributed, not correlated, and equal in variance.

\[
y_i = \beta_0 + \sum_{j=1}^{k} \beta_j x_{ij} + \epsilon_i
\]  

(3.1)
where:

- \( Y_i \): response or independent variable
- \( \beta_0, \beta_j \): model parameters
- \( x_y \): predictor or explanatory variable
- \( \varepsilon_i \): random error term, assumed to be normally distributed with the mean equal to zero and variance equal to one

3.3.2. Significance Testing

The first step in the process of developing a collision prediction model is choosing the model variables among a variety of geometric design variables of the road. In order to choose only the ones significantly contributing to explaining accident occurrences, the GLIM model is used to check the significance of each variable. Some safety studies assume that as the number of variables in an accident prediction model increases, the predictive accuracy of the model becomes high. However, this is not totally true, as some variables and some combination of variables might influence the prediction in a negative or insignificant way. Insignificant variables do not improve the model’s prediction ability. However, the model’s accuracy can be improved by including the largest number of significant variables. Therefore, it is important to choose only significant road geometric variables.

Several statistical measures can be used to assess the goodness of fit of GLM models. The two statistical measures used are those cited by McCullagh and Nelder (1989) for assessing model goodness of fit. These are a) the Pearson\( \chi^2 \) statistic, defined in equation
3.2, and b) the scaled deviance. The scaled deviance is the likelihood ratio test statistic measuring twice the difference between the maximized log-likelihoods of the studied model and the full or saturated model. The full model has as many parameters as there are observations so that the model fits the data perfectly. Therefore, the full model, which possesses the maximum log-likelihood achievable under the given data, provides a baseline for assessing the goodness of fit of an intermediate model with \( p \) parameters. The \( \text{Pearson}\chi^2 \) is defined as:

\[
\text{Pearson}\chi^2 = \sum_{i=1}^{n} \frac{(y_i - \hat{E}(Y_i))^2}{\text{Var}(Y_i)}
\]  

(3.2)

where \( y_i \) is the observed number of accidents on section \( i \), \( \hat{E}(Y_i) \) is the predicted accident frequency for section \( i \) as obtained from the APM, and \( \text{Var}(Y_i) \) is the variance of the accident frequency for section \( i \). McCullagh and Nelder (1989) have shown that if the error structure is follows the negative binomial distribution, the scaled deviance is:

\[
SD = 2 \sum_{i=1}^{n} \left[ y_i \ln \left( \frac{y_i}{\hat{E}(Y_i)} \right) - y_i + \kappa \right] \ln \left( \frac{y_i + \kappa}{\hat{E}(Y_i) + \kappa} \right)
\]

(3.3)

Where \( \kappa \) is the shape parameter.
Chapter 3: Data Description and Model Development

Both the scaled deviance and the Pearson $\chi^2$ have $\chi^2$ distributions for Normal theory linear models, but they are asymptotically $\chi^2$ distributed with $(n - p)$ degrees of freedom for other distributions of the exponential family.

The GLIM program estimates the coefficients of the entered variables using the principle of the maximum likelihood based on a given probability distribution and the form of the model. Using a fitting command and groups of various variables, the best combination of variables can be obtained from the model runs. First, variables that are statistically significant to the model are investigated. To obtain a good fit model and produce reliable predictions, over-fitting must be avoided.

The decision of whether a variable is significant or not depends on the t-ratio of its estimated parameters. The t-ratio is the ratio between the parameter estimate and the standard error. A significant value has a t-ratio greater than 1.96 (i.e. it is significant at 95% confidence level). Then, it must be checked whether adding the variable to the models results in a significant drop in the scaled deviance at the 95% confidence level. Several combinations are tried out, and the GLIM approach is repeated several times until the best model for explaining the accident data is obtained.
3.3.3. Model Structure

Traffic safety is generally expressed by the number of collisions occurring in a specific location. The more traffic there is on a certain length of the road, the higher the probability of collision. The main variables are the traffic volume and the road section (segment length). The model presented in the following equation describes the predicted accident frequency:

\[ E(\Lambda) = a_0 \times L^{a_1} \times V^{a_2} \]  

(3.4)

where:

\( E(\Lambda) \) = predicted accident frequency
\( L \) = segment length
\( V \) = segment traffic volume, AADT (Average Annual Daily Traffic)
\( a_0, a_1, a_2 \) = model parameters

Since road geometry is of primary significance in this research, other factors have to be added to the model equation to describe the road’s geometric characteristics. As a result, the modified model equation can be presented as follows:

\[ E(\Lambda) = a_0 \times L^{a_1} \times V^{a_2} \times e^{\sum b_j x_j} \]  

(3.5)

where the exponential term \( e^{\sum b_j x_j} \) stands for the geometry of the road and represents any additional \( x_j \) variables that are different than \( L \) and \( V \).
3.3.4. Model Development

The main objective of this research is to develop accident prediction models that take into consideration the geometric features of the road under study. Therefore, all significant horizontal and vertical variables are checked for their influence on accident occurrence. Variables are checked individually and in combinations. Several scenarios are tried, and the most promising one is taken as the basic model.

The basic model includes the exposure variables of traffic volume and segment length. Those variables have been found by traffic studies to be the most influential in collision models. As the volume of traffic increases, the accident occurrence increases as well. The basic model was considered as a reference model in this study. All other variables of the road's geometric characteristics were added to the basic model one by one, and the procedure of checking the variable significance by using the GLIM model was repeated for each variable.

The most significant combination of variables explaining accident occurrences is then checked again, and an outlier analysis is conducted to exclude outliers. After the removal of outlier data, the previous steps of model development are repeated until the most accurate model and the most influential factors have been found.
3.3.5. Estimating the Negative Binomial Distribution Parameter $\kappa$

The value of $\kappa$, the Negative Binomial Distribution Parameter, is to be adopted from the final model. This parameter is important, as it describes the dispersion of data around the established model. Models with different variables have different $\kappa$ values.

There are several approaches to estimating the parameter $\kappa$ of the negative binomial distribution such as: (1) the maximum likelihood method, (2) the mean $\chi^2$ method, which is the method of moments, (3) the mean deviance moments method, and (4) the method of moments proposed by Kulmala (1995), in which the parameter $\kappa$ is initially calculated from the estimates obtained from the Poisson distribution model.

The most widely used method is the maximum likelihood, because it is based on the log-likelihood function that coincides with the logarithm of the joint probability function of the negative binomial distribution, as presented in Equation 3.6. The maximum likelihood is a function of $\mu$ (mean value) and $\kappa$, where $\mu$ is also a function of the parameter estimate $\beta$ (parameter of the additional variable):

$$P(Y = y) = \frac{\Gamma(k + y)}{\Gamma(k) y!} \left(\frac{k}{k + \mu}\right)^k \left(\frac{\mu}{\lambda + \mu}\right)^y$$  \hspace{1cm} (3.6)

The expected value $E(Y)$ and variance $Var(Y)$ is calculated as follows:

$$E(Y) = \mu \; ; \; Var(Y) = \mu + \frac{\mu^2}{\kappa}$$  \hspace{1cm} (3.7)
Chapter 3: Data Description and Model Development

The mean chi-square ($\chi^2$) method is based on fitting the Pearson’s $\chi^2$ value to the number of degrees of freedom to get the value of $\beta$. This is achieved through an iterative process. It takes an initial estimate of the $\kappa$ value and replaces it with newly obtained parameters $\beta$ for new estimates of $\kappa$ until the desired degree of convergence is obtained.

The mean deviance moments method is similar to the chi-square method. The only difference is that the scaled deviance method is set equal to the numbers of degrees of freedom instead of Pearson $\chi^2$.

The method of moments, or the fixed $\kappa$-method proposed by Kulmala (1995), is based on first estimating a basic value for $\kappa$ using the following equation:

$$
\kappa \approx \frac{\sum_{i=1}^{n} E(\Lambda)^2_i}{\sum_{i=1}^{n} (\text{error}_i^2 - E(\Lambda)_i)}
$$

(3.8)

$E(\Lambda)_i$ is to be estimated based on the Poisson distribution model. Then, the $\kappa$ value is obtained by running the GLIM macro to estimate the parameters of the Negative Binomial distribution. This process is repeated until the desired degree of convergence is obtained.

Similar to the model building process, one must start with the basic reference model, which contains only the variables of exposure. In this case, the basic model is to be developed by one of the three methods described above. The fourth method (method of
moments) is used to add all the significant variables one by one while adjusting the $\kappa$ value. For each run, the new scaled deviance value and its drop as compared to the previous run is obtained. The scaled deviance is thus compared, and its change, which results from adding variables, can be easily detected and evaluated.

The importance of parameter $\kappa$ lies within the fact that the higher the $\kappa$ value, the lower the variance of the predicted accidents. Therefore, there is little model uncertainty. Conversely, the lower the $\kappa$ value, the higher the variance of the predicted accidents resulting in high model uncertainty.

### 3.3.6. Outlier Analysis

Outliers are data points that are split off or are substantially different from the rest of the data. They can be caused by irregularities, errors in data recording, or the observation process, or by instances when some of the data is genuinely different from the rest. Since traffic data is very sporadic by nature, many of those points might occur. It is therefore important to investigate them further and to verify the importance of their meaning and value.

This can be checked by using two measures, leverage values and Cook's distance. Both are calculated using the GLIM model. The leverage value is the measure of how far the x-coordinate value of a point is from the average of the x-values. A high leverage value of a point indicates that it has a leverage or that it is important in the fit, but it does not guarantee a significant effect on the regression line. This depends on the magnitude of the observed response for the point in question, not just on the explanatory variants (NAG,
1994). If the removal of the point would greatly change the regression line, then it is said to be influential. The amount of influence of each specific point cannot be reliably verified by the leverage value. Consequently, Cook's distance has been introduced.

Cook's distance has a measure of influence. Thus, the greater the Cook's distance the greater the influence. Cook's distance is calculated using the following equation:

\[
c_i = \frac{h_i}{p(1-h_i)}(r_{PS,i})^2
\]  

(3.9)

where:
- \(c_i\) = Cook’s distance
- \(h_i\) = leverage value
- \(p\) = number of parameters
- \(r_{PS,i}\) = standardized residual

The main disadvantage of this method is that there is no specific threshold to represent good value of Cook’s distance. The data is sorted out, the data points with the highest Cook’s distance values are removed, and the change in the scaled deviance is assessed. Maycock and Hall (1984) proposed that the difference in scaled deviance with a difference in degree of freedom of \(df_1\) and \(df_2\) is \(\chi^2\) distributed through parameters \((df_1 - df_2)\). This means that if only one point with a high Cook’s distance is removed, the difference in scaled deviance should be greater than 3.8, which is the \(\chi^2\) value corresponding to the 95% level of confidence and one degree of freedom. In this study,
this procedure was carried out for all runs, and the best run for each case of the four groups under study was chosen for further model development.

The procedure of discarding outliers requires sorting all data according to Cook's distance in ascending order or to plot the data and resulting Cook's distances. The data point that has an abnormally high Cook's distance value is removed and the resulting drop in scaled deviance is calculated. The resulting drop is significant if its value is equal to or greater than $\chi^2_{0.05,1}$.

In order to assess whether the removal of an outlier point is significant or not, it is important to fix the value of the $\kappa$ parameter for a model with (n) data points and impose it on the model with (n-1) data points after removing the outlier. Then, the significance of removing the point can be assessed.

A typical example of taking the exposure into consideration for Model 12, is shown in Figure 3.1. This example is based on the fixed $\kappa$-method and on identifying and removing the outliers as explained in this section.
3.3.7. Comparison of models

The last step in model development is to compare the models of all four groups with each other in order to study the safety effects of overlapping alignments. The comparison is done by considering one model at a time as a base case. Then, a new value of the coefficient $a_0$ is determined for the other models (with a similar formulation) applying the same value of coefficients of the base case model (excluding coefficient $a_0$). The
Chapter 3: Data Description and Model Development

coefficient for the basic model is $a_{0_{(Basic)}}$. The procedure is repeated for each of the six models. By running the GLIM model, a new value for $a_0$ is obtained ($a_{0_{(New)}}$). This value is first checked for significance. If the new $a_0$ is found significant, the ratio between $a_{0_{(New)}}$ and $a_{0_{(Basic)}}$ is calculated. This ratio represents the relative safety of one model over another.

3.3.8. Model Applications

The importance of collision prediction models is in the variety of their uses. In general, there are four applications of collision prediction models. First is the identification of accident-prone locations in a road network. Second is the ranking of accident-prone locations, so that transportation planners can get an idea about the most dangerous road sections and plan their schedules of countermeasures accordingly. In this way, priorities can be easily determined, especially when funding is limited. Third, is the estimation of safety during the planning stage to assess the effect of changes in a location’s characteristics on safety. Fourth, in a before and after studies to determine the effectiveness of safety interventions.

3.4 Summary

The purpose of this chapter is to describe the data and the methodology used in this research. The data used for the analysis has been described and split into different groups to enable a more specific analysis. The methodology adopted in this research is also
Chapter 3: Data Description and Model Development

presented. The model structure is described, and the procedure to develop an accurate model is summarized. The importance of the Pearson $\chi^2$ statistic data as a measure of goodness of fit for collision models is also presented. Finally, the steps of the data analysis and removal of outlier points used to obtain an unbiased model are presented, followed by a brief description of model application.
4.1 General

This chapter presents the results and model development, along with all relevant statistical information for the four group of models used in this study. The significance of the different investigated variables, and the outlier analysis are shown in tabular and graphical forms. In addition a comparison between the developed models is presented at the end.

4.2 Model Variables

The significance of the variables must first be statistically checked, as described in Section 3.3.2. This check was done using the GLIM model. The first variable selected for significance checking was exposure. Exposure is presented by two terms, traffic volume expressed by the Average Annual Daily Traffic (AADT) and segment length (L in km). The exposure is usually measured in million vehicles in a unit length of one kilometre (MVK). The next variable, noted by several studies to have a significant effect on collisions, is the horizontal curve radius (R) in meters. The results of the study show that the greater the value of horizontal curvature the fewer accidents occur.
Chapter 4: Results

The variables defining vertical curves are vertical gradients, namely the gradient leading in to the curve (G1) and the grading leading out of the vertical curve (G2), and the algebraic difference between the in and out gradients is the (A) value, which was also found to be of significance. An indicator value was added to state whether the curve was sag or crest. In addition, the percentage of overlap (OP) of vertical curve and horizontal curves was included.

Another factor found to be worth investigating is the distance of the vertical curve intersection point to the horizontal curve (D). An indicator value of whether the vertical curve intersection point lay outside or inside the horizontal curve was also added. The indicator value was equal to 1 if the intersection point lay within the horizontal curve, and it was equal to 0 if the intersection point lay outside the horizontal curve. The ratio between the radii of horizontal and vertical curve (RR) noted by the German guidelines was also considered for significance checking. All these variables were investigated for in groups and individually.

4.3 Model Development and Outlier Analysis

The most significant variable found in the GLIM model was the exposure. Both terms, the traffic volume and the segment length, were found to be statistically significant at the 95% confidence level. Both were positively correlated to accidents. Thus, the accidents are more probable with increasing traffic volume and section length. The t-ratio, defined as the ratio between the estimated GLIM coefficient parameter and its standard error, was used to define whether the variables in the model were significant. The variable is significant at the 95% level of confidence if its t-ratio is greater than 1.96.
First, the traffic volume and the horizontal curve length variables (called the basic evaluation model) were analyzed. Then, all variables were investigated to find the most significant ones. Their t-ratio values were ranked in descending order, and those variables which had the t-ratio value of less than 1.96 were taken out, as they would not be significant in the analysis. The variables found to be significant were added (one by one) to the basic model to check their effect on the t-ratio values of the used variables. This procedure was repeated for all probable groups of variables, until the most significant model was obtained.

An outlier analysis was then conducted. Cook’s distance was calculated and used in defining the outliers. The outliers might have an effect on models results if they are found to be significant. In this case, they should be excluded from the data. Figure 4.1 shows a graphical representation of Model 12 as an example and a tabulation of its outliers. The detailed outlier analysis of different developed models is presented in Appendix-3.

The outcome of this process was developed models (1 to 15), as presented in Table 4.1. The models developed for the four cases are shown together with their negative binomial distribution parameter $\kappa$. It was found that all models have relatively high $\kappa$ values, which means that their degree of uncertainty is small and can therefore be considered acceptable. Out of the 15 models developed, only eight have been chosen (two models for each case) for further investigation. The chosen models are presented in Table 4.2 and further discussed.
Chapter 4: Results

MODEL 12

<table>
<thead>
<tr>
<th>Point Analyzed (#)</th>
<th>Sample Size (#)</th>
<th>Scaled Deviance</th>
<th>Scaled Deviance *</th>
<th>SD Drop</th>
</tr>
</thead>
<tbody>
<tr>
<td>302</td>
<td>365</td>
<td>381.20</td>
<td>377.16</td>
<td>4.04</td>
</tr>
<tr>
<td>290</td>
<td>364</td>
<td>382.63</td>
<td>378.96</td>
<td>3.67</td>
</tr>
<tr>
<td>73</td>
<td>363</td>
<td>383.24</td>
<td>380.01</td>
<td>3.23</td>
</tr>
<tr>
<td>274</td>
<td>362</td>
<td>383.56</td>
<td>380.86</td>
<td>2.70</td>
</tr>
</tbody>
</table>

* after outlier removal

Figure 4.1: Cook’s Distance Graph and Tabulation for Outlier Removal
## Model Forms

### Group 1: No Vertical Curves (Models 1 - 2)

\[
\begin{align*}
\text{Acc} / 5 \text{yrs} &= 0.02228 \times V^{0.5396} \times L^{0.614} \\
\kappa &= 2.083 \\
\text{Acc} / 5 \text{yrs} &= 0.06469 \times V^{0.6822} \times L^{0.4604} \times e^{-0.0005469 R} \\
\kappa &= 2.287
\end{align*}
\]

### Group 2: Combined horizontal & crest curves (Models 3 - 6)

\[
\begin{align*}
\text{Acc} / 5 \text{yrs} &= 0.013 \times V^{0.3935} \times L^{0.7149} \\
\kappa &= 2.814 \\
\text{Acc} / 5 \text{yrs} &= 0.01275 \times V^{0.5273} \times L^{0.7461} \times e^{-0.000437 R} \\
\kappa &= 3.491 \\
\text{Acc} / 5 \text{yrs} &= 0.041089 \times V^{0.548} \times L^{0.602} \times e^{-0.0004225 R - 0.007136 OP} \\
\kappa &= 4.415 \\
\text{Acc} / 5 \text{yrs} &= 0.017 \times V^{0.5375} \times L^{0.7397} \times e^{-0.000383 R - 0.005062 OP - 0.001048 D} \\
\kappa &= 5.412
\end{align*}
\]

### Group 3: Combined horizontal & sag curves (Models 7 - 11)

\[
\begin{align*}
\text{Acc} / 5 \text{yrs} &= 0.0887 \times V^{0.7653} \times L^{0.3108} \\
\kappa &= 2.319 \\
\text{Acc} / 5 \text{yrs} &= 0.104 \times V^{1.065} \times L^{0.3088} \times e^{-0.0007281 R} \\
\kappa &= 2.976 \\
\text{Acc} / 5 \text{yrs} &= 0.3185 \times V^{1.183} \times L^{0.137} \times e^{-0.0007607 R - 0.004926 OP} \\
\kappa &= 3.001 \\
\text{Acc} / 5 \text{yrs} &= 0.6669 \times V^{1.347} \times L^{-0.0511} \times e^{-0.0007398 R - 0.007603 OP + 0.083664 A} \\
\kappa &= 3.5 \\
\text{Acc} / 5 \text{yrs} &= 0.3315 \times V^{1.044} \times L^{0.06977} \times e^{-0.008468 OP + 0.1228 A - 2.966 R R} \\
\kappa &= 2.957
\end{align*}
\]

### Group 4: All Horizontal Curves (Models 12 - 15)

\[
\begin{align*}
\text{Acc} / 5 \text{yrs} &= 0.029986 \times V^{0.5415} \times L^{0.5507} \\
\kappa &= 2.109 \\
\text{Acc} / 5 \text{yrs} &= 0.04293 \times V^{0.7129} \times L^{0.5178} \times e^{-0.000532 R} \\
\kappa &= 2.394 \\
\text{Acc} / 5 \text{yrs} &= 0.0595 \times V^{0.7438} \times L^{0.4781} \times e^{-0.0005372 R - 0.003759 OP} \\
\kappa &= 2.453 \\
\text{Acc} / 5 \text{yrs} &= 0.10056 \times V^{0.8092} \times L^{0.3604} \times e^{-0.0005061 R - 0.007746 OP + 0.08189 A} \\
\kappa &= 2.581
\end{align*}
\]

Table 4.1: Developed Model Forms
## Model Forms

### No vertical curves

**Model 1**
\[
\text{Acc/5yrs} = 0.02228 \times V^{0.5396} \times L^{0.614} \quad \kappa = 2.083
\]

**Model 2**
\[
\text{Acc/5yrs} = 0.06469 \times V^{0.6822} \times L^{0.4604} \times e^{-0.0005469R} \quad \kappa = 2.287
\]

### Combined horizontal & crest curves

**Model 3**
\[
\text{Acc/5yrs} = 0.013 \times V^{0.3935} \times L^{0.7149} \quad \kappa = 2.814
\]

**Model 4**
\[
\text{Acc/5yrs} = 0.06469 \times V^{0.6822} \times L^{0.4604} \times e^{-0.0005469R} \quad \kappa = 3.491
\]

### Combined horizontal & sag curves

**Model 7**
\[
\text{Acc/5yrs} = 0.0887 \times V^{0.7653} \times L^{0.3108} \quad \kappa = 2.319
\]

**Model 8**
\[
\text{Acc/5yrs} = 0.104 \times V^{1.065} \times L^{0.3088} \times e^{-0.0007281R} \quad \kappa = 2.976
\]

### All horizontal curves

**Model 12**
\[
\text{Acc/5yrs} = 0.029986 \times V^{0.5415} \times L^{0.5507} \quad \kappa = 2.109
\]

**Model 13**
\[
\text{Acc/5yrs} = 0.04293 \times V^{0.7129} \times L^{0.5178} \times e^{-0.000532R} \quad \kappa = 2.394
\]

**Table 4.2:** Model Forms for the four cases
Chapter 4: Results

4.4 Significance Results

The following tables show the results of significance for the developed models (1 to 15). Scaled deviance and Pearson $\chi^2$ are both significant at the 95% confidence level, indicating that the models have an acceptable fit to the data. Most t-ratios of the variables' parameters estimates are also significant at the 95% confidence level. The results of significance tests are presented in Tables 4.3 to 4.17 and discussed below.

where:

- $V =$ traffic volume
- $L =$ horizontal curve length
- $R =$ horizontal curve radius
- $\text{OP} =$ percentage of overlap
- $A =$ algebraic difference of vertical gradients
- $D =$ distance between the vertical curves intersection point to the horizontal curve
- $\text{RR} =$ ratio between the radii of the horizontal curve and the vertical curve
- $df =$ degrees of freedom

4.4.1. Best-fit models of Group 1 (No vertical curves)

All horizontal curves not overlapped with vertical curves were used to develop the best fit models. The total number of horizontal curves was 122. The basic model was taken including the traffic volume ($V$) and the horizontal curve length ($L$). For the second model the variable of the horizontal curve radius ($R$) was added. With the outliers
removed, Tables 4.3 and 4.4 were obtained. The scaled deviance and the Pearson $\chi^2$ values are both significant at the 95 percent confidence level indicating that Models 1 and 2 have an acceptable fit to the data. The t-ratios of the parameters are also significant at the 95 percent confidence level for (V) and (R) in Model 2 (Table 4.4). In Model 1 (V) and (L) are significant at the 90 percent confidence level (Table 4.3), and (L) in Model 2 is significant at the 80 percent confidence level.

\begin{table}[h]
\begin{tabular}{|l|l|l|}
\hline
Variable & Coefficient & t-ratio \\
\hline
Constant & 0.02228 & -1.965 \\
V & 0.5396 & 1.767 (at 90\%) \\
L & 0.614 & 1.576 (at 90\%) \\
\hline
\end{tabular}
\caption{Table 4.3: Significance Results for Model 1}
\end{table}

\begin{table}[h]
\begin{tabular}{|l|l|l|}
\hline
Variable & Coefficient & t-ratio \\
\hline
Constant & 0.06469 & -1.405 \\
V & 0.6822 & 2.25 \\
L & 0.4604 & 1.189 (at 80\%) \\
R & -0.0005469 & -1.969 \\
\hline
\end{tabular}
\caption{Table 4.4: Significance Results for Model 2}
\end{table}
4.4.2. Best-fit models of Group 2 (Horizontal curves overlapped with crest curves)

All horizontal curves overlapped with crest vertical curves were used to develop the best fit models. The total number of horizontal curves was 112. The basic model was taken including the traffic volume (V) and the horizontal curve length (L). For the second model the variable of the horizontal curve radius (R) was added, followed by (OP) and (D) in the other models. With the outliers removed, Tables 4.5 to 4.8 were obtained. The scaled deviance and the Pearson $\chi^2$ values are both significant at the 95 percent confidence level indicating that the models have an acceptable fit to the data. The t-ratios of the parameters are also significant at the 95 percent confidence level, except for some. In Model 3 (V) is significant at the 85 percent confidence level (Table 4.5), in Model 5 (L) is significant at almost the 95 percent confidence level (Table 4.7), and in Model 6 the percentage of overlap (OP) is significant at the 80 percent confidence level and the distance between the vertical curves intersection point to the horizontal curve (D) is significant at less than the 80 percent confidence level (Table 4.8).

**Model 3:**

\[
\frac{Acc}{5yrs} = 0.013 \times V^{0.3935} \times L^{0.7149}
\]

<table>
<thead>
<tr>
<th>Scaled Deviance</th>
<th>df</th>
<th>Shape Parameter $\kappa$</th>
<th>Pearson $\chi^2$</th>
<th>$\chi^2_{0.05, df}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>123.63</td>
<td>108</td>
<td>2.814</td>
<td>115.6</td>
<td>133.26</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Variable</th>
<th>Coefficient</th>
<th>t-ratio</th>
<th>Coefficient</th>
<th>t-ratio</th>
<th>Coefficient</th>
<th>t-ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant</td>
<td>0.013</td>
<td>-2.648</td>
<td>0.3935</td>
<td>1.461</td>
<td>0.7149</td>
<td>2.188</td>
</tr>
<tr>
<td>V</td>
<td>0.3935</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>L</td>
<td>0.7149</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Table 4.5:** Significance Results for Model 3
Chapter 4: Results

Model 4:

\[ Acc/5\text{yrs} = 0.01275 \times V^{0.5273} \times L^{0.7461} \times e^{-0.000437R} \]

<table>
<thead>
<tr>
<th>Variable</th>
<th>Coefficient</th>
<th>t-ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant</td>
<td>0.01275</td>
<td>-2.699</td>
</tr>
<tr>
<td>V</td>
<td>0.5273</td>
<td>1.992</td>
</tr>
<tr>
<td>L</td>
<td>0.7461</td>
<td>2.323</td>
</tr>
<tr>
<td>R</td>
<td>-0.000437</td>
<td>-1.998</td>
</tr>
</tbody>
</table>

Table 4.6: Significance Results for Model 4

Model 5:

\[ Acc/5\text{yrs} = 0.041089 \times V^{0.548} \times L^{0.602} \times e^{-0.0004225R-0.007136OP} \]

<table>
<thead>
<tr>
<th>Variable</th>
<th>Coefficient</th>
<th>t-ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant</td>
<td>0.041089</td>
<td>-1.921</td>
</tr>
<tr>
<td>V</td>
<td>0.548</td>
<td>2.151</td>
</tr>
<tr>
<td>L</td>
<td>0.602</td>
<td>1.888</td>
</tr>
<tr>
<td>R</td>
<td>-0.0004225</td>
<td>-1.999</td>
</tr>
<tr>
<td>OP</td>
<td>-0.007136</td>
<td>-2.061</td>
</tr>
</tbody>
</table>

Table 4.7: Significance Results for Model 5
### Model 6:

\[
\text{Acc}_{5\text{yrs}} = 0.017 \times V^{0.5375} \times L^{0.7397} \times e^{-0.000383R-0.005062OP-0.001048D}
\]

<table>
<thead>
<tr>
<th>Scaled Deviance</th>
<th>df</th>
<th>Shape Parameter ( \kappa )</th>
<th>Pearson ( \chi^2 )</th>
<th>( \chi^2_{0.05,df} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>128.20</td>
<td>105</td>
<td>5.412</td>
<td>122.2</td>
<td>129.92</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Variable</th>
<th>Coefficient</th>
<th>t-ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant</td>
<td>0.017</td>
<td>-2.248</td>
</tr>
<tr>
<td>V</td>
<td>0.5375</td>
<td>2.175</td>
</tr>
<tr>
<td>L</td>
<td>0.7397</td>
<td>2.215</td>
</tr>
<tr>
<td>R</td>
<td>-0.000383</td>
<td>-1.904</td>
</tr>
<tr>
<td>OP</td>
<td>-0.005062</td>
<td>-1.289</td>
</tr>
<tr>
<td>D</td>
<td>-0.001048</td>
<td>-0.985</td>
</tr>
</tbody>
</table>

### Table 4.8: Significance Results for Model 6

#### 4.4.3. Best-fit models of Group 3 (Horizontal curves overlapped with sag curves)

All horizontal curves overlapped with sag vertical curves were used to develop the best fit models. The total number of horizontal curves was 132. The basic model was taken including the traffic volume (V) and the horizontal curve length (L). For the second model the variable of the horizontal curve radius (R) was added, followed by (OP), (A) and (RR) in the other models. No outliers were removed in this group. Tables 4.9 to 4.13 were obtained. The scaled deviance and the Pearson \( \chi^2 \) values are both significant at the 95 percent confidence level indicating that the model has an acceptable fit to the data. The t-ratios of the parameter are also significant at the 95 percent confidence level,
except for some. The horizontal curve length \((L)\) is in all models significant at less than 80 percent confidence level. In Model 9 the percentage of vertical curves overlap \((OP)\) is significant at less than 80 percent confidence level (Table 4.11), in Model 10 the algebraic difference of vertical gradients \((A)\) is significant at the 90 percent confidence level (Table 4.12), and in Model 11 the ratio between the radius of the horizontal curve and the vertical curve \((RR)\) is significant at almost the 90 percent confidence level (Table 4.13).

| Model 7: |
|---|---|---|---|
| \(Acc/5\text{yrs} = 0.0887 \times V^{0.7653} \times L^{0.3108}\) |

<table>
<thead>
<tr>
<th>Variable</th>
<th>Coefficient</th>
<th>(t)-ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant</td>
<td>0.0887</td>
<td>-1.223</td>
</tr>
<tr>
<td>(V)</td>
<td>0.7653</td>
<td>2.291</td>
</tr>
<tr>
<td>(L)</td>
<td>0.3108</td>
<td>0.782 (at &lt;80%)</td>
</tr>
</tbody>
</table>

Table 4.9: Significance Results for Model 7
### Chapter 4: Results

#### Model 8:

\[ \text{Acc/5yrs} = 0.104 \times V^{1.065} \times L^{0.3088} \times e^{-0.0007281R} \]

<table>
<thead>
<tr>
<th>Variable</th>
<th>Coefficient</th>
<th>t-ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant</td>
<td>0.104</td>
<td>-1.15</td>
</tr>
<tr>
<td>V</td>
<td>1.065</td>
<td>2.91</td>
</tr>
<tr>
<td>L</td>
<td>0.3088</td>
<td>0.78</td>
</tr>
<tr>
<td>R</td>
<td>-0.0007281</td>
<td>-2.51</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Scaled Deviance</th>
<th>df</th>
<th>Shape Parameter $\kappa$</th>
<th>Pearson $\chi^2$</th>
<th>$\chi^2_{0.05,df}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>140.25</td>
<td>128</td>
<td>2.976</td>
<td>128.2</td>
<td>155.40</td>
</tr>
</tbody>
</table>

**Table 4.10: Significance Results for Model 8**

#### Model 9:

\[ \text{Acc/5yrs} = 0.3185 \times V^{1.183} \times L^{0.137} \times e^{-0.0007607R-0.004926OP} \]

<table>
<thead>
<tr>
<th>Variable</th>
<th>Coefficient</th>
<th>t-ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant</td>
<td>0.3185</td>
<td>-0.53</td>
</tr>
<tr>
<td>V</td>
<td>1.183</td>
<td>3.12</td>
</tr>
<tr>
<td>L</td>
<td>0.137</td>
<td>0.328</td>
</tr>
<tr>
<td>R</td>
<td>-0.0007607</td>
<td>-2.6</td>
</tr>
<tr>
<td>OP</td>
<td>-0.004926</td>
<td>-1.36</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Scaled Deviance</th>
<th>df</th>
<th>Shape Parameter $\kappa$</th>
<th>Pearson $\chi^2$</th>
<th>$\chi^2_{0.05,df}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>138.62</td>
<td>127</td>
<td>3.001</td>
<td>126.6</td>
<td>154.30</td>
</tr>
</tbody>
</table>

**Table 4.11: Significance Results for Model 9**
Chapter 4: Results

Model 10:

\[ AcclSyrs = 0.6669 \times V^{1.347} \times L^{-0.0511} \times e^{-0.0007398R - 0.007603OP + 0.08366A} \]

<table>
<thead>
<tr>
<th>Scaled Deviance</th>
<th>df</th>
<th>Shape Parameter ( \kappa )</th>
<th>Pearson ( \chi^2 )</th>
<th>( \chi^2_{0.05,df} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>140.03</td>
<td>126</td>
<td>3.5</td>
<td>123.7</td>
<td>153.20</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Variable</th>
<th>Coefficient</th>
<th>t-ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant</td>
<td>0.6669</td>
<td>-0.19</td>
</tr>
<tr>
<td>V</td>
<td>1.347</td>
<td>3.6</td>
</tr>
<tr>
<td>L</td>
<td>-0.0511</td>
<td>-0.12 (at &lt;80%)</td>
</tr>
<tr>
<td>R</td>
<td>-0.0007398</td>
<td>-2.5</td>
</tr>
<tr>
<td>OP</td>
<td>-0.007603</td>
<td>-1.9</td>
</tr>
<tr>
<td>A</td>
<td>0.08366</td>
<td>1.79 (at 90%)</td>
</tr>
</tbody>
</table>

Table 4.12: Significance Results for Model 10

Model 11:

\[ Accl/5yrs = 0.3315 \times V^{1.044} \times L^{0.06977} \times e^{-0.008468OP + 0.1228A - 2.966RR} \]

<table>
<thead>
<tr>
<th>Scaled Deviance</th>
<th>df</th>
<th>Shape Parameter ( \kappa )</th>
<th>Pearson ( \chi^2 )</th>
<th>( \chi^2_{0.05,df} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>139.39</td>
<td>126</td>
<td>2.957</td>
<td>122.4</td>
<td>153.20</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Variable</th>
<th>Coefficient</th>
<th>t-ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant</td>
<td>0.3315</td>
<td>-0.535</td>
</tr>
<tr>
<td>V</td>
<td>1.044</td>
<td>3.069</td>
</tr>
<tr>
<td>L</td>
<td>0.06977</td>
<td>0.171 (at &lt;80%)</td>
</tr>
<tr>
<td>OP</td>
<td>-0.008468</td>
<td>-2.084</td>
</tr>
<tr>
<td>A</td>
<td>0.1228</td>
<td>2.397</td>
</tr>
<tr>
<td>RR</td>
<td>-2.966</td>
<td>-1.600 (at almost 90%)</td>
</tr>
</tbody>
</table>

Table 4.13: Significance Results for Model 11
4.4.4. Best-fit models of Group 4 (All Horizontal Curves)

All horizontal curves of the database were used to develop the best fit models. The total number of horizontal curves was 366. The basic model was taken including the traffic volume (V) and the horizontal curve length (L). For the second model the variable of the horizontal curve radius (R) was added. In the third model (OP) was added, and in the fourth model (A) was added. With the outliers removed, Tables 4.14 to 4.17 were obtained. The scaled deviance and the Pearson $\chi^2$ values are both significant at the 95 percent confidence level indicating that the model has an acceptable fit to the data. The t-ratios of the parameter are also significant at the 95 percent confidence level, except for the horizontal curve length (L) in Model 15, which is significant at 90 percent confidence level (Table 4.17).

<table>
<thead>
<tr>
<th>Model 12:</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\text{Acc/5yrs} = 0.029986 \times V^{0.5415} \times L^{0.5507}$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Variable</th>
<th>Coefficient</th>
<th>t-ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant</td>
<td>0.029986</td>
<td>-3.25</td>
</tr>
<tr>
<td>V</td>
<td>0.5415</td>
<td>3.049</td>
</tr>
<tr>
<td>L</td>
<td>0.5507</td>
<td>2.54</td>
</tr>
</tbody>
</table>

Table 4.14: Significance Results for Model 12
### Model 13:

\[
\text{Acc}_{5\text{yrs}} = 0.04293 \times V^{0.7129} \times L^{0.5178} \times e^{-0.000532R}
\]

<table>
<thead>
<tr>
<th>Variable</th>
<th>Coefficient</th>
<th>t-ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant</td>
<td>0.04293</td>
<td>-2.92</td>
</tr>
<tr>
<td>V</td>
<td>0.7129</td>
<td>3.969</td>
</tr>
<tr>
<td>L</td>
<td>0.5178</td>
<td>2.409</td>
</tr>
<tr>
<td>R</td>
<td>-0.000532</td>
<td>-3.537</td>
</tr>
</tbody>
</table>

Table 4.15: Significance Results for Model 13

### Model 14:

\[
\text{Acc}_{5\text{yrs}} = 0.0595 \times V^{0.7438} \times L^{0.4781} \times e^{-0.000532R-0.003759OP}
\]

<table>
<thead>
<tr>
<th>Variable</th>
<th>Coefficient</th>
<th>t-ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant</td>
<td>0.0595</td>
<td>-2.614</td>
</tr>
<tr>
<td>V</td>
<td>0.7438</td>
<td>4.155</td>
</tr>
<tr>
<td>L</td>
<td>0.4781</td>
<td>2.2289</td>
</tr>
<tr>
<td>R</td>
<td>-0.0005372</td>
<td>-3.5837</td>
</tr>
<tr>
<td>OP</td>
<td>-0.003759</td>
<td>-2.107</td>
</tr>
</tbody>
</table>

Table 4.16: Significance Results for Model 14
Chapter 4: Results

Model 15:

\[ \text{Acc/5yrs} = 0.10056 \times V^{-0.8092} \times L^{0.3604} \times e^{-0.0005061R-0.007746OP+0.08189A} \]

<table>
<thead>
<tr>
<th></th>
<th>Coefficient</th>
<th>t-ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Constant</strong></td>
<td>0.10056</td>
<td>-2.13</td>
</tr>
<tr>
<td><strong>V</strong></td>
<td>0.8092</td>
<td>4.567</td>
</tr>
<tr>
<td><strong>L</strong></td>
<td>0.3604</td>
<td>1.674</td>
</tr>
<tr>
<td><strong>R</strong></td>
<td>-0.0005061</td>
<td>-3.387</td>
</tr>
<tr>
<td><strong>OP</strong></td>
<td>-0.007746</td>
<td>-3.226</td>
</tr>
<tr>
<td><strong>A</strong></td>
<td>0.08189</td>
<td>2.657</td>
</tr>
</tbody>
</table>

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Scaled Deviance</strong></td>
<td>376.90</td>
<td></td>
</tr>
<tr>
<td><strong>df</strong></td>
<td>359</td>
<td></td>
</tr>
<tr>
<td><strong>Shape Parameter</strong></td>
<td>( \kappa )</td>
<td>2.581</td>
</tr>
<tr>
<td><strong>Pearson</strong> ( \chi^2 )</td>
<td>347.8</td>
<td></td>
</tr>
<tr>
<td><strong>( \chi^2 ), df</strong></td>
<td>404.18</td>
<td></td>
</tr>
</tbody>
</table>

Table 4.17: Significance Results for Model 15

4.5 Model Comparison

A comparison between the developed models was conducted to study the effect of the presence of sag or crest curves on horizontal curves. The procedure as described in the previous chapter consists of forcing all parameters of the variables of one model (original model) on the other models, and then calculating new constant parameters \( a_0 \) for those models. Thus the resulting \( a_{b(\text{New})} \) can be compared with the \( a_{b(\text{Basic})} \) value of the original model, to study the effect of the presence or non presence of different kind of vertical curves on the available database of the study. This procedure is repeated for all models. The following groups of data are considered in this comparative study: no vertical curves

68
(group 1), combined crest curves (group 2), and combined sag curves (group 3). These groups include six different cases, as described in the previous chapter.

Table 4.18 presents the newly obtained constant parameters $a_{0(\text{New})}$. Those values will be further compared to each other as can be seen from ratio of the $a_{0}$ parameters in Table 4.19. When comparing the $a_{0(\text{New})}$ to the basic value, it can be observed that the presence of crest curves resulted in an increase in collisions in the cases of no vertical curves and in sag curves. The increase of collisions in sag curves is much less (2.7% & 1.3%) than that in the case of no vertical curves (11.5% & 10.9%). On the other hand, the presence of sag curves cause a slight increase in collisions in the case of no vertical curves (8.0% & 9.8%) and a decrease in collisions in the case of crest curves (-3.7% & -2.5%).

This proves the hypothesis that crest curves appear to be more dangerous than sag curves due to the perception of the vertical crest curve. Applying no vertical curve parameters to both crest and sag curves shows a significant decrease in collisions in both cases. The decrease was noted to be slightly more than in the case of crest curve.

<table>
<thead>
<tr>
<th>Study Case</th>
<th>$a_{0(\text{Basic})}$</th>
<th>$a_{0(\text{New})}$</th>
<th>$a_{0(\text{New})}$</th>
<th>$a_{0(\text{New})}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Group 1</td>
<td>Group 2</td>
<td>Group 3</td>
</tr>
<tr>
<td>Group 1</td>
<td>0.02228</td>
<td>-</td>
<td>0.019545</td>
<td>0.02018</td>
</tr>
<tr>
<td></td>
<td>0.06469</td>
<td>-</td>
<td>0.059605</td>
<td>0.060084</td>
</tr>
<tr>
<td>Group 2</td>
<td>0.01300</td>
<td>0.01468</td>
<td>-</td>
<td>0.013366</td>
</tr>
<tr>
<td></td>
<td>0.01275</td>
<td>0.014307</td>
<td>-</td>
<td>0.012919</td>
</tr>
<tr>
<td>Group 3</td>
<td>0.08870</td>
<td>0.096424</td>
<td>0.08552</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>0.10400</td>
<td>0.115325</td>
<td>0.101469</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 4.18: Comparison of models
where:
Group 1 = no vertical curves
Group 2 = combined horizontal and crest curves
Group 3 = combined horizontal and sag curves

<table>
<thead>
<tr>
<th>Study Case</th>
<th>Group 1</th>
<th>Group 2</th>
<th>Group 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Group 1</td>
<td>-</td>
<td>-14.0%</td>
<td>-10.4%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-8.5%</td>
<td>-7.7%</td>
</tr>
<tr>
<td>Group 2</td>
<td>11.5%</td>
<td>-</td>
<td>2.7%</td>
</tr>
<tr>
<td></td>
<td>10.9%</td>
<td>-</td>
<td>1.3%</td>
</tr>
<tr>
<td>Group 3</td>
<td>8.0%</td>
<td>-3.7%</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>9.8%</td>
<td>-2.5%</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 4.19: Percentages of reduction or increase in collisions

To study the significance of the \( Ratio \) in Table 4.19 and its impact on overlapping alignments another procedure has to be done. Considering that this \( Ratio \) equals to \( Z \), where:

\[
Z = \frac{a_{0(\text{New})}}{a_{0(\text{Basic})}} = a_{0(\text{New})} \times a_{0(\text{Basic})}^{-1} \quad (4.1)
\]

It is important to study the significance of \( (Z) \), by checking its t-ratio in correspondence to collisions. The t-ratio is the ratio between the estimate and the standard error. Since \( Z \) has the form of following standard equation

\[
Z = a \times X^n \times Y^q \times U^p \quad (4.2)
\]
Chapter 4: Results

The standard error for \( Z \) can be calculated by applying the general error equation 4.3.

\[
\left[ \frac{E_Z}{Z} \right]^2 = n^2 \left[ \frac{E_X}{X} \right]^2 + q^2 \left[ \frac{E_Y}{Y} \right]^2 + p^2 \left[ \frac{E_U}{U} \right]^2
\]

(4.3)

By making substitutions in Equation 4.3, the ratio \( E_z \) can be calculated as follows:

\[
E_z = \sqrt{\frac{E_X^2 + E_Y^2 \times X^2}{y^2 + E_Y^2}}
\]

(4.4)

where \( x \) and \( y \) are the estimates of \( a_{0(basic)} \) and \( a_{0(now)} \).

where:
\( Z \) = function, \( f(X,Y,U) \)
\( X, Y, U \) = independent variables of function \( Z \)
\( E_Z, E_X, E_Y, E_U \) = error in \( Z, X, Y \) and \( U \)

The estimated error in \( Z \) can thus be calculated and is as shown in the next Table 4.20:

<table>
<thead>
<tr>
<th>Study Case</th>
<th>Estimated Error (Z)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Group 1</td>
</tr>
<tr>
<td>Group 1</td>
<td>0.493</td>
</tr>
<tr>
<td>Group 2</td>
<td>0.389</td>
</tr>
<tr>
<td>Group 3</td>
<td>0.848</td>
</tr>
</tbody>
</table>

Table 4.20: Z-Error Calculation
Chapter 4: Results

Thus the calculation of the t-ratio becomes as follows in Table 4.21:

<table>
<thead>
<tr>
<th>Study Case</th>
<th>t-ratio of (Z)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Group 1</td>
</tr>
<tr>
<td>Group 1</td>
<td>1.779</td>
</tr>
<tr>
<td>Group 2</td>
<td>2.902</td>
</tr>
<tr>
<td>Group 3</td>
<td>1.282</td>
</tr>
<tr>
<td></td>
<td>1.217</td>
</tr>
</tbody>
</table>

Table 4.21: T-ratio of (Z)

The t-ratio results show that when removing vertical curves from crest or sag curves alignments, the resulting reduction in collisions is significant at the 90 percent confidence level. Forcing crest curves on a non-vertical curves alignment, or on sag curves alignments, results in an increase of collisions. The t-ratio shows that the significance is at the 95 percent confidence level (Row 2). On the other hand, when introducing sag vertical curves to non-vertical curves alignments results in an increase of collisions, which can be seen from the positive sign of the t-ratio (Row 3). The significance results are at the 80 percent confidence level. While introducing sag vertical curves to crest curves alignments will reduce collisions, but the significance of the results is only at the 80 percent confidence level.
4.6 Summary and Conclusions

This chapter presents the results of the work done for the development of collision prediction models. First, the most significant variables were identified. The most significant variables found were the exposure variables (traffic (V) and horizontal curve length (L)), the value of the horizontal curve radius (R), the algebraic difference in vertical gradients (A), the percentage of overlap between the vertical and horizontal curves (OP), the location of the vertical gradients intersection points with respect to the horizontal curve (D) and the ratio between the horizontal curve radius and the vertical curve radius (RR). Some of those variables have appositive relationship with collisions (an increase in these variables increases collisions) such as (V), (L) and (A), and some have a negative relationship such as (R), (OP), (D) and (RR).

Thus a basic model was developed with the exposure variables and segment length. Then the rest of the significant variables were added one by one. An outlier analysis was performed to exclude misleading data. Subsequently, fifteen models were developed for collision prediction. Out of these models, eight models were selected to conduct a comparative study of the effect of vertical curves on horizontal alignments. During the comparison of the models, it was found that introducing vertical curves to non vertical curves alignments increases collision occurrence. This increase was found to be more for the case of crest curves (10.9 to 11.5%) than in the case of sag curves (8.0 to 9.8%), which proves that crest curves may be more accident prone than sag curves.
5.1 General

This chapter provides an analysis of the results of this study and describes the relationship between accidents and the co-ordination of horizontal and vertical alignments. It also summarizes the influence of significant found road design variables on road safety, followed by a discussion of model comparison.

5.2 Discussion of the Developed Models

Fifteen models were developed, as presented in Table 4.1. The table includes the developed models for the four groups of this study. Several road variables have been tested for their significance in collisions. These variables are traffic volume (V), length of the horizontal curve (L), horizontal curve radius (R), difference in vertical gradient (A) for vertical curves, (K) value of vertical curves, and the percentage of overlap between vertical curves and their combined horizontal curve (i.e. the ratio of the length of the horizontal curve combined with vertical curves). An indicator value was also added to classify whether the vertical curve is a crest or a sag curve. Another variable investigated is the distance between the intersection point of the vertical grades and the intersection point of the horizontal curve’s tangents. An indicator value was also added to identify if
the vertical intersection point lies within or outside the horizontal curve. It has been found that the same variable does not show the same result when evaluated for the four groups.

5.2.1. No Vertical Curve Case (Models 1 and 2)

Regarding road geometry, this case is only dependent on the value of horizontal curves and vertical grades. The most significant variables found were the traffic volume and the curve length. The sign of the coefficient for the traffic volume in a certain length indicates that the greater the exposure, the greater the probability of accident occurrence. This agrees with all traffic studies and as mentioned before in the Literature Review.

Another significant variable was the radius of the horizontal curve with a negative coefficient sign, indicating that the greater the horizontal curve radius, the less the probability of accident occurrence. It is to be noted that in the absence of vertical curves, the driver has a full view of the road and the sight distance is not obstructed. (Lamm et al., 1999)

5.2.2. Horizontal Curves combined with Crest Curves Case (Models 3 to 6)

The most significant factors in this case were still the exposure variables. The sign of the coefficient of the traffic volume indicated that the greater the exposure, the greater the accident occurrence probability.
Chapter 5: Analysis

The indicator value for the location of the vertical curve intersection point (VPI) was also found significant. Locating the vertical intersection point within the horizontal curve has been found safer than when locating it outside the curve. However, the variable of the distance between the VPI and the horizontal curve was not found to be significant. This finding agrees with the US and Australian guidelines which recommend including the vertical curve within the horizontal curve wherever possible.

Another significant variable was the overlap percentage of vertical curves to horizontal curve length. The longer the percentage of overlap, the lower the probability of accident occurrence was found to be. From Model 6, it can also be concluded that by combining the overlap percentage with the distance between the VPI and the horizontal curve, the significance of the overlap can be significantly affected.

The horizontal curve radius was found to be significant, in a way that the greater the horizontal curve radius, the smaller the probability of accident occurrence. Lamm et al. (1999) referred this to an increase in sight distance and therefore less driver workload. The US guidelines as mentioned before recommended to increase the value of horizontal curve radius on crest curves ($R_{\text{horizontal}} > R_{\text{vertical}}$) to provide more sight distance.

Surprisingly, the (A) and (K) variables were not found to be significant in the case of crest curves. Crest curves appear more dangerous than sag curves to the drivers, who tend to reduce speed on crest curves. Thus, driving on crest curves might be safer from the point of view the drivers are more cautious. On the other hand, this might be more dangerous due to the danger of not having enough sight distance. It was not possible to figure out which of these two possibilities was true in this particular study case.
5.2.3. Horizontal Curves combined with Sag Curves Case (Models 7 to 11)

In this case again, the most significant variables were traffic volume and length of horizontal curve. The sign of their coefficients indicate that the higher the magnitude of the exposure, the higher the probability of accident occurrence.

The horizontal radius was also found of great significance. The greater its value, the lower the probability of accident occurrence due to the greater view provided when combining horizontal and sag curves. This is mainly because a prolonged sight distance and a safer previewed horizontal curve radius are available. (Bidulka et al., 2002b, Hassan et al., 2003) The US guidelines advised to avoid sharp horizontal curves in sag curves in order to overcome this problem.

The percentage of vertical curve overlap to the horizontal curve total length was very significant, indicating that the greater the percentage, the lower the probability of accident occurrence. Therefore, sag curves should be included as much as possible within horizontal curves, as mentioned by Lamm et al. (1999) and the Australian Guidelines.

In the case of sag curves, it was found that the (A) value, the difference of gradients at the vertical intersection point, was significant. The sign of its coefficient indicated that the greater the (A) value (i.e. the greater the change in vertical gradient), the greater the probability of accident occurrence. In the case of crest curves, this value was not found to be as significant as in the case of sag curves. This proves that sag curves are more sensitive to grade change than crest curves. Also, this might be related to the perceived horizontal curve, the preview sight distance, and the hypothesis that drivers tend to increase their driving speed when approaching sag curves. The Swiss guidelines referred
Chapter 5: Analysis

this to a ‘loss of sight’ caused by diving and as such can have an irritating effect on the driver.

Another factor studied was the ratio of the horizontal radius to the vertical curve radius. The German guidelines recommend that this ratio be between 0.1 and 0.2. The ratio was calculated for all sag curves, and the data was split into three categories: (1) all values of this ratio taken together, (2) only the values between 0.1 and 0.2 checked, and (3) the values below 0.1 and above 0.2 checked.

The tests indicated that only the first category was significant, illustrating that the greater the ratio (i.e. the smaller the value of the vertical curve radius to the horizontal curve), the more the probability of accident occurrence. By considering only the ranges of the ratio recommended by the German guidelines (Category 2), the significance test indicated that the greater the ratio, the greater the probability of accident occurrence. In the third category (ratio<0.1 & ratio>0.2), the t-ratio sign was negative, indicating the opposite of the last two statements. The ratio was significant, but it might be recommended with other ranges rather than with the 0.1 to 0.2 range.

5.2.4. All Horizontal Curves Case (Models 12 to 15)

The most significant variables are those related to exposure, namely traffic and the related corresponding curve length. This is due to the fact that the higher the traffic volume and the longer the curve length, the higher the probability of accidents.
Chapter 5: Analysis

The next variable found to be significant was the horizontal radius of curvature. The sign of its coefficient indicated that the greater the value of the horizontal radius, the fewer accidents would happen. Large radius curves enhance driving conditions, offer safety to drivers, and provide longer sight distances. Therefore, these curves have less effect on accident occurrence. As discussed in the Literature Review, small radius curves are normally associated with higher superelevation rates and distortions of outer pavement edges, which could confuse drivers at night and lead to an increased risk of accidents (Hassan et al., 1997).

The overlap in vertical curves has been found significant. Its negative coefficient identified that the greater the overlap of the vertical curves to the horizontal curves, the less the occurrence of accidents. This agrees with the observations of other studies and the recommendations of design guidelines for Australia. The guidelines recommend containing vertical curves within the horizontal curves. The results of this study indicate that the more the vertical curve is contained (i.e. the bigger the percentage of overlap), the safer the driving conditions.

Another significant factor was the vertical variable (A) (algebraic gradient difference) of the vertical curve. It was found that the greater the (A) value, the more accidents were expected to happen. This means that the greater the vertical grades differ or the more the vertical grades change, the higher the rate of accidents in that particular location. This explains why humps and diving conditions should be avoided, as presented in Figure 2.3 (Lamm et al., 1999).

The (K) value of the vertical curve was also found to be significant. The greater the (K) value, the less accidents were predicted to happen. The significance test results showed that the (K) value had a bigger effect on safety than the (A) value. Therefore, it is
recommended to enlarge the length of vertical curves (instead of taking the minimum values, as mentioned in design standards) in order to enhance their sight distance and thus provide more safety to vertical curves.

Another significant variable was the identifier value for the location of the vertical intersection point with respect to the horizontal curve, even though the distance between them was not found to be significant. When the vertical intersection point (VPI) was included within the horizontal curve fewer collisions were noted than when it was located outside the curve. Accordingly, the location of VPI with respect to the horizontal curve merits further studies, because it might affect 3D design procedures.

By studying a combination of variables including the exposure, overlap, and indicator value for crest and sag it was found that crest curves were more accident prone than sag curves. This proves the importance of the 3D effect on sight distance and collisions. This also indicates that combined curves appear flatter than combined crest vertical curves.

5.3 Discussion of Outlier Analysis

Two horizontal radii were found worth removing from the database (as outliers). The first one had a horizontal radius of 528 metres and a length of 940 metres, and its curve was not combined with vertical alignment. The second curve had a horizontal radius of 635 metres and a length of 285 metres with 33.3% of the curve overlapping with a vertical crest curve, and an algebraic difference (A) equal to 3.2.

No clear reason was found in the geometric features of these two radii, but their removal was significant. In this case, there might be another reason beside the geometric
characteristics of the road that caused accidents at that location such as driving or weather conditions.

After the removal of the outlier data points, new runs were prepared for a new regression of the models variables, and only the most significant road variables were used. The Negative Binomial Distribution coefficient $\kappa$ was satisfactory for the models, which proved that variance of the predicted accidents was low. Accordingly, there was little uncertainty in the model. Also, the scaled deviance and the Pearson $\chi^2$ were found to be significant at the 95% confidence level. Thus, it can be concluded that the models have an acceptable fit to the data.

5.4 Models Comparison

The models compared were those including the exposure variables and the radius of horizontal curvatures for the four cases in the study. Those models were chosen, because their variables are all significant in all cases of studies. Thus comparison of models will be easier for them.

It was found that the absence of vertical curves caused a decrease in the number of collisions in the case of sag curves (7.7% to 10.4%) and in the case of crest curves (8.5% to 14%). This means that avoiding vertical/horizontal curve combination can enhance safety. The degree of safety gained is worth the excess of earthwork and other problems, because it is widely known that road alignments follow existing contours of the landscape. Another way to increase safety is through elongating vertical curves in order
to enhance driving conditions. This also increases the overlap percentage and the (K) value of vertical curves.

Furthermore, it was found that the presence of crest curves caused an increase of collisions (1.3% to 2.7%) in the case of sag curves and an even bigger increase (10.9% to 11.5%) in the case of no-vertical curves. From these results it can be concluded that crest curves increase the risk of collision occurrence. This risk is considered very small and could be enhanced by increasing the curve length of horizontal and vertical curves. On the contrary, introducing crest curves to an alignment that had no vertical curves decreased the degree of safety by about 10%. Thus, any introduction of crests should be well justified.

The presence of sag curves has been found to cause an increase in the number of collisions in the case of no vertical curves (8% to 9.8%) and a decrease in the number of collisions in the case of crest curves (2.5% to 3.7%). Introducing sag curves to an alignment that has no vertical curves increases collisions, similar to introducing crest curves. Although this decrease in the number of collisions is slightly less than in the case of crest curves, it still represents a decrease in the level of road safety. Nevertheless, it is still better to have sag curves than crest curves, as they decrease collisions and thus enhance road safety.

It was noticed that crest curves had more severe effects than sag curves. This was mainly due to the value of the perceived radius, as discussed in Equation 2.1. Therefore, minimum horizontal curves should not be combined with crest curves, because this reduces the sight distance significantly, leading to an increase in the number of accidents. Design guidelines also recommend that on hilly slopes the horizontal radius of crest be
much larger than that of sag curves. The US guidelines recommend the use of large radii in the design of crest curves in order to increase safety and sight distance.

5.5 Summary and Conclusions

In this chapter, significant variables within the developed models for each group were discussed. Some variables were found significantly common in all four groups, such as the traffic volume, the horizontal curve length, the horizontal curve radius and the percentage of overlap between horizontal and vertical curves. Other variables were found only significant in crest curves cases like the location of the VPI (inside or outside the horizontal curve). In the case of sag curves, in addition to the common found variables, the algebraic difference of vertical gradients was found significant and the ratio of horizontal curve radius to vertical curve radius. The reason for significance was all mostly related to sight distance. Furthermore, the models were compared to findings of other studies of combined geometric design. This was followed by a discussion of the outlier analysis.

The comparison of models revealed that avoiding vertical/horizontal curves combination enhances safety, i.e. decrease collisions occurrences. Combined crest curves were also found to be more collision prone than combined sag curves. Therefore minimum horizontal curves should not be combined with crest curves. The value of the curve radius in the case of crest curves should be increased and its length should be elongated to improve safety.
6.1 Summary

Highway design is a creative process that combines both technical guidance and engineering judgment, in order to achieve a safe, efficient and reliable road design. Although the highway is a 3D structure, highway design is commonly based on 2D guidelines, as available in various manuals. Design guidelines deal with road elements individually, ignoring the sequence or combination of road elements and their effect on each other, and as such they are restrictive to the creative design process. Therefore, engineering judgment is often required when highway design problems are not adequately resolved by using the guidance in the technical design manuals. As a result, the success of any design decision depends on the quality and interpretation of the technical guidance and engineering judgment.

Several studies have stated the importance of the impact of 3D design on road construction. Design by objectives rather than by standards is emerging as a new approach to geometric design. This new approach calls on the assessment of objectives and one of the most important objectives is road safety. This study presents an extensive review of these studies and their recommendations. It has been found that all recommendations are not based on objective measures in terms of safety. As a result, the main objective of this research was to establish a quantitative relationship that best
describes road safety, and enables the degree of safety that can be achieved by making changes in road design, and while studying the 3D effect of one or more of the road design variables. Another objective was to compare the effect of the different types of vertical curves on road safety. As such, this study has focused mainly on the combined effect of vertical curves on horizontal curves, and on the significance of the different road design elements on safety.

6.2 Conclusions

The analysis was performed using the data from the Trans-Canada Highway, between Cache Creek and the Rockies. Between 1993 and 1995, the cost of accidents for this section of the highway was about $285 million (Government of British Columbia). Thus, geometric design can compromise both safety and economics when transportation operating cost is considered. Normally, these costs are not taken into consideration when designing a road.

The data for this study was split into four groups. Those groups are:
- Group 1, horizontal curves not combined with vertical curves
- Group 2, horizontal curves combined with crest curves
- Group 3, horizontal curves combined with sag curves
- Group 4, all horizontal and vertical curves combined

This grouping facilitated the investigation of the effects of vertical curves on horizontal alignments. The variables of geometric design were first analysed in order to identify the significant ones. As the result of the significance analysis, 15 collision prediction models relating to combining horizontal and vertical alignments have been developed.
The modeling proved the significance of some common variables in all models such as traffic volume, curve length and curve radius. In the case of crest combined curves, the percentage of overlap and the location of vertical grade intersection points with respect to the horizontal curve were also found significantly affecting road safety. For combined sag vertical curves, the percentages of vertical curve overlap, the algebraic difference of vertical gradients and the ratio between the value of the horizontal curve and the vertical curve, were found significantly affecting road safety in addition to the common variables. For sag curves, the ratio of the horizontal curve radius to the vertical curve radius was found to be significant at almost 90% confidence level. An increase in this ratio decreases accident potential. The significant ratio was found to be between 0.1 and 0.2.

The results also show that the effect of variables is different for both crest and sag vertical curves. Some variables affect safety in a positive way and some in a negative way. As a result, it was concluded that an increase in the value of either traffic volume, curve length or the algebraic gradient difference, results in an increase in collisions, i.e. decrease in road safety. While increasing the value of curve radius, overlap percentage, or the ratio between the horizontal curve radius and the vertical curve radius can enhance road safety, i.e. reduce collision occurrences. It was also noted that containing the vertical intersection point within the horizontal curve length wherever possible was advisable, because it resulted in a decrease in the number of collisions.

The locations of high driver workloads and sudden big changes in highway alignment have been found by most studies to be associated with higher accident potential, not enough sight distance and, therefore, poor design. This study showed that the smaller the value of horizontal curves and the higher the value of (A) the more collisions increase. On the other hand, aesthetically pleasing locations appear as safer to the drivers, positively affecting their performance. To drivers, sag curves appear more flat than their
original values and crest curves as more sharp and severe than their value. The results of the study have shown that crest curves experience a higher collision rate than sag curves. Another observation was that in absence of vertical curves fewer collisions occur. As such, the difference in percentages when imposing vertical curves on non-vertical curve alignment was found to be a decrease in safety by 14% for crest curves and 10% for sag curves.

For high traffic volumes and longer curve lengths, it has also been noted that avoiding vertical curves can enhance safety. Replacing a curve by a tangent, increasing and decreasing horizontal curve radii, or ignoring the effect of vertical curves cannot be left to chance or abandoned due to economic reasons. It should also be noted that an inappropriate change might cause a drop in safety and an increase in accident costs, which are part of the running operating cost of any road (e.g. high change in vertical grades, which is associated with a high (A) value, or short curve length).

The effect of the 3D sight distance should not be left to chance or designers’ discretion. It should be implemented in the design and calculation of vertical curves. In addition, sight distance determination can affect the location of roadside barriers or fences. These barriers obstruct sight distance if not properly implemented.

6.3 Recommendations for Future Research

Three-dimensional road alignment involves extremely complex calculations. There are several equations and cases that have been left unexplored in design guidelines. Therefore, a lot of research work is still required. Based on the findings of this research, it is recommended to revise the old design guidelines and provide new ones based on 3D
design equations. Three-dimensional sight distance must also be incorporated into design procedures or at least checked at the end of the design process.

It is believed that the ratio of the horizontal curve radius to the vertical curve radius deserves more research. This study found it to be significant at the 90% confidence level. A new range of ratios should be developed to complement German guidelines. Also the location of vertical intersection point (VPI) with respect to the horizontal intersection point deserves further research, as it was found of significance. A relation between this distance and the percentage of overlap or the length of both curves (horizontal and vertical) is worth investigating.

The algebraic difference between vertical gradients (A) has been found to be significant. Therefore, it is believed that more research could be done to define the critical value for this difference when combining vertical and horizontal alignments. This could be used during the design stage instead of encouraging engineers to increase the curve lengths of vertical curves. As such, sudden dips and humps could be avoided and enough sight distance provided.

The effects of 3D combined alignment also raised some questions that should be addressed during the design process. These questions are as follows: What should be the minimum horizontal radius when combined with crest or sag curves? What is the minimum length of the crest vertical curves for maximum safety? What is the effect of speed on combined alignments? How can accident reporting methods be more elaborated to help in future analyses of the subject instead of simply recording the number of accidents? Finally, it is recommended that the interaction between horizontal and vertical alignment be considered at all times for maximum safety. More research can and should be done on this subject.
References


APPENDIX – 1

COMPUTER OUTPUTS FROM THE GLIM PROGRAM

A full copy of Model 1’s output is provided. This copy includes the run for the Poisson distribution and that for the Negative Binomial Distribution. For the rest of the models, only the Negative Binomial distribution output is shown, as it is the one based on the analysis.

Model 1

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scale parameter 1.000

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<td></td>
<td>144.4</td>
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Model 2

[ML Estimate of THETA = 2.287
 Std Error = (0.9865)
NOTE: standard errors of fixed effects do not take account of the estimation of THETA
2 x Log-likelihood = -173.7 on 117 df
2 x Full Log-likelihood = -324.5

estimate s.e. parameter
1 -2.738 1.949 1
2 0.6822 0.3032 VOL
3 0.4604 0.3870 LL
4 -0.0005469 0.0002778 R
scale parameter 1.000
110.4
143.2

Model 3

[ML Estimate of THETA = 2.814
 Std Error = (1.498)
NOTE: standard errors of fixed effects do not take account of the estimation of THETA
2 x Log-likelihood = -145.8 on 108 df
2 x Full Log-likelihood = -316.3

estimate s.e. parameter
1 -4.338 1.638 1
2 0.7149 0.3267 LL
3 0.3935 0.2693 VOL
scale parameter 1.000
115.6
133.3

---

94
Model 4

- ML Estimate of THETA = 3.491
- Std Error = (2.130)
- NOTE: standard errors of fixed effects do not take account of the estimation of THETA
- \(2 \times \text{Log-likelihood} = -141.1 \text{ on 107 df}\)
- \(2 \times \text{Full Log-likelihood} = -311.6\)

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- Scale parameter 1.000
- 113.7
- 132.1

Model 5

- ML Estimate of THETA = 4.415
- Std Error = (3.207)
- NOTE: standard errors of fixed effects do not take account of the estimation of THETA
- \(2 \times \text{Log-likelihood} = -136.9 \text{ on 106 df}\)
- \(2 \times \text{Full Log-likelihood} = -307.4\)

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- Scale parameter 1.000
- 117.9
- 131.0
Model 6

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Model 7

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96
Model 8

scaled deviance = 140.25 (change = -47.75) at cycle 3
residual df = 128  (change =  0 )
ML Estimate of THETA =  2.976
Std Error = ( 1.427)
NOTE: standard errors of fixed effects do not take account of the estimation of THETA
2 x Log-likelihood = -184.4 on 128 df
2 x Full Log-likelihood = -372.0
estimate s.e. parameter
1  -2.263  1.964  1
2   1.065  0.3654 VOL
3   0.3088  0.3942 LL
4  -0.0007281  0.0002900  R
scale parameter 1.000
128.2
155.4

Model 9

scaled deviance = 138.62 (change = -47.65) at cycle 3
residual df = 127  (change =  0 )
ML Estimate of THETA =  3.001
Std Error = ( 1.425)
NOTE: standard errors of fixed effects do not take account of the estimation of THETA
2 x Log-likelihood = -182.5 on 127 df
2 x Full Log-likelihood = -370.1
estimate s.e. parameter
1  -1.144  2.144  1
2   1.183  0.3787 VOL
3   0.1370  0.4175 LL
4  -0.0007607  0.0002923  R
5   -0.004926  0.003607  OP
scale parameter 1.000
126.6
154.3
Model 10

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123.7

153.2

Model 11

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scale parameter 1.000

122.4

153.2
Model 12

```
[e] $eoff$
[w] -- model changed
[w] -- model changed
[o] scaled deviance = 382.63 (change = -183.1) at cycle 2
[o] residual df = 362 (change = 0)
[o] ML Estimate of THETA = 2.109
     Std Error = (0.4974)
[o] NOTE: standard errors of fixed effects do not
take account of the estimation of THETA
[o] 2 x Log-likelihood = -508.5 on 362 df
[o] 2 x Full Log-likelihood = -1039.
[o] estimate  s.e. parameter
[o] 1  -3.507  1.079  1
[o] 2   0.5415  0.1776  LV
[o] 3  0.5507  0.2167  LL
[o] scale parameter 1.000
[o] 365.2
[o] 407.4
```

Model 13

```
[e] $eoff$
[o] scaled deviance = 381.05 (change = -163.2) at cycle 3
[o] residual df = 361 (change = 0)
[o] ML Estimate of THETA = 2.394
     Std Error = (0.6034)
[o] NOTE: standard errors of fixed effects do not
take account of the estimation of THETA
[o] 2 x Log-likelihood = -494.2 on 361 df
[o] 2 x Full Log-likelihood = -1024.
[o] estimate  s.e. parameter
[o] 1  -3.148  1.076  1
[o] 2   0.7129  0.1796  VOL
[o] 3  0.5178  0.2149  LL
[o] 4  -0.0005320  0.0001504  R
[o] scale parameter 1.000
[o] 353.2
[o] 406.3
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Appendix-1
Model 14

Scaled deviance = 378.92 (change = -160.1) at cycle 3
residual df = 360  (change =  0 )

ML Estimate of THETA =  2.453
Std Error = ( 0.6203)

NOTE: standard errors of fixed effects do not take account of the estimation of THETA

2 x Log-likelihood = -489.7 on 360 df
2 x Full Log-likelihood = -1020.

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<th>parameter</th>
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Scale parameter 1.000

351.1
405.2

Model 15

Scaled deviance = 376.90 (change = -154.2) at cycle 4
residual df = 359  (change =  0 )

ML Estimate of THETA =  2.581
Std Error = ( 0.6635)

NOTE: standard errors of fixed effects do not take account of the estimation of THETA

2 x Log-likelihood = -482.9 on 359 df
2 x Full Log-likelihood = -1013.

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Scale parameter 1.000

347.8
404.2

100
APPENDIX - 2
RESULTS OF OUTLIER IDENTIFICATION

Figure A-1: Cook’s Distance Graph and Tabulation for Outlier Removal - Model 1
Appendix-2

Model 2

<table>
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<tr>
<th>Point Analysed(#)</th>
<th>Sample Size (#)</th>
<th>Scaled Deviance</th>
<th>Scaled Deviance*</th>
<th>SD Drop</th>
<th>$\chi^2$</th>
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* after outlier removal

Figure A-2: Cook’s Distance Graph and Tabulation for Outlier Removal – Model 2
Figure A-3: Cook’s Distance Graph and Tabulation for Outlier Removal – Model 3

* after outlier removal
**Figure A-4: Cook’s Distance Graph and Tabulation for Outlier Removal – Model 4**
Figure A-5: Cook’s Distance Graph and Tabulation for Outlier Removal – Model 5

* after outlier removal
Figure A-6: Cook’s Distance Graph and Tabulation for Outlier Removal – Model 6

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* after outlier removal
Figure A-7: Cook’s Distance Graph and Tabulation for Outlier Removal – Model 7
### Figure A-8: Cook's Distance Graph and Tabulation for Outlier Removal – Model 8

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* after outlier removal
**Figure A-9: Cook’s Distance Graph and Tabulation for Outlier Removal – Model 9**

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* after outlier removal
Figure A-10: Cook’s Distance Graph and Tabulation for Outlier Removal – Model 10

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* after outlier removal
Figure A-11: Cook's Distance Graph and Tabulation for Outlier Removal – Model 11

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* after outlier removal
### Figure A-12: Cook’s Distance Graph and Tabulation for Outlier Removal – Model 12

#### Table: Outlier Tabulation - Model 12

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* after outlier removal
Figure A-13: Cook’s Distance Graph and Tabulation for Outlier Removal – Model 13

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* after outlier removal
### Figure A-14: Cook’s Distance Graph and Tabulation for Outlier Removal – Model 14

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* after outlier removal
Figure A-15: Cook’s Distance Graph and Tabulation for Outlier Removal – Model 15