Development of Speed Based Consistency Evaluation of Four-Lane Highway Geometry Using Naturalistic Driving Data

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by

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Certificate

This is to certify that this thesis entitled **"Development of Speed Based Consistency Evaluation of Four-Lane Highway Geometry Using Naturalistic Driving Data"** submitted by **Suresh Nama** (Roll No.: 156104011) to the Indian Institute of Technology Guwahati for the award of the degree of Doctoral of Philosophy in Civil Engineering is a record of bonafide research work carried out by him under my supervision and guidance at the Department of Civil Engineering, Indian Institute of Technology Guwahati, Assam, India. In my opinion, the thesis has reached the requisite standard fulfilling the requirement for the degree of Doctor of Philosophy in Civil Engineering. To the best of my knowledge, no part of the work reported in this thesis has been presented for the award of any degree at any other institution.

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Declaration

I hereby declare that

- The work contained in this thesis is original and has been conducted by myself under the general supervision of my supervisor.
- The work reported herein has not been submitted to any other institute for any degree or diploma.
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Abstract

India is a developing nations with rapid growth in highway infrastructure. The expansion of two-lane to four-lane highways along with new four-lane highways construction in mountainous terrains have been increased rapidly. However, the accident safety on these highways has not beed increased at the same rate. In 2019 alone, a total of 4,42,996 persons were injured, and 1,81,113 persons died due to accidents. This raises the concerns about the road safety on such Highways. Therefore, the current study attempts to understand to the driving behaviour and to improve accident safety on such four-lane highways in mountainous terrains.

To conduct the study, a 45km four-lane highway was considered, and the necerasy data were collected from the GPS-equipped passenger cars with the help of various drivers. The collected data reveals that the 45 km four-lane highway covers 285 horizontal curves with a wide range of design speeds (varying between 30 km/h and 80 km/h), curve lengths (varying between 10m and 205 m), vertical gradients (varied between +6% and –6%), and superelevation (up to 7%), which were typical for highways in mountainous terrains.

Through the collected drivers' speed data, it was discovered that most drivers were travelling above the design speed of the highway sections. The data further revealed that the operating speeds vary across the curve, contrary to the prevailing uniform speed theory. Due to this reason, the existing two-lane consistency criteria provided ambiguous results while evaluating the safety of four-lane highways. These results indicate the requirement of separate four-lane consistency criteria to evaluate the safety of such highways.

In this study, to evaluate the safety of mountainous terrain four-lane horizontal curves two safety criteria, SS (Speed Synchronization) and SH (Speed Harmony), were developed considering the variation in speed across the curve. SS criterion was developed to evaluate the safety based on the speed variation between successive locations (PC, CC, and PT) within the curve. SH criterion was developed to evaluate the safety due to the variation in operating speed from the curve design speed. In addition, to evaluate the safety of existing four-lane curves, the developed SS and SH criteria were also helpful in highway geometric design. Therefore, a new speed-based geometric design is proposed using these SS and SH criteria along with the vehicle dynamics in this study.

It is also attempted to identify the geometric parameters that influence the drivers' speed over the four-lane horizontal curves. Through the developed operating speed models across the curve (PC, CC, and PT), it has been found that the tangent length, gradient, curve length, and deflection angle influences the operating speed. From subsequent percentile speed model development, it is found that the superelevation and radius of the curve combinedly contribute more than 50 percent in the distribution of the free-flow speed at the curve center. The developed continuous percentile speed distribution model revealed the possibility of accurately predicting any percentile speed across the four-lane highway alignment using the length, gradient, and curvature of the highway elements.

In this study, in addition to highway safety improvements through designing (SS & SH), the safety warning system is also studied. In this, using the V_{85} (operating speed) and V_{95} (Desing speed), a three leveled over-speed warning system is developed to assist the driver about any upcoming geometric hazards.

The major outcomes of this study can be beneficial in different ways.

- Any percentile speed value can be predicted with the developed speed models, which in turn helps in evaluating highway safety and design.
- The SS and SH criteria overcome the limitation of uniform speed across the curve assumption and help to evaluate the safety and design of four-lane highways.
- The proposed speed-based highway geometric design helps in four-lane highway geometric design on mountainous terrains both quantitatively and qualitatively.
- The developed over-speed warning system improves the driver's safety by alerting the driver in advance using the dynamic speed limits (V_{85} & V_{95}).

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CHAPTER 1
INTRODUCTION

1.0 Introduction

Highway geometric design safety is a critical area of study in transportation engineering, with significant socio-economic impacts, particularly in developing nations. The primary goal of transportation professionals is to ensure the highest level of safety across the entire road network. However, road traffic accidents continue to be a leading cause of death worldwide, especially in low and middle-income countries. In 2018 alone, an estimated 1.35 million deaths were attributed to road accidents globally, according to the Global Health Observatory (WHO, 2018). In the case of India, the numbers are alarming, with 4,42,996 injuries and 1,81,113 fatalities reported in 2019 (Joshi et al., 2020). These figures are comparable to the annual average number of COVID-19 deaths in India in 2021, as per WHO data, emphasizing the urgent need for greater focus on traffic-related accidents in the country. Additionally, the available accident data (MoRTH, 2020) indicates that fatal accidents on rural roads are twice as frequent as those on urban roads. Notably, Lamm et al. (1995) reported that over 50 percent of total fatalities are attributed to accidents on curved sections of rural highways.

One approach to reduce road accidents is to improve highway geometry or implement effective speed warning systems for drivers. Over the years, the philosophy of highway geometry design has evolved from a comfort-based approach (IRC 73-1980, 1990) to a consistency-based approach (Lamm et al., 2006). In the comfort-based design approach, highways are designed based on driver comfort and safety, considering the forces, primarily centrifugal, acting on the vehicle at the center of the curve. However, this independent design of each horizontal curve often results in design speeds and geometry inconsistencies. Lamm et al. (2006) proposed the consistency-based design approach, which incorporates safety criteria to address this issue.

Consistency in road design significantly impacts road safety, and previous researchers have defined and measured design consistency in various ways. Glennon and Harwood (1978) defined design consistency as the road design that aligns with drivers' expectations and allows them to guide and control their vehicles safely. Castro et al. (2008) described design consistency as the relationship between the geometric characteristics of the highway and the driver's anticipated conditions. When the driver's anticipation does not align with the geometry, inconsistencies arise, leading to an increased likelihood of crashes. Researchers have developed various methods to evaluate consistency based on factors such as vehicle stability, alignment indices, operating speed, and driver workload. Among these methods, the speed-based approach has proven to be particularly relevant for safety evaluation in terms of accident rates. By comparing operating speeds with design speeds at the center of the curve, the speed-based method provides a measure of design consistency for safety. Initially used to assess highway safety, the concept of consistency has been extended to include consistency-based highway geometric design (Lamm and Smith, 1994).

Another approach to reducing vehicle accidents on curves is to provide real-time warning systems to drivers when they exceed safe speeds using innovative technology. Commercial devices like "Carsense" offer real-time warnings based on in-vehicle onboard diagnostics II (OBD-II) information. These devices typically consider speeds above a fixed threshold, such as 80 km/h, as dangerous. However, in real-world scenarios, roads with speeds as low as 40 km/h can be dangerous due to geometric constraints, particularly in hilly terrain or sharp curves.

1.1 Motivation

The continuous increase in demand has led to highway agencies' widening of two-lane highways to four-lane highways, aiming to improve capacity and level of service. Consequently, there is a growing need to study the safety of vehicles on these widened highways. The speed of vehicles is a critical safety parameter, and many researchers have developed operating speed prediction models for horizontal curves on two-lane highways to assess geometric consistency. However, these models primarily focus on developed nations where traffic follows lane discipline. It has been established by Lamm and Smith (1994) that driver characteristics, including speed, acceleration, and deceleration rates, vary based on the country/region due to factors such as lifestyle, laws, altitude, and culture. Most existing speed prediction models are limited to V_{85} speed models and are confined to two-lane roads. While a few speed models exist for four-lane roads, they primarily focus on predicting speeds at the center of curves.

These circumstances raise several important questions:

Q1: What geometric parameters influence the operating speed of vehicles on horizontal curves of four-lane roadways?

Q2: How do these geometric parameters influence the operating speed of vehicles on four-lane highways?

Q3: Are the existing speed prediction models, which were primarily developed for two-lane roadways, suitable for predicting the speed of vehicles on four-lane highways?

Q4: Can the consistency criteria developed for two-lane roads be applied to four-lane roads?

Q5: Are multiple speed models necessary to predict percentile speeds at different locations, such as the point of the curve, center of the curve, and point of tangent, on the curve?

1.2 Problem Statement and Significance

The literature review reveals a gap in the existing research regarding the influence of geometric parameters on the operating speed of vehicles on horizontal curves of four-lane roadways. While numerous studies have focused on speed prediction models for two-lane roads in developed nations, there is limited research available for four-lane highways. Additionally, the existing models mainly consider speeds at the center of curves, neglecting other critical locations on the curve.

Addressing this research problem is of great significance for several reasons. Firstly, widening two-lane to four-lane highways is a common practice to accommodate increasing traffic demands. Understanding the impact of geometric parameters on operating speeds in this context is crucial for ensuring the safety of vehicles and improving the overall level of service on these widened highways. Secondly, the variation in driver characteristics across different countries and regions highlights the need for speed prediction models that account for local driving behaviors, laws, and cultural factors.

By addressing these research gaps, this study aims to contribute to the development of accurate and reliable speed prediction models designed explicitly for four-lane highways. These models will consider the influence of various geometric parameters and provide a comprehensive understanding of how these parameters affect the operating speed of vehicles on different sections of the curve. Additionally, this research will investigate the applicability of existing consistency criteria developed for two-lane roads to the context of four-lane highways.

The findings of this study will have practical implications for highway agencies, traffic engineers, and policymakers involved in the geometric design and safety improvement of four-lane highways. The development of accurate speed prediction models and consistency criteria for four-lane roads will assist in designing safer and more efficient highway systems, reducing the likelihood of accidents, and enhancing the overall level of service. Furthermore, this research will contribute to the body of knowledge in transportation engineering, specifically in the field of highway geometric design safety, and pave the way for further advancements in this important area of study.

1.3 Objectives

The primary goal of this work is to improve performance-based geometric design for four-lane highways satisfying speed consistency criteria. The secondary goal is to develop speed models that can interpret various percentile speeds of the vehicles along the length of the four-lane highway. The above-stated goal can be achieved through the following objectives:

- **Objective-1:** Preliminary speed data analysis to understand free-flow vehicle speed behavior on four-lane highways.
- **Objective-2:** Extension of the preliminary study on free-flow vehicle speed behavior with a more extensive data set.
- **Objective-3:** Development of operating speed models, safety criteria, and proposal of performance-based highway geometric design for four-lane highways

- **Objective-4:** Development of free-flow speed distribution models
- **Objective-5:** Development of over speed warning system (OSWS) using a continuous free-flow speed distribution model.

1.4 Scope of the Research Work

The proposed research investigates highway geometric parameters' influence on free-flow speed over four-lane highways. This work further extended into the development of performance-based highway geometric design and speed warning systems based on dynamic speed thresholds. The scope of the work is limited to rural four-lane highways in mountainous terrain sections under free-flow conditions, i.e., vehicles remain unhindered by bus stops, parking lots, interactions, and pedestrian movements.

1.5 Organization of the Thesis

This thesis is organized into eight chapters. The current Chapter discusses the introduction, motivation, objectives, and scope of the research topic. Chapter 2 presents the literature review on various topics such as highway safety analysis, speed models, highway geometric design, and speed warning systems.

Chapters 3 and 4 discuss the free-flow vehicle speed behavior across the horizontal curve on the four-lane highway through speed data analysis. (Objective 1 & 2)

Chapter 5 presents the development of operating speed models at various locations on the curve using Ordinary least square regression (OLSR) and Artificial neural network (ANN). Further in this Chapter 5, the two new consistency criteria, namely Speed Harmony (SH) and Speed Synchronization (SS), are presented for four-lane highway safety. The proposed speed-based highway geometric design is also presented with an example at the end of this chapter. (Objective 3).

Chapter 6 consists of developing the free-flow speed distribution model using OSLR and ANN at the center of the four-lane horizontal curve. (Objective 4)

Chapter 7 presents the work on the Over speed warning system (OSWS) proposed using the continuous free-flow speed distribution model. (Objective 5)

Chapter 8 presents the conclusions and recommendations of this research study.

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CHAPTER 2

LITERATURE REVIEW

2.0 Introduction

As seen in Chapter 1, a relatively high number of accidents occur on highways, especially in developing countries like India. The Indian road accident data report says that fatal accidents on rural roads are twice as many on urban roads (MoRTH, 2020). Therefore, a detailed literature review is carried out on rural highways to find ways to improve safety on these highways. The literature study revealed that highway safety could be improved by (i) following proper geometric design guidelines in accordance with the drivers' anticipation or (ii) providing an advanced warning to the driver about upcoming hazards. In this chapter, the detailed literature review on this topic is covered as shown in Figure 2.1 and presented in the following subsections.

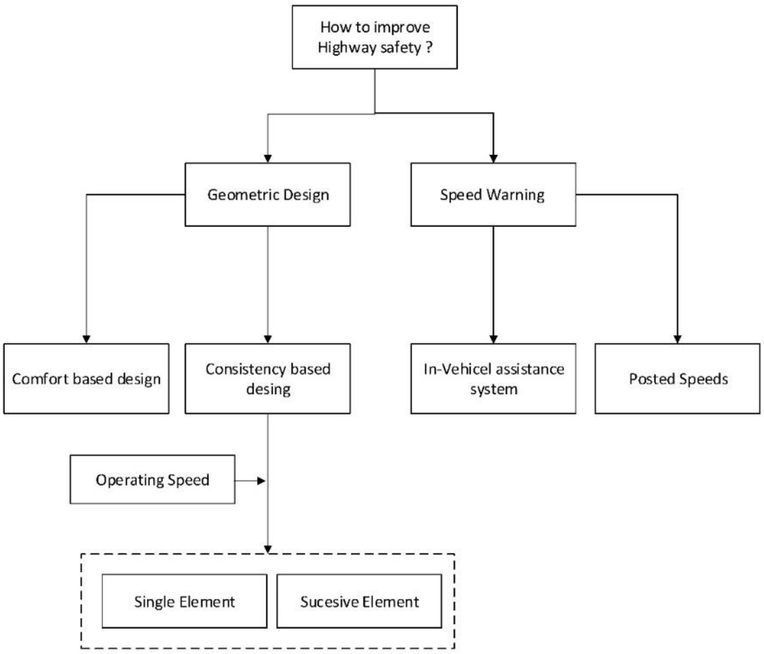

Figure 2.1 Methods to improve highway safety

2.1 Highway Geometric Design

An excellent highway geometric design ensures a safe and comfortable driving experience. Several researchers worked on highway geometric design to make this reality over time. So far, several countries have adopted their geometric design guidelines to improve highway safety as much as possible. The following subsection presents the widely used highway geometric methods for the construction of highway alignment.

2.1.1 Comfort-based geometric design:

The comfort-based geometric design has been the most widely used method in the last five decades worldwide. In the comfort-based method, for a given highway design speed, the values of the geometric parameters are derived mainly by nullifying the forces (Centrifugal and frictional) acting on the vehicle over the centre of the curve (AASHTO, 2018; IRC-73,1980). This way, the driver will be comfortable and free from the external forces acting on the vehicle over the curve. Furthermore, in this method, the initial selection of highway design speed is based on the terrain and functional classification of the highways (Fambro et al., 1997). The selection of highway design elements in this method is as follows:

2.1.1.1 Roadway Design Elements

The studies conducted on the geometric design of highways indicated that the design of a highway is influenced by several design elements, such as the design speed of the highway, Cross section features, and Alignment features (such as horizontal, vertical, and the combination of both horizontal and vertical profile) of the highway.

Design Speed:

One of the important tools for highway geometric design is design speed (V_d). Design speed is a selected speed used to determine the various geometric features of the roadway. The concept of design speed was first coined in 1937 by Barnett. Barnett (1937) defined the design speed as "the maximum reasonably uniform speed which would be adopted by the faster driving group of vehicle operations, once clear of urban areas. " Later on, in AASHTO (2004), for highway design purposes, the design speed definition was modified as "the maximum speed that can be maintained over a specified section of highway when conditions are so favourable that the design features of the highway govern." Loutzenheiser and Greenshields 1941) pointed out that vehicles' 95th (i.e., V_{95}) to 98th (i.e., V_{95}) percentile speed represents the design speed in free-flow conditions.

Design speed is the one which had a significant influence on the selection of geometric parameters in highway design. So, the speed selected as a design speed for geometric design should be logical with respect to topography, anticipated traffic, drivers' speed, and adjacent land use.

Originally the design speed selection concept had two fundamentals

1) All alignments of highway stretch should be designed for the same design speed.
2) Design speed should reflect the speed at which a high percentage of people desire to operate.

Based on these in India, the Indian Road Congress (IRC):73-1980 recommended design speeds (Table 2.1) based on the terrain and location. Even though these are the essential criteria of design speed selection, sometimes designers cannot provide all the sections of a highway with the same design speed. In some cases, like bridges and hilly terrains, constructing a highway with a design speed is not economically or topographically feasible. In that situation, the highway sections are not designed for the design speed. In these cases, the driver needs to process more information to drive over the section. The workload on the driver increases whenever there is a sudden change in the geometric design of a highway which causes speed inconsistency.

Table 2.1: Design speed selection based on terrain type as per IRC: 73-1980

S.NO	Road Classification	Design Speed in km/hr							
		Plain Terrain		Rolling Terrain		Hilly Terrain		Steep Terrain	
		Rolling	Min	Rolling	Min	Rolling	Min	Rolling	Min
1	National and State Highways	100	80	80	65	50	40	40	30
2	Major district roads	80	65	65	60	40	30	30	20
3	Other district roads	65	50	50	40	30	25	25	20
4	Village roads	50	40	40	35	25	20	25	20

Cross Section:

The highway cross-section consists of various parameters, such as the width of the road, median, shoulder, and the number of lanes. These parameters influence the accident rates on highways. Improper cross-section of a highway also poses specific problems to drivers, causing road accidents.

1) ***Lane Width:*** The lane width impacts the operating speed that intern on a road section's consistency. It is found through literature (karlaftis and Golias, 2002; Zegeer et al.,

1980) that the accident rate decreases with the increase of the lane width considering shoulder with remains constant. However, it is observed that a lane wider than 3.7 m does not necessarily imply safety provided other factors, for instance passing from one carriageway to another (Transportation Research Board, 1987). Therefore, safety studies (Zegeer et al., 1980; Mclean, 1985; Zegeer and Council, 1993) conducted on the lane width revealed that the occurrence of accidents for lane widths between 3.4m - 3.7m is lower. A wider lane than the minimum required results in a higher speed leading to more accidents (Yager and Van Aerdo, 1983).

2) ***Median:*** Other significant road cross-section elements related to road crashes are the presence of a median and median width (Ahmed et al., 2012; Yu & Abdel-Aty, 2013). The road median separates the bidirectional traffic, provides an emergency stop recovery area, and protects drivers from the opposite direction approaching vehicle headlight glare (Islam et al., 2019). The research concluded by Srinivasan (1982) revealed that the presence of a median on highways with high design speeds helps avoid head-on crashes. According to The Road Directorate of Denmark (1981), a Medians width of up to 3 m with barriers reduces accident rates. On the other hand, recent studies (Hughes, 1995) suggested that accident rates decrease for medians up to 12 m wide.

3) ***No of lanes:*** The number of lanes in the cross-section also impacts the occurrence of accidents. Crash rates will be reduced as the number of lanes increases. (Yu & Abdel-Aty, 2013). However, the final number of lanes will be decided mainly based on highway traffic capacity (PCU/Day) (IRC-73, 1980).

4) ***Shoulder:*** The addition of shoulders or improved shoulder widths could reduce the severity and frequency of crashes associated with run-off crashes. However, studies (Labi, 2011; Garder and Davies, 2006; Pokorny et al., 2020) conducted on the shoulder width over rural highways revealed that the accident rates decrease only on narrow shoulder widths. Whereas the severity of the accidents increases with the increase in shoulder width, providing drivers with a false sense of security. In addition to safety, the shoulders also work as a breakdown area for vehicles to stop for an emergency.

5) ***Superelevation:*** Superelevation is the transverse slope provided to counteract the effect of centrifugal force and reduce the vehicle's tendency to skid laterally outwards. The safe superelevation can be measured using equation 2.1.

$$e = \frac{V^2}{127*R} - f \tag{2.1}$$

Where e= superelevation (%), f=friction factor, V=vehicle speed (m/s) and R=Radius (m)

As per the Indian road congress (IRC: 73-1980), the maximum superelevation values recommended are as follows (i) In plain and roiling terrain, 7 %, (ii) In hilly areas, 10 %.

Alignment:

Alignment is a cross-section route of a road formed by combining a series of tangents and curves. Of all the sections on a highway, the driver needs to process more information whenever they encounter a horizontal, vertical, or a combination of horizontal and vertical alignment. Aram (2010) found that the crash rates over the curve are as high as 1.5 to 4 times compared to the tangent/straight sections. Lamm et al. (1992) stated that over 50 percent of the total fatalities are attributed to accidents on the curved section of rural highways. Over the horizontal alignment, several factors influence the safety of the highway, such as surface friction (f), superelevation (e), centrifugal force, the radius of the curve (R), the length of the curve, and the length of the tangent. So to find the safest radius for the horizontal alignment, the IRC-73 (1990) and AASHTO (2018) recommended the following equation

$$R \geq \frac{V^2}{127(e+f)} \tag{2.2}$$

.

2.1.1.2 Limitations of the comfort-based geometric design

Though this design method (IRC-73, 1990) is easy to adopt, it also has significant limitations. One such limitation is the assumption of the highway design speed (Barnett et al., 1937) should be the maximum reasonable uniform speed adopted by the fastest driving group. This design approach method is reasonable in theory. However, in reality, the vehicle's operating speed is not the same as the design speed (McLean., 1985; Garber & Gadiraju., 1988). If the variation between design speed and operating speed increases, the safety on the curve decreases. Fitzpatrick et al. (2003) showed that the driver's selection of operating speeds differs from design speeds. McLean et al. (1974, 1979) observed that for low-speed curves less than 90 kmph, the operating speed was higher than the design speed and vice versa for high-speed curves higher than 90 kmph. McLean's findings have revised the Australian design code for low-design speed roads (Fambro et al., 1997). Later in 2011, AASHTO revised the design speed definition by considering operating speed as a factor influencing the geometric parameters. However, it is unclear how to get those operating speeds in these guidelines. In the Indian geometric design guidelines IRC-73 (1980) & IRC-SP-73 (2018), the operating speeds are not yet incorporated in the design speed definition. Another limitation of this method is that every horizontal curve is designed independent of the geometric properties of the consecutive horizontal curve, increasing inconsistency in driver speed from one curve to the next (Ng and Sayed, 2004).

To overcome these Lamm et al. (1995) proposed a new design approach called consistency-based-geometric design. In this along with the highway's design speed, the vehicles' operating speed is also considered to improve safety.

2.1.2 Consistency-based highway geometric design

Lamm (1995) and Krammes et al. (1995) studied safety issues at horizontal curves in two-lane highways. They found that when the vehicles operating speed exceeds the design speed at the horizontal curve, a speed inconsistency arises, which may lead to a crash. Ng and Sayed (2004) studied the effect of roadway speed consistency on safety. They opined that driver expectancy could be satisfied by providing a consistence geometric design. Consistency has a significant impact on road safety.

The roadway geometry, traffic conditions, and roadside environment are the factors that affect driver expectancy. Researchers reported that inconsistent roads might violate drivers' expectancy; as a result, the driver may choose an inappropriate speed, which may lead to an accident. Fitzpatrick and Collins (2000) studied the speed behaviour of vehicles on two-lane highways. They investigated the effects of sequential horizontal curve elements. It was reported that accidents could be reduced by avoiding abrupt transitions in successive geometric elements. This can be accomplished by designing a consistent roadway. Hashim et al. (2016) developed operating speed profile models for two-lane highways in Egypt. They opined that a consistent geometrical design satisfies the driver's expectations. Dell’Acqua et al. (2013) studied speed behaviour at horizontal curves. They opined that the number of crashes decreases significantly with the increase in design consistency. Campbell et al. (2008) reported that drivers perform multiple tasks to approach and traverse a horizontal curve. Fitzsimmons et al. (2013) studied a vehicle's speed behaviour at the horizontal curve on two-lane roads. They reported that if the task required for approaching and negotiating a horizontal curve is not performed correctly, that may lead to a roadway departure crash. Lamm et al. (1995), considering the uniform operating speed across the curve, proposed the absolute difference between design speed and operating speed (i.e., the 85th percentile of free flow speed= V_{85}) of a horizontal curve to evaluate geometric consistency and safety of two-lane rural highways.

2.1.2.1 Speed as a Measure of Safety

Earlier studies on geometric design consistency and safety evaluation can be categorized into three general areas. These are (i) Speed considerations, (ii) Safety considerations, and (iii) Performance considerations (Gibreel et al., 1999). Therefore, vehicle speed is one of the surrogate performance measures to evaluate geometric design consistency and safety in horizontal curves (Gibreel et al., 1999; Lamm et al., 1995). "Speed considerations address the different effects of geometric parameters on the operating speed prediction" (Gibreel et al., 1999). Geometric design consistency of horizontal curve can be evaluated using operating speed. The following Figure shows the available geometric design consistency and safety evaluation scopes using speed as a surrogate measure (Gibreel et al., 1999).

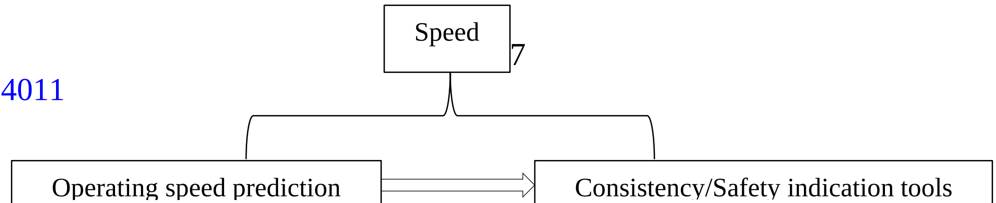

Figure 2.2 Geometric design consistency evaluation using speed

Lamm et al. (1995) developed consistency-based criteria for both single-element and successive-element cases, assuming uniform speed over the curve. Using the speed and accident information, Lamm et al. (1995) classified the highway sections into Good, Fair, and Poor. For a single element, the absolute difference between design speed and operating speed (i.e., the 85th percentile of free flow speed) of a horizontal curve is used to evaluate geometric consistency and safety. In comparison, for successive elements, safety evaluation considers operating speed differences in successive sections as a tool. Various conditions of these criteria to represent safety levels are presented in Table 2.2. Similarly, Jacob et al. (2013) evaluated the geometric design consistency criteria limits on two-lane Indian rural highways and found that the values in Table 2.2 are conservative.

Table 2.2: Geometric Design consistency evaluation criteria (Lamm et al. 1995)

Design Safety	Single element Criteria-I (kmph)	Successive elements Criteria-II (kmph)
Good	$\lvert V_{85}-V_d \rvert \leq 10$	$\lvert V_{85i}-V_{85i+1} \rvert \leq 10$
Fair	$10 < \lvert V_{85}-V_d \rvert \leq 20$	$10 < \lvert V_{85i}-V_{85i+1} \rvert \leq 20$
Poor	$\lvert V_{85}-V_d \rvert > 20$	$\lvert V_{85i}-V_{85i+1} \rvert > 20$

Note: Criteria-I = Difference between design speed and operating speed of a section
Criteria-II= Difference in operating speed between successive elements
V_{85} = 85th percentile speed or operating speed; V_d = Design speed
Good =No design corrections are necessary
Fair = Redesign is not necessary provided proper driver warning systems
Poor =Redesign is recommended

2.1.2.2 Limitations of the Consistency-based geometric design

Though this consistency-based geometric design focuses on improving the existing comfort-based geometric design, it has certain limitations. Majorly in this for consistency evaluation, the operating speed (V_{85}) used is considered at the centre of the curve only, assuming that the driver operating speed remains constant over the curve from the point of curvature (PC) to the point of tangent (PT). Another limitation is that the criteria limits (Table 2.2) developed are for two-lane horizontal curves, which are not validated for four-lane horizontal curves to apply directly to four-lane horizontal curve designing.

2.2 Speed Prediction Models

Consistent-based geometric design application needs operating speed values (Lamm et al., 1995; Jacob et al., 2013). Therefore over the years, several operating speed prediction studies have been conducted. Studies on operating speed prediction models started in the 1950s (Taragin, 1954). Since then, over the decades, several researchers have worked on developing vehicle speed prediction models at horizontal curves (Taragin, 1954; Fitzpatrick et al., 2000; Lamm et al., 1995; Lamm et al., 1999; Malaghan et al., 2020). The available models vary widely in terms of independent variables considered and the value of coefficients reported. Researchers have used serval data collection techniques to collect speed data and different techniques for modelling the operating speed. Numerous geometric variables have been used as a predictor in the literature. The following section will elaborate on the type of highway, data collection technique, number of samples and observation, predictor variables, modelling techniques, and category of vehicles considered for developing speed prediction models in the existing literature. Moreover, some well-cited models with a good coefficient of determination are presented in Table 2.4.

2.2.1 Type of highway (Number of lanes)

A large number of operating speed prediction models are available in the literature. These models are predominantly developed for two-lane highways (Fitzpatrick et al., 2000; Lamm et al., 1995; Mclean, 1979; Misaghi and Hassen, 2005; Jacob and Anjaneyulu, 2013). However, recently researchers developed speed prediction models for four-lane highways (Gong and Stamatiadis, 2008; Himes and Donnell, 2010; Sil et al., 2019). Lamm and Smith (1994) showed that the driver characteristics such as speed, acceleration, and deceleration rates are country or even region dependent in large countries due to variations in lifestyles, laws of the country, and the country's economy, altitude, and culture. However, most speed models are limited to V_{85} speed models confined to two-lane roads. A few speed models are also available for four-lane roads, but they were only confined to predicting speeds at the centre of the curves.

2.2.2 Category of vehicles

In literature, speed prediction models are available for different categories of vehicles. However, most of these models were developed for passenger cars only (Abdelwahab et al., 1998; Fitzpatrick et al., 2000; Islam and Seneviratne, 1994; Kanellaidis et al., 1990,; Lamm et al., 1995; Mclean, 1979). Some studies consider commercial vehicles, but these are limited in numbers and different geographic locations (Donnell et al., 2001; Misaghi and Hassen, 2005; Taragin, 1954). Jacob and Anjaneyulu (2013) proposed speed prediction models for cars, trucks, buses and two-wheelers separately for two-lane highways in India. Sil et al. (2019) proposed operating speed models for passenger cars on Indian four-lane highways on plane terrains in India. Researchers in India have not yet explored operating speed models over four-lane rural highways on mountainous terrains.

2.2.3 Data collection techniques

Vehicles that influence by the highway geometry and not by the surrounding vehicles are called as free-flowing vehicles (Hashim et al., 2016). The speed attained by the free-flowing vehicles is defined as free-flow speed. The Highway Capacity Manual (HCM 2010) suggests that vehicles travelling with a headway equal to or greater than a threshold headway value are considered as free-flowing. In some studies, researchers have considered 5-sec headway for free-flow conditions and used it in spot-speed data collection for developing the free-flow speed prediction models of horizontal curves (Fitzpatrick et al., 2000; Jacob and Anjaneyulu, 2013; Hashim et al., 2016; Gong, Stamatiadis, 2008). Some of the research has used user-operated devices like radar guns, lidar guns, and laser guns to collect speed data (Stamatiadis and Gong, 2006; Fitzpatrick et al., 2000; Islam and Seneviratne, 1994). Many have used traffic counters, classifiers and video recording for the data collection purpose (Misaghi and Hassen, 2005Jacob and Anjaneyulu, 2013; Sil et al., 2019). These studies did not consider the effect of inter-vehicle interaction in the prior segment. Therefore researchers started considering tracking vehicles throughout the study zone (i.e., in the horizontal curve and its preceding tangent) for the free-flow condition (Fitzsimmons et al., 2013). Now researchers are using global positioning system (GPS) fitted vehicles and roadside laser detectors, sensors or video cameras for the purpose of collecting free-flow speeds (Fitzsimmons et al., 2013; Glennon et al., 1985; Hashim et al., 2016).

2.2.4 Sample and observation Size

The sample size is defined as the number of sites selected for modelling (Fitzsimmons *et al*., 2013; Misaghi and Hassen, 2005). At the same time, the number of speed samples used for estimating 85th percentile speed is known as an observation size (Misaghi and Hassen, 2005; Fitzpatrick et al., 2000; Jacob and Anjaneyulu, 2013; Figueroa and Tarko, 2004; Malaghan et al., 2020). Literature shows that sample size varies widely (Table 2.5). A critical review of earlier studies reveals that people have used sample sizes ranging from 6 to 322 (Islam and Seneviratne, 1994;Misaghi and Hassen, 2005). Sil et al. (2019) opined that 25 observations are adequately large enough to represent a normal distribution. The observation size of spot speed data collected at each site varied from 25 to 275 (Stamatiadis and Gong, 2006; Fitzsimmons, 2012; Misaghi and Hassen, 2005).

2.2.5 Independent variables

Vehicle speed depends on the driver's perception of surroundings, which is influenced by highway geometry elements (Sil et al., 2019; Hashim et al., 2016). Hence, most studies try to correlate driver speed choice with geometric variables. Therefore, several geometric variables have been used as independent variables for operating speed model development. Geometric parameters mostly used as predictors for modelling in the last seven decades are presented in Table 2.3 (Lamm et al., 1986; Lamm and Chouriri, 1987; Lamm et al., 1990; Abbas et al., 2011; Morrall and Talarico, 1994; Ottesen and Krammes, 2000; Andjus and Maletin, 1998; Andueza, 2000; Donnell et al., 2001, Fitzpatrick et al., 2000; Islam and Seneviratne, 1994; Hashim et al., 2016; Gong and Stamatiadis, 2008; Poe et al., 1996; Russo et al., 2015, Russo et al., 2016)

Table 2.3: Geometric variables used in literature

R	**=**	**Radius**	**LW**	**=**	**Lane width**
CL	=	Curve length	**MW**	=	Median width

G	=	Gradient	**e**	=	Superelevation
Δ	=	Deflection angle	**SD**	=	Sight distance
DC	=	Degree of curvature	**K**	=	The abruptness of the grade change
CCR	=	Curvature change rate	**ADT**	=	Average daily traffic
CW	=	Carriageway width	**V_T**	=	Approach tangent speed
SW	=	Shoulder width	**Vp**	=	Posted speed limit

2.2.6 Modelling techniques

The statistics 85th percentile speed is generally used to describe the operating speeds for assessing the influence of the surroundings on the driver's speed selection (Wang, 2006). The 85th percentile speed (V_{85}) is the speed at or below which eighty-five percent of drivers travel on the road (AASHTO, 2018). V_{85} is a speed measurement and is most commonly used to set speed limits on roads in serval countries. Internationally it has been used as a reasonable representation of operating speed (Wang, 2006). Most of the researchers have adopted the ordinary least square (OLS) regression technique for developing the 85th percentile speed models (Misaghi and Hassan, 2005; Fitzpatrick et al., 2000; Lamm et al., 1995; Lamm et al., 1990; Hashim et al. 2016; Islam and Seneviratne, 1994; McFadden and Elefteriadou, 1997; Mclean, 1979; Jacob and Anjaneyulu, 2013). Researchers have applied the ordinary least square technique to panel data to estimate user-defined percentile speeds (Figueroa and Tarko, 2004). Himes and Donnell (2010) adopted the three-stage least-squares (3SLS) estimator method to model mean and standard deviation for speed prediction. Nonlinear regression has also been used in some studies (Andjus and Maletin, 1998; Gibreel et al., 2001; Morrall and Talarico, 1994). The regression techniques dominated the operating speed modelling for a long time; however, researchers in recent studies started using the Artificial neural network technique. McFadden et al., (2001) initially adopted the artificial neural network (ANN) technique to model 85th percentile speed using geometric parameters as independent variables. Semeida, A. M. (2014) compared the ANN and Regression models developed with spot speed data and concluded that the ANN provides better, more confident and logical results than the regression.

In summary, it is observed that several factors, such as sample size, vehicle type, road type, and geometric parameters, influence the operating speed on curves. To develop the operating speed models, predominantly Regression technique is used. However, recent studies showed that the ANN technique could provide a better operating speed prediction model than the regression technique. The operating speed models in the literature are predominantly conducted on highways with two lanes. Table 2.5 below shows some well-cited works conducted on operating speed models.

Table 2.4: List of operating speed models (V85) from the literature

Author	Model
Lamm et al. (1986)*	$V_{85} = 95.780 - 0.076CCR$
Lamm et al. (1990)	$V_{85} = 94.398 - \frac{3188.656}{R}$
Kanelaidies et al. (1990)*	$V_{85} = 129.88 - \frac{623.1}{\sqrt{R}}$
Donnell et al. (2001)*	$V_{85} = 75.1 + 0.0176R - 1.48GDEP - 0.0084LDEP$
Abbas et al. (2011)*	$V_{85} = 75.344 - \frac{368.14}{\sqrt{R}}$
Hashim et al. (2016)*	$V_{85} = 99.885 - \frac{3880.21}{R}$
Misaghi and Hassan (2005)*	$V_{85PC} = 91.85 + 9.81 \times 10^{-3} \times R$
Mawjoud and Sofia (2008)*	$V_{85} = 17.75 + 0.50V_{T85} + 0.052R - 0.161\Delta + 1.416e$
Jacob and Anjaneyulu (2013)*	$V_{85} = 69.00 - \left(\frac{1005.39}{R}\right) - 0.065\ CL$
Eboli et al (2017)*	$V_{85}=0.037R+0.858V_{T85}$

Gong and Stamatiadis (2008)**	$\mathrm{V}_{85\ \mathrm{innerlane}} = 51.52 + 1.56\mathrm{ST} - 2.79\mathrm{MT} - 4.00\mathrm{PT} - 2.15\mathrm{AG} + 2.22\ \ln(\mathrm{CL})$ $\mathrm{V}_{85\ \mathrm{outterlane}} = 60.77 + 1.80\mathrm{ST} - 2.52\mathrm{MT} - 1.07\mathrm{AG} - 1.51\mathrm{FC} + \frac{47}{10^5}\mathrm{R} + 2.40\frac{\mathrm{CL}}{\mathrm{R}}$
Sil et al (2019) **	$V_{85} = 40.549 + 0.108R + 0.053PTL$

Note:

*Two-lane highways

** Four-Lane highways

V_{85}= operating speed, CCR = Curvature change rate, R = Radius, ∆ =Deflection angle, e=superelevation, $\mathrm{V}_{\mathrm{T}85}$= 85th percentile speed on a tangent, CL=Curve length, ST=Shoulder type, MT=Median type, PT=Pavement type, AG=Approach grade, FC= Front curve index, PTL= previous tangent length.

Table 2.5: Details of operating speed prediction models

Sl. No.	Literature	Country	#Lane	Veh. Cat.	Model	Method	Predictors	Data collection	#Sample	# Obs	MAX R^2
1	Taragin (1954)	US	2	PC	V_{85}	OLSR	R	N/A	68	125	0.86
2	Mclean (1978)	AUS	2	PC	V_{85}	OLSR	R, CCR	N/A	N/A	N/A	0.87
3	Mclean (1979)	AUS	2	PC	V_{85}	OLSR	R, VT	N/A	120	N/A	0.92
4	Kerman et al. (1982)	UK	2	PC	V_{85}	OLSR	R, Va	N/A	N/A	N/A	0.91
5	Glennon et al. (1983)	US	2	PC	V_{85}	OLSR	DC	N/A	56	N/A	0.84
6	Guidelines of German (1984)	GER	2	PC	V_{85}	NLR	CCR, LW	N/A	N/A	N/A	0.79
7	Glennon et al. (1985)	US	2	PC	V_{85}	OLSR	R	N/A	N/A	N/A	0.84
8	Setra (1986)	France	2	PC	V_{85}	OLSR	CCR, LW	N/A	N/A	N/A	0.85
9	Lamm and Choueiri (1987)	US	2	PC	V_{85}	OLSR	CCR, R, LW, SW	Stopwatch	261	N/A	0.84
10	Kanellaidis et al. (1990)	Greece	2	PC	V_{85}	OLSR	R, Vd	N/A	58	200	0.93
11	Lamm et al. (1990)	US	2	PC	V_{85}	OLSR	DC	Radar gun	261	120 - 140	0.79
12	Lamm (1993)	GER	2	PC	V_{85}	OLSR	CCR	N/A	N/A	N/A	0.73
13	Islam and Seneviratne (1994)	US	2	PC	V_{85}	OLSR	DC	Radar gun	8	125	0.98
14	Krammes et al. (1994)	US	2	PC	V_{85}	OLSR	DC, DF, Lc	Following vehicle	138	50	0.92
15	Morrall and Talarico (1994)	Canada	2	PC	V_{85}	NLR	DC	Radar gun	9	N/A	0.99
16	Ottesen and Krammes (1994)	US	2	PC	V_{85}	OLSR	CCR, R	N/A	N/A	N/A	0.8
17	Al-Masaeid et al. (1995)	Jordan	2	PC, LCV, HCV	V_{85}, ΔV_{85}	OLSR	DC, Pcon, G, R1, R2, LT, DF1, DF2	40 mTrap	93	N/A	0.81
18	Choueiri et al. (1995)	Lebanon	2	PC	V_{85}	OLSR	CCR	N/A	N/A	N/A	0.81

19	Lamm et al. (1995)	Greece	2	PC	V_{85}	OLSR	CCR	N/A	N/A	N/A	0.81
20	Krammes et al. (1995)	US	2	PC	V_{85}	OLSR	DC, Lc, DF, LT, VT	Radar gun	284	50-100	0.9
21	Voigt (1996)	US	2	PC	V_{85}	OLSR	R	N/A	N/A	N/A	0.84
22	McFadden and Elefteriadou (1997)	US	2	PC	V_{85}	OLSR	DC, Lc, DF, VT	N/A	284	50-100	0.98
23	Abdelwahab et al. (1998)	Jordan	2	PC	ΔV85	OLSR	DC, DF	Stopwatch	46	35	0.92
24	Andjus and Maletin (1998)	Yugoslavia	2	PC	V_{85}	NLR	R	Radar gun	9	70-80	0.81
25	Cardoso et al. (1998)	Portugal	2	PC	V_{85}	OLSR	VT, R	N/A	50	N/A	0.92
26	Passetti and Fambro (1999)	US	2	PC	V_{85}	OLSR	R	Counter/ Classifier	51	100	0.68
27	Andueza (2000)	Venezuela	2	PC	V_{85}	OLSR	R, Ra, DC, LT	Radar gun	39	30-64	0.85
28	Fitzpatrick et al. (2000)	US	2	PC	V_{85}	OLSR	R, K, G	Rader & Lider gun	176	100	0.92
29	McFadden and Elefteriadou (2000)	US	2	PC	V_{85}	OLSR	V_{85T}, LT, R	Lider gun	21	75	0.71
30	Ottesen and Krammes (2000)	US	2	PC	V_{85}	OLSR	DC, LC, DF, LT1, LT2	Rader gun	216	50	0.81
31	Donnell et al. (2001)	US	2	HCV	V_{85}	OLSR	R, G1,G2, LT1, LT2	Lider gun	17	100	0.61
32	Gibreel et al. (2001)	Canada	2	PC	V_{85}	NLR	R, Lv, G1, G2, A, L0, e, K, DF	Rader gun	38	1hr	0.98
33	Jessen et al. (2001)	US	2	PC	V_{85}	OLSR	Vp, G1, ADT	Counter/ Classifier	70	275	0.61
34	Liapis et al. (2001)	Greece	N/A	PC	V_{85}	OLSR	DC, E	Magnetic counter	20	N/A	0.75
35	Schurr et al. (2002)	US	2	PC	V_{μ}, V_{85}, V_{95}	OLSR	DF, Lc, G, ADT, SL	Detector	70	N/A	0.46
36	Medina and Tarko (2004)	US	2 & 4	PC, CV	V_P	OLS-PD (Panel data), OLS_RE (Ramdom effect)	DC, SD, RES, e, R, VT, DFC, SW, Curve_Dir, G	Counter/ Classifier, laser gun	158	≥ 100	N/A
37	Misaghi and Hassen (2005)	Canada	2	PC(PC~ LCV)	V_{85}, $\Delta_{85}V$	OLSR	VT, Δ, SW, Curve_dir, G, Drv_flag	Counter/ Classifier	20	≥ 100	0.89
38	Stamatiadis and Gong (2006)	US	2 & 4	PC	V_{85}	OLSR	R, DS, Lc, DL, RSW	Rader gun	103	25-158	0.54
39	Gong and Stamatiadis(2008). Thesis	US	4	PC	V_{85}	OLSR	R,CL, ST, MT, AG , FC	Rader gun	63	≤100	0.68
40	McFadden (2001)	US	2	PC	V_{85}	ANN	D, Lc, Δ	Rader gun	138	50-100	0.68
41	Pérez-Zuriaga et al. (2013)	Spain	2	PC	V_{85}	OLSR	R, CCR	GPS	81	120	0.52
42	Jacob et al. (2013)	India	2	2W, PC, HCV	V_{85}	OLSR	R, C	Radar gun	152	N/A	0.86
43	Semeida (2014)	Egypt	2	PC, HCV	V_{85}	ANN & OLSR	MW, DA	Radar gun	78	100	0.93
44	Hashim et al. (2016)	Egypt	2	PC	V_{85}	OLSR	R	GPS	64	30	0.88
45	Sil et al. (2020)	India	4	PC	V_{85}	OLSR	R, DA, LT	Video	35	26	0.86

46	Maji et al. (2018)	India	2	PC	V_{85}	OLSR	R, DA, LC	Video	N/A	13	0.85
47	Malaghan et al. (2020)	India	6	PC	V_{85}	OLSR	CL, DC, R	GPS	N/A	49	0.90

2.3 Driver Warning System

As discussed earlier, one way of reducing highway accidents is through geometric design, and the other is by providing proper speed warnings to the driver. In general, the drivers were warned about the upcoming geometry speed limit using the posted speed signs to the sides of the road (Whitmire et al., 2011; AASHTO, 2018). The posted speed values are derived from the operating or the anticipated speed, implicitly considering the functional classification of the road and terrain type (Fitzpatrick et.al., 2003). Fitzpatrick (2002) recommended that the operating speed should be used as a reference point for posted speed values, and if possible, the posted speed values should be 8 to 12 mph less than the operating speed values. Drivers who exceed the posted speed limit are involved in nearly one-third of all fatal crashes (Harsha et al., 2007).

Other than posted speed, another way to warn the driver about over speed is by an In-vehicle warning system (Whitmire et al., 2011). With the advances in today's technology, vehicles can be equipped with In-vehicle warning systems either by the original equipment manufacturer (OEM) or aftermarket installations; these systems could help in driver decision-making processes (Parkes & Franzen, 1993). In 2017, the Indian government passed an order stating the requirement of a mandatory In-vehicle speed alert system for all vehicles entering the Indian market starting in July 2019. In this, the recommended speed warning system is designed to alert the drivers with two beeps every 60 seconds if the driver exceeds 80 kmph. On the other hand, the system will make a continuous beeping sound if the speed exceeds 120 kmph. In addition to the inbuilt In-vehicle speed warning systems, externally mountable systems are also developed by some Indian companies like Carsense and AUTOOL. The equipment developed by these companies is fitted to the vehicle OBD-II port to access the vehicle data and warn the drivers if the vehicle exceeds 80 or 120 kmph, as recommended by the government.

On observing the posted speed system and the current In-vehicle warning system, it is clear that these systems are rigid. On highways, based on vehicle type, the safety speeds vary, and so does the posted speed, as shown in Figure 2.3. These kinds of signposts confuse drivers in selecting their safe speed, and on some highways, the provision of posted speeds for all vehicle types is not possible. These limitations can easily be overcome with In-vehicle warning systems. However, the current In-vehicle system in India is fixed speed based (80 kmph or 120 kmph) systems which are not suitable for mountainous terrains where the design speeds are limited to 50kmph (Table 2.1). A dynamic speed limit system is needed to overcome these limitations in speed warning systems, rather than rigid 80/120 kmph speed limits, depending on the highway geometry and terrain conditions.

(Source: www.alamy.com)

Figure 2.3 Posted speed signpost

2.4 Overview on Literature Reviewed

This literature review chapter broadly covered various methods, such as the geometric design (comfort-based and consistency-based) and speed-based driver warning systems, to improve the safety of highways. Further, the literature review yields the following salient points and questions:

Salient Points

- Consistency-based design improves the safety of highways as it considers the accident information and drivers anticipated speed (V_{85}), unlike the comfort-based design, which is mainly based on neutralizing the forces acting on the vehicle.

- The relation between the operating speed, design speed and the posted speed varies depending on the highway's functional and terrain classification.
- The operating speed depends on various factors such as the vehicle type, terrain type, location and geometry of the highway.
- It is also found that a single operating speed model may not be suitable for all countries as it highly depends on socio-economic demographics.
- Driver warning system helps to reduce accidents, as data suggests that vehicles which exceed the posted speed limit are involved in fatal crashes.

Questions

- Which geometric parameters influence the operating speed of vehicles in horizontal curves of four-lane roadways?
- How do the geometric parameters influence the operating speed of vehicles over four-lane highways?
- Do the existing speed prediction models (developed primarily for two-lane roadways) suitable for predicting the speed of vehicles on four-lane highways?
- Does the consistency criteria developed for two-lane roads applicable for four-lane roads?
- Is the assumption of uniform speed in consistency theory over the curve from PC to PT valid on four-lane curves?
- Whether multiple speed models needed to predict percentile speeds at various locations (point of curve, centre of the curve, and point of tangent) on the curve?
- Apart from the constant speed limits for speed warning, is it possible to develop a dynamic speed warning system reflecting the driver's anticipated speed?

CHAPTER 3

PILOT STUDY ON FOUR-LANE HIGHWAYS TO UNDERSTAND DRIVERS' BEHAVIOR WITH FREE-FLOW SPEED DATA ANALYSIS

3.0 Introduction

Speed is an essential factor for safer and more comfortable highway geometric design. In modern highways, geometric design such as consistency-based geometric design vehicle operating speed is the one that provides a better assessment of driving behavior and geometric consistency. Therefore to understand the drivers' speed patterns, major studies were conducted on two-lane highways however limited studies also explored four-lane highways (Chapter 2). Even in these, the free flow speed behavior of drivers on four-lane highways in mountainous terrains are not studied in detail. Considering all these, the present thesis focuses on four-lane highways on mountainous terrains. This chapter presents a pilot study to explore the free-flow speed behavior of drivers over a four-lane highway in mountainous terrain.

3.1 Data Collection for Pilot Study

A total of 16 horizontal curves were chosen from National Highway 6 (NH-6), located in Meghalaya, India. The selected curves are shown in Figure 3.1. All these curves (i.e., S1 to S16) are in mountainous terrain as defined by IRC 73-1980(1990) and are designed for a speed of 50 kmph. Over these horizontal curves, sections such as the point of the curve

(PC), the center of the curve (CC), and the point of tangent (PT) were marked. Over these sections of curves, the speed and highway geometry data were collected and presented the details in the following subsections.

Figure 3.1: Satellite view of study sites on Guwahati-Shillong Highway (NH-6)

3.1.1 Free-flow speed data

As described in Chapter 2, the driver's speed is considered as free flow speed when the driver is influenced by the geometry of the curve only. To achieve this, special care was taken in curve selection which ensured that there were no intersections or median openings present within 500 m of the selected horizontal curve. All the curves were free from side friction, including on-street parking and illegal contraflow movements, bus bays, and bus stops.

The speeds of vehicles at PC, CC, and PT of the curves (S1 to S16) were measured during a sunny day on November 2015 between 10 AM to 4PM , using radar gun equipment, while the corresponding time was recorded using a digital clock. The collected speed data was analyzed to identify vehicle free flow speeds, based on the free flow speed criteria (time headway ≥ 5 sec) established by Figueroa & Tarko (2005). In the end at each of these sections (i.e., PC, CC, and PT), for all these curves, a minimum of 50 free-flow speed data points were obtained.

3.1.2 Geometric data

The data relating to road geometry features such as radius, length, gradient, extra widening, and superelevation rates of the curve were collected from the actual CAD drawings provided by the highway agencies. The data covers a wide range of curve lengths (varying between 10m and 205 m) and vertical gradients (varied between +6% and –6%), which were typical for highways in mountainous terrains. The details of the geometric features of the selected curves (S1 to S16) are presented in Table 3.1.

Table 3.1: Geometric features of the selected curves (S1 to S16)

Site	Radius (m)	Gradient (%)	Curve Length (m)
S1	50	4	74
S2	100	-2	139
S3	100	2	139
S4	100	-6	33
S5	100	6	33
S6	150	-6	31
S7	150	-4	64
S8	150	2	32
S9	150	4	43
S10	200	-4	56
S11	200	-2	27
S12	200	2	205
S13	200	4	10
S14	200	6	103

S15	300	-6	73
S16	300	2	74

3.2 Speed Data Analysis on Preliminary Data

This section presents the preliminary analysis of the free-flow speed data collected from the curves S1 to S16. The outcome of this preliminary speed data analysis are described in the following subsections.

3.2.1 Speed data statistics of vehicles at different locations on the curve

To analyze the drivers' general behavior, the average free flow speed is compared statistically with the design speed of the highway. A hypothesis test is conducted to check if the average vehicle speed is significantly different from the design speed (i.e., 50 kmph). This test is essential to justify the requirement of speed calming measures for safety. The test hypothesis statements are as follows:

Null Hypothesis (H_0): Average speed is less or equal to design speed

Alternate Hypothesis (H_1): Average speed is more than the design speed

The rejection rate of the null hypothesis in the pilot study for passenger car speed (Table 3.2) at the beginning of a curve (i.e., location PC) is 60%, and at other locations (i.e., CC and PT) is 35%. Further, on comparison of the mean speed of the passenger cars at various locations (PC, CC, and PT) on the 16 curves (Table-3.2) with highway design speed, it is observed that 45% of the cars are operating at speeds higher than the design speed. The average speed of vehicles is higher than the design speed at about 50% of locations.

Table 3.2: Speed Statistics of the passenger cars at various locations on the curve

Site	Car at location					
	PC		CC		PT	
	μ	σ	μ	σ	μ	σ
S1	48.92	7.79	39.55	6.53	33.71	5.60
S2	--	--	47.52	8.43	50.02	8.01
S3	47.85	7.55	43.10	7.85	--	--
S4	56.25	9.89	53.82	9.61	52.13	9.15
S5	49.92	7.09	50.83	7.13	51.05	7.18
S6	49.82	5.69	43.65	7.72	47.74	9.11
S7	54.33	7.17	47.86	8.68	58.25	8.43
S8	54.71	9.30	--	--	49.66	9.42
S9	52.12	8.05	54.48	8.39	56.88	8.37
S10	54.23	9.79	41.57	10.36	51.45	11.01
S11	59.62	11.17	53.45	10.90	53.62	10.50
S12	45.82	10.92	38.02	10.62	39.96	9.44
S13	60.91	9.51	57.73	9.95	56.33	10.20
S14	50.15	8.94	51.32	7.75	46.64	8.75
S15	58.26	8.33	58.73	9.04	63.85	9.88
S16	52.68	9.62	47.71	10.20	47.96	10.70

3.2.2 Comparison of 85th percentile vehicle speed at various locations on the curve

A hypothesis test is conducted at a 95% confidence interval to check the 85th percentile speed variation between the various curve sections. The method proposed by Hou et al. (2012) for the null hypothesis is $H_0 : (z_{0.85})_X - (z_{0.85})_Y = 0$, is used here. It is examined using equation 3.1, and obtained results are presented in Table 3.3.

$$Random\ variable = \frac{\left(X_{[n0.85]+1} - Y_{[n0.85]+1}\right) - \left((\zeta_{0.85})_X - (\zeta_{0.85})_Y\right)}{1.53\sqrt{\frac{S_X^2}{n_X} + \frac{S_Y^2}{n_Y}}} \tag{3.1}$$

Where,

$(\boldsymbol{\zeta_{0.85}})_X$ = The 85th distribution quantiles of sample *X*

$(\boldsymbol{\zeta_{0.85}})_Y$ = The 85th distribution quantiles of sample *Y*

$X_{[n0.85]+1}$ = The 85th sample quantiles of sample size $\boldsymbol{n_X}$

$Y_{[n0.85]+1}$ = The 85th sample quantiles of sample size $\boldsymbol{n_Y}$

S_X = Standard deviation of sample *X*

S_Y = Standard deviation of sample *Y*

To test the null hypothesis $H_0{:}\left(\zeta_{0.85}\right)_X = \left(\zeta_{0.85}\right)_Y$, which is equivalent to $H_0{:}(\zeta_{0.85})_X - (\zeta_{0.85})_Y = 0$, Therefore the random variable is

$$Random\ variable = \frac{\left(X_{[n0.85]+1} - Y_{[n0.85]+1}\right) - 0}{1.53\sqrt{\frac{S_X^2}{n_X} + \frac{S_Y^2}{n_Y}}} \tag{3.2}$$

The pilot analysis observed from Table-3.3 that about 25 to 40 percent of the sites have statistically different 85th percentile speeds between locations PC & CC and CC & PT. The null hypothesis is rejected for approximately 60% of cases belonging to sites with gradients within 4%. On comparison, it is observed that the null hypothesis is rejected for 10% of cases which belongs to sections with steeper gradients (i.e., gradient > 4% and gradient < –4%).

Driver discomfort and inability to accelerate or decelerate at steeper gradients could be one of the reasons behind this behavior. Further, it is also believed that having a more extended approach tangent length and sharp curve radius might also lead to the V_{85} speed difference between successive locations on the curve.

Table 3.3: Hypothesis Test Results for 85th Percentile Speed Variation

Site	PC & CC	CC & PT
S1	Yes	Yes
S2	NA	No
S3	No	Yes
S4	No	No
S5	No	No
S6	No	Yes
S7	Yes	Yes
S8	NA	NA
S9	No	No
S10	Yes	Yes
S11	No	No
S12	Yes	No
S13	No	No
S14	No	No
S15	No	Yes
S16	No	No

3.2.3 Design consistency safety evaluation of existing curves

Geometric design consistency and design safety level are measured using models suggested by Lamm et al. (1999) and Fitzpatrick et al. (2000) (see Table 3.4: Design consistency and safety evaluation criteria) using 85th percentile speed (V_{85}) and design speed (V_d). In this analysis, the variation of V_{85} from V_d is observed at PC, CC, and PT. Similarly, in criteria-II, rather than observing the operating speed V_{85} variation between successive sections conventionally, the variation in V_{85} within the curve section is observed (PC vs. CC and CC vs. PT).

Table 3.4: Design consistency and safety evaluation criteria

Design Safety	Criteria I (kph)	Criteria II (kph)
Good (G)	$\lvert V_{85}-V_d \rvert \le 10$	$\Delta V_{85} \le 10$
Fair (F)	$10 < \lvert V_{85}-V_d \rvert \le 20$	$10 < \Delta V_{85} \le 20$
Poor (P)	$\lvert V_{85}-V_d \rvert > 20$	$\Delta V_{85} > 20$

Table 3.5: Consistency-based geometric safety evaluation

Site	CRITERIA I (V_{85}-V_d)			CRITERIA II (ΔV_{85})	
	PC	**CC**	**PT**	$V_{85\lvert PC\text{-}CC\rvert}$	$V_{85\lvert CC\text{-}PT\rvert}$
S1	G	G	G	F	G
S2	NA	G	G	NA	G
S3	G	G	NA	G	NA
S4	G	F	G	G	G
S5	G	G	G	G	G
S6	G	G	F	G	G
S7	G	G	G	G	F
S8	G	NA	G	NA	NA
S9	G	G	G	G	G
S10	G	F	F	G	G
S11	G	G	F	G	G
S12	F	F	G	G	G
S13	F	F	G	G	G
S14	G	G	G	G	G
S15	G	G	F	G	G
S16	G	G	G	G	G

#NA =Not Available, G = Good, F = Fair, P = Poor

The design safety rating of all study sites considered is summarized in Table 3.5. It is observed from Table 3.5 that the safety on these 16 curves varies between good and fair.

3.3 Closing Remarks

Frequent horizontal curves with gradients are common in roadways located in mountainous terrain. This pilot study attempts to understand the driving behavior in roadways with frequent horizontal curves. Statistical data analysis produced several useful findings on vehicle speed in curve sections.

As part of geometric design consistent evaluation criteria, the 85th percentile vehicle speed is adopted to compare it with the roadway design speed. The comparisons suggest that about 45% of cars operate at speeds higher than the design speed. Additionally, the average speed of cars is also found to be more than the design speeds at 50% of the sites. The application of consistency criteria also revealed that 7% of sections in Criteria I and 21% of sections based on Criteria II are rated fair. In design consistency safety evaluation, it is also observed that within the curve (e.g., S4), the safety levels vary from PC to CC and then CC to PT.

This is a serious safety concern. Various engineering measures such as transverse rumble strips, transverse markings, speed feedback signs, lane narrowing, etc., have a proven track record in reducing vehicle speed in high-speed roadways. However, these methods are not tested for Indian four-lane highways. Therefore safety studies are needed to identify a way to contain the vehicle speed within the design speed.

Further in the pilot study, the curves considered are designed for only 50 kmph, and the speed data collected is spot speed data only. Therefore, to better understand drivers' behavior with free flow speed, it needed to consider more curves covering a wider range of design speeds. In addition to this, rather than spot speed data, if the entire speed profile is available for the curve from PC to PT, the variations in the speed pattern can be explored to minimize the speed variations within the curve from PC to CC and then from CC to PT.

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CHAPTER 4

UNDERSTANDING THE DRIVERS' BEHAVIOR ON FOUR-LANE HIGHWAYS THROUGH FREE-FLOW SPEED DATA ANALYSIS

4.0 Introduction

The pilot study revealed statistical relationships between free-flow speed, average speed, and design speeds. Even though the pilot study yielded some significant results, it was based on the speed data collected using a radar gun at limited number of curves with a design speed of 50 kmph. Therefore in this chapter, the speed data analysis is performed on an extensive dataset, which includes a large number of curves (285) with varied design speeds and continuous speed profile data of multiple vehicles (in free-flow conditions) collected using high precession GPS, to analyze the following goals:

- Speed data statistics of vehicles at different locations on the curve
- Comparison of 85th percentile vehicle speed at various locations on the curve
- Design consistency safety evaluation of existing curves

4.1 Site Selection and Data Collection

The data for this study were collected along the Guwahati-Shillong National Highway-6 (NH-6) with a four-lane median divided cross-section in the Assam state in India. The outer sides of the cross-section have a one-meter-wide paved shoulder, and the surface layer is asphaltic concrete. Furthermore, the entire section of NH-6 considered under this study belongs to mountainous terrains as per the IRC-73:1980 (1990). Over a stretch of 65 km between Guwahati and Shillong on this NH-6, 285 curves were selected for data collection and analysis. The selected curves are free from median openings and intersections within 500 meters. These curves' geometry also covers various radii, curve lengths, and gradients.

4.1.1 Speed data collection using VBOX

Over NH-6, a GPS device called VBOX is utilized to capture naturalistic free-flow speed data. The VBOX device is GPS-based and uses the Doppler Effect to diminish speed errors. The VBOX used can collect speed data at a frequency of 10Hz. This device operates with at least four low-earth satellites to obtain highly accurate data. The VBOX device has a speed accuracy of $\pm$ 0.1 $kmph$ and a position accuracy of $\pm$ 0.5 m. The device also collects video data using four cameras mounted on four sides of the vehicle.

The vehicles used in data collection belonged to the local drivers to ensure that the drivers were familiar with the vehicle and the road. This familiarity with the vehicle and route allows the driver to travel more naturally. To ensure the acquaintance of the hired drivers (31 drivers) with the VBOX instrument, an initial 7 km of the data is not used for analysis. Figure 4.1 shows the data collected from one of the drivers over a 65-kilometer stretch on NH-6. Among the collected speed profile data, the vehicle's free-flow speed data is segregated using the following criteria:

I: *Maintaining at least 5-sec headway between the subject vehicle and its lead vehicle*

II: *Maintaining at least 5-sec headway between the subject and the following vehicle*

III: *No parallel movements in the adjacent lane or space within the study zone*

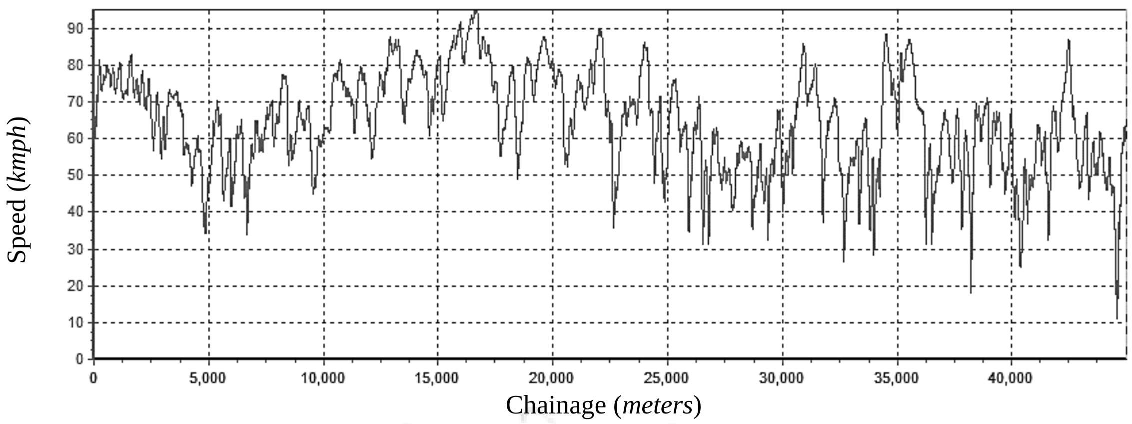

Figure 4.1 VBOX Speed profile data over a 65 km stretch

Speed Data Extraction from VBOX Device:

The VBOX data collected by the test drivers are extracted using software provided by the VBOX vendors. Vehicle parameters such as position, speed, time, height, and headings were retrieved at four-meter intervals. The vehicle's global latitude and longitude coordinates are saved in minutes in the vehicle's location information and are subsequently transformed to UTM coordinates using transformation algorithms.

The collected VBOX data contains information on vehicle speed synchronized with the vehicle position's latitude and longitude. So, to find the speeds at a specific location, such as the center of the curve (CC) for a particular curve, the actual latitude (Lat_{CC}) and longitude ($Long_{CC}$) at the CC of that curve are first collected from the highway drawing available. Next, speed values at CC were obtained by utilizing the nearest point search algorithm in MatLab. In this, the nearest location of the driver from the known position ($Lat_{CC}, Long_{CC}$) is measured, and the speed at that location is taken as the speed at the center of the curve (V_{CC}). Similarly, the free-flow speeds at the point of the curve (V_{PC}) and the point of tangent (V_{PT}) were also extracted.

4.1.2 Geometric data

Data on road geometry features such as curve radius, curve length, gradient, extra widening of the curve, and superelevation rates were collected from the actual CAD drawings provided by the highway agencies. Further, these geometric parameters extracted from drawings are cross-verified using Laser Distance Meter (LDM) and field data collection techniques. In addition to the geometric data, the design speed (V_d) data is also obtained from the highway authority. The descriptive statistics of the geometric parameters and design speeds are presented in Table 4.1. The curves' geometric data cover a broader range of road geometry, such as gradients, curve radius, and curve length.

Table 4.1 Independent variable descriptive statistics of 285 curves on NH-6.

	CL	R	V_d	SL	SE	VGT	VGC	PTL
Min	30	20	20	0	2.5	-7	-7	0
Max	244	800	80	75	7.0	9.0	9.0	642
Mean	39	149	44	27	6.2	0.2	0.2	37
Std	33	139	11	11	1.4	3.0	3.0	63

Where: Curve length (CL), Radius(R), Design Speed (V_d), Spiral length (SL), Superelevation (SE), Tangent vertical gradient (VGT), Curve vertical gradient (VGC), previous tangent length (PTL).

4.1.3 Accident data

Accident data for all 285 curves are also collected from the highway maintenance authority for three years, from March 2016 to March 2019. This data consists of all kinds of accident-related data such as the type of vehicle, location, time, road condition, climate, and type of accident.

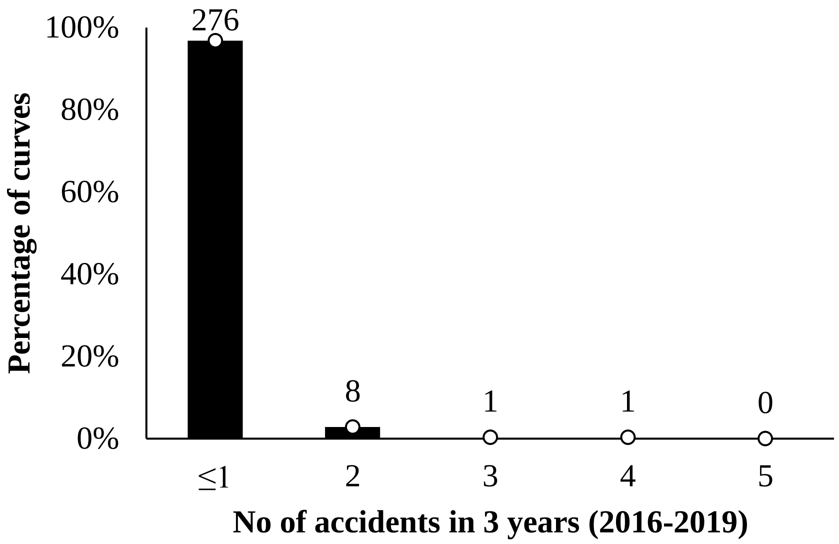

Figure 4.2: Accidents due to speed over 285 curves

The accident data related to the speed of the passenger cars were separated from the available accident data and presented in Figure 4.2. Over three years, there have been 70 accidents on 285 curves. It has also been discovered that for a large number of curves (97 percent or 276 curves), one or no accidents occur.

4.2 Speed Data Analysis

4.2.1 Drivers speed profile across the curve

The continuous speed data collected from the VBOX device is used to study the drivers' speed profile variations along the horizontal curve. The observed individual and V_{85} speed profiles for one of the curves are shown in Figures 4.3 and 4.4. The V_{85} speed profile (i.e., operating speed profile) drawn over the curve length is similar to the one proposed by Xu et al. (2017) for two-lane highways in mountainous terrains. According to the data, practically every driver hits their minimum speed within 10% of the curve length on either side of the curve center. Individual speed profiles revealed that approximately 43 percent of drivers reached their minimum speed just before the curve's center. The remaining 57 percent of the drivers are just after the center point of the curve. Through this, the drivers' acceleration and deceleration behavior over the curve is classified into three zones: deceleration zone, stable zone, and acceleration zone. In the deceleration zone, all the drivers are in the deceleration phase under the free-flow condition, and no vehicle will reach their minimum speed until the end of this zone. In the acceleration zone, all vehicles are in the acceleration phase, and they will be at their minimum speeds before starting the acceleration zone. Finally, the stable zone is where drivers travel with little to no fluctuations in their free-flow speeds, with the acceleration and deceleration rates being meager as equal to zero. The maximum and average deceleration values from the V_{85} profile in the deceleration zone are 1.12 m/s^2 and 0.90 m/s^2, respectively. Similarly, the maximum and average acceleration values in the acceleration zone are 1.06 m/s^2 and 0.86m/s2. The average acceleration obtained matches the value of 0.85 m/s2 proposed by Lamm et al. (2006) for two-lane highways, whereas the deceleration values of 0.85 m/s2 presented by Lamm et al. (2006) are lower than the obtained values in this study.

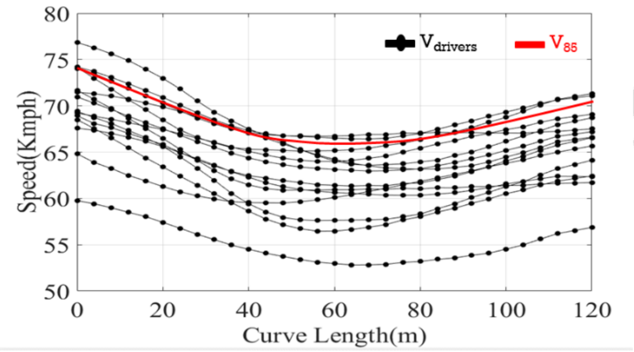

Figure 4.3: Speed Profiles of the drivers

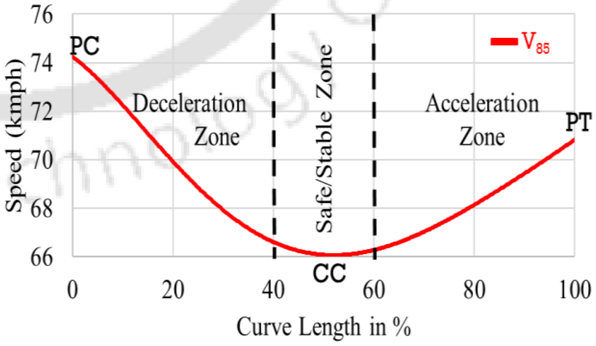

Figure 4.4: V_{85} Speed profile on the curve

4.2.2 Speed data statistics of vehicles at different locations on the curve

The typical behavior of the drivers was seen with a restricted number of curves created for 50 kmph in the pilot study detailed in the preceding chapter. The average free-flow speed was compared with the design speed statistically, and it found that at majority of the curves, the average speed of the drivers is greater than the design speeds, as shown in Section 3.2.1. Therefore, to analyze similar behavior with a larger dataset, Section 4.1.1 of this chapter describes the VBOX collected data from 285 curves with design speeds ranging from 20 kmph to 80 kmph. Over the collected VBOX data, the curve's speed at PC, CC, and PT was extracted as explained in Section 4.1.1, to conduct the statistical analysis with null (H_0) and alternate (H_1) hypotheses.

H_0: Average speed is less or equal to the design speed

H_1: Average speed is more than the design speed

Table 4.2: No of locations (number as well as in %) that satisfy the H1 hypothesis

Design Speeds	No of Curves	At PC	At CC	At PT
20	2	2 (100%)	2 (100%)	2 (100%)
25	4	4 (100%)	4 (100%)	4 (100%)
30	29	29 (100%)	29 (100%)	29 (100%)
35	5	5 (100%)	5 (100%)	5 (100%)
40	116	108 (93%)	105 (91%)	105 (91%)
50	71	69 (97%)	63 (89%)	64 (90%)
65	32	21 (66%)	18 (56%)	20 (63)
80	26	2 (8%)	0 (0%)	0 (0%)

Table 4.3: Free-flow speed data characteristics at PC, CC, and PT

	PC	CC	PT	σ at PC	σ at CC	σ at PT
Min	34	34	36	2.03	1.82	1.69
Max	78	80	83	11.80	12.67	14.02
	Percentage of curves satisfy: H_1			Percentage of curves $\sigma \geq$ 10 kmph		
Percentage	84	79	80	1.0	1.5	3.0

Note: σ= Standard Deviation of free-flow speed.

Table 4.2 shows that for design speeds less than 35 kmph, all the drivers traveled at speeds higher than the design speeds. As the design speed increases, the number of sections satisfying the alternate hypothesis (H_1) decreases. However, among all the 285 curves, the average free-flow speed is greater than the design speeds on most of the curves (> 80 %) at all critical locations (PC, CC, and PT), as shown in Table 4.3. These observed results align with the McLean (1981) studies on two-lane highways for curves with design speeds of less than 100 kmph. Further, the standard deviation (σ) of speed is greater than 10 kmph for less than 3% of the curves at PC, CC, and PT, as shown in Table 4.3.

4.2.3 Comparison of 85th percentile vehicle speed at various locations on the curve

The V_{85} speed profile study in Section 4.2.1 revealed three critical locations on the curve, namely PC, CC, and PT, where the acceleration/deceleration patterns change, leading to the rise and fall of V_{85} speeds across the curve. Therefore, in this section, a hypothesis test proposed by Hou et al. (2012) is conducted to compare the V_{85} speeds between PC, CC, and PT at a 95% confidence interval.

$$\text{Null hypothesis of } H_0 : (z_{0.85})_X - (z_{0.85})_Y = 0$$

$$\text{The alternate hypothesis of } H_1\text{: } (z_{0.85})_X - (z_{0.85})_Y \neq 0$$

Where $$(\zeta_{0.85})_X - (\zeta_{0.85})_Y = \frac{\left(X_{([n0.85]+1)} - Y_{([n0.85]+1)}\right) - 0}{1.53\sqrt{S_X^2/n_X + S_Y^2/n_Y}} \tag{4.2}$$

,

$(\zeta_{0.85})_X$ = The 85th distribution quantiles of sample X

$(\zeta_{0.85})_Y$ = The 85th distribution quantiles of sample Y

$X_{[n0.85]+1}$ = The 85th sample quantiles of sample size $\boldsymbol{n_X}$

$Y_{[n0.85]+1}$ = The 85th sample quantiles of sample size $\boldsymbol{n_Y}$

S_X = The standard deviation of sample X

S_Y = The standard deviation of sample Y

Comparing the V_{85} speeds at PC, CC, and PT through this hypothesis, it is found that between PC & CC and CC & PT, around 69 and 72 percent of the sites, respectively, have statistically different 85th percentile speeds. The results in Table 4.4 also show that the curves with lower design speeds have higher chances of having significant speed variation between successive locations than the curves with higher design speeds. Further, for a curve with a given design speed, the ratio of H_0 to H_1 between PC to CC and CC to PT is almost the same. Overall the values in Table 4.4 suggests that a significant number of curves have statistically varying V_{85} speeds between successive curve locations.

Table 4.4: Comparison of V85 speeds between successive locations on the curves

Design Speeds	# Curves	V_{85PC} to V_{85CC}				V_{85CC} to V_{85PT}			
		H_0		H_1		H_0		H_1	
		#	%	#	%	#	%	#	%
20	2	0	0	2	100	0	0	2	100
25	4	0	0	4	100	0	0	4	100
30	29	0	0	29	100	0	0	29	100
35	5	0	0	5	100	0	0	5	100
40	116	8	7	108	93	5	4	111	96
50	71	27	38	44	62	24	34	47	66
65	32	28	87	4	13	27	84	5	16
80	26	25	96	1	4	25	96	1	4
	Total	Percentage of curves satisfying H_0 and H_1 hypothesis							
	285	31%		69%		28%		72%	

Table 4.5: Safety evaluation of four-lane curves with different design speeds using design consistency

Design Speeds	# Curves	GOOD						FAIR						POOR					
		PC		CC		PT		PC		CC		PT		PC		CC		PT	
		#	%	#	%	#	%	#	%	#	%	#	%	#	%	#	%	#	%
20	2	0	0	0	0	0	0	0	0	0	0	0	0	2	100	2	100	2	100
25	4	0	0	0	0	0	0	2	50	2	50	2	50	2	50	2	50	2	50
30	29	0	0	0	0	0	0	1	3	2	7	2	7	28	97	27	93	27	93
35	5	0	0	0	0	0	0	2	40	2	40	2	40	3	60	3	60	3	60
40	116	24	21	25	22	24	21	60	52	58	50	60	52	32	28	33	28	32	28
50	71	45	63	43	61	46	65	24	34	25	35	22	31	2	3	3	4	3	4
65	32	24	75	26	81	25	78	7	22	5	16	6	19	1	3	1	3	1	3
80	26	16	62	16	62	18	69	4	15	4	15	2	8	6	23	6	23	6	23

Table 4.6: Design Consistency safety evaluation on 285 curves

Design Consistency	No of locations at PC out of 285.	No of locations at CC out of 285.	No of locations at PT out of 285.	No of locations (PC+CC+PT) out of 855(=285*3)	Percentage of Total Locations (%)
Good	109	121	113	343	40
Fair	100	107	96	303	35
Poor	76	57	76	209	25

4.2.4 Safety evaluation based on design consistency of existing curves

Horizontal curve consistency evaluation results in Chapter 2 for 50 kmph design speed curves revealed that the safety levels vary from PC to CC for a given curve. Therefore, in this section, for a better understanding of design consistency across curves with various design speeds, Lamm et al. (1999) consistency criteria ($|V_{85} - V_d|$) are applied over the existing 285 curves on four-lane highways and segregated into the following categories Good, Fair, and Poor. The obtained results are presented above in Table 4.5

The results show a rough trend between the design speeds and the safety levels. The curves with the lowest design speeds are most likely to have accidents as they have poor design consistency in most cases. As curve design speed increases, the trend for the percentage of curves with poor design consistency decreases roughly, while the percentage of curves with fair and good design consistency increases. This is due to the increased difference between observed and design speeds on curves with lower design speeds.

According to the comprehensive analysis, approximately 40% of the locations (i.e., 343 out of 855) meet the Good consistency criteria, indicating a low risk of property and injury-related accidents. Similarly, 35% (i.e., 299 of 855) fair and 25% (i.e., 214 of 855) poor design safety levels were observed across 855 locations in 285 curves. Property and injury-related accidents are relatively common in the poor design safety category. In such circumstances, safety can be increased by introducing measures that slow operating speed or by changing geometric elements that help manage operating speed so the discrepancy between operating speed and design speed can be minimized. However, the design consistency levels obtained in some curves vary between Good, Fair, and Poor between PC, CC, and PT because of non-uniformity in speed. As a result, categorizing the level of safety for a given curve (based on its PC, CC & PT) can create ambiguity. It is believed that the variation in consistency levels between PC, CC, and PT for given four-lane curve results from the application of Lamm's consistency criteria (which was designed for two-lane curves with uniform speed assumptions).

Furthermore, it is observed from Table 4.5 that the trend in the percentage of curves for a given safety level is irregular as the design speed increases from 20 kmph to 80 kmph. This means that the application of Lamms' two-lane highway consistency criterion to four-lane highways yielded some crucial results, but the method's reliability on four-lane highways remains uncertain. As a result, in order to improve the classification of design consistency for four-lane highways, new design consistency criterion limits must be devised to account for speed non-uniformity (as depicted in Figure 4.4).

4.3 Closing Remark

This chapter conducts an in-depth analysis to comprehend the behavior of drivers' free-flow speed over curves with varying design speeds. Initially, for the analysis using the VBOX device, high-quality and quantity of data are collected from a four-lane highway consisting of 285 curves stretched along 65 km. The design speeds over these curves range from 20 to 80 kilometers per hour.

The data gathered in this study provided crucial insight into the pattern of speed profile variation along the curve. This resulted in separating the curve into three distinct zones: designated acceleration zone, stable zone, and deceleration zone, as shown in Figure 4.4. Furthermore, the V_{85} speed profile drawings reveal three critical locations on the curve, PC, CC, and PT, as shown in Figure 4.4, where the speeds are at optimal levels. Therefore, the studies conducted in this chapter from Sections 4.2.2 to 4.2.4 focus only on these critical locations to better understand the drivers' speed behavior over the four-lane horizontal curve.

The speed data study comparing average speed to curve design speed shows that the drivers' average speed is statistically much higher than the curve's design speeds. In this study, for curves with a design speed of less than 40 kmph, the drivers' average speed is higher than the curve's design speed at all three locations, PC, CC, and PT of the curve. Further, as the design speed increases from 40 kmph to 80 kmph, the number of locations with average drivers' speeds less than the design speed increases gradually. At 80kmph design speeds, the average speed at all three locations is statistically lower than the design speeds. Therefore, from the design point of view, special care must be taken while designing curves for lower design speeds.

The speed profile drawings revealed the existence of critical operating speed (V_{85}) over the curve at PC, CC, and PT, where V_{85} reaches its optimal. An 85th percentile hypothesis test is performed based on the study conducted by Hou et al.(2012) to determine whether these V_{85} speeds at PC, CC, and PT are statistically different. The study's findings revealed that most curves have statistically different V_{85} from location to location for a given curve. The V_{85} from PC to CC and CC to PT are statistically different, especially for curves with design speeds $\leq$ 35 kmph. Above the design speeds of 35 kmph, the number of curves with statistically different V_{85} speeds across the curve (PC to CC and CC to PT) decreases gradually, reaching almost zero at design speeds of 80 kmph.

As reported in Sections 4.2.1 to 4.2.3, V_{85} speeds are not uniform across the curve. Therefore, design consistency analysis was conducted (and reported in Section 4.2.4) at the curve's three critical locations (PC, CC, and PT) to verify whether the design consistency analysis only at the CC is sufficient to define consistency. This analysis exhibited different consistency levels across PC, CC, and PT for a given curve, ranging from Good to Poor. It is believed that this variation in consistency levels within the curve is due to the following reasons (i) the application of two-lane consistency criteria limits to four-lane highways and (ii) the assumption of uniform speed over the curve while developing the two-lane consistency criteria. These observations over multiple curves emphasize the need for developing separate consistency criteria for four-lane highways to improve the safety of highway geometric design.

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CHAPTER 5

DEVELOPMENT OF OPERATING SPEED MODELS, SAFETY CRITERIA, AND SPEED BASED HIGHWAY GEOMETRIC DESIGN

5.0 Introduction

Speed behavior analysis in the previous chapter provided critical information about drivers' behavior on four-lane highways. Such as, design speeds have little to no influence on drivers' speed choices. The speed profile study revealed that the speed is not uniform over the curve. Furthermore, the statistical analysis conducted on the operating speeds (V_{85}) at critical locations PC, CC, and PT revealed that these are statistically different across the curve from PC to CC & CC to PT. This statistical information shows that the assumption of uniform speed over the curve while designing horizontal curves is far from reality. Therefore, this chapter tries to resolve some geometry design issues based on operating speed variance over the curve by proposing new safety criteria and highway geometric design methodology. The details of these are provided in the subsequent sections.

5.1. Development of operating speed models (V_{85}) at PC, CC, and PT.

5.2. Development of speed harmony and speed synchronization safety criteria.

5.3. Geometric design using the developed operating speed models and safety criteria.

5.1 Development of Operating Speed Models (V_{85})

In the literature, most works on operating speed models were conducted at the center of the curve, believing that the speed remains uniform throughout the curve. However, the speed profile study (Section 4.2.1) revealed that the operating speed profile follows an inverted bell-shaped curve for four-lane highways in mountainous terrains. Further, in Section 4.2.3, it is discovered that the operating speeds at the different locations (PC, CC, and PT) on a curve are statistically different. Therefore, this section develops different operating speed models at PC, CC, and PT locations of a curve on a four-lane highway.

The speed and highway geometry data collected over 285 curves in NH-6 are used in model development (refer to Section 4.1 for details). The data from 250 of the 285 curves were used for calibration, while the remaining 35 curves were used for validation. The literature review presented (in Chapter 2) shows that the operating speed modeling was primarily developed using the ordinary least square regression (OLSR) method. Even in OLSR, the backward elimination method yielded better models for predicting the spot speeds (Sil et al., 2019) Therefore, in the present study, the V_{85} models at PC, CC, and PT for passenger cars (V_{85PC}, $V_{85CC,}$ and V_{85PT}) are estimated using the backward elimination OLSR method. Before starting the operating speed models, the collected geometric and operating speed data were tested for correlation and normality, respectively.

5.1.1 Correlation analysis

Pearson correlation (r) analysis is conducted to check the correlation among various geometric parameters of the 250 curves at a 95% confidence interval. The results obtained from this analysis are presented in Table 5.1. This analysis shows that the parameters have only mild ($r \leq 0.30$) to moderate correlation ($0.30 < r \leq 0.60$); therefore, all these parameters, Curve length (CL), Radius (R), Super elevation (SE), Spiral length (SL), Vertical gradient on the curve (VG_C), Vertical gradient on preceding tangent (VG_T), Preceding tangent length (PTL), and Deflection angle (△) are considered for modeling.

Table 5.1 Pearson Correlation (r) analysis on geometric parameters

	CL	**R**	**SL**	**SE**	**VG_T**	**VG_C**	**PTL**
R	0.25						
SL	-0.12	0.37					
SE	-0.20	-0.30	0.47				
VG_T	0.08	-0.11	-0.01	0.06			
VG_C	0.04	-0.21	-0.06	0.14	0.51		
PTL	0.16	0.16	0.18	-0.04	0.22	-0.07	
Δ	0.40	-0.35	-0.25	0.17	0.32	0.32	-0.34

5.1.2 Operating speed modelling

The OLSR technique is chosen in this study to predict the operating speeds at PC, CC, and PT. The V_{85} dependent parameter data at PC, CC, and PT was checked for the normality test and found statistically satisfied under the Anderson–Darling normality test. Then, the models were developed using the backward elimination OLSR technique, as presented in Table 5.2. Among these, the final model is selected based on the p-values, Standard error of estimate (SEE), Mallows's *Cp*-statistic, and Adjusted R^2 values for better-operating speed predictability. The final selected models for V_{85PC}, V_{85CC}, and V_{85PT} from Table 5.2 based on the above statistics are presented in Equations 5.1 to 5.3. In the final model, among the vertical gradients, only VG_C is available; therefore, the term VG is used in place of VG_C for convenience in the following sections.

Operating speed model at PC

$$V_{85PC} = 62.01 + 0.08 * PTL - 0.58 * VG + 0.16 * CL - 0.26 * \Delta \tag{5.1}$$

Operating speed model at CC

$$V_{85CC} = 62.07 + 0.08 * PTL - 0.59 * VG + 0.13 * CL - 0.31 * \Delta \tag{5.2}$$

Operating speed model at PT

$$V_{85PT} = 61.99 + 0.07 * PTL - 0.67 * VG + 0.21 * CL - 0.31 * \Delta \tag{5.3}$$

Figures 5.1 to 5.3 are drawn from the developed operating speed models in Equations 5.1, 5.2, and 5.3 for PTL of 150 m and VG of 0%. The inclined lines in these figures represent the operating speeds (V_{85}).

Table 5.2 V_{85} Speed model development using a stepwise backward elimination regression approach

V_{85}@	R^2_{adj}	SEE	Cp	Predictors	P
PC	72.49%	5.21	8.00	PTL, VG_C, VG_T, Δ, CL, R, SL, SE	CL < 0.001, PTL <0.001, Δ <0.001, VG_C =0.053
	72.65%	5.20	6.62	PTL, VG_C, VG_T, Δ, CL, SL, SE	CL < 0.001, PTL <0.001, Δ <0.001, VG_C =0.053
	72.64%	5.20	5.65	PTL, VG_C, VG_T, Δ, CL, SL	CL < 0.001, PTL <0.001, Δ <0.001, VG_C =0.050
	72.76%	5.19	4.37	PTL, VG_C, Δ, CL, R	CL < 0.001, PTL <0.001, Δ <0.001, VG_C =0.050
	72.11%	**5.17**	**2.40**	**PTL, VG_C, Δ, CL**	**CL < 0.001, PTL <0.001, Δ <0.001, VG_C =0.041**
CC	76.70%	5.08	8.00	PTL, VG_C, VG_T, Δ, CL, R, SL, SE	CL < 0.001, PTL <0.001, Δ <0.001, VG_C =0.048
	76.93%	5.05	6.39	PTL, VG_C, VG_T, Δ, CL, R, SL	CL < 0.001, PTL <0.001, Δ <0.001, VG_C =0.055
	77.17%	5.02	4.70	PTL, VG_C, VG_T, Δ, CL, R	CL < 0.001, PTL <0.001, Δ <0.001, VG_C =0.064
	77.41%	5.00	3.02	PTL, VG_C, Δ, CL, R	CL < 0.001, PTL <0.001, Δ <0.001, VG_C =0.053
	76.56%	**5.00**	**2.16**	**PTL, VG_C, Δ, CL**	**CL < 0.001, PTL <0.001, Δ <0.001, VG_C =0.044**
PT	77.99%	4.89	8.00	PTL, VG_C, VG_T, Δ, CL, R, SL, SE	CL < 0.001, PTL <0.001, Δ <0.001, VG_C =0.017
	78.12%	4.87	6.64	PTL, VG_C, VG_T, Δ, CL, R, S	CL < 0.001, PTL <0.001, Δ <0.001, VG_C =0.023
	78.32%	4.85	5.05	PTL, VG_C, VG_T, Δ, CL, R	CL < 0.001, PTL <0.001, Δ <0.001, VG_C =0.022
	78.36%	4.84	3.92	PTL, VG_C, Δ, CL, R	CL < 0.001, PTL <0.001, Δ <0.001, VG_C =0.017
	78.17%	**4.84**	**2.47**	**PTL, VG_C, Δ, CL**	**CL < 0.001, PTL <0.001, Δ <0.001, VG_C =0.014**

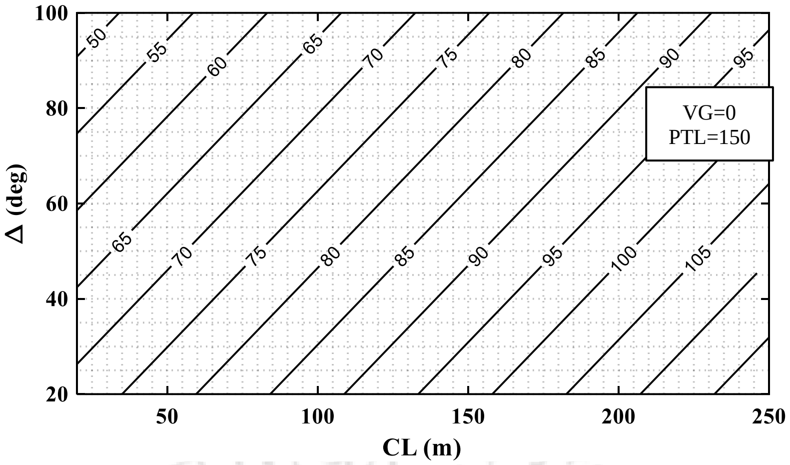


Figure 5.1 Predicted operating speeds (V_{85}) at PC

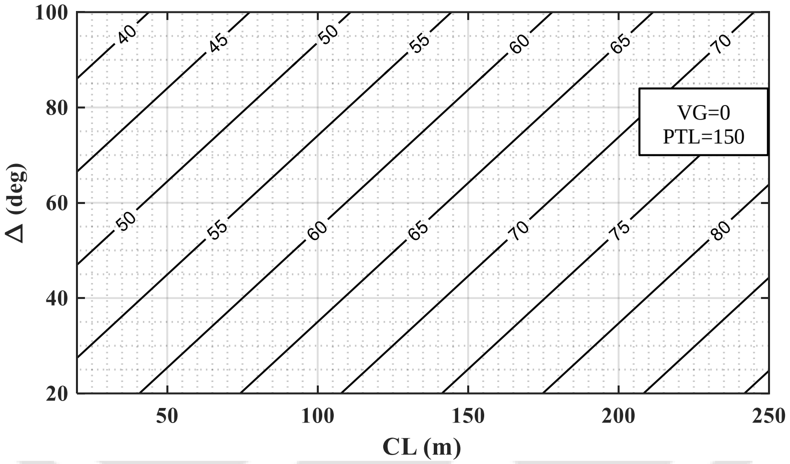


Figure 5.2 Predicted operating speeds (V_{85}) at CC

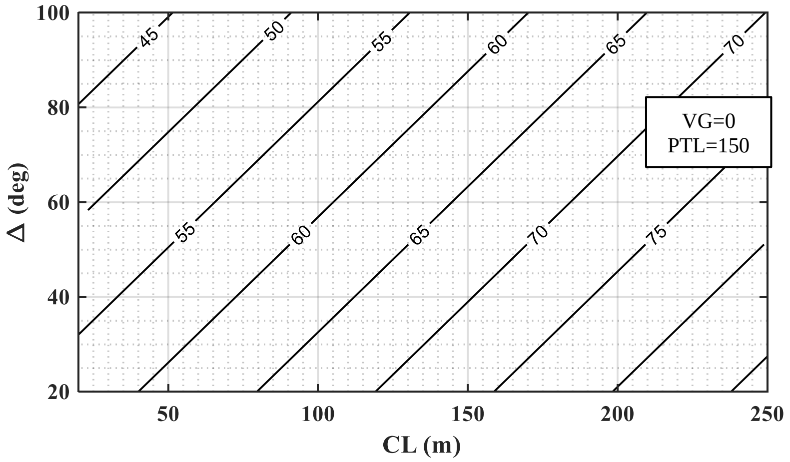


Figure 5.3 Predicted operating speeds (V_{85}) at PT

5.1.3 Model validation

The validation index (I) method is used to validate the developed operating speed models. This method evaluates the relationship between the deviation and the expected speed values using Equation 5.4. If the evaluated results are between 0 and 0.2, then the model is acceptable statistically (Esposito, 2011; Dell'Acqua and Russo, 2010).

$$I = \frac{\left(\sqrt{\frac{\sum_{i}^{n}(Observed\, V_{85} - Predicted\, V_{85})_{i}^{2}}{n}}\right)}{\left(\sum_{i}^{n} Predicted\, V_{85i}\right)/n} \tag{5.4}$$

Where: *i* refers to the site number, *n* refers to the total number of sites considered.

The validation analysis on V_{85PC}, V_{85CC}, and V_{85PT} models (Equations 5.1 to 5.3) using the validation data obtained from 35 curves yielded that for all the selected speed models, the I value is less than 0.2. Hence it concludes that the operating speed models presented in Equations 5.1 to 5.3 can predict the operating speed with high accuracy.

5.1.4 Sensitivity analysis

The parameter sensitivity analysis is conducted over the operating speed models presented in Equations 5.1, 5.2, and 5.3. To measure the sensitivity of a selected parameter, the operating speed is measured by varying the selected parameter, keeping the rest of the parameters fixed to their mean values. The total variation and percentage change in V_{85} due to the variation on the selected parameter are presented in Table 5.3. The same is also presented in Figures 5.4, 5.5, and 5.6, with the X-axis representing the percentage change in selected individual parameters from its mean value. The X-axis percentage values -50, 0, and 50 represent the minimum, mean, and maximum values, respectively.

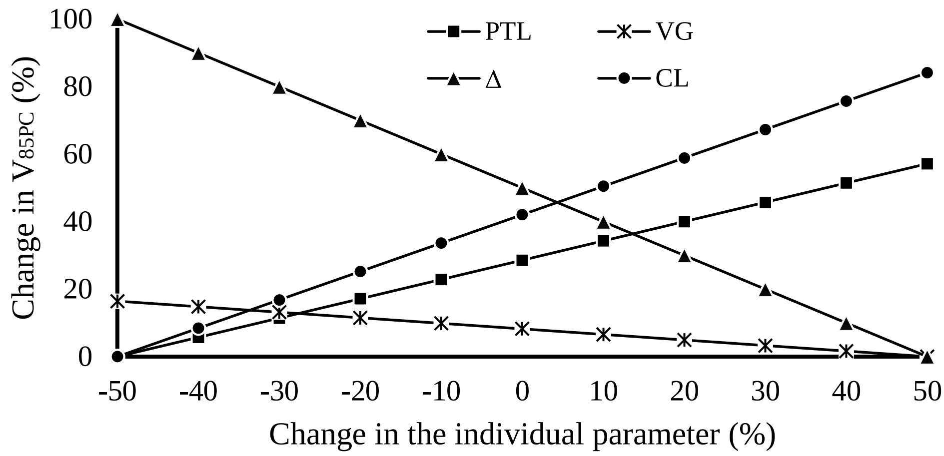


Figure 5.4 Parameter sensitivity on operating speeds at PC

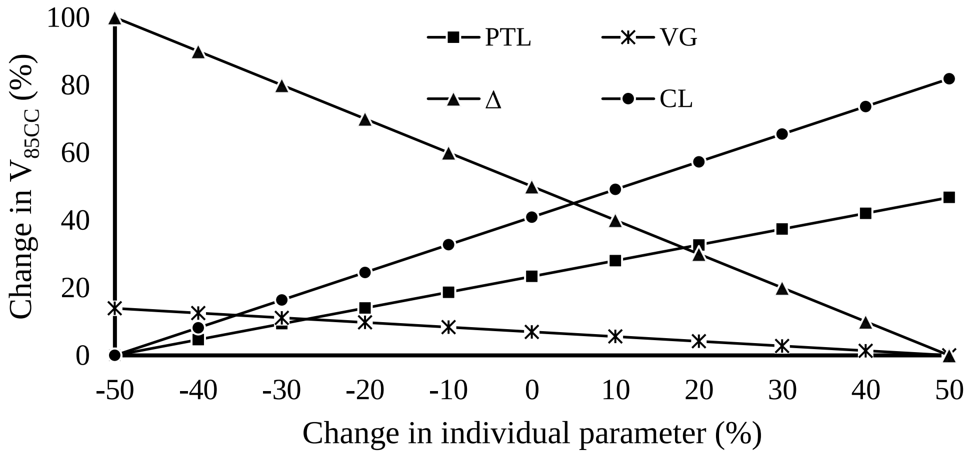


Figure 5.5 Parameter sensitivity on operating speeds at CC

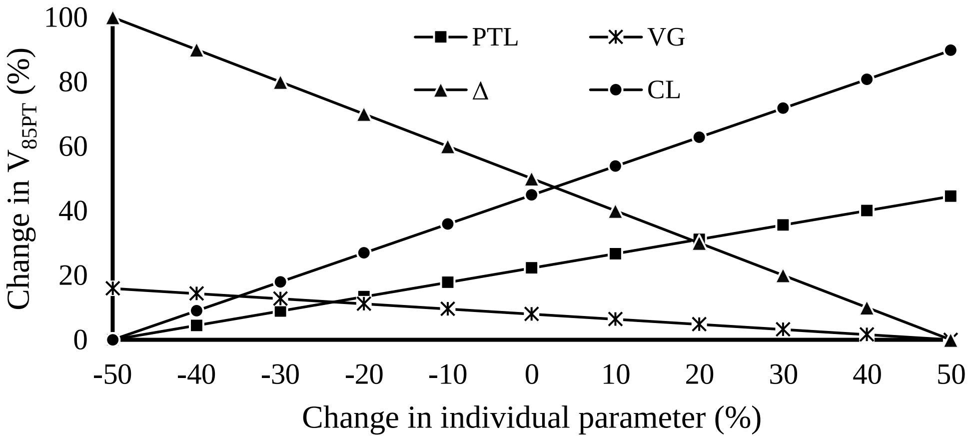


Figure 5.6 Parameter sensitivity on operating speeds at PT

Table 5.3 Parameter sensitivity analysis in the developed speed models

Location	Total change in V_{85} due to change in the parameter (in kmph)				Percentage change in V_{85} due to change in the parameter (in %)			
	CL	PTL	VG	Δ	CL	PTL	VG	Δ
PC	+6.32	+4.29	-1.23	-7.51	+84.11	+57.15	-16.44	-100.00
CC	+7.46	+4.26	-1.27	-9.11	+81.85	+46.73	-13.92	-100.00
PT	+8.13	+4.03	-1.44	-9.06	+89.73	+44.49	-15.90	-100.00

Table 5.3 and Figures 5.4, 5.5, and 5.6, revealed that V_{85} is highly sensitive to Δ compared to the rest of the parameters at all three locations of the curve. The sensitivity analysis revealed that CL has the highest positive effect on V_{85}, whereas Δ has the highest negative effect on V_{85}. Further, the following order of sensitivity is observed Δ > CL > PTL >VG at all three curve locations, namely PC, CC, and PT.

These developed operating speed models and geometric parameters are helpful in highway geometric design. The safety of a highway can be evaluated using the developed operating speed models in consistency and modifying the road geometry to improve safety if needed. The sensitivity analysis also provides deep insight into the interaction of geometric parameters with operating speed (V_{85}). This helps select the specific geometric parameter to adjust the road geometry per drivers' safety requirements.

5.2 Development of Speed Harmony and Speed Synchronization Criteria

The performance-based geometric design explained in Chapter 2 extensively depends on geometric design consistency criteria. In geometry design consistency criteria, the variation in vehicle operating speed (V_{85}) to the curve's design speed (V_d) is used to measure the level of safety. In the prevailing literature, this concept of geometric design consistency is only measured concerning the operating speed (V_{85}) at the center of the curve, assuming that the speed remains constant throughout the curve. However, on four-lane highways in mountainous terrains, it is observed (refer Section 4.2.1) that the speed does not remain constant throughout the curve. It is also observed (Section 4.2.4) that the existing consistency criteria show ambiguous results when applied to the curve's PC, CC, and PT locations. Therefore, in this section, a couple of new consistency criteria are proposed and evaluated for four-lane highways in mountainous terrains.

The two consistency criteria proposed in this study are Speed Harmony (SH) and Speed Synchronization (SS).

- *Speed Harmony (SH): The variation in V_{85} from V_d should be minimum*
- *Speed Synchronization (SS): The variations in V_{85} across various locations on the curve should be minimum.*

The speed variation limits to define SH and SS criteria are based on the methodologies followed by Lamm et al. (1999), Jacob et al. (2013), and Cafiso & Cava (2009), the same has been described in the following subsections.

5.2.1 Speed harmony criteria (SH)

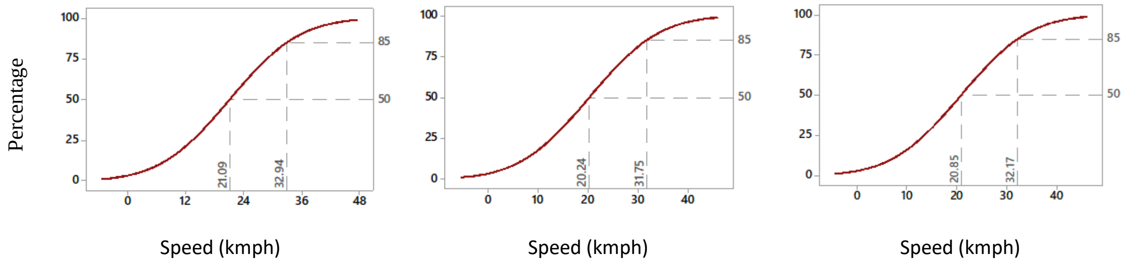
The speed harmonic (SH) criteria is an extension of geometric design consistency criteria (GDCC) proposed by Lamm et al. (1999). In the GDCC, the speed variation is measured only at the center of the curve. In contrast, in the present SH criteria, the variation in V_{85} from V_d is measured at various critical locations on the curves, namely PC, CC, and PT, considering the operating speed profile variation.

5.2.1.1 Cafiso & Cava Method (Method-1)

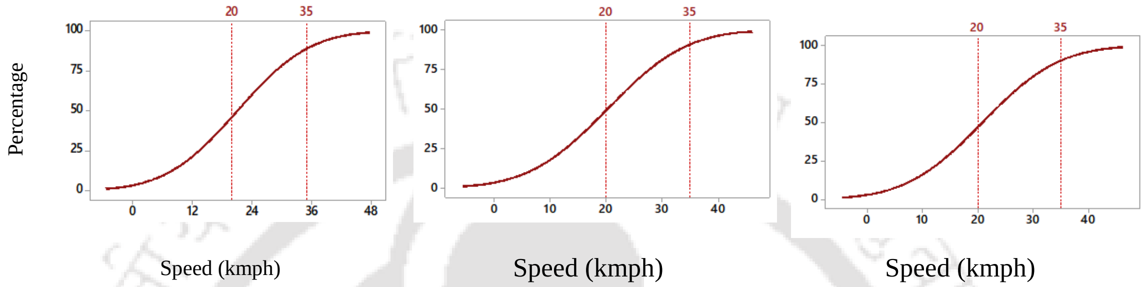
Cafiso & Cava (2009) developed this method to find consistent criteria safety limits at the center of the curve. In this method, using the curves V_{85CC} and V_d data, the cumulative distribution function (CDF) of $|V_{85CC}-V_d|$ is drawn. The 50th and 85th percentile values obtained from CDF of $|V_{85CC}-V_d|$ define the safety limits at the center of the curve. This method measures the variance in V_{85CC} and V_d of the horizontal curve to determine safety on the curve. If the speed variation value falls less than the 50th percentile of the CDF, then the curve is said to be *Good*. Else, check the value with the 85th percentile of the CDF. If the difference in V_{85CC} and V_d of the horizontal curve is less than the 85th percentile, then the curve comes under *Fair*. Else, it will have *Poor* design consistency leading to fatal accidents. The current study on four-lane highways has extended the same approach to the other critical locations on the curve (namely PC and PT) with the help of V_{85PC} and V_{85PT}, respectively.

Speed harmony safety limits using Cafiso & Cava Method.

In this, the cumulative distribution frequency (CDF) plots are drawn using the $|V_{85PC}-V_d|$, $|V_{85CC}-V_d|$, and $|V_{85PT}-V_d|$ as shown in Figures 5.7 (a-c). The 50th percentile and 85th percentile values of the CDF plots are drawn for PC, CC, and PT locations from Figure 5.7 (a), (b), and (c), respectively. In all these three locations, the 50th percentile values are almost 20 kmph, and the 85th percentile value is 35 kmph. Therefore, through the Cafiso & Cava method, the obtained three levels of SH are presented in Figure 5.7 (d-f), Good when speed variation is less than 20kmph, Fair when speed variation is between 20 kmph & 35 kmph, and Poor when speed variations are above 35 kmph.



$(a) CDF for |V_{85PC} - V_d|$ $(b)\ CDF for\ |V_{85CC} - V_d|$ $(c) CDF for\ |V_{85PT} - V_d|$



$(d)\ CDF for\ |V_{85PC} - V_d|$ $(e)\ CDF for\ |V_{85CC} - V_d|$ $(f)\ CDF for\ |V_{85PT} - V_d|$

Figure 5.7 Cumulative distribution frequency plots for V_{85}-V_d across PC, CC, and PT

5.2.1.2 Jacob's Method (Method-2)

This approach was developed by Jacob et al. (2013) based on Lamm et al. (1999) using three parameters, namely V_{85}, V_d, and Equivalent property damage (EPD). This approach defines the safety levels at the curve's center (CC) based on the empirical relations obtained between the $|V_{85CC}$-$V_d|$ and EPD.

Jacobs's method consists of two parts to obtain the consistency criteria safety limits. In part one, the CDF is plotted for the EPD. Then tangent lines were drawn on the straight sections of the CDF plot. The EPD value corresponding to the point of intersection of these tangent lines represents the change in the frequency of the accidents. The scattered plot is drawn in part two between the EPD and $|V_{85CC}$-$V_d|$. Through this scattered plot, safety limits were obtained by segregating the scattered plot values based on the EPD values obtained in step one.

The current study on four-lane highways has extended the same approach to the other critical locations on the curve (namely PC and PT) with the help of V_{85PC} and $V_{85PT,}$ respectively.

Speed harmony safety limits using Jacobs Method

To find the safety limits for speed harmony criteria, $V_{85PC,}$ V_{85CC}, $V_{85PT,}$ and EPD data were used. EPD was calculated from the accident data obtained at each curve during 2017-19. The number of speed-based accidents that took place at each curve was identified. The accident data included curve location, vehicle type, and crash severity. Accidents of different severity were then normalized using the severity indexing method. An Equivalent Property Damage (EPD) is calculated for each curve after giving severity indexing weights of 1, 4, and 12 for property damage only crashes, injury crashes, and fatal crashes, respectively. These weights were determined based on a study conducted on insurance claims given to various types of crashes by insurance companies in India.

A cumulative distribution frequency (CDF) plot using these EPD values is shown in Figure 5.8. A critical EPD value of 3.5, where the accident rate changes from the intersection point of the straight section slopes in Figure 5.8. Figure 5.9 consists of the scattered plots between the speed variations ($|V_{85PC}-V_d|$, $|V_{85CC}-V_d|$ and $|V_{85PT}-V_d|$) and EPD. The SH safety limits were then obtained from Figure 5.9 using the critical EPD value obtained in Figure 5.8, as shown in Figure 5.9.

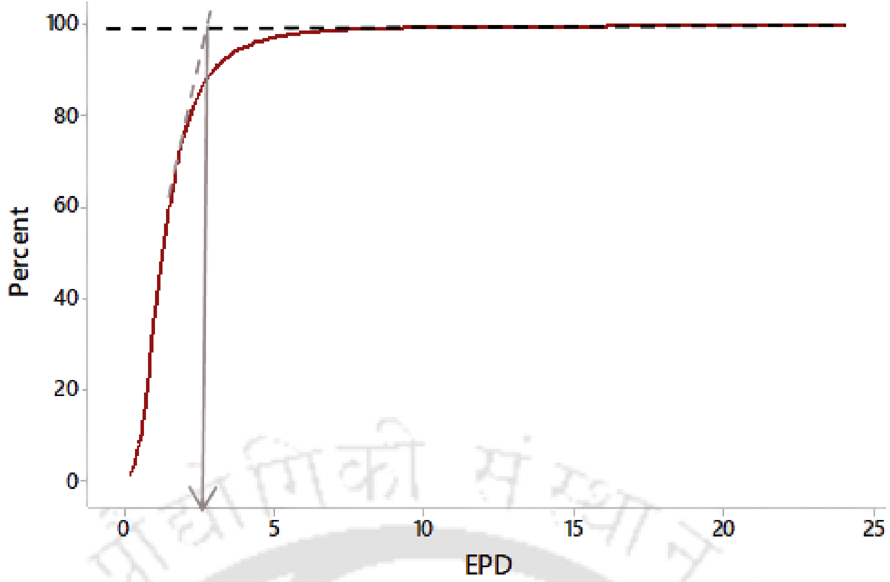
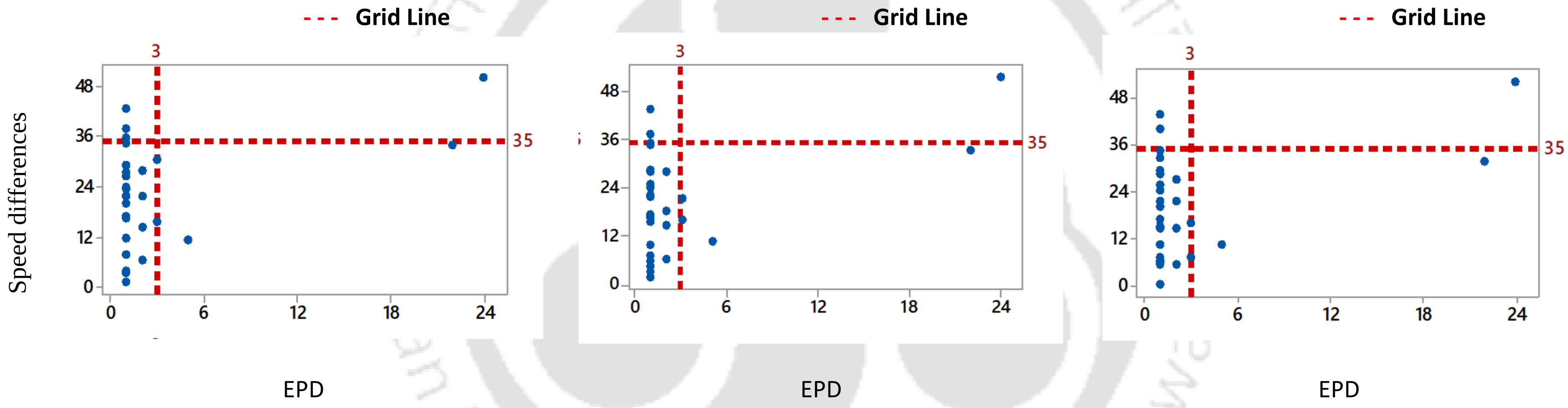


Figure 5.8 CDF of EPD on four-lane highways

Through Jacobs's Method, two levels of safety are obtained for SH criteria. If the variation in speed is less than 35 kmph, it comes under a good level of safety, and if it is greater than 35 kmph, it has a poor level of safety.

In this section, SH safety criteria limits were developed by Cafiso & Cava's and Jacob's methods. It is found from both methods that if speed variation between the operating and design speeds at any location in the curve is above 35 kmph, then the curve comes under poor safety leading to fatal accidents. However, compared to Jacobs's method, the Cafiso & Cava method provided better separation between the Good and Poor safety levels by creating a buffer zone where the speed variation is between 25 kmph and 35 kmph. Therefore, the results obtained from Cafiso & Cava method is chosen for finding the SH criteria safety limits as it provides better segregation between the Good and Poor safety limits compared to the Jacobs method for four-lane highways in mountainous terrains.



(a) $|V_{85PC}-V_d|$ Vs. EPD (b) $|V_{85CC}-V_d|$ Vs. EPD (c) $|V_{85PT}-V_d|$ Vs. EPD

Figure 5.9 Development of SH criteria evaluation

5.2.2 Speed synchronization criteria (SS)

The speed synchronization (SS) criteria is an extension of the speed consistency criteria proposed by Lamm et al. (1999). In the speed consistency criteria, the speed variation ($V_{85atCurve1}$ - $V_{85atCurve2}$) is measured between successive curves assuming the speed remains constant throughout the curve. In contrast, in the present SS criteria, the variation in V_{85} is measured between the successive critical locations on the curves, namely PC, CC, and PT.

As observed in SH criteria, the Cafiso & Cava method provides feasible results with smooth transitions between various safety levels. Therefore, the Cafiso & Cava method is used for SS criteria development, and the following results were obtained, as shown in Figure 5.10.

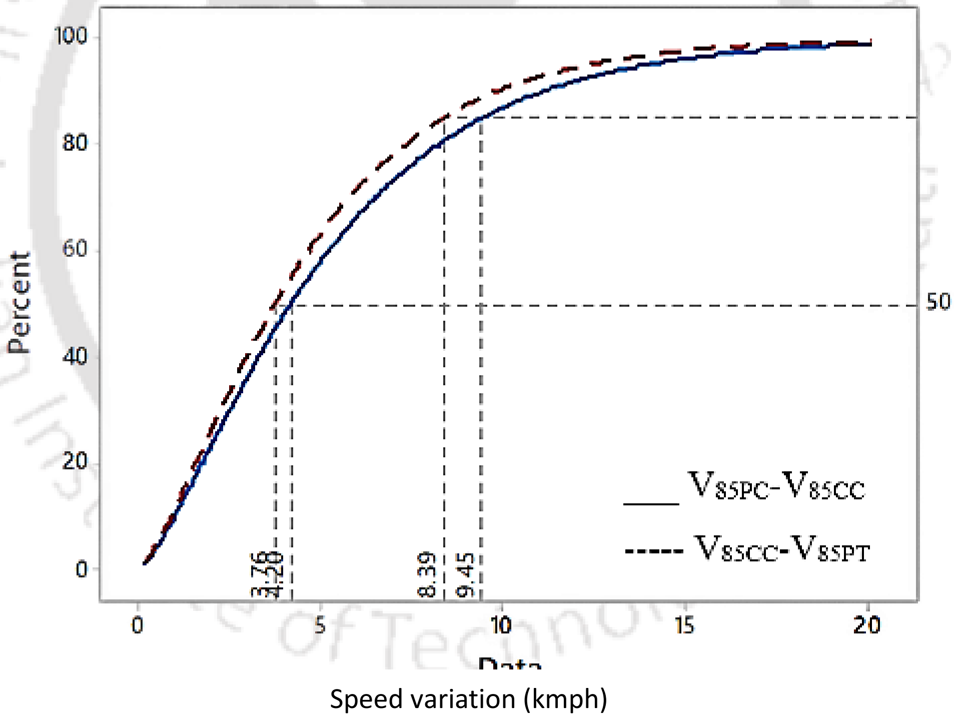


Figure 5.10 Cumulative distribution frequency plots for variations in V_{85} between PC & CC, CC & PT

From the Figure 5.10 we rounded up the values to ensure that the SS criteria would err on the side of caution and provide a conservative estimate of speed consistency. This is because a conservative estimate of speed consistency may help to prevent overconfidence in the safety of the roadway and promote greater caution in driving. Therefore for SS The speed variation within 5 kmph is considered *good*, 5 to 10 kmph as *fair*, and above 10 kmph as *poor*.

Thus final safety limits obtained for SH and SS criteria on four-lane highways are as follows

Table 5.4 SH and SS based safety evaluation criteria

Safety Level	SH Criteria *(kmph)*	SS Criteria *(kmph)*
Good	$\lvert V_{85}-V_d \rvert \leq 20$	$\lvert \Delta V_{85} \rvert \leq 5$
Fair	$20 < \lvert V_{85}-V_d \rvert \leq 35$	$5 < \lvert \Delta V_{85} \rvert \leq 10$
Poor	$\lvert V_{85}-V_d \rvert > 35$	$\lvert \Delta V_{85} \rvert > 10$

5.3 Geometric Design Using the Developed Operating Speed Models

A good geometric design ensures a safe and comfortable driving experience. To make this reality over time, several researchers worked to improve the concept of highway geometric design. So far, several countries have adopted highway design guidelines such as AASHTO (2011), IRC: 73-1980 (1990), to minimize accidents as much as possible. As explained below, these adopted guidelines fall under either comfort-based or consistency-based geometric design.

5.3.1 Comfort-based geometric design:

To achieve driver comfort over the curve against the centrifugal force, the curve geometric parameters are designed based on the design speed as per AASHTO (2011) green book or IRC:73-1980 (1990) (in India) design guidelines. In these, the design speeds are obtained based on the terrain and functional classification of the highways (Fambro et al. 1997). One of the significant limitations of this design speed concept is that the assumed design speed of a highway should be the maximum reasonable speed adopted by the fastest driving group (Barnett et al., 1937). This design approach method is reasonable in theory; however, in reality, the vehicle's operating speed is not the same as the design speed (McLean., 1981; Garber & Gadiraju., 1988). If the variation between design speed and operating speed increases, the safety of the curve decreases (Lamm et al. 1999). McLean et al. (1974, 1979) observed that for low-speed curves less than 100 kmph, the operating speed was higher than the design speed and vice versa. McLean's findings have revised the Australian design code for low-design speed roads (Fambro et al., 1997). Later in 2011, AASHTO revised the design speed definition by considering operating speed as a factor influencing the geometric parameters. In the Indian geometric design guidelines IRC:73-1980 (1990) & IRC-SP-73 (2018), the operating speeds are not yet incorporated in the design speed definition.

5.3.2 Consistency-based geometric design.

In a comfort-based design approach, the physical characteristics of the geometry are derived from the selected design speed. In contrast, the driver's operating speed depends on the driver's subjective judgment of the curve characteristics (Shinar et al., 1980). The safety of curves reduces because of this variation in design speed and the drive's demanding speed. So to overcome this limitation, a consistency-based design method is adopted.

The Consistency based geometric design aims to improve safety by allowing smooth vehicle passage across various geometries. This design methodology considers the operating and design speeds so that the geometry matches the drivers' expectancy. This consistency-based geometric design approach brings the operating speed nearer to the design speed and increases safety on a curve.

In the consistency-based geometric design method, the geometric parameters are derived from the developed operating speed model, considering the operating speed varies within certain limits over the chosen design speeds. Donnel et al. (2009) said that safety and consistency in speed could be achieved when the variation between design and operating speed is maintained at a range of ± 5 mph (≅ 10 kmph). In consistency-based geometric design, Lamm et al. (1999) defined three levels of safety (good, fair, and poor) based on the magnitude of speed variation (10 kmph, 20kmph, and 30 kmph, respectively). Many researchers (Dell'Acqua and Russo, 2010; Fitzpatrick et al., 2000; Krammes et al., 1995; Misaghi and Hassan, 2005) proposed road design based on the operating speed and consistency-based concept. In these, curve geometry is obtained considering both the design and predicted operating speeds, concealing the variation between them within reasonable limits to reduce accidents because of curve geometry.

So far, in the consistency-based methods, the operating speeds are developed for the center of the curve only, considering the constant speed over the entire curve. However, studies on driver speed behavior over the four-lane highway curves (Section 4.2) revealed that the operating speed is not statistically the same throughout the curve. The operating speed is higher on either end of the curve (PC and PT), having the lowest at the center (CC). It implies that to increase safety, the curve geometry needs to accommodate the variations in drivers' speed over various locations. To overcome these limitations, a new speed-based design approach is proposed. The proposed design methodology is based on Vehicle Dynamics, Speed Harmony, and Speed Synchronization; a detailed explanation of this is presented in the following section.

5.3.3 Proposed speed-based curve geometric design method (based on vehicle dynamics, speed harmony, and speed synchronization)

The proposed design methodology overcomes the limitations of both the comfort and the consistency-based geometric design methods. The comfort-based method fails to maintain the Speed Harmony (SH) between the operating and the design speed. The existing consistency-based design method fails to maintain the Speed Uniformity over the curve by hypothesizing constant speed. Thus, a new approach using three safety criteria is introduced to overcome this limitation.

Vehicle Dynamics (VD): Maintains the vehicle over the curve against the centrifugal force and provides comfort to the driver.

Speed Harmony (SH): All the speeds over the curve are within the limits of safe design speed

Speed Synchronization (SS): The variations in speed over the curve should be minimum.

Vehicle dynamics (VD)

Over the curve, the vehicle experiences multiple forces, such as gravitational (g), centrifugal (CF), and frictional (f) forces. These forces' magnitude depends on the curve's radius (R), Speed, and Superelevation (e). Therefore, conventional geometric design methods use the following relation (Equation 5.5) to balance the vehicle with all these forces over the curve. Upon rearranging this equation, the vehicle dynamics criteria for maximum speed limits are obtained (Equation 5.6) for the safe travel of the vehicle over the curve for a given radius.

$$R_{min} \geq \frac{V^2}{127(e+f)} \tag{5.5}$$

$$V_{max} \leq \sqrt{R * 127(e+f)} \tag{5.6}$$

The other safety criteria SH and SS, are shown in Table 5.5 below, and a detailed explanation is provided in Sections 5.2.1 and 5.2.2.

Table 5.5 SH and SS criteria for four-lane highways

Safety level	***Speed Harmony (SH)***	***Speed Synchronization (SS)***
	At section X *(X= PC, CC & PT)*	*Between successive sections* *(PC & CC, CC & PT)*
Good	$\lvert V_{85atX} - V_d \rvert \leq 20$	$\lvert \Delta V_{85} \rvert \leq 5$
Fair	$20 < \lvert V_{85atX} - V_d \rvert \leq 35$	$5 < \lvert \Delta V_{85} \rvert \leq 10$
Poor	$\lvert V_{85atX} - V_d \rvert > 35$	$\lvert \Delta V_{85} \rvert > 10$

Note: V_d *= Design Speed of the curve in kmph,* V_{85} *= Operating Speed in kmph.*

5.3.3.1 Geometric design using the developed operating speed models and safety criteria:

In this section, the procedure for speed-based geometric design is presented. Initially in this the selected parameters V_d, e, f and VG should satisfy 1) All the relevant IRC codes matching four-lane highways in hilly terrains such as IRC 52:2019 Guidelines for the Alignment Survey and Geometric Design of Hill Roads (Third Revision) and 2) The values of these input parameters need to be within the feasible range based on the data used for the development of the V85 regression models (Equation 5.1 to 5.3), and the remaining procedure is presented in a flowchart, as shown in Figure 5.11, and a detailed sample exercise is also presented in the subsequent section.

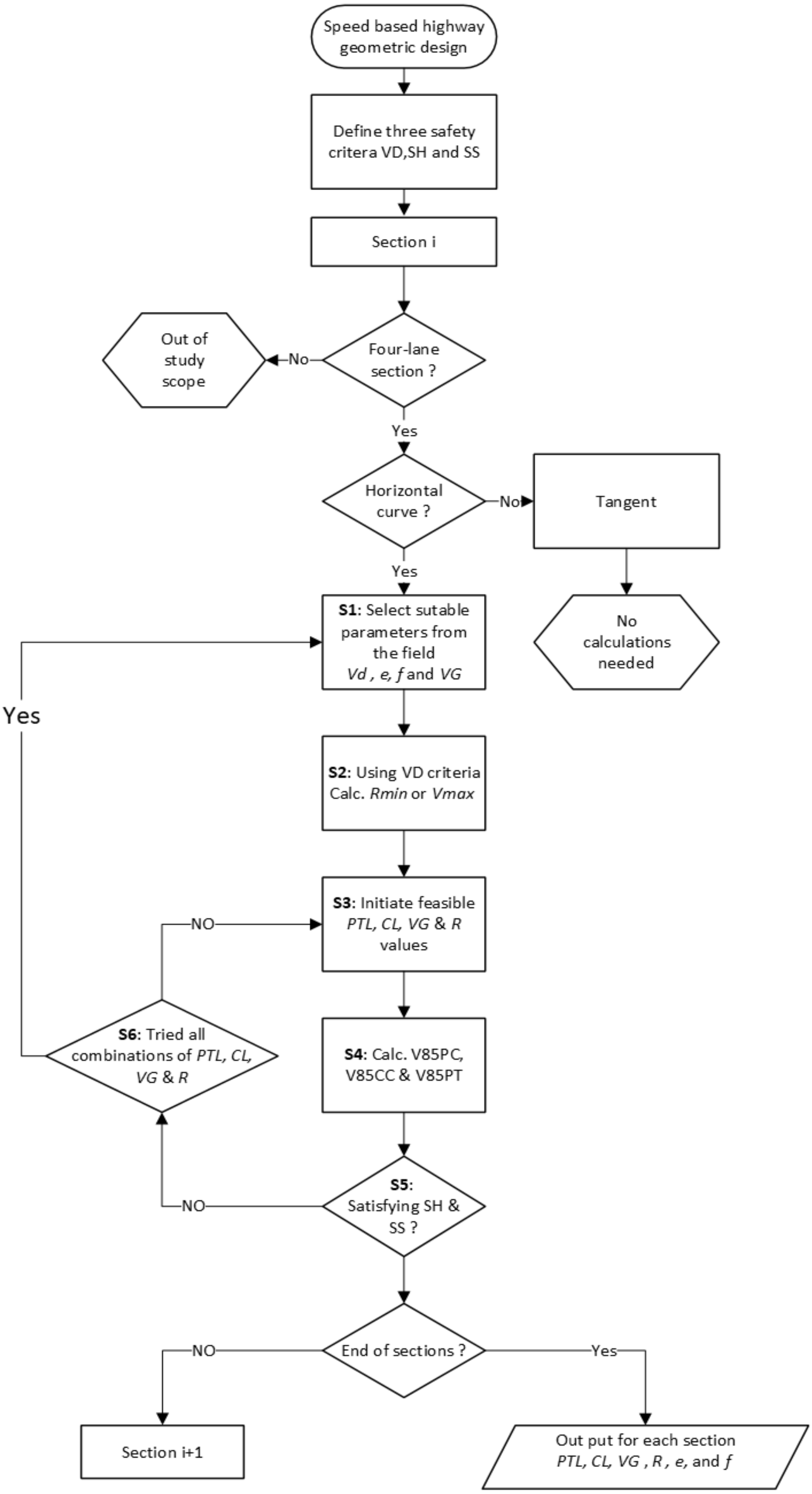


Figure 5.11: Flow chart of proposed new highway geometric design

<u>Application:</u> Geometric design using the developed operating speed models and safety criteria

Step 1: *Take input parameters V_d, e, f, and VG based on field conditions*

Say V_d =55 kmph , *e* = 7%, *f*=0.15 and *VG*= 0%

Step 2: *Measure R_{min}* or V_{max} *based on the VD criterion*

For V_d= 55 kmph, measure R_{min} = 130 m.

Step 3: *Initiate PTL, CL, VG, and R values within the feasible region. (falling with the data used for V_{85} model development and following step 2)*

PTL= 50 m; CL= 100 m; VG= 0% and R= 165 m (> R_{min})

Step 4: *Measure V_{85} at PC, CC, and PT using the parameters considered in step 3*

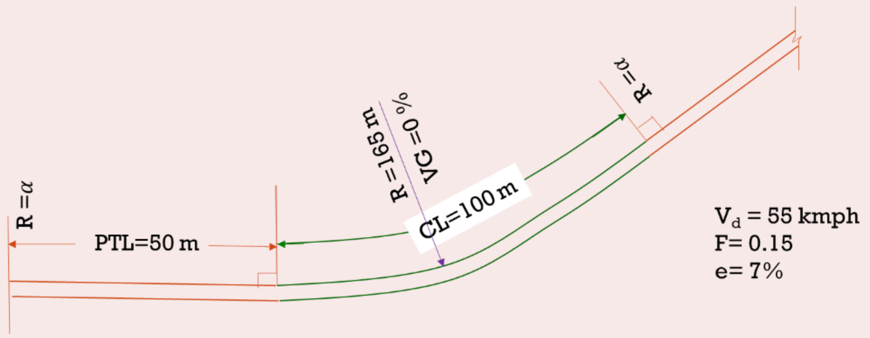
V_{85PC}=66 kmph, V_{85CC}=65 kmph, and V_{85PT}=67 kmph.

Step 5: *Check the values obtained in step 4 satisfying SH and SS; if not, revise values in step 3.* (Giving priority to safety evaluation criteria GOOD or Designer preference*)*

At PC, CC, and PT, it is found that SH< 20 kmph; SS<5 kmph thus comes under the *GOOD* safety level

Step 6: *In step 5, if it fails to achieve preferred safety levels in SS or SH, revise step 1 values until preferred safety is achieved in Step 5. Else if it satisfies, consider those parameters for design.*

Therefore the final parameters are PTL= 50 m; CL= 100 m and R= 165 m for Vd =55 kmph, e = 7%, f=0.15 and VG= 0%.



5.4 Closing Remark

Studies showed that the operating speed models are region-specific, and separate operating speed models need to develop for every region. Furthermore, the speed profile study revealed that the speed varies from PC to CC and CC to PT. Therefore, in this chapter, three operating speed models were developed for the four-lane curves at PC, CC, and PT locations. The operating speed models showed that for a four-lane horizontal curve, the parameters PTL, CL. **Δ** and VG significantly influence the operating speeds. Among these parameters, through sensitivity analysis, it is found that **Δ** has the most significant influence on the operating speeds compared to the rest at all three locations on the curve. Through sensitivity, it is also found that VG has the least significant influence on the operating speeds among the parameters in the final operating speed models.

Chapter 4 concludes that the operating speeds at PC, CC, and PT are statistically different. As a result, the uniform speed assumption used to evaluate consistency criteria is no longer valid. To address these issues, speed harmony and speed synchronization consistency criteria are proposed for four-lane highways. The safety limits for the SH and SS criteria were calculated based on the method proposed by Cafiso and Cava (2009) and Jacob et al. (2013). Cafiso and Cava's method was found to be more appropriate than Jacobs' method for determining SH and SS criteria safety limits because it provided a smooth transition of safety limits from Good to Poor.

Furthermore, based on the operating speeds, vehicle dynamics, speed harmony, and speed synchronization criteria, this chapter proposed a new geometric design approach. The proposed method overcomes the limitations of geometric design based on comfort and consistency. The proposed geometrics design increases safety by bringing operating speeds closer to the design speeds (via the SH criteria) and minimizing operating speed variations within the curve (via the SS criteria). This method employs VD criteria and ensures the driver's comfort. As operating speeds and highway elements are interrelated, this geometric design approach further contributes to the qualitative results for selecting highway elements.

In addition to the observations made above, the developed speed models can be used to assess the geometric consistency of highway geometry using the safety criteria proposed by Lamm and Choueiri (1999). Furthermore, the current study paves the way for future research by incorporating other highway elements such as side friction, curve length, vertical gradient, and curve deflection angle in the first step of geometric design. As a result, future research should look into the effect of various other geometric parameters on operating speed. Future research can also consider different types of terrain, such as plane and rolling. The SH and SS criteria developed here for foul-lane highways in mountainous terrains can be extended to other two-lane and multilane highways in future studies.

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CHAPTER 6

DEVELOPMENT OF FREE-FLOW SPEED DISTRIBUTION MODELS AND PREDICTION OF GEOMETRIC PARAMETER INFLUENCE ON DRIVING SPEED

6.0 Introduction

Prediction of speed distribution on four-lane rural highways is of great significance for both transportation planners & designers. Based on the past literature (Chapter 2), it is established that in horizontal curve design, the selection of different geometric parameters (radius, curve length, superelevation, curbs) relates to various percentile speed values (V_{15}, V_{85}, and V_{95}) observed in the free flow speed distribution at the center of the curve. It is also noticed in consistency, speed harmony, and speed synchronization criteria that percentile speeds help to assess the curve safety level. Therefore, percentile speed distribution models are necessary for geometric design and safety analysis.

Thus, this Chapter aims to develop a free-flow percentile speed distribution model that can predict any percentile speed (Vp) at the center of the curve. Further, this work also aims to identify the influence of various geometric parameters on vehicle speed at the curve's center. The present study focuses on four-lane highways due to the rapid increase in the length of four-lane highways in India and the lack of availability of speed distribution models for Indian four-lane highways in mountainous terrains.

6.1 Field Data

In order to develop a percentile speed model, the present study needs three kinds of data i) Vehicle speed, ii) Vehicle position, and iii) Road geometry. A detailed procedure of data collection techniques, processing, and extraction, is explained in Sections 4.1.1 and 4.1.2 of Chapter 4.

6.1.1 Speed and geometric data used in modeling

As explained in Section 4.1.1, the vehicle speed data over a 65-kilometer stretch is collected by mounting a VBOX device over various passenger cars. The used VBOX device has an accuracy of $\pm$ 0.1 kph in speed and $\pm$ 0.5 m in position. The raw data collected from the VBOX is then filtered using the criteria mentioned in Section 4.1.1 to get the free-flow speed data. Using these free-flow speed data of different drivers at the center of each curve, the percentile speed (Vp) data is extracted (e.g., for V_{85}, percentile=p=85). The speed at every five-percentile interval is extracted to produce 19-speed values (from V_5 to V_{100}) at the curve center. In this way, over 285 curves on the 65 km stretch, a total of 5415 (=285 x 19) percentile speed values are extracted and used in percentile speed modeling.

The geometric data of the curves are collected from the highway maintenance authority, as described in Section 4.1.2. The descriptive statistics of the geometric data collected are presented in Table 6.1.

Table 6.1 Independent variable Descriptive Statistics

	CL	**R**	**V_d**	**SL**	**SE**	**VG_T**	**VG_C**	**PTL**	***p***
Min	30	20	20	0	2.5	-7	-7	0	0
Max	244	800	80	75	7.0	9.0	9.0	642	100

Mean	39	149	44	27	6.2	0.2	0.2	37	50
Std. Dev.	33	139	11	11	1.4	3.0	3.0	63	33

6.2 V_p Prediction Model

Two well-known methods are available for developing speed prediction models, as discussed in Chapter 2. These are the regression-based and artificial neural network (ANN) methods. In this study, both of these methods were used to develop percentile speed (V_p) prediction models, and the details are presented in the following subsections.

6.2.1 Regression-based V_p model

The percentile speed model is developed by considering percentile speed as a dependent variable and geometry as an independent variable. In this section, to develop the percentile speed (V_p) model, about 80% of the collected data (i.e., 228 out of 285 curves) is used in model calibration, and the rest 20% is used in validation. The correlation analysis of the geometric variables in the calibration data is measured and presented in Table 6.2. The Pearson correlation analysis shows that these variables are not highly correlated (i.e., r <0.6), so it is decided to consider all these variables in modeling as independent variables.

The percentile speed regression model is developed at a 95 % confidence level using the backward elimination method in this section. The developed regression model is presented in Equation 6.1. This model has adjusted R^2 of 0.45 and RMSE of 7.95 on calibration data, R^2 of 0.41 (Figure 6.1), adjusted R^2 of 0.33, and RMSE of 7.97 on validation data.

Table 6.2 Pearson correlation (r) among independent variables

	CL	**R**	**V_d**	**SL**	**SE**	**VG_T**	**VG_C**
R	0.25						
V_d	0.24	0.37					
SL	-0.12	0.37	0.27				
SE	-0.20	-0.30	-0.41	0.47			
VG_T	0.08	-0.11	-0.09	-0.01	0.06		
VG_C	0.04	-0.21	-0.20	-0.06	0.14	0.51	
PTL	0.16	0.16	0.25	0.18	-0.04	0.22	-0.07

$$V_p = 34.693 - 0.01\,CL + 0.01\,R + 0.41\,V_d + 1.63\,VG_T - 3.34\,VG_C + 0.02\,PTL + 0.13\,p \tag{6.1}$$

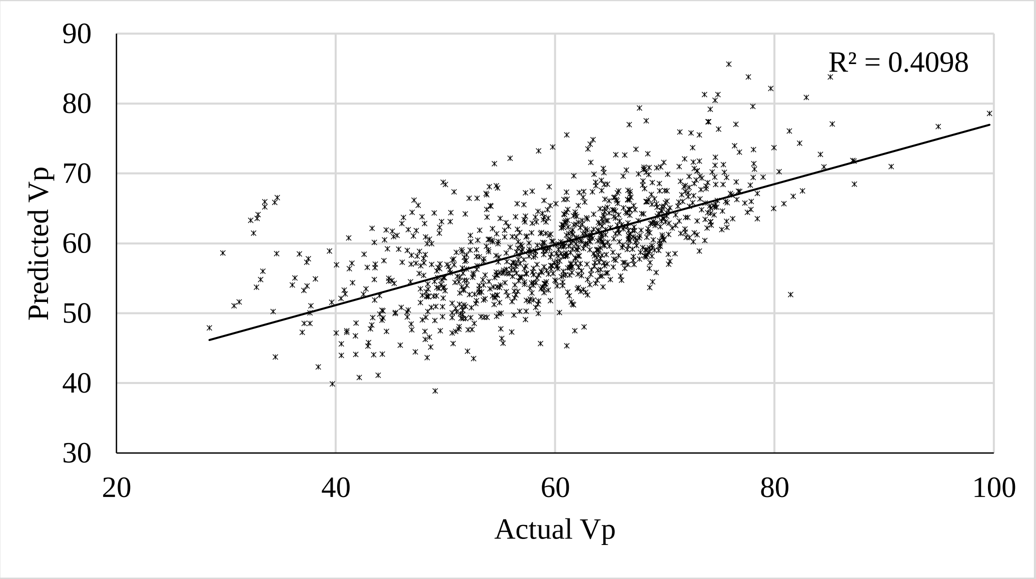

Figure 6.1 Actual Vp vs. Predicted Vp in regression

6.2.2 Artificial neural network (ANN) based V_p prediction model

The ANN has a significant advantage over linear regression, as there are no limitations on using a specific structure with well-defined inputs. The ANN can also solve a wide range of problems with complex relations, where assumptions such as non-linearity and homoscedasticity can complicate regression models. Furthermore, ANN models learn much like humans. The model learns through the dataset, trains itself, and adjusts the weightage assigned to its parameters according to the input and output values. So in this section, the percentile speed prediction model is developed using the ANN techniques.

The ANN model is typically divided into layers containing a unique set of neurons. These ANN structure layers are divided into input, output, and hidden. Each of these layers' neurons is linked to the neurons of the next layer. The neurons in the input layer feed the known information to the ANN model. In this case, the number of neurons usually equals the number of available independent variables. The output layer comprises neurons that are proportional to the number of dependent or output parameters desired to be known. Finally, the third layer is the hidden layer between the input and output layers. Multiple hidden layers may exist with different sets of neurons for a given ANN model.

In the hidden layer to determine the number of neurons, there are many empirical methods:

1. The number of hidden neurons should be between the size of the input layer and the output layer.
2. The number of hidden neurons should be 2/3 the size of the input layer plus the size of the output layer.
3. The number of hidden neurons should be less than twice the size of the input layer.

The above three rules provide a starting point only for the ANN modeling. The optimal number of neurons with minimum error in model predictability is decided based on trial and error.

In ANN modeling, to train the model, several training algorithms are available, as explained in Chapter 2. Among those methods, the widely used BPNN (Back Propagation Neural Network) and the GA-BPNN (Genetic Algorithm with BPNN) are used in this study to develop an ANN-based Vp model.

Development of percentile speed distribution model to predict V_P

A three-layered neural network with nine neurons in the input layer and one in the output layer architecture is used to predict the percentile speeds.

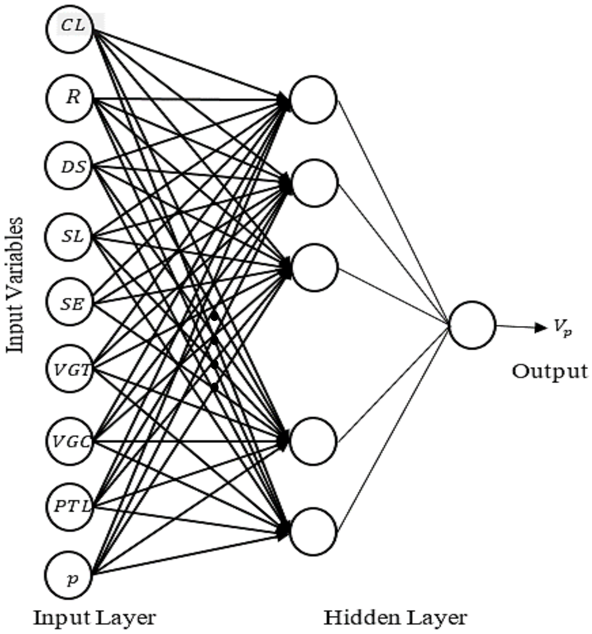

Figure 6.2 Neural Network Architecture for Vp prediction

A total 5415-speed observations obtained from 285 curves (Section 6.1.1) were used in ANN modeling. Out of the total speed observations, 80% (4332) of data points are used to train the ANN model, and the rest, 1083 data points, are used in testing the model. In the architecture defined in Figure 6.2, the input layer takes the independent variables (CL, R, V_d, SL, SE, VG_T, VG_C, PTL, and p) as inputs.

Several ANN model structures were trained using different sets of hidden layers and neurons with these input variables. Among these, the optimal ANN architecture (Input-Hidden-Output Layers (I-H-O)) is chosen based on the minimum error criteria and less computationally intensive. Table 6.3 presents the results of several ANN structures configured for BPNN and GA-BPNN. GA-BPNN with more than one hidden layer are also studied. However, it has been found that the Vp predictability is not improved much from BPNN models with higher hidden layers.

Among the BPNN based operating speed distribution model with a BPNN architecture of 9-30-1 (input-hidden-output parameters with one hidden layer) showed a high performance with an R^2 value of 0.94, which is considered an excellent fit for the given data. Although we also developed a GA-BPNN model with a larger hidden layer of 9-50-1, it showed only a slightly higher R^2 value of 0.95. We ultimately chose to use the BPNN with a smaller hidden layer as our final model selection. The reason for this decision was simplicity and efficiency of the model. A BPNN (9-30-1) model with a smaller hidden neutrons is generally easier to train, quicker to execute, and less computationally intensive. Additionally, the difference in the R^2 values between BPNN (9-30-1) and GA-BPNN (9-50-1) was small enough that the added complexity of the larger hidden neurons did not justify its use in our final model selection. Therefore, the BPNN with 9-30-1 architecture configuration at 82 Epoch (Figure 6.3) for activation function ReLU with RMSE of 0.34 and NSE of 0.12 was selected as our final model to evaluating the operating speed distribution at the center of the curve

Using the remaining 20% of data, Vp predicted vs. Vp actual plot was drawn from the selected BPNN (9-30-1) model, as shown in Figure 6.4. The R^2 value from this is 0.92, which is much higher than 0.41, the one obtained from regression modeling. Therefore, after comparing regression, BPNN, and GA-BPNN models, for further analysis in percentile speed prediction and for developing speed distribution, BPNN with 9-30-1 (I-H-O) architecture is considered.

Table 6.3 Summary of the developed ANN-based Vp models predictability

ANN model	Input	ANN (I-H-O)	MSE	RMSE	NSE	R^2
BPNN	*CL, R, V_d, SL, SE, VG_T, VG_C. PTL and p*	9-5-1	0.23	0.48	0.45	0.74
		9-10-1	0.20	0.45	0.33	0.81
		9-15-1	0.18	0.42	0.26	0.85
		9-20-1	0.17	0.42	0.20	0.86
		9-25-1	0.15	0.39	0.14	0.89
		9-30-1	0.12	0.34	0.11	0.94
		9-35-1	0.11	0.33	0.11	0.94
	CL, R, V_d, SL, SE, VG_T, VG_C. PTL and p	9-5-5-1	0.23	0.48	0.44	0.77
		9-10-5-1	0.19	0.43	0.29	0.84
		9-20-5-1	0.14	0.38	0.17	0.91
GA-BPNN	*CL, R, V_d, SL, SE, VG_T, VG_C. PTL and p*	9-50-1	0.11	0.33	0.09	0.95

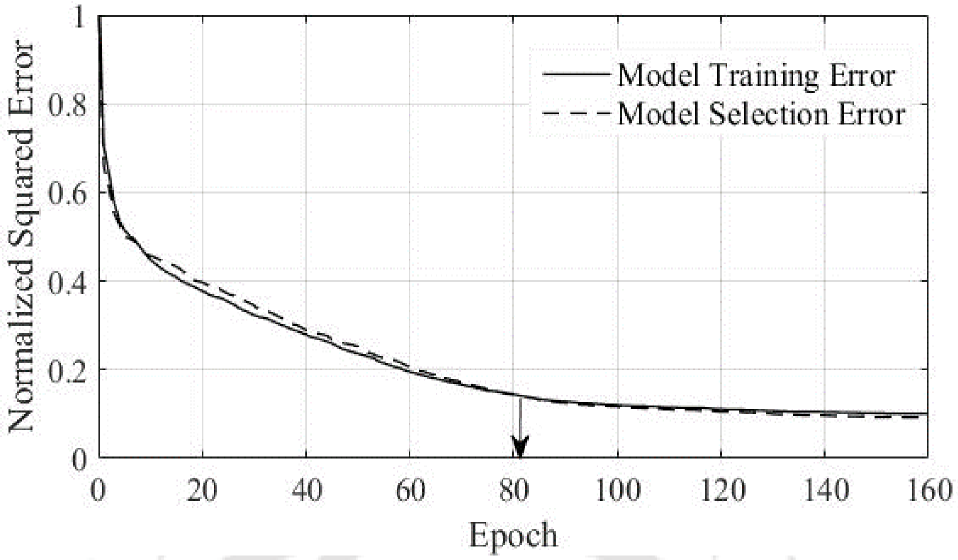

Figure 6.3 ANN (9-30-1) model calibration error data

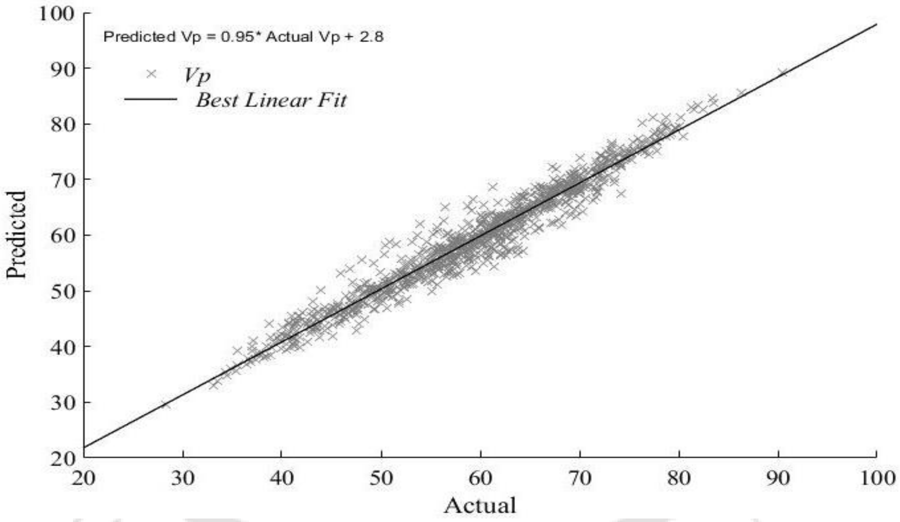

Figure 6.4 ANN (9-30-1) predicted vs. actual percentile speeds

The K-S normality test conducted on the model outputs conformed to the predicted free-flow speed follows a normal distribution having P > 0.05. Hence with all these R, RMSE, and normality tests, one can conclude that the developed model predicts the Vp with much better accuracy compared to the regression model developed. Further, the modeling result efficiency is demonstrated by an example.

For example, the speed distribution and percentile speed values (Vp) are measured using the developed ANN model for a curve with dimensions CL=120m, R=90m, V_d =50kph, SL=25, SE=7%, VG_T=0%, VG_C=0%, PTL=100m, and "*p*" values ranging 5 to 100.

The obtained results are used to plot the cumulative distribution function of speeds at the curve center. Figures 6.5 and 6.6 represent the various percentile speed values and probability distribution of Free-flow speeds, respectively, at the center of the curve. The obtained speed values have a mean and standard deviation of 63.59 kmph and 4.73 kmph, respectively. Further, the predicted free-flow speed values satisfied the K-S normality test having P > 0.05, and the probability plot of the same is presented in Figure 6.7.

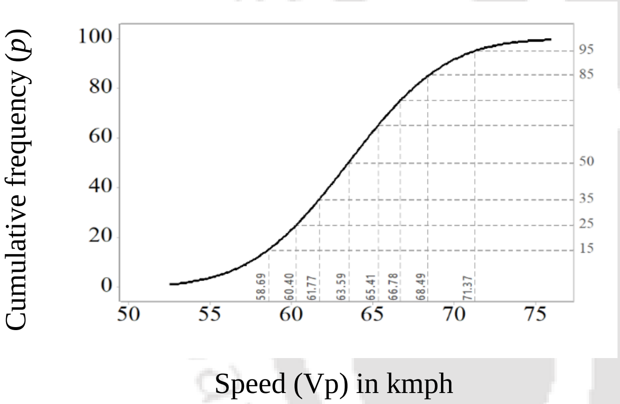

Figure 6.5 CDF of free-flow speeds in kmph

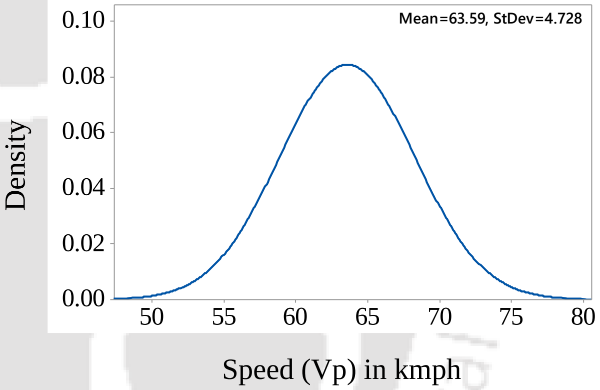

Figure 6.6 Distribution of Free-flow speeds

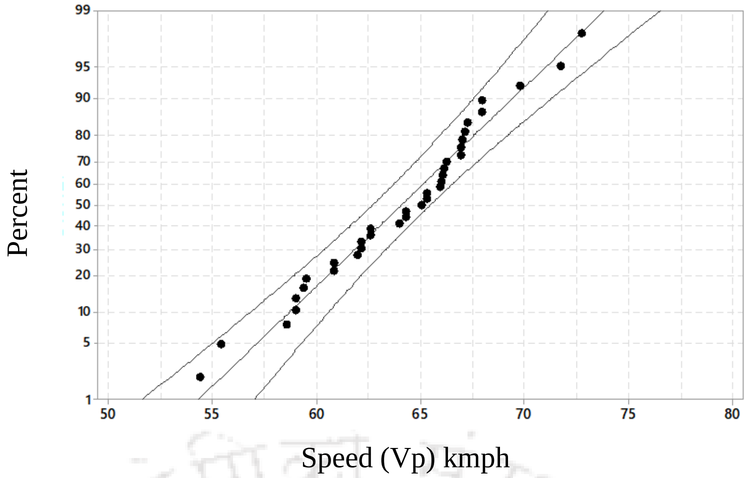

Figure 6.7 Normal distribution probability plot of free-flow speeds at the center of the curve

6.3 Parametric Contribution on V_p

Parameter contribution is an elemental analysis for any model to know how the parameter influences the dependent parameter. The 'profile' method is one of the widely used techniques on ANN models to measure parameter contribution (Grevey *et al.*, 2003). Therefore, the parameter contribution is studied using the 'Profile' method in the present study. The details of the methods are explained in the following paragraphs.

To measure the parameter contribution in the profile method, the model output (V_p) is measured by varying one parameter (say CL) and keeping the remaining input parameters fixed. In this process, each parameter is divided into a certain number of equal intervals between its minimum (say CL_{min}) and maximum (say CL_{max}) values. The chosen number of intervals is called the scale. If the parameter is divided into 12 intervals, then it's called an interval of scale 12. Now measure the model output for all the values of the parameter (from CL_{min} to CL_{max}) for five different sets of the rest of the parameters, namely at their minimum, first quartile (Q_1), median, third quartile (Q_3), and maximum. Details of the same are presented in Table 6.4

Table 6.4 Profile model pattern

INPUT PARAMETER							OUTPUT
CL_{min} CL_2 . . CL_{max}	R_{min}	$V_{d\,min}$	SL_{min}	.	.	PTL_{min}	$V_{min-min}$ V_{min-2} . . $V_{min-max}$
CL_{min} CL_2 . . CL_{max}	R_{Q1}	$V_{d\,Q1}$	SL_{Q1}	.	.	PTL_{Q1}	V_{Q1-min} V_{Q1-2} . . V_{Q1-max}
.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.
CL_{min} CL_2 . . CL_{max}	R_{max}	$V_{d\,max}$	SL_{max}	.	.	PTL_{max}	$V_{max-min}$ V_{max-2} . . $V_{max-max}$

The parameter's contribution at each scale of variation is obtained by taking the average of the outputs (Contribution of $= \frac{V_{min-min}+V_{Q1-min}+\cdots.+V_{max-min}}{5}$). The contribution of all the parameters on a scale of 12 is shown in Figure 6.8. Further, each parameter's relative contribution is measured from the profile plots, the relative contributions of each input variable can be expressed by the range values (maximum–minimum) of their contributions (shown in Figure 6.9).

Table 6.5 Values of independent parameters on a scale of variation 12

SCALE	1	2	3	4	5	6	7	8	9	10	11	12
CL	0	20	41	61	81	102	122	142	163	183	203	244
R	20	85	150	215	280	345	410	475	540	605	670	800
V_d	20	25	30	35	40	45	50	55	60	65	70	80
SL	0	6	13	19	25	31	38	44	50	56	63	75
SE	3	3	3	4	4	4	5	5	6	6	6	7
VG_T	-7	-6	-4	-3	-2	0	1	2	4	5	6	9
VG_C	-7	-6	-4	-3	-2	0	1	2	4	5	6	9
PTL	0	54	107	161	214	268	321	375	428	482	535	642
P	0	8	17	25	33	42	50	58	67	75	83	100

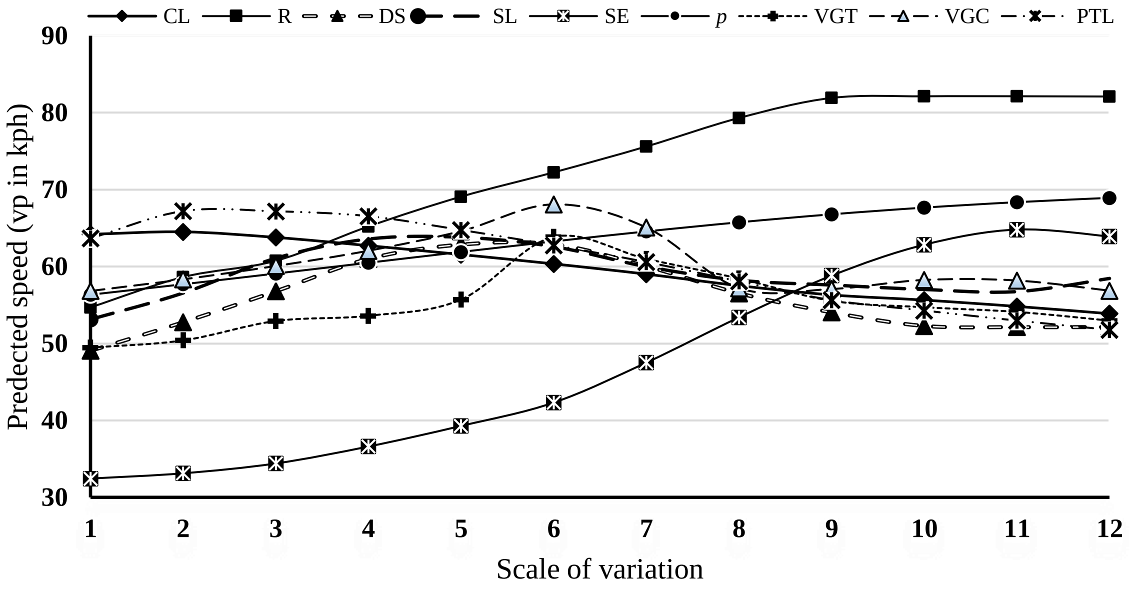

Figure 6.8. Profiles to measure parameter contribution

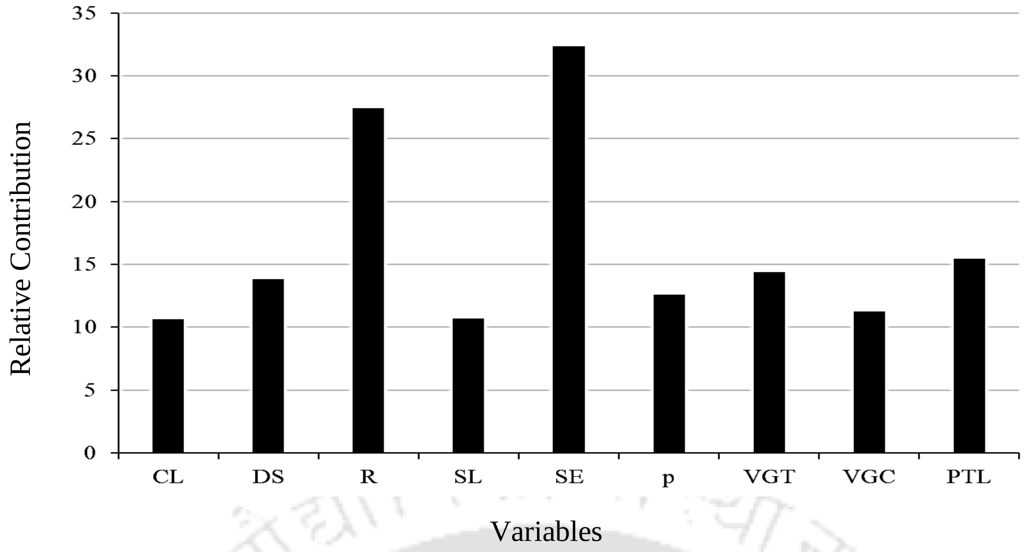

Figure 6.9 Relative parameter contribution through profiles method

6.4 Closing Remark

Information on free-flow speed distribution over the curve is of prime importance both for highway design and safety evaluation. This demands the researchers to develop models to predict the free-flow speed distribution models as a whole (prediction of distribution parameters such as μ and σ) or in parts (such as Vp). In the current study, the Vp (Percentile speed) models are developed using OLSR and ANN methods to provide direct results to design and safety practitioners.

A 65 km four-lane divided highway with 285 horizontal curves covering a wide range of geometry is considered for modeling in this study. A total of 30 drivers were used to collect the naturalistic speed data using a vehicle-mounted GPS device. A total of 5415 percentile speed data points are generated using the data collected from 285 curves. About 80% of the generated data is used for calibration/training, and the rest 20% is used for validation/testing the model.

In the first step, a backward elimination OLSR regression model at a 95% confidence interval is developed to predict the percentile speed model. The Vp model obtained through OLSR had a very low R^2 value of 0.41 on validation. Furthermore, the developed OLSR Vp model has an RMSE of 7.9 kmph, representing low model predictive power.

In addition to OLSR, an ANN model is also developed to select the best model to predict the percentile speed (Vp). ANN has an advantage over the OLSR as it doesn't require any prerequisite relationship (linear, non-linear) between the independent and dependent variables. To develop an ANN-based Vp model, both BPNN and GA-BPNN algorithms were used in this study. Up on comparing the Vp ANN models obtained from BPNN and GA-BPNN algorithms in terms of predictability power (Error values and R_2) and the number of computations required to predict Vp (i.e., the number of connections in the neural network), the final ANN architecture with the best predictability is obtained for BPNN with 9-30-1 (I-H-O) configuration at 82 Epoch (Figure 6.3) for activation function ReLU with RMSE of 0.34 and MSE of 0.12 (Table 6.3). Further on the selected ANN model (BPNN 9-30-1), the profile method is used to find the influence of geometric parameters on the percentile speeds (Vp) at the center of a four-lane horizontal curve. The results show that the parameter *SE* (superelevation) has the highest contribution among all the parameters considered. The parameter *SL* (Spiral length) shows the lowest contribution on percentile speeds.

One of the advantages of the present study is that with one single model, one can predict any percentile speed values and can also say which parameters are influencing much on the percentile speeds. This model can also be used to predict operating speeds (i.e., 85th percentile speeds) without modifying the base model. Therefore, it can be further used to study highway geometry's consistency using the predicted 85th percentile speeds.

Further studies can be conducted on four-lane highways to predict the speeds at other locations, such as tangents start and end of the curve. A similar ANN method can also be used to develop a complete speed profile prediction method rather than a specific position speed prediction model.

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CHAPTER 7

DEVELOPMENT OF CONTINUOUS FREE-FLOW SPEED DISTRIBUTION MODEL AND ITS APPLICATION IN DRIVER WARNING SYSTEM

7.0 Introduction

Speed-based studies focused mainly on evaluating operating speeds at particular locations on the curves, such as CC (Center of the curve). Even the U.S. Interactive Highway Safety Design Model is based on spot-based operating speed models. Studies on continuous free-flow speed distribution models for four-lane Indian mountainous terrains are rare. Therefore, this Chapter presents a continuous free-flow speed distribution model as a more representative alternative for four-lane roads with complex alignments on Indian mountainous terrains. Further developed a methodology for drivers' over-speed warning system (OSWS), using the free-flow speed distribution model.

7.1 Data Collection and Development

The vehicles and highway geometric data needed for this study are collected, as explained in Section 4.1. Using multiple drivers over a stretch of 65 km (285 curves) on NH-6, high precession naturalistic driving speed data was collected using VBOX. Figure 7.1 shows the naturalistic speed profile of over a 65 km stretch of one of the drivers.

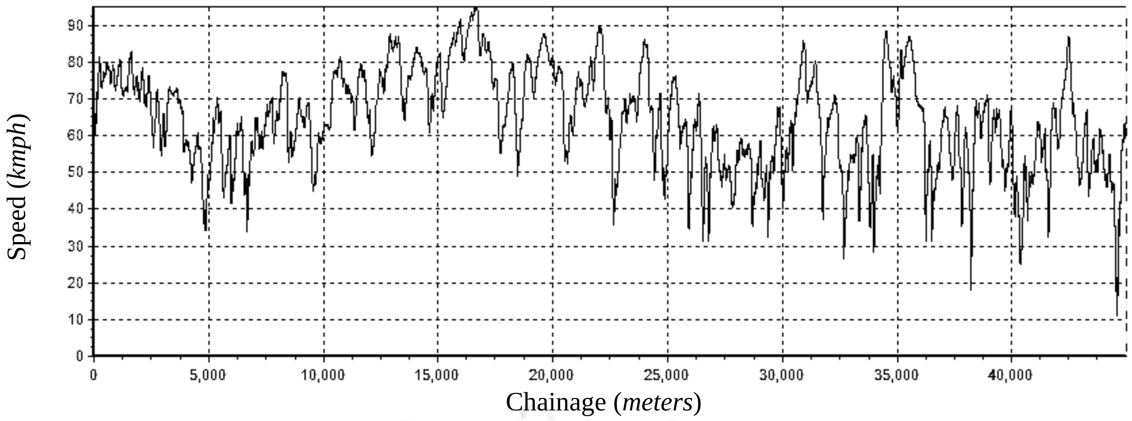

Figure 7.1 Driver Speed profile data over a 65 km stretch

Among the collected speed profile data from different drivers, the vehicles' free-flow speed data is segregated using free-flow speed criteria mentioned in Section 4.1.1, along with the available vehicle video and VBOX GPS data. Figure 7.2 shows the extracted free-flow speed data at a 4m interval of all the drivers between 10,400 km and 10,900 km chainage.

This free-flow speed data is used to get the various percentile speeds, as shown in Figure 7.3, in multiple uniform intervals where the bottom dotted line represents the 5th percentile speed values, and the top one represents the 95th percentile speed values. Further, for all analytical purposes in this Chapter, the percentile speed values were extracted from the free-flow speed data at five percentile intervals ranging from 5th to 100th percentiles. Extracted percentile speed data is smoothened using the moving average smoothing function, and the obtained data is shown in Figure 7.4. The bottom-most dotted line in Figure 7.4 represents the 5th percentile speed values, and every line above is incremented by a ten-percentile interval reaching the top-most dotted line with 95th percentile speed values. To verify that the obtained moving average smoothened data represents the actual collected data, the t-test, and Gauss-distribution test were conducted at various chainages and found that for a window size of 5 in the moving average, the smoothened data represents the actual data at 95% confidence interval.

Using the above procedure, generating (5^{th} to 95^{th}) percentile speed values (with the increase of 5 percentile) at every 4 m interval on the study stretch, a total of 2,13,750 speed data points were obtained. Among this, about 80% of the collected data (i.e.,171,000) is used to train the model (training and validation), and the rest 20% (i.e., 42,750) is used in model testing. In the next Section, the continuous free-flow speed distribution model is developed using the obtained percentile speed data points.

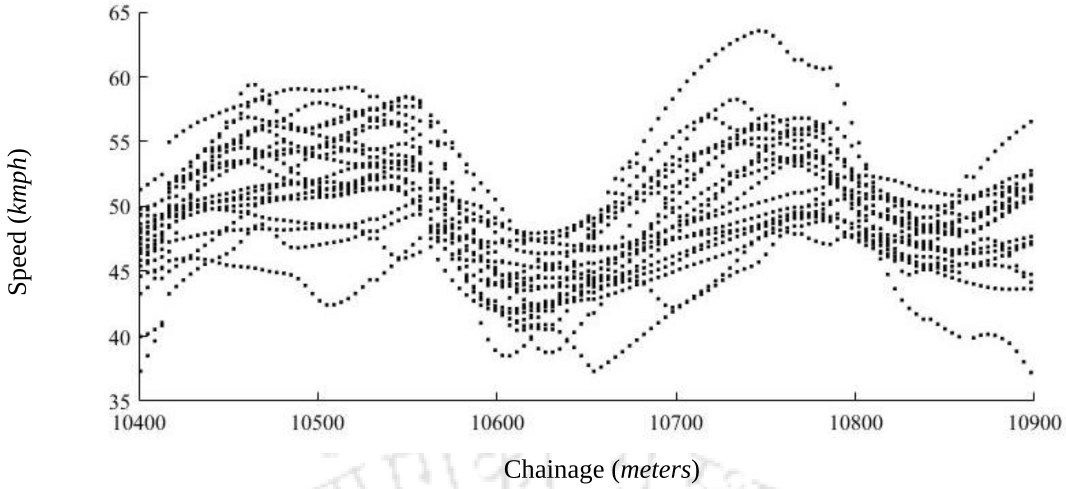

Figure 7.2 Drivers' free-flow speed

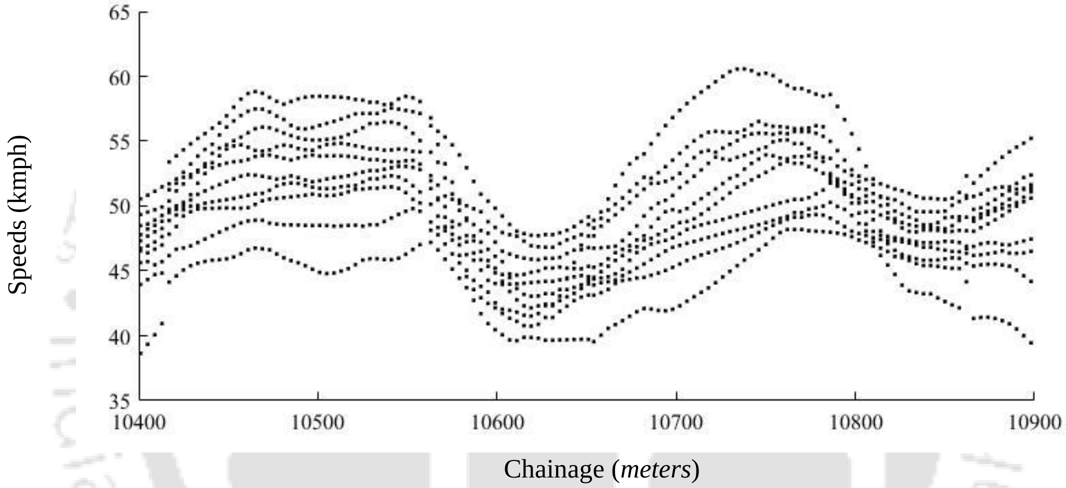

Figure 7.3 Percentile free-flow speed

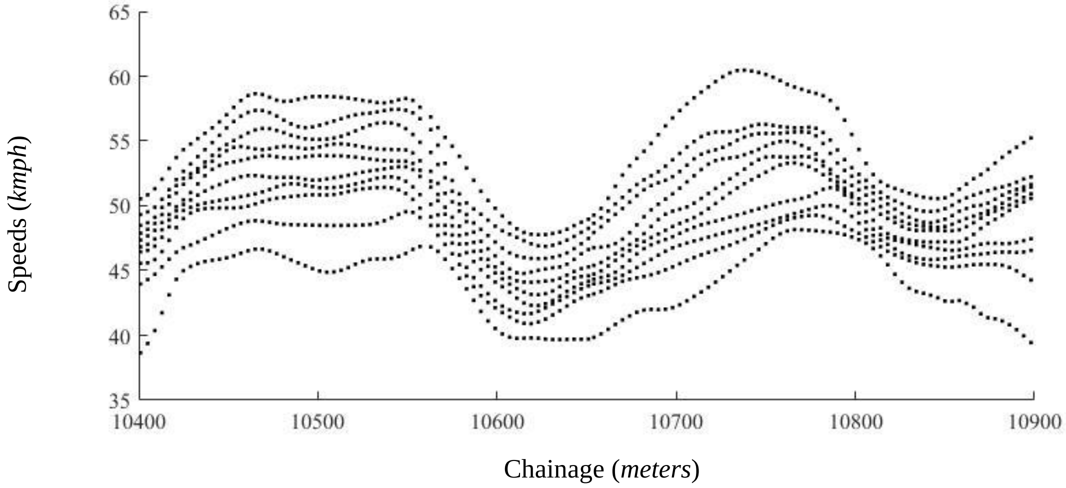

Figure 7.4 Smoothened percentile free-flow speed

7.2 Continuous Free-Flow Speed Distribution Model

7.2.1 Development of continuous free-flow speed distribution model

The selection of a driver's speed on a highway is based on his/her gained experience from geometry before reaching that point on the highway, plus his/her perception of the upcoming highway geometry. Therefore, considering these driving characteristics, the geometric details of the preceding and succeeding sections are incorporated as input parameters in developing a continuous free-flow speed distribution model.

Ordinary least square regression is not used in developing the continuous percentile speed model here as they failed to produce accurate percentile speed values at the center of the curve, as shown in Chapter 6. Therefore, the continuous speed profile model is developed with ANN using the BPNN and GA-BPNN algorithms, as explained in Chapter 6. However, to predict the continuous percentile speed over the highway alignment (curve section, tangent section), various highway geometric parameters surrounding the driver that influence the driver's speed are considered, as shown in Table 7.1 and Figure 7.5. The input parameters are preceding section length (l_p), current section length (l_c), succeeding section length (l_s), preceding section curvature (c_p), current section curvature (c_c), succeeding section curvature (c_s), preceding section gradient (g_p), current section gradient (g_c), succeeding section gradient (g_s), preceding section spiral (s_p), succeeding section spiral (s_s), the position of the vehicle on current Section (pv_c) and percentile (p) corresponds to the percentile in the speed distribution at a given pv_c were used. In this model, if the vehicle is on the curve/tangent, the current section becomes the curve/tangent section. It will have different preceding & succeeding sections (tangents or curves). The parameter pv_c

corresponds to the vehicle position on the current section, and it ranges from zero (start of the current section) to hundred (end of the current section) for any given section.

Table 7.1 Geometric parameters used in modelling

Parameter	Preceding Section	Current Section	Succeeding section
length	l_p	l_c	l_s
curvature	c_p	c_c	c_s
gradient	g_p	g_c	g_s
Spiral length	s_p	-	s_s

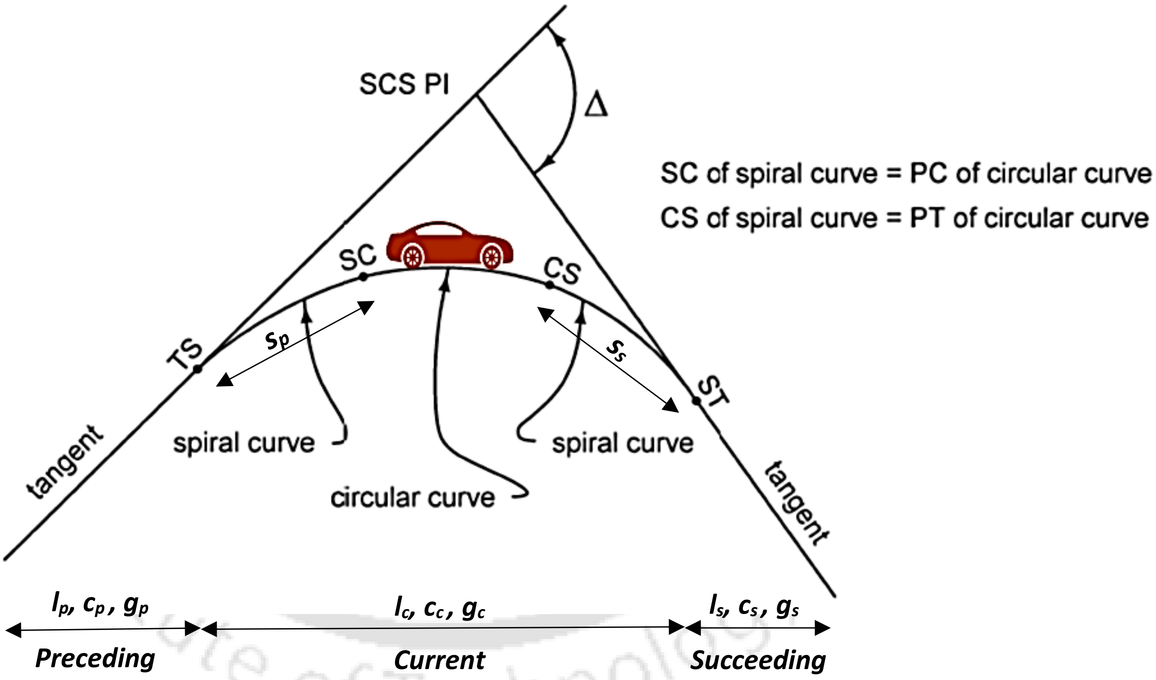

Figure 7.5 Parameters considered in model development

Using the 171,000 training data points, the ANN model was trained under both BPNN and GA-BPNN algorithms with various combinations of I-H-O layer neurons. Upon conducting several trials, as shown in Table 7.2, a 3-layered BPNN 13-20-1 architecture with a single hidden layer is found to have better predictability with the least error, MSE of 0.041, and R of 0.991. Using the model testing data, the relation between the model predicted speeds corresponding to the actual speed is presented in Figure 7.6 and found that it had an R^2 of 0.97, representing the excellent ability of the developed model to predict the percentile speeds at various locations on the highway.

Table 7.2 ANN architecture results for the continuous speed prediction model

ANN model	Input	ANN (I-H-O)	MSE	RMSE	NSE	R
BPNN	l_p , l_c , l_s , c_p , c_c , c_s , g_p , g_c , g_s , s_p , s_s , pv_c and p	13-5-1	0.065	0.253	0.058	0.972
		13-10-1	0.048	0.218	0.032	0.986
		13-15-1	0.043	0.207	0.026	0.990
		13-20-1	0.041	0.203	0.024	0.991
		13-25-1	0.052	0.229	0.038	0.987
		13-30-1	0.051	0.226	0.037	0.987
	l_p , l_c , l_s , c_p , c_c , c_s , g_p , g_c , g_s , s_p , s_s , pv_c and p	13-10-5-1	0.046	0.215	0.030	0.980
		13-20-5-1	0.039	0.197	0.025	0.989
		13-20-10-1	0.038	0.194	0.020	0.990
GA-BPNN	l_p , l_c , l_s , c_p , c_c , c_s , g_p , g_c , g_s , s_p , s_s , pv_c and p	13-50-1	0.043	0.207	0.026	0.987

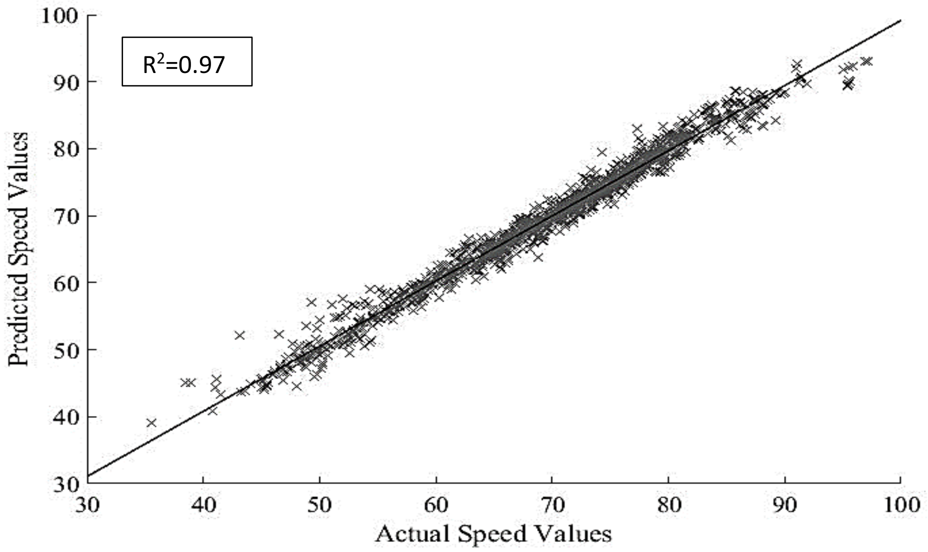

Figure 7.6 Real Vs. Predicted continuous speed (kmph) values using an ANN-based speed model

7.2.2 Deviation in parameter selection in continuous free-flow speed distribution model from V_{85} and Vp models.

The deviation in continuous speed modeling from the rest of the V_{85} or Vp in Chapter 5 and Chapter 6 respectively is due to the following reasons, which were incorporated in the thesis now.

Curvature:

In developing the continuous speed model, the values of the geometric parameters of the curves and tangents were used. The value of the geometric parameter radius is finite on curves, whereas the tangents will have an infinite (∞) radius. Taking such values as an input parameter in modeling is not feasible; hence, we replace radius with curvature. Further, such an issue with the radius is not there on curves when we considered developing V_{85PC}, V_{85CC}, V_{85PT}, and Vp at CC.

Design speed:

One of the main reasons for developing the continuous speed distribution model in this chapter 7 is to use it in GPS-based OSWS. In the GPS-based method, the geometry of the section can be easily obtained from the GPS data where as for the design speed, field data collection is needed again. Considering that as one of the criteria, the design speed of the vehicle is not involved in the contiguous speed distribution model.

Superelevation:

Similar to the design speed for the collection of superelevation field survey is needed; hence superelevation was not considered in the model.

Furthermore, the design speed and superelevation are local parameters pertaining only to the curve in this study. Where curvature, length, and gradient are universal parameters of a highway section. Finally, the R^2 (0.99) of the obtained ANN (13-20-1) model also justifies our approach for the model development.

7.3 Application of Continuous Speed Model on Over-Speed Warning System (OSWS)

The safety of vehicles can be improved by providing real-time warnings using innovative technology to drivers when they are over speeding. Earlier, drivers were warned through posted speed limits. Later on, OBD-II-based devices like "Carsense" provided a real-time warning from the GPS data generated in the vehicle. These devices are set to a predefined fixed threshold speed (such as 80 Kmph) as dangerous and warn the driver if the vehicle goes beyond that fixed threshold. However, in today's life, one encounters road where speeds as low as 40 kmph are dangerous because of their geometric constraints, especially on highways in mountainous terrains. Therefore, an over-speed warning system (OSWS) is developed using a dynamic speed limits approach.

7.3.1 Dynamic speed limits for OSWS warning levels

In the proposed OSWS, the warning levels are decided based on the speeds considered in highway design and safety. The 85th percentile speed (V_{85}) of vehicles in the free-flow condition is considered the operating speed. This V_{85} speed is the most prominent speed used in performance-based consistency designing. Further, V_{85} is also used to select posted speeds for highways to improve safety. However, the geometric features of highways in the conventional method are designed based on design speeds. Several studies (Layton and Dixon 2012; Fitzpatrick et al. 2003; Loutzenheiser and Greenshields 1941) pointed out that vehicles' 95th (V_{95}) to 98th (V_{98}) percentile speed might represent the design speed in free-flow conditions. Since the difference between V_{95} and V_{98} is very small, the V_{85} and V_{95} percentile speeds are considered to define the speed limits for over-speed warning systems on four-lane highways.

The relationship between 85th percentile speed and design speed is not well understood. However, the approximate relationship can be defined as follows, based on the standard Normal Distribution. The design speed has been defined as about the 95th percentile speed; therefore:

The normal distribution representing the distribution of speeds is symmetrical; therefore, 50% of the area under the curve is on either the mean or median (Mean = Median = Average).

The 85th percentile speed	=	mean speed	+	1 std. deviation
(Or minimum design speed)		(50% area)		(33.7% area)
Design speed (98% speed)	=	mean speed	+	2 std. deviations
		(50% area)		(47.8% area)

Typically, the standard deviation for speeds is about 10 kmph. Thus, if the standard deviation is not known, a rule of thumb is:

> The 85th percentile speed, or minimum design speed, is the mean operating speed+10 kmph. Design speed is 85th percentile speed + 10 km/h

Therefore, the following two speeds, V_{85} and V_{95}, are considered to derive criteria for over-speed warning levels as described below. Further, the warning is provided by voice assistance or warning beep sounds as per convenience.

> *No warning:*
>
> *No warning will be issued if the driver's speed is less than the V85.*
>
> *Primary Warning:*
>
> *When drivers travel at speeds greater than V85 but less than V95 primary warning is provided. This acts as a buffer zone between safe and unsafe speeds, where the driver is traveling safely yet very close to reaching an unsafe speed*
>
> *Advanced warning:*
>
> *If the driver exceeds the* V_{95} *speed limit (i.e., design speed of that section), an advanced warning is provided. In this, the highway geometry safety systems become ineffective as the driver has already reached unsafe speeds* ($> V_{95}$)*,*

Algorithm for over-speed warning

This method is developed to warn drivers when they exceed the dynamic speed limits prescribed earlier. To warn the drivers, the parameters such as initial speed V, acceleration a, and position p of the vehicle on the highway are needed, which can be gathered remotely by attaching any OBD-II devices to the vehicle. To provide a proper warning to the driver, forecast the driver's speed for "t = 2.5" sec (which is the perception and reaction time of drivers as per AASHTO) and also measure the distance (s) traveled by the vehicle during this "t" time interval. As per the vehicle kinematics, the forecasted speed will be v(t)= v+a*t and distance traveled s =v*t+0.5*a*t^2. Along with this, also measure the 85th and the 95th percentile speeds at the "p+s" position V_{85}(s) and V_{95} (s), respectively, using the ANN model developed in Section 7.2. Now provide the OSW to the driver as per the relation in Table 7.3 and Figure 7.7.

Table 7.3 Various levels of OSW

S.No	*Warning Levels*	*Condition*
1	No warning	$\frac{V(t)}{V_{85}\,(s)} \leq 1$
2	Primary Warning	$\frac{V(t)}{V_{85}(s)} > 1 \leq \frac{V(t)}{V_{95}(s)}$
3	Advanced warning	$\frac{V(t)}{V_{95}(s)} > 1$

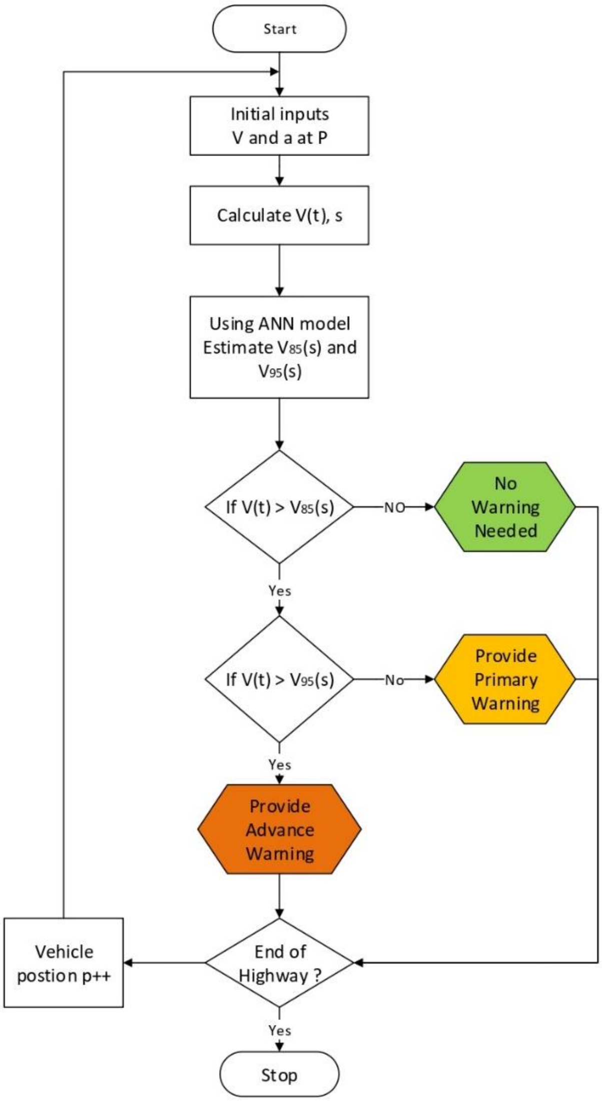

Figure 7.7 Algorithm for over-speed warning

Experimental results

In this, a group of four drivers were randomly selected and asked to travel over a set of four curves on a four-lane highway in mountainous terrain. These drivers traveled four times on these selected curves generating 16 different cases. Through this, drivers' speed over these curves was collected and observed the obtained speeds from the proposed OSWS criteria for safety. The observations provided that out of sixteen cases, in 13 cases, the vehicles traveled at speed $V(t) \leq V_{85}(s)$ where no warning is needed. In the other two cases, $V(t) >$

$V_{85}(s)$ but $V(t) \leq V_{95}(s)$ and in one case $V(t) > V_{95}(s)$ is observed, which falls in primary and advance warning levels, respectively. These three cases fall under risky behavior, where a warning is needed for overspeeding.

Table 7.4 OSW count on experimental data

	No Warning	**Primary Warning**	**Advanced Warning**
Condition	$\frac{V(t)}{V_{85}(s)} \leq 1$	$\frac{V(t)}{V_{85}(s)} > 1 \leq \frac{V(t)}{V_{95}(s)}$	$\frac{V(t)}{V_{95}(s)} > 1$
No. Cases	13	2	1

To determine how the driver avoided the accident in the scenario where the vehicle was travelling above V_{95}, additional data was examined. Figure 7.8 depicts the driver's speed trajectory for this specific journey. The driver at curves C1 and C2 (circled in yellow in the figure) travelling at speed greater than V_{85} but less than V_{95} falls in the primary warning zone. As per the proposed warning system, if the driver had been warned before the first curve, the driver would not have passed the V85, at least for the second curve, further bringing him to the safety speed. Since it is an experimental study, the driver was not warned during this driving period.

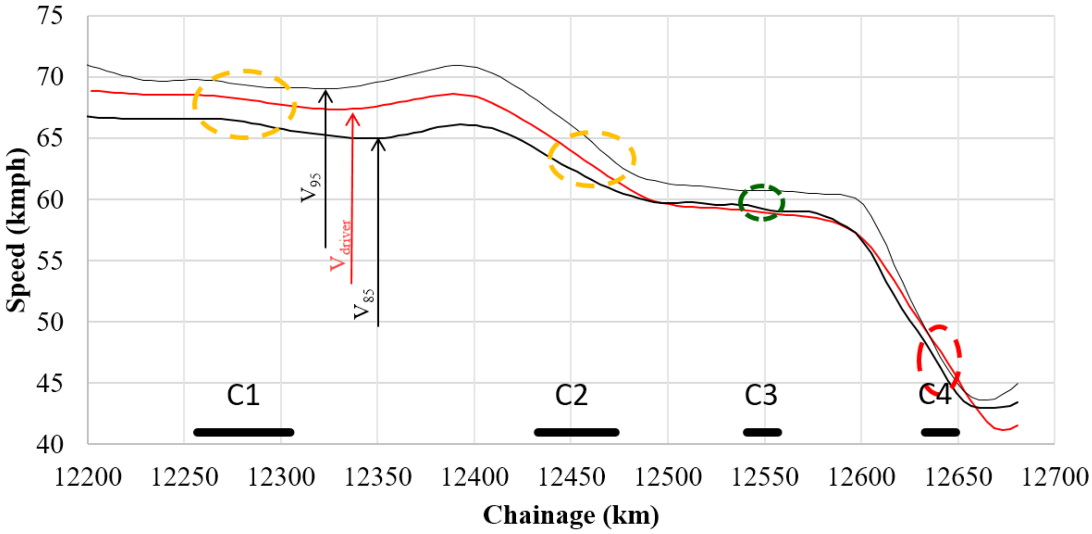

Figure 7.8 Various Speed profiles across the experimental study stretch

Moving on to curves C3 and C4, the driver speed profile showed that the driver maintained a uniform speed throughout Section C3. However, a sudden drop in speed (nearly 15 km) is observed between C3 and C4 within a span of 50 meters (12600 to 12650). Field data indicated that the curve C4 is not in the field of vision of the driver from C2, and it appears that they can only see C4 once after reaching C3, leaving no room for a gradual speed reduction. Even after falling the curve C4 in the driver's field of vision from C3, the driver took some time to assess the situation. That is why the speed profile is uniform near C3 (between 12550 to 12600). Over C4, the driver was seen traveling above V95 and avoided the accident, which contradicts the proposed OSWS. Therefore, on the available video recordings of this particular trip, it was found that the driver was on the shoulder and not on the carriageway to avoid an accident while traversing the C4 curve. The same can be seen in Figure 7.9 vehicle before entering curve C4 and Figure 7.10 while traversing curve C4. Figures 7.9 and 7.10 shows that the driver took less than 2 seconds to swift from the median lane to the shoulder to avoid the accident. However, this situation could have been completely avoided if the driver had received the appropriate warning in advance, as proposed by the OSWS.

Figure 7.9 Vehicle before reaching C4

Figure 7.10 Vehicle while on C4

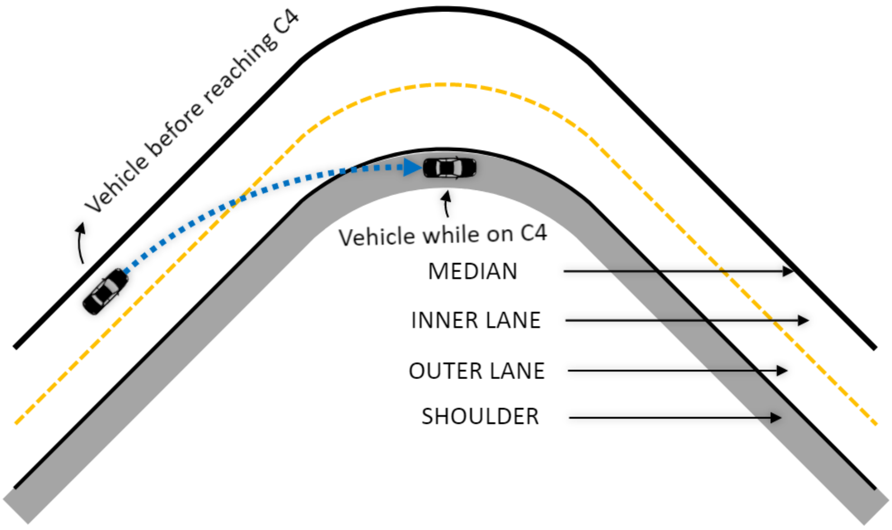

Figure 7.11 Vehicle trajectory at C4

7.4 Closing Remarks

Information on various percentile speeds such as V_{15}, V_{50}, V_{85}, and V_{95} across the highway is needed to construct safer highway geometry. Therefore, in this chapter, a continuous percentile speed distribution model is developed using the ANN technique. In this model, in addition to the current section geometry, both the preceding and succeeding geometric sections (l_p, l_c, l_s, c_p, c_c, c_s, g_p, g_c, g_s, s_p, s_s, and p) relative to the driver positions (pv_c) are also considered. The preceding (l_p, c_p, gp & s_p) and the succeeding (l_s, c_s, g_s & s_s) sections incorporate the drivers' gained knowledge about the geometry up to that position (pv_c) and the driver's perception of the upcoming geometry respectively. Through the ANN analysis for the continuous percentile speed distribution model with 171,000 speed data points, it is found that for a four-lane highway in mountainous terrain in the North-Eastern region of India, a three-layered ANN 13-20-1 (I-H-O) architecture with a single hidden layer has better predictability with MSE of 0.041 and R^2 value of 0.99. Using the model testing data of 42,750 speed data points, it is found that the relation between the model predicted speeds corresponding to the actual speed is of 0.97 R^2, representing the ability of the developed model to predict the percentile speeds at various locations on the highway.

In addition to developing a continuous percentile speed model for geometric purposes in this Chapter, an advanced over-speed warning system (OSWS) is also developed. Unlike the fixed speed limits in the existing warning systems, such as posted speed or OBD-II devices, the current OSWS dynamic speed limits were proposed to alert the driver to prevent accidents. The V_{85} and V_{95} speeds were considered for dynamic speed limits as V_{85} is the driver's free-flow operating speed used in developing posted speed limits, and V_{95} represents the geometric design speed. In the current OSWS, three warning levels are proposed based on the vehicle speed relative to the V_{85} and V_{95} geometric speeds.

Later a case study was conducted with four drivers over a study area with four curves, it was found that out of total of 16 cases, 13 cases the drives were traveling safely below V_{85}. In two cases, drivers were travelled above V_{85} and below V_{95} where the primary warning is needed. In one case, the vehicle speed was above V_{95}, which required an advanced speed warning as per the proposed OSWS method. Further, when checked on how the driver travelled above V_{95} speed limits to avoid the accident, it was found that the driver went out of the existing carriageway, but the presence of a wide shoulder prevented the driver from causing the accident. This case study suggested that this risk would have been easily avoided if the driver had used the proposed OSWS on this trip.

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CHAPTER 8

CONCLUSIONS AND FURTHER RESEARCH

8.0 Summary

This research investigates highway geometric parameters' influence on free-flow speed over four-lane highways in mountainous terrain. To better understand the driver's free flow behaviour on a four-lane highway, we identified a 65-kilometer segment with 285 curves that encompass a wide range of design speeds and geometry. Over this, passenger cars' naturalistic driving data (in free flow conditions) were collected using different drivers with the attached VBOX device.

In this research, operating speed models were initially developed for the curves' center. Later a performance-based highway geometric design (using speed harmony, SH, and speed synchronization, SS) was developed. Further, the percentile speed model at the center of the curve and the continuous percentile speed distribution models were developed, which were used to propose an over-speed warning system (OSWS).

8.1 Study Findings

This study analyses the influence of highway geometric parameters on free-flow speed behavior over four-lane highways in mountainous terrain in India. The major conclusions drawn from this study are presented below.

8.1.1 Free flow speed on curves

Speed profile

The individual vehicle speed data profile revealed that the speed variation falls in three zones (deceleration/stable/acceleration) over four-lane horizontal curves from PC to PT, with the lowest vehicle speeds falling in the middle 20 % of the curve length (i.e., the stable zone).

Average speed versus design speed

Speed data shows that the average speed of the vehicles on four-lane mountainous horizontal curves is higher than the design speed for curves (with <80 kmph design speeds). Therefore, special care is needed while designing these curves.

V_{85} speed across the curve

The V_{85} speed is found to be statistically different from PC to CC and CC to PT for most of the curves, indicating that the assumption of constant speed across the curve used in the geometric design is not valid on four-lane curves with design speeds less than 80 kmph.

Safety evaluation based on design consistency

Extending the Lamms' consistency criteria to PC, CC, and PT of the four-lane horizontal curve provided ambiguous results about the curve safety level, stipulating that the Lamms' two-lane criteria are unsuitable for four-lane horizontal curves where the assumption of uniform speed over fails.

8.1.2 Operating speed model, Safety Criteria, and Highway geometric design

Developed speed models

Through sensitivity analysis over the developed operating speed models (Equation 8.1-8.3) for curves, it is found that the following geometric parameters PTL, VG, Δ, CL are influencing the operating speeds in the following order Δ > CL > PTL > VG at all three curve locations (PC, CC, and PT).

$$\mathrm{V}_{85\mathrm{PC}} = 62.01 + 0.08 * \mathrm{PTL} - 0.58 * \mathrm{VG} + 0.16 * \mathrm{CL} - 0.26 * \Delta \qquad (8.1)$$

$$\mathrm{V}_{85\mathrm{CC}} = 62.07 + 0.08 * \mathrm{PTL} - 0.59 * \mathrm{VG} + 0.13 * \mathrm{CL} - 0.31 * \Delta \qquad (8.2)$$

$$\mathrm{V}_{85\mathrm{PT}} = 61.99 + 0.07 * \mathrm{PTL} - 0.67 * \mathrm{VG} + 0.21 * \mathrm{CL} - 0.31 * \Delta \qquad (8.3)$$

Developed Speed Harmony and Speed Synchronization safety criteria

Through Speed Harmony (SH) and Speed Synchronization (SS), the safety levels (Table 8.1) are established for the four-lane horizontal curves with varying operating speeds across the curve.

Table 8.1 Speed Harmony and Speed Synchronization Criteria

Safety Level	SH Criteria *(kmph)*	SS Criteria *(kmph)*
Good	$\lvert V_{85}-V_d \rvert \leq 20$	$\lvert \Delta V_{85} \rvert \leq 5$
Fair	$20 < \lvert V_{85}-V_d \rvert \leq 35$	$5 < \lvert \Delta V_{85} \rvert \leq 10$
Poor	$\lvert V_{85}-V_d \rvert > 35$	$\lvert \Delta V_{85} \rvert > 10$

Proposed new highway geometric design

Considering the operating speed variation across the curve, a new speed-based geometric design methodology is proposed using Vehicle Dynamics (VD), Speed Harmony (SH), and Speed Synchronization (SS) criteria. The proposed geometrics design increases safety by ensuring the drivers' comfort (via the VD criteria), bringing operating speeds closer to the design speeds (via the SH criteria), and minimizing operating speed variations within the curve (via the SS criteria).

8.1.3 Percentile speed distribution model

Model development

The development of percentile speed distribution models at CC revealed that the BPNN-based model provided better speed predictability than the other models developed through the OLSR and GA-BPNN techniques.

Parameter sensitivity

The profile method sensitivity analysis on the developed BPNN percentile speed model with 9-30-1 architecture revealed that the speed distribution at the center of the curve depends on various geometric parameters in the following order SE >R > PTL >VGT >DS >P >VGC > CL >SL.

The advantage of this percentile speed distribution model is that with one single base model (without modifying anything), it is possible to predict any percentile speed values and can also say which parameters influence the percentile speeds much.

8.1.4 Continuous Percentile speed distribution model

Model development

Similar to the percentile speed models at the CC, here in the continuous percentile speed distribution modeling, the BPNN-based model with 13-20-1 (I-H-O) architecture provided better results over GA-BPNN models with R^2 of 0.99 and RMSE of 0.203

OSWS for four-lane highways

Unlike the existing systems, the current OSWS warns the driver with the help of the permissible operating (V_{85}) and design (V_{95}) speeds of the upcoming highway alignment. The experimental results conducted on four-lane highways (Section 7.3.1) also showed the validity of this approach in improving driver safety.

8.2 Significant Contribution of this Research Work

The current work contributes to improving the safety of four-lane horizontal curves in mountainous terrains in the following ways:

- This thesis evinces that the operating speed is not uniform and varies across the curve from PC to PT.
- Among various geometric parameters, it was found that PTL, VG, Δ, and CL significantly influence the operating speed at PC, CC, and PT.
- Existing consistency criteria of two-lane highways are unsuitable for evaluating the consistency of four-lane highway safety.

- The new consistency criteria Speed Synchronization (SS) and Speed Harmony (SH) developed in this thesis will help to evaluate the safety of four-lane highways in mountainous terrains.
- With the increasing amount of foul-lane highway construction in India nowadays, the proposed speed-based geometric design helps in improving safety as it is an improvement over the existing geometric methods with the consideration of operating speed variation over the curve in the geometric design.
- In predicting the percentile speed, it is found that BPNN technique models could predict the percentile speeds more accurately than the models developed using the GA-BPNN and OLSR regression techniques.
- As the existing over-speed warning systems are rigid with a single safe speed threshold in this thesis, a dynamic speed-based over-speed warning system is developed using operating speed (V_{85}) and design speed (V_{95}) as safety thresholds.

8.3 Future Scope

The current study deals with only one type of vehicle, i.e., passenger car; therefore, the scope of the work can be extended to other types of vehicles, such as Trucks. Further, the present study paves the way for future studies by incorporating other highway elements such as side friction, curvature change rate, and curve deflection angle. Therefore, it is suggested to explore the influence of these parameters on speed in future studies. It can also be conducted considering different terrains (plane and rolling), periods of the day (day and night), and monsoons (winter and summer) to find out the influence of these on the drivers' behavior as well as in geometric design.

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