RELIABILITY-BASED DESIGN OF FREEWAY ACCELERATION SPEED-CHANGE LANES

by

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ABSTRACT

Adequate length of acceleration speed change lanes (SCL) enables drivers to comfortably accelerate from their current speed to the speed of the freeway, find a gap in traffic flow of the freeway and merge with the traffic flow in a safe and secure manner. Instead of current deterministic approach a probabilistic approach to highway geometric design was examined in this study. The required SCL length for different types of vehicles was calculated using reliability-based methods. The main benefit of this approach is that traffic flow characteristics are assumed to be stochastic. The outcome of this methodology is a distribution for the design problem instead of one value. It was shown that the reliability-based analysis enables designers and highway professionals to choose a specific design, which matches better with driver acceleration behaviour, increase the safety of freeway elements and avoid unnecessary extra construction costs. The analysis showed that current deterministic approach for SCL length calculation is not satisfactory in most cases. SCL length recommendations in the design manuals were shown to be inadequate due to unsupported design assumptions and unsatisfactory design approach.

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LIST OF SYMBOLS

$AADT$ = Annual average daily traffic, veh/day

$AASHTO$ = American Association of State Highway and Transportation Officials

HV = Heavy vehicles

HCM = Highway Capacity Manual

R = Radius of controlling ramp curve, m

R^2 = Coefficient of determination

PC = Passenger cars

P_h = Probability of hazard

RL = Right lane

SCL = Speed-change lane

SD = Standard deviation

TAC = Transportation Association of Canada

$TCol$ = Total collisions on the section along the SCL

$TcolAcc$ = Total collision on Acceleration lane

V_G = Speed at the gore, km/h

V_M = Merging speed, km/h

1.0 INTRODUCTION

1.1 Background

Roadways, airports, public transit and all other elements of transportation systems are planned and constructed not only to transport people and goods but also to do so safely and securely. Transportation systems have been serving their users for centuries and these systems have been modernized by time. During the development towards a fast and easy to use system, the costs of building and using the system have increased. One main element of modern transportation systems is the roadway, which is the main mode used to move people and goods. Similar to other modes of transportation, collisions are possible on roadways costing society in human life, injuries and damages. According to the World Health Organization (WHO) report on road traffic injury prevention (2004), every year there are over a million deaths on roadways around the world, and ten million people are injured, costing an estimated \$520 billion, this means over 3,000 deaths per day (two deaths per minute). So the importance of safety of transportation systems is highly influenced by road traffic collisions, and as such governments are trying to reduce this cost by improving the system and obligating users to obey safety protocols.

According to National Highway Traffic Safety Administration (NHTSA), there were nearly 6,420,000 automobile accidents in the United States (US) roadways in 2005. The financial cost of these collisions is more than \$230 billion. In addition, 2.9 million people were injured and 43,443 killed. This means about 115 people died every day in roadway collisions in the United States (one death every 13 minutes only in the US). Driver behaviour, such as lane changes, acceleration and deceleration patterns, and speed choice,

play the most important role in roadway collisions (Kockelman et al. 2004). Many of the above mentioned losses and costs take place on freeways. Interchanges and terminals on freeways are the most the probable sites of collision occurrence, because in freeways there are no traffic lights, stops, or other common traffic regulations, and the only merging area where traffic flows join other traffic streams is at interchanges. As mentioned above, governments are trying to reduce the number of collisions by enforcing safe driving practices. For example, in the US alone by regulating the use of seat belts as mandatory for all passengers of motor vehicles, deaths from roadway crashes decreased by 10 percent (to 37,313 deaths) in 2008. This is the lowest number of deaths on US roads since 1961 when 36,285 lives were lost (NHTSA annual report, 2009). But the safety of transportation system will not be improved only by practicing safe driver behaviour, other system elements should be improved for a higher level of safety as well. It is obvious that the safety of roadways must be monitored all the time and required changes made to improve safety of roadways. Consequently, it is important to determine where the focus of this monitoring should be. Typically, the focus of monitoring should be at points of traffic flow merging, or in other words, the merging areas of freeways, where a second roadway connects to a freeway and vehicles enter the freeway through an interchange.

In order to enter a freeway without interrupting the flow, users have to use interchanges. An interchange is a road junction that utilizes grade separation to permit traffic on a crossing roadway to pass through the junction without interrupting the freeway main traffic stream. According to the *Geometric Design Guide for Canadian Roads* of the Transportation Association of Canada (TAC 1999), the basic function of an interchange

is to facilitate the safe and efficient movement of vehicles to and from a freeway. During the 1920's, the idea of controlled access facilities for the movement of vehicular traffic came into transportation engineering through the use of isolated grade separations. From that time on, the geometric design of freeways changed in support of this idea. AASHTO (2004) is one of design manuals for roadway design, which is widely used all around the world, it should be mentioned that most of the design criteria and recommendations in AASHTO (2004) are based on the data that was gathered in 1950's (Koepke 1993). Since the time that the data was gathered, vehicle characteristics and driver behaviour have been updated and changed. In order to capture the changes required in roadway designs as a result of changing vehicle characteristics and driver behaviour, further studies are needed in these areas.

The safety of the interchanges is directly related with their geometric design, however, there are other influencing parameters, such as driver behaviour, speed choice, and traffic flow. Interchanges consist of loops, ramps, and speed change lanes. When entering an interchange, the driver drives through a controlling curve, enters the speed change lane (SCL). While driving in SCL, the driver has to accelerate to the designated speed of the freeway, find a gap in the traffic flow, accept the gap, and then merge with the traffic flow in the freeway. The merging point of interchanges in which traffic flows in the freeway and other roads merge together is at some point along the SCL. This point is the only merging point of freeways with other roadways. This demonstrates the importance of the design of SCLs, because if the driver cannot accelerate and merge with traffic flow before end of SCLs, an interruption would occur at the end of SCL, and this traffic flow interruption might result to a collision. The geometric design of SCL should be in a way

that provides the driver with adequate length to accelerate to the speed of freeway and safely merge with traffic flow. Therefore, TAC (1999) recommended that safety of SCLs can be increased with their increased associated lengths. On the other hand, freeway diverge areas should give drivers adequate length to exit traffic flow, enter the deceleration speed change lanes, reduce their speed to the advisory ramp speed, and exit the freeway in a safe manner.

Several studies have proven that interchanges are the most collision prone areas in terms of the quantity and severity of collisions. This is due to the high speed of freeways and chain traffic flow in freeways, where one collision will result in a series of collisions. For example, based on data from the US Fatality Analysis Reporting System (FARS) and General Estimates System (GES), McCartt et al. (2004) stated that approximately 82,609 police reported collisions occurred at interchanges on interstate freeways in 2001, where 24,996 collisions resulted in injuries and 544 were fatal. Janson et al. (1998) indicated that nationally (in US) 20 to 30 % of freeway truck collisions occur on or near ramps.

In spite of all the studies about vehicle collisions and the importance of safety of interchange ramps, researchers are paying less attention to safety of roadway elements geometric design. There appears to be very limited amount of research to improve the safety of interchanges from a geometric design point of view, mainly entrance ramps and merging areas (SCL). Currently, SCL length is calculated using a deterministic design approach, where one value for each variable would be considered and one value for design problem would be resulted. This approach would result in ignoring the whole population of vehicles, and considering only one value to represent vehicles traffic characteristics such as speed. In this study, a new approach to freeway geometric design

was examined. Unlike the current design approach, the characteristics of traffic flow in this approach are assumed to be stochastic, and the outcome of design is a distribution instead of one value. The study then uses real world data to establish the distribution for each variable and provide an application example of the new design approach. By applying the reliability based methods to design process, potential recommendations have been made to improve the level of safety in freeway merging areas.

Freeway to freeway interchanges are not considered in this research because these connections are mostly provided by high speed ramps which will reduce the flow interruption. Entrance to a freeway from arterial roads is usually associated with change in speed, as, due to the nature of their design classification, arterials have lower posted and operating speeds compared to those of freeways. These speed differences exist between vehicles entering from an arterial road to a freeway. Therefore in this study speed change lanes that connect an arterial to a freeway are considered.

1.2 Thesis Objectives

This study is the fourth phase of a comprehensive study into safety of freeway merge and diverge areas. Previous studies included, Sarhan (2004) who studied the safety performance using existing data, and Ahammed (2005) and El-Basha (2006) who studied driver behaviour on merge and diverge areas using collected data. The main goal of this study is to evaluate the adequacy of length of acceleration speed change lanes for drivers to accelerate and reach the speed of freeway traffic flow and finally merge with the existing freeway traffic stream in a safe and secure manner. While previous studies have

provided the foundation to evaluate the design of speed change lanes, in this study by using reliability-based approaches the current design procedure for SCL length calculation will be evaluated. The analysis results will be compared with currently provided lengths and recommended SCL lengths in design manuals. Using previously gathered data by Ahammed (2005) on the acceleration lane and freeway right lane speeds, this study will evaluate real world examples and provide the results of analysis. Based on the availability of relevant data, use of reliability-based analysis and literature review, the objectives of this thesis are as follow:

- To review the relevant studies on speed change lane design and safety of freeway merge areas and driver behaviours in these areas;
- To review studies that utilize reliability analysis in freeway geometric design;
- To create models and analyze data using reliability-based approach;
- To evaluate the adequacy of the provided length for SCL using reliability- based approaches;
- To evaluate the influence of vehicle type (passenger cars and heavy vehicles) on the required length of SCL;
- To compare the provided length (from design manuals) and required length (from reliability-based approaches results) and evaluate the values provided in design manuals.

It is expected that the findings of this study will provide designers and highway professionals with a more reliable procedure for the geometric design of acceleration lanes and prove the importance of safety analysis in highway geometric design

procedure. This study also makes a foundation for future safety studies on highway geometric design.

1.3 Thesis Organization

This thesis consists of six chapters. An introduction to this study has been already represented in this Chapter 1.0. Chapter 2.0 provides a review of design guides on speed change lane length calculation, their procedures, assumptions and considerations. Also, a review of relevant literature to the research goals of this study is provided in Chapter 2.0. Chapter 3.0 provides information about the geographical area covered in this study and data used in this research, along with a summary of the design variable characteristics. Chapter 4.0 provides an introduction and detailed review about the methodology used in this research. In Chapter 5.0 provides the analysis results followed by a comprehensive discussion. Finally, Chapter 6.0 provides a summary of the findings of this study and recommendations for future research.

2.0 LITERATURE REVIEW

In this chapter, previous studies related to the objectives of this study have been reviewed. Section 2.1 provides a brief definition of freeway elements and their design criteria and more specifically an introduction to acceleration lane design procedure as stated by the following design manuals:

- I. Transportation Association of Canada, Geometric design guide for Canadian roads (TAC 1999)
- II. The American Association of State Highway and Transportation Officials, A Policy on Geometric Design of Highways and Streets (AASHTO 2004)

Section 2.2 represents the relevant available literature on freeway speed change lanes and driver behaviour at freeway merging areas. Also in this section, questionable assumptions which were made by above design manuals on SCL geometric design will be discussed.

2.1 Review of Design Guides

Before discussing the design criteria of entrance terminals, there are some terms that should be defined. As such, the main design guides in North America (AASHTO 2004, TAC 1999) were reviewed and a basic definition of terms and related design criteria is provided in this section.

2.1.1 An Introduction to Interchange, Ramp, and Speed Change Lanes

Interchange: Based on AASHTO (2004), “an interchange is a system of interconnecting roadways in conjunction with one or more grade separations that provides for the movement of traffic between two or more roadways or highways on different levels”. Since the choice of interchange type will influence cost and efficiency, designers should make the best choice to provide the highest possible level of safety.

As stated in TAC (1999), interchange configuration selection should be made under the following considerations: safety, functional and design classification of interchanging roads, traffic volume and traffic mix, number of intersecting legs, traffic control devices to be provided, topography of the area, right of way requirements and availability, service requirements for adjacent communities, overall systems considerations and design consistency, environmental factors, and economics.

Ramp: As defined in AASHTO (2004), “the term ramp includes all types, arrangements, and sizes of running roadways that connect two or more legs at an interchange.” As mentioned in TAC (1999), a ramp has two components at each leg; a terminal and a connecting road.

Ramp Terminal: As previously mentioned, a terminal is a component of a ramp, and the terminal ramp is the portion of the ramp near the traveled way. This includes speed change lanes, tapers, and islands.

Speed-Change Lanes: Drivers entering a freeway are required to accelerate to the speed of freeway flow while drivers leaving a freeway need to reduce their speed. Since the change in speed is substantial, space should be provided to accomplish

acceleration or deceleration while minimizing crash potential. This space is made possible by an auxiliary lane, which is known as a speed change lane.

Taper-type SCL: As stated by AASHTO (2004), these types of SCL can operate smoothly at all traffic volumes up to design capacity of freeways if they are designed properly. The benefit of this type of SCL is that they can provide the entering driver with a clear sight distance allowing the driver to find a gap and merge with freeway flow.

Parallel-type SCL: The benefit of this type of SCL is the added lane which allows the driver to accelerate in a relaxed manner to the freeway speed and at same time merge with the stream if a gap is accepted. This type of SCL has a taper at the end of the added lane. Here, the process of entering the freeway is like a lane change to the left. A

2.1.2 Speed Change Lane Design Criteria

Based on AASHTO (1965), the SCL length design is based on the following factors:

1. The speed at which drivers enter the speed change lane;
2. Acceleration factors or the way drivers accelerate; and
3. The speed of the freeway flow which drivers need to reach in order to merge with freeway flow in a safe manner.

With regards to the speed at which the drivers enter the SCL, AASHTO (1965) assumes that drivers leave the curve in a speed lower than the speed of controlling curve design

speed, which is called the “Average Running Speed”. This assumption is no longer supported due to new findings (Fitzpatrick et al. 2006).

For the second factor, AASHTO (1965) provides graphs showing acceleration rates based on data collected in 1937 for passenger vehicles on level grade. AASHTO (2004) results are based on the same tabulated data.

About the third factor, AASHTO (1965) states that the entering cars’ speed should be close to the speed of freeway flow, which would be equal to average running speed of freeway traffic.

AASHTO (1965) calculated the SCL length based on the above considerations, and as stated by (Fitzpatrick et al. 2006) the following equation was used in order to determine SCL lengths:

$$L = \frac{(0.278V_M)^2 - (0.278V_G)^2}{2a} \quad (2.1)$$

Where:

L = SCL length, m

V_M = Freeway flow speed, Km/h

V_G = Speed at the end of controlling curve for ramp (speed at gore), Km/h

a = Acceleration rate, m/s²

Table 2.1 and Table 2.2 are a reproduction of AASHTO (1965) and AASHTO (1973) SCL lengths recommendations.

Table 2.1: SCL Lengths as Recommended by AASHTO 1965

Highway		L - Length of Acceleration Lane (meter)								
Design Speed, km/h	Speed Reached (V_M), km/h	For Entrance Curve Design Speed, km/h								
		Stop Condition	24	32	40	48	56	64	72	80
		And Initial Speed (V_G), km/h								
		0	23	29	35	42	48	58	64	71
80	63	232	213	192	177	152	116	49	-	-
97	76	357	341	326	305	277	244	180	122	52
113	85	485	469	457	430	405	375	308	253	177

As shown in Table 2.2, the same values were recommended for SCL length in AASHTO (1973).

Table 2.2: SCL Lengths as Recommended by AASHTO 1973

Highway		L - Length of Acceleration Lane (meter)								
Design Speed, km/h	Speed Reached (V_M), km/h	For Entrance Curve Design Speed, km/h								
		Stop Condition	24	32	40	48	56	64	72	80
		And Initial Speed (V_G), km/h								
		0	23	29	35	42	48	58	64	71
80	63	232	213	192	177	152	116	49	-	-
97	76	357	341	326	305	277	244	180	122	52
113	85	485	469	457	430	405	375	308	253	177

In AASHTO (2004) several updates were made to the recommended SCL lengths compared to previous versions of AASHTO. Table 2.3 is a reproduction of the SCL

lengths as stated in AASHTO (2004). As shown in Table 2.1, Table 2.2 and Table 2.3, the speed values are assumed to be smaller than the design speed of freeways. For example in Table 2.3, for a design speed of 120 km/h, the vehicles speed is assumed to be 88 km/h, whereas there is a virtual consensus in the literature that operating speeds on highways are usually very close or exceed the speed limit and design speed.

Table 2.3: SCL Lengths as Stated in AASHTO 2004

Highway		L - Length of Acceleration Lane (meter)							
Design Speed, km/h	Speed Reached (V_M), km/h	For Entrance Curve Design Speed, km/h							
		Stop Condition	20	30	40	50	60	70	80
		And Initial Speed (V_G), Km/h							
		0	20	28	35	42	51	63	70
90	67	260	245	225	205	175	125	35	-
100	74	345	325	305	285	255	205	110	40
110	81	430	410	390	370	340	290	200	125
120	88	545	530	515	490	460	410	325	245

The geometric design guide for Canadian roads has recommended longer lengths for SCL, instead of providing one value for length, a range of lengths are recommended and freeways with design speeds greater than 120 km/h are covered. These SCL length values have been reproduced in Table 2.4.

Table 2.4: SCL Lengths as Stated in TAC (1999)

Speed of Roadway		Length of Taper (m), L_t	Length of Acceleration Lane Excluding Taper (m), L_a							
Design Speed, km/h	Assumed Operating, km/h		Design Speed of Turning Roadway Curve (km/h)							
			Stop Condition	20	30	40	50	60	70	80
90	77-90	80	215-325	200-310	180-300	160-285	140-250	50-200	40-145	-
100	85-100	85	275-450	250-440	240-420	225-405	200-375	140-325	100-285	40-230

110	91-100	90	330-650	320-645	305-630	290-600	260-575	210-525	150-475	100-410
120	98-120	95	410-730	400-725	375-710	370-690	340-660	285-590	250-515	195-430
130	105-130	100	550-885	540-880	510-870	500-850	470-820	400-745	340-655	300-550

2.1.3 Relevant Studies on Basic Design Assumptions

As defined in section 2.1.2 there are three points which are considered as design factors in design guides, the methods used in AASHTO (1965) and later in AASHTO design guides is based on the following:

1. Speed on limited-access roads and ramps; and
2. Acceleration behaviour

There are some assumptions made in the mentioned above areas in order to calculate the values for SCL lengths. According to researchers these assumptions are outdated and should be reconsidered.

Fitzpatrick et al. (2000) and Krammes et al. (1994) have demonstrated that speeds on rural two-lane highways usually have 85th percentile speeds in excess of the inferred design speed of horizontal curves. Fambro et al. (1997) and Fitzpatrick et al. (2003) have shown that 85th percentile operating speed reaches posted speed on arterial streets and rural highways. Therefore, it would be logical to also assume that drivers may exceed the design speed or the posted speed on limited-access roads.

One recent study which gathered driver behaviour at 23 entrance terminals (Ahammed et al. 2006) found a typical 85th percentile merging speed of 105 km/h for motorists entering freeways with a 100 km/h posted speed limit. While the merging speed was higher than

the advisory speed, it was generally within 8 km/h of the speeds in the right-most lane (99 to 119 km/h).

The above studies show that assuming that vehicles will enter freeways with a speed much less than free flow speed is questionable. At the same time, the design guides assume that drivers will leave the controlling curve at a speed lower than curve design speed, but as mentioned before this assumption is no longer supported by researchers.

As for acceleration behaviour, it should be mentioned that the values used in design guides (AASHTO 2004 and TAC 1999) were generated based on data gathered during the 1930's. Therefore, this is an area in dire need of further research as driver behaviours and vehicle characteristics have changed considerably since that time.

2.2 Driver Behaviour on Freeway Merging Areas

Blumenfeld et al. (1971) found that the delay associated with merging does not depend strongly on SCL length. They found that most of the merging occurs at the beginning of the acceleration lane, and SCLs longer than 600 ft (183 m) do not result in easier merging.

Olsen et al. (1976) studied driver behaviour on three on-ramps and found that merging is strongly related with SCL length.

Huberman (1982) gathered speed data on five entrance ramps in Edmonton, Alberta, Canada and found that 85% or more of the vehicles leaving the controlling curves have speeds higher than the curve design speed and very close to the highway

running speed. The following relation was found between speed and acceleration rate, in which geometric variables were not considered:

$$y = 159.91e^{-0.44x}, \quad R^2 = 0.91 \quad (2.2)$$

Where, y = passenger car speed leaving the ramp in km/h, and x = passenger car acceleration rate in km/h/s.

Fazio (1988) tried to predict the vehicle speed at freeway merging areas and developed a model which led to the following equation for average running speed in each lane of freeway:

$$S_i = 29.3 - 0.0066 \left[\frac{V}{PHF * f_{HV}} \right] + 0.0392 * Length + (Lane_i) \quad (2.3)$$

Where S_i = Average running speed of the vehicles in lane i (mph), i = Lane position number (1 for the auxiliary lane, 2 for the freeway lane adjacent to auxiliary lane, 3 for the next freeway lane, and 4 for the outermost lane), V = Sum of flow rates in lanes 1 through 4 (vehicles/h), PHF = Peak hour factor based on five-minute intervals, f_{hv} = Heavy vehicle adjustment factor, $Length$ = Length of weaving section (ft), $Lane_i$ = number of lane.

Michaels et al. (1989) developed a model for the angular velocity of approaching vehicles relative to vehicles in the SCL. The model was tested during peak hours and it was found that a speed change lane of 800 ft (244 m) will be enough for 85% of vehicles to merge with freeway flow.

Kou et al. (1998) gathered data from four entrance ramps in Houston and Austin, Texas, US. There were both long and short length speed change lanes among the four

ramps and acceleration/deceleration data were collected using the car following technique. It was concluded that traffic parameters such as traffic flow level, ramp vehicle approach speed, and relative speeds between entering and freeway lag vehicles had no statistically significant affect on merging position. It was recommended that more freeway merge and ramp data should be gathered in order to develop more accurate models.

Hunter et al. (2001) gathered data to study speed-distance relationships on six ramps in three Texas cities. SCL length, grade, and visibility were all measured. Vehicle speed was calculated based on distance travelled and travel time. It was concluded that regardless of the ramp design speed, 85% of vehicles drive within 70 to 80% of the freeway design speed. It was also found that good geometry results in small positive acceleration rates, whereas bad geometrics produces larger positive and negative values for acceleration.

Liapis et al. (2001) developed two models in order to predict operating speed on ramp controlling curves based on data collected from twenty ramps in Greece. Using equations based on their findings, it was predicted that speed on entrance ramps is 6 to 8.6 km/h higher than the controlling curve design speed. These models for off and on ramp were given as:

$$\text{Off-Ramps:} \quad V_{85} = 75.161 - 0.009886CCR - 3.6835e \quad R^2 = 0.75 \quad (2.4)$$

$$\text{On-Ramps:} \quad V_{85} = 85.186 - 0.01295CCR - 3.795879e \quad R^2 = 0.73 \quad (2.5)$$

Where, V_{85} = Operating speed in km/h, CCR = Rate of change curvature of ramp curve including transition curves (gon/km), e = super-elevation rate (%)

2.3 Safety Related Studies

Cirillo (1970) studied the effect of the geometry of ramps on accident rate using data collected from twenty US states. It was found that increasing the length of speed change lane is helpful in increasing the level of safety. It was also mentioned that deceleration lanes in general are safer than acceleration lanes, and so an increase in length would be more beneficial in acceleration lanes.

Harwood et al. (1993) found that problems with acceleration lanes and crashes mostly occur for vehicles with speeds higher than the posted speed limit.

Persaud et al. (1993) developed microscopic and macroscopic traffic models in order to predict the accident rates using accident data from 1988 and 1989. It was found that higher collision rates are directly related to the level of congestion, and higher crash rates are more likely to occur during rush hour congestion in urban areas.

Twomey et al. (1993) reviewed accident rates in previous studies of interchange design and found that lengthening acceleration lanes, adding ramp lanes, and optimizing current ramps, etc. are all effective methods in reducing accident rates.

Bauer et al. (1997) developed statistical models to find the relation between geometric characteristics and accidents rates using three years worth of accident data. It was found that models were statistically significant at 10 to 20% significance level with R^2 value of 0.10 to 0.42.

Kockelman et al. (2004) studied speed variation patterns and average speeds in relation to crash occurrences. No evidence was found to support a correlation between such parameters and crash occurrences.

3.0 STUDY AREA AND DATA USED IN THIS RESEARCH

As discussed in Chapter (1.0), this research is the fourth phase of a comprehensive study. Previous studies include: Sarhan (2004) who studied the safety performance using existing data, Ahammed (2005) and El-Basha (2006) who studied driver behaviour on merge and diverge areas using collected data.

Since the goal of this study is to evaluate the adequacy of SCL length at entrance terminals using a reliability based approach. The required data for reliability based models were received from Ahammed (2005), who studied the merge areas of freeways. Data were received in form of several Excel sheets; each sheet represented a single vehicle speed profile, which includes the time and speed of vehicle from the point that vehicle enters to SCL to the point that vehicle merges with freeway traffic flow. In order to provide the required data for this study, based on equations of motion and using the speed profile and recorded times, the merge length and acceleration rate of each vehicle were calculated.

In this chapter the study, collected data, characteristics of collected data and traffic data covering the study area will be discussed.

Section 3.1 discusses the study area and site selection process, section 3.2 and section 3.3 discusses the traffic data and collision data required for safety analysis.

Section 3.5 discusses the characteristics of data which was used in this study.

The goal of this chapter is to provide more information about real world examples which were used in the analysis of this study.

3.1 Site Selection

Data were collected from Highway 417, which is part of the Trans-Canada highway. Highway 417 is one of the major freeways in Ontario. It is a high speed freeway with a posted speed of 100 km/h. Highway 417 is the major freeway in City of Ottawa, the capital and the fourth largest city of Canada. A high amount of traffic commutes through Highway 417. Depending on the level of traffic in a particular area, Highway 417 has two to four lanes in each direction.

The selected area for data collection was a portion of Highway 417 which lies within the City of Ottawa. This stretch of the Highway 417 was chosen because it was believed to provide sufficient variability in driver behaviour, traffic level and geometry, which are major variables for analysis of this study. Figure 3.1 shows the selected study area.

Figure 3.1: Map of Study Area

There are 27 interchanges with 66 entrances in the study area. After excluding freeway to freeway ramps, there were sixty entrance ramps left in the selected study area. Out of the remaining locations, Forty SCLs were selected as candidate sites based on suitable position for data collection, accessibility to the position and visibility of full SCLs from the proposed position.

Laser speed guns were used for vehicle speed data collection, which required a minimum distance from the target to generate an accurate reading. In some sites adequate space was not available or building management did not provide permission for equipment positioning, therefore these sites were excluded from the selected SCLs. Also some sites were excluded due to safety problems. All of these factors reduced the selected sites to 23 SCLs.

Table 3.1 shows a list of the selected SCLs, from which speed and traffic data were collected. Out of the 23 selected sites fourteen were located in the east-bound of Highway 417 and the remaining eight sites were located along the west-bound. The selected SCLs' lengths vary from 188 meters to 1366 meters. SCLs with length in range of 188 to 468 meters are designated as limited type SCLs and SCLs with length in range of 673 to 1366 meters are designated as extended type SCLs. The Limited length type SCL includes both taper and parallel geometric configurations. Except for two SCLs that have upgrade ramps, the rest were preceded by downgrade ramps (where the arterial road passes above the freeway).

According to the data provided by the Ontario Ministry of Transportation (MTO), in the area of selected SCLs, the freeway Average Annual Daily Traffic (AADT) ranges from

11,705 to 66,600 vehicles per day and the ramp AADT ranges from 1,263 to 14,811 vehicles per day.

Table 3.1: List of Selected SCL Sites

Sl.	IC #	Dir.	Ramp and SCL	Data Category
1	110	WB	Walkley Rd. W-W	Merge Speed Only
2	112	EB	Innes RD. E-E	Merge Speed Only
3	115	WB	St. Laurent Blvd. N-W	Full Profile
4	117	WB	Vanier Pwy N-W	Full Profile
5	117	EB	Vanier Pwy N-E	Merge Speed Only
6	118	EB	Nicholas N-E, Lees-E	Merge Speed Only
7	122	WB	Parkdale NS-W	Full Profile
8	126	EB	Maitland Ave. NS-E	Full Profile
9	127	WB	Woodroffe Ave. NS-W	Full Profile
10	127	EB	Woodroffe Ave. N-E	Merge Speed Only
11	127	EB	Woodroffe Ave. S-E	Merge Speed Only
12	129	EB	Greenbank Rd. S-E	Merge Speed Only
13	120	EB	Richmond Rd. S-E	Full Profile
14	134	WB	Moodie Drive N-W	Full Profile
15	138	WB	March Rd. N-W	Merge Speed Only
16	138	EB	Eagleson Rd. S-E	Full Profile
17	139	EB	Castlefrank Rd. NS-E	Full Profile
18	140	WB	Terryfox Drive N-W	Full Profile
19	140	WB	Terryfox Drive S-W	Merge Speed Only
20	140	EB	Terryfox Drive N-E	Merge Speed Only
21	140	EB	Terryfox Drive S-E	Full Profile
22	144	EB	Carp Rd. N-E	Merge Speed Only
23	144	EB	Carp Rd. S-E	Full Profile

As shown in Table 3.1 for fifteen SCLs, vehicle speeds were available over the full length of acceleration lane, from the area of physical gore to the end of taper; these sites are represented as “Full Profile” in the table. For the remaining eight acceleration lanes, the available data do not include the gore speed and speed data are available from some

distance after the gore. Thus, data available for these sites include merging speed only, which is indicated as “Merge Speed Only” in the table. *Merge speed only* sites are not suitable for the purpose of this study, because the availability of vehicle speed at gore is one of the main variables in length calculation equation.

After excluding the “Merge Speed Only” sites, the “Full Profile” sites and their geometric characteristics are summarized in Table 3.2.

Table 3.2: Selected Sites with Their Geometric Information

SCL Name	Ramp Type	SCL Configuration	Length, m	Fwy Lane	Ramp Radius, m	Ramp Grade	Converge Angle, deg	Ramp Width, m
Carp Rd (S-E)	Outer	Parallel	430	2	200	Down	3.0	4.8
Castlefrank(NS-E)	Outer	Extended	696	2	N/A	Down	2.0	4.8
Eagleson(N-W)	Outer	Extended	673	2	95	Down	3.0	5.0
Eagleson(S-E)	Outer	Parallel	327	2	350	Down	3.0	4.8
Greenbank(S-E)	Outer	Extended	1366	3	95	Down	5.0	4.8
Maitland(NS-E)	Loop	Parallel	468	3	74	Down	10.5	4.0
Moodie(N-W)	Outer	Parallel	323	2	238	Down	3.0	4.8
Parkdale(NS-W)	Outer	Taper	188	4	N/A	Up	4.0	3.5
Richmond(S-E)	Outer	Parallel	321	4	295	Down	5.0	4.8
St_Laurent(N-W)	Outer	Extended	881	3	45	Up	3.0	4.8
Terryfox(N-W)	Outer	Parallel	419	2	155	Down	3.0	5.0
Terryfox(S-E)	Outer	Parallel	437	2	155	Down	3.0	5.5
Vanier(N-W)	Outer	Extended	800	3	82	Down	5.0	4.8
Woodroffe(NS-W)	Loop	Parallel	346	3	113	Down	3.5	4.6
Woodroffe(S-E)	Outer	Extended	1222	3	90	Down	3.0	4.8

The length of SCL was measured from the point where the pavement edges of the ramp and mainline are 1.25 m apart at the entrance gore to the similar point at the exit gore for extended type acceleration lane or to the end of taper for limited length type acceleration

lane. The same distance (1.25 m) was recommended by AASHTO (2004) and TAC (1999) for SCL length measurements.

Limited length type SCLs range from 188 to 468 meters and extended type SCLs vary from 673 to 1366 meters. In the next chapters, these two categories will be analyzed separately, in order to find out the length effect on driver acceleration behaviour.

The radius of ramp curvature is the radius of the controlling ramp which varies from 45 to 350 meters.

The number of basic freeway (Fwy) lanes vary from two to four based on the level of traffic in the area of entrance terminal. Out of 15 sites listed in Table 3.2 there are seven sites with two freeway lanes, six with three freeway lanes and only two sites with four freeway lanes.

In order to merge safely, the geometry of the gore is important for the driver in making a merging decision. The angle of convergence is part of the geometry of the gore which has to be measured at the physical nose where paved area begins, and as shown in Table 3.2, varies from 2.0 to 10.5 degrees. Widths of the ramp travelled way at physical nose vary from 3.5 to 5.5 meters.

Out of 15 sites, 13 have an outer type ramp. In this type of ramp, most of the acceleration of speed occurs before the time the driver reaches the physical gore. The other two ramps are loop type, in which most of the acceleration takes place in the vicinity of or downstream from the physical gore.

As shown in Table 3.2, thirteen ramps are located on a downgrade (arterials passing over the freeway) and two ramps on an upgrade (freeway passing over the arterial). While an upgrade ramp retards the speed, downgrade ramps help the acceleration process.

It was shown in Table 3.2 that out of nine limited type SCLs, eight SCLs are parallel and just one SCL had taper configuration. Because the number of tapered SCLs is not sufficient for a comparison, it is not possible to make a judgment on the influence of this configuration in acceleration and merging process.

The categorical geometric data is summarized in Table 3.3.

Table 3.3: Summary of Categorical Geometric Data

Geometry	Group	Frequency	Total
Ramp Type	Outer/Direct	13	15
	Loop/Reverse	2	
Ramp Grade	Upgrade	2	15
	Downgrade	13	
SCL Type	Limited Length	9	15
	Extended	6	
SCL Grade	Upgrade	2	15
	Flat/Downgrade	13	
Configuration: Limited Length SCL	Parallel	8	9
	Taper	1	

3.2 Traffic Data

In addition to speed data, traffic volume data were collected by Ahammed (2005). This data was used to examine the influence of traffic volume on acceleration behaviour. Traffic data was collected on both SCL and the right lane of the freeway. The numbers of

passenger cars (PC), buses and trucks, and recreation vehicles (RV) were counted during data collection process. The equivalent hourly volumes (vehicle/h/lane) were obtained from the whole count duration and by converting bus, truck and RV volumes to passenger car equivalent. On calculating the passenger car equivalent, the Heavy Vehicle (HV) adjustment factors were taken as 1.5 and 1.2 for bus/truck and RV, respectively, as recommended in HCM (2000).

Figure 3.2 shows the hourly traffic volume on the SCL and the freeway right lane (RL). The equivalent hourly traffic on the SCL ranged from 111 to 751 (veh/h/lane), and on the freeway right lane ranged from 492 to 1604 (veh/h/lane). Figure 3.3 and Figure 3.4 shows the distributed hourly percentage for PC and HV on SCL and freeway right lane separately.

Figure 3.2: Equivalent Hourly Traffic Volume on SCL and RL

The percentage of heavy vehicles on the SCL ranged from 0.4 to 6.7 percent and the percentage of heavy vehicles on the freeway right lane ranged from 1.8 to 20.2 percent. The percentage of passenger cars on the SCL ranged from 93.3 to 100 percent and the percentage of passenger cars on the freeway right lane ranged from 79.8 to 100 percent.

Figure 3.3: SCL Vehicle Classification

Figure 3.4: RL Vehicle Classification

As shown in Figure 3.2, out of 15 SCLs nine SCLs have an hourly traffic around 250 veh/h/lane and six SCLs have hourly traffic greater than 500 veh/h/lane. This represents two categories based on hourly traffic. Some SCLs with a higher traffic and the rest with a lower traffic. Therefore, SCLs with hourly traffic volumes of more 500 veh/h/lane are labelled as high traffic SCL and SCLs with lower hourly traffic amount labelled as low traffic SCL. Based on above discussion, six high traffic SCLs were determined and the remaining nine SCLs were labelled as low traffic SCLs. Five of these SCLs with a traffic rate higher than 500 (veh/h/lane) are extended type SCLs, which supports the idea that the reason for SCL length extension was higher traffic volume. Table 3.4 shows these two categories with the entrance terminal names.

Table 3.4: Traffic Based Categories

High Traffic SCLs	Low Traffic SCLs
Castlefrank NS-E	Carp S-E
Greenbank S-E	Eagleson N-W
Maitland NS-E	Eagleson S-E
St. Laurent N-W	Moodie N-W
Vanier N-W	Parkdale NS-W
Woodroffe S-E	Richmond S-E
	Terryfox N-W
	Terryfox S-E
	Woodroffe NS-W
	Woodroffe S-E

Also passenger cars and heavy vehicles were analyzed separately and then analyses were applied to all vehicles. These categories and categories defined above for traffic rate will be considered in the analysis.

3.3 Collision Data

In order to measure the level of safety of the entrance terminals, five years of collision data (covering the period from 1998 to 2002) for the whole study area which were collected by Sarhan (2004) were received. Data were gathered from the City of Ottawa, which included the information regarding the date, time, location, day of the week, and the accident type (e.g. fatal injury, non-fatal injury and property damage only). The classification for accident type was based on the level of injury, in the way that collisions resulted in the death of at least one person within a month of the accident. Non-fatal injury collisions included those accidents which resulted in bodily injury only of at least one person but did not result in the death of anyone. Finally, property damage only (PDO) collisions that resulted in property damage exceeding \$1,000 and did not cause any bodily damage to anyone. The Excel file received from Sarhan (2004) provided data for the study area of this research.

The total number of collisions were used as an indicator of the level of safety in each acceleration lane. Figure 3.5 shows the distribution of total collisions on sections including the SCLs (designated as TCol), and the total collisions on speed change lanes (designated as TColAcc).

It should be noted that Castlefrank NS-E was not constructed at the time of collision data collection. Also, the collision data was collected, before the length of Eagleson N-W SCL was changed due to Castlefrank NS-E construction. Therefore, due to unavailability of accurate collision data, these two sites were not included in safety study of the selected sites.

Figure 3.5: Distribution of Total Collisions on Segments

3.4 Data Processing and Variable Characteristics

As mentioned in the previous section, data used for analysis in this study were collected by Ahammed (2005). Data were received in several Excel files. They were categorized and processed for the purpose of this study, and characteristics of variables that are used for SCL length calculation were identified.

In the received data files each vehicle has a separate data sheet. The speed profile of each vehicle was recorded from gore point to merging point. Using the speed and time values Ahammed (2005) calculated following for each vehicle:

- Merging point distance from gore
- Merging Speed
- Mean Speed
- Gore Speed
- Overall Acceleration
- Maximum Speed

- Minimum Speed
- Mean Acceleration
- Maximum Acceleration
- Minimum Acceleration

As discussed in previous section, several categories were identified for analysis purposes in this study. These categories were created to identify the effect of vehicle type, SCL location, and SCL type and traffic rate on the minimum required length of SCLs. At first there were two main categories created based on vehicle type. These categories are: passenger car (PC), heavy vehicle (HV). Using these two main categories, several categories were identified based on traffic volume, geometric characteristics of each site and limited/extended type SCL. A summary of the identified categories is represented in Table 3.5.

Table 3.5: Identified Categories for Analysis

Vehicle Type	Categories
PC	Site by Site
	Extended or Limited type SCL
	High traffic or Low Traffic type SCL
	All PC
HV	Site by Site
	Extended or Limited type SCL
	High traffic or Low Traffic type SCL
	All HV

As shown in Table 3.5, for each type of vehicle there would be fifteen sets of data based on site location, two categories based on SCL type, two categories based on traffic volume and one category which include all the vehicles of that type. This will result in twenty categories for each vehicle type and forty categories for all vehicle types.

The collected values of each vehicle were moved to a separate data sheet in order to shape the defined category, and statistical characteristics of variables in each category have been identified.

As shown in Equation 2.1, variables for acceleration lane length calculation are: speed at the Gore, merge speed and acceleration rate. It is important to know the statistical characteristics of variables for length calculation; therefore in following section these characteristics will be discussed.

3.5 Statistical Characteristics of SCL Length Calculation Variables

As discussed in Chapter 2.0, the current procedure for SCL length design is based on the sufficiency of length for accelerating to the speed of freeway (as recommended by AASHTO). In this design procedure, the main variables are speed at the gore, merging speed and acceleration rate. Because of their important role in length design, it is very important to know the key statistical characteristics of these variables. In this section the key statistical characteristics of design variables are identified from the data received from Ahammed (2005).

The collected data includes the complete details of 1,411 vehicles in study area. Number of vehicles in each SCL varies based on the level of traffic. The following section discusses the characteristics of each variable.

3.5.1 Gore Speed

Based on the data received from Ahammed (2005), regardless of vehicle type, the gore speed varied from 38.42 to 143.93 (km/h) with a total mean of 87.78 km/h and standard deviation (SD) of 14.43. This shows that the mean gore speed among all vehicles can exceed the maximum provided gore speed in design manuals SCL length tables, where the maximum gore speed of AASHTO (2004) SCL length table is 80 km/h (average running speed assumed to be 70 km/h) and for TAC (1999) the maximum possible gore speed is 80 km/h.

For the heavy vehicles (HV), gore speed ranges from 52.93 to 110.37 km/h, with a mean of 80.98 and standard deviation of 11.49. For passenger cars (PC) gore speed ranges from 38.42 to 143.93 km/h with mean of 88.25 and standard deviation 14.50. Again as could be seen, the gore speed for both HV and PC is higher than the maximum possible gore speeds in SCL length tables. This shows that for freeways with a possible gore speed higher than 80 km/h, the designer cannot make a choice of SCL length from the design manuals.

Figure 3.6 shows the mean gore speed comparison for PC and HV among different SCLs. Figure 3.7 represents the standard deviation comparison of all SCLs for PC and HV, and the comparison of 85th percentile gore speed is provided in Figure 3.8.

Figure 3.6: Mean Gore Speed Comparison of All SCLs for All Vehicles

Figure 3.7: Gore Speed SD Comparison of All SCLs for All Vehicles

Figure 3.8: 85th percentile Gore Speed Comparison of All SCLs for All Vehicle

As shown in Figure 3.8, in six SCLs 85th percentile gore speed was greater than 100 km/h, this shows the need for revisions in design manuals for SCL length design criteria.

Mean gore speed for the extended type SCLs is 89.52 km/h with standard deviation of 10.79, whereas mean gore speed for the limited length SCL type is 86.83 km/h with a standard deviation of 16.00.

The mean gore speed of SCLs with a high level of traffic, was found to be 82.44 km/h with a standard deviation of 13.57, where at SCLs with a low level of traffic, the mean gore speed was recorded at 90.81 km/h with a standard deviation of 14.02. The reason for this difference could be the level of traffic, which influences the driver's acceleration behaviour. On SCLs with low level of traffic drivers can accelerate comfortably, but the acceleration rate will decrease as the traffic rate increases.

The same comparisons were provided for categories based on SCL type, traffic rate and all vehicles. Figure 3.9 represents the mean comparison, Figure 3.10 shows the standard deviation comparison and Figure 3.11 shows the 85th percentile gore speed comparison of these categories.

Figure 3.9: Mean Gore Speed Comparison of SCL categories for all Vehicles

Figure 3.10: Gore Speed SD Comparison of SCL Categories for All Vehicles

Figure 3.11: 85th percentile Gore Speed Comparison of SCL Categories for All Vehicles

3.5.2 Merging Speed

Merging speed of all vehicles ranges from 43.03 to 147.44 km/h, with a mean of 94.52 km/h and standard deviation (SD) of 12.30. The 85th percentile merging speed was 107.21 km/h. This value shows the inadequacy of criteria provided by design manuals. ASSHTO (2004) shows the maximum possible average running speed is 88 km/h. Assuming the mean merging speed as average running speed would leave the designer with no choice for SCL length selection from SCL length table. However, the 85th percentile merging speed is a better representation for average running speed. This makes the use of the SCL length table even harder because the 85th percentile merging speed of collected data was 107.21 km/h. Compared to AASHTO (2004), TAC (1999) provides a

greater range for merging speeds, because in TAC (1999) possible merging speeds (freeway speed) range from 55 to 130 km/h.

For the heavy vehicles (HV), the merging speed ranged from 60.91 to 110.60 km/h, with a mean of 87.20 and standard deviation of 10.57. For passenger cars (PC) merging speeds ranged from 43.03 to 147.44 km/h with mean of 95.02 and standard deviation of 12.25.

Figure 3.12 shows the mean merging speed comparison for PC and HV among different SCLs. Figure 3.13 represents the standard deviation comparison of all SCLs for PC and HV, and the comparison of 85th percentile merging speed is provided in Figure 3.14.

Figure 3.12: Mean Merging Speed Comparison of All SCLs for all Vehicle

Figure 3.13: Merging Speed SD Comparison of All SCLs for All Vehicles

Figure 3.14: 85th percentile Merging Speed Comparison of All SCLs for All Vehicles

The mean merging speed of extended type SCLs is 95.10 km/h with standard deviation of 10.94, whereas the mean merging speed of the limited length SCL type is 94.19 km/h with a standard deviation of 10.94.

The mean merging speed of SCLs with a high level of traffic, was found to be 92.29 km/h with a standard deviation of 10.75, where at SCLs with a low level of traffic, the mean merging speed was recorded to be 95.78 km/h with a standard deviation of 12.92. As seen for gore speeds as well, this difference might be because of the level of traffic, which influences the driver's acceleration behaviour.

The same comparisons were provided for categories based on SCL type, traffic rate and all vehicles. Figure 3.15 represents the mean comparison, Figure 3.16 shows the standard deviation comparison and Figure 3.17 shows the 85th percentile merging speed comparison of these categories.

Figure 3.15: Mean Merging Speed Comparison of SCL Categories for All Vehicles

Figure 3.16: Merging Speed SD Comparison of SCL Categories for All Vehicles

Figure 3.17: 85th percentile Merging Speed Comparison of SCL Categories for All Vehicles

3.5.3 Overall Acceleration Rate

Overall acceleration rate probably plays the most important role in SCL length calculation. It is very important to identify the most comfortable acceleration rate for drivers and makes a safe merging manoeuvre. Unfortunately acceleration rates used by the design manuals to generate the SCL length are not provided so that they could be compared to acceleration rates in the collected data.

Overall the acceleration rate of the collected data for all vehicles ranged from -0.78 to 5.14 m/s^2 , with a mean of 0.32 and standard deviation of 0.35 m/s^2 . The 85th percentile acceleration rate of all vehicles at all SCLs was recorded as 0.65 m/s^2 .

The mean acceleration rate of passenger cars at all SCLs was 0.33 m/s^2 with a standard deviation of 0.35 m/s^2 , and mean acceleration of heavy vehicles was 0.26 m/s^2 with standard deviation of 0.21 .

Figure 3.18 shows the mean acceleration rate comparison for PC and HV among different SCLs. Figure 3.19 represents the acceleration rate's standard deviation comparison of all SCLs for PC and HV, and the comparison of 85th percentile acceleration rate for PC and HV of all SCLs is provided in Figure 3.20.

Figure 3.18: Mean Acceleration Rate Comparison of All SCLs for All Vehicles

Figure 3.19: Acceleration Rate SD Comparison of All SCLs for All Vehicles

Figure 3.20: 85th percentile Acceleration Rate Comparison of All SCLs for All Vehicles

Among SCL categories, the mean acceleration rate for extended type SCLs was 0.24 m/s^2 with a standard deviation of 0.24, whereas for limited type SCLs the mean acceleration rate was 0.37 m/s^2 with a standard deviation of 0.38. This difference is probably due to the difference of length in these two categories. In extended type SCLs, because of a greater length drivers tend not to accelerate a lot, while in the limited type SCLs because of the limitation of SCL length, drivers tend to accelerate more to make sure that they will achieve the required speed when they get to the end of the acceleration lane.

For traffic categories, the mean of the acceleration rate at high traffic SCLs was collected as 0.38 m/s^2 with a standard deviation of 0.33, and for low traffic SCLs the mean of the acceleration rate was 0.29 m/s^2 with a standard deviation of 0.35. This shows that although it was assumed that higher traffic decreases the speed, at the same time it

changes the acceleration behaviour of drivers. The acceleration rate increases in order to make sure the sufficiency of speed at the end of SCL, consequently this raise in acceleration rate mixed with a higher traffic will increase the probability of collision.

The same comparisons were provided for categories based on SCL type, traffic rate and all vehicles. Figure 3.21 represents the mean comparison, Figure 3.22 shows the standard deviation comparison and Figure 3.23 shows the 85th percentile overall acceleration rate comparison of these categories.

Figure 3.21: Mean Acceleration Rate Comparison of SCL Categories for All Vehicles

Figure 3.22: Acceleration Rate SD Comparison of SCL Categories for All Vehicles

Figure 3.23: 85th percentile Acceleration Rate Comparison of SCL Categories for All Vehicles

3.5.4 Distribution, Correlation and Covariance of Variables

Before applying the analysis to data, it is very important to know the distribution of each variable, also check the correlation among variables. For both methods used in this study the correlation and distribution of each variable is needed to be identified, which will be discussed in next chapter.

Using SPSS (statistical software), the normality of each variable has been tested, also histograms of collected data for each variable are provided. For normality test the *Kolmogorov-Smirnov* and *Shapiro-Wilk* methods were used with a 95% confidence interval. Table 3.6 shows the normality tests results of the variables.

Table 3.6: Normality Test Results for All variables

	Kolmogorov-Smirnov(a)			Shapiro-Wilk		
	Statistic	df	Sig.	Statistic	df	Sig.
Gore Speed	0.031	1,410	0.003	0.994	1,410	0.000
Merging Speed	0.024	1,410	0.080	0.998	1,410	0.007
Overall Acceleration rate	0.097	1,410	0.000	0.893	1,410	0.000

Histograms of all variables were drawn. Figure 3.24 represents the histogram for gore speed, and Figure 3.25 and Figure 3.26 show the histogram for merging speed and overall acceleration rate. Based on normality test results and the following histograms it could be seen that distributions of gore speed and acceleration rate collected data are not perfectly normal. Since the proposed methodology's equations are based on normal distribution, in this study a normal distribution was assumed for all variables.

Figure 3.24: Gore Speed Histogram

Figure 3.25: Merging Speed Histogram

Figure 3.26: Overall Acceleration Rate Histogram

The correlation coefficient and covariance of all variables were calculated. These values were calculated between following paired variables:

- Gore speed and Merging Speed
- Gore Speed and overall Acceleration Rate
- Merging Speed and overall Acceleration Rate

The values of the correlation coefficient and covariance were calculated and used for both simulation and first order second moment reliability method. These values are shown in Appendix A. Table A-1 and Table A-2 represent the correlation coefficient of the variables. Table A-3 and Table A-4 represent the covariance of design variables. A summary of the received data is provided in Appendix B.

4.0 METHODOLOGY OF ANALYSIS

In this chapter an introduction to methods for reliability analysis will be provided. Two different methods are utilized to determine the required length of speed change lanes for vehicles. This length must be long enough so that vehicles can accelerate from the speed of the controlling curve to the speed of freeway.

Section 4.1 discusses two approaches to SCL length calculation; the first approach will discuss the current design equation for SCL length, which is based on constant acceleration. The second approach will determine the equation for SCL length calculation, where the acceleration rate is not constant.

Section 4.2 will provide an introduction to the reliability based approach for highway geometric design.

Section 4.3 will discuss the proposed reliability based method for the SCL length calculation that was used in this study.

In section 4.4 the First Order Reliability Method (FORM) will be applied to both SCL length calculation equations which were identified in section 4.1.

Section 4.5 discusses the simulation method used for SCL length calculations in this study.

4.1 Two Criteria for SCL Length Calculation

The scope of this study is to review the design of speed change lanes to find out whether the current length of SCLs or those values recommended by design manuals are adequate for motorists so that they can accelerate from their current speed to the speed of freeway or not. Safe and smooth acceleration will help the driver to merge with the traffic flow of freeway, whereas the unavailability of this required length might result in a collision.

In physics, equations of motion are equations that describe the behaviour of a system as a function of time. Sometimes this term refers to the differential equations that the system satisfies (e.g., Newton's second law or Euler–Lagrange equations), and sometimes to the solutions to those equations.

The goal of this section is to identify the best physical relationship for SCL length calculation, SCL length should be long enough to let the driver to accelerate from the vehicle's current speed to the speed of freeway. SCL length equation variables are gore speed, merging speed and overall acceleration rate. The acceleration rate could be assumed constant or non-constant for the duration of time that vehicle is in the SCL. The equations that apply to bodies moving linearly (that is in one dimension) with constant acceleration are those which have been used to solve engineering and design problems in the past. Lately the credibility of those equations for real world cases has been questioned. There are several facts that have been neglected for simplification reasons in these equations.

One incorrect assumption often employed for simplification purposes is considering the rate of acceleration to be constant. Since this is one of the three variables in SCL length calculation, it is very important to take into account the fact the acceleration rate could be not constant. In the following two sections design scenarios based on constant and non-constant acceleration rates will be reviewed, and proper equations for the non-constant acceleration scenario will be calculated.

4.1.1 Constant Acceleration Design

Currently the simplest way to calculate a length required for accelerating from a lower speed to a higher speed is Equation (4.1).

$$L = \frac{(0.278V_M)^2 - (0.278V_G)^2}{2a} \quad (4.1)$$

Based on the goal of this study, the terms in the Equation (4.1) can be defined as:

L = SCL length, m

V_M = Average running speed of vehicles in freeway or merging speed, Km/h

V_G = Average running speed on controlling curve for ramp or gore speed, Km/h

a = Overall acceleration rate, m/s^2

0.278 = Correction coefficient for (Km/h) to (m/s)

Equation (4.1) is based on two basic rules in physics:

$$a = \frac{dv}{dt}$$

$$v = \frac{dl}{dt}$$

Calculating dt from the above equations gives:

$$dt = \frac{dv}{a} , dt = \frac{dl}{v}$$

Equating dt from the two above equations results in:

$$\frac{dv}{a} = \frac{dl}{v} \xrightarrow{\text{yields}} a \cdot dl = v \cdot dv \quad (4.2)$$

Integration of the above equation yields:

$$\int a \cdot dl = \int_{v_1}^{v_2} v \cdot dv \xrightarrow{\text{yields}} a \cdot L = \frac{V_2^2 - V_1^2}{2}$$

And finally:

$$L = \frac{V_2^2 - V_1^2}{2a}$$

The coefficient (0.278) which was added to above equation for SCL length calculation accounts for the speed dimension correction where in the above equation speed is entered as meters per seconds dimensions but in Equation (4.1) speed is based on kilometres per hour. In the above calculations, acceleration was considered to be constant.

4.1.2 Non-Constant Acceleration Design

As discussed previously, there are many concerns about constant acceleration design (Fitzpatrick et al. 2006). These concerns show the need to review the constant acceleration design to take into account the possibility of a non-constant acceleration rate. In this study proper equations for non-constant acceleration are provided.

It should be mentioned that with the assumption that acceleration is non-constant, all current equations of motion, which were defined based on constant acceleration will need to be revised.

The first step in calculating satisfactory equations based on a non-constant acceleration rate is to select a variable that defines the non-constant acceleration rate, and then the type of relationship between dependent (acceleration) and independent variable/s should be identified. Finally, with having the variables, relationship type and relevant data the coefficients of non-constant acceleration rate equation can be calculated.

4.1.3 Variable Selection and Relationship Type Definition

For variable selection, there are some concerns that should be taken into account: one variable could be time which is used in equations of motion as an independent variable. The reason for this selection is that the independency of time is not questionable, but at the same time the selected variable should satisfy following concerns:

- Availability of collected data including the selected variable
- Availability of prediction models for the data generation process

Since the required data are not available and there are not many models defined based on time, another variable should be chosen to define the equation for non-constant acceleration. On the other hand, almost all data collection regarding freeway operations are based on speed. Speed is the key variable for highway geometric design where design tables provided in design manuals (TAC, AASHTO, etc.), are based on speed. At the same time there are many studies developed to predict driver behaviour and speed. With the availability of many speed prediction models, it would be easy to calculate the acceleration rate and finally identify the SCL length calculation equation.

Based on the above discussion, speed seems to be an appropriate variable to be used in a non-constant acceleration equation. After selecting this variable, the type of relationship between speed and acceleration should be defined.

There are several types of relationship functions that can define an equation for non-constant acceleration based on speed. This relationship could be second degree, exponential, logarithmic or the simple linear type. There not many models in the literature defining the type of function which represents the acceleration behaviour. For simplicity reasons, this study utilizes a linear function based on speed to define the acceleration equation. This function is represented in Equation (4.3).

$$a = Bv + C \quad (4.3)$$

Where:

a = Acceleration (m/s^2)

v = Speed (m/s)

B, C = Coefficients of linear function (B : $1/\text{s}$, C : m/s^2)

4.1.4 SCL Length Equation

Equation (4.3) defines the non-constant acceleration rate. While taking into account this assumption in the design procedure, all design equations should be revised to represent the non-constant acceleration rate. Therefore, with using this equation in calculations the new equation for SCL length can be calculated.

By definition the acceleration rate is the change of speed in a single time unit (second), as represented in the following equation:

$$a = \frac{dv}{dt}, dv = a \cdot dt \xrightarrow{\text{yi elds}} \int_{v_G}^v dv = \int_0^t a \cdot dt \quad (4.4)$$

Considering Equation (4.3) for acceleration and substituting this equation instead of acceleration in equation (4.4), the following equation is obtained:

$$\int_{v_r}^v \frac{dv}{Bv+C} = \int_0^t dt \quad (4.5)$$

Integration of Equation (4.5) leads to an equation for speed which can be used to calculate acceleration based on time:

$$\frac{1}{B} * \ln(Bv + C) \Big|_{v_0}^v = t \xrightarrow{\text{yi elds}} \ln\left(\frac{Bv + C}{Bv_G + C}\right) = Bt$$

$$\frac{Bv+C}{Bv_G+C} = e^{Bt} \xrightarrow{\text{yields}} V = \frac{e^{Bt}(Bv_G+C)-C}{B} \quad (4.6)$$

$$a = (Bv_G + C)e^{Bt} \quad (4.7)$$

Where:

a = Non-constant acceleration rate, (m/s²)

t = time (seconds)

V = Vehicle speed at time t (sec), (m/s)

V_G = Initial speed, in this case speed of vehicles entering to SCL (m/s)

B, C = Coefficients of linear equation for the non-constant acceleration calculation

As defined before in Equation (4.2) which led to the current equation for the SCL length calculation, using the same relations between acceleration, speed and length will lead to an equation for SCL length calculation based on non-constant acceleration rate.

By substituting the values for speed from Equation (4.6) and acceleration from Equation (4.7) into Equation (4.2) the following is obtained:

$$\int_{v_r}^v \left(\frac{e^{Bt}(Bv_G + C) - C}{B} \right) . dv = \int_0^l (Bv_G + C)e^{Bt} . dl$$

$$\left(\frac{e^{Bt}(Bv_G + C) - C}{B} \right) * (V - V_r) = (Bv_G + C)e^{Bt} * L$$

And finally Equation (4.8) is calculated for SCL length calculation with respect to non-constant acceleration rate.

$$L = \left(1 - \frac{C}{a}\right) * \left(\frac{V_M - V_G}{B}\right) \quad (4.8)$$

Where:

L = SCL length, m

a = Average acceleration rate of vehicles in the acceleration lane, m/s²

V_M = Average running speed of vehicles in freeway or merging speed, m/s

V_G = Average running speed while entering to SCL or gore speed, m/s

B, C = Coefficients of relation between non- constant acceleration and speed

4.2 Introduction to Reliability Based Approach for Highway Geometric Design

Ben-Akiva et al (1985) proposed an approach to highway geometric design which takes into account the probabilistic and economic factors. Compared with deterministic approach which gives one value for a design problem based on one value entered for the design variables, the new approach assumes that traffic flow characteristics are stochastic. These input variables will determine the properties of alternative designs and instead of one value, there would a distribution of values for design problem. The choice of a specific design among many other possibilities is based on the minimization of the cost factor that includes an explicit trade off between road users, construction and maintenance costs on one hand and the safety index on the other hand.

The geometric design manuals which are widely used in highway design are deterministic in character and thus ignore important probabilistic factors of highway operations. Most design values are based on two main input variables: the highway type and the design speed.

The design values for highway elements are determined from the input parameters using physical and driver behaviour relationships. The value of an input parameter is usually chosen as the 85th, 90th, or 95th percentile value of its distribution (e.g. 85th percentile speed). Using this percentile, a single design value is calculated instead of a distribution of possible design values. However, the risk is possible that for example by using the 85th percentile values for the speed and lateral acceleration distributions, the resulting design value of the horizontal radius may represent only the 70th percentile value of all desired radii. Moreover, there are design problems that cannot be solved by using unique percentile values. For example, in horizontal curves, it is desirable to have a balanced super-elevation rate that does not cause excessive positive lateral acceleration for a high speed driver, or a negative lateral acceleration for a slow moving vehicle. In this case, a high percentile value of the speed distribution may result in a poor design. Thus, it is necessary to consider the full range of potential speeds.

The second drawback of deterministic design procedures is that they are not sufficiently sensitive to important operational and economic factors such as volume, accident rate, and monetary costs. Recently, a stronger emphasis in design has been placed on economic factors. Highway construction agencies are relying increasingly on expedient and cost effective principles which are essentially below current AASHTO procedures. The U.S. federal Highway Administration is investigating the appropriateness of the

existing procedures for low volume highways. It has also been concluded that the developing countries should not uniformly adopt the highway design standards of the developed countries because of their high cost. (Ben-Akiva et al. 1985)

In this study a new approach is used for speed change lane design of highways that takes into account probabilistic factors. In this process, the designer uses all available information about values of input parameters for speed change lane (SCL) design and employs explicit design criteria. Then the designer can select the optimal design value that brings to a minimum the objective function. The following section describes the various stages of the design process, and the remainder develops the application of this approach to the design of Speed Change Lanes in highways.

4.3 Reliability-Based Analysis

4.3.1 Introduction

Navin and Zheng (1998) proposed a reliability-based method for highway geometric design which takes into account safety consequences for uncertainty; the methodology gives a definition for acceptable risk.

As stated by Navin and Zheng (1998) the proposed methodology is based on reliability theory which describes the design situation with a performance function:

$$G(X) = G(x_1 + x_2 + \cdots + x_N)$$

Where X represents the design variables, some of the variables represent Demand (D), and the other characterize the Supply (S), by convention the performance function G is written as:

$$G = S - D \quad (4.9)$$

Where $G < 0$ indicates system failure when the demand exceeds supply and $G > 0$ corresponds to system survival. The $G = 0$ is a “limit state” between survival and failure. For the “limit state” approach the designer has to take into account the demand of vehicles for a particular highway parameter (e.g. length of speed change lane or sight distance) and the supply based on current provided length or extracted from design manuals tables (such as AASHTO or TAC).

Where the supply S may be exceeded by the demand D , system failure, non-performance or non-compliance might be probable. The objective of reliability-based design is to reduce this overlapping to a relatively acceptable value.

4.3.2 Margin of Safety and Reliability Index

As stated by Navin and Zheng (1998) Margin of Safety, M , is the difference between the expected value of supply and that of the demand. The Reliability Index or the Safety Index, β , is defined as the ratio of the Margin of Safety, M , and the combined variance. They are as follows:

$$M = E(S) - E(D) \quad (4.10)$$

$$\beta = \frac{M}{\sqrt{\text{Var}(S) + \text{Var}(D)}} \quad (4.11)$$

Where, $E(S)$ = Expected value of Supply

$E(D)$ = Expected value of Demand

β = Reliability Index

M = Margin of Safety

$\text{Var}(S)$ = Variance of Supply

$\text{Var}(D)$ = Variance of Demand

Figure 4.1 is a graphical representation of the reliability index, β .

Figure 4.1: Reliability Index

Equation (4.9) shows that the probability of hazard can be obtained by calculating the probability of the event $G < 0$. However, in general, many random variables are involved in the G function and the calculation requires the joint probability density function and integration over the failure region $G < 0$. This exact procedure can rarely be applied because the required joint probability density function is not known or is difficult to obtain. As an alternative, approximate methods have been developed to estimate the probability of noncompliance. These, known as FORM/SORM procedures (First Order or Second Order Reliability Methods), are based on a reliability index β , from which the probability of hazard P_h can be estimated using the standard normal probability distribution function $\Phi(\beta)$ as represented in Equation (4.12). The relationship between β and P_h is unique. In particular, the probability of hazard decreases with increasing values of β .

$$P_h = \Phi(-\beta) = 1 - \Phi(\beta) \quad (4.12)$$

4.3.3 Types of Reliability Analysis

There are several probabilistic methods for obtaining the distribution of performance function G . There are three main categories and each method can be categorized under one of them. These main categories are: simulation method, first-order second-moment, and point estimate method. For the first method just like Monte Carlo Simulation, the results can be derived by using computers to generate a series of numbers for input variables (in rows) and each column should follow a predefined distribution with specific characteristics. Then a physical relationship (equation) uses the generated

numbers to calculate the design element. The calculated results would describe the probable distribution of the output.

The second method is based on a truncated expansion of Taylor series. The following equations describe the mean and variance of design equation; these equations are calculated based on First Order Reliability Method (FORM):

$$E(Y) \approx f(\mu_{x1}, \mu_{x2}, \dots, \mu_{xn}) \quad (4.13)$$

$$Var(Y) = \sum_{i=1}^n \left(\left(\frac{\partial f}{\partial x_i} \right)^2 \sigma_{x_i}^2 \right) + \sum \sum_{i \neq j}^n \left(\frac{\partial f}{\partial x_i} \right) \left(\frac{\partial f}{\partial x_j} \right) COV[x_i, x_j] \quad (4.14)$$

Where μ_{xi} and σ_{xi} are the mean and standard deviation of x_i , and $COV [x_i, x_j]$ is the covariance between x_i and x_j . The covariance term in Equation (4.14) takes into account the correlation between the variables, in case the variables were correlated, which in this study variables are gore speed, merging speed and overall acceleration rate. The other simple method for calculating this covariance is to use the standard deviation of the variables and the correlation coefficient between them:

$$cov[x_i, x_j] = \rho_{xi,xj} * \sigma_{xi} * \sigma_{xj} \quad (4.15)$$

The disadvantage of this method can be seen when dealing with complex equations, because it would be difficult to conduct the derivations on such an equation.

By including the second-derivative terms in a truncated Taylor series the Second Order Reliability Method (SORM) is obtained. In this case the calculations of mean and derivations would be even more difficult, mainly with complex equations, but the variance of SORM usually taken the same as FORM.

Equation (4.16) provides the Taylor series expansion of a general nonlinear function $g(X_1, X_2, \dots, X_n)$ at the value $(x_1^*, x_2^*, \dots, x_n^*)$:

$$g(X_1, X_2, \dots, X_n) = g(x_1^*, x_2^*, \dots, x_n^*) + \sum_{i=1}^n (x_i - x_i^*) \frac{\partial g}{\partial x_i} + \frac{1}{2} \sum_{i=1}^n \sum_{j=1}^n (x_i - x_i^*)(x_j - x_j^*) \frac{\partial^2 g}{\partial x_i \partial x_j} + \dots \quad (4.16)$$

4.4 Application of First-Order Reliability Method (FORM) in Design Procedures

The reliability analysis and its common methods in transportation engineering has been introduced in previous sections. In this section First-Order Reliability Method (FORM) will be applied to two design criteria:

- I. Constant Acceleration Design
- II. Non-Constant Acceleration Design

Section 4.1.1 will discuss the application of FORM on the constant acceleration design procedure and its verification. Section 4.1.2 will introduce the results of application of FORM method on the non-constant acceleration design procedure and its verification.

4.4.1 Application of FORM on Constant Acceleration Design Procedure

As defined in the reliability analysis types section, the First Order Reliability Method (FORM) calculates the mean and the variance of the performance function. Using a first order reliability method, by applying Equations (4.13) and (4.14) to Equation (4.1) the following equations will be obtained:

$$E(L) = f(\mu_{V_M}, \mu_{V_G}, \mu_a) \quad (4.17)$$

$$Var(L) = \left(\frac{\partial L}{\partial V_M} \right)^2 \sigma_{V_h}^2 + \left(\frac{\partial L}{\partial V_G} \right)^2 \sigma_{V_r}^2 + \left(\frac{\partial L}{\partial a} \right)^2 \sigma_a^2$$

Where:

$$\frac{\partial L}{\partial V_h} = \frac{V_M}{13a}$$

$$\frac{\partial L}{\partial V_r} = \frac{-V_G}{13a}$$

$$\frac{\partial L}{\partial a} = \frac{-26(V_M^2 - V_G^2)}{(26a)^2}$$

The variance would be:

$$Var(L) = \left(\frac{V_M}{13a} \right)^2 \sigma_{V_M}^2 + \left(\frac{-V_G}{13a} \right)^2 \sigma_{V_G}^2 + \left(\frac{-26(V_M^2 - V_G^2)}{(26a)^2} \right)^2 \sigma_a^2 \quad (4.18)$$

4.4.2 Application of FORM on Non-Constant Acceleration Design Procedure

For the non-constant acceleration design procedure the same progress is followed. This means Equations (4.13) and (4.14) are applied to Equation (4.8) yielding:

$$E(L) = f(\mu_{V_M}, \mu_{V_G}, \mu_a) \quad (4.19)$$

$$Var(L) = \left(\frac{\partial L}{\partial V_M} \right)^2 \sigma_{V_h}^2 + \left(\frac{\partial L}{\partial V_G} \right)^2 \sigma_{V_r}^2 + \left(\frac{\partial L}{\partial a} \right)^2 \sigma_a^2$$

Where:

$$\frac{\partial L}{\partial V_M} = \left(1 - \frac{C}{a} \right) * \left(\frac{1}{B} \right)$$

$$\frac{\partial L}{\partial V_G} = \left(1 - \frac{C}{a} \right) * \left(-\frac{1}{B} \right)$$

$$\frac{\partial L}{\partial a} = \left(\frac{C}{a^2} \right) * \left(\frac{V_M - V_G}{B} \right)$$

The variance would be:

$$Var(L) = \left(\left(1 - \frac{C}{a} \right) * \left(\frac{1}{B} \right) \right)^2 \sigma_{V_M}^2 + \left(\left(1 - \frac{C}{a} \right) * \left(-\frac{1}{B} \right) \right)^2 \sigma_{V_G}^2 + \left(\left(\frac{C}{a^2} \right) * \left(\frac{V_M - V_G}{B} \right) \right)^2 \sigma_a^2 \quad (4.20)$$

4.5 Simulation Method

4.5.1 Introduction

There are several methods with various degrees of complexity that can be used to estimate the reliability or safety index or the probability of hazard. Many of these methods are applicable when the limit state equations are explicit functions of the random variables involved in a problem. Using the FORM method it is possible to evaluate reliability when the limit state equations are implicit functions of the random variables involved in a problem. In any case, estimating the probability of hazard using these reliability techniques requires a strong background in probability and statistics, but with a simple simulation technique, it is possible to calculate the probability of hazard for both the explicit or implicit limit state functions without having strong knowledge on these complicated analytical techniques. In fact, to evaluate the accuracy of these sophisticated techniques (e.g. FORM or SORM) or to verify a new technique, simulation is routinely used to independently evaluate the underlying probability of hazard. In this study, a simulation technique was used to verify/support results from FORM method.

In the simplest form of the basic simulation, each random variable in a problem is sampled several times to represent its real distribution according to its probabilistic characteristics. Considering each set of all the random variables in the problem produces a set of numbers that indicates one realization of the problem itself. Solving the problem deterministically for each realization is known as a simulation cycle, trial or run. Using many simulation cycles gives the overall probabilistic characteristics of the problem, particularly when the number of cycles N tends to infinity.

4.5.2 Monte Carlo Simulation Technique

The simulation method used in this study for the reliability evaluation is called Monte Carlo Simulation. The Monte Carlo simulation technique has six essential elements (Lindqvist and Doksum 2003):

- 1- Defining the problem in terms of all random variables;
- 2- Generating the random numbers;
- 3- Quantifying the probabilistic characteristics of all random variables;
- 4- Evaluating the problem deterministically for each set of realizations of all random variables, that is, numerical experimentation;
- 5- Extracting the probabilistic information from N such realizations; and
- 6- Determining the accuracy of the simulation.

In following sections all six elements will be discussed in relation to the purpose of this study.

4.5.3 Formulation of the Problem

The purpose of this study is to evaluate the probabilistic characteristics of the SCL length calculation. As discussed in Section 4.1.1, Equation (4.1) defines the physical relationship among the design variables for constant acceleration SCL design (length, speed at gore, merging speed and overall constant acceleration rate).

$$L = \frac{(0.278V_M)^2 - (0.278V_G)^2}{2a} \quad (4.1)$$

Equation (4.8) describes the physical relationship of variables for non-constant acceleration SCL design:

$$L = \left(1 - \frac{C}{a}\right) * \left(\frac{(0.278V_M) - (0.278V_G)}{B}\right) \quad (4.21)$$

Where:

L = SCL length, m

V_M = Freeway speed, Km/h

V_G = Speed at the end of controlling curve for ramp, Km/h

a = Overall acceleration rate, m/s²

B, C = Coefficients of relation between non- constant acceleration and speed

4.5.4 Generation of Random Numbers

Using Microsoft Excel uncorrelated random numbers have been generated, for each variable 60,000 random numbers have been generated. The reason for generating 60,000 random numbers for each variable will be discussed in following sections.

4.5.5 Quantifying the Probabilistic Characteristics of Random Variables

After generating the random numbers, probabilistic characteristics of variables had to be applied to these random numbers. As discussed in previous chapters variables in SCL length equation are correlated and this correlation has to be applied to the generated random numbers.

Several attempts were made to apply the correlation among the variables to random numbers. Several issues emerged after applying the correlation. These issues were related to the relation among variables. The resulting correlated random numbers did not reflect the physical relationship between gore speed, merging speed and acceleration rate. For example, in most data records the random acceleration rate could not satisfy the change in speed. To resolve this issue, it was important to take into account the physical relationship among these variables. This relationship is represented in Equation (4.22).

$$a = \frac{V_M - V_G}{t} \quad (4.22)$$

Where t is the required time for acceleration/deceleration from V_G to V_M .

To resolve this issue, the “required time” for acceleration/deceleration was used in the analysis in order to satisfy the physical relationship between speed and acceleration, which was defined in Equation (4.22).

The correlation between time, gore speed and merging speed was calculated and after generating 60,000 uncorrelated random numbers for each variable in Excel, uncorrelated random numbers were moved to *Matlab*. By applying the *Cholesky* decomposition method to the correlation matrix of variables, and finally by multiplying the correlation

matrix with uncorrelated random numbers, correlated random numbers for gore speed, merging speed and time were generated. The following process is an example of the *Cholesky* decomposition method for correlating a random uncorrelated array of numbers (Kaiser and Dichman 1962):

$$\text{Correlation Matrix} = C = \begin{bmatrix} 1 & 0.6 & 0.3 \\ 0.6 & 1 & 0.5 \\ 0.3 & 0.5 & 1 \end{bmatrix}$$

Doing Cholesky decomposition on the correlation matrix gives the following matrix:

$$U = \begin{bmatrix} 1 & 0.6 & 0.3 \\ 0 & 0.8 & 0.4 \\ 0 & 0 & 0.866 \end{bmatrix}$$

It is possible now to transform following three uncorrelated random numbers (R) into correlated numbers (R_c) by multiplying them with the U matrix:

$$\begin{aligned} R &= [-0.3999 \quad -1.6041 \quad -1.0106] \\ R_c &= R * U = [-0.3999 \quad -1.6041 \quad -1.0106] * \begin{bmatrix} 1 & 0.6 & 0.3 \\ 0 & 0.8 & 0.4 \\ 0 & 0 & 0.866 \end{bmatrix} \\ &= [-0.3999 \quad -1.5232 \quad -1.6368] \end{aligned}$$

Correlated random numbers were moved back to Microsoft Excel and using the statistical characteristics of each variable (distribution, mean and standard deviation) the values for time, gore speed and merging speed have been generated.

Based on the fact that the collected data did not cover the whole population, unacceptable random values for each variable have been excluded. For example negative values for speeds and time were excluded.

Having the random variables for gore speed, merging speed and time, and using Equation (4.22) the resulting and satisfactory random values for overall acceleration rate have been calculated.

Finally the correlation among the random variables was calculated again and compared with the correlation coefficient calculated from the collected data. The reason for generating 60,000 random numbers lies in the final correlation evaluation among the random variables. Because of excluding large number of unacceptable generated variables, the generation of 60,000 random numbers was necessary, in order to reflect the same correlation among the variables after removing unacceptable values for variables. A summary of the steps taken in the simulation method is provided in Appendix C.

4.5.6 Numerical Experimentation

N random numbers for each variable in the problem (gore speed, merging speed and overall acceleration rate) will give N sets of random numbers for SCL length. Thus, using the Equation (4.1) and solving the problem N times deterministically gave N sample points for SCL length, essentially generating information on the randomness in the output or response of the system to each set of input variables. The N generated sample points for the output was used to calculate all the required sample statistics, the histogram, the frequency diagram, and the probability of hazard considering various performance criteria, which will be discussed in following chapter.

4.5.7 Extracting Probabilistic Information

A simulation method was used to evaluate the risk or reliability of the current provided length of SCL for the entrance terminals that had an available speed profile; also these results will be compared with the recommended SCL lengths in design manuals (AASHTO and TAC). Considering Equation (4.9) for the limit state calculation, a collision mode could be identified.

It is known that if the value of $G()$ is less than zero, it indicates collision. Having the simulation results for each sample point, N_h number of simulation cycles when $G()$ is less than zero could be calculated and knowing N the total number of simulation cycles. Then probability of hazard (P_h) of simulation method would be expressed as Equation (4.23)

$$P_h = \frac{N_h}{N} \quad (4.23)$$

4.5.8 Accuracy and Efficiency of Simulation

Because the ability of simulation method to accurately estimate the probability of hazard is a matter of concern, and obviously accuracy of the estimate depends on the number of simulation cycles, in this study a large number of cycles was generated in order to get more accurate results. There were several ways of studying the accuracy of Equation (4.23), one way is to evaluate the variance or COV of the estimated probability of hazard (Ayyub and Haldar, 1985). In current study, this method was used to evaluate the accuracy of simulation method results. According to the method, the variance or COV can be estimated by assuming each simulation cycle to constitute a Bernoulli trial, and

the number of failures in N trials can be considered to follow a binomial distribution.

Then, the COV of P_h could be expressed as Equation (4.24).

$$COV(P_h) = \delta_{P_h} \approx \frac{\sqrt{\frac{(1-P_h) \cdot P_h}{N}}}{P_h} \quad (4.24)$$

A smaller value of δ_{P_h} represents a more accurate value of P_h . Equation (4.24) indicates that δ_{P_h} approaches zero as N approaches infinity.

In this chapter, the methodology used in this study was discussed in detail. In following chapter the analysis results are presented followed by a comprehensive discussion.

5.0 ANALYSIS AND RESULTS

The methodology, study area, data categories have been discussed in previous chapters. As mentioned in Chapter 3 data were categorized into two main categories based on vehicle type (passenger car and heavy vehicle), and subcategories were defined based on traffic volume, site location and SCL geometry. In this chapter FORM and simulation methods will be applied to each category and the results will be presented. It should be mentioned that the main benefit of FORM method is that instead of a single solution for SCL length design (as it is in design manuals, e.g. AASHTO and TAC), a distribution of possible values for the problem will be available for designer, and designer could make a choice based on the distribution of possible lengths.

In Chapter 4, two possible design criteria were discussed for SCL length calculation, which are based on constant and non-constant acceleration rates. After analysing the received data it was observed that acceleration rate was constant for the majority of the vehicles on SCLs. This could be the result of the short length of SCLs, because the longest SCL length was 1366 meters, and in this short length most of vehicles are accelerating with a constant acceleration rate. Figure 5.1 and Figure 5.2 represent speed-time graphs of two random selected SCLs. From each SCL, five vehicles were selected randomly and their speed-time graph was drawn. As shown in the figures, all randomly selected vehicles had linear speed graphs which represent a constant acceleration rate for each vehicle. It should be mentioned that R-squared value for all trend lines in the figures were greater than 0.77.

Figure 5.1: Speed-Time Graph of Five Randomly Selected Vehicles (SCL 1)

Figure 5.2: Speed-Time Graph of Five Randomly Selected Vehicles (SCL 2)

Based on the above discussion the non-constant acceleration design criteria was not taken into account in this study and results which are provided in this chapter are based on constant acceleration rate equations.

In this chapter, section 5.1 provides the results of analysis and related discussions for PC and categories for PC based on SCL type, traffic level and site geometry. In section 5.2 the analysis of HV and categories for HV are provided, followed with comprehensive discussions.

5.1 Passenger Cars (PC)

For each subcategory under PC category, separate data sheets have been prepared and statistical characteristics were calculated. Using those statistical characteristics both methods were applied and mean and standard deviation for required SCL length were calculated. The following sections will provide the results of each subcategory for passenger cars.

5.1.1 PC Site by Site Analysis

As mentioned in previous chapters, the study area covered fifteen acceleration lanes on Highway 417 (Queensway). Detailed information on study area can be found in Chapter 3. In this section, the results of applying FORM and simulation methods to the data of each SCL are presented. The output of FORM method is mean and standard deviation of required SCL length for comfortable acceleration and safe merging for PC of

those fifteen SCLs. For 85th percentile required SCL length 4,000 random numbers were generated in Excel and using the mean and standard deviation a normal distribution for SCL length was generated and 85th percentile SCL length was extracted from the distribution. A summary of FORM results is provided in Table 5.1. As shown in the Table 5.1 the mean of length ranges from 81.60 to 213.21 meters and standard deviation calculated using FORM method ranges from 25.99 to 166.07 meters, and 85th percentile required length of FORM method is in the range of 108.74 to 383.18 meters.

Table 5.1: Summary of FORM Results

SCL		FORM Results	Current length(m)	SCL		FORM Results	Current length(m)
Carp Rd(S-E)	μ Length	213.21	430	Richmond(S-E)	μ Length	97.25	321
	σ Length	143.66			σ Length	56.72	
	85th:	383.18			85th:	159.1	
Castelfrank(NS-E)	μ Length	162.91	696	St_Laurent(N-W)	μ Length	174.2	881
	σ Length	118.85			σ Length	110.21	
	85th:	301.83			85th:	300.01	
Eagleson(N-W)	μ Length	161.23	673	Terryfox(N-W)	μ Length	164.32	419
	σ Length	30.11			σ Length	116.68	
	85th:	192.81			85th:	299.76	
Eagleson(S-E)	μ Length	129.51	327	Terryfox(S-E)	μ Length	168.56	437
	σ Length	166.07			σ Length	149.19	
	85th:	333.09			85th:	344.86	
Greenbank(S-E)	μ Length	173.68	1366	Vanier(N-W)	μ Length	141.78	800
	σ Length	142.17			σ Length	142.94	
	85th:	343.42			85th:	312.15	
Maitland(NS-E)	μ Length	168.06	468	Woodroffe(NS-W)	μ Length	92.6	346
	σ Length	45.34			σ Length	67.05	
	85th:	216.81			85th:	171.1	
Moodie(N-W)	μ Length	105.19	323	Woodroffe(S-E)	μ Length	160.84	1222
	σ Length	163.41			σ Length	107.54	
	85th:	324.17			85th:	279.99	
Parkdale(NS-W)	μ Length	81.6	188				
	σ Length	25.99					
	85th:	108.74					

* μ Length and * σ Length: Mean and standard deviation of calculated required SCL length using FORM

method.

Also using the results of simulation method mean, standard deviation and 85th percentile of required length were calculated, and are presented in Table 5.2 for each SCL. As shown in the Table 5.2 the mean of lengths calculated using simulation method ranges from 86.75 to 221.28 meters and standard deviation calculated using results of simulation method ranges from 27.81 to 89.44 meters, and finally 85th percentile required length of simulation method is in the range of 115.50 to 291.15 meters.

Table 5.2: Summary of Simulation Method Results

SCL		FORM Results	Current length(m)	SCL		FORM Results	Current length(m)
Carp Rd(S-E)	μ Length	221.28	430	Richmond(S-E)	μ Length	99.08	321
	σ Length	71.25			σ Length	45.22	
	85th:	295.15			85th:	146.56	
Castelfrank(N-S-E)	μ Length	178.37	696	St_Laurent(N-W)	μ Length	197.36	881
	σ Length	80.45			σ Length	89.4	
	85th:	262.86			85th:	291.45	
Eagleson(N-W)	μ Length	193.11	673	Terryfox(N-W)	μ Length	173.11	419
	σ Length	74.13			σ Length	59.8	
	85th:	269.65			85th:	234.84	
Eagleson(S-E)	μ Length	164.5	327	Terryfox(S-E)	μ Length	171.71	437
	σ Length	70.61			σ Length	56.82	
	85th:	237.48			85th:	230.42	
Greenbank(S-E)	μ Length	190.37	1366	Vanier(N-W)	μ Length	149.95	800
	σ Length	89.44			σ Length	57.31	
	85th:	284.43			85th:	209.44	
Maitland(NS-E)	μ Length	179.3	468	Woodroffe(NS-W)	μ Length	106.48	346
	σ Length	61.58			σ Length	42.44	
	85th:	242.86			85th:	150.56	

Moodie(N-W)	μ Length	131.46	323	Woodroffe(S-E)	μ Length	171.85	1222
	σ Length	52.26			σ Length	75.8	
	85th:	185.86			85th:	251.07	
Parkdale(NS- W)	μ Length	86.75	188				
	σ Length	27.81					
	85th:	115.5					

* μ Length and * σ Length: Mean and standard deviation of calculated required length using SCL simulation method.

Also mean, standard deviation and 85th percentile of lengths which were collected for vehicles in each SCL were calculated and presented in

Table 5.3. As shown in the

Table 5.3 the mean of collected required length for each vehicle ranges from 85.72 to 220.80 meters and standard deviation calculated from collected data ranges from 25.73 to 95.37 meters, and finally 85th percentile required length of collected data is in the range of 109.49 to 318.37 meters.

Table 5.3: Summary of Collected Data

SCL		FORM Results	Current length(m)	SCL		FORM Results	Current length(m)
Carp Rd(S-E)	*μ Length	220.8	430	Richmond(S-E)	μ Length	96.86	321
	*σ Length	69.72			σ Length	45.96	
	85th:	293.12			85th:	126.29	
Castelfrank(N-S-E)	μ Length	173.84	696	St_Laurent(N-W)	μ Length	193.91	881
	σ Length	81.5			σ Length	95.37	

	85th:	254			85th:	318.37	
Eagleson(N-W)	μ Length	191.18	673	Terryfox(N-W)	μ Length	172.66	419
	σ Length	70.7			σ Length	60.91	
	85th:	258.9			85th:	217.73	
Eagleson(S-E)	μ Length	161.06	327	Terryfox(S-E)	μ Length	170.84	437
	σ Length	66.42			σ Length	55.9	
	85th:	230.07			85th:	230.09	
Greenbank(S-E)	μ Length	185.55	1366	Vanier(N-W)	μ Length	148.17	800
	σ Length	94.17			σ Length	57.42	
	85th:	251.39			85th:	203.18	
Maitland(NS-E)	μ Length	177.64	468	Woodroffe(NS-W)	μ Length	105.13	346
	σ Length	65.92			σ Length	42.26	
	85th:	248.31			85th:	150.62	
Moodie(N-W)	μ Length	129.75	323	Woodroffe(S-E)	μ Length	169.76	1222
	σ Length	52.29			σ Length	82.18	
	85th:	176.58			85th:	242.92	
Parkdale(NS-W)	μ Length	85.72	188				
	σ Length	25.73					
	85th:	109.49					

* μ Length and * σ Length: Mean and standard deviation of calculated required SCL length using Collected

Data.

With a preliminary comparison between the results from FORM and the simulation method, it could be found that in all SCLs the value of mean from FORM method is smaller than simulation mean and the mean of collected data, also in all SCLs the mean from the simulation method is greater than the mean of the collected data. In Figure 5.3 the results of the mean of length from FORM, and the simulation method and collected data have been compared.

Figure 5.3: Mean Comparison for PC Site by Site Analysis

On the other hand as shown in Figure 5.4 the value of standard deviation from FORM method, is greater than those from the collected data and simulation method.

Figure 5.4: Standard Deviation Comparison for PC Site by Site Analysis

Also using the mean and standard deviation, the required 85th percentile length was calculated for each site, Figure 5.5 represents the calculated 85th percentile length for each site. In most cases FORM method has a greater 85th percentile length, because of a greater standard deviation.

Figure 5.5: 85th percentile Required Length Comparison for PC Site by Site

Analysis

5.1.2 PC Site by Site Comparison with Design Manuals Recommended Lengths

Based on highway 417 posted speed (100 km/h) and each SCL's controlling curve posted speed, the design speed of freeway was assumed to be 120 km/h and the design speed of controlling curves of SCLs assumed to be 80 km/h. Using the design speeds, the

recommended SCL lengths by AASHTO (2004) and TAC (1999) were extracted from the design tables. Based on the inputs it was assumed that the longest possible length was the recommended length by design manuals. Where the freeway design speed is 120 km/h and entrance curve design speed is 80 km/h, AASHTO (2004) recommends 245 meters for SCL length, and TAC (1999) recommends a SCL length in the range of 195 to 430 meters. In this study, 312 meters for SCL length was chosen as the recommended length by TAC (1999), this value is the middle point of the recommended length.

Figure 5.6 represents the comparison between the results for the mean of the required SCL length of FORM, simulation method and collected data, with the SCL lengths recommended by AASHTO (2004) and TAC (1999).

Figure 5.6: Design Manuals Recommendations Comparison with Mean Length of Analysis

As shown in Figure 5.6, TAC (1999) offers a more reliable length for SCLs. The major issue with design manuals was found to be the limited possibilities for controlling curves with speeds higher than 80 (km/h), where collected data shows that vehicles have greater speeds when they reach the gore point. This problem was discussed in literature review as one of major problems with the design manuals' assumptions (Fitzpatrick et al. 2006).

Also the collected data show that the merging speed of several SCLs is greater than the freeway posted speed. This is the other assumption made by design manuals that seems to be wrong in most cases, because design manuals assume that vehicles will have a lower speed than the freeway posted speed when they merge with the freeway traffic flow (Fitzpatrick et al. 2006).

Also the comparison of the 85th percentile required length (resulting from the analysis and collected data) with design manuals length recommendations shows that in some sites a longer length is required for acceleration. Figure 5.7 shows the comparison between 85th percentile required length from the analysis and collected data with the recommended length recommended by the design manuals.

Figure 5.7: Comparison of 85th percentile Required Length with Design Manuals Recommendations

As shown in Figure 5.7 in some SCLs the 85th percentile required length for acceleration is greater than the one recommended by both design manuals.

In following section using the analysis results the safety index and probability of hazard of each SCL will be calculated.

5.1.3 Probability of Hazard of SCLs (PC Site by Site Analysis)

The methodology for the probability of hazard calculation was discussed in Section 4.3.2, in this section the probability of hazard (P_h) using the results of FORM and simulation method will be calculated based on AASHTO (2004), TAC (1999) length recommendation and the current provided SCL length.

Using the equation provided for safety index calculation in Chapter 4, safety index values of FORM method were calculated, and then based on the safety index the probability of hazard (P_h) of each SCL was calculated.

Table 5.1 provides the safety index values based on design manuals' recommendations and the current provided length. A negative safety index indicates that mean of calculated required SCL length is smaller than design manual recommendations or current provided length.

Table 5.4: Safety Index Values of FORM Method Results (PC site by Site analysis)

SCL	Safety Index (β)		
	AASHTO	TAC (1999)	Current Length
Carp Rd(S-E)	-0.22	-0.69	-1.51
Castelfrank(NS-E)	-0.69	-1.25	-4.49
Eagleson(N-W)	-2.78	-5.01	-17.00
Eagleson(S-E)	-0.70	-1.10	-1.19
Greenbank(S-E)	-0.50	-0.97	-8.39
Maitland(NS-E)	-1.70	-3.17	-6.61
Moodie(N-W)	-0.86	-1.27	-1.33
Parkdale(NS-W)	-6.29	-8.86	-4.09
Richmond(S-E)	-2.61	-3.79	-3.95
St_Laurent(N-W)	-0.64	-1.25	-6.41
Terryfox(N-W)	-0.69	-1.27	-2.18
Terryfox(S-E)	-0.51	-0.96	-1.80
Vanier(N-W)	-0.72	-1.19	-4.60
Woodroffe(NS-W)	-2.27	-3.27	-3.78
Woodroffe(S-E)	-0.78	-1.41	-9.87

Using above safety index values, probability of hazard for each length is calculated, Figure 5.8 represents the probability of hazard for each site. The probability values are out of one, this means 0.5 represents 50 percentile probability of hazard.

Figure 5.8: Probability of Hazard Using FORM Method Results

As shown in Figure 5.8 based on provided lengths with design manuals, in most sites there would be a high probability of hazard, as mentioned before TAC (1999) recommends more reliable SCL lengths compared to AASHTO (2004), where probability of hazard of AASHTO (2004) recommended length in most sites is greater than the one of TAC (1999).

The current provided SCL length in most sites is greater than the recommendations made in both design manuals, but still in five SCLs there is high probability of hazard.

The probability of hazard from the simulation method was calculated as discussed in Chapter 4. The simulation method's probability of hazard was calculated based on three values which are AASHTO (2004) SCL length recommendation, TAC (1999) SCL length recommendation and current provided SCL length of each site. Figure 5.9 represents the values of P_h for each SCL.

Figure 5.9: Probability of Hazard based on Simulation Method Results

Again as shown in Figure 5.9, TAC (1999) recommends more reliable SCL length compared to AASHTO (2004), but still collision is probable in some SCLs. Overall the comparison between probabilities resulting from both methods show that because simulation method showed a greater mean but smaller standard deviation compared to FORM method, the probabilities calculated using simulation method are smaller than those ones calculated using FORM method.

As discussed in Chapter 4, the accuracy of P_h resulting from simulation method could be evaluated. By calculating the covariance of P_h using the methodology provided in Chapter 4, the accuracy of the simulation method can be measured.

Table 5.5 shows the COV of P_h values resulting from the simulation method. It should be mentioned that a smaller COV represents a more accurate value for P_h .

Table 5.5: Covariance of Calculated P_h

SCL	Covariance of Pf	
	AASHTO	TAC
Carp Rd(S-E)	0.005	0.012
Castelfrank(NS-E)	0.008	0.018
Eagleson(N-W)	0.007	0.017
Eagleson(S-E)	0.011	0.030
Greenbank(S-E)	0.007	0.013
Maitland(NS-E)	0.010	0.032
Moodie(N-W)	0.033	0.246
Parkdale(NS-W)	1.358	4.567
Richmond(S-E)	0.163	3.658
St_Laurent(N-W)	0.006	0.012
Terryfox(N-W)	0.011	0.040
Terryfox(S-E)	0.012	0.049
Vanier(N-W)	0.018	0.084
Woodroffe(NS-W)	0.174	5.102
Woodroffe(S-E)	0.009	0.022

5.1.4 PC Categories

This section presents the analysis of the categories for PC which are based on traffic and geometry of SCLs.

The analysis results for FORM method, simulation method and collected data of the categories have been summarized in Table 5.6.

Table 5.6: Analysis Results of PC Categories

Category		FORM	Simulation	Collected Data
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ALL PC	μ Length	146.07	159.69	157.70
	σ Length	126.74	72.19	75.74
	85th:	290.54	234.67	235.77
PC Extended SCL	μ Length	165.03	181.47	178.46
	σ Length	137.67	79.88	82.72
	85th:	317.23	264.16	257.14
PC Limited SCL	μ Length	139.36	147.97	146.65
	σ Length	116.50	66.15	69.31
	85th:	277.11	216.72	220.63
PC High Traffic SCL	μ Length	176.03	179.04	176.00
	σ Length	120.26	78.67	81.31
	85th:	312.30	260.33	253.46
PC Low Traffic SCL	μ Length	121.28	146.54	147.46
	σ Length	120.09	62.88	70.44
	85th:	263.84	211.89	223.53

* μ Length and * σ Length: Mean and standard deviation of calculated required SCL length

As shown in Table 5.6 for most of the categories, the analysis shows that mean resulted from FORM method is smaller than the mean of collected data, and the mean of collected data is smaller than the mean resulted from simulation method. Also FORM resulted in a greater standard deviation compared to the simulation method and collected data.

It can be seen in Table 5.6 that, the required SCL length in extended and high traffic SCLs is longer than the required length for limited and low traffic SCLs. This shows the effect of traffic rate on the required length for acceleration. Figure 5.10 is a better representation on this discussion since it shows the mean comparison of analysis results with collected data.

Figure 5.10: PC Categories Mean Comparison

Also the comparison of standard deviation of required length resulted from analysis and collected data is provided in Figure 5.11. Figure 5.12 represents the 85th percentile required length of these categories.

Figure 5.11: PC Categories SD Comparison

Figure 5.12: PC Categories 85th percentile Length Comparison

As discussed above and shown in Figure 5.10 and Figure 5.12, traffic level highly affects the required length of SCL.

5.1.5 Comparison of PC Categories Analysis with Design manuals

In this section the analysis results for PC categories are compared with the length recommendations by AASHTO (2004) and TAC (1999). Figure 5.13 shows the mean comparison and Figure 5.14 represents the resulted 85th percentile required SCL length with recommended lengths from the design manuals.

Figure 5.13: PC Categories Mean Comparison with Design Manuals

Recommendation

Figure 5.14: PC Categories 85th percentile Length Comparison with Design Manuals Recommendation

As shown in Figure 5.14 the recommended SCL length from both design manuals do not satisfy the required length in extended and high traffic SCLs, but in all categories the TAC (1999) length recommendation is a more reliable value.

5.1.6 Safety index and Probability of Hazard of PC Categories

Using the same methodology which was discussed in Chapter 4, the safety index and probability of hazard (P_h) of FORM method were calculated for PC categories.

Table 5.7 shows the safety index values of PC categories which were calculated using recommended SCL length by design manuals.

Table 5.7: Safety Index Values of PC Categories

Category	Safety Index (β)	
	AASHTO (2004)	TAC (1999)
ALL PC	-0.78	-1.31
PC Extended SCL	-0.58	-1.07
PC Limited SCL	-0.91	-1.48
PC High Traffic SCL	-0.57	-1.13
PC Low Traffic SCL	-1.03	-1.59

Using safety index values represented in

Table 5.7, P_h values of FORM method were calculated and shown in Figure 5.15. As shown in Figure 5.15, for all categories the calculated P_h value of AASHTO (2004) is greater than TAC (1999), but the P_h is greater than 10 percent in most categories for both recommended SCL lengths.

Figure 5.15: FORM Method's Probability of Hazard

Figure 5.16 represents the calculated values for P_h based on the simulation method results, the same pattern could be observed from the results of simulation method but the values of P_h for simulation method are smaller than the values of P_h calculated based on FORM method results. Compared to simulation method, FORM method results show that a longer SCL length is required.

Figure 5.16: Simulation Method's Probability of Hazard

The accuracy of the simulation method for PC categories has been evaluated and the results are provided in

Table 5.8. it should be mentioned the smaller values for COV represent a more accurate simulation.

Table 5.8: Covariance of P_h

Category	Covariance of P_h	
	AASHTO (2004)	TAC (1999)
ALL PC	0.011	0.031
PC Extended SCL	0.008	0.018
PC Limited SCL	0.015	0.050
PC High Traffic SCL	0.008	0.019
PC Low Traffic SCL	0.016	0.062

5.2 Heavy Vehicles (HV) Analysis

In this section the analysis of heavy vehicles categories will be provided, in order to evaluate the effect of vehicle type on the required length of SCL. In most cases it is assumed that HV require a longer length for acceleration, in this section this idea will be discussed.

The analysis were applied to the same categories as they were for passenger cars. This means first site by site analysis were studied, and the analysis were followed by HV categories based on SCL geometry and level of traffic.

It should be mentioned that three SCLs were excluded from analysis, because the collected data for these SCLs were less than what was required to perform accurate analysis. These sites are: Moodie (N-W), Woodroffe (NS-W) and Woodroffe (S-E).

5.2.1 HV Site By Site Analysis

FORM and simulation methods were applied to HV data collected from each SCL, mean (μ), Standard Deviation (SD) and 85th percentile required length for HV of each SCL calculated, the results of analysis and the collected data are presented in Table 5.9.

Table 5.9: HV Site by Site Analysis Results

SCL		FORM Results	Simulation Results	Collected Data
Carp Rd(S-E)	μ Length	224.46	208.92	205.72
	σ Length	138.77	53.58	41.24
	85th:	398.74	264.13	228.63
Castelfrank(NS-E)	μ Length	211.48	212.32	210.48
	σ Length	75.67	33.33	27.83
	85th:	306.12	246.60	238.59
Eagleson(N-W)	μ Length	204.10	218.00	214.80
	σ Length	64.95	64.87	53.49
	85th:	281.03	284.79	247.54
Eagleson(S-E)	μ Length	138.12	160.26	162.12
	σ Length	117.24	59.90	68.73
	85th:	283.36	222.42	220.20
Greenbank(S-E)	μ Length	162.51	180.43	176.25
	σ Length	76.80	89.68	109.04
	85th:	252.28	276.01	205.94
Maitland(NS-E)	μ Length	114.74	117.88	116.27
	σ Length	34.38	36.15	33.34
	85th:	156.48	155.08	144.86
Parkdale(NS-W)	μ Length	84.63	86.74	86.32
	σ Length	18.15	20.04	19.45
	85th:	104.01	107.28	103.94

Richmond(S-E)	μ Length	130.39	123.45	121.35
	σ Length	248.57	33.09	22.93
	85th:	474.85	157.72	141.57
St_Laurent(N-W)	μ Length	179.48	196.68	187.93
	σ Length	66.61	95.23	95.56
	85th:	253.14	296.72	278.60
Terryfox(N-W)	μ Length	206.66	207.15	203.05
	σ Length	143.14	89.31	85.92
	85th:	363.76	298.95	276.13
Terryfox(S-E)	μ Length	182.67	153.45	152.51
	σ Length	137.37	46.52	41.51
	85th:	346.20	201.51	199.88
Vanier(N-W)	μ Length	94.67	134.35	130.96
	σ Length	137.50	39.12	28.15
	85th:	291.58	174.73	155.09
Woodroffe(NS-W)	μ Length	97.73	95.88	97.89
	σ Length	42.77	39.42	45.01
	85th:	142.92	136.69	128.47

* μ Length and * σ Length: Mean and standard deviation of calculated required SCL length

As shown in Table 5.9 FORM method results for mean of required SCL length ranges from 86.74 to 218.00 meters, and simulation method results ranges from 84.63 to 224.46 meters, where collected data mean ranges from 86.32 to 214.80 meters. In comparison with the site by site analysis of PC, the required length for HV is greater than the required length for PC.

Figure 5.17 represents the mean comparison between FORM method, simulation method and collected data, also the recommended lengths by AASHTO (2004) and TAC (1999) are included in this figure. In most sites the calculated mean using the FORM method is smaller than the simulation method and data results, and the simulation method results are greater than what collected data shows in most sites.

Figure 5.17: HV Site by Site Mean Comparison

Standard Deviation (SD) comparison of analysis with collected data are represented in Figure 5.18. As discussed for PC, in most sites the calculated SD using FORM method is greater than simulation method and collected data. At Richmond (S-E) SCL a great difference between FORM method results and simulation method was observed, in this SCL because of a small sample of data a greater SD was resulted.

Compared to PC results, the minimum calculated SD for HV is smaller than results of PC. But the results show that SD for HV covers a greater range, where the maximum SD calculated is 248.57, whereas the maximum SD calculated for PC was 166.07.

Figure 5.18: HV Site by Site SD Comparison

Figure 5.19 represents the 85th calculated required length for heavy vehicles; also the recommended length by AASHTO (2004) and TAC (1999) are included in this comparison. As shown in Figure 5.19 the FORM method results show a greater length required for SCL and overall results shows that a longer length is required by HV compared to PC.

Figure 5.19 supports the idea that current recommended lengths by design manuals need to be revised, since in some sites the required length is greater than the recommended length and this will increase the probability of hazard.

Figure 5.19: HV Site by Site 85th percentile Length Comparison with Design Manuals Recommendation

5.2.2 Safety index and Probability of Hazard of HV site by site Analysis

Based on the methodology discussed in Chapter 4, the safety index of FORM method results was calculated and presented in Table 5.10. Using safety index, the probability of hazard (P_h) values were calculated and presented in Figure 5.20.

Table 5.10: Safety Index Values of FORM Method Results (PC site by Site analysis)

SCL	Safety Index (β)		
	AASHTO (2004)	TAC (1999)	Current SCL Length
Carp Rd(S-E)	-0.15	-0.63	-1.48
Castelfrank(NS-E)	-0.44	-1.33	-6.40
Eagleson(N-W)	-0.63	-1.66	-7.22
Eagleson(S-E)	-0.91	-1.48	-1.61
Greenbank(S-E)	-1.07	-1.95	-15.67
Maitland(NS-E)	-3.79	-5.74	-10.27
Parkdale(NS-W)	-8.84	-12.53	-5.70
Richmond(S-E)	-0.46	-0.73	-0.77
St_Laurent(N-W)	-0.98	-1.99	-10.53
Terryfox(N-W)	-0.27	-0.74	-1.48
Terryfox(S-E)	-0.45	-0.94	-1.85
Vanier(N-W)	-1.09	-1.58	-5.13

As shown in Figure 5.20 at some SCLs the values of P_h for HV are greater than observed values for PC. Also it is shown in Figure 5.20 that TAC (1999) recommends a more reliable SCL length compared to AASHTO (2004), but in most SCLs the recommended length is not adequate for vehicles to accelerate to the speed of the freeway.

Figure 5.20: P_h based on FORM Method Results for HV Site by Site Analysis

Based on the methodology discussed for simulation method in Chapter 4 the probability of hazard (P_h) for simulation method results have been calculated and presented in Figure 5.21. Simulation method results show a smaller probability of hazard compared to FORM method results.

Figure 5.21: P_h based on Simulation Method Results

Greater P_h values for HV compared to PC, might raise the idea that heavy vehicles should be considered as the controlling vehicle type for SCL length design, but reviewing the analysis results for combined vehicles (PC and HV) show that PC is the controlling vehicle type for SCL length calculation. The probabilities of hazard for combined vehicles are presented in Figure 5.22. As shown in Figure 5.22 the P_h values for combined vehicle are similar to PC results.

Figure 5.22: P_h based on FORM Method Results for Combined Vehicles

The accuracy of simulation method was evaluated using the methodology introduced in Chapter 4 and the results are provided in

Table 5.11. As mentioned before, the accuracy of simulation method results could be measured by calculating the COV of calculated P_h , smaller values of COV represents a more accurate analysis.

Table 5.11: COV of P_h for HV Site by Site Analysis

SCL	Covariance of P_h	
	AASHTO (2004)	TAC (1999)
Carp Rd(S-E)	0.007	0.024
Castelfrank(NS-E)	0.009	0.109
Eagleson(N-W)	0.006	0.014
Eagleson(S-E)	0.014	0.054
Greenbank(S-E)	0.007	0.015
Maitland(NS-E)	0.276	20.533
Parkdale(NS-W)	2.785	6.547
Richmond(S-E)	0.373	52.453
St_Laurent(N-W)	0.006	0.011
Terryfox(N-W)	0.006	0.011
Terryfox(S-E)	0.026	0.226
Vanier(N-W)	0.084	2.439

As shown in

Table 5.11, the analysis of the simulation method shows an acceptable level of accuracy.

5.2.3 HV Categories

The analysis has been applied to HV categories and the mean, standard deviation and 85th percentile required SCL length are provided in Table 5.12.

Table 5.12: HV Categories Analysis results

Category		FORM Results	Simulation Results	Collected Data
ALL HV	μ Length	157.11	167.59	167.33
	σ Length	108.79	68.26	71.58
	85th:	272.35	238.24	241.70
HV Extended SCL	μ Length	182.71	192.48	190.37
	σ Length	80.87	75.32	76.93
	85th:	271.62	270.55	248.03
HV Limited SCL	μ Length	138.39	147.19	148.43
	σ Length	110.72	56.33	61.41
	85th:	255.94	205.19	211.86
HV High Traffic SCL	μ Length	166.76	176.83	176.03
	σ Length	86.02	73.25	80.42
	85th:	260.50	253.14	237.89
HV Low Traffic SCL	μ Length	148.73	161.14	161.63
	σ Length	121.11	63.39	65.30
	85th:	275.79	226.94	240.15

As shown in Table 5.12, the same pattern which was seen in previous sections is observed for HV categories results, this means FORM in most categories show a smaller mean but greater standard deviation, and therefore a greater 85th percentile required SCL length.

Figure 5.23 represents the required SCL length mean in comparison with the design manuals recommendations. As shown in the figure for mean comparison, the design

manuals recommendations look reliable, but a better comparison is the comparison of 85th percentile required length, which represents a greater portion of the population.

Figure 5.23: HV Categories Mean Comparison with Design Manuals Recommendations

Figure 5.24 represents the standard deviation comparison of analysis results. As shown in the figure, the FORM method results represent a greater standard deviation compared to collected data and simulation method.

Figure 5.24: HV Categories SD Comparison

After calculating mean and standard deviation, a sample population was generated and the 85th percentile required length of population was calculated, the resulting values are shown in Figure 5.25. Compared to PC categories, HV categories represent a smaller required SCL length. Whereas in site by site analysis, HV required a longer SCL length, this difference might be resulted from the different geometry of SCLs.

Figure 5.25: HV Categories 85th percentile Length Comparison with Design Manuals Recommendation

5.2.4 HV Categories Probability of Hazard

The safety index values of FORM method, for HV categories were calculated and provided in Table 5.13. Using safety index values, the probability of hazard (P_h) of FORM method for AASHTO (2004), TAC (1999) length recommendations have been calculated and presented in Figure 5.26.

Table 5.13: HV Categories Safety Index

Category	Safety Index (β)	
	AASHTO (2004)	TAC (1999)

ALL HV	-0.81	-1.42
HV_Extended SCL	-0.77	-1.60
HV_Limited SCL	-0.96	-1.57
HV_High Traffic SCL	-0.91	-1.69
HV_Low Traffic SCL	-0.79	-1.35

As shown in Figure 5.26, TAC (1999) length recommendations are more reliable compared to AASHTO (2004), but both recommended lengths show probability of hazards. This supports the idea that instead of a deterministic design, a stochastic design will be more reliable for highway operations.

Figure 5.26: HV Categories FORM Method P_h

The probability of hazard based on the simulation method has been calculated for AASHTO (2004) and TAC (1999) length recommendations and results are represented in Figure 5.27. As discussed in previous sections, the simulation method results show a smaller probability of hazard.

Figure 5.27: HV Categories P_h based on Simulation Method Results

The accuracy of the simulation method results was calculated using the methodology provided in Chapter 4, and represented in Table 5.14. The results show that the simulation method for HV categories had an acceptable level of accuracy.

Table 5.14: COV of P_h of HV Categories

Category	Covariance of P_h	
	AASHTO (2004)	TAC (1999)
ALL HV	0.011	0.031
HV Extended SCL	0.007	0.017
HV Limited SCL	0.020	0.098
HV High Traffic SCL	0.009	0.022
HV Low Traffic SCL	0.013	0.044

6.0 CONCLUSIONS AND RECOMMENDATION

6.1 Conclusions

Safe and efficient freeway operations are sensitive to the geometry and operations of merging areas at the interchanges. Due to less attention to highway geometric design, in this study, using real world examples and reliability based analysis, a new methodology for designing merging areas of freeways was examined and results provided. In the analysis different aspects were considered, such a vehicle type, traffic rate, and geometry of SCLs. These aspects were considered separately to evaluate the effect of each aspect on required length of SCLs.

In this study, it was assumed that traffic flow characteristics are stochastic and probabilistic factors were taken into account in design process. Therefore, a new proposed approach for highway geometric design was used instead of current methodology. Unlike the deterministic approach where for each input variable there is one possible solution for problem, the new approach provides for a distribution of possible values for the design problem and provides the designer with opportunity to select a specific solution from all possible solutions, based on safety and cost factors. The main benefit of this methodology is that instead of using one value for representing vehicles traffic characteristics (such as vehicle speed), the whole population was considered in analysis. This approach most likely results in more accurate results, compared to current methodology.

FORM and simulation methods were used in this research to discuss the efficiency of the new approach for SCL length design. It was shown that recommendations made by

design manuals (AASHTO, TAC) are not satisfactory in most cases. Most likely this lack of satisfaction is due the methodology used in design manuals for calculating the required length of SCLs.

Analysis using the new approach showed that, among the SCL sites covered in this study, some SCLs were unnecessarily long (such as Greenbank S-E with a length of 1366 meters), and some SCLs were not long enough to provide the driver with required length for a safe acceleration from their current speed to the speed of freeway traffic flow (such as Parkdale NS-W with a length of 188 meters). Results show the necessity of using safety and reliability based analysis in highway geometric design process and supports the idea that current criteria for SCL length design is no longer satisfactory.

Analysis results of different categories showed that merging length and merging speed are highly influenced by vehicle type (heavy vehicle or passenger car). Also it was found that traffic volume, SCL geometry and current provided length affect the required SCL length for safe and efficient merging manoeuvre.

FORM and Simulation Method Results

- The reliability-based analysis results were shown to be more accurate compared to current design. Since in this methodology whole population are considered in analysis using this approach would increase safety of freeways SCLs and reduce unnecessary construction costs;

- The analysis results of both methods show that a SCL length of 450 meters is satisfactory for both type of vehicles, and provides enough length for vehicles that they could accelerate from their current speed to the speed of freeway, find a gap, accept the gap and merge with the traffic flow of freeway in a safe and secure manner;
- It was shown that recommended lengths by AASHTO (2004) and TAC (1999) were not satisfactory in most of sites and categories, since 85th required SCL length for vehicles was greater than the recommended lengths from above design manuals;
- Based on calculated probability of hazard values, it was observed that TAC (1999) length recommendations are more reliable compared to AASHTO (2004);
- Based on categorical analysis it was shown that in limited type SCLs, because of shorter provided length, the merging speed is greater compared to extended type SCLs where longer length is provided for vehicles. Therefore, at limited type SCLs, the limitation of provided length affects the driver behaviour. Drivers tend to accelerate with a greater overall acceleration rate, in other words, drivers are forced to accelerate to speed of freeway in a shorter length;
- It was shown that traffic volume increases the required SCL length;
- Based on FORM analysis results for heavy vehicles, a high probability of hazard was observed at all limited type SCLs; and
- Unlike the PC categorical analysis, which probability of hazard at limited type SCLs was smaller than extended type SCLs, HV categorical analysis showed that

heavy vehicles are more affected by limited length, and the probability of hazard was greater at limited type SCLs.

6.2 Recommendations for Future Studies

Despite the limitations of the data employed in this research and a variety of numerous possible methodologies, the following key recommendations are made. These recommendations might improve the research findings.

- The analysis results should be evaluated using data from different freeways;
- More accurate reliability based methods (such as second order reliability method) should be investigated;
- More data for heavy vehicles would help to compare the required length for merging with passenger cars more accurately;
- Collecting more data from different freeways with different geometry would increase the accuracy of analysis;
- Collecting speed data of each vehicle in a longer length (for example from the entry point of controlling curve) would help to identify the acceleration behaviour more accurately, and if needed, use non-constant acceleration design for required SCL length calculation; and
- Replacing acceleration based model with gap acceptance model or a mixed model which considers both acceleration and gap acceptance should be studied.

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**APPENDIX A: CORRELATION COEFFICIENTS AND
COVARIANCE OF VARIABLES AT SCLS AND
CATEGORIES**

Table A-1: Correlation Coefficient of Variables at Each SCL Site

Site		Variables	Correlation Coefficient	
			PC	HV
Carp Rd(S-E)		Vm & Acc	0.209	-0.016
		Vg & Acc	-0.417	-0.342
		L & Acc	-0.159	0.552
		Vm & Vg	0.741	0.939
Castlefrank(NS-E)		Vm & Acc	0.416	0.833
		Vg & Acc	-0.042	-0.019
		L & Acc	-0.136	0.154
		Vm & Vg	0.758	0.520
Eagleson(N-W)		Vm & Acc	0.031	0.891
		Vg & Acc	-0.297	0.868
		L & Acc	-0.249	-0.674
		Vm & Vg	0.895	0.982
Eagleson(S-E)		Vm & Acc	0.285	-0.023
		Vg & Acc	-0.150	-0.407
		L & Acc	-0.235	-0.463
		Vm & Vg	0.880	0.907
Greenbank(S-E)		Vm & Acc	0.372	0.134
		Vg & Acc	-0.140	-0.052
		L & Acc	-0.099	-0.238
		Vm & Vg	0.793	0.918
Maitland(NS-E)		Vm & Acc	0.469	0.787
		Vg & Acc	0.188	0.307
		L & Acc	-0.352	-0.154
		Vm & Vg	0.555	0.481
Moodie(N-W)		Vm & Acc	0.336	N/A
		Vg & Acc	-0.135	N/A
		L & Acc	-0.203	N/A
		Vm & Vg	0.870	N/A
Parkdale(NS-W)		Vm & Acc	0.528	0.567
		Vg & Acc	0.259	0.468
		L & Acc	-0.297	-0.370
		Vm & Vg	0.921	0.902
Richmond(S-E)		Vm & Acc	0.391	-0.144
		Vg & Acc	0.042	-0.509
		L & Acc	0.024	-0.108
		Vm & Vg	0.885	0.923

St_Laurent(N-W)		Vm & Acc	0.191	0.021
		Vg & Acc	-0.265	-0.164
		L & Acc	-0.278	-0.352
		Vm & Vg	0.796	0.842
Terryfox(N-W)		Vm & Acc	0.309	0.839
		Vg & Acc	-0.127	0.679
		L & Acc	-0.131	0.286
		Vm & Vg	0.882	0.953
Terryfox(S-E)		Vm & Acc	0.313	0.035
		Vg & Acc	-0.071	-0.430
		L & Acc	-0.001	0.718
		Vm & Vg	0.911	0.879
Vanier(N-W)		Vm & Acc	0.468	0.991
		Vg & Acc	-0.049	0.912
		L & Acc	-0.007	-0.543
		Vm & Vg	0.803	0.943
Woodroffe(NS-W)		Vm & Acc	0.302	0.742
		Vg & Acc	0.032	0.593
		L & Acc	-0.351	0.389
		Vm & Vg	0.848	0.970
Woodroffe(S-E)		Vm & Acc	0.313	N/A
		Vg & Acc	-0.029	N/A
		L & Acc	-0.105	N/A
		Vm & Vg	0.885	N/A

Table A-2: Correlation Coefficient of Variables at SCL Categories

Category		Variables	Correlation Coefficient	
			PC	HV
ALL		Vm & Acc	-0.095	-0.139
		Vg & Acc	-0.490	-0.460
		L & Acc	-0.232	-0.224
		Vm & Vg	0.845	0.911
ALL Extended		Vm & Acc	0.220	0.474
		Vg & Acc	-0.188	0.104
		L & Acc	-0.152	-0.142
		Vm & Vg	0.856	0.848
ALL Limited		Vm & Acc	-0.177	-0.308
		Vg & Acc	-0.547	-0.585
		L & Acc	-0.235	-0.289
		Vm & Vg	0.849	0.935
ALL High Traffic		Vm & Acc	0.064	0.029
		Vg & Acc	-0.548	-0.362
		L & Acc	-0.108	-0.216
		Vm & Vg	0.701	0.862
ALL Low Traffic		Vm & Acc	-0.144	-0.197
		Vg & Acc	-0.440	-0.494
		L & Acc	-0.357	-0.264
		Vm & Vg	0.921	0.932

Table A-3: Covariance of Variables at Each SCL Site

Site		Variables	Covariance	
			PC	HV
Carp Rd(S-E)		Vm & Vg	2.923	7.580
		Vm & Acc	0.079	-0.005
		Vg & Acc	-0.172	-0.112
Castlefrank(NS-E)		Vm & Vg	3.988	7.196
		Vm & Acc	0.252	0.410
		Vg & Acc	-0.023	-0.007
Eagleson(N-W)		Vm & Vg	8.890	3.460
		Vm & Acc	0.022	0.115
		Vg & Acc	-0.214	0.106
Eagleson(S-E)		Vm & Vg	7.712	3.150
		Vm & Acc	0.191	-0.009
		Vg & Acc	-0.097	-0.163
Greenbank(S-E)		Vm & Vg	6.071	3.597
		Vm & Acc	0.259	0.025
		Vg & Acc	-0.090	-0.008
Maitland(NS-E)		Vm & Vg	2.378	0.623
		Vm & Acc	0.324	0.156
		Vg & Acc	0.075	0.051
Moodie(N-W)		Vm & Vg	5.049	N/A
		Vm & Acc	0.185	N/A
		Vg & Acc	-0.073	N/A
Parkdale(NS-W)		Vm & Vg	7.331	1.732
		Vm & Acc	0.450	0.132
		Vg & Acc	0.199	0.087
Richmond(S-E)		Vm & Vg	4.488	5.769
		Vm & Acc	0.197	-0.061
		Vg & Acc	0.020	-0.265
St_Laurent(N-W)		Vm & Vg	4.508	4.220
		Vm & Acc	0.102	0.005
		Vg & Acc	-0.141	-0.046
Terryfox(N-W)		Vm & Vg	5.381	7.617
		Vm & Acc	0.162	0.386
		Vg & Acc	-0.064	0.229
Terryfox(S-E)		Vm & Vg	7.066	2.760
		Vm & Acc	0.171	0.007
		Vg & Acc	-0.037	-0.102
Vanier(N-W)		Vm & Vg	5.068	2.706

		Vm & Acc	0.370	0.579
		Vg & Acc	-0.031	0.247
Woodroffe(NS-W)		Vm & Vg	4.504	6.258
		Vm & Acc	0.412	0.404
		Vg & Acc	0.037	0.212
Woodroffe(S-E)		Vm & Vg	5.861	N/A
		Vm & Acc	0.179	N/A
		Vg & Acc	-0.015	N/A

Table A-4: Covariance of Variables at SCL Categories

Category		Variables	Covariance	
			PC	HV
ALL		Vm & Vg	11.580	8.512
		Vm & Acc	-0.115	-0.087
		Vg & Acc	-0.697	-0.314
ALL Extended		Vm & Vg	7.698	3.712
		Vm & Acc	0.165	0.138
		Vg & Acc	-0.139	0.027
ALL Limited		Vm & Vg	13.544	12.327
		Vm & Acc	-0.248	-0.273
		Vg & Acc	-0.952	-0.594
ALL High Traffic		Vm & Vg	7.925	6.121
		Vm & Acc	0.065	0.013
		Vg & Acc	-0.717	-0.171
ALL Low Traffic		Vm & Vg	12.813	9.410
		Vm & Acc	-0.184	-0.141
		Vg & Acc	-0.608	-0.383

APPENDIX B: A SUMMARY OF RECEIVED DATA

Table B-1: Summary of Site by Site Received Data

SCL Site		Passenger Cars				Heavy Vehicles			
		Gore Merge Pt.	Gore Speed	Merge Speed	SCL ACC	Gore Merge Pt.	Gore Speed	Merge Speed	SCL ACC
Carp Rd(S-E)	Min	80.41	78.47	87.21	-0.50	141.41	73.14	79.00	0.01
	Max	386.69	115.38	120.41	0.78	276.47	110.37	110.61	0.32
	Mean	220.80	100.13	106.30	0.23	205.72	92.71	97.91	0.17
	SD	69.72	7.53	6.87	0.20	41.24	11.62	10.50	0.12
	85th	293.12	107.93	112.75	0.40	228.63	100.55	105.57	0.29
Castlefrank(NS-E)	Min	3.36	77.19	81.51	-0.35	168.85	73.74	83.51	0.12
	Max	508.33	123.95	123.91	1.42	251.69	84.99	96.41	0.44
	Mean	173.84	92.39	98.77	0.29	210.48	81.30	89.70	0.26
	SD	81.50	7.96	8.66	0.25	27.83	3.45	4.51	0.12
	85th	254.00	100.71	107.11	0.48	238.59	83.83	94.29	0.40
Eagleson(N-W)	Min	9.35	74.71	79.62	-0.45	150.61	71.55	77.73	0.14
	Max	379.20	143.93	147.44	1.37	314.23	91.11	97.52	0.34
	Mean	191.18	99.30	101.93	0.13	214.80	81.72	88.59	0.22
	SD	70.70	11.49	11.33	0.23	53.49	6.99	7.35	0.07
	85th	258.90	108.30	110.41	0.29	247.54	90.35	96.64	0.28
Eagleson(S-E)	Min	39.68	71.37	58.10	-0.77	98.85	82.98	86.01	0.10
	Max	386.64	134.84	140.51	0.61	257.70	100.50	103.00	0.70
	Mean	161.06	96.81	98.86	0.12	162.12	88.62	93.35	0.24
	SD	66.42	10.49	10.93	0.22	68.73	7.59	7.12	0.23
	85th	230.07	106.30	109.38	0.32	220.20	97.04	100.75	0.33

Summary of Site by Site Received Data, Continued

SCL Site		Passenger Cars				Heavy Vehicles			
		Gore Merge Pt.	Gore Speed	Merge Speed	SCL ACC	Gore Merge Pt.	Gore Speed	Merge Speed	SCL ACC
Greenbank(S-E)	Min	61.61	68.54	69.31	-0.75	92.29	76.98	80.61	0.01
	Max	489.81	113.85	119.01	0.89	463.08	100.36	105.71	0.31
	Mean	185.55	89.99	95.61	0.23	176.25	83.97	88.74	0.20
	SD	94.17	9.66	10.41	0.24	109.04	6.98	8.08	0.09
	85th	251.39	98.65	105.41	0.41	205.94	89.39	96.94	0.28
Maitland(NS-E)	Min	69.95	41.88	55.41	0.28	87.37	52.93	63.71	0.37
	Max	380.46	77.40	111.21	1.54	156.96	62.75	75.61	0.77
	Mean	177.64	62.29	86.91	0.84	116.27	58.12	70.76	0.55
	SD	65.92	5.71	9.82	0.26	33.34	4.32	5.18	0.18
	85th	248.31	67.16	96.84	1.11	144.86	61.66	74.62	0.70
Moodie(N-W)	Min	57.29	73.32	74.31	-0.65	89.34	78.99	81.30	0.04
	Max	295.23	111.89	114.61	0.52	190.78	87.72	88.31	0.07
	Mean	129.75	92.00	93.47	0.10	140.06	83.36	84.81	0.06
	SD	52.29	8.66	8.80	0.23	71.73	6.17	4.95	0.02
	85th	176.58	101.07	102.43	0.33	175.57	86.41	87.26	0.07
Parkdale(NS-W)	Min	33.13	38.42	43.04	-0.20	56.89	56.79	69.24	0.56
	Max	157.18	91.65	103.83	1.51	104.14	68.37	84.96	0.94
	mean	85.72	69.74	79.71	0.71	86.32	63.18	75.25	0.76
	SD	25.73	9.70	10.75	0.29	19.45	5.00	6.22	0.17
	85th	109.49	78.28	90.48	0.96	103.94	67.69	80.29	0.93

Summary of Site by Site Received Data, Continued

SCL Site		Passenger Cars				Heavy Vehicles			
		Gore Merge Pt.	Gore Speed	Merge Speed	SCL ACC	Gore Merge Pt.	Gore Speed	Merge Speed	SCL ACC
Richmond(S-E)	Min	26.13	66.91	70.12	-0.41	96.65	63.84	68.32	-0.35
	Max	299.32	110.36	107.82	0.83	158.93	94.25	94.83	0.21
	Mean	96.86	83.80	88.13	0.30	121.35	79.26	81.16	0.09
	SD	45.96	8.01	8.28	0.22	22.93	10.72	8.82	0.20
	85th	126.29	91.77	96.72	0.51	141.57	88.49	90.87	0.20
St_Laurent(N-W)	Min	49.19	70.75	75.41	-0.45	77.32	64.55	75.71	0.11
	Max	450.58	112.41	116.63	0.88	350.37	95.51	98.13	0.51
	Mean	193.91	87.92	95.18	0.29	187.93	77.91	87.16	0.33
	SD	95.37	8.62	8.62	0.22	95.56	9.23	7.91	0.12
	85th	318.37	95.98	105.12	0.49	278.60	83.49	95.43	0.44
Terryfox(N-W)	Min	52.15	80.79	85.50	-0.46	110.05	75.63	79.71	-0.06
	Max	390.79	124.72	128.21	0.83	319.45	97.63	109.11	0.36
	Mean	172.66	100.99	105.59	0.22	203.05	85.80	91.52	0.19
	SD	60.91	8.74	9.14	0.21	85.92	9.55	13.01	0.15
	85th	217.73	109.13	114.81	0.42	276.13	93.88	104.98	0.33
Terryfox(S-E)	Min	62.77	78.01	80.13	-0.31	83.03	80.55	86.42	-0.07
	Max	301.15	127.54	128.93	0.63	214.10	100.10	102.82	0.32
	Mean	170.84	99.70	103.19	0.16	152.51	91.57	95.01	0.14
	SD	55.90	9.81	10.33	0.19	41.51	7.51	6.09	0.13
	85th	230.09	110.41	114.99	0.35	199.88	99.38	100.80	0.25

Summary of Site by Site Received Data, Continued

SCL Site		Passenger Cars				Heavy Vehicles			
		Gore Merge Pt.	Gore Speed	Merge Speed	SCL ACC	Gore Merge Pt.	Gore Speed	Merge Speed	SCL ACC
Vanier(N-W)	Min	16.88	66.20	57.01	-0.78	107.98	67.82	61.41	-0.22
	Max	363.44	106.95	108.91	0.93	165.44	77.43	84.51	0.41
	Mean	148.17	80.66	85.55	0.22	130.96	73.44	75.93	0.15
	SD	57.42	8.20	10.15	0.28	28.15	4.79	10.35	0.27
	85th	203.18	88.44	94.42	0.46	155.09	77.43	83.38	0.34
Woodroffe(NS-W)	Min	27.48	63.54	64.81	-0.25	33.02	58.32	60.91	0.29
	Max	201.36	103.07	109.81	5.14	130.68	76.85	91.71	0.74
	Mean	105.13	79.27	89.24	0.70	97.89	69.52	77.18	0.44
	SD	42.26	7.76	8.97	0.55	45.01	8.57	13.02	0.20
	85th	150.62	87.13	99.17	0.88	128.47	76.26	87.34	0.58
Woodroffe(S-E)	Min	42.78	72.62	74.32	-0.34	No HV data available for this SCL			
	Max	405.48	113.75	129.61	1.21				
	Mean	169.76	88.20	94.26	0.27				
	SD	82.18	8.91	9.78	0.21				
	85th	242.92	99.04	103.73	0.45				

Table B-2: Summary of Categories Received Data

Category	Stats	ALL Passenger Cars				ALL Heavy Vehicles			
		Gore Merge Pt.	Gore Speed	Merge Speed	SCL ACC	Gore Merge Pt.	Gore Speed	Merge Speed	SCL ACC
ALL	Min	3.36	38.42	43.04	-0.78	33.02	52.93	60.91	-0.35
	Max	508.33	143.93	147.44	5.14	463.08	110.37	110.61	0.94
	Mean	157.70	88.25	95.02	0.33	167.33	80.98	87.20	0.26
	SD	75.74	14.50	12.25	0.35	71.58	11.49	10.57	0.21
	85th	235.77	102.67	107.71	0.67	241.70	92.41	98.07	0.41
ALL Extended	Min	3.36	66.20	57.01	-0.78	77.32	64.55	61.41	-0.22
	Max	508.33	143.93	147.44	1.42	463.08	100.36	105.71	0.51
	Mean	178.46	90.32	95.80	0.24	190.37	80.53	87.32	0.24
	SD	82.72	10.71	10.91	0.25	76.93	7.20	8.08	0.13
	85th	257.14	100.89	106.41	0.45	248.03	87.47	96.03	0.38
ALL Limited	Min	26.13	38.42	43.04	-0.77	33.02	52.93	60.91	-0.35
	Max	390.79	134.84	140.51	5.14	319.45	110.37	110.61	0.94
	Mean	146.65	87.15	94.61	0.38	148.43	81.35	87.11	0.27
	SD	69.31	16.05	12.90	0.39	61.41	14.14	12.33	0.26
	85th	220.63	104.07	108.42	0.77	211.86	97.38	101.19	0.60

Summary of Categories Received Data, Continued

Category	Stats	ALL Passenger Cars				ALL Heavy Vehicles			
		Gore Merge Pt.	Gore Speed	Merge Speed	SCL ACC	Gore Merge Pt.	Gore Speed	Merge Speed	SCL ACC
ALL High Traffic	Min	3.36	41.88	55.41	-0.78	77.32	52.93	61.41	-0.22
	Max	508.33	123.95	129.61	1.54	463.08	100.36	105.71	0.77
	Mean	176.00	82.78	92.82	0.39	176.03	77.74	85.16	0.28
	SD	81.31	13.76	10.66	0.34	80.42	9.94	9.52	0.18
	85th	253.46	96.24	103.83	0.74	237.89	83.85	94.23	0.42
ALL Low Traffic	Min	9.35	38.42	43.04	-0.77	33.02	56.79	60.91	-0.35
	Max	390.79	143.93	147.44	5.14	319.45	110.37	110.61	0.94
	Mean	147.46	91.31	96.25	0.30	161.63	83.10	88.54	0.24
	SD	70.44	14.00	12.90	0.36	65.30	12.02	11.09	0.24
	85th	223.53	105.34	109.41	0.63	240.15	96.81	100.81	0.36

APPENDIX C: A SUMMARY OF SIMULATION METHOD STEPS

Table C-1: Summary of Simulation Method Steps 1

Generation of Uncorrelated random numbers in Excel:	Generation of Correlated random numbers in <i>Matlab</i> based on the methodology introduced in Section 4.5.5 and moving the resulting correlated random numbers to Excel:										Correlated Random numbers of each variable:	Processed correlated random numbers of each variable:
	Vg	Vm	Time	Vg	Vm	Time						
0.42	0.94	0.26	0.18	0.43	0.58	0.18	0.43	0.58				
0.12	0.60	0.24	0.52	0.58	0.94	0.52	0.58	0.94				
0.08	0.25	0.56	0.05	0.14	0.27	0.05	0.14	0.27				
0.12	0.64	0.58	0.36	0.43	0.44	0.36	0.43	0.44				
0.33	0.11	0.63	0.59	1.08	0.63							
0.60	0.28	0.79	0.43	0.73	0.07	0.43	0.73	0.07				
0.09	0.68	0.98	0.93	0.89	0.62	0.93	0.89	0.62				
0.86	0.13	0.61	0.66	1.11	0.18	0.66	1.11	0.18				
0.03	0.66	0.74	0.78	0.68	0.34	0.78	0.68	0.34				
0.96	0.16	0.94	0.67	0.87	0.24	0.67	0.87	0.24				
0.76	0.07	0.72	0.49	0.85	0.53	0.49	0.85	0.53				
0.21	0.40	0.58	0.89	1.10	0.53	0.89	1.10	0.53				
0.67	0.43	0.71	0.47	0.86	0.86	0.47	0.86	0.86				
0.17	0.57	0.32	0.44	0.63	0.63	0.44	0.63	0.63				
0.91	0.29	0.77	0.66	0.84	0.54	0.66	0.84	0.54				
0.80	0.77	0.43	0.74	1.18	0.32	0.74	1.18	0.32				
0.81	0.52	0.93	0.40	0.34	0.96	0.40	0.34	0.96				
0.31	0.42	0.65	0.76	1.17	0.93	0.76	1.17	0.93				
0.68	0.26	0.66	0.70	1.09	0.96	0.70	1.09	0.96				

Table C-2: Summary of Simulation Method Steps 2

	Generating Distributions of variables based on their mean and standard deviation:							
		Time (sec)	V _m (km/h)	V _g (km/h)				
	Mean	7.72	106.30	100.13			Acc (m/s ²)	L (m)
	SD	2.50	6.87	7.53				
Using acceptable correlated random numbers for each variable and based on mean and standard deviation a distribution of values for each variable is calculated:		8.22	105.11	93.14	Calculating Acceleration rate based on Equation (4.21)	Calculating required SCL length based on Equation (4.1):	0.40	226.60
		11.66	107.64	100.42			0.17	337.56
		6.21	98.81	87.97			0.48	161.29
		7.32	105.09	97.52			0.29	206.38
		3.97	110.41	98.77			0.81	115.49
		8.47	114.73	111.06			0.12	265.90
		6.67	109.55	105.93			0.15	200.04
		5.94	113.95	103.53			0.49	179.69
		7.94	113.45	99.87			0.48	235.52
		10.38	113.57	99.49			0.38	307.52
		8.57	108.50	99.06			0.31	247.48
		7.95	113.14	103.18			0.35	239.27
		12.00	103.45	98.21			0.12	336.60