Assessing Safety Performance of Transportation Systems using Microscopic Simulation

by

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I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

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Abstract

Transportation safety has been recognized as a public health issue worldwide, consequently, transportation researchers and practitioners have been attempting to provide adequate safety performance for the various transportation components and facilities to all road users given the usually scarce resources available. Safety engineers have been trying to make decisions affecting safety based on the knowledge extracted from different types of statistical models and/or observational before-after analysis. It is generally recognized that this type of factual knowledge is not easily obtained either statistically or empirically. Despite the intuitive link between road safety and observed crashes, a good understanding of the sequence of events prior to the crash can provide a more rational basis for the development of engineering countermeasures.

The development of more comprehensive mechanistic models for safety assessment is heavily dependent on detailed vehicle tracking data that is not readily available. The potential of microscopic simulation in traffic safety and traffic conflict analysis has gained increasing interest mostly due to recent developments in human behaviour modelling and real-time vehicle data acquisition.

In this thesis, we present a systematic investigation of the use of existing behavioural microscopic simulation models in short-term road safety studies. Initially, a microscopic framework is introduced to identify potentially unsafe vehicle interactions for different vehicle movements based on three types of traffic behaviour protocols: car-following, lane change and gap acceptance. This microscopic model for safety assessment applies a safety performance measure based on pairwise comparisons of spacing and speed differential between adjacent vehicles and individual braking power in real-time. A calibration/validation procedure using factorial analysis is presented to select best model input parameters for this safety performance measure by using high resolution vehicle tracking data. The ability of the proposed safety performance measure to reflect real-life observed high-risk vehicular interactions is explored in three intuitive tests using observed crash data. Finally, the usefulness of the model is illustrated through its application to investigate the safety implications of two different geometric and operational traffic strategies.

The overall results indicate that, notwithstanding the fact that actual behavioural microscopic algorithms have not been developed strictly to model crashes, they are able to replicate several factors directly related to high risk situations that could lead to crashes with reasonable accuracy. With the existing upward trend in computing power, modelling techniques and increasing availability of detailed vehicle tracking data, it is likely that safety studies will be carried out using a more mechanistic and inclusive approach based on disruptive driving behaviour rather than ultimate unpredictable and heavily restrictive crash events.

Acknowledgements

Over the past 1561 days in Canada we definitely expanded and improved our perspective of happiness. This was, in part, caused by natural body and mind "wear and tear", but mostly, because we have been blessed to cross the path of some fascinating people. I would like to express my gratitude to some of these friends.

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Dedication

This thesis is dedicated to my beloved Glenda, Rayssa and Enzo.

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Chapter 1

Introduction

1.1 Background

One of the main goals of transportation researchers and practitioners is to ensure adequate safety performance of the various transportation components and facilities to all road users given the resources available. This has proved to be one of the most challenging subjects since the first documented traffic related fatality in 1896. According to the World Health Organization, 1.2 million fatalities and 50 million injuries are estimated every year worldwide due to crashes [83].

Road crashes statistics in Canada reveal that approximately three thousand fatalities are expected to occur every year. In 2006, for instance, 2,889 fatalities and 199,337 injuries were registered [24]. According to Transport Canada [23], despite the relative reduction in casualties over the last two decades, traffic collisions is still one of the main contributors to years of lost life among Canadians. The annual economic cost associated with these traffic collisions is estimated to be over $11 billions.

Government agencies and private organizations usually need to allocate limited resources in order to maximize safety improvements of existing network components. Furthermore, in transportation planning, different geometric features and operational strategies are required to have their safety implications adequately verified prior to implementation. Thus, it is crucial to both transportation operation and planning field to initially establish an objective framework to evaluate the safety performance of transportation systems.

This thesis is primarily focused on assessing the safety performance of the various transportation components and facilities. In traffic safety literature, one can find terms, such as “accident”, “collision” and “crash” being used interchangeably to represent events between one (or more) road users that resulted in property damage, injury or fatality. In this thesis the term “accident” will be avoided due to its inherent connection to unforeseen random occurrences rather than causal factors that lead to those events.

Traffic collisions usually happen in consequence of a very specific combination of factors that, in many cases, can not be unveiled thus compromising the accuracy and reliability of road safety diagnosis. Hauer [40] has pointed out that unlike other fields, one can not design scientific experiments to estimate changes in safety by controlling road system attributes for ethical and operational reasons.

The most common approach to estimate safety makes use of inferential statistics applied to police-reported crashes therefore being considered a reactive approach to the problem. Despite the intuitive link between road safety and observed crashes, a good understanding of the sequence of events prior to the crash can provide a more rational basis for the development of engineering countermeasures. Furthermore, issues related to data reliability and availability as well as methodological challenges posed by the very random and unique nature of accidents have fostered complementary approaches to improve road safety assessment, such as the observation of traffic conflicts and the use of microscopic traffic simulation.

Computer simulation models applied to transportation engineering are recognized as a powerful tool in the analysis and assessment of highway transportation systems and its components [68]. Individual representation of vehicles travelling in a transportation network is the fundamental goal of microscopic traffic simulation programs. One of the most relevant features of this analytical approach is to allow the occurrence of experiments with new engineering alternatives before its implementation in the real world.

The use of microscopic traffic simulation over the last two decades has essentially focused on the analysis of transportation efficiency, such as signalized intersections, arterial networks and freeway corridors. The potential of microscopic simulation in traffic safety and traffic conflict analysis was initially recognized by Darzentas et al. [30] and has gained increasing interest mostly due to recent developments in human behaviour modelling and real-time vehicle data acquisition.

The usefulness of microscopic simulation for assessing safety depends on the ability of these models to capture complex behavioural relationships that could lead to crashes and to establish a link between simulated safety measures and crash risk. Moreover, it becomes necessary to estimate model inputs such that they accurately replicate safety performance at a given location over time. Accordingly, one of the major steps in applying simulation is to ensure that important model inputs have been accurately determined based on observational data, and that simulation models produce estimates of safety performance that can be verified from real world observations.

This thesis explores the use of microscopic simulation models to evaluate and predict the safety impact of alternative traffic engineering strategies applied to the various components of transportation systems.

1.2 Objectives and Scope

The primary objective of this thesis is to present a systematic investigation of the potential for adopting a more mechanistic approach to short-term road safety studies based on microscopic simulation of safety performance. The following five specific objectives are also addressed in this work:

1. Develop a microscopic framework to identify potentially unsafe vehicle interactions for different vehicle movements based on three types of traffic behaviour protocols: car-following, lane change and gap acceptance.
2. Introduce a safety performance measure obtained from microscopic simulation as a function of pairwise comparisons of spacing and speed differential between adjacent vehicles in the traffic stream in real-time.
3. Calibrate and validate microscopic models input parameters for a specific safety performance indicator using high resolution vehicle-tracking data.
4. Provide a link between simulated safety performance indicator and observed high risk vehicular interactions.
5. Evaluate safety implications of two different geometric and operational traffic strategies applied to urban intersections and freeway segments using microscopic simulation.

1.3 Thesis Outline

This thesis is structured in eight chapters. Chapter 2 presents basic definitions and concepts used in traffic safety, as well as explores a number of safety performance measures developed for alternative safety studies, such as the traffic conflict technique and simulation-based safety studies. The various advantages as well as shortcomings associated with their use are also discussed.

Chapter 3 presents the most common underlying theories and approaches applied to the science of traffic safety, including observational traffic safety studies, traffic conflict studies and real-time and simulation based safety analysis.

Chapter 4 introduces the microscopic safety assessment model to identify potentially unsafe vehicle interactions for different vehicle movements based on existing types of traffic behaviour protocols.

An heuristic procedure for calibration and validation of microscopic simulation models for safety purposes is presented in Chapter 5.

Chapter 6 describes three tests applied to explore the relationship between the proposed safety performance measure and empirical observational crash data.

Chapter 7 illustrates the merits of the proposed microscopic safety assessment model and explores its sensitivity to a number of geometric and traffic attributes when applied to investigate the safety implications of two engineering countermeasures: 1) Upgrading a 4-legged stop controlled intersection into a signalized intersection, and 2)Introducing mandatory speed limiters for large trucks in freeways.

Chapter 8 summarizes the major contributions of this research along with general conclusions and recommendations for possible further research to enhance the use of simulation for safety purposes.

Chapter 2

Traffic Safety Concepts and Safety Performance Measures

2.1 Introduction

From the engineering perspective, traffic safety studies are heavily dependent on how safety is defined and measured. Historically, researchers have been trying to represent safety throughout empirical studies based on observed crash occurrences. The underlying assumption of these studies is that crashes are individually unpredictable, although groups of crashes observed on a given location can produce predictable statistical pattern [31].

On the other extreme, individual crashes can be treated as deterministic events that resulted from failures of human-made systems. These systems are hypothesized to be modeled if the required knowledge of their inherent mechanism is available. In-depth crash investigation or accident reconstruction analysis attempts to provide this background knowledge, however, this kind of an approach demands a considerable amount of information not often available in police-reported collisions.

This Chapter presents fundamental definitions and concepts in traffic safety and introduces a number of indicators applied to evaluate the safety performance of transportation systems components. The potential applications and shortcomings of these safety performance measures are also discussed.

2.2 Safety Research: a Multidisciplinary Science

Roadway transportation systems can be divided into three basic components: 1) The road users, 2) The vehicles, and 3) The roadway environment. These three sub-systems interact in a dynamic and often complex fashion, consequently a comprehensive understanding of all these areas of expertise acting as one system can not be found in isolated disciplines, such as psychology, sociology, or engineering.

2.2.1 Road Users

The road user and its interaction with vehicles, the roadway environment and other road users while driving is the main subject of human research in traffic safety. In high level hierarchy, the driving task can be broken down into three elements: control, guidance, and navigation [33].

Control refers to drivers interaction with the vehicle to maintain desirable alignment and speed during the journey by acting on vehicle components, such as the steering wheel, throttle, and brake pedals. The guidance component is the driver's interaction with the roadway environment (alignment, grade, and geometric features), traffic (speed, relative position, and gaps) and traffic control devices (signs, signals, and markings) in order to maintain safe speed and path. Navigation is the process of planning and executing trips using past experience or other information, such as maps, guide signs and landmarks.

The control level is related to activities with low demand of driver's cognitive capabilities that are executed almost automatically by the driver. Information has to be frequently processed in intermittent short time intervals varying from few seconds to almost continuous feedback. Drivers responses at this level have the highest priority when compared to both guidance and navigation components given that unexpected events that could jeopardize the journey (e.g. a flat tire or a crossing vehicle) can only be avoided at this low level. The guidance component requires higher level of cognitive skills from driver's when compared to control and, the decision-making process demands information in periods from few seconds to minutes. The navigation process, on the other hand, is usually more time consuming and complex as compared to the other two processes.

It is worth noting that there is a chaotic pattern associated with the information exchange among these three levels of control [107]. Figure 2.1 illustrates the complexity and primacy for different levels of driving task.

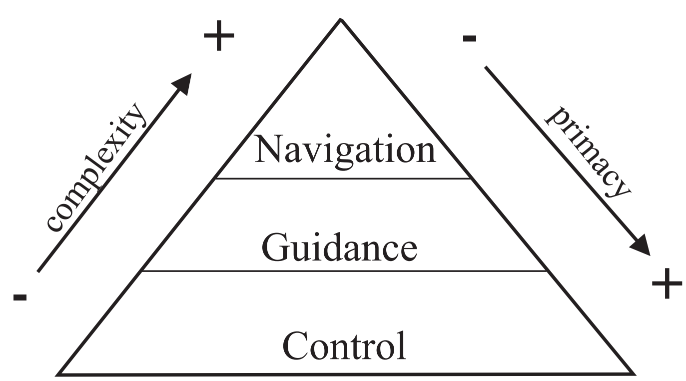

Figure 2.1: Levels of the driving task (Source: [107])

2.2.2 Vehicles

The automobile industry has been responsible for considerable advances in safety since the first patent for a restraining belt for passengers in road vehicles was granted to E.J. Claghorn in 1885. Safety devices in vehicles can be classified according to its role in avoiding crashes or minimizing its severity as passive or active in-vehicle safety features.

Active safety features help the driving task in situations where drivers could lose control of the vehicle, such as in slippery conditions, sharp curves, and congested highways with vehicles subjected to frequent stops. Most commonly active safety devices presented in high-end vehicles are: anti-lock braking system (ABS), adaptive cruise control (ACC), traction control (TCS), dynamic steering response (DSR), intelligent speed adaptation (ISA), electronic stability control (ESC), directional headlights, reverse backup sensors, among others.

Passive safety features are designed to minimize the consequences of a crash given that its avoidance is no longer possible. Some of the most commonly found passive safety devices are: seat belts, air-bags, side impact bars, and collapsible steering columns.

With increasing application of electronic systems and wireless technologies to the automobile industry, a number of new active safety features will be commercially available soon. According to Leen and Heffernan [58], more than 80 percent of all modern automotive innovation comes from electronics. Modern vehicles have more than 4 kilometers of wiring compared to approximately 45 meters in vehicles manufactured in 1955.

More recently, the National Highway Traffic Safety Administration (NHTSA) has sponsored a number of crash avoidance research projects under the Intelligent Transportation Systems program. The aim of the program is to enable real-time wireless communications among motor vehicles and between motor vehicles and roadside infrastructures. This real-time inter-vehicle communication can provide the state of the art for the development of more effective safety devices in vehicles [20].

The crash avoidance database structure suggested by the NHTSA would make use of four driving states grouped according to levels of evasive action needed and types of countermeasure (active or passive) to keep vehicles interacting at a low risk level [102]. The driving conflict states, potential countermeasures and applications are shown in Figure 2.2.

2.2.3 Roadway Environment

The roadway environment can be defined as the main infrastructure available in the transportation system for vehicles to travel efficiently. Planning, design, and operation of this component is the natural domain of transportation engineers.

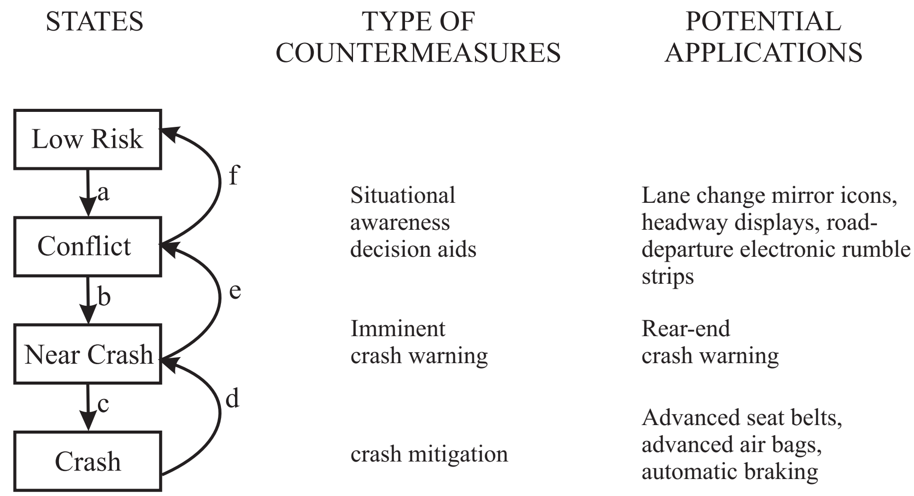

Figure 2.2: Driving states, countermeasures and potential applications (Source: [102])

Safety in the roadway environment depends primarily on factors, such as pavement materials, standards for road geometry, and traffic control devices. While great advances in pavement materials and highway design standards have been achieved in the last century, geometric improvements to existing roads are now becoming costly and disruptive in nature. Common pavement and road geometry related engineering countermeasures that frequently result in safety benefits are: lane widening, shoulders paving, dedicated left-turn and right-turn lanes, and roundabouts.

Traffic control devices are designed with the purpose of standardizing as much as possible the driving behaviour and optimize the traffic flow pattern where conflicting trajectories are apparent. Pavement marking, signs, traffic signals, and variable message signs (VMS) are examples of such devices.

Over the last 20 years major safety improvements have been obtained throughout the application of electronic systems to the roadside environment. As noted previously, there is an increasing number of researches focusing on cooperative systems that integrate both in-vehicle and roadside devices throughout wireless communication protocols.

The FHWA and the states of California, Minnesota and Virginia are investigating the application of ITS technology to help drivers in making safer judgments with respect to crossing path manoeuvres at intersections. This research project called Intersection Decision Support (IDS) analyzes potential conflicting trajectories and estimates if there is sufficient time for the manoeuvre to be finished. When it is not safe to proceed, according to a safe gap criteria, the driver in the lower priority movement receives an advisory "no go" message [101].

2.3 Police-reported Crashes as a Measure of Safety

In the context of this thesis, a crash or collision is defined as an event between one or more road users that results in property damage, injury, or fatality. Crashes are considered by safety engineers as ultimate failure of transportation systems and therefore highly undesirable events.

Historically, safety has been defined and measured in terms of observed number of crashes in part by the intuitive and logical link between these two. The majority of safety studies found in the literature are based on police-reported crash data. As noted previously, the main advantage of using these data is that these are objective measures of failures in at least one of the three major components of the transportation systems: the vehicle, the road user or the road environment.

Unfortunately, a number of problems related to the use of this source of information are found in the literature, such as low reportability rates, incomplete and mis-reporting information, errors in the data entry, and statistical challenges posed by the inherent rare nature of crash occurrences [31, 40, 41, 46, 79, 95].

The reportability criteria, i.e. the minimum requirement for drivers to report a crash, is not uniform between jurisdictions and it is also subjected to changes over time in a given jurisdiction. For example, in Ontario, when the police is not on the scene, collisions where damage to vehicles or property is more than $1,000 must be reported to collision reporting centres [81]. Nevertheless, in several occasions drivers are prone not to report crashes since this would affect their driving records and subsequently automobile insurance premiums.

According to Hauer and Hakkert [43], the number of crashes that are not reported increases as the crash severity decreases. Around 20% of crashes that resulted in serious injuries and 50% of cashes with injuries that did not require hospitalization are not reported to the police. They also estimated that approximatelly 60% of property damage only (PDO) collisions are not present in police accident database systems.

A study on the reliability of police-reported information for determining crash and injury severity was performed by Farmer [35]. Police-reported information of posted speed limit and driver injury severity were investigated for a sample of more than 10,000 crashes obtained from the National Automotive Sampling System/Crashworthiness Data System (NASS/CDS) from 1996 to 2000. One of the key findings of this study was that police reports frequently overstate drivers injury severity, in particular, 49% of the drivers coded by police as having incapacitating injuries actually had sustained only minor injuries.

As noted previously, crashes represent a complex hierarchical process of interrelated causes and consequences for different driving situations, locations and time intervals and are very random in nature. These underlying characteristics produce a number of challenges to the development of reliable statistical models to correlate historical crash data with traffic and road attributes, and these are:

1. The high frequency of zeros in collision counts and unobserved/unexplained heterogeneity leads to data over-dispersion. This undermines the power of statistical models based on crash data and raises concerns related to their spatial and temporal transferability [39, 60, 71, 89, 97].

2. Discrepancies between predicted and actual crash rates following the implementation of a countermeasure could occur normally as a result of historical trends in crash occurrence regardless of the countermeasure. This is frequently referred to as the regression-to-the-mean (RTM) phenomenon [8, 40, 66].

3. Statistical models developed using historical crash data assume that group of crashes observed on a given location can yield predictable statistical pattern. Researchers have argued that this is only true if the underlying mechanism generating the aggregated data is understood. Otherwise, relationships observed in aggregated data may not hold true at disaggregated level (ecological fallacy) [31].

4. Variables that are identified as been potentially significant for reducing crashes may fail to meet minimum thresholds for inclusion in statistical models. Their contribution to crashes may be plagued by problems of collinearity [1, 94, 97].

5. Due to the rare random nature of crashes and data availability, the effect of an important variable may not be large enough to be detected reliably in a before and after observational data, despite the fact that its effect cannot be denied intuitively [94].

Despite the intuitive link between road safety and observed crashes, a good understanding of the sequence of events prior to the crash could provide a more rational basis for the development of engineering countermeasures. In addition, some researchers argue that observational studies using only reported crashes constitutes in essence a reactive approach to the safety problem by which countermeasures are often triggered after a significant number of collisions has been observed [88, 95, 107].

2.4 Safety Continuum

The notion of safety for road users while in the transportation system can be hypothesized as a series of time-dependent events that range from undisturbed passages to actual collisions. This is referred to as the safety continuum of traffic events [13, 40, 49, 107].

A visual representation of the frequency and severity of these events proposed by Hydén in 1987 is illustrated in Figure 2.3. The volume corresponding to the class of events described in Figure 2.3 can be linked to its relative rate of occurrence. This theoretical concept provides a bottom-up and more rational approach to safety research as opposed to the traditional top-down perspective of safety given by collision frequency. However, it is well recognized that while the extremes of the pyramid are promptly detected (crashes and undisturbed passages), intermediate events lack objective definitions and thresholds, as well as effective procedures for their measurement.

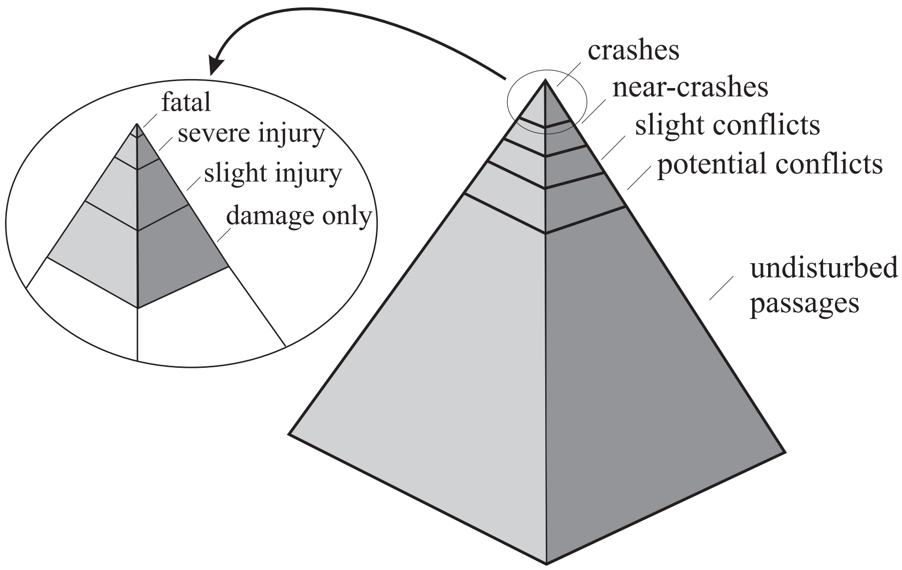

Figure 2.3: The safety pyramid (Source: [49])

The next section describes a number of performance measures applied to safety studies based on the bottom-up approach.

2.5 Safety Performance Measures

Safety performance measures, also known as proximal safety indicators or surrogate safety measures [13, 36], are defined to reflect high risk events in relation to a projected point of collision. These measures are usually based on pair-wise vehicular velocity and spacing attributes.

The main assumption underlying the use of safety performance measures is that if one is able to detect high risk situations that occur considerably more frequent than crashes, then statistically reliable results would be possible without the need of historical crash data. The use of safety performance measures also constitutes in essence a proactive approach to road safety studies since it is able to detect safety problems before they result in crash [15, 30, 88].

A potential problem to the application of such measures is the need for an objective definition of "high risk" situations or "near-misses" that did not result in a crash because of some evasive manoeuvre or other factors to be used in lieu of historical crash data. One of the first attempts to outline a definition of high risk situations was given by Perkins and Harris in 1967 in the form of traffic conflicts [87]. Amundsen and Hydén [11] provided the most accepted definition of traffic conflict as *"an observable situation in which two or more road users approach each other in space and time to such an extent that there is a risk of collision if their movement remain unchanged"*.

The vast majority of the safety performance measures described in this section makes use of the above definition to define thresholds between undisturbed passages and high risk situations. These assumptions and definitions ultimately lead to the development of a new technique for safety assessments that is described in the next Chapter.

2.5.1 Time Based Measures

A number of safety performance measures based on the projected time of a potential collision can be found in the literature. The most common are: time to collision (TTC), time to accident (TTA), post-encroachment time (PET), encroachment time (ET), and gap time (GT).

Time to Collision (TTC)

The concept of time to collision, initially proposed by Hayward in 1972, is defined as *"the time required for two vehicles to collide if they continue at their present speeds and on the same path"* [45]. For vehicles traveling in the same direction TTC can be continuously measured over time using the following expression

$$TTC_{i,t} = \frac{(X_{i-1,t} - X_{i,t}) - L_{i-1,t}}{V_{i,t} - V_{i-1,t}} \tag{2.1}$$

where
t= time interval
X= position of the vehicles (i = following vehicle, *i-1* = lead vehicle)
L= vehicle length
V= velocity

In situations where vehicles coming from a minor approach should yield for vehicles in the major approach there is a potential for angled crashes. Time to collision in these cases can be calculated by

$$TTC_{i,t} = \frac{D_{i,t}}{V_{i,t}} \tag{2.2}$$

where
$D_{i,t}$= distance between the projected point of collision and vehicle i on the major approach

Obviously, the TTC measure implies the existence of a collision course, i.e., vehicles traveling in the same direction must be approaching each other ($V_{n,t} > V_{n-1,t}$) and, for potential angled crashes, the projected position of conflicting vehicles must overlap at a given time interval.

Values of TTC can vary from infinity when vehicles are not in collision course to minimum safe values ranging between 1 and 1.5 seconds [22, 45, 107]. A classical illustration of the TTC concept is given in Figure 2.4. While in a collision course, driver from vehicle 1 normally requires a certain amount of time to perceive and react to the situation (point A in the Figure 2.4). A brief time interval after the beginning of the evasive action, TTC reaches its minimum value (TTC$_{min}$) in point B increasing sharply thereafter. Point C in Figure 2.4 is the potential point of impact for vehicles 1 and 2.

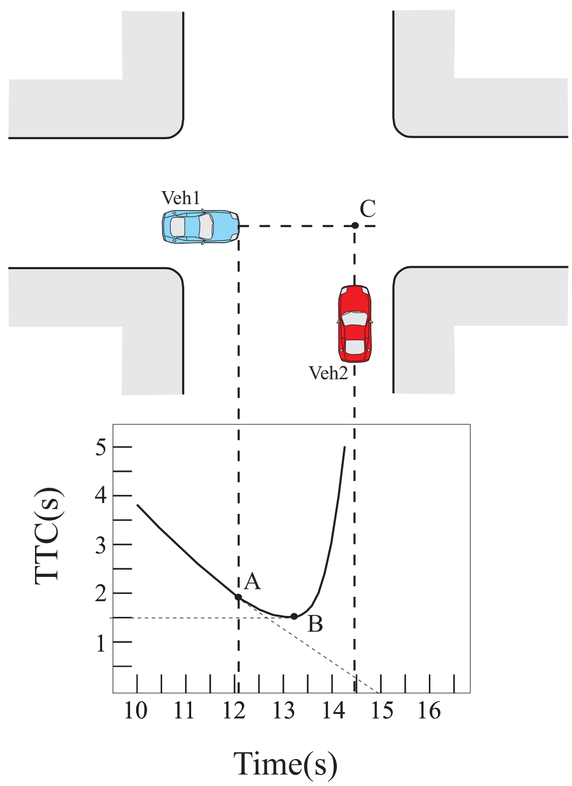

Figure 2.4: TTC empirical curve

As noted before, the usefulness of TTC for safety assessments depends on the use of some arbitrary scale of danger between inter-vehicle interactions that separates undisturbed passages from near-misses. Several researchers have tried to establish minimum value of TTC that could be used to estimate the number of conflicts in field studies [22, 45, 108, 109]. van der Horst [109] noted that the likelihood of crashes becomes a concern when TTC for a given vehicle is less than 1.5s. This result was obtained from an experiment involving the application of a driver simulator to a closed course road. It is worth noting that TTC_{min} usually occurs after the evasive action taken by the driver and thus it does not include the reaction time of the road user. Nevertheless, alternative measures of TTC can overcome this problem, such as a continuous measure of TTC for the entire event [13].

A problem that limits the application of this safety measure is that several combinations of speed and distance can produce the same TTC measure, for example, consider conflict A where two vehicles are 42m apart approaching at a rate of 100km/h and conflict B with vehicles 4.2m away approaching at a rate of 10km/h. Although both situations yield TTC values of 1.5s, it is reasonable to expect that conflict A, with considerable higher kinetic energy and linear momentum would result in a higher severity crash when compared to conflict B.

Another issue that has prevented the widespread use of the TTC concept is related to techniques to estimate reliable TTC values. Continuous measurements of TTC require detailed speed-spacing information normally available through the use of resource-demanding and laborious techniques, such as photometric video-analysis [13].

Time to Accident (TTA)

The Time to accident (TTA) attempts to simplify TTC measurements and was defined by Hydén as "*the time that passes from the moment that one of the road users reacted and starts braking or swerving until the moment the involved road user had reached the point of collision if both road users had continued with unchanged speed and direction*". In other words, instead of continuous measurements of TTC, one would only record the TTC value at the moment the evasive action took place.

This measure is the basis for the development of the Swedish version of the traffic conflict technique (TCT). Since TTA is measured only once during the conflict, traffic conflict studies can be performed by trained observers that judge the precise moment of the evasive action and estimate speed and distance measurements relative to conflicting vehicles. The observers reduce much of the data acquisition effort as compared to TTC-based studies, however, a new type of bias is introduced to the process since judgments of speed and distance could result in unreliable measurements [42].

More than a decade after his initial studies with TTA, Hydén [49] improved its scope by introducing a series of "uniform severity levels" and "uniform severity zones" to provide different conflict categories ranging from "non-serious" to "serious". These categories were based on equidistant parallel non-linear functions considering average rate of deceleration needed to avoid a collision at different speeds and standard coefficient of friction (Figure 2.5). Thus, TTA and the proposed conflict categories can provide a better platform for determining severity in safety studies as compared to TTC.

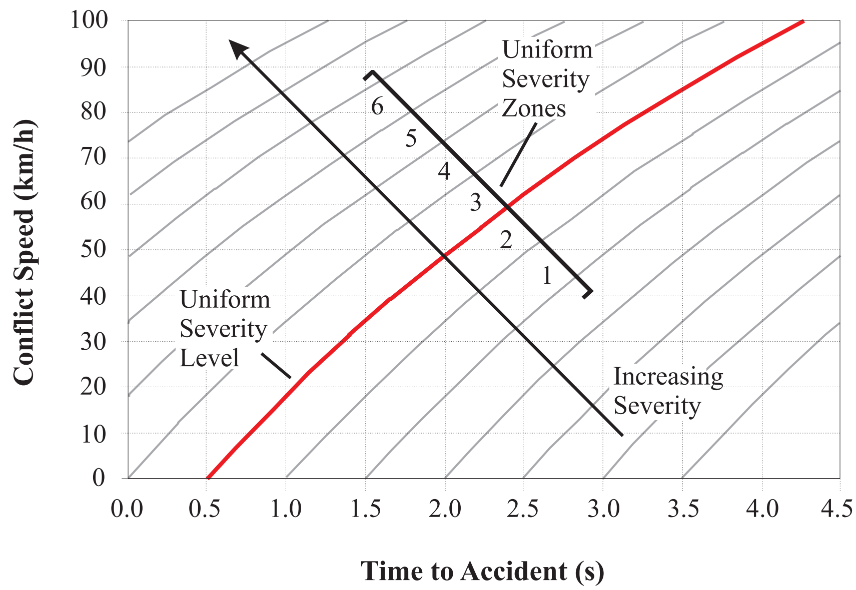

Figure 2.5: Severity levels and zones according to Hydén (Source: [13])

Post Encroachment Time (PET)

The Post Encroachment Time (PET) is defined as the time difference between the moment an "offending" vehicle leaves the area of potential collision and the moment the other vehicle arrives the collision area [26]. Figure 2.6 illustrates the definition of post encroachment time for an angled conflict.

This measure differs from TTC and TTA in the sense that the collision course is not required, thus the data acquisition process can be simplified since relative speed and spacing are no longer needed.

Major drawbacks of the application of PET in traffic safety studies include: 1) The basic event used for defining PET may not be comparable to processes that lead to crashes, 2) Likewise TTC, the "pure" PET measure has limited application in studies focused on crash severities, and 3)The measure is more suitable for crossing conflicts (angled crashes). For rear-end conflicts there is a "moving" conflict area as vehicles progress along their path which adds considerable complexity to field measurements [13, 107].

Allen et al. [10] examined 347 left-turn conflicts events from two weeks of video records to investigate the feasibility of three other time based safety performance: encroachment time (ET), initially attempted post encroachment time (IAPT), and gap time (GT). Figure 2.7 shows the time-space diagram for a left-turn manoeuvre illustrating the concept of these measures.

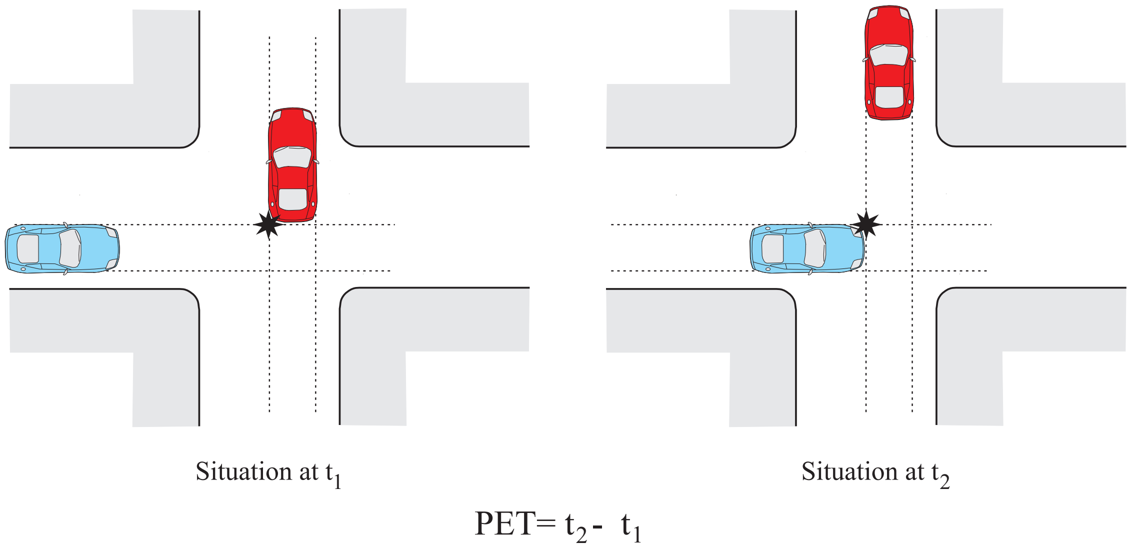

Figure 2.6: PET concept

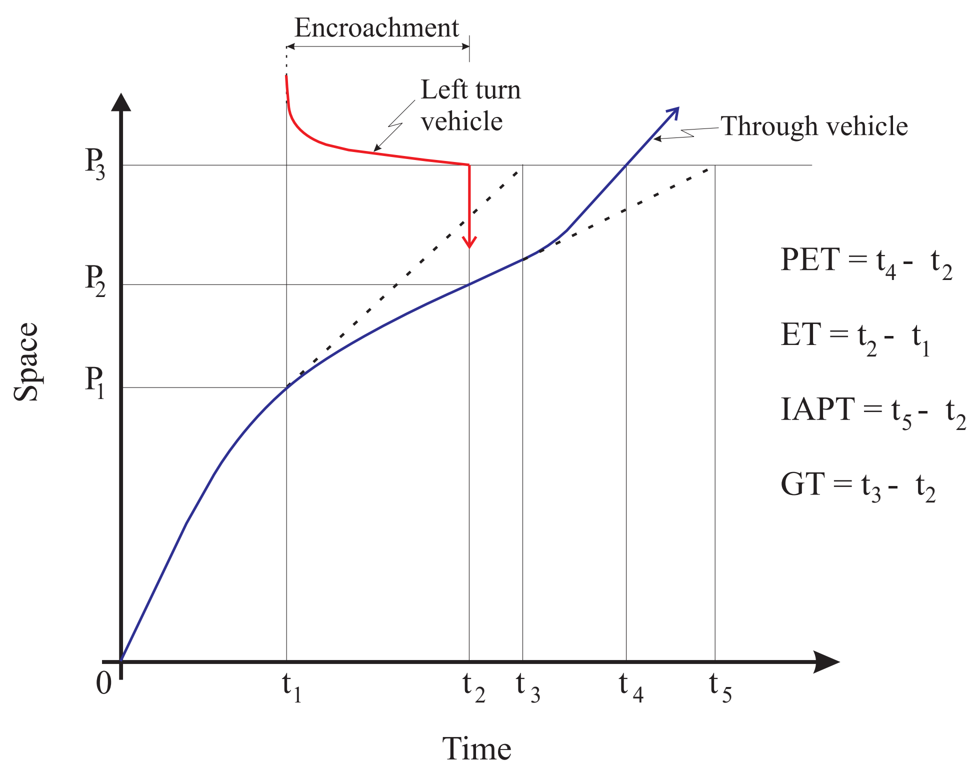

Figure 2.7: Time-space diagram for a typical left-turn conflict (Source: [10])

Encroachment Time (ET)

The Encroachment Time (ET) reflects the period that the "offending" vehicle occupies the conflict area therefore infringing the right-of-way of the vehicle in the major approach.

According to Allen et al. [10], ET would be a good measure of conflicts if vehicles on the major approach could be hypothesized as having constant speeds. If this was true, longer ETs would mean higher severity conflicts since vehicles on the major approach would need higher deceleration rates to avoid potential collisions.

The use of ET requires objective definitions of conflict areas for each manoeuvre as well as precise measurements of the time interval during which "offending" vehicles is occupying these conflict areas. These requirements can be complex and difficult to detect and quantify hence limiting the scope of this measure.

Initially Attempted Post Encroachment Time (IAPT)

This measure is similar to PET, however it uses the projected arrival time at the conflict area of the major approach vehicle (t_5 in Figure 2.7) with respect to the moment the encroachment has ended.

Gap Time (GT)

Gap Time (GT) is given by the projected time arrival of the vehicle in the main traffic stream reaches the conflict area minus the time required for the yielding vehicle to clear the conflict area. The projected time arrival of the main road vehicle is estimated using distance and speed relatives to the moment which the yielding vehicle begins the manoueuvre.

Several other time based safety performance measures have been suggested with limited application. Most of them using variations of the initial time to collision concept. Examples of these measures are: time to intersection (TTI), time to stopline (TTS), time to zebra (TZ), and time to line crossing (TLC).

2.5.2 Required Braking Power Measures

The differential speeds of vehicles at the moment of impact plays a major role in crash severity due to the kinetic energy of the system right before the collision. Safety measures based on the required rate of speed reduction or braking power of vehicles have the best theoretical formulation to provide good estimates of potential conflicts, as well as to produce an objective platform for safety studies on which severity is a major factor.

Two safety performance measures based on vehicles require braking power while in conflicts are: deceleration rate to avoid the crash (DRAC) and proportion of stopping distance (PSD) [10, 13, 25, 30, 36].

Deceleration Rate to Avoid the Crash (DRAC)

Cooper and Ferguson [25] made one of the first documented attempts to use the deceleration rate to avoid the crash (DRAC) as a measure of conflicts. DRAC can be defined as the rate at which a vehicle must decelerate to avoid the collision with other conflicting vehicle [13, 36]. A more complete definition requires assumptions about the vehicle that initiated the conflict ("offending vehicle"). In this thesis, DRAC is defined as the required deceleration rate to avoid a collision if the offending vehicle continues with the same speed and trajectory.

For vehicles traveling in the same direction, DRAC can be expressed as

$$DRAC_{i,t+1} = \frac{(V_{i,t} - V_{i-1,t})^2}{2[(X_{i-1,t} - X_{i,t}) - L_{i-1,t}]} \tag{2.3}$$

where
t= time interval
X= position of the vehicles (i = following vehicle, i-1 = lead vehicle)
L= vehicle length
V= velocity

For potential angled collisions, estimations of DRAC are obtained by

$$DRAC_{i,t+1} = \frac{V_{i,t}^2}{2D_{i,t}} \tag{2.4}$$

where
$D_{i,t}$= distance between the projected point of collision and vehicle i on the main stream

The use of DRAC allows a more intuitive (but not less arbitrary) classification of traffic conflicts. In a study of simulated conflicts from gap acceptance manoeuvres, McDowell et al. [69] introduced five grades of severity according to ranges of deceleration (Table 2.1). Severity grade 1 and 2 were considered low severity while grades 3 to 5 were considered high severity conflicts.

Table 2.1: Severity grade and deceleration ranges (Source: [69])

Severity grade	1	2	3	4	5
DRAC (m/s^2)	<1.5	$1.5<3.0$	$3.0<4.5$	$4.5\leq6.0$	>6.0

Hydén [50] have suggested an alternative classification for conflicts using DRAC that is based on the expected driver reaction in order to achieve the required deceleration. The severity levels proposed are presented in Table 2.2

The main drawback of this safety measure relates to the data acquisition process. In order to calculate DRAC, detailed speed/spacing information of both vehicles

Table 2.2: Braking levels suggested by Hydén (Source: [50])

Conflict level	DRAC (m/s^2)	Description
No conflict	0	evasive action not necessary
No conflict	0 to 1	adaptation necessary
1	1 to 2	reaction necessary
2	2 to 4	considerable reaction necessary
3	4 to 6	heavy reaction necessary
4	$\geq$6	emergency reaction necessary

involved in the conflict must be available. This detailed information is normally obtained through the application of laborious and non-trivial photometric analysis.

In theory, DRAC has the potential to be applied in safety evaluations of traffic scenarios that include different weather conditions, such as dry, wet or snowy conditions and for different traffic composition. It is reasonable to suggest that achieving a DRAC of say, 6m/s^2 can be more challenging when under adverse (wet) pavement conditions as compared to normal (dry) conditions. Furthermore, due to differences in braking systems and masses, a DRAC of 6m/s^2 for a truck must correspond to a more serious conflict when compared the the same level of DRAC for small cars. Unfortunately, studies involving this safety measure that explores these aspects are not commonly found in the literature. In the scope of this thesis, DRAC is considered the most promising safety performance measure.

Proportion of Stopping Distance (PSD)

The proportion of stopping distance (PSD) was initially suggested by Allen et al. [10] and can be defined as the ratio between the remaining distance to the potential point of collision and the minimum acceptable stopping distance. This can be expressed as

$$PSD = \frac{RD}{MSD} \tag{2.5}$$

where
RD= remaining distance to the potential point of conflict (m)
MSD= acceptable minimum stopping distance = $V^2/2D$ (m)
V= approaching velocity (m/s)
D= acceptable maximum deceleration rate (m/s^2)

It is worth noting that according to Allen and colleagues, PSD values must be measured at the moment that the "offending vehicle" starts to infringe upon the right-of-way of the other vehicle (t_1 in Figure 2.7). However this does not guarantee that vehicles are in a collision course.

2.5.3 Safety Indices

Recent developments in real-time data acquisition techniques and increasing use of microscopic simulation in safety studies have fostered the development of safety indices that incorporate a temporal dimension to traditional safety performance measures. The fundamental assumption underlying the use of safety indices is that the conflict severity and the correspondent time exposed to such conflict can provide a better measure of safety that a single measurement, such as the lowest TTC, the highest DRAC, etc.

Three safety indices will be discussed in this section: time exposed time to collision (TET), time integrated time to collision (TIT), and the unsafety density parameter (UD) [15, 70]

Time Exposed Time to Collision (TET)

Minderhoud and Bovy [70] define TET for a given vehicle as the summation of all time intervals this vehicle experienced TTC-values lower than a specific TTC threshold value (TTC*) representing the boundary between safe and critical conflicits. TET also needs specification of the total observed time (H) and the length (L) of the road section evaluated. TET can be calculated using the following expression

$$TET_i^* = \sum_{t=0}^{T} \delta_i(t) \cdot \tau_{sc} \tag{2.6}$$

$$\delta_i(t) = \begin{cases} 1 \quad \forall \quad & 0 \leq TTC_i(t) \leq TTC^* \\ 0 \quad else & \end{cases}$$

where
TET_i^* = time exposed time-to-collision (s) for vehicle i given the threshold TTC*
$T = H/\tau_{sc}$ total number of observed time intervals
H = total time considered in the study (s)
τ_{sc} = time interval to assume a constant TTC (e.g. 0.1s)

An overall TET value can be produced for the entire scenario by accumulating TET for all observed vehicles. Furthermore, this indicator can be calculated separately for different vehicle categories or different weather conditions.

Unfortunately, the TET indicator does consider the severity of the conflict, once it is expected that, the risk of collision for a very low TTC value is higher than for a higher TTC value, although both remain under the established threshold.

Time Integrated Time to Collision (TIT)

This parameter was also suggested by Minderhoud and Bovy [70] to account for the severity of conflicts based on a time to collision threshold value. TIT measures the difference between observed TTC and threshold TTC value (TTC*) for a given time interval cumulative to the time the vehicle traverses the study area. In continuous time,

$$TIT^{*} = \sum_{i=1}^{N} \int_{T}^{0} [TTC^{*} - TTC_{i}(t)]\,dt \tag{2.7}$$

$$\forall \quad 0 \leq TTC_{i}(t) \leq TTC^{*}$$

Figure 2.8 exemplifies TET and TIT concepts with typical observed time to collision profile for one vehicle in the traffic stream.

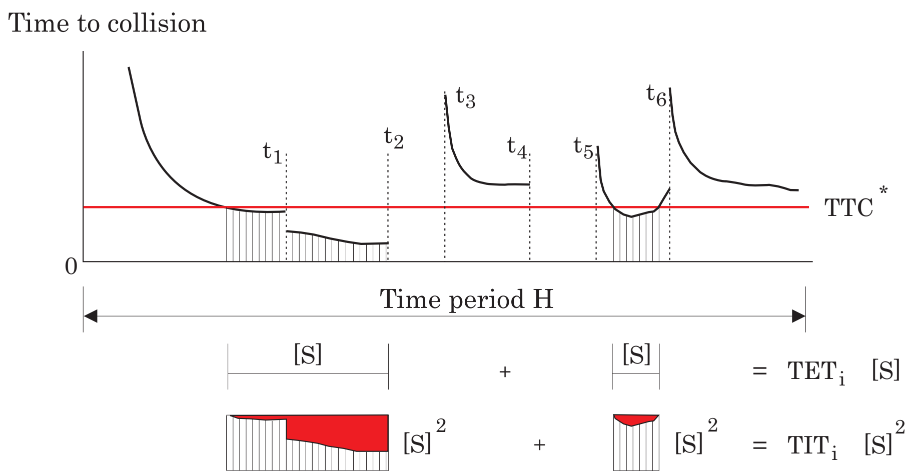

Figure 2.8: Time extended and time integrated time to collision concepts (Source: [70])

Parameters TET and TIT can provide useful insights about safety using microscopic simulation, however the same issues found in TTC are "transfered" to these parameters and need to be further investigated. For a given TTC, for example, the likelihood of a crash is influenced by factors, such as weather conditions, vehicle type and configuration, and driver's braking skills. In other words, different TTC threshold values should be assigned for different combinations of the variables described above.

Unsafety Density Parameter (UD)

Barceló et al. [15] presented a safety performance measure for car-following situations based on vehicle speeds, relative position between the lead and the following vehicle and the reaction time of the following driver. The basic rules of Newtonian physics are applied to verify if a hypothetical crash would have taken place if the lead driver was required to stop the vehicle at its maximum braking capacity. The reaction time of the following driver was assumed equal to a standard value of 2 seconds for all drivers.

If during a given time interval the hypothetical crash would have occurred then both the speed of the following vehicle (S) and the speed differential (ΔS) at the moment of the collision are calculated. The authors use these speed attributes to define an "unsafety" parameter as follows:

$$unsafety = \mathit{\Delta} S \cdot S \cdot R_d \tag{2.8}$$

where
$R_d = \begin{cases} b/b_{max} & if \quad b > 0 \\ 0 & else \end{cases}$
b = deceleration rate of the leading vehicle
b_{max} = maximum possible deceleration rate of the leading vehicle

In order to assess the safety level of different links of the network over time, the "unsafety density" (UD) safety indicator is estimated using the summation of the "unsafety" paremeter for all the vehicles in the simulation normalized with respect to section length (L) and total time period considered in the analysis (T) as follows

$$UD = \frac{\sum_{s=1}^{S_t} \sum_{i=1}^{N} unsafety_{i,s} \cdot \mathit{\Delta} t}{T \cdot L} \tag{2.9}$$

where
S_t = number of simulation time steps
N = total number of vehicles in the simulation
Δt = simulation step duration (s)

The use of the UD as a safety performance measure is limited in scope due to some conceptual problems as follows: 1) Adopting a fixed following driver reaction time will increase the bias in the UD measure, 2) UD values are greater than zero only when the lead vehicle is braking and thus some conflicts that take place during stop-and-go situations are not considered, 3) The measure is restricted to potential rear-end crashes only, and 4)The unsafety factor expression has little mathematical meaning.

Chapter 3

Traffic Safety Studies

3.1 Introduction

The ultimate goal of transportation engineers is to maximize safety of the road network, whether by improving existing projects or enhancing design standards for new transportation components. Traffic safety studies provide a systematic tool for transportation professionals to evaluate safety of existing projects and rationally direct scarce resources to improve safety in the network (network screening).

Another important application of traffic safety studies relates to evaluating of the safety implications associated with changes in existing characteristics of a given entity of the road system (before-after studies), for example, what would be the safety impact of installing a traffic signal in a previously stop controlled intersection?

The most common category of safety studies makes use of inferential statistics applied to historical crash data, known as observational traffic safety studies. Additional methodologies for safety studies have been introduced mostly to address some of the methodological challenges posed by the very random and unique nature of accidents and these are: traffic conflict safety studies and real-time and simulation-based safety studies. This chapter discusses the advantages and shortcomings of these approaches.

3.2 Observational Traffic Safety Studies

Observational studies can be viewed as a passive learning process where the knowledge comes from meticulous analysis of the outcome of events that have not been formally designed to address the problem. The fundamental assumption in observational traffic safety studies is that safety is a property of traffic entities and can be defined as "*the number of crashes by kind and severity, expected to occur on the entity during a specific period*"[40].

Researchers have been applying a number of statistical methods and numerical techniques to model the number of crashes of a given road entity based on geometric and traffic attributes, and other relevant information found in police-reported crashes.

Statistical models for safety assessment also known as crash prediction models (CPMs), accident prediction models (APMs) or safety performance functions (SPFs) are regression models describing the relationship between the number of crashes and relevant geometric and traffic attributes, such as traffic flow, number of lanes, segment length, etc.

Initially, CPMs were developed using linear regression modelling, which assumes normal distribution of errors and homoscedasticity. These assumptions were found to be inconsistent with the nature and frequency of crash events and further research have confirmed the advantages of using Poisson models over standard regression models. In this case, the generalized linear modelling (GLM) approach can provide an adequate platform for better models once it is possible to assume a non-normal distribution of errors. Recently, it has been suggested that crash data used in the calibration of CPMs are usually more dispersed than what would be consistent with the Poisson assumption. This is why most recently developed CPMs assume crashes follow a negative binomial distribution [39, 32, 65, 79].

According to Sawalha and Sayed [97], mathematical expressions of CPMs must satisfy two basic requisites: 1) It should yield logical results, i.e. neither negative number of crashes must be obtained nor positive number of crashes in case of zero values of explanatory variables and 2) The expression must be linear for the purpose of coefficient estimation in order to use generalized linear regression. These models are calibrated from crashes observed in sites with "similar" characteristics assuming the general form as follows:

$$E_c = \alpha \left[\prod_{i=1}^{M} (F_i)^{\beta_i} \right] \cdot e^{\sum_{j=1}^{N} (\gamma_j G_j)} \tag{3.1}$$

where
E_c= expected number of crashes/year (intersections) or expected number of crashes/km–year (road segments)
F, G = relevant road and traffic attributes such as major and minor road AADT, #lanes, segment length, pedestrian volume, intersection skew angle, etc (explanatory variables)
α, β, γ = model parameters

Different CPMs developed for intersections and road segments are normally found in the literature. The basic difference between these models is that the length of the segment must be included either as an independent variable or accounted for by the dependent variable (e.g. expected number of crashes/km-year).

Bonneson and McCoy [19] developed a CPM for stop controlled intersections for Minnesota rural highways. The study considered 125 intersections which experienced 250 crashes in 3 years (1985-1987). The data included two general types of major road geometry: 1)108 intersections with two lanes and no median and 2)17 intersections with 4-lane major road and median (median width $\geq$ 10.4m).

The analysis of the calibrated model results indicated that the model based on negative binomial error structure produced the best results for predicting collision frequency for the sample investigated. The proposed model is as follows:

$$E_c = 0.692 \left(\frac{T_m}{1,000}\right)^{0.256} \left(\frac{T_c}{1,000}\right)^{0.831} \tag{3.2}$$

where
E_c= expected number of crashes/year
T_m = major road volume (veh/day)
T_c = cross road volume (veh/day)

The coefficients in the model were found to be statistically significant at the 95% level of confidence. The model goodness of fit was evaluated using the Pearson chi-square statistic, a visual assessment using a plot of the predicted and observed crash rate and the dispersion parameter. These indicators suggested that the model provides a good fit between independent variables and crash rate and the error structure assumed (negative binomial) was approximately equivalent to what was found in the data.

A study focused on the development of crash prediction models for a sample of 270 three-legged and four-legged signalized intersections in Ontario was carried out by Persaud and Nguyen [91]. A total of 12,661 crashes recorded in the period from 1988 to 2003 was used in this analysis.

Two basic types of models were developed with respect to data availability and aggregation level. In level 1 models (aggregated), equations were calibrated for three and four-legged intersections by accident severity (injury and PDO) for all impact types combined and separately for angle, rear-end, and turning movement. For level 2 models (dissagregated), CPMs considered four-legged intersections for 15 different crash types defined by the movements of involved vehicles before collision. Level 1 and 2 models general expressions were defined as follows:

Level 1 models:

$$E_c = \alpha F^{\beta} \tag{3.3}$$

Level 2 models:

$$E_c = \alpha F_1^{\beta_1} F_2^{\beta_2} \tag{3.4}$$

where
E_c= expected number of crashes/year
F = sum of all entering flows for the corresponding time period (daily, weekday morning peak, and weekday afternoon peak)
F_1, F_2 = AADT for the smaller and larger conflicting flows, respectively, for a specific accident pattern

Model parameters for angle and rear-end crashes for four-legged rural intersections are illustrated in Table 3.1. This Table also includes models for different crash severities and time of the day.

Table 3.1: Model parameters and standard error for 4-legged rural intersections (Source: [91])

Type of crash	Time period	PDO			Severe		
		α (x10^6)	β	s.e. of β	α (x10^6)	β	s.e. of β
Angle	Daily	77924	0.171	0.073	24609	0.283	0.075
	AM peak	1684	0.422	0.105	12831	0.155	0.105
	PM peak	1790	0.441	0.108	2781	0.309	0.116
Rear-end	Daily	0.054	1.569	0.062	0.323	1.352	1.730
	AM peak	0.158	1.659	0.089	0.930	1.364	2.490
	PM peak	0.224	1.619	0.087	0.163	1.580	2.250

Several other crash prediction models for intersections can be found in the literature. Tables 3.2 and 3.3 provide a summary of other relevant studies focused on the development of CPMs worldwide.

Table 3.2: Crash prediction models for intersections (Source: [16, 44, 55, 74, 99])

Researchers	Location	Years of data	# crashes	Intersection			Explanatory variables
				# Int.	Control	Configuration	
Hauer et al. (1988)	Toronto/CA	3	2,573	145	Signalized	4-legged	Traffic flow by movement or time of the day
Bélanger, C. (1994)	Quebec/CA	-	1,084	149	Stop controlled	4-legged	Total, minor and major AADT, flashing beacon, sight distance, turning lanes, speed limit
Kulmala, R. (1995)	Finland	5	-	1,762	-	4 and 3-legged	AADT
Montain et al. (1996)	7 counties/UK	5 to 10	25,983	5,359	Stop controlled	4 and 3-legged	AADT, # minor intersections in the link, length of the link
Sayed and Rodrigues (1999)	Vancouver/CA	3	2,160	419	Stop controlled	4 and 3-legged	AADT major and AADT minor road

Since not every transportation agency is able to develop CPMs from local crash data, it is important to investigate the possibility of using CPMs developed for

Table 3.3: Crash prediction models for road segments (Source: [37, 90, 96, 110])

Researchers	Location	Years of data	# crashes	Road segment attributes	Explanatory variables
Persaud and Mucsi (1995)	Ontario/CA	2	30,757	2,104 two-lane rural road sections	Traffic volume, time of the analysis and segment length
Vogt and Bared (1998)	Minnesota and Washington/US	8	3,400	two-lane rural state highways	ADT, total road width, roadside hazard rating, driveway density, grade and horizontal/vertical attributes
Sawalha and Sayed (2001)	Vancouver and Richmond/CA	3	-	392 segments of arterial roads	AADT, segment length and unsiganlized intersection density
Greibe (2003)	Denmark	5	1,058	345 segments (approx. 450m/segment) with various attributes	AADT, posted speed, # exits/km, minor side roads/km, parking, land use, road width

"similar" entities but using a different population of drivers (spatial transferability). Researches indicate that models developed in other jurisdiction can not be used interchangeably among different jurisdictions and must be recalibrated using local data to better suite the model to local conditions [89, 97, 110].

It has been recognized that CPMs reliability is improved if the model is based on data for as many years as possible, however, it is necessary to account for the year-to-year variation or trend in the collision dataset. This trend can be caused by factors, such as traffic growth or the impact of national road safety policies and local programs in observed crashes and creates a temporal correlation that presents difficulties for traditional model calibration procedures [61, 75, 89, 97].

Sawalha and Sayed [97] suggested that another concern with the development of CPMs is the process by which model explanatory variables are selected. There is a considerable amount of judgment based on experience to select the variables and to choose the way these variables will be considered, i.e., continuous versus categorical variables. In their study an attempt was made to introduce a procedure for building a more parsimonious and best-fit models.

CPM expressions applied alone to specific sites may lead to inaccurate estimations of crashes mainly because of the over dispersion phenomenon in crash data. A relatively recent methodology to improve crash estimations known as the Empirical Bayes method (EB method), uses concepts of conditional probability applied to both the reference population (represented by CPMs) and the specific site to produce a weighted value of the expected number of crashes. The EB estimate of crashes is given by [40]

$$E\left(m|x\right) = w \cdot E\left(m\right) + \left(1 - w\right) \cdot x \tag{3.5}$$

where
$E(m|x)$ = the expected number of crashes for entity m given that x crashes have been observed for the same entity
$E(m)$ = crash estimate obtained from regression model developed using crash data

of similar sites (CPMs)
w = weight assigned to $E(m)$ $(0 \leq w \leq 1)$
x = observational crash data for the site

The expression that yields the best estimate of w is given by

$$w = \frac{1}{1 + \frac{VAR(m)}{E(m)}} \tag{3.6}$$

where $VAR(m)$ is the variance associated with the regression model developed. Basically, the weight w in Equations 3.5 and 3.6 is a function of the variability found in the data used to develop the crash prediction model. The lower the variation in these data the higher the weight placed on the model estimates of crashes, i.e., higher level of confidence in the model. The EB method has been largely adopted in hot-spot identification (network screening) and in before-after analysis.

A number of alternative techniques to investigate safety using crash data that are less frequently applied than CPMs and EB method include the use of contingency tables, log-linear analysis, logit models, tree-based regression, artificial neural networks, among others.

In the contingency tables the data is grouped by the levels of the discrete variables. For two variables X and Y with m and n levels respectively, a matrix m x n can be produced with the observed number crashes in the correspondent combination of X and Y category. Contingency tables display the data in a suitable format and permits the use of significant tests such as chi-square. Sunanda and John [103] explored the relationship between driver age (15-25, 25-65, 65+), light condition (daylight, dusk, dawn, darkness with and without street lights), and crashes using contingency tables. The major conclusions of the work can be summarized as follows: 1) As lightning condition worsens, the involvement of old drivers in crashes increases, 2) Under all light conditions older drivers are more likely to be involved in crashes, and 3) Middle age drivers were found to be less involved in crashes when compared to young and old drivers for all light conditions.

Abdel-Aty et al. [3] developed four log-linear models to explain crashes observed in Florida as a function of driver age, crash severity, collision type, average daily traffic (ADT), roadway configuration (straight or curve), speed ratio, alcohol involvement, and accident location. The data was categorized according to combinations of three variables and log-linear models were developed for both main factors, as well as two-way interactions assuming the general form

$$log(m_{ijk}) = \nu + \lambda_i^x + \lambda_j^y + \lambda_k^z + \lambda_{ij}^{xy} + \lambda_{ik}^{xz} + \lambda_{jk}^{yz} \tag{3.7}$$

where
m_{ijk} = expected frequency of cell in which $x = i, y = j, z = k$

ν = overall effect and all other terms are the effect of the level of each variable and the interaction between variables on the response variable

Abdel-Aty and colleagues found that old drivers tend to be involved in angle and turning collisions and that young and middle age drivers have higher likelihood to be involved in collisions where alcohol was a factor.

Mannering and Grodsky [67] used logit models to investigate factors influencing motorcyclists' perceived likelihood of being involved in a crash. The results of a questionarie with 23 questions applied to a sample of 1,373 riders were used to develop the model. Logit models assume the general form:

$$P_{ni} = \frac{e^{U_{ni}}}{\sum_i e^{U_{ni}}} \tag{3.8}$$

where
P_{ni} = the probability that rider n would categorize himself as having low, medium or high risk of being involved in an accident in the next 10 years
U_{ni} = linear function of variables which determine the probability of a rider himself in the low, medium or high risk group

In the study, model coefficients were estimated using the maximum likelihood procedure. Mannering and Grodsky found that the estimate of self-risk is significantly affected by the age, gender, and driving experience and that, in general, riders have a good "grasp" or their relative crash risk.

A tree-based regression methodology was adopted by Abdel-Aty et al. [1] to model crash occurrence at signalized intersections. This method reduces problems related to the multicollinearity between variables and missing observations in the database. Furthermore, the hierarchical tree based regression (HTBR) does not require assumptions about population's functional form in advance given that, the model is developed by splitting data into branches on a tree diagram that is built using independent variable categories and average number of crashes for each node. A sample of 33,592 crashes obtained from 832 intersections in Florida in the period 1999-2002 was used in the study and a total of 23 independent and 14 dependent variables were included in the final database for the model development. One of the key findings was that different types of collision often rely on different variables to better predict the number of crashes, consequently aggregated models may not be able to provide accurate estimations of the predicted number of crashes.

Artificial neural networks (ANN) have been recently applied to predict crashes and their severity from observational crash data [2, 4, 59, 77]. This methodology is particularly indicated in situations where analytical functional relationships are complex and laborious, since it does not require any a priori information about the relationship between independent and response variables. In a neural network model, simple nodes or "neurons" are linked together by algorithms designed to change the weights by which each variables must be weighted in order to achieve a given objective function.

3.3 Traffic Conflict Safety Studies

Safety studies using traffic conflicts were initially proposed by Perkings and Harris, researchers from the General Motors laboratory, as an alternative approach to overcome some of the issues found in the observational traffic safety studies [88].

Traffic conflicts have been defined as *"an observable situation in which two or more road users approach each other in space and time to such an extent that there is a risk of collision if their movement remain unchanged"*[11].

The gist of safety studies using traffic conflicts is that these events occur more frequently than crashes, although the mechanism leading to both types of events is reasonably comparable. As a consequence of this, traffic conflicts are deemed to produce short-term safety studies and address some of the statistical issues linked to the rare nature of crashes. Additionally, such an approach has been advocated to be more inclusive than observational crash studies since it considers the vehicle collision failure mechanism from a somewhat broader perspective than observational crash data alone [22, 98, 107].

Following the research of Perking and Harris in 1968, a number of studies in different parts of the world have formed what is known today as the traffic conflict technique (TCT). Most of the research effort over the last two decades have been toward the development of objective and reliable measurements of traffic conflicts and to link these measurements to "real" crashes. Unfortunately, differences in the way conflicts (and their severity) are measured and consequently, how traffic conflict surveys are conducted are found to vary considerably between countries, thus, different versions of the TCT are now available [13, 14, 26, 48, 86, 107].

Two methodological issues regarding the TCT have raised doubt and skepticism about the potential use of this approach as a technique for safety assessment[13, 22, 38, 45, 98]:

1. Measurements of traffic conflicts and conflict severity have been heavily based on subjective judgment by conflict observers and therefore considerable bias is introduced in the methodology. This influences the statistical requirements of sample size and the minimum required time duration of conflict surveys, undermines the predicting power of developed regression models and reduces significantly the transferability of such models to different jurisdictions.

2. Despite its intuitive and somewhat rational link to crashes, some researchers have argued that results from traffic conflict surveys have not been adequately linked to conventional observed crash data or other comparable safety measure.

The Swedish version of the TCT is considered to be one of the most successful applications of traffic conflicts to investigate safety. This technique is based on situations where two vehicles would have collided if no evasive manoeuvre was taken by any of the drivers. The point at which the evasive action was is taken determines the point where observers should estimate the value of the time to accident (TTA)(refer to Chapter 2 for additional information).

TTA is calculated on the basis of estimations of speed and distance for the vehicles involved made by conflict observers. The severity of a given traffic conflict is graphically estimated from TTA and speed differential values obtained for the vehicles involved (Figure 2.5)[13, 49, 107].

A typical application of the Swedish TCT to signalized intersections from Stockholm is found in a study by Archer [13]. This research tried to address important issues concerning the usefulness of the TCT for safety assessment, particularly, aspects related to its validity and measurement reliability.

Traffic conflict surveys were performed by three trained observers in four signalized urban intersections in the city of Stockholm, Sweden. For each intersection, 18 hours of conflict observation were carried out during morning and afternoon peak periods. Three types of conflicts were considered: 1) Conflicts between vehicles and vulnerable road users (pedestrians and cyclists), 2) Rear-end conflicts, and 3) Conflicts between vehicles with different trajectories. The study also considered two categories of conflict severity: serious and non-serious. Figure 3.1 illustrates the results of the TCT survey for the four intersection considered in this research.

This study also investigated the relationship between serious traffic conflicts and crash occurrences obtained from the period 1997-2002. The author found that there was a "reasonable" level of agreement between vehicle-vulnerable road user events since these were more frequent in either the TCT and the historical crash data. Similar trend was not observed for rear-end interactions suggesting that such type of conflict is more difficult to identify and quantify for observers in comparison to other types of conflicts.

An attempt to explore the transferability of the traffic conflict survey performed by Archer was made by comparing the number of observed conflicts with similar studies from Canada. Linear regression models developed by Sayed and Zein [100] estimating the number of conflicts as a function of traffic volume were compared to the traffic conflict survey. The results showed that in three of the four intersections, the survey yielded higher observed conflicts when compared to the upper limit of the model estimation thus, raising doubts regarding the transferability of such studies to different jurisdictions.

Recent efforts to improve TCT have focused on the development of objective (and more reliable) measurements of traffic conflicts. Studies have supported that better measures of traffic conflict can be obtained from the application of video data collection techniques or by using microscopic simulation of traffic conflicts [10, 13, 30, 95, 98].

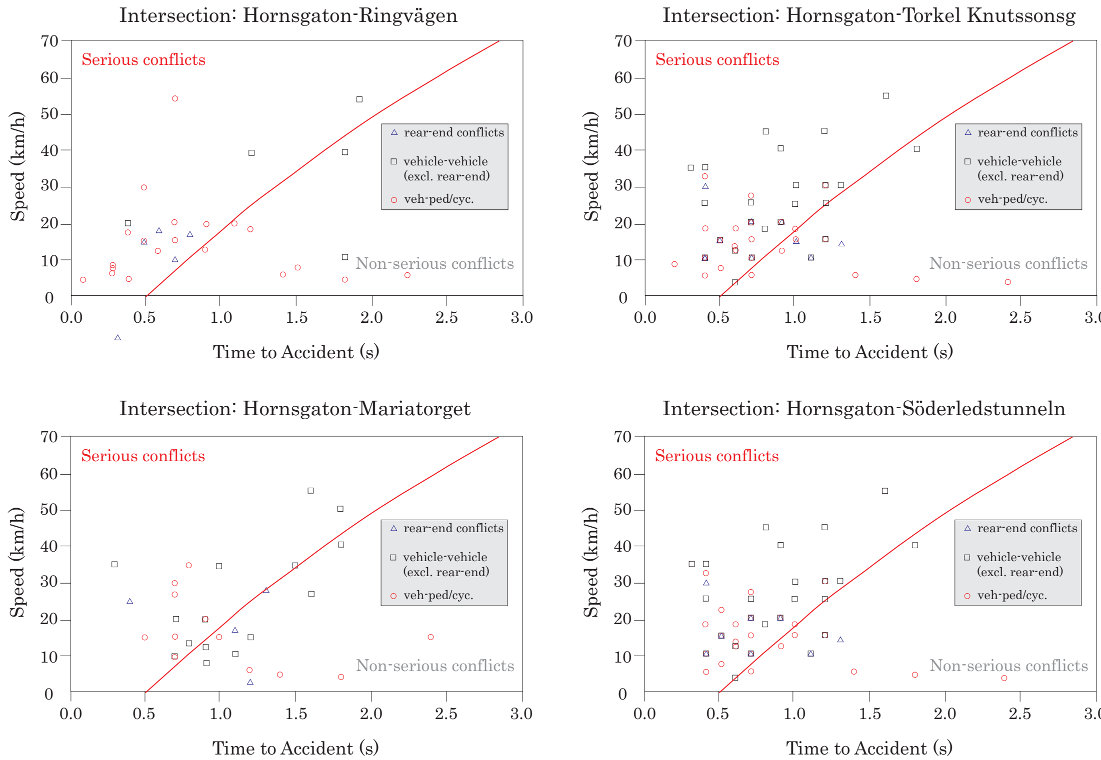

Figure 3.1: Observed traffic conflicts at four Swedish intersections (Source: [13])

A study from Saunier and Sayed [95] investigates the application of advanced vehicle tracking algorithms to the automatic detection of traffic conflicts using video taped data. The merits of the approach were illustrated with an evaluation of 10 traffic sequences recorded for training traffic conflict observers in the 1980s. A total of 1,501 interactions were detected by the calibrated model and 5 traffic conflicts initially recognized by observers were also detected by the algorithm, however, the number of false alarms in the algorithm, i.e., "normal" interactions being counted as traffic conflicts could be as high as 38. The results were found to be promising, although the detection algorithm needs to be improved and a more representative dataset is needed to further confirm the validity of the technique.

The following section describes in detail the most relevant studies focused on the use of real-time traffic information applied to traffic safety studies.

3.4 Real-time Traffic Safety Studies

Over the past few years many traffic jurisdictions have developed instrumented freeway traffic management systems (IFTMS) consisting of road sensors, surveillance cameras, variable message signs, algorithms for automatic incident detection and ramp meters. These systems can provide real-time traffic flow information obtained from road sensors installed under the pavement (loop detector stations) in specific sections of the freeway [56].

In theory, real-time information from loop detectors is valuable for the development of preemptive systems to identify short-term turbulence in the traffic flow and intervene on these high risk situations before it evolves into a crash. This has motivated several researchers to investigate the application of real-time information to predict crash occurrence [5, 56, 57, 63, 82, 84].

One of the first attempts to predict crashes from real-time loop detectors information was presented by Oh et al. [82]. Real-time traffic conditions were hypothesized as having two discernible patterns: disruptive and normal. The disruptive pattern is defined as a series of traffic attributes leading to a crash occurrence and, normal traffic conditions, would be linked to traffic dynamics patterns typically observed in situations where no crash was verified. According to Oh et al., this traffic turbulence could be objectively measured by a traffic dynamics index as illustrated in Figure 3.2.

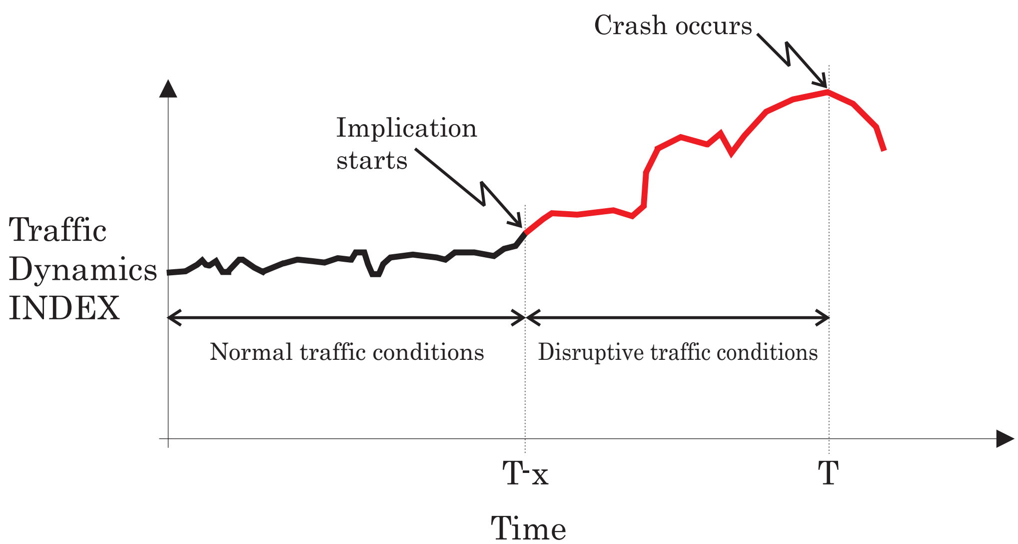

Figure 3.2: Crash occurrence caused by traffic dynamics (Source: [82])

Real-time traffic data corresponding to 30 minutes prior the occurrence of 52 crashes in I-880 freeway in California was used by Oh et al. The authors defined two traffic conditions as follows: the normal condition as a 5-minute period 30 minutes before the crash and the disruptive traffic condition as a 5-minute period right before the crash occurrence. Average values of volume, occupancy, speed, and their respective standard deviations were compared for normal and disruptive conditions in order to identify an indicator that best represents the difference between traffic conditions. Using statistical t-tests, non-parametric density functions and Bayesian theory the authors concluded that the standard deviation of vehicle speed, as recorded by loop detectors, provides reasonably strong explanation of crash occurrences in real-time.

Lee et al. [57] developed a probabilistic real-time crash prediction model relating crash potential to a number of traffic flow attributes that lead to crash occurrence. In their study, these traffic flow conditions prior the crash occurrence were called "crash precursors". Log-linear models were calibrated as a function of the coefficient of variance of speed (CVS), traffic density (D), average speed difference between upstream and downstream loop detectors (Q) assuming the following functional form:

$$ln\left(F\right) = \alpha + \lambda_{CVS(i)} + \lambda_{D(j)} + \lambda_{Q(k)} + \lambda_{R(l)} + \lambda_{P(m)} + \beta ln\left(EXP\right) \tag{3.9}$$

where
F = expected number of crashes over the analysis time frame
λ = variable effect on expected number of crashes
α, β = model parameters CVS, D, Q = crash precursors
R = road geometry (straight or merge/diverge section)
P = time of day (peak or off-peak)
EXP = exposure (veh.km)
i, j, k, l, m = levels for corresponding variables

Some key findings of this study can be summarized as follows:

1. Abrupt transition in speed within the road section, i.e., the formation and dissipation of queues has a significant impact on crash occurrences.

2. The observed time slice duration before crash occurrence should be determined so that the difference between traffic conditions obtained for crash and corresponding non-crash situations is maximized. The study suggested that this optimum time slice duration may vary for different crash precursors.

3. The categorization of each crash precursors should be determined on the basis of the its overall fit and the statistical significance of coefficients.

A study from Abdel-Aty and Pande [5] was focused on determining optimum time interval prior the crash and road segment length that optimize the detection of high turbulence situations resulting in crashes. This research investigated the logarithm of coefficient of variation of speed (Logcvs) and average occupancy up to 5 upstream loop detector stations, the station where the crash occurred and one station downstream. Additionally, six 5-minute intervals were used to explore the effect of time prior the crash on the precursors. Traffic information from a sample of 377 crashes recorded on the Interstate-4, Orlando, from April 1999 to November 1999 and corresponding non-crash conditions were analyzed throughout a probabilistic neural network (PNN) classification paradigm.

The results of the research by Abdel-Aty and Pande suggest that PNN models achieved the best classification performance between 10-15 minutes prior the crash from three stations: the station of the crash and two adjacent upstream stations. The authors also suggested that these models would function better under the congested traffic flow regime, since rear-end crashes are more likely to be caused by frequent formation and dissipation of ephemeral queues.

Unfortunately, the use of crash precursors in safety studies is limited to instrumented freeway segments. Studies involving real-time traffic flow attributes and crashes for different road entities, such as intersections and roundabouts appear to be more challenging since different types of conflicts and traffic flow regimes are involved. In addition, crash precursors are representative of overall traffic stream conditions at specific road sections and thus, individual vehicle interactions over time that caused the crash are not directly considered.

The following section describes major aspects of studies focused on the use of driving simulators to assess crash risk as a function of driving behaviour and roadway attributes.

3.5 Safety Studies Using Driving Simulators

Driving simulators have been applied mostly to investigate psychological and ergonomic aspects of driving including aspects of impaired driver behaviour (effects of drugs, alcohol, and driver fatigue) and vehicle dynamics and layout (e.g. vehicle braking systems, 4-wheel driver, vehicle interior design, etc) [18]. More recently, transportation researchers increased their interest in applying advanced driving simulators to investigate safety aspects of ITS devices, such as crash avoidance systems, in-vehicle navigation systems, active pedals and impacts of innovative road design [9, 52, 72, 114, 115].

Driving simulators usually provide considerable control over important variables affecting road safety such as, geometry, traffic control devices, and vehicle features, thus creating a desirable platform for human factors research. Moreover, since these simulators are linked to computer systems, data can be obtained in various types and formats and it can also be processed in real-time [18, 80].

In general, driving simulators consist of a series of projectors linked to computer units that simulates the field environment in high resolution screens. These screens are strategically mounted to provide from 150 to 180 degrees of field view to drivers in the simulation cab (Figure 3.3). Softwares provide the graphical display and simulation dynamics as well as help researchers to edit traffic scenarios and establish the interface for the data acquisition [53, 114].

Considerable research effort over the last three decades have aimed to address three fundamental problems posed by the use of simulators for training, vehicle design, and safety research as follows: 1) The issue of transferability, 2) The issue of reliability or physical validation, and 3) The issue of behavioural validation.

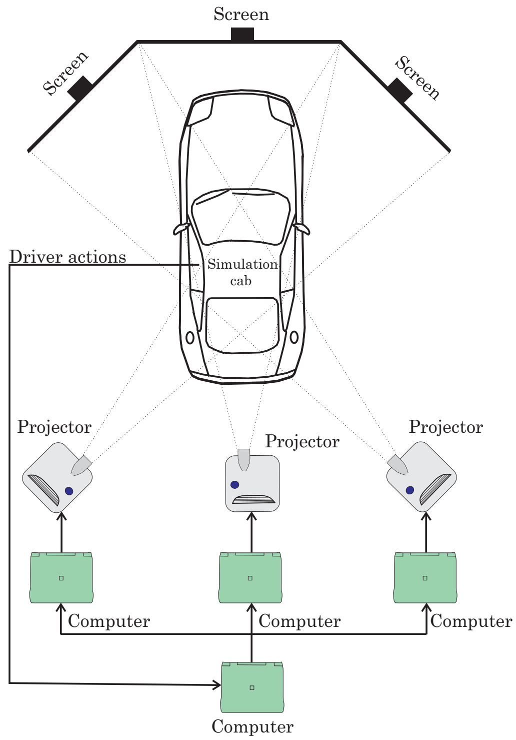

Figure 3.3: Schematic of a typical driving simulator

The issue of transferability, i.e, how comparable are drivers (or pilots) operational actions in the simulator to the “real world”. This is of critical importance when simulators (especially flight simulators) are used for training purposes. According to Blana [18], in order to be valid, driving simulators must provide an environment where basic driving skills are transfered from real driving and drivers are subjected to realistic visual and auditory cues from traffic scenarios.

Simulators reliability or physical validation refers to how accurate the simulator represents vehicle dynamics and the visual environment surrounding the traffic scenario. With increasing computing power and technological advances in driving simulator systems, a number of vehicle dynamics types have been fully validated [18, 114].

A more complex issue is the simulator’s ability to induce drivers responses that would be comparable to those observed in real life similar situations (behavioural validity). Two types of behavioural validity are considered: the absolute validity, when simulated and observed measurements are directly matched and the relative validity, when relative differences from simulated and observed measurements are in the same direction [17]. As noted by Yan and colleagues [114], several behavioural validation studies focused on traffic performance measures such as speed, lateral position and route choice can be found in the literature, however, validation efforts focused on traffic safety measures are scarce.

A driving simulator experiment was carried out by Alexander et al. [9] to explore the impact of a in-vehicle device designed to assist old drivers in choosing suitable gaps for right-turn movements (in UK) from major to minor roads. A sample of 2004 right-turns was collected from 30 volunteer drives aged 65 years or over and 10 drivers under 65 years subjected to different combinations of lightning conditions (day/night), average speed (30/60mph), and status of the in-vehicle device (on/off). The authors developed a probit model to represent the probability of a gap being accepted as follows:

$$\begin{aligned}\varphi =& 0.401gs - 0.377s + 0.917v - 0.438c + 0.462m - 0.587g- \\ &- 0.371a - 0.266t - 3.456\end{aligned} \tag{3.10}$$

where
φ = normalized probability of gap being accepted
gs = gap size (s)
s = sex (female = 1, male = 0)
v = velocity (60mph = 1, 30mph = 0)
c = vehicle colour (red = 1, non-red = 0)
m = device (on = 1, off = 0)
g = lag or gap (lag = 1, gap = 0)
a = age (old = 1, young = 0)
t = vehicle type (truck = 1, car = 0)

Using the above expression, the probability of a near-miss or accident was estimated using the expression:

$$P_{nm} = P_{gs} \cdot P_t \tag{3.11}$$

where
P_{nm} = probability of accident or near-miss at gap size gs
P_{gs} = probability of a gap size gs being accepted
P_t = probability that time taken to cross is greater than gap size - 1s

Probabilities curves drawn for male and female drivers have shown that female drivers have higher probability of being involved in incidents than male drivers when gaps are higher than 7s. This can be explained by the fact that, in general, female drivers tend to reject gaps below 7s as compared to male drivers, however, since female drivers are not as aggressive as male drivers (higher crossing time), 7s (or higher) gaps are slightly more problematic for female drivers. Notwithstanding the usefulness of the study, two major caveats mentioned by the authors warn that the results have validity limitations given the artificial environment provided by the simulator and, since drivers were not influenced by having other vehicles queuing behind them (a quite common situation in real world), the gap choice process was not fully replicated.

A study to investigate the effect of different speed control strategies in highway work zones using driving simulators was presented by Mitchell and colleagues [72]. Three scenarios were investigated in the simulation experiment: 1) Base case (no speed reduction strategy), 2) Rumble strips in two location prior the work zone, and 3) Narrow traffic lane through the work area. Tests were conducted by 15 drivers to investigate differences in speed pattern for the simulated scenarios. The results indicate that narrow traffic lanes appear to be effective in reducing average speed when compared to the base case. Rumbles strips, on the other hand, appear to be effective only in the vicinity of the area they are installed.

Inman et al. [52] conducted a study to provide partial validation for a conceptual system to warn potential victims of red-light violators using driving simulators. Red light violators were deliberately generated (simulated) and warnings to potential victims (subject drivers) were sent in terms of changes in the normal signal plan by reducing the amber phase, changing from green to red phase or reducing the green phase as soon as the red light violator was detected. In this case, it was important that participants were not told that emergency warnings would be present or that the research was focused on red light running. The results from the driving simulator experiment were compared to a field experiment carried out in a closed course road (Virginia Tech Smart Road). The overall results indicate that in the two studies, most drivers would respond appropriately to the collision warning system, however, as no other vehicles were in the study, it's not clear how the presence of following vehicles would have affected drivers reactions and furthermore, what would be the impact of these abrupt decelerations/stops in rear-end crashes.

Yan et al. [114] investigated rear-end crash risk from stop/go decisions due to signal change using the University of Central Floria driving simulator. In the driving simulator experiment, 62 participants from different age groups (15-19, 20-24, 25-34, 35-44, 45+) were requested to drive in two virtual scenarios representing two approaches of a major signalized intersection from Orange County. When subjects were approaching the intersection at 90m away from the stop line, the traffic signal was changed from green to amber and red in order to investigate drivers reactions to the dilemma zone.

A logistic regression model was developed to estimate the probability of drivers to stop when facing the amber phase at the dilemma zone. Four independent variables were selected to describe the model as follows: 1) The projected travel time from the time of onset of amber phase to the moment the vehicle reaches the stop line (GAP), 2) The two test locations (LOC), 3) Drivers gender (GENDER), and 4) Drivers age (AGE). The results showed that only GAP, LOC, and GENDER were statistically significant (5% level). Males drivers were found to be 72.7% less likely to stop when facing the crossing dilemma than female drivers, keeping the other variables constant. The authors concluded that driver simulators have the potential to be applied to investigate rear-end crash risk at intersections, however, differences between the simulation environment and the "real world" need further research in order to support the validity of such studies.

Advances in data acquisition techniques coupled with increasing computational power seem to suggest that driving simulators have the potential to provide an objective platform for the delopment of engineering countermeasures to enhance road safety.

3.6 Safety Studies Using Microscopic Simulation

The use of computer simulation applied to transportation has become more frequent since the mid 1980s, as transportation planners and engineers focused their efforts to improve the efficiency and safety of existing transportation systems. New transportation technologies emerging from this effort, also known as intelligent transportation systems (ITS), make extensive use of modern computers, electronic, communication systems coupled with an improved psychological knowledge of the human behaviour while driving. Some examples of existing ITS are the advanced vehicle control and safety systems (AVCSS), adaptive cruise control (ACC), advanced traveller information system (ATIS), and advanced traffic management system (ATMS).

Over the last two decades, microscopic traffic simulation has been essentially applied to investigate the operational efficiency of different transportation components measured in terms of average speed, travel times, average delay, average queue length, etc [68]. The potential of microscopic simulation in traffic safety and traffic conflict analysis was initially recognized by Cooper and Ferguson [25] and Darzentas et al. [30]. One of the most attractive features found in the use of simulation is that potential alternatives can be tested in a "virtual world" before implementation. This is especially appealing in situations where geometric and operational changes to a given scenario are expensive and operationally troublesome.

According to Archer [13], simulation allows the possibility of tailoring models to traffic situations with considerably high level of details (factors) that have direct or indirect influence on traffic safety such as:

- High level of geometric details of the traffic site including, correct lane widths and stop/yield signs positions.
- Accurate representation of traffic control devices, including vehicle actuated and coordinated traffic signals.
- Good representation of traffic flows, turning movements, and traffic compositions over time and link specific.
- Flexibility and accuracy in terms of different speed levels and speed variation over time and link specific. It is possible to control speed in specific location such as turning movements and speed humps.

- Differences in vehicle characteristics such as length, weight, engine-power, and acceleration/braking power.
- Differences in behaviour and performance of different driver categories are allowed.

Cooper and Ferguson [25] and Darzentas et al. [30] attempted to develop a simulation model to account for the occurrence of traffic conflicts at 3-leg intersections (T-junctions). In their model, vehicles were assumed to be identical and having the same acceleration and braking capabilities. A total of six vehicle movements were identified and an exponential gap acceptance model was used to represent turning attempts that could develop into crossing conflicts. It was assumed that conflict seriousness between left-turn vehicles from the minor approach and thru vehicles on the major is proportional to the deceleration rate to avoid collision. This study found that conflict rate was independent of average vehicle speeds, however, conflict severity increased with increasing mean speed and increasing speed standard deviation.

In order to produce data for traffic conflict studies, Sayed et al. [98] developed a stochastic model to simulate traffic conflicts at unsignalized intersections.The major assumptions in the model were:

- No overtaking or lane changing allowed at the intersection.
- The subject intersection is isolated.
- All drivers have an unobstructed view of the intersection.
- There is no pedestrian interference.
- Drivers must allow a minimum headway with the vehicle immediately ahead.
- All drivers coming from lower priority road have perfect knowledge of signalization and priority rules of the road.

Two major components in the simulation model were the initial vehicle headways and the gap acceptance model. A shifted negative exponential distribution was used to create vehicle headways from the the average headway obtained from the assumed flow rate. The gap acceptance model considered an initial critical gap for four types of drivers: youg males, young females, old males, and old females drawn from a truncated normal distribution with mean and standard deviation as shown in Table 3.4. This gap acceptance algorithm also included factors to account for the number of lanes to be crossed, heavy vehicles, and delay for vehicles in the minor road traffic stream.

Three types of conflicts considered in the study were: crossing, merging, and rear-end. Whenever vehicles accept gaps from the minor approach that would

Table 3.4: Mean and standard deviation of critical gap time (Source: [98])

Group	Yield control		Stop control	
	Mean (s)	Std. Dev (s)	Mean (s)	Std. Dev (s)
Young males	4.0	0.75	5.0	0.75
Old males	4.5	0.85	5.5	0.85
Young females	5.5	1.00	6.5	1.00
Old females	6.0	1.25	7.0	1.25

bring about a collision course with another vehicle in the main stream, the time to collision (TTC) measure is estimated by the model. Traffic conflicts were defined to occur when the estimated TTC is lower than 1.5 seconds.

An important aspect of Sayed's research is that he has attempted to validate the model by comparing simulated and observed traffic conflicts using a sample of two hours (7:00-9:00AM) traffic conflict survey in four urban unsignalized intersections. Three different computational speed limits were tested and the results are summarized in Table 3.5. While limited to a small number of intersections, the results on Table 3.5 suggest that the model can be used in similar applications with reasonable confidence. This study also found simulated conflicts to increase exponentially with volume and conflict severity (as measured by TTC) to increase with approaching speed.

Table 3.5: Total observed and simulated traffic conflicts (Source: [98])

Intersection	Observed conflicts	Simulated conflicts 50km/h	Simulated conflicts 60/70km/h
156^{th} Street & 20th Avenue	8	5	10^{*}
Holdon Avenue & Broadway	19	17	$21^{\dagger}$
116^{th} Street & 75A Avenue	10	6	$8^{\dagger}$
Chesterfield Avenue & Keith Road	15	9	12^{*}

† 60km/h

* 70km/h

Recently, the Federal Highway Administration (FHWA) [36] presented a study that investigates the application of microscopic simulation in safety studies for intersections. This report explores the use of different safety performance measures (surrogate safety measures), compares nine commercially available microscopic simulation packages with respect of their strengths and limitations for safety assessments and, attempts to provide some guidelines regarding data requirements and analysis for simulation-based safety studies.

The simulation packages CORSIM, SIMTRAFFIC, VISSIM, HUTSIM, PARAMICS, TEXAS, AIMSUM, WATSIM, and INTEGRATION were evaluated in terms of 5 major groups of attributes: 1) General features, 2) Behavioural modeling of driver/vehicle interactions, 3) Ability to extract detailed data from the simulation, 4) Ability to calibrate and select parameters of models, and 5) Cost to modify source or outputs to support safety performance measures. The detailed list of features considered important to be present in simulation packages to allow simulation–based safety studies are presented in Table 3.6.

The FHWA report does not indicate a clear superiority of any particular model for safety assessments, although, VISSIM was found to support most of the features required for safety studies using simulation at a reasonable level of fidelity. An important section of this report was dedicated to the validation of safety performance measures. Three hypothesis for the utility of simulated safety measures have been presented and these are: 1) Discriminating between the safety of two design alternatives in a simulation, 2) Correlation of the surrogate safety measure with real world traffic conflict studies, and 3) Correlation of surrogate safety measure reductions with predicted reductions in traffic conflicts. According to the FHWA, simulated safety performance measures are not required to be correlated directly to the actual number of crashes, but the relative difference of various intersection designs as measured by simulated safety performance must be consistent with similar studies with real world conflict measurements.

Huguenin et al. [47] applied the microscopic traffic simulator AIMSUM to investigate the occurrence of potential for rear-end collisions in freeways. A safety performance measure called "unsafety density"(UD) (refer to Chapter 2 for details) defined as function of speed differential between the leader and following vehicles, following vehicle speed and ratio between actual and maximum deceleration rate of the lead vehicle was applied in this study. The usefulness of the UD parameter was investigated by a case study using 3 years of crash data obtained from a 7km road segment of a freeway in Geneva that included two on-ramp segments. In the simulation exercise, the UD parameter was estimated for 13 simulation replicates for the morning peak hour (7h00-8h00). A visual comparison between the evolution of UD and observed crashes is presented in Figure 3.4.

Results in Figure 3.4 suggest that the simulation was able to detected spatial variations in safety, although, a space shift between observed and simulated outputs is noticeable. Unfortunately, the authors did not attempt to calibrate AIMSUM algorithms with respect to UD estimations. This lack of calibration may have caused the space shift observed in the results.

Archer [13] investigated the potential use in safety studies of the commercially available microsimulation package VISSIM©. This study was focused on the estimation of traffic conflicts at 3-leg stop controlled intersections using microscopic simulation. The author have selected VISSIM as simulation platform because of its high level of detail in modeling, as well as the general flexibility regarding to road

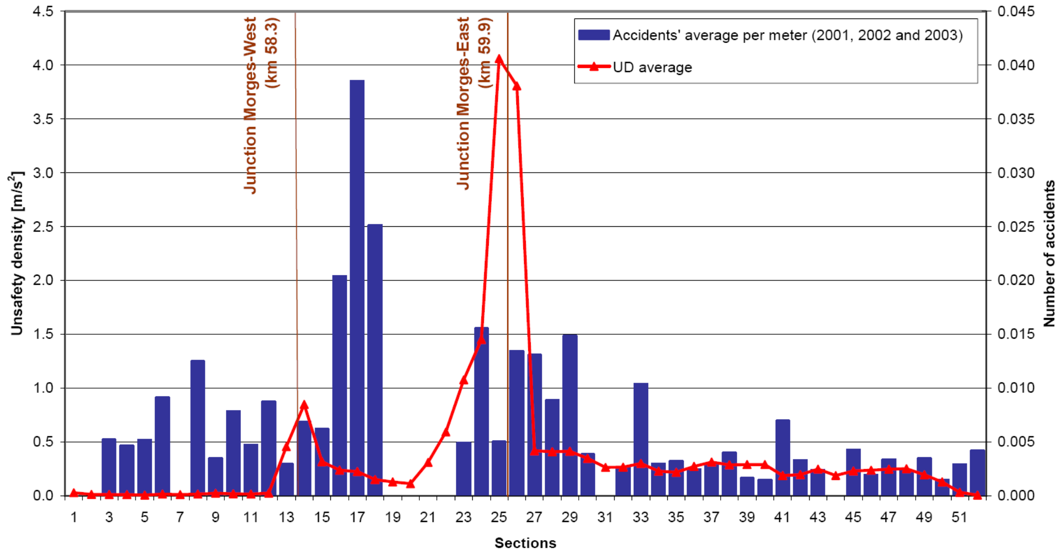

Figure 3.4: Crash rate and UD parameter values per freeway sections (Source: [47])

design, vehicle performance and road user behaviour.

The simulation experiment was designed to consider 3 different two-hour time intervals: morning peak, off-peak, and afternoon peak period. A total of 20 simulation runs for each time interval were performed. It is worth noting that Archer formally attempted to calibrate and validate VISSIM algorithms with respect to three measures of performance (MOPs): 1) Time gap distribution, 2) Traffic flow rates, and 3) Speed and speed variance.

Four safety performance measures were tested in this study: 1) Time to collision (TTC), 2) Post-encroachment time (PET), 3) Time to accident (TTA), and 4) Required braking rate (RBR). Observed measures of TTC, PET, and RBR were obtained from a resource-demanding video-analysis procedure over 6 hours of videotaping and TTA values were obtained from 18 hours of conflict survey in same the time-periods chosen for the simulation exercise. Figure 3.5 illustrates the five types of conflicts of particular interest in this exercise.

In discussing the results, Archer suggested that, in general, the simulation experiment shows a reasonable level of consistency in both frequencies and severities in the four safety performance indicators tested. Furthermore, differences between simulated and observed safety measurements were hypothesized to be due to the nature of microscopic models which are not able to fully emulate the complex road user behaviour and vehicle performance subjected to high crash risk situations.

In theory, microscopic traffic models have the potential to account for important factors that heavily influence crash occurrences, including different behavioural aspects of drivers and individual pair-wise vehicular interactions in real-time. This would provide a platform for the development of safety studies that apply a more microscopic "mechanistic" approach to improve the knowledge of crash occurrence

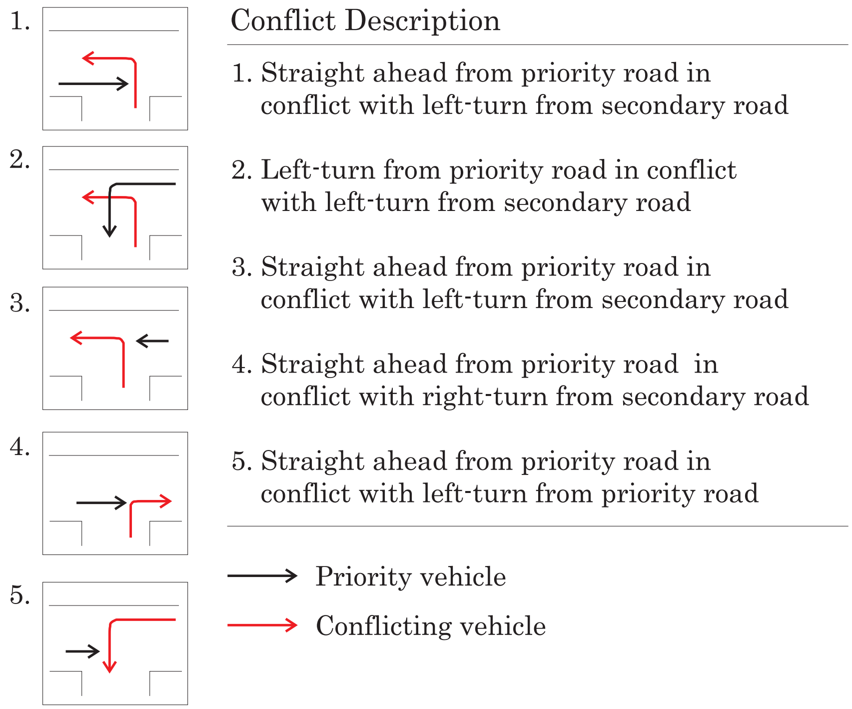

Figure 3.5: Simulated conflict types (Source: [13])

mechanism. However, some methodological aspects of this approach need to be investigated as these are

1. Traditional microscopic car-following, gap acceptance, and lane changing algorithms have not been developed specifically to account for the full range of factors explaining the potential for crashes. Outputs from these models may not be representative as to the "real life" behaviour, especially when drivers are experiencing high risk situations. Models should allow errors to occur as the result of "less-than-perfect" perception, decision-making, and action, thereby causing different levels of risk in the interactions between road-users and the environment [12, 13, 113].

2. These "less-than-perfect" models must have their inputs accurately determined based on observational data, and simulation models must produce estimates of safety performance that can be verified from field observations (model calibration and validation).

3. An objective link between simulated safety performance and observed high risk traffic events would likely to enhance the scope of microscopic modeling as a tool for safety assessments of transportation systems.

It is worth noting that advances in modeling techniques in conjunction with powerful computers and readily available vehicle tracking information will likely to produce advanced behavioural microscopic algorithms. This seems to be a promising scenario for the use of simulation in safety studies. A recent study in Minnesota [113] developed one of the first behavioural car–following models that explicitly considered crash occurrence. A sample of 54 detailed vehicle trajectories extracted from 10 "real life" crashes were used to calibrate and validate the model. Notwithstanding the early stage of this research, preliminary tests indicate that the model is able to replicate both normal and unsafe driver behaviour that could lead to a rear-end crashes.

The next Chapter introduces the overall characteristics of the proposed model for safety assessment using microscopic simulation.

Table 3.6: Important features in microscopic models for simulation–based safety assessments (Source: [36])

Group	Characteristics
1. General features	a. Availability of source code
	b. Interaction with external codes
	c. Post-processing analysis tools
	d. Graphical network editor
	e. Runs on PC
	f. Object oriented structure
	g. Actuated signals modeled
2. Behavioural modeling	a. Parameterized gap–acceptance model
	b. Parameterized lane change model
	c. Parameterized car following model
	d. Parameterized turn speed
	e. Reaction to yellow
	f. Variable driver reaction time
	g. Intersection box movements
	h. Sight distance limits
	i. Rolling yield
	j. Vehicles interact with pedestrians
	k. Friendly merging
	l. Multi-lane merging
	m. Intersection right-of-way
	n. Maneouvre failure recording
	o. Parking manoeuvres
	p. Turn signal modeling
	q. U-turns
	r. Driveways in the intersection corner
3. Data extraction capabilities	a. Vehicle state variables exportable to file
	b. Published animation file format
	c. API available
	d. Output file configurable
	e. Gap-acceptance events exportable
	f. Gap-acceptance rejections exportable
	g. Lane change events exportable
	h. Vehicle state variables include x,y, position
	i. Currently includes conflict stats output
4. Calibration and validation	a. Variable time steps
	b. Time steps $<$ 1.0s
	c. Gap-acceptance criteria change by delay
	d. Vehicle length
	e. Vehicle length considered in gap logic
	f. Variable headways
	g. Variable queue discharge headways
5. Modification cost	a. Cost to modify API
	b. Cost to modify output
	c. Cost to modify input

Chapter 4

Microscopic Model For Safety Assessment

4.1 Introduction

The safety performance of a given road entity can be hypothesized to be function of the road geometry, traffic attributes, environmental conditions, and their interaction with different road users over time. This dynamic and complex combination of factors introduces a level of "turbulence" to the traffic stream which dictates the overall road safety performance.

According to the safety continuum concept previously introduced, traffic turbulence could be expressed in terms of both frequency and severity of vehicle interactions over time. For the purpose of this thesis, vehicle interaction is a time-dependent event where two vehicles would collide if their respective trajectory and speed remain unaltered. Crashes, on the other hand, can be viewed as a small subset of relevant high risk vehicle interactions, which by their very random nature represent a narrow somewhat biased view of the larger safety problem. This conceptual framework is illustrated in Figure 4.1.

Ideally, it would be preferable to obtain measures of traffic turbulence directly from field studies. However, such an approach still not feasible given that it would require real-time monitoring of vehicles in the traffic stream, including those rare combinations of events when a crash is observed and this type of information is not readily available. Microscopic simulation has been successfully applied for estimating transportation systems performance and, in theory, has the potential to investigate traffic turbulence in lieu of real-time vehicle tracking data.

The proposed microscopic model for safety assessment attempts to reproduce inter-vehicular interactions for different transportation scenarios using existing microscopic behavioural car-following, lane changing, and gap acceptance algorithms. Traffic turbulence as represented by individual vehicle interactions is measured by a crash potential index (CPI) estimated over time. This Chapter describes major assumptions, limitations, and scope of the proposed model.

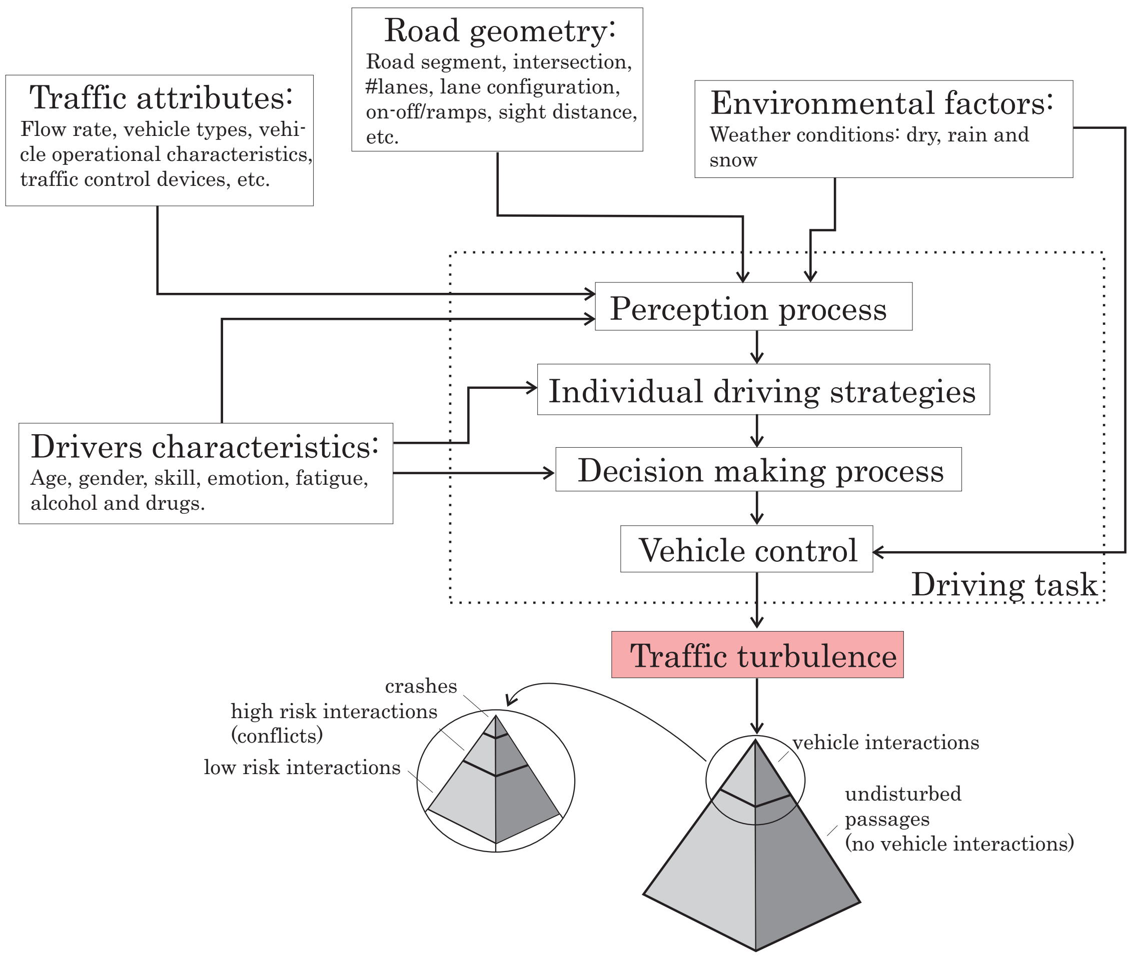

Figure 4.1: Traffic stream turbulence and vehicle interactions conceptual framework

4.2 Vehicle Interactions

An objective definition of vehicle interactions is required for the safety model since these events will determine the overall group of vehicles exposed to various degrees of crash risk. As noted previously, vehicle interactions are characterized by the existence of a collision course between two vehicles over time.

The basic difference between vehicle interactions and traffic conflicts is that the latter was initially conceptualized to allow field studies using "trained conflict observers". This implies the existence of a somewhat subjective threshold to define the conflict. Moreover, in general, traffic conflicts are recorded only at the moment that some evasion action happened, such as a sudden deceleration (brakes lights on) and not continuously.

The vehicle that triggers the interaction whether by decelerating to stop or turn, changing lanes or accepting a gap to enter from a low priority road is named the stimulus vehicle (SV). Once SV starts the manoeuvre, the driver of the vehicle directly affected by this manoeuvre should react or respond the action to avoid a possible crash. This vehicle is called the response vehicle (RV). The two basic types of vehicle interactions can be defined as rear-end and angled interactions.

4.2.1 Rear-end Interactions

In this type of interaction, SV is usually a lead vehicle adjusting its speed to deal with a stop sign, amber/red phases of traffic signals or to perform turning manoeuvres at intersections vicinity. Rear-end interactions can also be originated when SV change lanes and the immediate following vehicle (RV) in the target lane is traveling faster than the lane changing vehicle. These situations are illustrated in Figures 4.2 and 4.3.

It should be noted that car-following situations where the following vehicle (RV) speed is greater than the lead vehicle speed (SV) are also considered as vehicle interactions even if the lead driver is not braking.

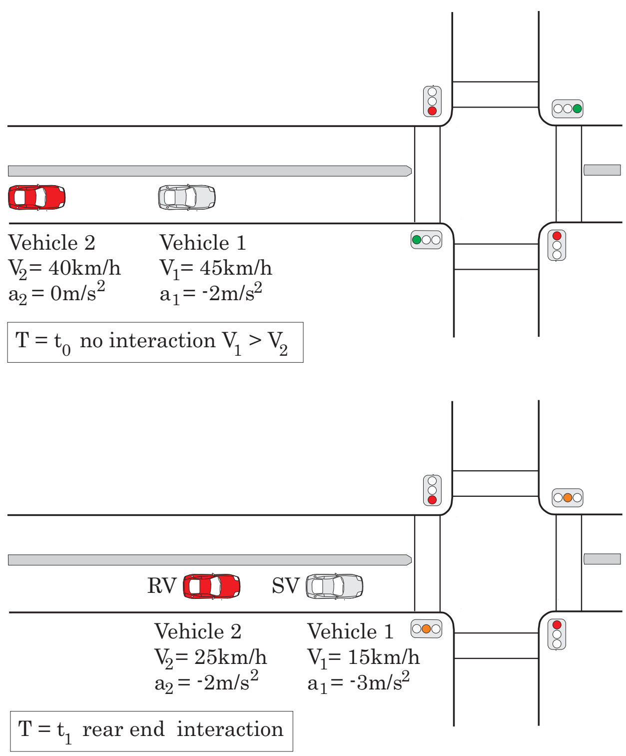

Figure 4.2: Rear-end interaction for lead vehicle deceleration

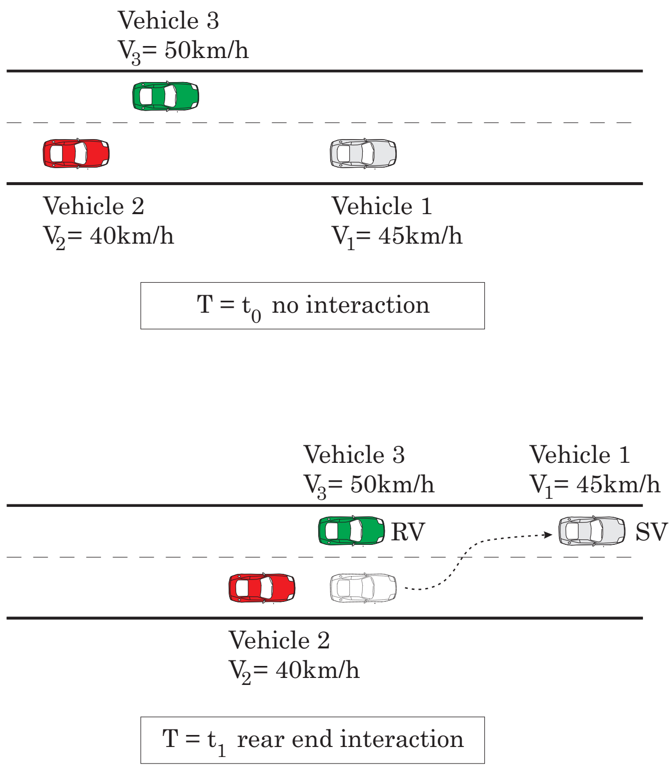

Figure 4.3: Rear-end interaction during a lane change

4.2.2 Angled Interactions

Angled interactions normally begins when vehicles in lower level priority road (or movement) cross or merge higher priority movements. This process is represented in gap acceptance models. Figure 4.4 gives an example of an angled interaction emerging from a stop controlled intersection. When vehicle 1 decides to proceed (gap acceptance model), it becomes the stimulus vehicle (SV) to vehicles 2 which should react to SV stimuli in order to avoid a potential collision. This vehicle is referred to as the response vehicle (RV).

Since for angled interactions, SV and RV trajectories are not parallel, crash zones need to be defined for all combination of approaching movements. Vehicle speeds and distances to crash zones are used to verify the existence of a collision course between SV and RV. Figure 4.4 also illustrates instantaneous requirements for a collision course in angled interactions.

As illustrated in Figure 4.4, potential crashes are assumed to result from a combination of both erroneous SV gap acceptance and RV actions taken in response to SV stimuli. It is also reasonable to assume that the severity of a given interaction should vary with respect to differential vehicle speeds and spacing and for how long vehicles remained interacting. For example, vehicles with higher speed differentials traveling close to each other are more likely to be involved in crashes than vehicles

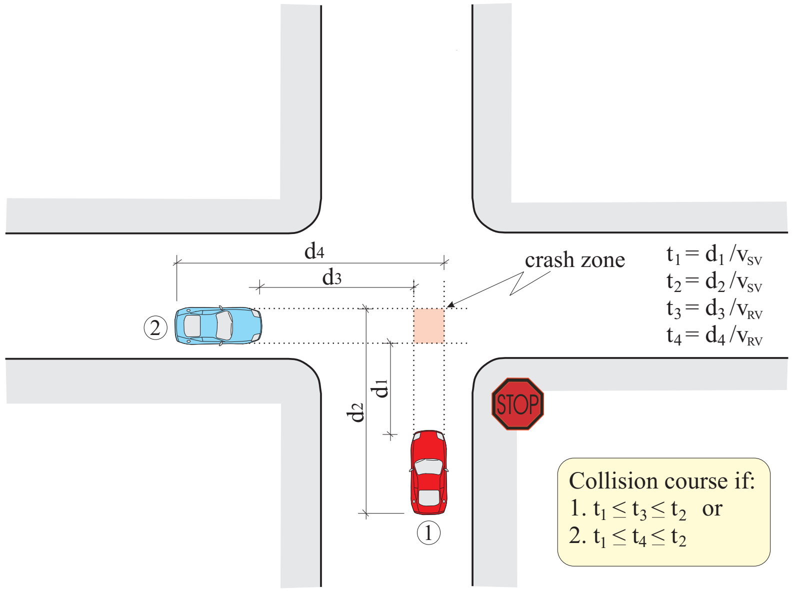

Figure 4.4: Collision course in angled interaction

with lower speed differentials traveling further apart. The next section introduces the safety performance measure used to express both frequency and severity of simulated vehicle interactions for different traffic scenarios.

4.3 Crash Potential Index (CPI)

As discussed in Chapter 2, a number of safety performance measures have been investigated over the past two decades. The literature review suggested that safety performance measures based on individual braking requirements, such as the deceleration rate to avoid the crash (DRAC), provide a better measure to represent both frequency and severity of high risk vehicle interactions.

Unfortunately, DRAC itself does not account for important factors that play a major role in the braking process, especially in critical situations. For example, consider a rear-end interaction where the following vehicle requires a deceleration of $8 \mathrm{m/s}^2$ to avoid the crash. It is reasonable to expect that a car would have better chances to achieve this braking rate as compared to a truck due to obvious differences in braking systems and vehicle masses, assumed everything else constant. The same rationale can be applied for different environmental conditions, i.e. assuming everything the same, achieving a DRAC of $8 \mathrm{m/s}^2$ for wet pavement is considerably more challenging (reduced friction) than if conditions were satisfactory (dry pavement).

The crash potential index (CPI) introduced in this work is a safety performance measure that attempts to address some of the issues found in DRAC. This measure captures three important aspects of vehicle interactions, namely the RV braking requirements to avoid the crash, the maximum available RV braking power and the time exposed to the interaction. The RV braking requirements during a vehicle interaction is represented by the deceleration rate to avoid the crash (DRAC) estimated using Newtonian physics for every time interval.

The maximum available braking power or maximum available deceleration rate (MADR) is a stochastic component introduced to account for different vehicles categories under different pavement conditions (e.g. dry/wet) that are expected to perform differently during a braking event that requires a specific DRAC level. The analysis in this thesis considers two vehicles types, cars and trucks, operating under good conditions, i.e. daylight and dry pavements. For these set of conditions MADR was assumed to be normally distributed with average of 8.45m/s^2 and 5.01m/s^2 for cars and trucks, respectively, with standard deviation of 1.40m/s^2. These values were obtained from field tests for different vehicles with initial speeds from 80 to 100km/h coming to a full stop [78, 76].

As noted previously, the total time vehicles interact corresponds to the time exposed to a certain likelihood of crash and, consequently, should be considered in the safety performance measure. The crash potential index (CPI) is defined as the probability that a given vehicle DRAC exceeds its maximum available deceleration rate (MADR) during a given time interval. The CPI index is obtained using an equation of the form

$$CPI_i = \frac{\Sigma_{t=ti_i}^{tf_i} P\left(MADR^{(a_1,a_2,\ldots,a_n)} \leq DRAC_{i,t}\right) \cdot \Delta t \cdot b}{T_i} \tag{4.1}$$

where
CPI_i = crash potential index for vehicle i
$DRAC_{i,t}$ = deceleration rate to avoid the crash (m/s^2)
$MADR^{(a_1,a_2,\ldots,a_n)}$ = random variable following normal distribution for a given set of traffic and environmental attributes $(a_1, a_2, ..., a_n)$ (m/s^2)
ti_i = initial simulated time interval for vehicle i
tf_i = final simulated time interval for vehicle i
Δt = simulation time interval (sec)
T_i = total travel time for vehicle i (sec)

The parameter b in the above equation denotes a binary state variable, 1 if a vehicle interaction exists and 0 otherwise. As noted previously, the probability term in Equation 4.1 is function of DRAC, the vehicle type and environmental conditions. Figure 4.5 indicates the difference in CPI calculations for a given time interval considering different vehicle types under the same braking requirements (DRAC). This probability is illustrated as the cross-hatched area in Figure 4.5. From this figure it is apparent that for a given level of DRAC trucks are more challenged to meet the braking requirements than cars. The same analogy can be applied within the same group of vehicles but for different environmental conditions (dry, wet or snow).

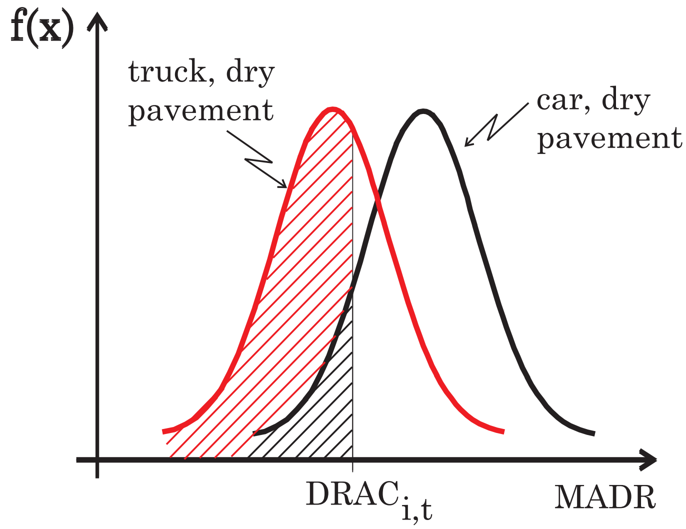

Figure 4.5: CPI calculations for a given DRAC level

DRAC can be calculated for both rear-end and angled interactions using the following expressions

1. DRAC for rear-end interactions

$$DRAC_{RV,t}^{rear\ end} = \frac{\left(V_{RV,t-1} - V_{SV,t-1}\right)^2}{2\left[\left(X_{SV,t-1} - X_{RV,t-1}\right) - L_{SV}\right]} \tag{4.2}$$

   where
   V = RV or SV velocity (m/s)
   X = RV or SV position (m)
   L_{SV} = SV length (m)

2. DRAC for angled interactions

$$DRAC_{RV,t}^{angled} = \frac{2\left[V_{RV,t-1} \cdot t''_{SV} - \left(X'_{RV} - X_{RV,t-1}\right)\right]}{t''_{SV}} \quad ; \tag{4.3}$$

$$\forall \quad \frac{\left(X'_{RV} - X_{RV,t-1}\right)}{V_{RV,t-1}} \leq t''_{SV} \leq 2\,\frac{\left(X'_{RV} - X_{RV,t-1}\right)}{V_{RV,t-1}}$$

where
X'_{RV} = position of the closest boundary of the crash zone with respect to RV trajectory (m)
t''_{SV} = time for SV to clear the crash zone (s), expressed as

$$t''_{SV} = \frac{\left(X''_{SV} - X_{SV,t-1}\right) + L_{SV}}{V_{SV,t-1}} \tag{4.4}$$

where
X''_{SV} = position of the farthest boundary of the crash zone with respect to SV trajectory (m)

While interacting, vehicles are supposed to apply DRAC in order to avoid high risk situations. In reality, combinations of differential speed and spacing are perceived by the RV driver which, after a given delay, will respond in a particular fashion. The simulation algorithm updates DRAC for every time interval (0.1 secs) based on driver reaction in the previous interval. For example, if in a given interval (t_i) the RV driver applies a deceleration rate greater than DRAC then in the next time interval (t_{i+1}) it is expected that DRAC will be lower assuming everything else constant.

The above CPI expression is computationally sound since it reflects a probability that unsafe conditions present themselves to any given driver as he or she progresses along the road. The CPI also captures the gamut of interaction levels from undisturbed passages to vehicle crashes as a continuous measure.

As noted previously, although more desirable, estimating CPI directly from field measurements would require a comprehensive and detailed vehicle tracking data rarely available. This way, the procedure for estimating CPI in this work applies microscopic simulation as a platform to model geometric configuration, traffic attributes and overall driving behaviour for different transportation scenarios. The general framework for estimating CPI is illustrated in Figure 4.6.

4.4 Simulation Platform

The simulation platform is a key component in the safety model since its algorithms should replicate with high fidelity the whole spectrum of traffic situations that could lead to crashes. This way, it is possible to ensure that model outputs would yield safety measures that closely match “real world” situations.

Notwithstanding the fact that the vast majority of microscopic models have not been explicitly developed for safety assessment, recent advances in modelling techniques, data acquisition and human behaviour research have produced more

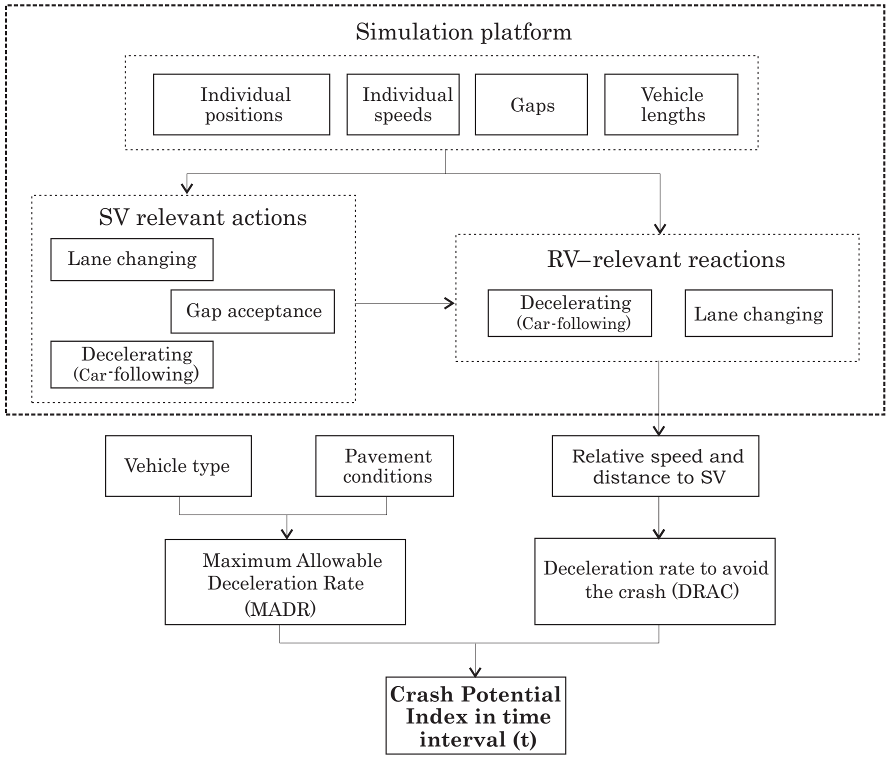

Figure 4.6: Framework to establish CPI for a given time interval (Source: [28])

comprehensive and "non-normative" simulation algorithms. The most advanced group of microscopic models known as psycho-physical or action point models are based on the assumption that the driver would be able to ascertain if he/she is approaching the leader vehicle by changes in its apparent size. Furthermore, drivers would perceive relative speed by changes on the visual angle of the vehicle ahead. These thresholds for human perception are usually referred to as action points [21].

Wiedemann [111, 112] created the first action point car-following model using extensive research on the limits of human perception. Wiedemann's car-following, lane change, and gap acceptance models are incorporated in a traffic simulation program developed in Germany called VISSIM which serves as the simulation platform in this work.

4.4.1 VISSIM Psycho-Physical Car Following Model

Wiedemann's car-following model (CFM) considers four types of regimes where drivers adjust their desired spacing and speeds through changes in their acceleration and deceleration rates. These four driving regimes are: un-influenced driving, closing process, following process, and emergency braking.

In the un-influenced driving regime (gray area in Figure 4.7), the following driver is trying to reach its desired speed once there is no lead vehicle in a reasonable distance (150m) or when the distance is decreasing but the perception threshold of speed difference at long distance (SDV) has not been achieved. Speed differential (DV) and spacing (DX) for this regime should satisfy the following conditions: DV<SDV or DX>150m at each time interval.

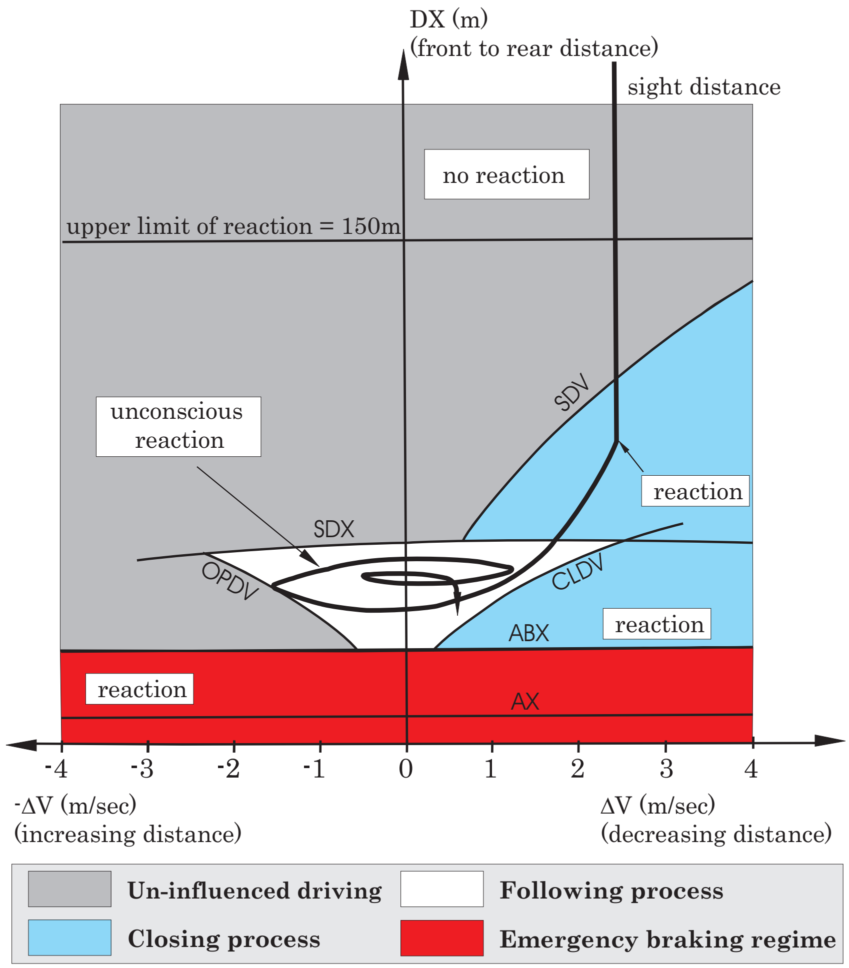

Figure 4.7: Perception and reaction thresholds and distances in Wiedemann's CFM (Source:[92])

When both the distance between the lead and the following vehicle is less than 150 meters and the SDV threshold have been surpassed, the following driver enters the closing process regime. In this regime, drivers realize that a slower vehicle is approaching and, after a given delay, begin to decelerate. At this point, drivers intend to decelerate matching its own desired minimum following distance (ABX). The applied deceleration rate is based on the kinematics equation for deceleration to a moving target. An additional error term is added to represent the error of human estimation, that varies for the same driver every second, and a parameter to account for the learning process also updated each second (blue area in Figure 4.7).

In the following process, the trailing vehicle has almost the same speed of the lead vehicle and the following driver does not consciously react to movements of front vehicle. Acceleration and deceleration rates are applied in a very low oscillating level around the average value equals to $0.2 m/s^2$. The transition from the closing to the following process happens when DV<SDX. The following process is delimited by two perceptual thresholds for small speed differences at short, decreasing and increasing distances (CLDV and OPDV) and two thresholds corresponding to the minimum desired distance at low speed differences and the perception of growing distance in the following process (ABX and SDX). This regime is illustrated in the white area in Figure 4.7.

The emergency braking regime happens when drivers need to react to avoid a crash and to come back to a distance longer than the minimum desired distance for standing vehicles (AX). The transition to the emergency braking situation can happen either from the closing process or from the following process. If the vehicle still in the closing process (DV>SDX) and the spacing between the lead and the follower vehicle becomes smaller than (ABX) the emergency braking regime begins. If the vehicle is in the following regime and the lead vehicle brakes suddenly leading to DV>CLDV and DX<ABX the emergency regime is also triggered (red area in Figure 4.7) .

4.4.2 VISSIM Lane Change Model

In VISSIM, the human decision to change lane is represented by a hierarchical scheme considering three major questions as follows [112]:

1. Is there a desire to change the lane?
2. Is the traffic situation at the target lane better than the traffic conditions at the actual lane?
3. Is the movement to the target lane possible?

Initially, the desire to change the lane arises from obstructions on the current lane by a slower vehicle. Changing to a faster lane is valued to be advantageous if the vehicle is not obstructed by a new lead vehicle in the fast lane and, finally changes to both faster and slower lanes are possible, given that no dangerous situations results from the manoeuvre [112]. If all three questions are answered positively the lane will be changed. This hierarchical process follows analogous perception models applied in car-following situations, however, in this case, the vehicle changing lanes should analyze up to two more vehicles in the target lane (lead and following vehicles in the target lane). Figure 4.8 illustrates the parameters for lane change manoeuvres.

Lane changes can also be motivated by necessary adjustments in drivers positions in order to reach a necessary connector and maintain their routes (mandatory

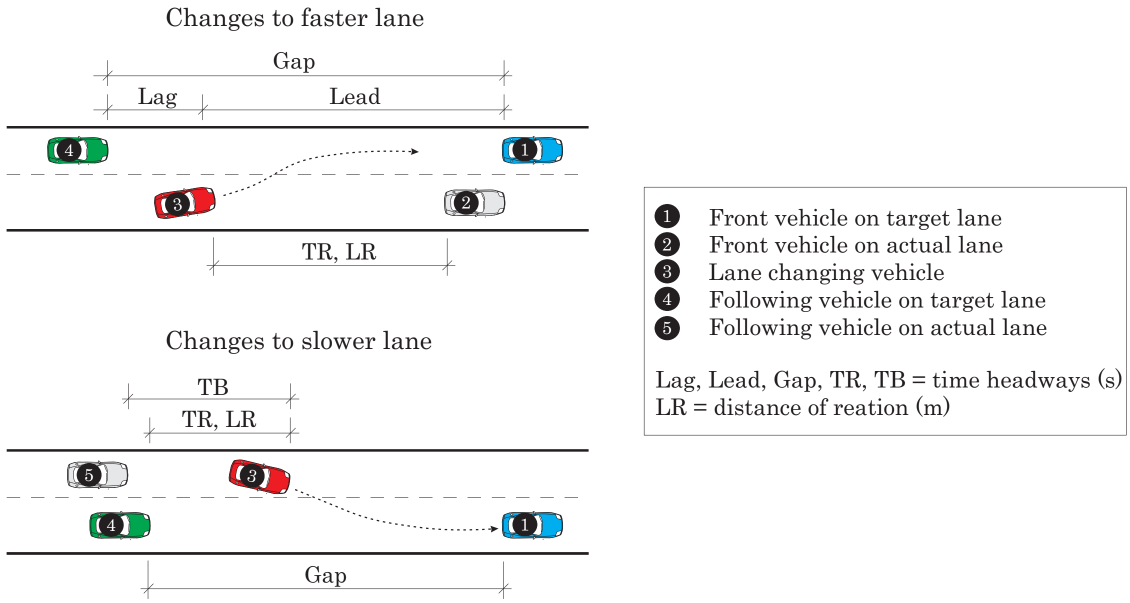

Figure 4.8: Parameters in VISSIM lane changing manoeuvres (Source: [112])

lane change). Driver aggressiveness for mandatory lane changes in VISSIM 4.3 is considered by defining deceleration thresholds for both the vehicle that is changing the lane and the vehicle ahead in the target lane. While coding the network, users can also specify the distance upstream of a given connector that drivers would start to search for suitable gaps in order to perform a mandatory lane change. These two features are especially useful when modeling congested situations.

4.4.3 VISSIM Gap Acceptance Model

Gap acceptance manoeuvres in VISSIM 4.3 can be modeled by using two strategies, namely the “priority rules” and the “conflict areas”. When adopting the “priority rules”, users must define major and minor priority movements, place virtual stop markers on the minor road to determine where the vehicle should stop (if needed) and define a minimum gap time bellow which the gap is rejected. This minimum gap time is equivalent to the concept of a critical gap (a gap with equal probability of acceptance and rejection). In essence, this is a deterministic gap acceptance model, however, other types of models such as logistic regression model can be defined throughout a programming tool embedded in VISSIM called Vehicle Actuated Programming (VAP) [13, 92].

“Conflict areas” have been introduced to yield a more realistic and “intelligent” vehicle behaviour in the gap acceptance manouvre. Based on intersection geometric characteristics as defined by the user, VISSIM automatically detects overlapping areas (conflict areas) and the user establish which movement should yield the right-of-way. A visibility parameter determines the closest point to the intersection where drivers should observe other drivers approaching from conflicting movements. The driver in lower priority approach evaluates gaps on the main stream, the situation behind the conflict area, and its current speed/acceleration profile before deciding to proceed or stop at the intersection.

One of the main differences of the use of "conflict areas" as compared to the "priority rules" is that in the former gap acceptance approach, vehicles in the main steam also react in case of a crossing vehicle misjudges the available gap or the situation beyond the conflict area and has to stop or slow down in the middle of the conflict area. In this case the main stream vehicle would react, changing lanes, slowing down or even stopping to avoid the crash. Unfortunately, there is little information about how the software perform these tests.

Accurate and complex behavioural modeling of driver/vehicle interactions is not the only desirable characteristic in microscopic models in their use in safety studies. Microscopic simulation packages should also allow detailed specification of network components, provide detailed and user adjustable output information and provide a rational platform for calibrate, modify, and manipulate key parameters of sub-models [36].

A number of additional features present in VISSIM supported its selection as the simulation platform in this thesis and these include:

1. Configurable output files.
2. Allows short simulation time interval (0.1sec).
3. Permits different vehicle dimensions and operational characteristics between vehicle types and within the same vehicle type.
4. High flexibility in defining traffic flow and traffic composition, including turning movements and time-dependent traffic flow.
5. Allows modeling of speed reductions for turning movements.
6. Permits user to access objects and data in the model during run-time processing throughout an open application programmer interface (API).
7. Allows high level of modeling details for traffic signals, including semi and fully actuated traffic signals.

Notwithstanding that VISSIM algorithms have not been initially designed for safety studies, this simulation package appears to support most of the modeling features necessary for estimating safety performance measures of traffic scenarios with reasonable level of fidelity [13, 36].

It has been recognized that microscopic simulation users should perform visual inspections during simulation run-time to search for abnormal vehicle behaviour such as, sudden vehicle stoppage, abrupt lane-change and others. Three of these situations have been observed during VISSIM simulations that would have impacted our safety performance measure (CPI/veh): 1) "Crashes" during gap-acceptance situations, 2) Sudden vehicle stoppage for vehicles trying to reach off-ramp links, and 3) Vehicles too close during lane change manoeuvres.

Crashes have been observed in VISSIM for complex intersection environment where a considerably high number of vehicles and turning manoeuvres exist. These situations must be excluded for the analysis since it is considered that VISSIM cannot realistically simulate crashes. In this research, VISSIM output files (.fzp files) were filtered for vehicles occupying the "same" space at the same time throughout a VB.net application developed for estimating CPI, named CPI calculator. Such occurrences were identified by unreasonably high DRAC values ($> 15m/s^2$) and/or very low (or negative) spacing between leader and follower vehicles.

Problems with sudden vehicle stoppage were observed mostly for vehicles trying to exit the freeway in high volume regime. In this case VISSIM generates an error file that indicates that a vehicle has been removed from the simulation and the respective number seed was not considered in the analysis.

In situations where the following vehicle has started to change the lane to improve its travel speed (discretionary lane change) the following driver starts to "look" at the target lane although for a brief period, say 0.2 to 0.5 seconds the vehicle is still occupying its original lane. In some occasions, especially when the lead vehicle in the original lane is too close, this transition yield very low spacing between vehicles with considerably high speed differentials. In the CPI calculator VB.net application these situations have also been filtered by comparing the status of follower vehicle's VISSIM variable called *Lch* (direction of current lane change). The signs "<" or ">" in *Lch* variable indicate that vehicle has started the lane change manoeuvre to the left or right lane even though the vehicle still in the original lane.

Chapter 5

CPI Calibration and Validation Using Vehicle Tracking Data

5.1 Introduction

In order to estimate CPI values one would need highly detailed and almost continuous (every 0.1s) information about speed and spacing for every vehicle traveling on a given road segment. Additionally, in order to have a representative sample of high risk situations in the traffic stream, it is necessary to gather sufficient data to ensure these type of events are included in the dataset. These data prerequisites bring considerable limitations to the use of existing vehicle tracking data in the proposed safety framework. This thesis attempts to overcome this void by applying microscopic traffic algorithms to represent driver behaviour as observed in real world situations.

It is recognized that the merits of microscopic simulation for assessing safety depend on the ability of these models to capture complex behavioural relationships that could lead to crashes and to establish a link between simulated safety measures and crash risk. Furthermore, it becomes necessary to estimate model inputs such that they accurately replicate safety performance at a given location over time. Accordingly, one of the major steps in applying simulation for safety purposes is to ensure that important model inputs have been accurately determined based on observational data and that simulation models produce estimates of safety performance that can be verified from real world observations.

The main objective of this chapter is to introduce a systematic and objective procedure for determining best estimates of simulation model inputs that reflect safety performance measures as obtained from field observations. This is referred to as model calibration. A secondary objective is to assess the transferability of selected model inputs for different traffic conditions (model validation). This objective investigates whether the input values suggested in the calibration yield safety performance measures that reflect safety profiles verified in other “real world” comparable situations.

5.2 NGSIM Vehicle Tracking Data

The observational vehicle tracking data used to calibrate and validate safety performance was obtained from the Next Generation SIMulation (NGSIM) program administered by the FHWA. One of the major aims of this program is to provide high quality detailed vehicular information in real time that can be used to improve driving simulation algorithms [54]. The products of the NGSIM program are freely available to transportation researchers and practitioners from the FHWA web site http://www.ngsim.fhwa.dot.gov.

5.2.1 The Lankershim Boulevard Dataset (Signalized Intersection)

This NGSIM vehicle tracking data was extracted for a segment of an urban arterial road (Lankershim Boulevard) in Los Angeles, California. This segment is approximately 500m in length consisting of three to four lanes and four coordinated signal-controlled intersections. Digital video images were collected from 5 cameras mounted on a 36 story building over a 9 hour period from 7:00 a.m. to 12:00 p.m. and 3:00 p.m. to 7:00 p.m. [6]

Individual vehicle trajectories were transcribed for every 1/10 second and grouped into two independent 15 minute samples from 8:30 to 8:45 a.m. and from 8:45 to 9:00 a.m. The first 15 minute sample was used for calibration, while the second sample was used to validate the model results. The case study focuses on potential rear-end crashes on the southbound approach of Universal Hollywood Driveway and Lankershim Boulevard (intersection 2) and over a segment bounded by the stop line on the major approach and a point 100 meters upstream (Figure 5.1).

5.2.2 The Highway 101 Vehicle Tracking Data (Freeway Segment)

This NGSIM dataset was obtained from the southbound lanes of Highway 101 (US 101), also known as the Hollywood Freeway, in Los Angeles, CA, on June 15, 2005. The study area was approximately 640 meters (2,100 feet) in length and consisted of five mainline lanes throughout the section (Figure 5.2). Eight synchronized digital video cameras installed on the top of a 36-story building adjacent to the freeway were used to record vehicles trajectories in the study area [7]. Individual vehicle trajectories were transcribed from the video images for every 0.1 second interval and grouped into two independent 15 minute samples covering the periods: 1) 7:50 to 8:05 a.m. and 2) 8:20 to 8:35 a.m. The first 15 minute sample was used for calibration, while the second 15 minute sample was used to validate the model results.

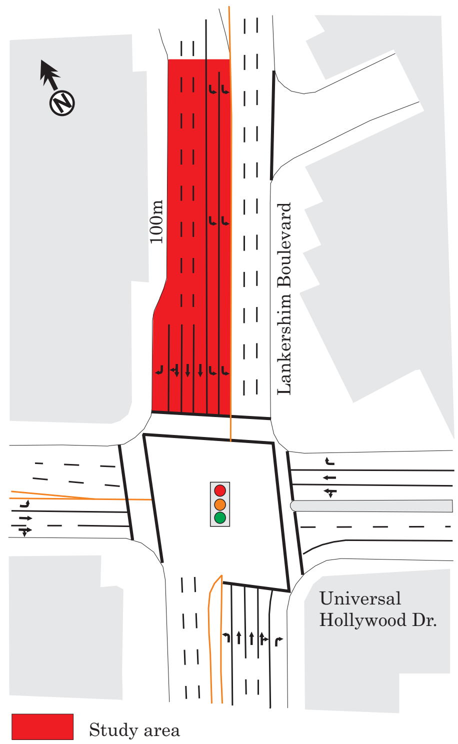

Figure 5.1: Lankershim study area (Source: [29])

Two geometric scenarios were investigated using the NGSIM freeway dataset: the off-ramp segment and the combined on/off ramp segment. In the off-ramp analysis the area of interest was defined from the downstream end of the surveyed segment to approximately 320m upstream, corresponding to the mid point of the total segment length. The combined on/off-ramp considered the full segment length (640m). These two scenarios served as a basis for inferences about differences in input parameters for different regions of the freeway where drivers may have conflicting preferences.

The NGSIM data analysis report also provides detailed information on several parameters used in calibration and validation, including vehicle type distribution, O-D matrix, traffic volume for 5 minute intervals, average speed, average travel time, number of lane changes, headway, and spacing analysis.

5.3 Microscopic Calibration/Validation Procedure

The primary focus of the calibration/validation exercise is to obtain model inputs and simulated outputs that closely match observed safety performance as obtained from the NGSIM vehicle tracking data. Two safety performance measures obtained from the proposed microscopic safety model were used as measures of performance (MOP) in the simulation calibration/validation procedure and these are: CPI/veh

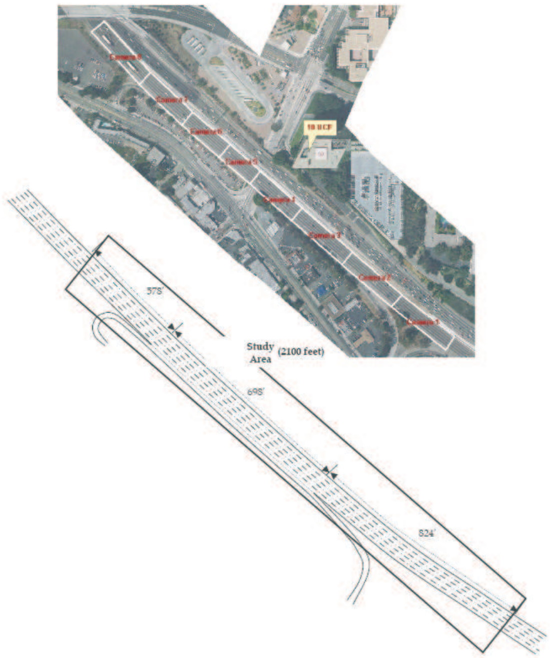

Figure 5.2: Highway 101 study area (Source: [7])

and the number of vehicles in conflict. It is worth mentioning that this study accounts only for rear-end vehicle interactions originated by drivers either adjusting their speed/spacing or their traveling lane to account for the surrounding traffic environment. This type of interaction is considered to be predominant in both selected study areas.

The CPI/veh represents the average level of traffic turbulence and is expressed by the sum of all individual CPI divided by the number of vehicles in the simulation. In contrast, the number of vehicles in conflicts, represents a subset of interactions such that the deceleration rate required to avoid a crash (DRAC) exceeds the maximum braking capability of the vehicle (MADR). For conflicts, unique values of MADR are assigned to individual vehicles entering the simulation from a truncated Normal distribution with average of 8.45m/s^2 for cars and 5.01m/s^2 for trucks with a standard deviation of 1.40m/s^2. Every time interval where the DRAC exceeds the MADR a conflict is ascribed by the model. To avoid unrealistic MADR values, deceleration rates of 12.69m/s^2 and 4.23m/s^2 were used as upper and lower limits respectively for cars and 7.98m/s^2 and 2.05m/s^2 for trucks.

As noted previously, the NGSIM vehicle tracking data is based on two "independent" 15 minute time windows. As a result the calibration/validation framework also uses the 15 minute simulation time window for the simulation exercise. A visual basic.net application was developed to scan the original NGSIM output files, determine CPI on a per vehicle basis, and to check for vehicles in conflict. Table 5.1 summarizes target values for CPI/veh and the number of vehicles in conflict as extracted from the NGSIM Lankershim and Highway 101 dataset.

Table 5.1: Target CPI/veh and number of vehicles in conflict from NGSIM dataset

NGSIM Dataset	Time	CPI/veh	#Veh in conflict
Lankershim Boulevard	8:30 a.m. - 8:45 a.m. (*)	3.40E-05	3
	8:45 a.m - 9:00 a.m. (**)	5.80E-05	6
Highway 101	7:50 a.m. - 8:05 a.m. (*)	8.85E-05	20
	8:20 a.m. - 8:35 a.m. (**)	9.52E-05	17
Highway 101 - Off-ramp	7:50 a.m. - 8:05 a.m. (*)	9.92E-05	8
	8:20 a.m. - 8:35 a.m. (**)	1.24E-04	10

(*) used for calibration

(**) used for validation

The microscopic model calibration/validation framework illustrated in Figure 5.3 consists of five computational steps:

1. Selection of initial model inputs.
2. Initial statistical screening of inputs (Placket-Burnman with foldover).
3. Establishing linear expression relating significant inputs to safety performance (fractional factorial analysis).
4. Obtaining best estimates of model inputs using a genetic algorithm.
5. Validating selected inputs based on an independent traffic sample.

The first four steps apply to the model calibration procedure; i.e. obtaining the best estimates for simulation inputs. The 5^{th} step applies to validating the simulated output based on independent observed traffic dataset, i.e. it investigates whether the input values suggested in the calibration yield safety performance measures similar to those observed in the independent dataset.

This heuristic procedure is based on sequential applications of factorial designs that provide a systematic investigation of factors (independent variables) that can influence a given response (dependent variable). One of the main advantages of factorial designs is that it is more efficient than one-factor-at-a-time experiments. Furthermore, when there is interaction between factors, this approach is essential to avoid misleading conclusions [73].

The step-by-step procedure is initially illustrated below throughout its application to the NGSIM Lankershim dataset (signalized intersection) and subsequently, the major findings obtained from the application of the same calibration/validation framework to the NGSIM freeway segment are summarized.

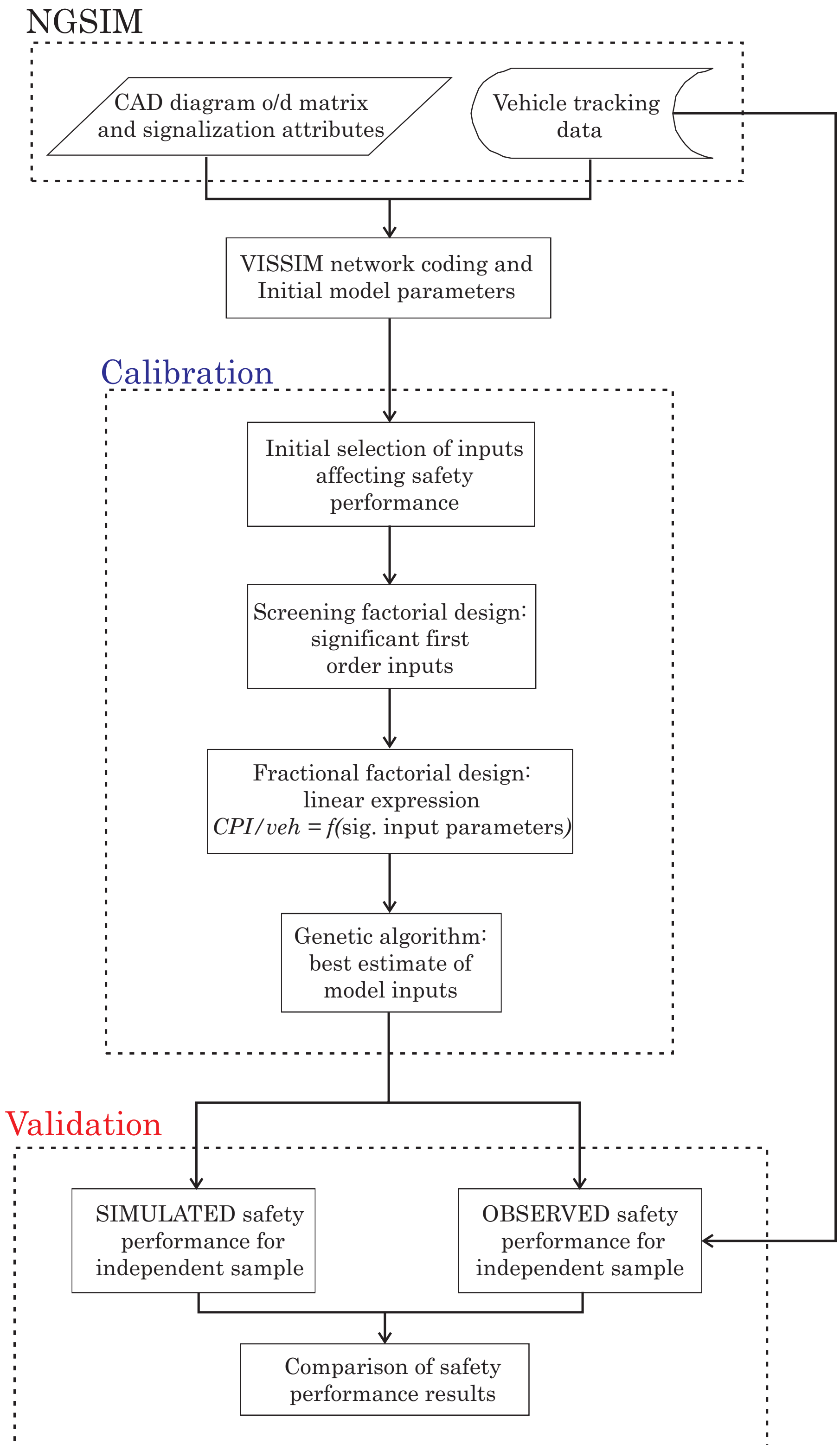

Figure 5.3: Calibration/validation framework

5.3.1 Selection of initial model inputs

VISSIM requires specification of 15 input parameters for use in its car-following model, 10 inputs for the lane change model as well as 8 driver behaviour input functions. Based on sound engineering judgment these inputs were initially reduced to 13 parameters of relevance for explaining safety performance at signalized intersections. This reduced list of inputs is summarized in Table 5.2 along with their corresponding low/high values and explanatory comments. The low and high input values given here were suggested by Park and Schneeberger [85] and Lownes and Machemehl [62] based on analysis of each individual parameter definition and acceptable ranges.

Table 5.2: Initial model input parameters (Source: [29])

Factor	Parameter	Low level (-1)	High level (+1)	Description
A	Desired speed (average) (km/h)	30	60	Individual free flow speed. Vehicles will travel at this speed (with oscillation) if they are not delayed by other vehicles
B	Desired speed (std deviation)	2.9	8.7	Standard deviation of the desired speed
C	Desired deceleration (m/s ^{2})	-4.5	-1.3	It is the maximum deceleration drivers are willing to apply in "normal" (not emergency) situation
D	Observed vehicles ahead	1	4	Influences drivers' ability to adjust their speed/distance according to a given number of lead vehicles
E	CC0	0.5	3	Standstill distance (m). Defines the desired distance between stopped cars
F	CC1	0.5	1.5	Headway time (s). Defined as the minimum time a driver wants to keep from the lead vehicle. The higher the value, the more cautious the driver is. CC0 and CC1 are combined to express the safety distance
G	CC2	1.5	6	Following variation (m). It controls the longitudinal oscillation in the car-following process
H	CC3	-15	-4	Threshold for entering "following". Influences the start of the deceleration process when a following driver recognizes a slower vehicle ahead
I	CC5	0.1	2	Positive "following" threshold. Controls speed differences in the following process. Small values lead to a more sensitive reaction of following vehicles to decelerations of the lead vehicle
J	CC6	2	20	Speed dependency of oscillation. Controls speed oscillation with distance to the lead vehicle
K	Min. headway (m)	0.5	4	Minimum distance to the lead vehicle that must be available for a lane change in standstill condition.
L	Safety distance reduction factor	0.2	0.8	Factor applied to the original safety distance during lane change situations. Lane changing driver will reduce its original safety distance during the manoeuvre
M	Max. deceleration for cooperative breaking (m/s ^{2})	-9	-4	

5.3.2 Statistical screening of inputs (Plackett-Burnman with foldover)

As noted previously, both the statistical screening of inputs and the linear expression with important input parameters apply concepts of two-level factorial design. In this type of experimental design, the relationship between factors (independent variables) and responses (dependent variables) is systematically investigated by experiments exploring combinations of both the highest and lowest possible level of each factor.

A typical outcome of factorial analysis is a linear model where the response is estimated as a function of significant factors and their effects. For example, in a 2^3 (3 variables tested over 2 levels) factorial design, the underlying linear model is of the form

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_4 x_1 x_2 + \beta_5 x_1 x_3 + \beta_6 x_2 x_3 + \beta_7 x_1 x_2 x_3 + \epsilon \tag{5.1}$$

where
y= dependent variable or response
x =independent variables or factors
β = coefficients
ϵ = error

Usually, when designing factorial experiments, independent variables are normalized within the range $-1 \leq x \leq +1$, where -1 and +1 represent the lowest and highest possible level of a given factor respectively. This coded space representation is useful for determining the relative size of factor effects and therefore eliminating scale problems between different variables. In this case, coefficients (β) for different variables provide the relative importance of a given factor over the others.

It is worth noting that as the number of variables increases the number of experiments (runs) needed to produce the full linear expression increases dramatically. For example, in testing 4 independent variables, the full factorial experiment requires $2^4 = 16$ runs in order to explore the full combination of factor levels. In the calibration exercise described here $2^{13} = 8192$ simulation runs would be required to fully investigate the variables. However, it is possible to adopt a sequential approach to avoid this excessive number of runs and focus initially on model inputs that deserve further investigation. This initial step is referred to as the screening design.

The Plackett-Burnman with foldover fractional design is a particular case of 2-level factorial design that is recommended for screening purposes [73]. This design is focused on the statistical significance of the main interaction terms. Since the full experiment is not performed, a set of confounding variables arises and the level of these confounding variables determines the overall quality of the model (design resolution). According to Montgomery [73], screening experiments should be designed in order to provide at least resolution IV.

For the initial set of 13 factors, 32 simulations were performed using the Plackett-Burnman with foldover design structure [73]. The simulation input parameter combinations as suggested in the Plackett-Burnman design with corresponding CPI/veh is presented in Appendix A. An additional 12 simulations were run to obtain the requisite number of 3 replicates for each level of the only discrete input variable (observed vehicles ahead). Replicates of the experiment are necessary to estimate the error/variance due to the random nature of the simulation and subsequently the importance/significance of each factor can be established using a N-way analysis of variance (ANOVA). The application of ANOVA to the 13 factor combinations in this exercise is summarized in Table 5.3. This Table also includes information on a fitted linear expression relating factor inputs to model response or safety performance in the coded space.

Table 5.3: Analysis of variance table Plackett-Burnman with foldover (Source: [29])

Source	Coefficients (10^{-3})	Effects (10^{-3})	SS (10^{-3})	df	MS	F_{obs}	p-value
Intercept	16.33						
Factors							
A	**-3.44**	**-6.87**	**0.38**	**1**	**0.38**	**7.29**	**0.03**
B	-0.29	-0.58	0.00	1	0.00	0.05	0.83
C	**-7.62**	**-15.23**	**1.86**	**1**	**1.86**	**35.81**	**0.00**
D	-1.56	-3.11	0.08	1	0.08	1.50	0.26
E	**-7.91**	**-15.81**	**2.00**	**1**	**2.00**	**38.58**	**0.00**
F	**-10.35**	**-20.70**	**3.43**	**1**	**3.43**	**66.15**	**0.00**
G	**-3.06**	**-6.12**	**0.30**	**1**	**0.30**	**5.79**	**0.04**
H	0.69	1.38	0.02	1	0.02	0.30	0.60
I	-1.95	-3.90	0.12	1	0.12	2.35	0.16
J	-1.59	-3.18	0.08	1	0.08	1.56	0.25
K	-0.88	-1.76	0.02	1	0.02	0.48	0.51
L	-0.24	-0.47	0.00	1	0.00	0.03	0.86
M	**3.82**	**7.64**	**0.47**	**1**	**0.47**	**9.01**	**0.02**
Error			0.41	8	0.05		

From Table 5.3 it should be noted that 6 first order factors were found to be statistically significant at the 5% level, i.e., desired speed (average), desired deceleration, CC0, CC1, CC2 and maximum deceleration for cooperative braking. The relationship was also found to yield intuitively reasonable results for explaining CPI. The next step in the procedure is to investigate the presence of possible higher order interactions among significant factors as obtained from the screening exercise.

5.3.3 Obtaining Linear Expression Relating Significant Inputs to Safety Performance (Fractional Factorial Analysis)

This step attempts to refine the statistical relationship between safety performance and input parameters by considering possible confounding effects in explaining CPI that could not be identified from the above Plackett-Burnman design.

To reduce the number of factor combinations considered, 1/2 fraction of a 2^6 factorial design (2^{6-1}) was used. The 2^{6-1} fractional factorial experiment produces a design resolution VI and the recommended design generator for the experiment ($M = ACEFG$) will produce a defining relationship of the form $I = ACEFGM$, where I is a column with only high levels of a given factor (plus signs). The simulation input parameters combination as suggested by the 2^{6-1} fractional factorial design with corresponding CPI/veh is presented in Appendix B.

It is possible to determine the confounding pattern of a fractional factorial experiment by applying its defining relationship. For example, main factors or higher order interactions confounded with the desired speed (factor A) can be found by multiplying both sides of the defining relation by this factor:

$A \cdot I = ACEFGM \cdot A$

$A \cdot I = A^2CEFGM$ note that $X \cdot I = X$ and $X^2 = I$, therefore

$A = CEFGM$

This suggests that factor A (desired speed) can be confounded with the mix of factors CEFGM in explaining CPI. The fractional factorial design expands our search window of possible effects to include the input factors summarized in Table 5.4. To obtain these results a total of 37 simulation runs were carried out, 32 to reflect the 2^{6-1} fractional factorial design and 5 replicate simulations for the centre points (Table 5.4).

The application of factorial analysis reduced the six significant factors from the previous step to three first order effects, i.e. desired deceleration (C), CC0 (E), and CC1 (F), and two second order interactions, i.e. desired deceleration and CC0 (CE) and desired deceleration and CC1 (CF). Table 5.4 indicates the statistical significance of the parameters in the fitted expression and their respective values in coded space. Converting the coded factors from Table 5.4 in terms of selected VISSIM traffic inputs, an expression for CPI/veh ($x10^{-5}$) is obtained of the form:

$$\begin{aligned} CPI/veh(x10^{-5}) = 7.7 - 11.7 \cdot Desired\,deceleration + 2.3 \cdot CC0 - \\ - 4.7 \cdot CC1 + 2.2 \cdot Desired\,deceleration \cdot CC0 + \\ + 4.3 \cdot Desired\,deceleration \cdot CC1 \end{aligned} \tag{5.2}$$

The R^2, residual sum of squares (SSE) and F-value for the above expression were found to be 0.72 , 0.0020 and 16.1 respectively. The SSE from the fitted model can

Table 5.4: Analysis of variance table - 2^{6-1} fractional factorial design (Source: [29])

Source	Coefficients (10^{-3})	Effects (10^{-3})	SS (10^{-3})	df	MS	F_{obs}	p-value
Intercept	**14.58**	**29.16**	**6.80**	**1.00**	**6.80**	**139.83**	**0.00**
Factors							
A	1.51	3.01	0.07	1	0.07	1.49	0.29
C	**5.44**	**10.87**	**0.95**	**1**	**0.95**	**19.44**	**0.01**
E	**5.20**	**10.41**	**0.87**	**1**	**0.87**	**17.81**	**0.01**
F	**8.64**	**17.29**	**2.39**	**1**	**2.39**	**49.17**	**0.00**
G	1.34	2.68	0.06	1	0.06	1.18	0.34
M	2.26	4.52	0.16	1	0.16	3.36	0.14
A * C	2.50	5.00	0.20	1	0.20	4.11	0.11
A * E	2.38	4.76	0.18	1	0.18	3.73	0.13
A * F	2.50	5.00	0.20	1	0.20	4.12	0.11
A * G	1.10	2.21	0.04	1	0.04	0.80	0.42
A * M	0.80	1.61	0.02	1	0.02	0.42	0.55
C * E	**4.43**	**8.85**	**0.63**	**1**	**0.63**	**12.89**	**0.02**
C * F	**3.46**	**6.92**	**0.38**	**1**	**0.38**	**7.89**	**0.05**
C * G	0.49	0.98	0.01	1	0.01	0.16	0.71
C * M	0.58	1.16	0.01	1	0.01	0.22	0.66
E *F	0.93	1.86	0.03	1	0.03	0.57	0.49
E * G	1.87	3.75	0.11	1	0.11	2.31	0.20
E * M	0.49	0.99	0.01	1	0.01	0.16	0.71
F * G	1.65	3.29	0.09	1	0.09	1.78	0.25
F * M	0.06	0.12	0.00	1	0.00	0.00	0.96
G * M	1.76	3.52	0.10	1	0.10	2.04	0.23
A * C * E	0.25	0.49	0.00	1	0.00	0.04	0.85
A * C * F	0.51	1.02	0.01	1	0.01	0.17	0.70
A * C * G	0.21	0.43	0.00	1	0.00	0.03	0.87
A * C * M	0.05	0.11	0.00	1	0.00	0.00	0.97
A * E * F	0.30	0.60	0.00	1	0.00	0.06	0.82
A * E * G	2.63	5.25	0.22	1	0.22	4.54	0.10
A * E * M	0.56	1.11	0.01	1	0.01	0.20	0.68
A * F * G	0.86	1.72	0.02	1	0.02	0.48	0.52
A * F * M	0.10	0.20	0.00	1	0.00	0.01	0.94
A * G * M	2.02	4.03	0.13	1	0.13	2.67	0.18
Error			0.19	4	0.05		

be separated into two constituent components: the sum of squares of the pure error (SSPE) and the sum of squares due to lack of fit (SSLF). A significance in the lack of fit suggests that the above expression (Equation 5.2) could be improved by considering the presence of curvature in the model (significant quadratic terms, etc). Such a test was carried out that yielded a non statistically significant F-value of 1.38. This result suggests that the above linear expression provides a good explanation for CPI without the need to consider curvature.

Having established the statistical significance of factor inputs and structure of the relationship linking CPI to these inputs, it remains to obtain best estimate values of the parameters describing this relationship.

5.3.4 Obtain Best Estimates of Model Inputs Using Genetic Algorithm Procedure

The expression obtained from the previous step has an infinite number of solutions; i.e. parameter values that yield a given CPI per vehicle. Clearly a procedure needs to be established for obtaining the "best estimate" values of the parameters in Equation 5.2. In this case, parameter values that yield a CPI per vehicle of $3.4\text{x}10^{-5}$ as observed in the vehicle tracking data.

A genetic algorithm procedure was used to search for an optimum solution to the CPI expression given above. Genetic algorithm (GA) is a search technique used to obtain exact or approximate solutions to a given optimization problem. A typical genetic algorithm requires the specification of two constraints:

1. Genetic representation of the solution domain.
2. Fitness function to evaluate the solution domain.

In this case, the genetic representation of safety performance is the linear expression obtained from the fractional factorial experiment in the previous step (equation 5.2). The fitness function on the other hand, is defined in terms of the residual sum of squares error obtained by comparing the simulated and observed (vehicle tracking data) measures of CPI per vehicle. This fitness function reflects the precision of the represented solution.

Once the genetic representation and the fitness function have been defined, GA proceeds to initialize a population of solutions randomly. These are then improved through repetitive application of mutation, crossover, inversion, and selection operators.

To reduce the number of optimal solutions a second measure of safety performance namely, the number of vehicles in conflict during the 15 minute simulation period was obtained from the simulation. Initially, 50 genetic algorithm runs were carried out using MATLAB ©. Only desired deceleration rate was found to yield any significant variation in values. Estimates of these deceleration rates were subsequently sorted in ascending order for the 50 feasible solutions. To obtain a reduced number of representative values, these estimates were aggregated into 6 representative groupings for input into simulation. To ensure that the full spectrum of desired deceleration values is included for simulation, minimum and maximum estimates from the first and last groupings as well as midpoint values for the other 4 groupings were obtained as summarized in Table 5.5.

Ten simulation runs were carried out for the six combinations of input values in Table 5.5. This satisfies the FHWA guidelines [34] for the minimum number of simulations for a desired 95% confidence interval and observed variability in the response variable (CPI/veh). Best estimates of the inputs are those that correspond

Table 5.5: Simulated safety measures and genetic algorithm best estimates of inputs (Source: [29])

Sim.	Input parameter (GA)			Safety measures			Squared error		
	Desired deceleration (m/s^2)	CC0	CC1	CPI/veh ($x10^{-5}$)	#Veh in conflict	Total time in conflict/veh (s)	CPI/veh ($x10^{-8}$)	#Veh in conflict	Total time in conflict/veh (s) ($x10^{-4}$)
1	-4.5	2.7	1.5	5.2	4.4	0.21	3.25	1.96	0.50
2	-4.1	2.7	1.5	6.1	4.6	0.22	7.15	2.56	3.00
3	-3.7	2.7	1.5	4.7	3.8	0.21	1.74	0.64	1.10
4	-3.3	2.8	1.5	5.5	4.3	0.18	4.45	1.69	5.40
5	-3.0	2.8	1.5	5.4	4	0.21	3.95	1.00	0.60
6	**-2.6**	**3**	**1.5**	**3.6**	**3.2**	**0.17**	**0.03**	**0.04**	**9.80**
Observed values				**3.4**	**3**	**0.2**			

to the lowest sum of squares error. This was obtained for the set of parameter values associated with simulation 6 (Table 5.5).

The number of vehicles in conflict was found to be 3.2 (average of 10 simulation runs) comparing favourably with the observed number of 3 in the vehicle tracking data. The optimum solution from Table 5.5 corresponds to parameter values of -2.6m/s^2 for desired deceleration, 3.0 for CC0, and 1.5 for CC1. These input values yielded simulated average CPI/veh of 3.6x10^{-5}, which compares favourably to the observed value of 3.4x10^{-5} in the tracking data.

5.3.5 Validation of Selected Inputs Based on Independent Traffic Sample

One of the major concerns in calibration is whether the inputs obtained from the exercise are transferable to separate and independent data sets with similar geometry and traffic conditions (validation).

In selecting the validation dataset it is desirable that similar driving behaviour relationships apply to both calibration and validation samples. For example, we would not expect observations at intersections to explain vehicle/driver behaviour on road segments all other factors constant. In this step the NGSIM 15 minute vehicle tracking validation data was assumed to be representative of behavioural relationships that are distinct and yet comparable to those observed in the calibration sample.

Table 5.6 summarizes the simulated and observed CPI/veh measure used to reflect safety performance in the validation exercise. Assuming normality the 95% confidence intervals was obtained based on the 10 simulation runs. The results suggest that the average observed CPI/veh lies well within the 95% confidence interval generated from the simulation. In addition the number of vehicles in conflict and total conflict time per vehicle as obtained from the model compared favourably with the values obtained from the vehicle tracking data. Four vehicles in conflict were obtained from simulation as compared to six observed.

Table 5.6: Validation results for CPI per vehicle (Source: [29])

	Average CPI per vehicle ($x10^{-5}$)
Simulated:	
Mean	4.91
Standard deviation	3.14
Number of simulations	10
Confidence interval (95%)	[2.71 , 7.22]
Observed	**5.82**

5.4 Calibration/Validation for Freeway Segments

The same calibration/validation procedure described for the signalized intersections was applied to a sample of vehicles from NGSIM vehicle tracking data for a freeway segment (Highway 101). This exercise was performed as part of a research project sponsored by Transport Canada. The major goal of this project was to investigate the safety impacts of mandatory speed limits for trucks on Canadian highways [93]. As noted previously, different calibration/validation exercises were performed for the off-ramp and combined on/off-ramp segments.

5.4.1 Initial Model Inputs and Statistical Screening

The selection of initial model inputs yielded 16 candidate input parameters to be further investigated using the factorial analysis. Table 5.7 summarizes selected input parameters with their respective description and investigated range of values.

For the off-ramp segment, the Plackett-Burnman with foldover statistical screening of inputs found a total of 10 first order factors to be statistically significant at the 5% level. These include: average desired speed, desired deceleration, observed vehicles ahead, maximum look ahead distance, CC0, CC3, CC5, CC6, accepted deceleration for lane change vehicle, and safety distance reduction factor. The ANOVA results obtained for the 16 first order effects are summarized in Table 5.8.

For the combined on/off ramp segment, a total of 12 first order terms were found to be statistically significant at the 5% level (Table 5.9). These significant terms are: average desired speed, desired deceleration, observed vehicles ahead, maximum look ahead distance, CC0, CC1, CC3, CC5, CC6, accepted deceleration of lane change and trailing vehicles, and the safety distance reduction factor.

Table 5.7: Model input parameters for freeway segments (Source: [93])

	Parameter	Low Level (-1)	High Level (+1)	Center Points (0)
A	Desired Speed (average) (km/h)	80	120	100
B	Desired Speed (standard deviation in km/h)	2.9	8.7	5.8
C	Desired Deceleration (m/s^2)	-4.5	-1.3	-2.9
D	Observed vehicles ahead	1	3	2
E	(max) Look ahead Distance (m)	50	300	175
F	CC0	0.5	3	1.75
G	CC1	0.5	1.5	1
H	CC2	1.5	6	3.75
I	CC3	-15	-4	-9.5
J	CC5	0.1	2	1.05
K	CC6	2	20	11
L	Accepted deceleration fir the lane change vehicle	-3.5	-0.5	-2
M	Accepted deceleration for the trailing vehicle	-2.5	-0.25	-1.375
N	Min. Headway (m)	0.5	4	2.25
O	Maximum deceleration for cooperative braking (m/s^2)	-9	-4	-6.5
P	Safety distance reduction factor	0.2	0.8	0.5

5.4.2 Fractional Factorial Analysis

In order to reduce the number of factor combinations for the off-ramp case, a 1/8 fraction of a 2^{10-3} factorial design was implemented. The 1/8 fractional factorial experiment produces a design resolution V with a recommended design generator of the form: $H = BCGG; I = BCDE; J = ACDF$ resulting in a defining relationship of the form: $I = ABCGH = BCDEI = ACDFJ = ADEGHI = BDFGHJ = ABEFIJ = CEFGHIJ$, where I is the identity matrix with unit values along the diagonal.

To obtain the results for off ramp segments, a total of 160 simulations were carried out, 128 runs to reflect the 2^{10-3} fractional factorial design, and 32 replicate runs for the centre points. The application of factorial analysis reduced the 10 significant factors from the previous step (Table 5.8) to 4 first order effects: observed vehicles ahead (A), CC5 (J), CC6 (K), and the safety distance reduction factor (P) and 11 second order interactions: AD, AE, BE, CD, CG, CI, DE, EH, FJ, GI,

Table 5.8: ANOVA Table - Plackett-Burman with Foldover (Off-Ramp Segment) (Source: [93])

Source	Effects (10^{-5})	SS (10^{-5})	df	MS	F-value
A. Desired Speed (average) (km/h)	**3.80**	**115.0**	**1**	**115.35**	**6.82**
B. Desired Speed (standard deviation) (km/h)	-0.33	0.9	1	0.90	0.05
C. Desired Deceleration (m/s^2)	**-15.29**	**1870.0**	**1**	**1870.14**	**110.64**
D. Observed vehicles ahead	**-4.19**	**140.0**	**1**	**140.49**	**8.31**
E. (max) Look ahead Distance (m)	**-5.98**	**287.0**	**1**	**286.55**	**16.95**
F. CC0	**4.91**	**193.0**	**1**	**193.06**	**11.42**
G. CC1	-0.70	3.9	1	3.94	0.23
H. CC2	0.47	1.8	1	1.77	0.1
I. CC3	**-3.76**	**113.0**	**1**	**112.81**	**6.67**
J. CC5	**3.71**	**110.0**	**1**	**110.37**	**6.53**
K. CC6	**3.80**	**116.0**	**1**	**115.81**	**6.85**
L. Accepted deceleration (lane change vehicle)	**7.34**	**431.0**	**1**	**430.79**	**25.49**
M. Accepted deceleration (trailing vehicle)	2.70	58.4	1	58.40	3.45
N. Min. Headway (m)	-1.63	21.3	1	21.26	1.26
O. Maximum deceleration for cooperative braking (m/s^2)	-3.22	83.2	1	83.15	4.92
P. Safety distance reduction factor	**6.19**	**306.0**	**1**	**306.14**	**18.11**
Error		118.0	7	16.90	

and HI. The linear expression relating CPI/veh ($x10^{-5}$) for the significant first and second order interactions in the coded space is:

$$CPI/veh(x10^{-5}) = 13.71 - 36.47(D) + 10.97(P) + 11.73(A)(E) - \\ - 30.60(A)(F) - 42.79(D)(L) \tag{5.3}$$

where
A = average desired speed (-1 = 80km/h; +1 = 120km/h)
D = observed vehicles ahead (-1 = 1; +1 = 3)
E = max. look ahead distance (-1 = 50m; +1 = 300m)

Table 5.9: ANOVA Table - Plackett-Burman with Foldover (Combined On/Off Ramp Segment) (Source: [93])

Source	Effects (10^{-5})	SS (10^{-5})	df	MS	F-value
A. Desired Speed (average) (km/h)	**2.63**	**55.2**	**1**	**55.20**	**12.13**
B. Desired Speed (standard deviation) (km/h)	0.54	2.3	1	2.30	0.5
C. Desired Deceleration (m/s^2)	**-8.55**	**585.0**	**1**	**585.00**	**128.35**
D. Observed vehicles ahead	**-3.77**	**114.0**	**1**	**114.00**	**25.01**
E. (max) Look ahead Distance (m)	**-4.92**	**193.0**	**1**	**193.00**	**42.44**
F. C00	**4.71**	**178.0**	**1**	**178.00**	**38.98**
G. CC1	**2.83**	**64.1**	**1**	**64.10**	**14.07**
H. CC2	-0.17	0.2	1	0.24	0.05
I. CC3	**-2.67**	**56.9**	**1**	**56.90**	**12.49**
J. CC5	**3.46**	**96.0**	**1**	**96.00**	**21.08**
K. CC6	**3.29**	**86.5**	**1**	**86.50**	**18.99**
L. Accepted deceleration (lane change vehicle)	**4.68**	**175.0**	**1**	**175.00**	**38.48**
M. Accepted deceleration (trailing vehicle)	**2.16**	**37.3**	**1**	**37.30**	**8.19**
N. Min. Headway (m)	-1.22	12.0	1	12.00	2.63
O. Maximum deceleration for cooperative braking (m/s^2)	-1.74	24.3	1	24.30	5.33
P. Safety distance reduction factor	**3.84**	**118.0**	**1**	**118.00**	**25.87**
Error		31.9	7	4.55	

F = CC0 (-1 = 0.5m; +1 = 3m)
L = accepted deceleration lane change veh (-1 = -3.5m/s^2; +1 = -0.5m/s^2)
P = safety distance reduction factor (-1 = 0.2; +1 = 0.8)

In the combined freeway segment, in order to reduce the number of factor combinations to be considered, a 1/32 fraction of a 2^{12-5} factorial design was implemented. The 1/32 fractional factorial experiment produces a design resolution IV and the recommended design generator for the experiment is of the form: $H = ABCDEFG; I = CDEFG; J = BDEFG; K = ADEFG; andL = BCEFG$. In this case, 128 runs to reflect the 2^{12-5} fractional factorial design and 1 run for the centre point were carried out. Additionally, each run was replicated four times with different random seeds to obtain greater accuracy for the estimated pure error.

This way, the full experiment comprised a total of 516 simulations. The application of factorial analysis reduced the 12 significant factors from the previous step to 4 first order effects: average desired speed (A), maximum look ahead distance (D), CC0 (E), and CC1 (F) and 7 second order interactions: AE, AF, DE, DF, EF, KJ, and HL.The linear expression relating CPI/veh ($x10^{-5}$) for the significant first and second order interactions in the coded space is:

$$\begin{aligned} CPI/veh(x10^{-5}) = 44.21 - 37.77(A) - 36.75(E) + 29.88(F) + 37.06(G) + \\ + 29.72(A)(F) - 34.40(A)(G) - 28.66(E)(F) - \\ - 29.77(I)(M) - 31.63(J)(P) \end{aligned} \tag{5.4}$$

where
A = average desired speed (-1 = 80km/h; +1 = 120km/h)
E = max. look ahead distance (-1 = 50m; +1 = 300m)
F = CC0 (-1 = 0.5m; +1 = 3m)
G = CC1 (-1 = 0.5m; +1 = 1.5m)
I = CC3 (-1 = -15; +1 = -4m)
J = CC5 (-1 = 0.1m; +1 = 2m)
M = accepted deceleration trailing veh (-1 = -2.5m/s^2; +1 = -0.25m/s^2)
P = safety distance reduction factor (-1 = 0.2; +1 = 0.8)

5.4.3 Best Estimate of Input Parameters - GA Procedure

In this step, Equations 5.3 and 5.4 were used to establish a mix of values that yields the average CPI/veh observed in the NGSIM vehicle tracking data for both off-ramp and combined freeway segments. The vehicle tracking data suggests target values of CPI/veh of 9.92x10^{-5} and 9.53x10^{-5} for the off-ramp and combined freeway cases, respectively.

The previously described optimization procedure based on genetic algorithms was applied for both off-ramp and combined segments. The best estimate VISSIM parameter values are summarized in Table 5.10.

For the off-ramp case, the inputs correspond to a simulated average CPI/veh of 1.05x10^{-4} slightly higher than the desired NGSIM target value of 9.92x10^{-5}. The average simulated number of vehicles in conflict (6.6) closely matched the NGSIM target value of 8. For the calibration data, the percentage error in the CPI/veh was found to be fairly low at about 5.7%.

For the combined on/off-ramp configuration, the inputs from Table 5.10 correspond to a simulated average CPI/veh of 8.27x10^{-5} slightly lower than the desired NGSIM target value of 8.85x10^{-5}. For the calibration data, the percentage error in the CPI/veh was found to be of 7%. The simulated average number of vehicles in conflict was 10.7 as compared to 20 in the NGSIM data.

Table 5.10: Genetic algorithm best estimates of inputs for freeway segment (Source: [93])

VISSIM parameters	Inputs (off-ramp)	Inputs (combined on/off-ramp)
Observed vehicles ahead	2*	2*
Safety distance factor	**0.46**	**0.76**
Desired average speed	**106.8**	**106.7**
Maximum look ahead distance	**114.13**	**243.97**
Acceptable deceleration of lane change vehicles	**-2.25**	-1.00*
Acceptable deceleration of trailing vehicles	0.00*	**-1.10**
CC0	**2.88**	**2.44**
CC1	0.90*	**1.09**
CC3	-8.00*	**-6.09**
CC5	0.35*	**1.88**

(*) default parameter

Despite the fairly good match between observed and simulated average turbulence (CPI/veh) in the two cases, the higher number of vehicles in conflict obtained from the vehicle tracking data suggests that the simulation may be underestimating high risk interactions in the freeway environment. Such a difference can be explained by:

1. The lack of network "continuity" in the simulation. Since the highway segment was only coded in the area of interest (640m), traffic shockwaves caused by downstream turbulence may not have been fully replicated in the simulation environment.

2. VISSIM lane change algorithms were not able to completely handle the dynamic and complex environment represented by the combined on/off highway lane configuration.

3. The main focus of the calibration was the CPI/veh and not the number of vehicles in conflicts. The latter was used as an additional criteria for choosing the best estimates in the GA procedure.

5.4.4 Validation of Selected Inputs

Using traffic conditions for the second 15-minute data sample and the input parameters as summarized in Table 5.10, the validation exercise yielded a "transferability error" of approximately 6% for the off-ramp case and -13% for the combined segment case for the CPI/veh safety measure. This suggests that the VISSIM input parameters obtained from calibration are indeed transferable to the validation vehicle tracking sample for the two geometric configurations considered in this analysis.

For the number of vehicles in conflict, the NGSIM data yield 10 and 17 conflicts for off-ramp and combined on/off-ramp segment respectively, while the simulation produced averages of 6.6 and 10.6 vehicles in conflict. This finding is consistent with the same underestimation of high risk situations by the simulation model observed in the calibration exercise for the freeway environment.

5.5 Major Findings

Microscopic simulation models are finding increased application in crash prediction and evaluation of safety performance. Before these models can be applied they must be calibrated based on real world traffic conditions. The main purpose of calibration is to ensure that parameter inputs in the simulation model produce best estimates of safety performance by minimizing residual error between simulated and observed values.

This Chapter presents a systematic and objective procedure for calibrating microscopic simulation models based on safety performance. Safety performance has been expressed in terms of a crash potential index (CPI) that relates deceleration rate required to avoid a crash (DRAC) to vehicle braking capabilities (MADR). The scope of the application is concerned with potential rear-end crashes at a signalized four-legged intersection and freeway segments. For the calibration, real-time vehicle tracking data extracted from the NGSIM study were used for a representative urban intersection and freeway segment.

Best estimates of simulation input parameters were obtained as a result of the calibration exercise. These input parameters yielded estimation errors between average and simulated CPI/veh to be fairly low (between 5.7% and 7%) for all traffic scenarios investigated.

In the validation exercise, the average simulated CPI/veh (obtained using best estimate input parameters) was compared to observed values from an independent sample of vehicle tracking data. In the intersection scenario, the observed CPI/veh was well within the 95% confidence interval of the simulated values. In the freeway scenario, the observed measures were found to be comparable to the values obtained from the simulation (transferability errors between 6% and 13%). This suggests that the model is able to replicate safety performance as reflected in rear-end crash potential for a sample of vehicles that were not part of the calibration exercise.

The reasonably consistent match between observed and simulated average turbulence (CPI/veh) was not observed for the average number of vehicles in conflict, especially for the freeway segment. In this case, the simulation appears to underestimate high risk interactions ad this can be due to: 1) The lack of network "continuity" in the simulation may have limited the simulation environment and therefore traffic shockwaves caused by downstream turbulence may not have been fully replicated, 2) VISSIM lane change algorithms were not able to completely handle the dynamic and complex environment represented by the combined on/off highway lane configuration, and 3) The main focus of the calibration was the CPI/veh and not the number of vehicles in conflicts. The latter was used as an additional criteria for choosing the best estimates in the GA procedure.

The results of this analysis focus only on the accuracy and reproducibility of the simulated output (CPI) and not on the ability of this performance measure to reflect actual crashes. However, with an accurate estimate of CPI from the simulation it would be possible to compare simulated safety performance to observed crashes or high risk situations. This not only underscores the value of the simulation model but also the need to provide accurate and reliable outputs that have been verified based on real world conditions.

The following Chapter describes three tests performed to establish a link between simulated safety measures as obtained by the calibrated model and observational data that reflects high risk behaviour in the traffic stream.

Chapter 6

Linking CPI to High Risk Behaviour

6.1 Introduction

Unlike conventional empirical models of crash prediction, safety performance measures have not been adequately linked to observational crash occurrence. Researchers have argued that such a link is a necessary step to enhance the scope of safety performance measures as surrogates for collisions in road safety studies [40, 95, 104]. There are essentially two reasons why safety performance has not been adequately linked to crash occurrence:

1. Such a link has been deemed to be unnecessary, since most high risk events that compromise safety at a given site may not be identified in the reported crash data. Reported crashes can actually be viewed as a small "unlucky" subset of relevant high risk events, which by their very nature represent a narrow somewhat biased view of the larger safety problem. Lack of safety can only be expressed from a thorough mechanistic understanding of complex driver relationships and the road and traffic environment being faced. This is clearly outside the scope of conventional empirical crash prediction models.

2. Even taking the position that validation of high risk behaviour in observational crash data is an important step in accepting safety performance measures, the task of establishing a reliable link can be quite challenging. The nature of safety performance is both disaggregate (based on individual driver responses and actions) and temporal (varying with changes in traffic conditions over time at a given location). Hence, any objective link to crash occurrence must be mindful of traffic conditions "**prior**" to the crash itself. These conditions would have caused the crash but are not readily available in historical crash databases.

This Chapter describes an objective approach for linking safety performance to observed crash occurrence. The underlying premise in this approach is that if safety performance reflects high risk behaviour and crashes are caused by such behaviour, then these crashes should be taking place when safety performance is low (higher crash risk). This needs to be established for the period preceding each crash. Conversely, it is expected that in non-crash situations this measure would be closer to the average for the prevailing traffic conditions and location.

6.2 Simulation Test Framework

Three tests were proposed for exploring the link between simulated safety performance and observed crash occurrence for a period preceding the crash. These tests were applied to a sample of crash and non-crash data extracted from an instrumented freeway segment in Toronto. It is worth mentioning that the primary focus this application concerns the safety performance for rear-end vehicle interactions. The three tests can be summarized as follows:

- Test 1: compare safety performance measures in 1 minute increments for a period five minutes prior to the time of the crash.
- Test 2: compare safety performance measures in aggregated 1 minute increments over five minutes prior to the crash and compare this to non-crash results for the same location and traffic volumes.
- Test 3: compare average safety performance measures to crash rate observed over a one hour period at the same site.

Test 1 investigates temporal variations in traffic turbulence in 1 minute time intervals for a period of 5 minutes before the crash. The basic assumption here is that in situations where traffic conditions played a major role in the crash, an increase in observed traffic turbulence can be verified as the precise time of the crash is approached. This increase in traffic turbulence is estimated in "real-life" by average speed and vehicle spacing as well as speed variance as obtained from loop detectors. If one can replicate these conditions in the simulation environment and simulated CPI/veh can capture the increase in turbulence as the time of the crash is approached, then CPI/veh could be applied as a surrogate measure for high risk situations that lead to crashes.

In Test 2, the safety performance 5 minutes prior the crash is compared to the safety performance of the same freeway segment using "normal" traffic attributes; i.e. speed and volume profiles obtained when no crash occurred. It is expected that the CPI/veh estimated from the crash situation is significantly higher than the CPI/veh obtained under "normal" conditions.

Test 3 attempts to link the traffic turbulence simulated over a 1-hour period to the observed hourly crash rate in the same freeway segment. It is hypothesized that the traffic pattern aggregated over 60 minutes is directly related to the observed long term crash rate at the same location.

The framework for linking safety performance to crash occurrence is illustrated in Figure 6.1. The framework consists of several steps: 1) Preparing an integrated database of crash occurrence with corresponding real-time traffic information from loop detector station counts, 2) Estimating the precise time of the crash from speed profiles at upstream and downstream detectors, 3) Pre-simulation matching of observed volume and speeds at both upstream and downstream detectors, 4) Estimating safety performance measures for crash and non-crash events at the same location for similar traffic conditions, and 5) Comparing the results for the three tests.

6.3 ADS-IFTMS Data Integration

Step 1 is concerned with incorporating real-time traffic features extracted from instrumented loop detector data with detailed information on the crash itself (time and location, etc). The data used in this analysis was extracted from an instrumented segment of the Queen Elizabeth Way (QEW) west of Toronto. This segment of QEW extends for 19km along the north shore of Lake Ontario from Royal Windsor Drive to Highway 427 (Figure 6.2).

Traffic and crash data were extracted from the combination of two separate databases, namely the Accident Data System (ADS) and the IFTMS incident data log. The ADS is a compilation of accidents reported by the police and administered by the Ministry of Transportation of Ontario (MTO). Speed, volume and occupancy values were obtained from IFTMS loop detector counts aggregated in 20-second time slices. The QEW segment in this study comprises a total of 50 loop detector stations.

The IFTMS system also provides information on incidents with visual verification to establish if these incidents can be classified as crashes. Crash logs from IFTMS were matched to the loop detector traffic data and detailed information on each crash as reported in the ADS database. The integration of data from the IFTMS and ADS systems provides the connection between real-time traffic conditions on the QEW near the time of the crash and the attributes of the crash itself.

Freeway segments directly affected by on/off-ramps (i.e. first upstream and downstream loop detectors from its entry/exit points) where excluded from the analysis given that these segments have a more complex environment to be simulated with respect to safety. Figure 6.3 illustrates the loop detector stations considered for the proposed tests. Furthermore, crashes that have occurred on weekends

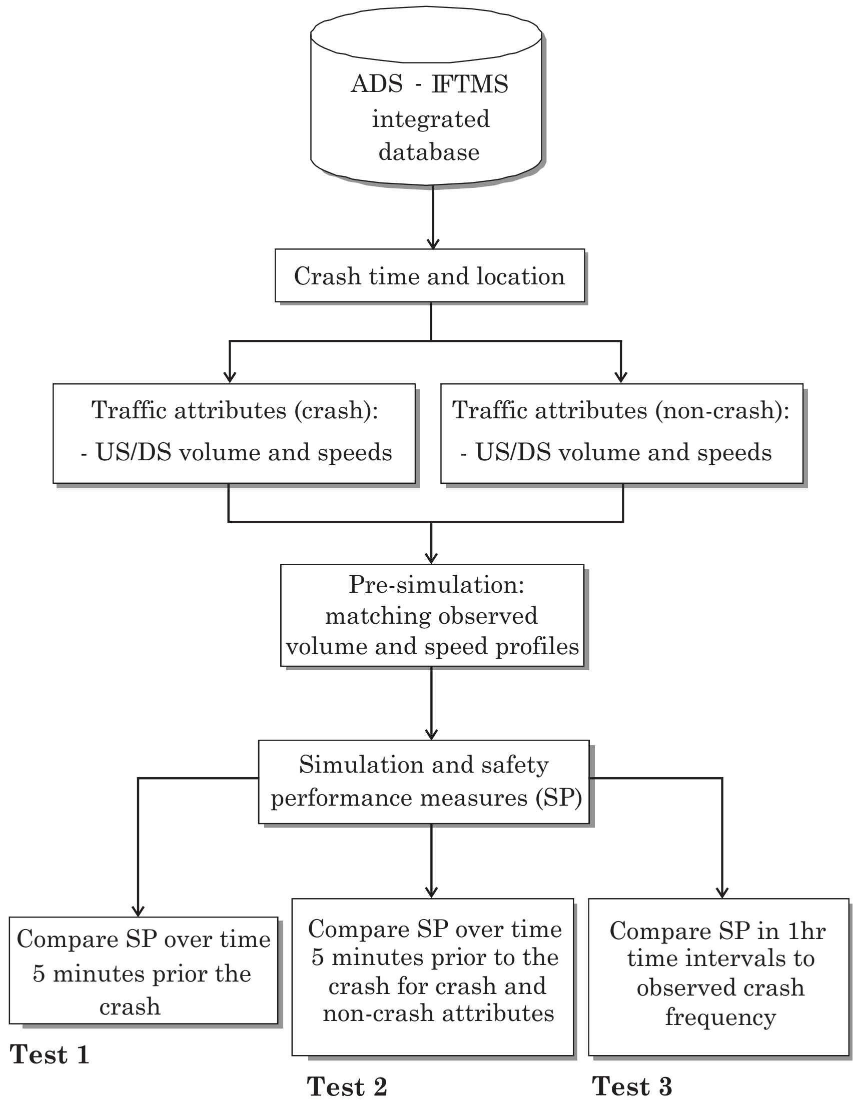

Figure 6.1: Framework for linking safety performance to crash occurrence

Figure 6.2: Study site along QEW (Source: [51])

or with adverse road surface conditions (other than dry) or adverse light condition (other than daylight) were also excluded from the dataset. It is understood that additional calibration/validation would be needed to reasonably simulate these conditions.

6.4 Estimating the Precise Time of the Crash

The initial procedure for estimating the precise time of the crash was developed in a research by Corby [27]. The crash time was estimated to be the time of maximum speed reduction for each crash at the first upstream detector minus an approximate time it takes the crash shockwave to propagate back from the crash location to this detector. Lee et al. [56] found the expected interval between the time the shockwave reaches the first US detector and the time of the crash to be between 2 to 3 polling intervals (40 to 60 seconds).

Figure 6.4 illustrates the visual procedure used to determine the precise time of the crash (crash number 118) using observed IFTMS speed profiles. The maximum speed reduction at the first US loop detector takes place during the interval 16:51:00 and 16:53:00. The earliest estimate for the shockwave arrival time at this point is 16:51:00. For crash number 118, the estimated time of the crash is between 16:51:40 and 16:52:00. A similar line of reasoning was applied to the other crashes in the IFTMS/ADS sample. For the QEW segment, Ibarrola [51] investigated a total of 297 observed crashes and estimated the "precise" time of each crash based on loop detector speed profiles.

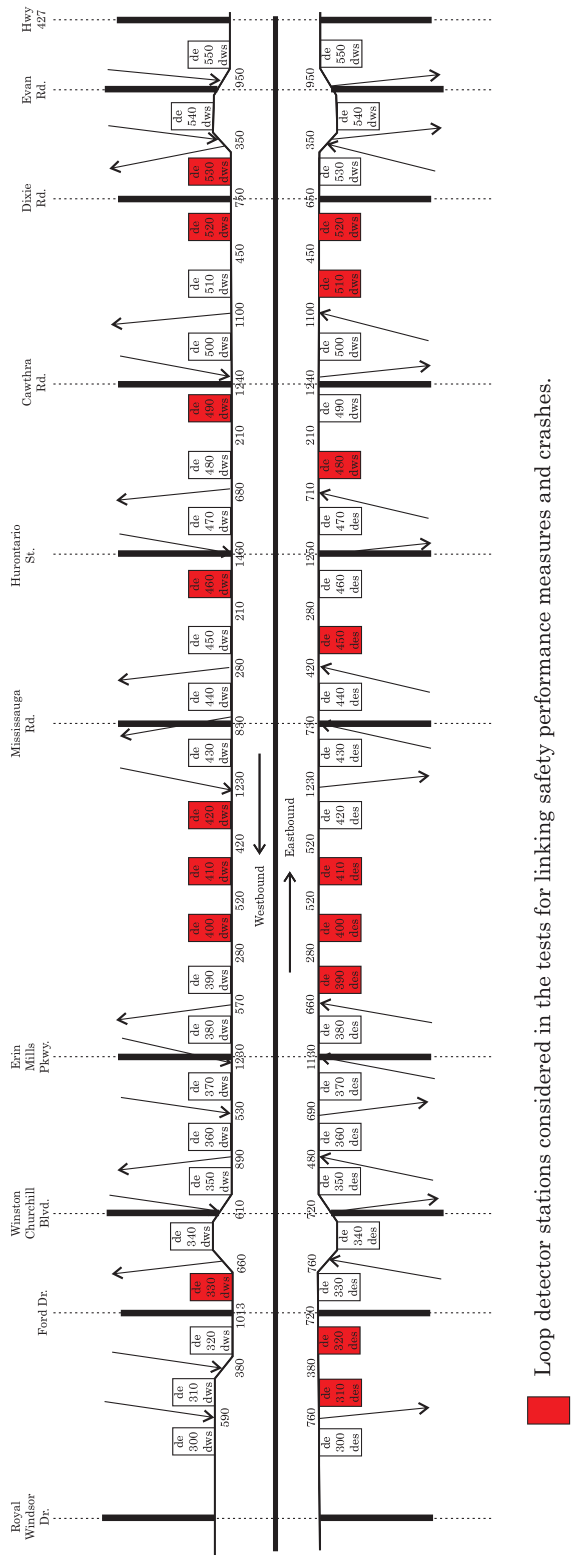

Figure 6.3: Loop detector stations in QEW segment

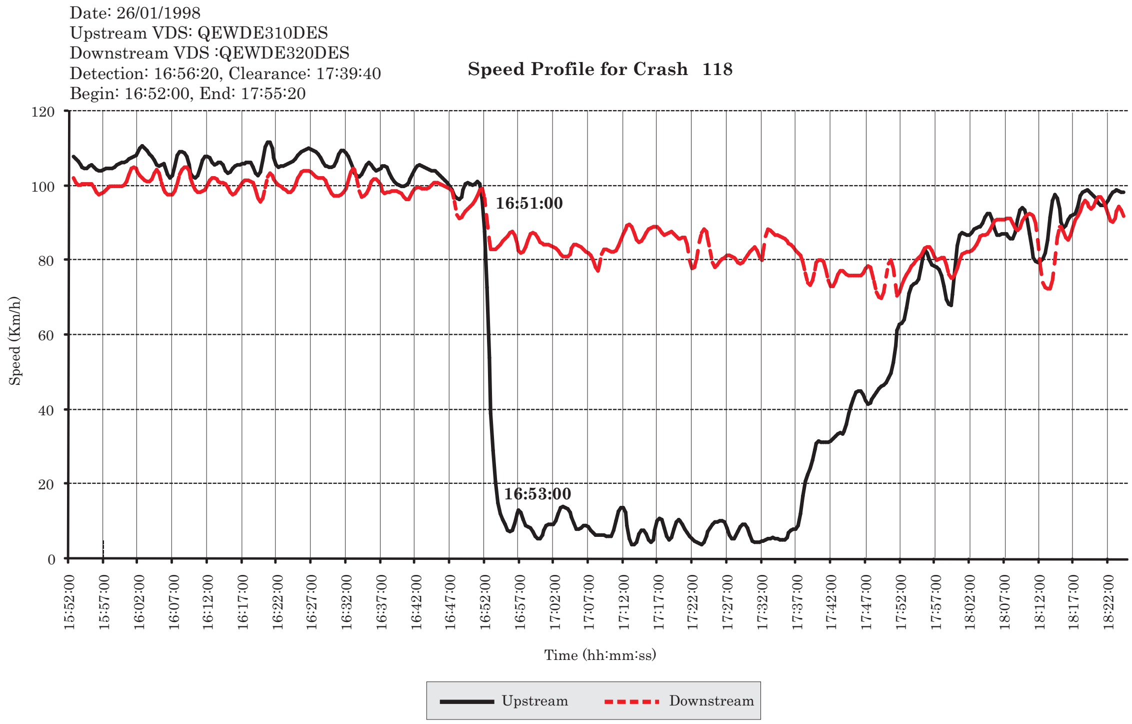

Figure 6.4: Speed profile for crash 118

6.5 Pre-simulation: Matching Observed Traffic Attributes at Loop Detectors

For all three tests, a pre-simulation phase is performed to ensure that simulated volume/speed profiles obtained at both upstream (US) and downstream (DS) detectors match those observed in the IFTMS data. The pre-simulation attempts to precisely match space headways and speeds at the moment vehicles enter in the simulation (upstream loop detector) and to provide similar downstream environment as observed in the field. Obviously, a perfect match of speed/spacing inside the area of interest (between the two loop detectors) cannot be verified since this would require individual vehicle tracking data not available for crash occurrences.

In all tests, the observed US flow rate was used as initial input in the simulation and the other variables (US speed and DS flow rate and speed) were recorded and compared with observed data. As expected, as the traffic regime approached the capacity, identified by reasonably high flow rate with medium to low speeds, the input volume alone was not enough to replicate the somewhat complex driving pattern observed in the field. To improve the matching process in those cases, "artificial" congestion was created in the area downstream of the DS detector to account for the discontinuity in the network. The congestion was imposed with a function in VISSIM called "reduced speed areas" using speeds as observed in the downstream loop detector station. To ensure that the system (US and DS) was operating in a similar traffic regime, variable warm-up periods from 5 to 15 minutes were allowed to stabilize the flow.

The 10 best estimate simulation seeds were chosen after 1000 initial simulation runs using volume at the upstream detector and speed at the downstream detector as initial traffic attributes. These 10 best seeds were selected by considering the root mean square percentage error (RMSP) for volume and speed measurements at the two loop detectors corresponding to each situation. The RMSP error expression is of the form:

$$RMSP = \sqrt{\frac{1}{n}\sum_{n}^{i=1}\left(\frac{x_i - y_i}{y_i}\right)^2} \tag{6.1}$$

where
x_i, y_i = simulated and observed traffic measurement (volume and speed) for time interval i

For test 1, target volumes and speeds as reported in the IFTMS data (for crash situations) were obtained as the average aggregated every minute for both downstream and upstream loop detectors. In Test 2 for the non-crash case, a sample of 12 days was obtained at the same location during which time no crash was observed. One weekday for each month of the year was randomly selected and target volumes and speeds were estimated by averaging the 12 values for each of the five 1-minute intervals. A total of 1000 RMSP values were obtained and the 10 lowest values were used to establish the 10 best number seeds. For Test 3, the same sample used for the non-crash case was applied to obtain the 10 best number seeds, but in this case, volume and speeds were aggregated in twelve 5-minutes intervals.

A sample of 34 crashes was found for the selected loop detector stations meeting the weekend, dry pavement, and daylight criteria. For 7 crash attributes, the volume/speed information could not be reasonably matched (average RMSP $\leq$ 20%) and therefore these crashes were excluded from the data set. The best number seeds and respective RMSP for the 27 crash and non-crash traffic attributes are summarized in Appendix C and D respectively. For test 3, two locations were investigated from 6:00AM to 6:00PM and the best number seeds with their respective RMSP are presented in Appendix E.

In general, for the 27 crash and non-crash cases considered in this exercise, RMSP values were found to be in the range between 3% and 18% respectively for Tests 1 and 2. It should be noted that for Test 1 only crash conditions were considered. For Test 3, the RMSP value was found to be in the range 2% to 20%. As expected, during peak periods the average RMSP values were found to be higher than those obtained for off-peak periods since the traffic is subjected to a more unstable and therefore less predictable regime.

6.6 Test 1 Simulation Results

The time interval 5 minutes prior to each crash was assumed to be an appropriate interval during which changes in traffic conditions would have a direct effect on crash occurrence. The two principal factors affecting traffic flow were assumed to be volume (vph) and speed (km/h).

Based on the 10 best number seeds, the CPI/veh was estimated and averaged for each one minute time increment. The profiles for this performance measure were established for each crash event 5 five minute prior to its occurrence. In this Test, increased crash risk is reflected through increases in the corresponding simulated performance measure (CPI/veh). It is expected that as the time of the crash is approached, the values of CPI/veh will increase, reflecting increases in traffic turbulence and corresponding crash risk.

As summarized in Table 6.1, an increase in average CPI/veh with time to crash was found to occur in 21 of the 27 crashes sampled. A single factor analysis of variance performed using values from Table 6.1 revealed that the time to crash has a significant effect on CPI/veh (p-value = 0.003). These results suggest that the average CPI/veh for the traffic stream prior to the crash provides an indication of increased crash risk. The increase in crash risk appears to be especially pronounced for the period between the first and second minute prior to the crash (Figure 6.5).

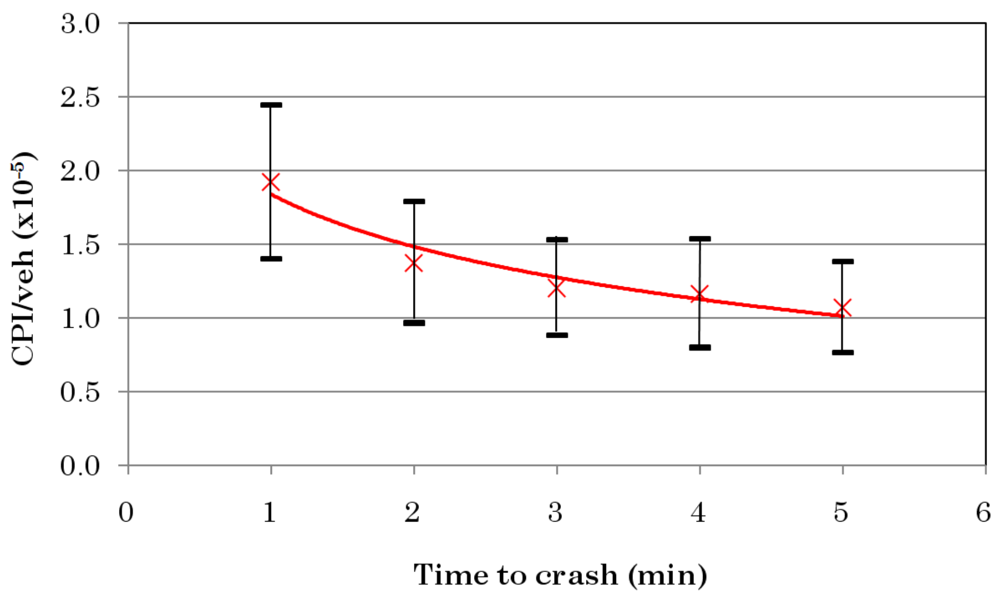

Figure 6.5: CPI/veh average and 95% confidence interval - Test 1

Table 6.1: Simulated CPI/veh Values Over Time - Test 1

Crash #	CPI/veh (x10^{-5}) - Time intervals prior the crash					Highest CPI time
	0-1min	1-2min	2-3min	3-4min	4-5min	
	1	2	3	4	5	
118	1.08	0.89	1.38	1.50	1.42	4
170	1.79	1.49	1.19	0.90	0.80	**1**
222	0.76	0.82	1.00	0.89	1.13	5
223	0.58	0.59	0.59	0.66	0.65	4
239	1.03	0.00	0.13	0.00	0.00	**1**
320	4.29	1.90	1.13	1.10	0.75	**1**
371	0.88	0.74	0.58	0.55	0.60	**1**
405	1.15	0.96	0.98	0.84	0.64	**1**
454	1.36	0.74	0.71	0.75	0.83	**1**
455	1.74	1.42	1.22	0.92	0.80	**1**
478	4.01	1.20	1.22	1.50	0.60	**1**
521	1.04	0.72	0.60	0.70	0.83	**1**
522	0.73	0.89	0.98	0.96	1.01	5
571	2.22	1.02	1.21	1.08	1.05	**1**
595	2.23	2.98	3.50	4.20	2.37	4
647	1.11	0.91	0.74	0.86	0.81	**1**
688	2.72	2.44	1.86	2.27	2.65	**1**
702	4.42	3.67	1.90	1.68	1.58	**1**
710	1.50	0.94	0.77	0.68	0.67	**1**
731	3.16	3.27	2.39	2.01	1.77	2
739	2.58	0.93	1.02	0.89	0.88	**1**
781	0.91	0.75	0.66	0.59	0.71	**1**
854	1.26	0.98	0.92	1.08	1.14	**1**
858	0.98	0.79	0.65	0.63	0.48	**1**
884	3.03	2.41	2.24	2.23	2.94	**1**
888	2.18	1.44	1.90	1.33	1.18	**1**
903	3.10	2.22	1.02	0.65	0.64	**1**
Average	**1.92**	**1.37**	**1.20**	**1.16**	**1.07**	
Std. Dev:	**1.14**	**0.90**	**0.71**	**0.80**	**0.67**	

6.7 Test 2 Simulation Results

In this Test, safety performance measures (CPI/veh) were simulated for traffic conditions found to be present at the crash location (US and DS detectors) 5 minutes prior to the crash and for comparable non-crash conditions at the same road segment. It is expected that safety performance between crash and non-crash cases would differ, such that crashes are more likely to occur when the CPI/veh profiles are higher than normal for the same 5 minute interval.

Table 6.2 summarizes the CPI/veh values for the 27 sample crashes with their corresponding non-crash situations. The values are given in cumulative 1 minute increments 0 to 5 minutes prior to the crash. As noted previously, these measures of safety performance were obtained by averaging the results from 10 separate simulation runs with their respective number seeds.

Table 6.2: Simulated CPI/veh Values Over Time - Test 2

ID	CPI/veh ($x10^{-5}$) - Crash					CPI/veh ($x10^{-5}$) - Non-crash				
	0-1min	0-2min	0-3min	0-4min	0-5min	0-1min	0-2min	0-3min	0-4min	0-5min
118	1.08	1.29	1.19	1.17	1.20	1.81	1.55	1.51	1.39	1.49
170	1.79	1.64	1.54	1.39	1.26	0.92	0.82	0.83	0.76	0.77
222	0.76	0.73	0.79	0.76	0.82	1.41	1.00	0.87	0.86	0.88
223	0.49	0.50	0.52	0.56	0.59	1.11	0.94	1.11	1.01	0.96
239	1.03	0.83	0.76	0.79	0.76	0.68	0.71	0.69	0.70	0.68
320	4.29	3.03	2.16	1.92	1.64	0.69	0.73	0.76	0.72	0.74
371	0.88	0.67	0.66	0.65	0.67	0.75	0.70	0.73	0.76	0.77
405	1.15	1.03	0.93	0.90	0.91	1.50	1.33	1.27	1.30	1.22
454	1.36	0.98	0.89	0.82	0.80	0.94	0.95	0.92	0.91	1.00
455	1.74	1.53	1.39	1.25	1.17	1.81	1.64	1.69	1.59	1.58
478	4.01	3.20	2.69	2.46	2.24	0.97	0.84	0.79	0.75	0.76
521	1.04	0.80	0.72	0.70	0.74	0.97	0.99	1.04	1.11	1.09
522	0.73	0.80	0.87	0.89	0.89	0.82	0.78	0.80	0.75	0.78
571	2.22	2.26	2.36	2.72	3.00	1.90	1.80	1.77	1.78	1.71
595	2.23	2.25	1.98	1.92	1.98	0.53	0.46	0.53	0.56	0.56
647	1.11	0.97	0.87	0.92	0.89	0.91	0.80	0.93	0.96	0.90
688	2.72	2.50	2.29	2.35	2.33	1.24	1.23	1.27	1.27	1.23
702	4.42	3.78	2.94	2.48	2.08	1.34	1.23	1.15	1.15	1.13
710	1.50	1.14	0.99	0.89	0.84	0.80	0.73	0.71	0.71	0.71
731	3.16	2.42	1.95	1.76	1.60	1.71	1.58	1.56	1.49	1.40
739	2.58	1.83	1.58	1.40	1.34	1.02	0.91	0.89	0.86	0.90
781	0.91	0.82	0.86	0.89	0.84	0.65	0.63	0.66	0.70	0.71
854	1.26	1.10	1.11	1.13	1.14	0.99	1.00	0.96	0.98	1.00
858	0.98	0.75	0.70	0.66	0.62	0.65	0.71	0.72	0.68	0.71
884	3.03	2.61	2.38	2.45	2.26	1.22	1.33	1.44	1.42	1.44
888	2.18	2.11	1.91	1.78	1.69	1.85	1.59	1.53	1.49	1.47
903	3.10	3.07	2.36	1.97	1.70	1.25	1.17	1.05	1.04	1.04
Average	**1.92**	**1.65**	**1.46**	**1.39**	**1.33**	**1.13**	**1.04**	**1.04**	**1.03**	**1.02**
Std. Dev:	**1.14**	**0.94**	**0.73**	**0.68**	**0.64**	**0.41**	**0.36**	**0.35**	**0.33**	**0.32**

A simple ANOVA was carried out on the above values with the results given in Table 6.3. These results suggest that CPI/veh between crash and non-crash differed from each other at the 5% level. We note that when crash and non-crash cases are combined the time measure has almost no effect on safety performance. This is because there is a dampening effect caused by the cumulative measure of time and by the combination of crash and non-crash observations in the same sample. This is illustrated with reference to Figure 6.6 for crash and non-crash cases respectively. In Figure 6.6 the CPI/veh is reduced with increases in cumulative time to crash for crash conditions, whereas in the non-crash case, no change in the CPI/veh was observed over time. The average CPI/veh for attributes is visually compared with the 95% confidence interval for CPI/veh estimated using non-crash attributes in Figure 6.7.

6.8 Test 3 Simulation Results

As discussed previously, the fundamental hypothesis underlying the proposed safety model is that for a given road segment interactions between geometric attributes and traffic characteristics lead to traffic turbulence that can be expressed in terms

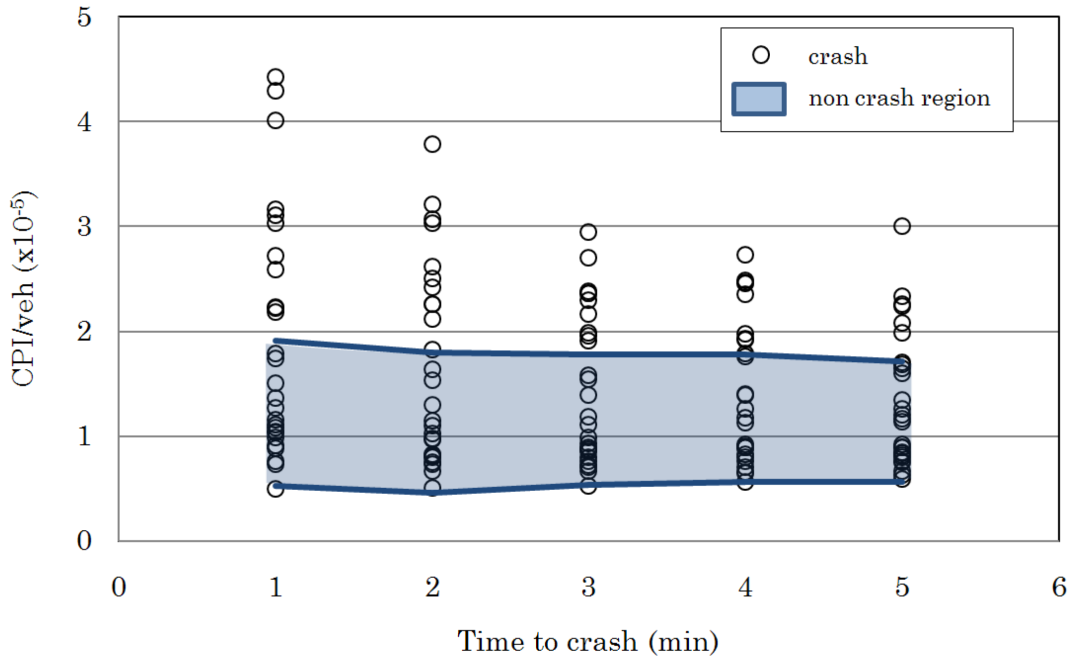

Figure 6.6: CPI/veh versus cumulative time to crash for crash and non-crash conditions - Test 2

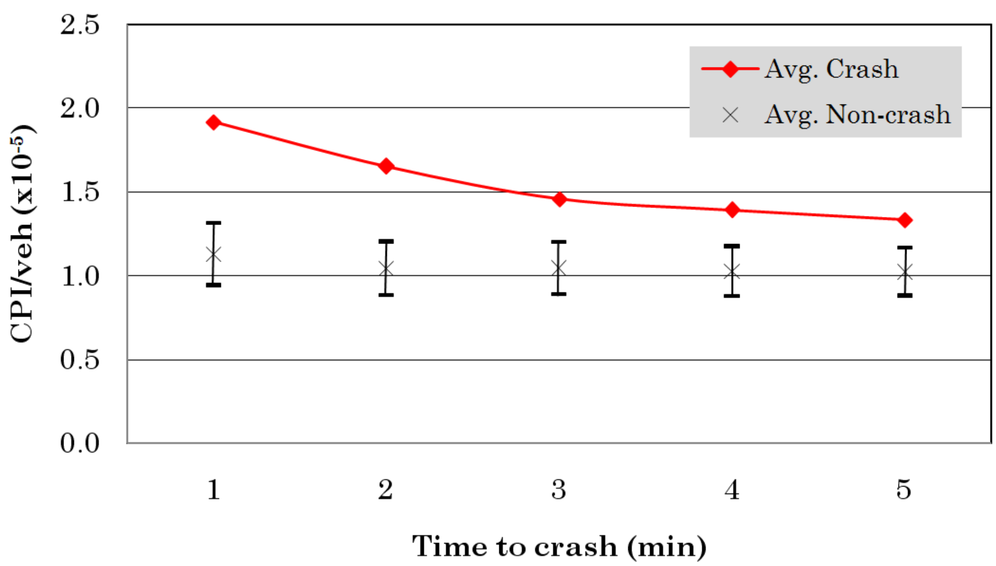

Figure 6.7: Average CPI/veh for crash and non-crash attributes - Test 2

Table 6.3: Two-Way ANOVA Results for Test 2

Tests of Between-Subjects Effects
Dependent Variable: CPI_veh

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Crash	16.78	1	16.78	39.74	0.00
Time	4.17	4	1.04	2.47	0.05
Crash * Time	2.12	4	0.53	1.25	0.29
Error	109.75	260	0.42		
Total	590.12	270			

of vehicle interactions. These vehicle interactions can be measured by safety performance measures such as CPI. Since crash occurrences are considered a sub-sample of events in the vehicle interactions "population", a link between safety performance measures and crashes should be possible in some degree.

Test 3 investigates the link between simulated safety performance and crash rates aggregated in periods of 1 hour. This test attempts to address two important questions regarding CPI/veh and observed crashes as follows: 1) Is there a positive correlation between simulated safety measures and crashes? (i.e., average CPI/veh increases with increasing number of crashes) and 2) Is there a relative validity between simulated safety measures and crash rates over time? (i.e., CPI/veh variations over 1-hour periods are consistent with crash rate changes for a given road segment).

Four years of crash data (1998-2001) for two segments of the QEW freeway extracted from Toronto ADS were used in Test 3. The freeway segments in this analysis are between loop detectors 410des and 420des (segment A) and 450des and 460des (segment B) with 710m and 688m in length respectively. Crash rates were estimated for twelve 1-hour period from 6am to 6pm for every segment. It was assumed that volume and speed profiles obtained in the pre-simulation phase for non-crash attributes are representative of typical traffic attributes for weekdays under good conditions (dry pavement) and therefore, crashes that happened during weekends,under adverse weather and light conditions were excluded from the dataset. Table 6.4 summarizes crash rate estimates for every 1-hour period investigated.

As suggested in Test 2, the CPI/veh estimated one minute prior the crash (CPI_{t-1}/veh) was found to be significantly higher when traffic attributes corresponding to crash conditions were applied than when "normal" traffic conditions were simulated. Thus, this can be used as a threshold for defining high levels of turbulence in the traffic stream where crash occurrences are more likely to occur. Using the results from Test 2, the threshold to define high level turbulence intervals (HLTI) can be established by using the average CPI_{t-1}/veh of $1.92\text{x}10^{-5}$.

Table 6.4: Crash rates for QEW segments A and B

1-hour period		Segment A			Segment B		
		Vol (vph)	Crashes	Crash Rate (10^6 vehicles.km)	Vol (vph)	Crashes	Crash Rate (10^6 vehicles.km)
6:00	7:00	4977	1	0.208	5335	4	0.870
7:00	8:00	4069	4	1.020	5116	5	1.135
8:00	9:00	3922	4	1.058	5141	5	1.129
9:00	10:00	4374	1	0.237	5115	5	1.135
10:00	11:00	4206	1	0.247	4621	3	0.754
11:00	12:00	4055	0	0.000	4426	0	0.000
12:00	13:00	3877	2	0.535	4231	0	0.000
13:00	14:00	3734	1	0.278	4050	1	0.287
14:00	15:00	3840	2	0.540	4155	2	0.559
15:00	16:00	4246	0	0.000	4603	0	0.000
16:00	17:00	4758	1	0.218	5111	1	0.227
17:00	18:00	5016	0	0.000	5406	3	0.644
Total:			17			29	
Length(m):			770			688	
Days (1998-2001):				1252			

Applying best number seeds as determined in the pre-simulation step, 10 simulations were performed for the twelve 1-hour periods for each segment (a total of $12x2x10 = 240$ runs). Three safety measures were recorded from the simulation as follows: 1) The average CPI/veh aggregated over 1 hour (CPI$_{1hr}$/veh), 2) The average CPI/veh aggregated over 1 minute (CPI$_{1min}$/veh), and 3) The average number of simulated HLTI. The average CPI/veh represents the average turbulence of the traffic stream and the HLTI frequency captures unacceptably high turbulence periods (1 minute).

Table 6.5 summarizes the average results obtained for CPI/veh and HLTI frequency and rate for the 10 simulation runs. Initially, simple linear regressions were attempted to provide a link between CPI/veh (averaged over 1hour and over 1minute) and HLTI rate to observed crash rate.

Figures 6.8 and 6.9 show the linear trend for CPI/veh averaged over 1-hour and crash/rate for segments A and B respectively. These figures indicate positive correlation for both segments with R-squares of 0.76 and 0.39 for segment A and B respectively. When using CPI/veh values estimated over 1-minute both correlations yielded higher R-square values (0.80 and 0.41) suggesting that, CPI/veh aggregated over 1-minute time interval would better represent aggregated crash rates for the sites investigated.

Similar linear regression models were developed considering the HLTI rate and crash rate (Figures 6.10 and 6.11). As described previously, this safety measure captures the frequency of time intervals the traffic turbulence observed in the system surpasses the threshold for high risk situations ($CPI_{1min}/veh = 1.92x10^{-5}$)

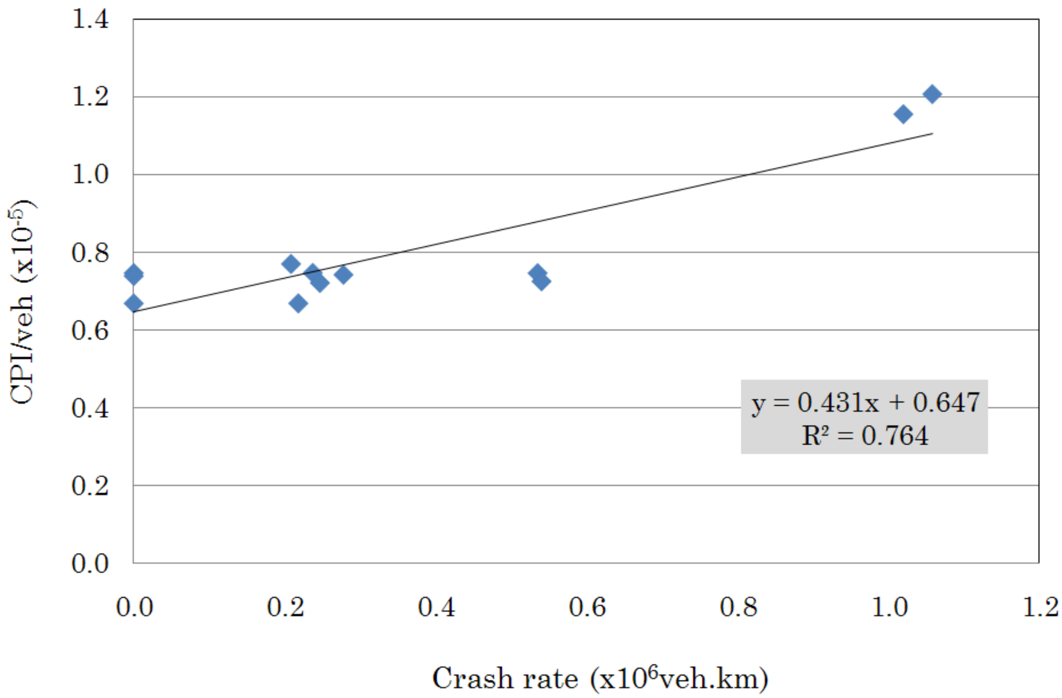

Figure 6.8: CPI/veh and crash rate for segment A

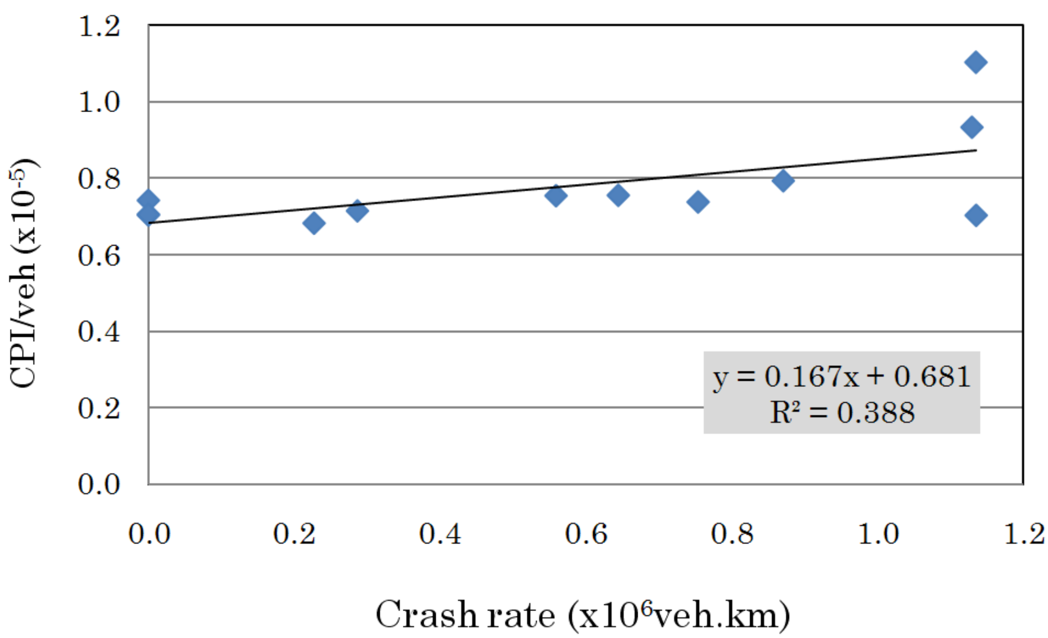

Figure 6.9: CPI/veh and crash rate for segment B

Table 6.5: CPI/veh and HLTI results for segments A and B

Time		Segment A					Segment B				
		CPI/veh (x10^{-5})		HLTI			CPI/veh (x10^{-5})		HLTI		
		1hr	1min	Avg/hr	Total (*)	Rate(**)	1hr	1min	Avg/hr	Total (*)	Rate(**)
6:00	7:00	0.77	0.79	0.8	1002	188.3	0.79	0.89	1.6	2003	401.3
7:00	8:00	1.15	1.15	2.4	3005	711.3	1.10	1.13	2	2504	482.5
8:00	9:00	1.21	1.20	3.3	4132	944.5	0.93	0.97	1.5	1878	352.5
9:00	10:00	0.75	0.82	0.5	626	128.5	0.70	0.79	1.1	1377	289.0
10:00	11:00	0.72	0.79	0.5	626	154.5	0.74	0.82	0.8	1002	250.0
11:00	12:00	0.75	0.83	1.3	1628	416.9	0.70	0.77	0.4	501	129.9
12:00	13:00	0.75	0.82	1	1252	320.7	0.74	0.84	0.8	1002	272.5
13:00	14:00	0.74	0.80	1.4	1753	469.7	0.71	0.81	1.5	1878	533.9
14:00	15:00	0.73	0.81	1.1	1377	381.6	0.75	0.84	0.8	1002	277.9
15:00	16:00	0.74	0.76	0.4	501	135.1	0.70	0.78	0.6	751	188.6
16:00	17:00	0.67	0.77	0.4	501	108.8	0.68	0.78	0.2	250	56.5
17:00	18:00	0.67	0.75	0.4	501	103.1	0.75	0.84	1	1252	268.1

(*) expected HLTI for the period of 1998-2001
(**) in 10^6veh.km

normalized with respect to exposure. These regression models also indicated a positive correlation between HLTI and crash rate for both segment A and B with R-squares of 0.70 and 0.55 respectively.

The ability of simulated average CPI/veh and HLTI rate to account for temporal variations in crash rate according to traffic conditions (relative validity) is graphically represented throughout Figures 6.12 to 6.15. In general, these Figures suggest that both CPI/veh and HLTI rate were reasonably sensitive to variations in traffic flow attributes per hour for both segments investigated. Furthermore, a fairly good level of consistency between the two safety performance measures and crash rates for different 1-hour periods for both segments A and B was obtained. This suggests that the simulated safety measures have a good mapping with aggregated measures of crashes, i.e. these safety performance indicators tend to be high for periods when observed crash rates were also high and *vice-versa*.

Discrepancies verified in both linear regression and relative validity plots are likely to be due the following factors:

- The very rare and random nature of crashes that produces large variability in observational data.
- Situations where “artificial” congestion was necessary in the pre-simulation phase may have introduced additional differences between the simulated and real world environments, which may have influenced the results.
- The aggregation time for the study (1 hour) was somewhat arbitrary and, in reality, there is not such rigid distinction in traffic flow regimes. A more narrow time interval aggregation can produce better results.

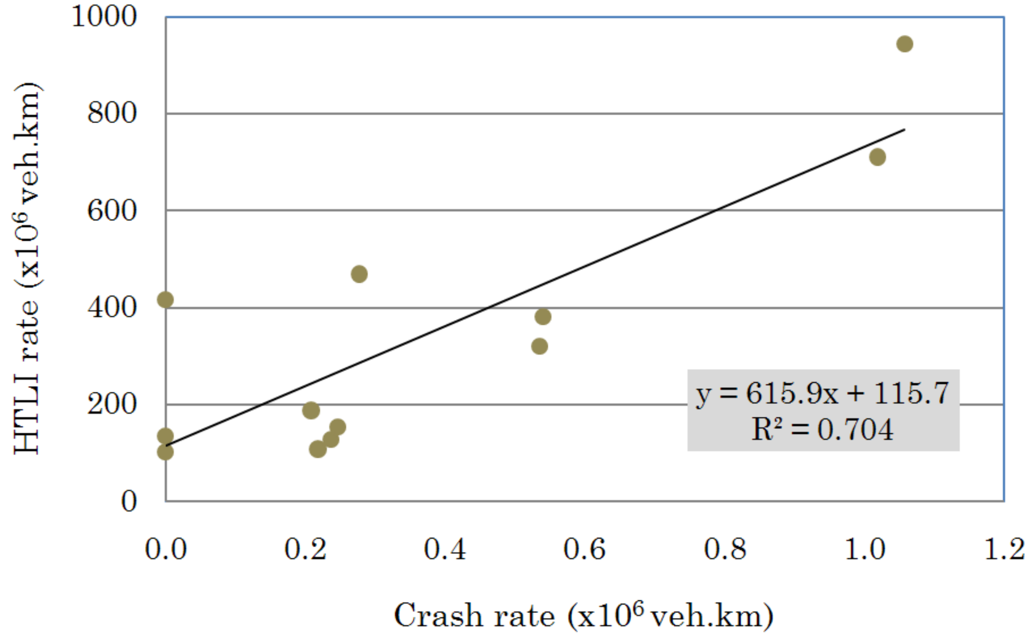

Figure 6.10: HLTI and crash rate for segment A

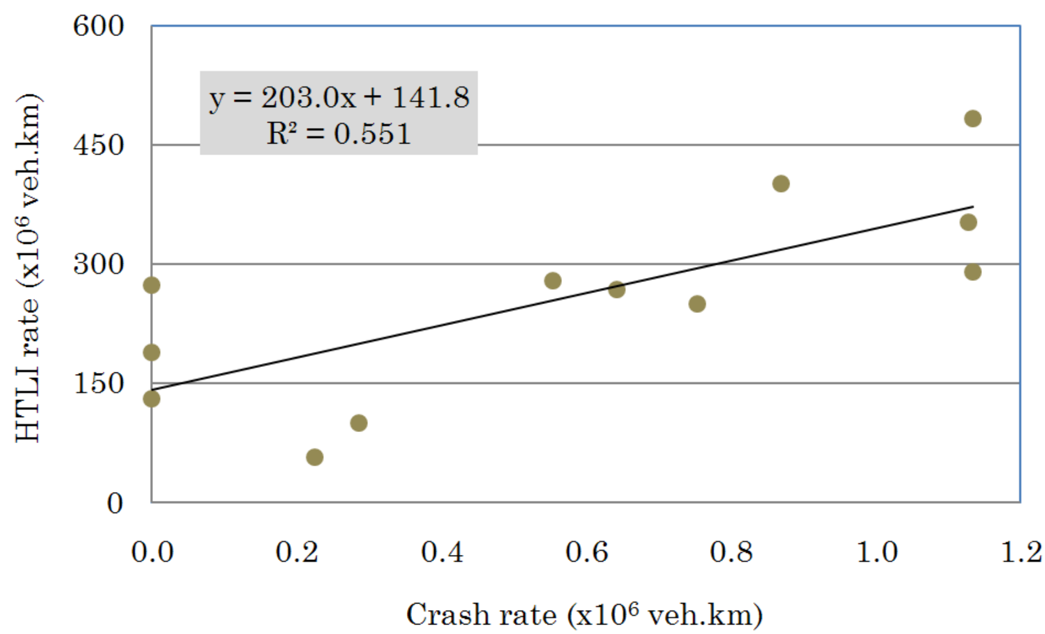

Figure 6.11: HLTI and crash rate for segment B

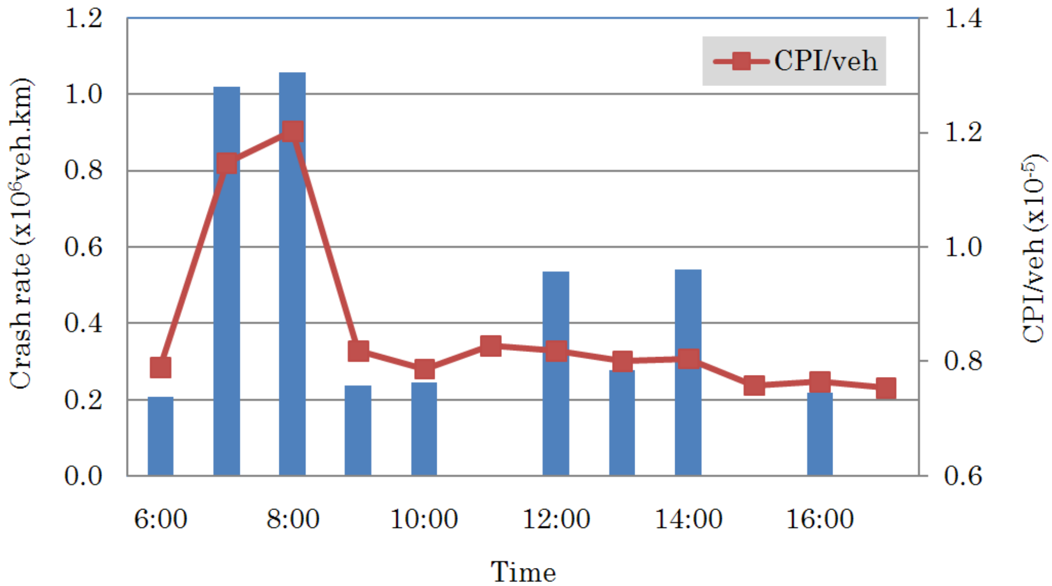

Figure 6.12: CPI/veh and crash rate over time for segment A

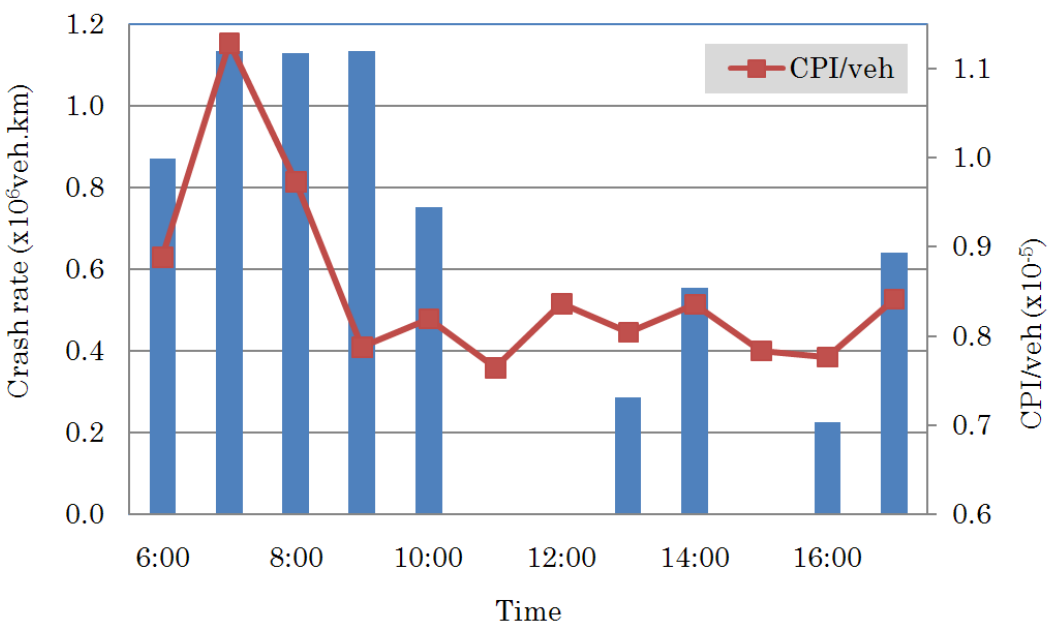

Figure 6.13: CPI/veh and crash rate over time for segment B

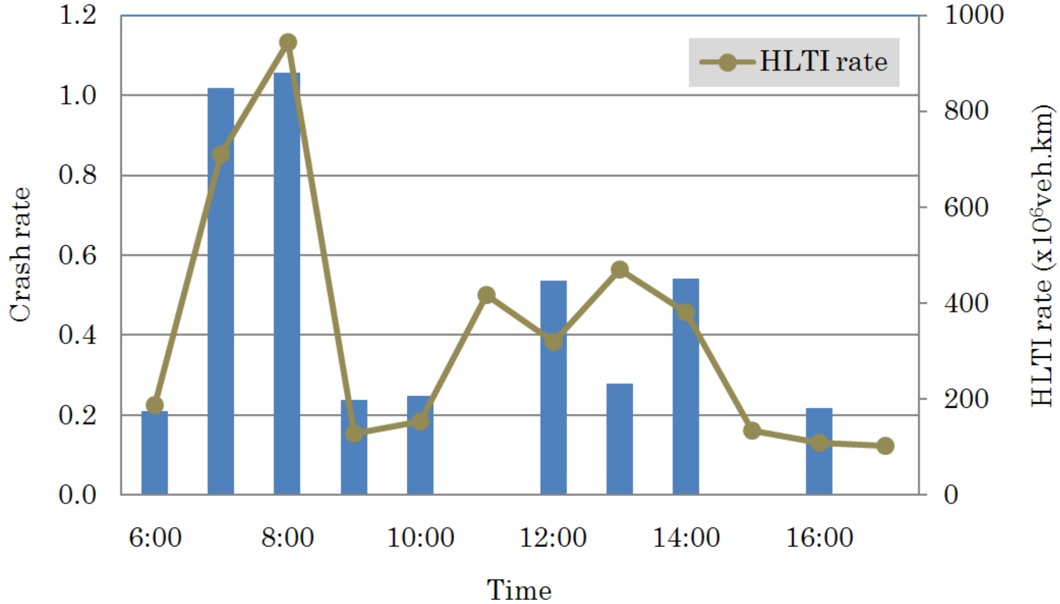

Figure 6.14: HLTI and crash rate over time for segment A

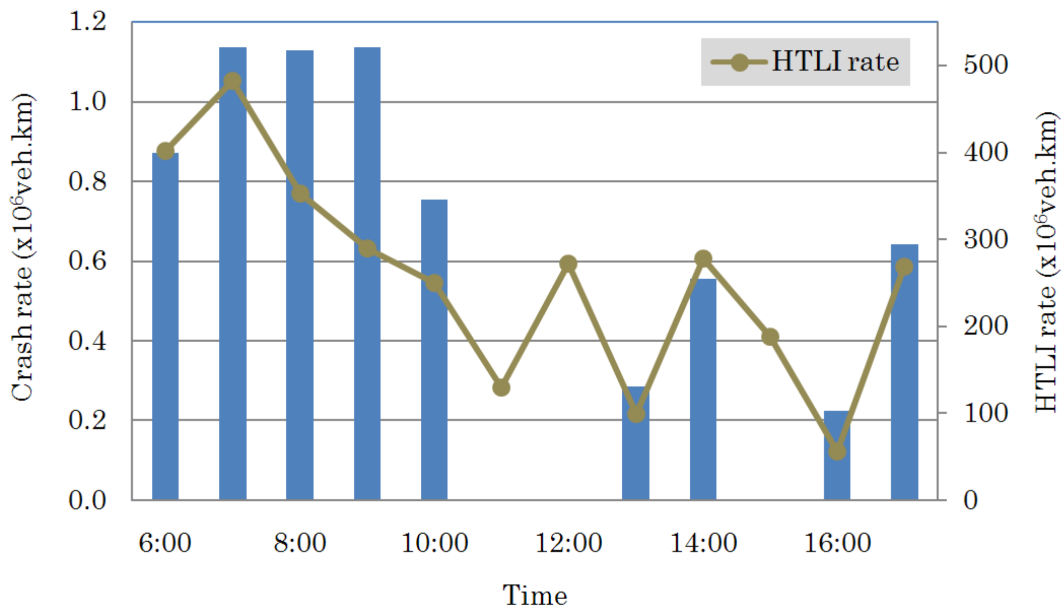

Figure 6.15: HLTI and crash rate over time for segment B

6.9 Concluding Remarks

This Chapter presented a series of intuitive tests to support the link between safety performance (CPI/veh) and observed crashes. Three tests were carried out: 1) Compare safety performance measures in aggregated 1 minute increments for a period five minutes prior to the time of the crash, 2) Compare safety performance measures in 1 minute increments over five minutes prior to the crash and compare this to non-crash results for the same location and traffic volume, and 3) Compare average safety performance measures to crash frequency estimated over a one hour period at the same site.

The results suggest objective evidence that crashes tend to occur when the measure of safety performance (CPI/veh) is high. CPI/veh was found to be sensitive to the time interval preceding each crash, i.e. as the time to crash is approached the CPI/veh increases non linearly, particularly for the one minute period prior the crash. In general, the tests discussed in this paper support two assertions: 1) Crashes occur during periods when CPI/veh is higher than "normal" at the same location and 2) Increases in average CPI/veh rates correspond to increases in crash frequencies (relative validity).

Ideally it would be preferable to perform such tests using "real world" vehicle tracking data in order to avoid the somewhat simplistic environment provided by current microscopic simulation models. However, such detailed vehicle tracking data for crash and comparable non-crash traffic conditions are not readily available.

The CPI expression itself (Equation 4.1) was developed using deterministic relationships from Newtonian physics for two particles in motion and thus it should yield sound estimates of required braking effort to avoid crashes and consequently account for the dynamics leading to crashes. Furthermore, the link between CPI and crashes may not be strictly necessary given that the latter can be viewed as a small "unlucky" subset of relevant high risk events, which by their very nature represent a narrow somewhat biased view of the larger safety problem.

Chapter 7

Case Study Applications

7.1 Introduction

The usefulness of the proposed methodology for safety assessment relies on its ability to capture the overall level of turbulence for different transportation scenarios as a function of a number of geometric and traffic attributes. The methodology must be able to provide meaningful insights about changes in overall safety for different engineering countermeasures. For example, what would the safety benefits (or disbenefits) be of upgrading a stop controlled intersection into a signalized intersection? Are the results sensitive to changes in volume, lane configuration, and signal plan?

In this Chapter, the proposed microscopic model for safety assessment is applied to investigate the safety implications of engineering countermeasures applied to two transportation scenarios as follows: 1) Upgrading a stop-controlled 4-leg intersection into a signalized intersection (Case Study 1) and 2) Introducing mandatory speed control for large trucks in a freeway environment (Case Study 2). A sensitivity analysis has been carried out for different levels of exposure (volume), traffic composition, and freeway geometric attributes. It is expected that, when combined at different levels, these factors will produce different levels of traffic interactions therefore influencing the safety performance of each scenario.

It is worth mentioning that the safety implications of the two case study applications were investigated using microscopic simulation algorithms that have been calibrated and validated for safety performance measure (CPI/veh) as obtained from vehicle tracking data. This calibration/validation procedure has been performed for both transportation scenarios and is described in detail in Chapter 5.

7.2 Case Study 1: Introducing Signalization to a 4-legged Stop-controlled Intersection

In this exercise, a simulation experiment was designed to investigate differences in CPI-based measures of safety performance caused by three factors, namely: 1) The introduction of fixed signal control to replace a previous stop sign on the minor approach, 2) The changes in traffic volume on the major approach, and 3) The type of vehicle interaction (rear-end or angled).

The intersection being simulated in this application consists of four-legs with 2 lanes on each major approach (WestBound and EastBound) and 1 lane on each minor approach. All lanes have a fixed width of 3.5m and the angle between major and minor approaches is set at 90 degrees. In total, ten different levels of traffic volumes were investigated for both stop controlled and signalized cases. Table 7.1 summarizes the assumed approach volumes and relevant traffic parameters for the simulation experiment.

Table 7.1: Intersection approach volumes and traffic attributes

Level(*)	Volume (vph)				Stop controlled		Signalized		
	EB	WB	NB	SB	Major approach LOS	Minor approach LOS	Cycle (s)	Major approach LOS	Minor approach LOS
1	300	300	100	100	A	C	40	A	A
2	400	400	100	100	A	C	40	A	A
3	500	500	100	100	A	D	40	A	A
4	600	600	100	100	A	F	40	A	A
5	700	700	100	100	A	F	40	A	A
6	800	800	100	100	A	F	40	B	A
7	900	900	100	100	A	F	45	B	A
8	1000	1000	100	100	B	F	45	B	A
9	1100	1100	100	100	B	F	50	B	B
10	1200	1200	100	100	B	F	60	B	B

(*) Levels 7, 8, 9 and 10 satisfy MUTCD warrant 3 for signalization

For the signalized intersection, right turns on red have been permitted, however, the traffic signal option does not allow for advanced green left turn manoeuvres. Signals are assumed to operate independent of timings at other adjacent intersections with semi-actuated phases optimized using Synchro 7©. The traffic directional split is assumed to be constant for all approaches during the simulation period for both signalized and unsignalized cases (i.e. 5% for left turns, 5% for right turns, 90% through movements).

The safety performance measures were simulated using VISSIM 4.3 using input parameters as per the calibration/validation exercise described in Chapter 5 for the Lankershim Boulevard signalized intersection. In order to better model left/right turn movements, VISSIM allows users to define "reduced speed areas" which corresponds to the maximum operational speeds of turning vehicles. These turning speeds are generated according to a user-defined distribution. In this case, "reduced speed areas" were defined following a linear distribution with an average of 38km/h and 23km/h for left and right turns respectively and a standard deviation of 10% of the mean. The average values were obtained for turning radii of 20m and 15m using the following linear expression suggested by Tarris et al. ([105]): $Speed = 53.8 - 0.27DC$, where $Speed$ is operating speeds on low-speed urban streets (km/h) and DC is the degree of the curve ($degree/30m$).

Each simulation has a 15 minute duration plus 5 minutes warm-up interval. In order to account for variations in different simulation runs for the same traffic volumes, 15 replicates were carried out for each run using different random seeds. In total, the analysis in this Chapter involved 300 simulation runs.

7.2.1 Measuring Traffic Interactions

As discussed in Chapter 4, two types of vehicle interactions are considered in the simulation model: rear-end and angled interactions. In the simulation package, rear-end interactions in both stop controlled and signalized intersections can occur in the following situations:

1. Stimulus vehicle (SV) stopping for a traffic light, stop signal or a slower vehicle ahead.
2. SV slowing down to avoid a crash with a vehicle that crossed the road.
3. SV slowing down for a left/right turn.
4. Mandatory or discretionary lane change from the SV.

For rear-end conflicts, it is possible to directly determine DRAC and consequently CPI for every 0.1s simulation time interval, given that VISSIM .fzp output files provide the information needed to link lead (SV) and following vehicles (RV) respectively.

For angled interactions, a total of 12 manoeuvres are possible in the vicinity of a four-leg intersection. Figure 7.1 presents the HCM2000 manoeuvre numbering scheme considered in this analysis. Estimating angled interactions requires further specifications when compared to rear-end conflicts, since it needs the definition of crash zones for every possible combination of crossing trajectories. Furthermore, it is necessary to verify the existence of a collision course (see Figure 4.4) for every simulation time interval (0.1s). For a four-leg intersection a total of 24 angled interactions are possible using the full combination of SV/RV manoeuvres. These angled interactions are illustrated in Figure 7.2. In this exercise, possible angled conflicts generated by red light running events were not considered.

VISSIM output files were scanned by a search algorithm coded in visual basic.net in order to determine the RV and its corresponding SV, as well as DRAC and CPI

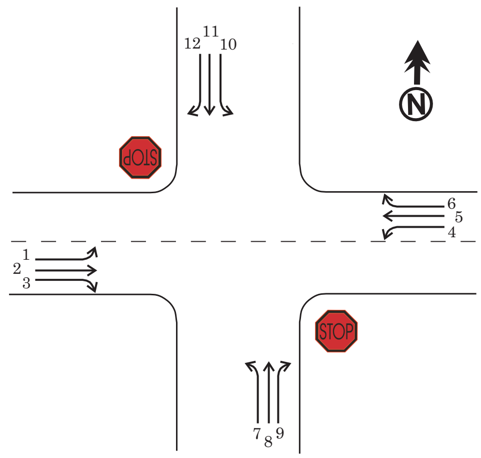

Figure 7.1: Manoeuvre numbering scheme for a four-legged intersection. (Source: [106])

in 0.1s increments for every vehicle in the simulation. Geometric definitions for every crash zone, as well as checking for the existence of angled collision courses were made externally to VISSIM's environment throughout the VB.net application.

7.2.2 Simulation Results

Four safety performance measures based on CPI were used to reflect changes in intersection safety that result from signalization: 1) CPI/veh, 2) CPI85th percentile (CPI85), 3) Percentage of vehicles interacting (CPI $\geq$ 0), and 4) Percentage of vehicles in conflict (DRAC $\geq$ MADR).

CPI/veh is obtained by summing the CPI for all interacting vehicles and dividing this by the number of simulated interacting vehicles. This measure reflects the average individual safety performance associated with each traffic scenario. The CPI85 establishes a threshold for comparing safety performance of individual traffic control (value of CPI/veh that is exceeded 15% of the time). The percentage of vehicles interacting represents the total number of vehicles with CPI greater than zero divided by the total of simulated vehicles. The percentage of vehicles in conflict captures extreme traffic interactions where the maximum deceleration required to avoid the crash (DRAC) exceeds the braking capacity of the vehicle (MADR). This value is also divided by the total number of vehicles in the simulation.

Table 7.2 summarizes the simulated average measures of safety performance for both stop controlled and signalized scenarios. These are based on the average of 15 simulations carried out using different number seeds. This Table also provides results for different major approach volumes and the two types of interactions (rear-end and angled).

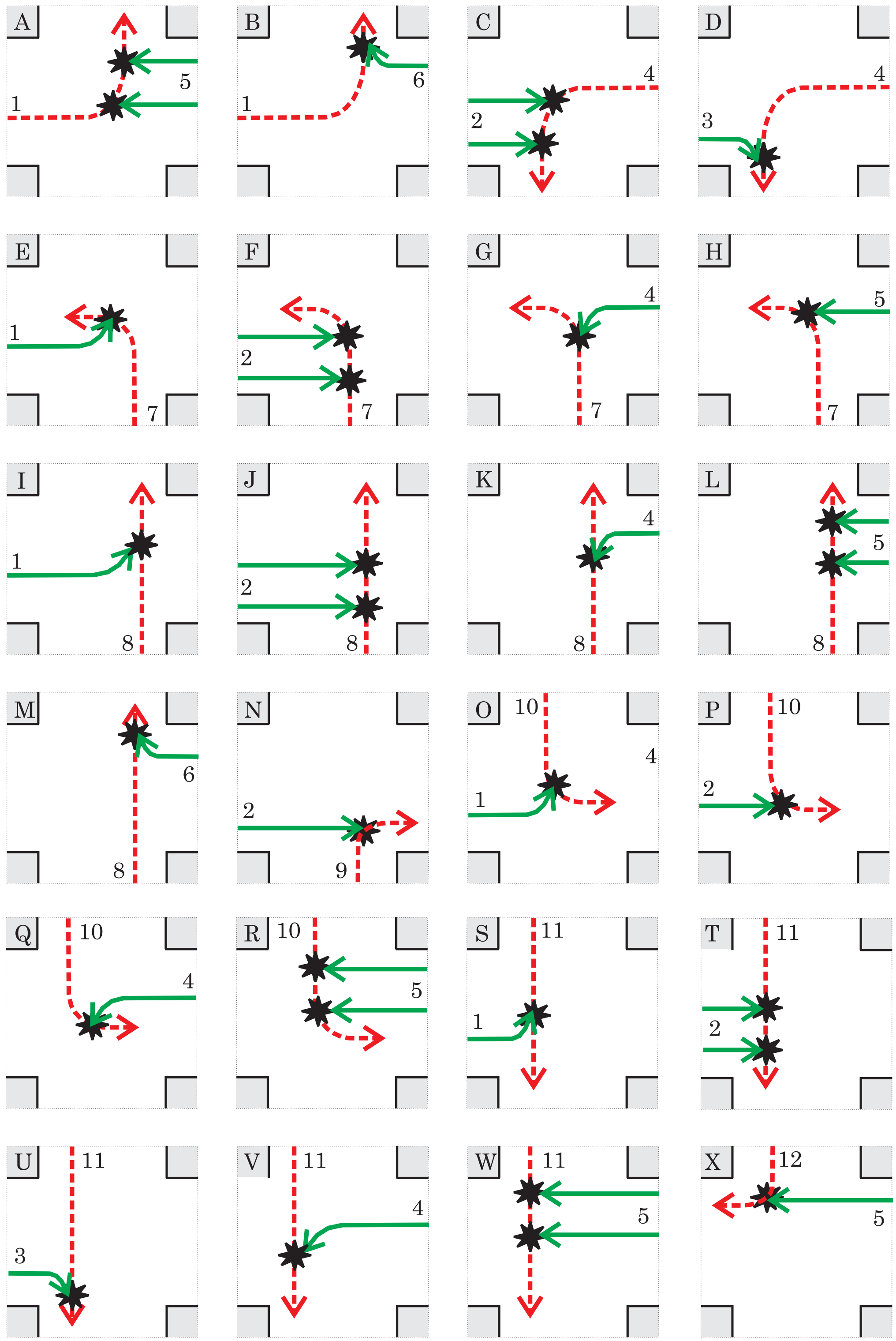

Figure 7.2: Possible angled interactions

Table 7.2: Safety performance indicators for stop controlled and signalized intersections

	Volume level	Simulated vehicles	Rear-end interactions				Angled interactions			
			CPI/veh	CPI85	%Veh interacting	%Veh in conflict	CPI/veh	CPI85	%Veh interacting	%Veh in conflict
Stop controlled	1	198	1.03.E-08	1.48.E-08	19.8	0.00	1.45.E-05	9.98E-09	4.8	0.03
	2	247	5.87.E-09	6.60.E-09	22.4	0.00	1.98.E-05	2.63E-08	4.5	0.00
	3	300	1.17.E-08	9.80.E-09	27.7	0.00	8.77.E-05	2.36E-08	6.2	0.02
	4	347	1.85.E-06	7.44.E-09	31.6	0.02	1.36.E-05	1.42E-08	6.7	0.02
	5	396	7.48.E-08	5.12.E-09	37.1	0.00	3.14.E-08	1.83E-08	6.9	0.00
	6	454	9.90.E-06	7.04.E-09	42.7	0.02	6.30.E-05	2.72E-08	7.1	0.06
	7	506	2.58.E-08	4.51.E-09	47.2	0.00	8.53.E-05	3.16E-08	7.0	0.04
	8	555	2.64.E-06	4.24.E-09	51.1	0.02	1.82.E-05	3.00E-08	5.9	0.02
	9	610	1.88.E-06	3.06.E-09	56.5	0.01	1.02.E-04	3.03E-08	5.1	0.06
	10	659	1.67.E-06	2.65.E-09	60.5	0.02	1.04.E-04	3.65E-08	4.2	0.04
Signalized	1	199	4.08.E-08	6.35.E-08	27.2	0.00	1.59.E-09	1.59E-09	0.2	0.00
	2	250	6.22.E-08	5.67.E-08	31.0	0.00	1.68.E-09	3.34E-09	0.1	0.00
	3	301	2.09.E-07	5.21.E-08	36.5	0.00	1.18.E-08	3.17E-08	0.4	0.00
	4	349	9.45.E-06	4.29.E-08	42.1	0.06	6.74.E-06	1.35E-05	0.3	0.00
	5	398	1.32.E-06	4.35.E-08	47.8	0.03	9.15.E-04	1.61E-03	0.4	0.03
	6	454	6.03.E-06	4.07.E-08	54.1	0.10	6.40.E-04	1.28E-03	0.5	0.03
	7	506	4.61.E-06	3.65.E-08	59.6	0.09	1.00.E-03	2.20E-04	0.9	0.06
	8	557	4.84.E-06	3.20.E-08	64.3	0.04	5.27.E-04	1.15E-03	0.7	0.02
	9	614	1.13.E-05	3.23.E-08	70.4	0.27	3.28.E-04	2.12E-05	1.0	0.04
	10	666	1.35.E-05	3.35.E-08	76.1	0.33	5.24.E-04	7.19E-04	1.1	0.08

Rear-end Interactions

When comparing the two traffic control strategies for rear-end interactions, the introduction of signalization consistently results in an increase in the average CPI/veh values, suggesting that signalization may yield negative safety dividends. This could be due to disruptions in traffic flow along the major approach that didn't exist under stop control. Furthermore, the introduction of the traffic signal results in an increase in the percentage of vehicles interacting from 7% to 15% conditional on increasing volume.

The relationship between volume and CPI/veh and percentage of vehicles in conflict is not as consistent as the percentage of vehicles interacting. This could be explained by the high variability in these measures. The influence of volume on the percentage of vehicles in conflict seems to become more apparent for the signalized scenario at higher levels of volume.

A visual analysis of the results for CPI/veh and CPI85 (Figure 7.3 and 7.4) confirm the findings from Table 7.2. From Figure 7.3, a high degree of variability in CPI/veh was observed with increasing volume (heteroscedasticity). This suggests that experiments to detect differences in simulated CPI/veh should be carefully designed to account for more subtle differences in the measure of safety performance and that a large number of simulations may be required to enhance confidence in the results. Figure 7.4 indicates that for rear-end interactions the CPI85 decreases with volume regardless of traffic control, stop or fixed signal. This suggests that high risk drivers are restricted by volume in achieving their desired speeds. Volume in this instance acts as a kind of speed dampening-effect to discourage high risk behaviour as measured by the 85th percentile.

Figures 7.5 and 7.6 provide additional evidence concerning the influence of volume on the number of vehicles in conflict for stop and fixed signal control respectively. These figures show that as volume increases the percentage of vehicles not interacting (i.e. CPI = 0) decreases with volume for both stop controlled and signalized scenarios, and the percentage of vehicles interacting (CPI>0) increases with volume for both control strategies. This result appears to be reasonable considering that at higher volumes the average spacing between vehicles is reduced with increased interactions requiring braking.

The introduction of signalization significantly increases the percentage of vehicles with high probability of DRAC exceeding MADR per second. For example, for a volume of 2600vph, the percent of vehicles with CPI between $1x10^{-08}$ and $1x10^{-07}$, increases from 4% to 14% after signalization. This suggests that for rear-end interactions there is a shift in the CPI/veh distribution to the right and hence a reduction in safety following signalization.

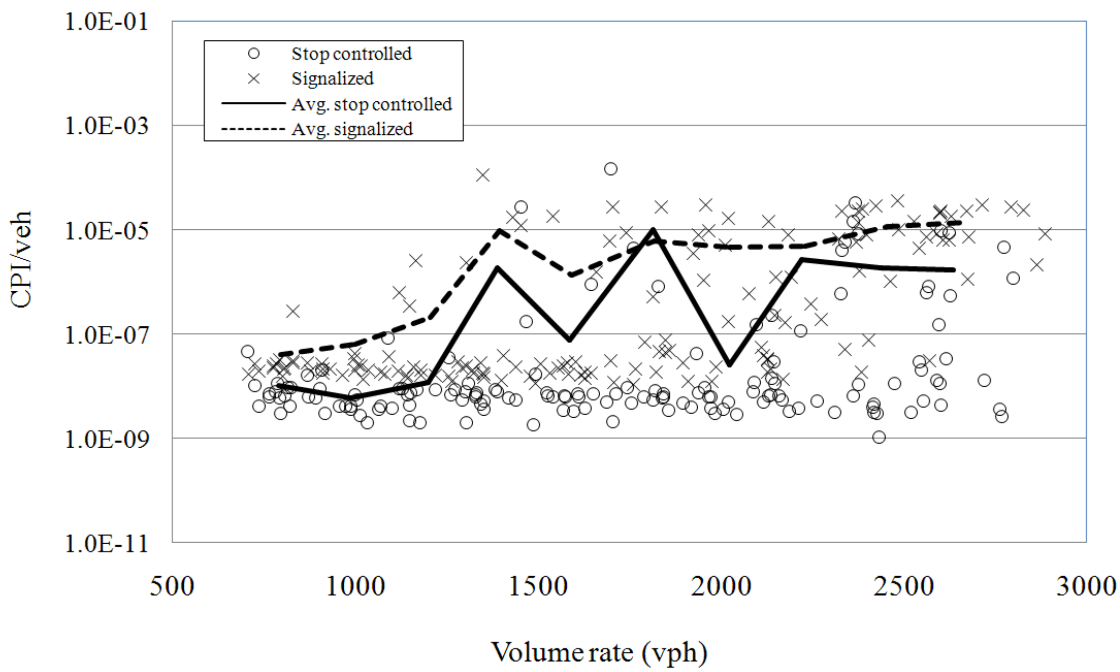

Figure 7.3: CPI/veh for rear-end interactions

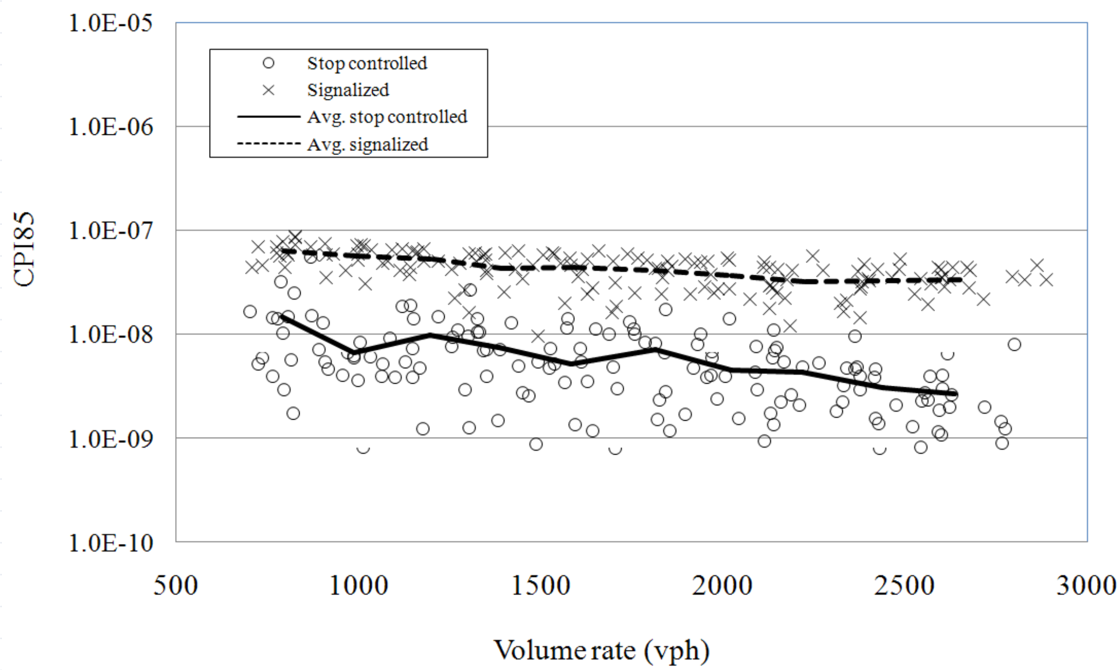

Figure 7.4: CPI85 for rear-end interactions

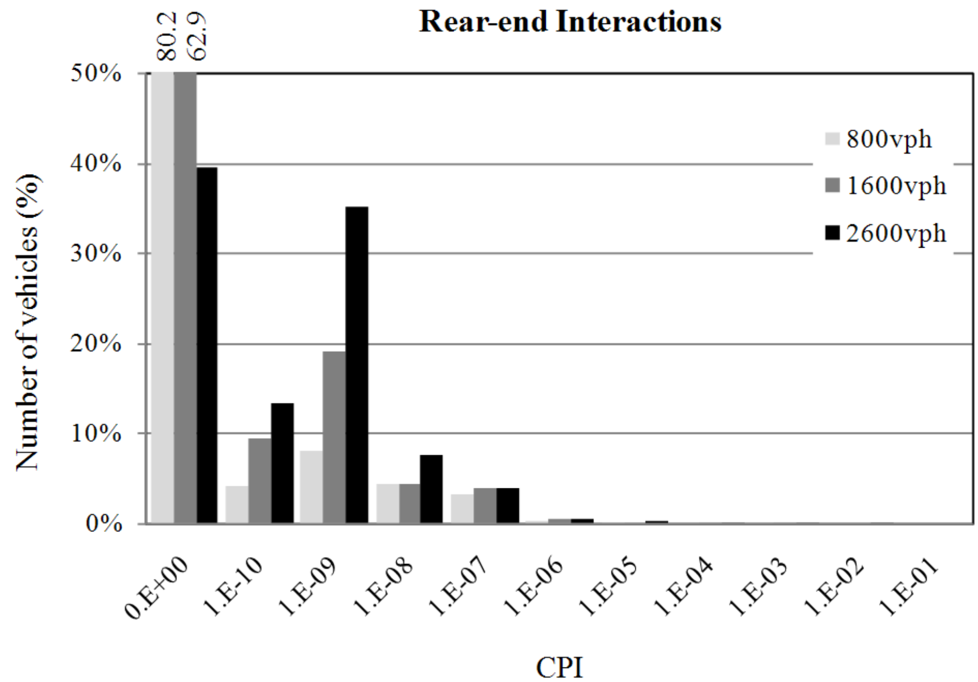

Figure 7.5: Distributions of CPI values for rear-end interactions: stop controlled scenario

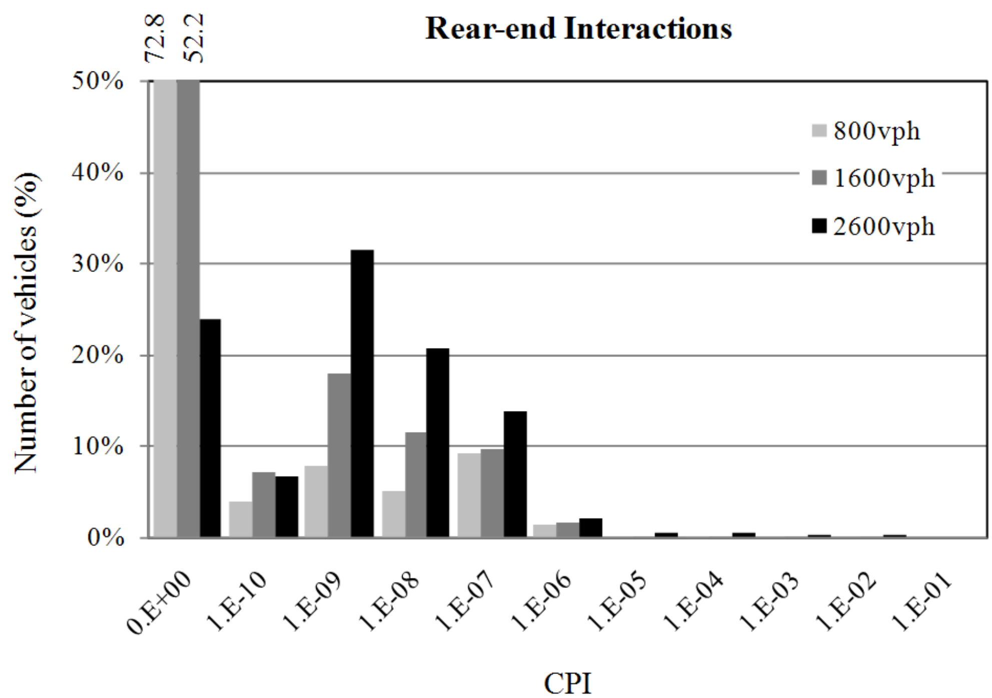

Figure 7.6: Distributions of CPI values for rear-end interactions: signalized scenario

Angled Interactions

For angled interactions, signalization yields lower CPI/veh values at lower traffic volumes. However, at higher volumes no such trend was observed. At lower volumes it is expected that there are more opportunities for left turn maneovres from the major approach, whereas at higher volumes the presence of a traffic signal creates a kind of "platooning" effect along the major approach reducing the number of available safe gaps for left turn vehicles (and hence higher average CPI/veh). For example, for the stop control strategy, at the volume level 8, Table 7.2 suggests that 5.9% of vehicles are interacting as compared to only 0.7% for the signalized case. Nevertheless the 0.7% of vehicles yield CPI values for the signalized case that are considerably higher than for the stop control case. This suggests that in the absence of an advanced green for left turn maneovres a greater proportion of shorter gaps is accepted.

For angled interactions and stop controlled, the percent of vehicles interacting increases at low volumes until a maximum value of 2000vph (volume level 7) is reached and decreases thereafter. For signalized intersections the percentage of vehicles interacting was found to increase consistently with volume. Figure 7.7 and 7.8 illustrate the frequency of simulated angled interactions for different CPI values and volume for stop controlled and signalized scenarios, respectively.

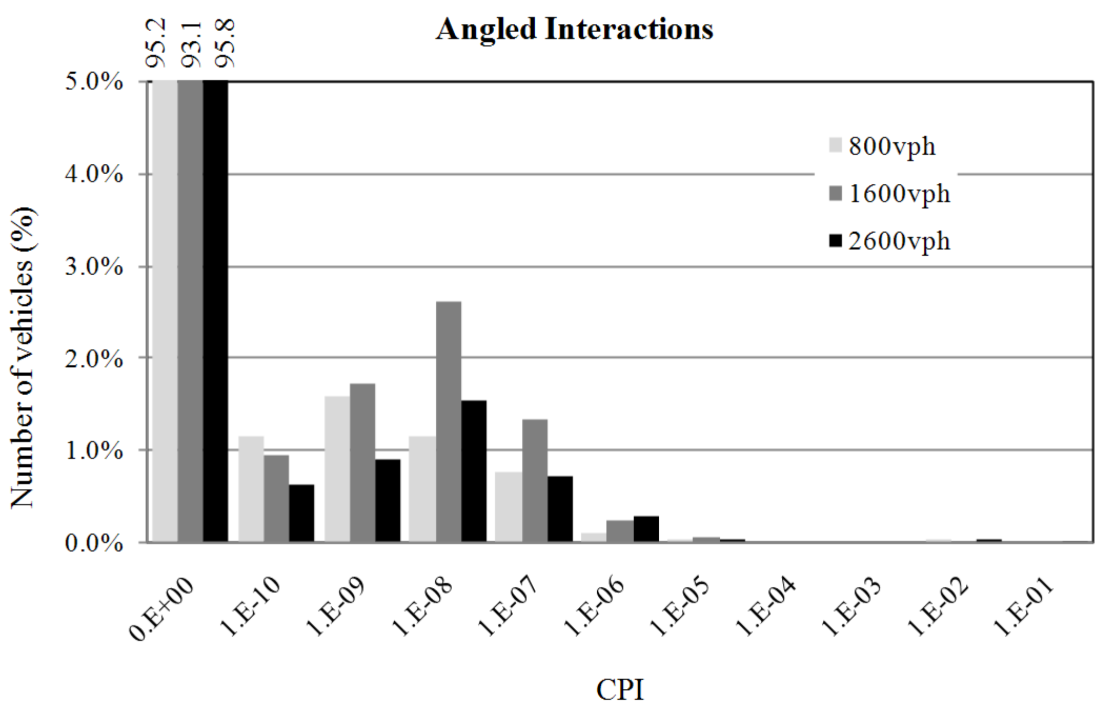

Figure 7.7: Distributions of CPI values for angled interactions: stop controlled scenario

For angled interactions, a key finding of the simulation runs is that the num-

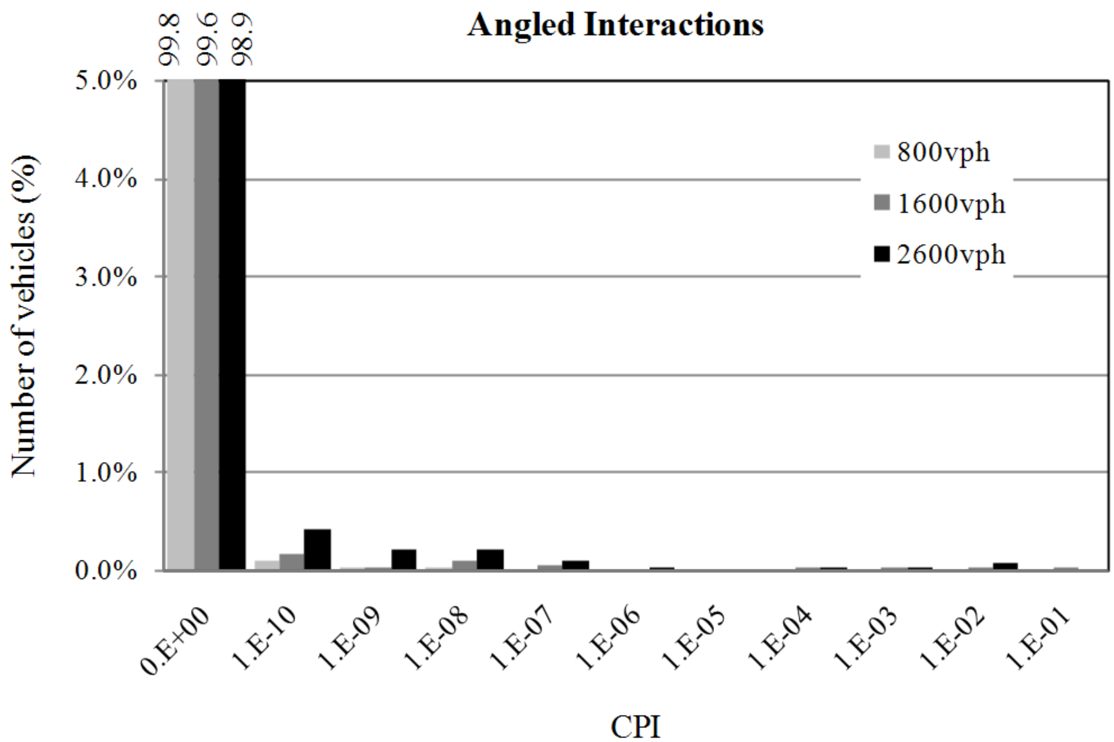

Figure 7.8: Distributions of CPI values for rear-end interactions: signalized scenario

ber of vehicles interacting is reduced after signalization. However, a small number of vehicles with very high CPI values continue to be present after signalization, especially under high volumes. The signalization scenario considered in this analysis does not permit advanced left turn control even at high volumes. In practise an advanced green for left turn movements would be considered at such volumes, reducing the problem of unsafe gap acceptance and resultant angled interactions.

In order to statistically verify the influence of volume and type of control in the average CPI/veh, the results in Table 7.2 were grouped into two major categories: 1) low volume (levels 1, 2, and 3) and 2) high volume (levels 8, 9, and 10). A two-way ANOVA analysis was carried out for rear-end and angled interactions and the results are summarized in Tables 7.3 and 7.4, respectively.

The ANOVA results indicate that all main factors (volume and type of control) as well as their interaction have a significant effect on average CPI/veh for both rear-end and angled interactions. This confirms the findings from visual inspection that the introduction of fixed signal controls at the stop-controlled intersection can compromise safety by increasing the potential for rear-end traffic conflicts.

Table 7.3: Two-way ANOVA: CPI/veh for rear-end interactions

Source	Type III Sum of Squares	df	MS	F	Sig.
Volume	15.74	1	15.74	44.20	0
Control	7.03	1	7.03	19.74	0
Volume * Control	6.70	1	6.70	18.81	0
Error	62.66	176	0.36		
Total	108.47	180			

Table 7.4: Two-way ANOVA: CPI/veh for angled interactions

Source	Type III Sum of Squares	df	MS	F	Sig.
Volume	21326.50	1	21326.50	5.95	0.02
Control	18432.12	1	18432.12	5.15	0.02
Volume * Control	15209.71	1	15209.71	4.25	0.04
Error	630358.08	176	3581.58		
Total	743035.21	180			

7.2.3 Major Findings

The merits of the proposed microscopic safety model have been verified with the investigation of the safety implications of introducing fixed signal control at a stop-controlled intersection for different traffic conditions. The model produces a number of meaningful measures of safety performance such as CPI/veh, CPI85th percentile, percentage of vehicles interacting and percentage of vehicles in conflict.

For rear-end interactions, the introduction of fixed signal control increased the percentage of vehicles interacting and in conflicts, as well as the average CPI/veh and CPI85. This suggests that signalization could increase rear-end crash risk when compared to a stop signal control. Increase in volume on the major approach was found to yield higher levels of vehicles interacting and in conflict with associated higher crash risks.

For angled interactions the introduction of fixed signal control resulted in a reduction in the percentage of vehicles interacting. The effect on safety performance however, was not consistent for all assumed volumes. At low volumes CPI/veh was found to be lower after signalization (i.e. safety was enhanced), on the contrary, at high volumes, CPI/veh indicated a small increase. This inconsistency was due to the absence of an advanced green signal for left turn manoeuvres from the major to the minor approach. The relationship between CPI/veh and signal control and volume was found to be statistically significant at 5% level for both rear-end and angled interactions.

Another important finding is that simulation experiments should be carefully planned according to the expected volume and interaction type. In general, angled interactions do not occur as often as rear-end interactions especially for low levels of volume. This introduces higher variability to CPI results for angled interactions therefore requiring a larger number of simulation runs in order to yield meaningful results.

7.3 Case Study 2: The Safety Implications of Mandated Truck Speed Limiters

Several jurisdictions in North America (national and state) are currently considering the introduction of mandatory speed limiters to reduce energy costs and crash risks. A speed limiter, also called a governor, is a built-in microchip that limits the maximum revolutions that an engine can achieve, hence restricting the vehicle's maximum speed.

Logically, we would expect a reduction in crashes would follow a reduction in the maximum speed limit where the reduction is applied uniformly to all vehicles in the traffic stream, and there is 100% compliance. The challenge for this application has been to determine the effect on safety of a speed control strategy that targets one group of vehicles (trucks) and not another (cars). If speed controls produce either intentional or unintentional increases in speed differentials or variance between cars and trucks, then there is a chance that both crash frequency and severity could be compromised by the introduction of these controls.

The focus of this case study is to investigate the safety implications of mandating speed limiters for large trucks (weight greater than 11,794 kg) using the proposed microscopic safety assessment model. A number of maximum speed thresholds (including 105 km/h) and compliance rates were investigated for different freeway geometric and traffic scenarios. This study was performed for a research project sponsored by Transport Canada [93].

7.3.1 The Simulation Experiment

In order to assess the safety implications of truck speed limiters, different maximum speed control strategies must be tested against important factors such as geometric characteristics, volume, percentage of trucks, and compliance rates. These factors were assumed to have some effect on the average speed and speed variance, and hence the CPI of individual vehicles in the traffic stream for different road and traffic conditions. In this study, we have considered three freeway geometric configurations: on-ramp, off-ramp, and straight segments with two-lanes and three-lanes per direction. The attributes of the off-ramp, straight, and on ramp configurations used in this sensitivity analysis are illustrated in Figure 7.9 for the three-lane case.

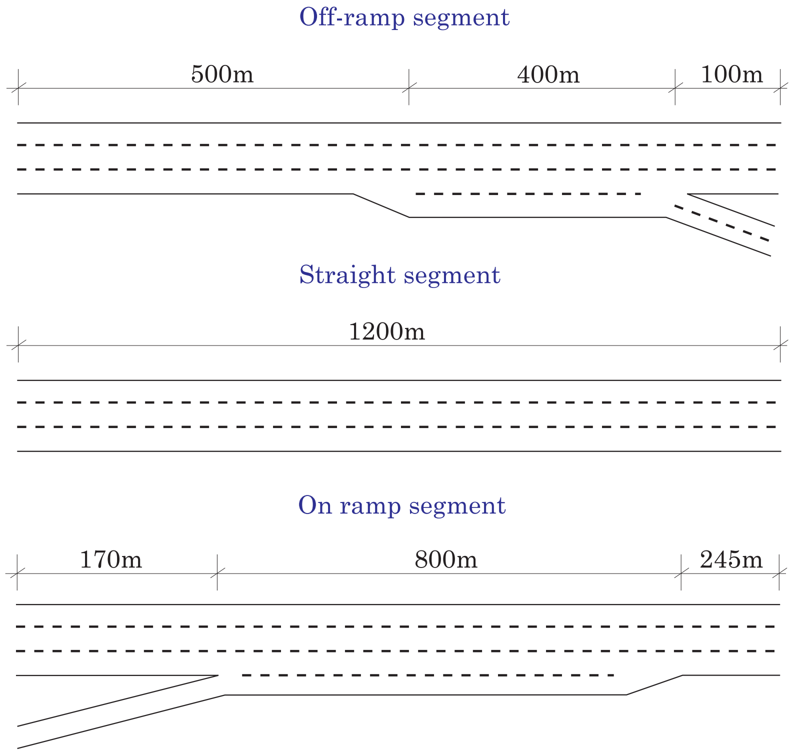

Figure 7.9: Geometry and lane configuration (Source: [93])

Two levels of freeway volume (500vphpl and 2000vphpl), percentage of trucks in the traffic stream (2.5% and 15%), and mandatory truck limiter compliance rates (75% and 100%) were considered in the study. The above geometric and traffic scenarios were applied initially to a 105km/h maximum speed control strategy as suggested by Transport Canada.

Table 7.5 summarizes the different traffic, lane-configuration, and speed control factors used in this investigation of safety performance. A two-level factorial experiment was undertaken to consider all possible interactions between the above scenarios and simulated average CPI/veh.

Table 7.5: Simulation factorial design (Source: [93])

Factor	Parameter	Low level (-1)	Centre point (0)	High level (+1)	Description
A	Volume	500	1250	2000	Volume (vphpl)
B	Truck Rate	0.025	0.088	0.15	Truck rate (2.5% to 15%)
C	CompRate	0.75	0.875	1	Compliance rate
D	NbrLanes	2	-	3	number of lanes (2 or 3)
E	SpeedControl	-1	-	1	Speed limiter: -1 = no control; 1 = speed limit 105

The full 2^5 factorial design requires 32 simulations. Centre points of volume, percentage trucks and compliance rate were considered which required 4 additional simulations to include these centre points combined with low and high levels of categorical/discrete variables (number of lanes and maximum speed). An additional 5 replicates of the entire experiment were carried out to account for random variability in the simulation, and this results in a total of 180 simulation runs per geometric configuration (i.e. on/off ramp or straight segment). A major objective in the factorial analysis is to estimate the effect of independent variables on the average CPI/veh in absence of possible scaling biases introduced by the units of the variables. The factorial experiment also yields a linear expression relating independent variables of interest with the average CPI/veh indicator.

Survey results obtained from a study conducted by McDonald and Brewster [64] indicated that 50% of large carriers are currently equipped with limiters compared to 25% for small carriers, regardless of whether they are mandated or not. Accordingly, the base case strategy (no mandatory limiter) assumes that 35% of all trucks are currently equipped on a voluntary basis with speed control devices set at the maximum 105 km/h. For the non-base case strategies the maximum speed on all limiters (voluntary and mandatory) has been set by the regulations as given above.

Simulations were performed for a total of 20 minutes including 5 minutes of warm-up where no information was recorded. The input parameters for the off-ramp freeway sections in this analysis were as suggested from the best estimate calibration exercise (see Chapter 5). For the straight and off ramp sections the combined on/off ramp parameter inputs were used in the simulation.

7.3.2 Simulation Results

Preliminary analysis of residuals suggested that the natural log transform of the average CPI/veh yields less variability, and hence is more representative of the underlying relationship. The resulting ANOVA table for each geometric configuration is presented in Appendix F. From these tables, significant factors and respective interactions were used to develop the following simple linear regression models for factors in the coded space:

- Off-ramp freeway segments:

$$\begin{aligned} ln(CPI/veh) = & -13.07 + 0.94\,(A) + 1.11\,(B) - 0.30\,(D) - 0.22\,(E) - \\ & - 0.18\,(A)\,(B) + 0.17\,(A)\,(C) + 0.20\,(A)\,(D) + \\ & + 0.22\,(A)\,(E) + 0.17\,(B)\,(E) + 0.17\,(A)\,(C)\,(E) \end{aligned} \tag{7.1}$$

- Straight freeway segments:

$$
\begin{aligned}
ln(CPI/veh) = & - 13.32 + 0.64\,(A) + 1.01\,(B) - 0.18\,(C) - 0.25\,(E) - \\
& - 0.24\,(A)\,(B) + 0.16\,(A)\,(C) + 0.21\,(A)\,(E) + \\
& + 0.18\,(B)\,(E) - 0.18\,(C)\,(E) + 0.16\,(A)\,(C)\,(E)
\end{aligned} \tag{7.2}
$$

- On ramp freeway segments:

$$
\begin{aligned}
ln(CPI/veh) = & - 10.61 + 2.54\,(A) + 0.66\,(B) - 0.55\,(A)\,(B) - \\
& - 0.11\,(B)\,(D) + 0.09\,(A)\,(E) + 0.20\,(A)\,(B)\,(D)
\end{aligned} \tag{7.3}
$$

where
A = volume (-1 = 500vphpl; +1 = 2000vphpl)
B = truck rate (-1 = 2.5%; +1 = 15%)
C = compliance rate (-1 = 75%; +1 = 100%)
D = number of lanes (-1 = 2 lanes; +1 = 3 lanes)
E = speed limit strategy (-1 = no control; +1 = control)

The above models provide a good explanation of the variance in safety performance with R-squares of 0.93, 0.67, and 0.69 for on ramp, straight, and off-ramp segments respectively. It should be noted that the coefficients in the coded space provide a relative impact of the independent variable in the response variable. For example, in Equation 7.3 the influence of volume on ln(CPI/veh) is approximately 4 times greater than the impact of increasing the percentage of trucks.

The residual plot of the fitted model illustrated in Appendix F indicates that both the normality distribution of residuals and homoscedasticity assumptions are valid. Additional tests performed using the lack of fit error and pure error for the three expressions are summarized in table 7.6. These tests suggest that all models adequately deal with the linear trend in the data (no need for quadratic terms, etc).

Table 7.6: Lack of fit test for regression models

Model	Pure error		Lack of fit		F_{obs}	p-value(*)
	Sum of squares	Df	Sum of squares	Df		
On ramp	66.66	144	15.64	29	1.16	0.27
Straight	125.95	144	26.73	29	1.05	0.40
Off-ramp	153.23	144	27.99	25	1.05	0.41

(*) If > 0.05, Ho representing no lack of fit, cannot be rejected

In the off-ramp case, by evaluating the coefficients from Equation 7.1 it can be said that as compliance is increased, there is a small corresponding increase in safety for the mandatory speed limiter case. It should also be noted that as volume and percent of trucks increase, the safety gains associated with full compliance are offset by additional traffic turbulence caused by higher volume and percentage trucks.

A graphical analysis of the relationship between CPI/veh, volume, and percentage trucks was carried out for 2 and 3 lane freeway segments, with the results for the off-ramp scenario illustrated in Figures 7.10 and 7.11. The analysis suggests that for the base case (no limiter), the CPI/veh is higher than for the mandatory 105km/h limiter case. This supports the assertion that limiters have positive safety gains. However, this result does not appear to apply to all volumes and percentage trucks. When volume is increased, the difference between the limiter and non-limiter case becomes less pronounced. In fact for volumes in excess of 1250 vphpl the introduction of mandatory limiters set at 105 km/h can actually have a negative effect on safety (i.e. higher CPI/veh).

It should be noted that this finding holds true for volumes in the uncongested region of traffic flow. Presumably as the volume approaches capacity, the speed of vehicles in the traffic stream will be determined by congestion, and hence the limiter is not expected to have any significant effect on safety. The relationship between increased volume and CPI/veh in the uncongested region appears to be especially pronounced with higher percentage trucks. At different volumes, safety performance is reduced with higher percentage trucks. At certain volumes and high percentage trucks the CPI/veh for the mandatory limiter case is higher than for the base case. Given the volumes and percentage trucks experienced on many freeways in Canada, this result could present some safety challenges for the introduction truck speed limiters.

Similar results were obtained for the on-ramp segment as for the off-ramp (Appendix G). As the volume increases, the CPI/veh also increases, especially for higher percentage trucks. The introduction of limiters set at 105 km/h results in safety gains with respect to the base case (no limiter mandated). We note that as volume increases to levels close to capacity the introduction of limiters can have a negative effect on safety (i.e. higher CPI/veh). This result holds for both 2 lane and 3 lane configurations. Increases in percentage trucks produces pronounced negative safety effects for limiters in comparison to the base case. At very high volumes the CPI/veh versus percentage trucks is lower for the base case strategy. This suggests that for high volumes the introduction of limiters set at 105 km/h could have a negative safety effect for higher percentage trucks in the traffic stream for the on-ramp configuration.

For straight segments the CPI/veh was found to be consistently lower for the mandatory limiter strategy. This suggests that for this configuration where we would expect reduced vehicle interaction, the safety gains of limiters set at 105 km/h can be more pronounced than for segments with on and off-ramps (Appendix

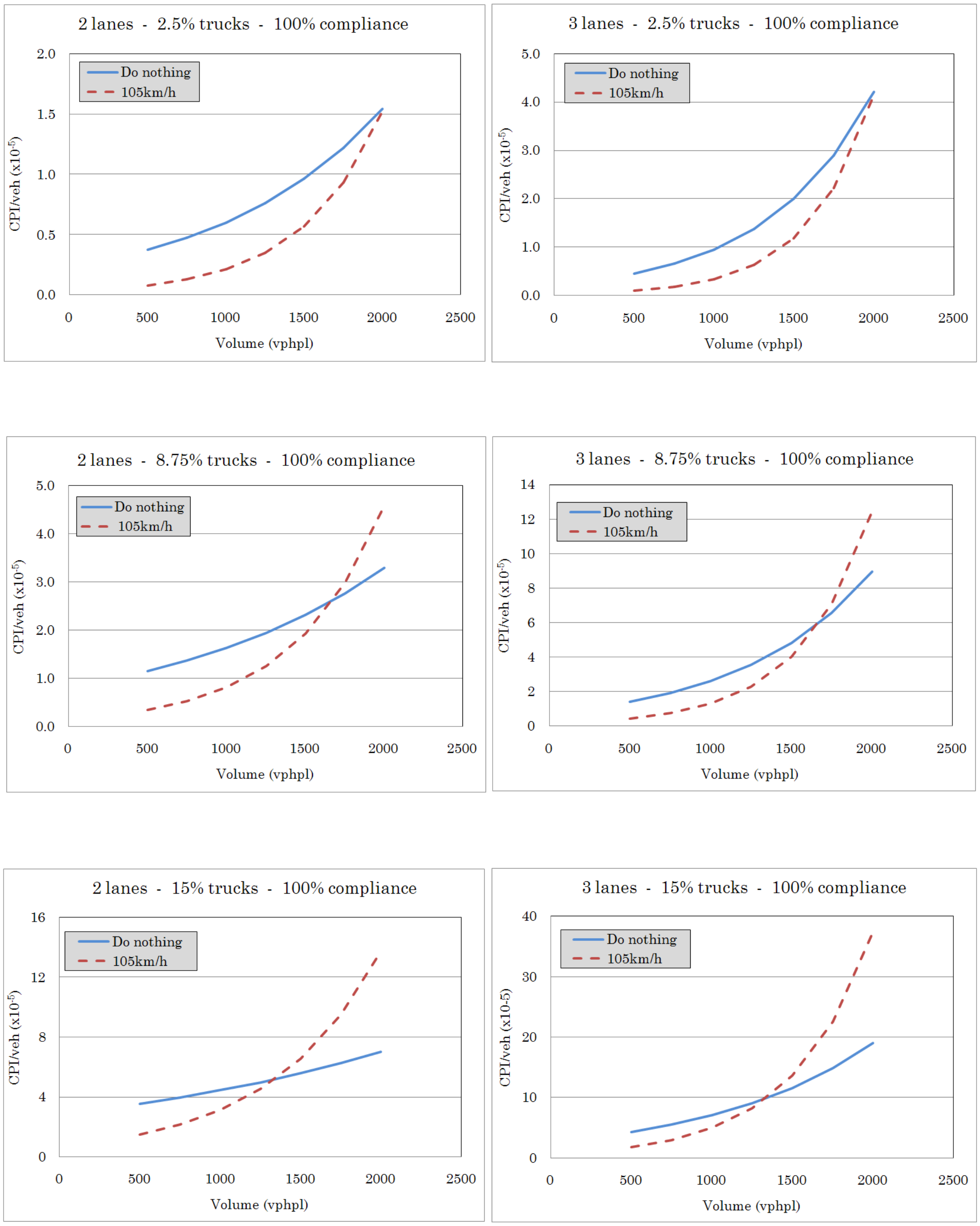

Figure 7.10: Estimates of CPI/veh as a function of volume for off-ramps (Source: [93])

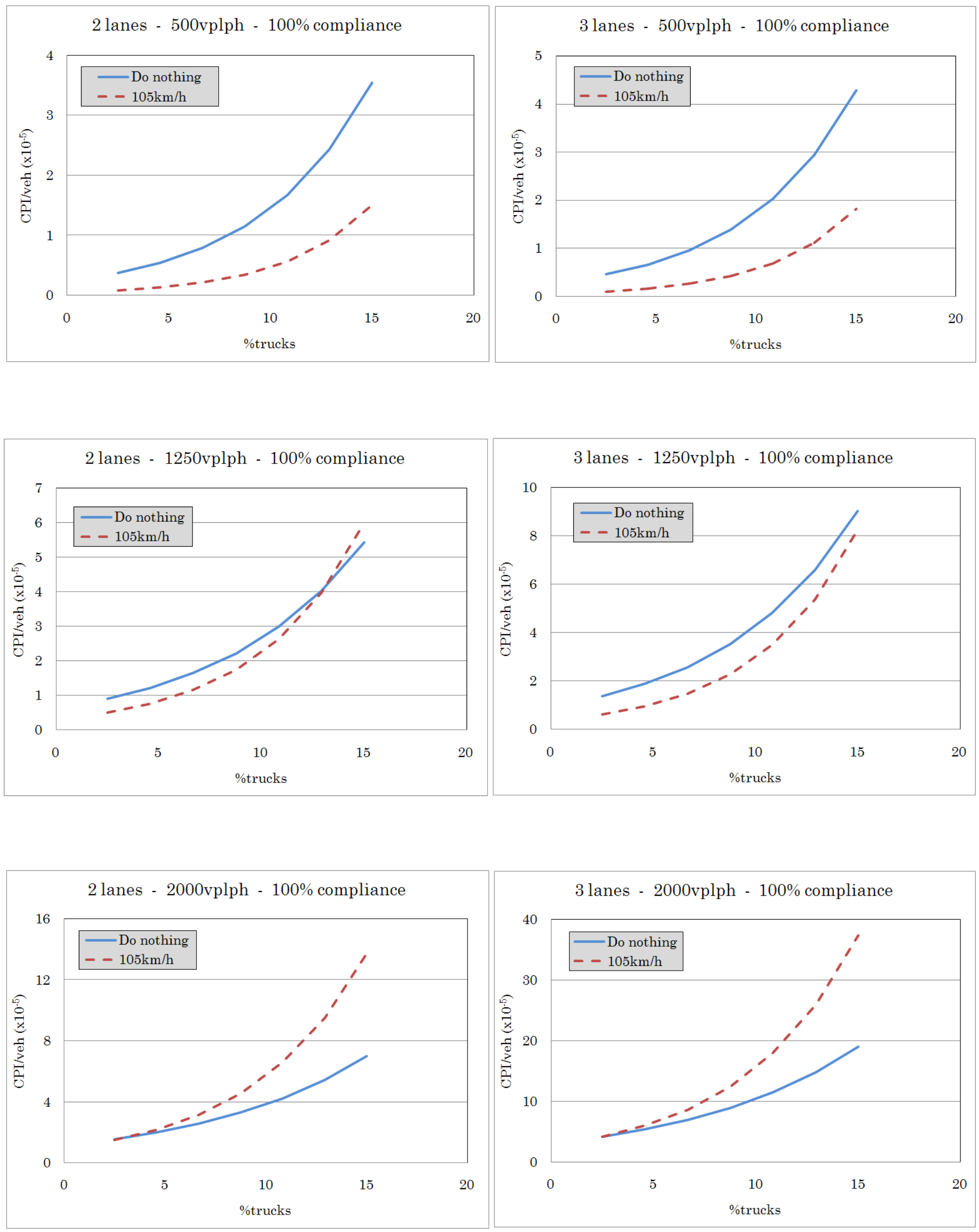

Figure 7.11: Estimates of CPI/veh as a function of the percentage of trucks for off-ramps (Source: [93])

H).

A sensitivity analysis of safety performance subject to changes in maximum speed limit policy was undertaken with the results illustrated in Figure 7.12. For this analysis, the average CPI/veh estimated for 15 simulation was used. Five levels of speed control strategies (80, 90, 100, 105, and 110km/h) were explored for the centre points of volume (1250vphpl), percentage of truck (8.75%), and assuming 100% compliance rate.

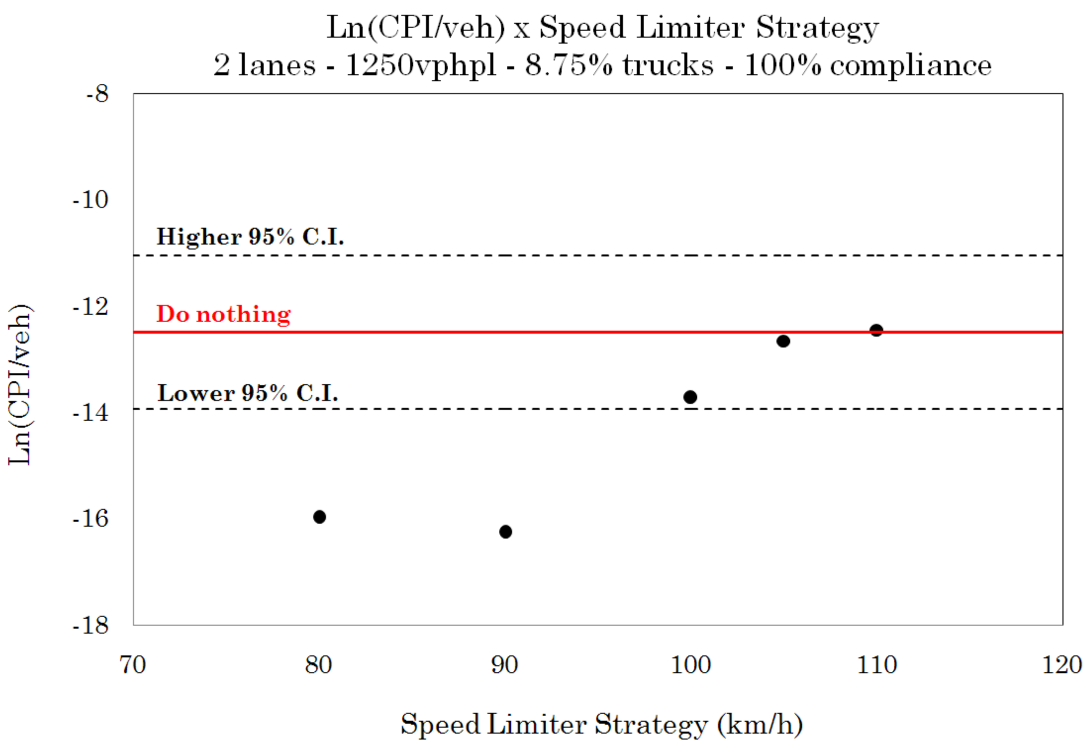

Figure 7.12: CPI/Veh under different speed limiter strategies (Source: [93])

Figure 7.12 indicates that the introduction of limiters can enhance safety (lower CPI/veh values) for all maximum speed settings below 105km/h, with the highest safety gains corresponding to a maximum speed set at 90km/h. At a speed of 110km/h or greater the mandatory limiter strategy has no significant effect on safety.

7.3.3 Major Findings

The simulation of the above scenarios has yielded a number of significant conclusions as to the safety implications of truck speed limiters.The introduction of speed limiters set at 105 km/h increases safety in the uncongested region of traffic flow for all geometric configurations, especially in the straight segment. As maximum speed is set at 110 km/h the safety gains with the introduction of mandatory limiters becomes negligible. This result also applies to the uncongested region of traffic flow.

As the volumes and percentage trucks are increased the safety gains associated with mandatory limiters becomes less pronounced. As volume approaches capacity, increased vehicle interactions are expected resulting in reduced safety in areas with more merging and lane-change manoeuvres. This relationship is especially pronounced at on and off-ramp freeway segments. As compliance is increased, there is a small corresponding increase in safety for the mandatory speed limiter case. It should also be noted that as volume and percent of trucks increase, the safety gains associated with full compliance can be offset by the additional traffic turbulence due to higher volume and percentage trucks.

7.4 Concluding Remarks

The main purpose of this Chapter was to assess changes in simulated safety performance for two transportation scenarios as a function of different geometric and traffic attributes. This exercise serves to provide a sensitivity analysis regarding the proposed safety performance measure (CPI/veh) and to illustrate the merits of the microscopic safety assessment framework.

Using previously calibrated and validated microscopic model inputs, two case study applications were identified in this Chapter as follows: 1) Upgrading a stop-controlled 4-legged intersection into a signalized intersection and 2) Introducing a mandatory speed control for large trucks in a freeway environment. The safety performance was estimated for various combinations of factors that were expected to affect safety for both scenarios and these included geometry, lane configuration, traffic exposure (volume), traffic composition, and compliance rate.

The results suggest that the proposed microscopic framework was sensitive to variations in volume, geometry, lane configuration, type of interaction (rear-end and angled), intersection control, and percentage of trucks. Furthermore, these results yielded useful insights regarding changes in safety that could be drawn specifically for each one of the transportation scenarios investigated.

Chapter 8

Conclusions

Researchers have been attempting to estimate safety using statistical models based on historical crash data. The underlying assumption of these studies is that crashes are individually unpredictable, although groups of crashes observed on a given location can produce predictable statistical patterns. Despite the great research effort on Bayesian methods and advanced statistical techniques, absolute number of crashes and crash rates are still difficult to estimate mostly due to issues related to data reliability and availability, as well as methodological challenges posed by the very random and unique nature of crashes.

It has been argued that a better understanding of the sequence of events prior to the crash could provide a more rational basis for the development of engineering countermeasures. However, this type of knowledge requires real-time monitoring of vehicles in the traffic stream, including detailed vehicle speed/spacing profiles for the unusual combination of events that lead to crash occurrences. Unfortunately, this type of information is not readily available.

Microscopic traffic simulation has been successfully applied to investigate operational performance of traffic systems. Recent developments on microscopic behavioural algorithms and traffic data acquisition have fostered a few systematic studies for the use of such a tool to investigate safety. However, most of these studies have not fully addressed some of the fundamental issues of microscopic modelling applied to safety studies, such as the need for a sound measure of safety performance, appropriate calibration/validation using safety indicators and establishing a reliable link between safety performance measures and "real world" high risk situations.

The primary objectives of this thesis were to develop a microscopic framework to identify potentially unsafe vehicle interactions for different vehicle movements based on traditional car-following, lane change and gap acceptance protocols. As part of the thesis objectives, these microscopic algorithms were applied to a new safety performance measure that has been calibrated and validated using real-time vehicle tracking data and linked to observed crash occurrences.

This Chapter highlights the main contributions of this thesis research and presents directions for future work in the field of safety research using short-term microscopic approach.

8.1 Major Contributions

The major contribution of this research concerns the conceptual aspects of the use of microscopic simulation for safety assessments in order to provide sound elements to enhance the scope of such a tool in road safety studies. Three important contributions can be highlighted as follows: 1) The development of a safety performance measure that takes into account individual vehicle braking capabilities (CPI), 2) The development of a heuristic calibration/validation procedure for microscopic models applied to safety studies, and 3) The development of a systematic procedure to link safety performance measures to observed crashes.

8.1.1 Development of the Crash Potential Index (CPI)

In safety studies where crash occurrences are not applied as the only measure of safety, such as in traffic conflict and simulation based safety studies, it is crucial to define safety performance measures that closely capture inter-vehicle interactions that could lead to crashes. It is also important that the measure be sensitive to different vehicle classes and environmental conditions.

In this thesis, a Crash Potential Index (CPI) was defined using the notion of vehicle interactions as the probability that braking requirements for a given vehicle to avoid a future crash exceed its maximum braking power during a given time interval. The crash potential index attempts to capture three important aspects of vehicle interactions as follows: 1) Braking requirements to avoid the crash during interactions, 2) Maximum available braking power as a function of vehicle type (e.g. cars and trucks) and environmental conditions, and 3) Time exposed to the interaction.

Braking requirements to avoid a crash are deterministically estimated using Newtonian physics applied to instantaneous spacing/speed profiles of vehicles involved in the conflict. In the CPI index, however, it has been recognized that different vehicles operating under different environmental conditions are likely to have variable performance to a given level of braking requirement. This aspect has been accounted for in the index by introducing a stochastic component defined in terms of assumed probability distributions for the maximum braking power as a function of vehicle category and environmental conditions (MADR).

Since the CPI index is mechanistic and highly disaggregated in nature, this provides a more rational platform to better understand the sequence of events prior to crashes, therefore serving as more robust basis for the development of engineering safety countermeasures.

8.1.2 Calibration and Validation of Microscopic Models for Safety Studies

The use of simulation in safety studies is only possible if existing microscopic simulation algorithms are able to capture, with reasonable accuracy, the complex behavioural relationships that could lead to crashes. Therefore, a fundamental prerequisite to increase the scope of this tool applied to safety is to ensure that important model inputs have been accurately determined based on observational data and that simulation models produce estimates of safety performance that can be verified from real world observations.

A thorough methodology for calibration and validation of microscopic models for safety studies has been introduced in this thesis. This methodology makes use of five sequential steps as follows: 1) Selection of initial model inputs, 2) Statistical screening of inputs using a Placket-Burnman with foldover factorial analysis, 3) Establishing linear expression relating significant inputs and CPI/veh, 4) Applying the genetic algorithm procedure to obtain the model best estimates, and 5) Validating the selected inputs. This heuristic procedure based on sequential applications of factorial analysis provides a systematic investigation of input parameters that influence the response (CPI/veh) leading to more meaningful results as compared to other screening designs.

The methodology was applied in two different geometric configurations (an intersection in an arterial road and at freeway segments). The results revealed that the average CPI/veh as obtained from simulation compared well with observed values as obtained from both intersection and straight segment vehicle tracking data. Furthermore, the validation results were found to be well within the 95% confidence interval of the values obtained from the simulation. This suggests that the model is able to replicate safety performance as reflected in rear-end crash potential for a sample of vehicles that were not part of the calibration exercise.

8.1.3 Development of a Systematic Procedure to Link Safety Performance Measures to Observed Crashes

Despite the intuitive and logical link between CPI and crashes, a more regimented link between these two safety measures supports the assertion that if simulated safety performance reflects high risk behaviour and crashes are caused by such behaviour, then these crashes should be taking place when safety performance is low (higher crash risk).

Three intuitive test were introduced in this thesis in order to provide further evidence of the link between simulated CPI and crashes. In Test 1, temporal variations in CPI/veh in 1 minute time intervals for a period of 5 minutes before the crash were investigated. The underlying assumption of this test is that as the precise time of the crash is approached, there is an increase in simulated crash risk (CPI/veh). Test 2 compares simulated safety performance 5 minutes prior the crash to the safety performance of the same freeway segment using traffic attributes recorded at the same time when no crash occurred. Finally, test 3 establishes a link between observed crash rates aggregated over periods of 1 hour with simulated safety performance for equivalent periods of time.

The results indicate objective evidence that crashes tend to occur when the measure of safety performance (CPI/veh) is high. CPI/veh was found to be sensitive to the time interval preceding each crash; i.e. as the time to crash is approached the CPI/veh increases non linearly, especially for the one minute period before the crash. In general, the tests discussed in this thesis supported the hypothesis that crashes occur during periods when CPI/veh is higher than normal at the same location and that average CPI/veh rates correspond to increased crash rates.

8.2 Future Research

The microscopic approach for safety studies presented in this thesis can provide a mechanistic, highly detailed and controlled environment to investigate crash occurrence in real-time. However, a number of areas with potential for improvement have been identified before this methodology can be systematically adopted by researchers and practitioners as an effective tool for road safety studies.

The microscopic framework for safety assessment relies on a large collection of highly detailed vehicle tracking information. This database can be used either to provide continuous real world vehicle interaction information for empirical studies using safety performance or to allow the development of improved microscopic algorithms to support short-term safety studies using simulated safety measures. The development of advanced algorithms for vehicle detection and tracking techniques applied to "ordinary" closed circuit television cameras (CCTC), as well as the use of in-vehicle technologies such as GPS or mobile phones can be viewed as natural ways of obtaining detailed, accurate, and systematic vehicle tracking information to be applied in safety studies.

The current state of the art microscopic simulation algorithms have not been strictly developed to include crash occurrences and thus these models can only replicate disruptive driver behaviour with a certain level of accuracy and detail. The development of more comprehensive microscopic traffic algorithms that account for a wider range of behavioural attributes including misjudgments of speed and distance, visibility restrictions, incorrect decisions due to inexperience, fatigue, attentional lapses, and motivational factors is not only highly desirable, but would further support the use of microscopic models in safety studies.

Further experimental research on factors influencing the stochastic component in the CPI measure that accounts for the maximum braking attributes (MADR) would improve the scope of this safety performance measure. Ideally, individual MADR distributions for combinations of different vehicle types (motorcycle, cars, truck configurations, etc), braking system (conventional, ABS), pavement conditions (dry, wet, snow), and pavement type should be available. Furthermore, different driver attributes such as age, experience, and level of impairment could influence the maximum achievable deceleration rate during an emergency situation.

In theory, CPI index represented by the deceleration rate to avoid the crash (DRAC) and the maximum braking power (MADR), presents a robust theoretical formulation to provide good estimates of crash severity. As noted previously the speed difference of vehicles at the moment of impact plays a major role in resultant crash severity due to the kinetic energy of the system right before the collision. Unfortunately, due to data restriction this aspect was not fully investigated in this thesis. Additional research using crash tests, accident reconstruction analysis and driving simulators could provide useful insights regarding average speed at the impact and therefore expected severity for different levels of CPI values.

Despite its inherent microscopic nature the CPI safety measure can provide a robust and objective platform for safety assessment of digital urban transportation networks during the planning process. For this type of application, a flexible platform capable of integrating macroscopic 4-stage modelling components and microscopic algorithms must be developed. This platform would fill an important void in the traditional planning process that is related to the lack of available tools needed to estimate safety in high level transportation policies.

The proposed crash potential index is sensitive to changes in geometric and traffic attributes. In this thesis, however, only two major geometric scenarios (intersections and freeway segments) and a limited number of traffic attributes were explored. Sensitivity analysis of CPI for additional scenarios that include different geometries (curved segments, roundabouts, overpasses, etc), driver, and vehicle attributes and adverse traffic conditions, such as rain and snow, can ultimately yield the development of a more comprehensive CPI expression. Regression coefficients representing a given set of traffic conditions can be included in the initial expression to account for individual contribution of independent variables in the CPI value. This way, predictive safety modelling would be possible in early stages of safety assessments of a given engineering countermeasure.

A natural extension of this work is the investigation of interactions for different road users, such as vehicles-motorcycles, vehicles-bicycles, vehicles-pedestrians, and special transportation components, such as highway-railway grade crossings and tunnels. The methodology described in this thesis can be applied with little modification once data regarding these scenarios or microscopic algorithms to replicate such conditions are available.

Appendix A

Plackett-Burnman Factorial Desing Structure and CPI/veh Results

Table A.1: Plackett-Burnman design structure and CPI/veh results

Run	A	B	C	D	E	F	G	H	I	J	K	L	M	CPI/veh ($x10^{-5}$)
1	1	-1	-1	-1	1	-1	-1	1	1	-1	1	-1	1	37.93
2	-1	-1	-1	1	-1	-1	1	1	-1	1	-1	1	1	62.14
3	-1	-1	1	-1	-1	1	1	-1	1	-1	1	1	1	5.87
4	-1	1	-1	-1	1	1	-1	1	-1	1	1	1	1	9.66
5	1	-1	-1	1	1	-1	1	-1	1	1	1	1	-1	4.25
6	-1	-1	1	1	-1	1	-1	1	1	1	1	-1	-1	1.73
7	-1	1	1	-1	1	-1	1	1	1	1	-1	-1	-1	6.20
8	1	1	-1	1	-1	1	1	1	1	-1	-1	-1	1	16.02
9	1	-1	1	-1	1	1	1	1	-1	-1	-1	1	-1	6.13
10	-1	1	-1	1	1	1	1	-1	-1	-1	1	-1	-1	0.64
11	1	-1	1	1	1	1	-1	-1	-1	1	-1	-1	1	0.00
12	-1	1	1	1	1	-1	-1	-1	1	-1	-1	1	1	10.35
13	1	1	1	1	-1	-1	-1	1	-1	-1	1	1	-1	22.52
14	1	1	1	-1	-1	-1	1	-1	-1	1	1	-1	1	29.53
15	1	1	-1	-1	-1	1	-1	-1	1	1	-1	1	-1	14.84
16	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	71.87
17	-1	1	1	1	-1	1	1	-1	-1	1	-1	1	-1	7.91
18	1	1	1	-1	1	1	-1	-1	1	-1	1	-1	-1	0.37
19	1	1	-1	1	1	-1	-1	1	-1	1	-1	-1	-1	20.91
20	1	-1	1	1	-1	-1	1	-1	1	-1	-1	-1	-1	7.59
21	-1	1	1	-1	-1	1	-1	1	-1	-1	-1	-1	1	16.85
22	1	1	-1	-1	1	-1	1	-1	-1	-1	-1	1	1	22.28
23	1	-1	-1	1	-1	1	-1	-1	-1	-1	1	1	1	27.03
24	-1	-1	1	-1	1	-1	-1	-1	-1	1	1	1	-1	10.69
25	-1	1	-1	1	-1	-1	-1	-1	1	1	1	-1	1	62.16
26	1	-1	1	-1	-1	-1	-1	1	1	1	-1	1	1	27.32
27	-1	1	-1	-1	-1	-1	1	1	1	-1	1	1	-1	47.64
28	1	-1	-1	-1	-1	1	1	1	-1	1	1	-1	-1	0.82
29	-1	-1	-1	-1	1	1	1	-1	1	1	-1	-1	1	8.90
30	-1	-1	-1	1	1	1	-1	1	1	-1	-1	1	-1	10.12
31	-1	-1	1	1	1	-1	1	1	-1	-1	1	-1	1	17.59
32	1	1	1	1	1	1	1	1	1	1	1	1	1	2.82
33	0	0	0	-1	0	0	0	0	0	0	0	0	0	2.18
34	0	0	0	-1	0	0	0	0	0	0	0	0	0	16.63
35	0	0	0	-1	0	0	0	0	0	0	0	0	0	11.46
36	0	0	0	-0.33	0	0	0	0	0	0	0	0	0	9.19
37	0	0	0	-0.33	0	0	0	0	0	0	0	0	0	23.38
38	0	0	0	-0.33	0	0	0	0	0	0	0	0	0	11.87
39	0	0	0	0.33	0	0	0	0	0	0	0	0	0	12.12
40	0	0	0	0.33	0	0	0	0	0	0	0	0	0	20.06
41	0	0	0	0.33	0	0	0	0	0	0	0	0	0	5.39
42	0	0	0	1	0	0	0	0	0	0	0	0	0	0.20
43	0	0	0	1	0	0	0	0	0	0	0	0	0	12.60
44	0	0	0	1	0	0	0	0	0	0	0	0	0	2.71

Appendix B

Fractional Factorial Design Structure and CPI/veh Results

Table B.1: 2^{6-1} fractional factorial design structure and CPI/veh results

Run	A	C	E	F	G	M=+-ACEFG	CPI/veh ($x10^{-5}$)
1	-1	-1	-1	-1	-1	-1	42.68
2	1	-1	-1	-1	-1	1	52.04
3	-1	1	-1	-1	-1	1	13.34
4	-1	-1	1	-1	-1	1	22.52
5	-1	-1	-1	1	-1	1	28.38
6	-1	-1	-1	-1	1	1	48.58
7	1	1	-1	-1	-1	-1	16.66
8	1	-1	1	-1	-1	-1	10.56
9	1	-1	-1	1	-1	-1	11.51
10	1	-1	-1	-1	1	-1	47.00
11	-1	1	1	-1	-1	-1	5.74
12	-1	1	-1	1	-1	-1	5.80
13	-1	1	-1	-1	1	-1	16.63
14	-1	-1	1	1	-1	-1	3.85
15	-1	-1	1	-1	1	-1	18.14
16	-1	-1	-1	1	1	-1	22.97
17	1	1	1	-1	-1	1	21.39
18	1	1	-1	1	-1	1	15.17
19	1	1	-1	-1	1	1	20.95
20	1	-1	1	1	-1	1	4.83
21	1	-1	1	-1	1	1	38.48
22	1	-1	-1	1	1	1	7.03
23	-1	1	1	1	-1	1	3.43
24	-1	1	1	-1	1	1	9.12
25	-1	1	-1	1	1	1	9.91
26	-1	-1	1	1	1	1	3.99
27	1	1	1	1	-1	-1	0.01
28	1	1	1	-1	1	-1	33.80
29	1	1	-1	1	1	-1	3.93
30	1	-1	1	1	1	-1	3.75
31	-1	1	1	1	1	-1	0.16
32	1	1	1	1	1	1	16.31
33	0	0	0	0	0	0	21.15
34	0	0	0	0	0	0	6.79
35	0	0	0	0	0	0	9.64
36	0	0	0	0	0	0	5.23
37	0	0	0	0	0	0	17.67

Appendix C

Pre-simulation Volume and Speed RMSP - Crash Conditions

Table C.1: Test 1 and 2 pre-simulation volume/speed RMSP - crash conditions (#118, #170 and #222)

Crash #	Seed	Upstream Flow Rate (vph)					Upstream Speed (km/h)					Downstream Flow Rate (vph)					Downstream Speed (km/h)					RMSP
		0 - 1'	**1 - 2'**	**2 - 3'**	**3 - 4'**	**4 - 5'**	**0 - 1'**	**1 - 2'**	**2 - 3'**	**3 - 4'**	**4 - 5'**	**0 - 1'**	**1 - 2'**	**2 - 3'**	**3 - 4'**	**4 - 5'**	**0 - 1'**	**1 - 2'**	**2 - 3'**	**3 - 4'**	**4 - 5'**	
118	3	2940	2700	3360	3300	2700	106.1	107.1	104.5	106.5	103.5	2520	3120	3060	3240	2220	99.8	104.7	94.7	91.7	104.2	**0.078**
	71	2940	2580	3420	3240	2760	106.0	106.6	104.4	104.6	105.9	2940	2700	3420	2700	2400	99.0	104.9	93.8	91.2	105.9	**0.070**
	76	3120	2580	3300	3300	2820	105.4	107.0	105.2	104.9	102.8	2820	2820	3240	3180	2880	100.5	106.3	94.8	91.9	106.7	**0.064**
	95	2940	2760	3300	3180	2820	103.6	105.3	106.2	106.4	107.8	3000	3120	3240	2940	2820	98.3	105.1	94.5	91.9	104.8	**0.061**
	169	3060	2580	3480	3180	2700	101.6	103.1	105.7	106.3	106.8	2820	3180	3420	3060	2280	97.8	102.5	94.4	91.7	106.9	**0.062**
	247	3000	2700	3300	3360	2700	107.2	103.9	104.4	105.1	107.3	3060	3060	3360	3060	2520	99.8	103.4	92.2	91.1	105.4	**0.060**
	648	2820	2640	3420	3180	2760	107.6	108.7	101.8	104.1	104.8	2040	3120	3360	3120	2460	101.2	103.4	93.9	90.4	107.4	**0.086**
	750	3180	2460	3360	3300	2820	106.7	108.3	106.8	101.6	103.2	3120	2400	3300	3000	2640	100.4	107.5	93.7	90.8	104.9	**0.082**
	770	3000	2820	3180	3240	2820	103.7	107.0	106.0	107.3	103.6	2820	3120	2580	3000	2700	100.3	104.5	94.9	91.5	105.5	**0.085**
	801	2940	2580	3420	3240	2760	106.0	106.6	104.4	104.6	105.9	2940	2700	3420	2700	2400	99.0	104.9	93.8	91.2	105.9	**0.070**
	Obs.	**2940**	**2460**	**3360**	**3240**	**2520**	**99.0**	**101.3**	**99.3**	**95.5**	**98.9**	**2820**	**3240**	**3480**	**2940**	**2760**	**97.2**	**107.7**	**93.1**	**93.3**	**98.7**	
170	881	4800	6060	6600	6660	5940	46.8	55.7	73.0	76.2	57.9	3900	4560	5160	6180	6060	22.4	28.6	38.8	67.2	70.4	**0.102**
	778	4980	6600	6600	6720	6240	44.2	60.5	73.4	80.9	65.1	4260	4800	5280	6420	6060	21.8	27.5	41.4	67.6	71.4	**0.102**
	507	5700	6000	6480	6060	6360	47.3	54.7	61.8	58.8	61.0	3900	4500	5520	6420	5700	21.8	27.4	42.2	68.2	72.2	**0.105**
	357	4860	5820	7200	6120	6180	42.8	55.5	79.4	58.4	53.9	3540	4500	5640	6420	6240	21.6	27.6	40.7	64.8	69.4	**0.106**
	369	5580	6540	6000	6300	6780	44.9	57.6	58.9	63.1	66.2	4140	4380	5520	6360	6240	22.6	28.1	38.5	67.3	71.4	**0.107**
	462	5400	6300	6060	6660	6240	46.9	58.0	54.9	71.7	56.5	3900	4620	5340	6120	6420	22.0	29.4	39.7	59.6	70.9	**0.108**
	549	5640	6300	6780	6240	6660	42.5	59.7	75.4	63.9	74.2	4020	4560	5580	6360	6360	22.7	28.0	38.4	64.1	70.8	**0.110**
	98	5940	6300	6180	6720	6120	48.5	63.2	55.1	64.2	57.2	3840	4740	5640	6060	6240	21.6	26.9	40.1	68.4	70.9	**0.111**
	727	5520	6060	6600	5880	6360	48.3	56.0	65.5	57.6	58.5	3900	4440	5340	6180	6060	21.1	27.4	39.6	66.4	70.8	**0.113**
	486	5700	6360	6420	6120	6720	46.4	56.5	64.5	56.4	68.1	3900	4620	5700	6120	6480	21.2	28.0	40.7	68.4	69.3	**0.114**
	Obs.	**5340**	**6300**	**7140**	**7080**	**6540**	**37.9**	**62.3**	**67.6**	**68.1**	**57.1**	**3840**	**4860**	**6000**	**5880**	**5640**	**26.1**	**32.4**	**44.8**	**68.3**	**76.3**	
222	120	4260	4080	3900	3960	4080	99.4	102.1	104.4	104.3	103.7	4560	3780	3300	4320	3840	86.6	87.8	88.9	91.3	81.3	**0.044**
	183	4260	4080	3900	3840	4200	102.8	102.2	106.2	101.8	104.9	4440	3600	3600	4620	3780	85.4	88.5	87.9	93.5	83.1	**0.046**
	173	4380	3960	3780	3780	4380	98.3	103.4	107.0	103.9	105.0	4200	3900	3720	4260	4200	87.1	86.8	87.4	92.2	80.9	**0.049**
	179	4260	4200	3960	3780	4200	105.3	105.7	104.4	106.5	104.1	4140	3900	3660	4260	4020	87.0	85.7	87.1	93.4	83.9	**0.051**
	42	4080	4080	4020	3720	4260	104.5	101.3	104.7	105.6	100.8	4320	3720	3780	4020	4140	86.6	87.6	88.4	94.1	82.1	**0.052**
	80	4260	4140	4080	3540	4260	104.0	106.8	104.8	105.6	105.2	4380	3660	3900	4320	3900	84.8	89.3	86.0	91.9	82.6	**0.053**
	25	4380	4200	3900	3780	4140	104.9	105.3	105.7	105.9	102.1	4500	3600	3780	4320	4140	85.1	87.5	85.1	93.7	82.5	**0.053**
	3	4380	4140	3840	3840	4260	103.8	104.1	106.2	104.4	102.1	4500	3960	3780	4200	3960	84.7	87.1	86.9	94.1	81.9	**0.055**
	195	4320	4080	3960	3720	4200	104.1	105.7	106.6	106.6	104.0	4440	3960	3780	4200	3660	85.3	87.7	87.2	93.3	84.2	**0.056**
	126	4260	4200	3960	3840	4020	104.9	106.2	104.1	106.6	105.6	4080	3900	3840	4260	4140	86.7	85.9	86.2	94.8	83.4	**0.057**
	Obs.	**4260**	**4200**	**3960**	**3720**	**4200**	**90.6**	**100.4**	**100.0**	**100.9**	**106.8**	**4200**	**3540**	**3480**	**4200**	**3840**	**86.2**	**84.5**	**86.3**	**95.9**	**81.2**	

Table C.2: Test 1 and 2 pre-simulation volume/speed RMSP - crash conditions (#223, #239 and #320)

Crash #	Seed	Upstream Flow Rate (vph)					Upstream Speed (km/h)					Downstream Flow Rate (vph)					Downstream Speed (km/h)					RMSP
		0 - 1'	**1 - 2'**	**2 - 3'**	**3 - 4'**	**4 - 5'**	**0 - 1'**	**1 - 2'**	**2 - 3'**	**3 - 4'**	**4 - 5'**	**0 - 1'**	**1 - 2'**	**2 - 3'**	**3 - 4'**	**4 - 5'**	**0 - 1'**	**1 - 2'**	**2 - 3'**	**3 - 4'**	**4 - 5'**	
223	339	3480	3780	3180	3480	4200	106.3	106.1	106.7	107.1	104.5	3180	3840	3120	3240	4680	88.5	92.6	97.2	100.0	93.7	**0.053**
	884	3480	3840	3060	3480	3780	103.6	106.3	107.1	106.8	105.2	3180	3600	2880	3660	4500	87.6	91.6	99.8	98.5	93.7	**0.054**
	752	3720	3540	3120	3360	4200	106.7	109.0	108.2	107.4	103.3	3180	3660	3060	3360	4620	89.3	92.8	98.9	99.6	93.9	**0.055**
	560	3600	3660	3120	3300	4080	105.7	105.1	105.7	105.7	106.0	3420	3600	3060	3360	4500	86.5	92.1	98.1	97.3	95.7	**0.055**
	906	3540	3840	3000	3240	4080	107.5	106.5	105.5	107.3	104.4	3540	3720	3060	3180	4380	89.3	92.2	99.8	97.4	95.4	**0.055**
	215	3480	3960	3060	3540	4080	107.7	106.8	107.4	104.4	104.3	3360	3780	3060	3420	4860	89.5	92.3	100.4	97.0	93.8	**0.055**
	504	3660	3780	3300	3360	4020	105.9	103.2	105.8	106.9	104.5	3420	3720	3000	3420	4800	87.5	92.5	99.8	101.5	93.7	**0.056**
	990	3420	3900	3180	3420	3840	105.1	106.0	103.1	105.0	105.3	3240	3900	3120	3420	4560	88.6	90.5	99.8	99.8	94.0	**0.056**
	162	3420	3900	3060	3300	4020	105.6	105.5	105.9	104.6	104.6	3180	3780	3180	3180	5100	87.3	91.4	97.5	97.8	93.6	**0.058**
	351	3420	3900	3240	3120	4020	102.3	107.4	106.5	103.9	106.2	3240	3420	3060	3480	4560	86.7	94.6	99.3	98.1	93.6	**0.058**
	Obs.	**3480**	**3900**	**3120**	**3360**	**3840**	**112.8**	**109.4**	**112.4**	**112.9**	**115.6**	**3120**	**3600**	**2760**	**3120**	**4620**	**91.0**	**92.3**	**99.2**	**100.2**	**96.0**	
239	378	6060	6360	6840	6420	5220	97.4	95.0	97.7	100.7	104.0	6180	6420	6720	5040	6120	59.5	74.6	91.6	103.6	97.1	**0.088**
	141	6000	6540	6480	6480	5160	92.6	100.9	88.1	97.7	103.5	6120	6540	6600	4860	5460	62.3	66.3	91.9	104.0	100.5	**0.091**
	398	5940	6780	6660	6540	5220	102.2	87.6	91.5	97.2	93.7	6480	6540	6600	5280	6000	62.6	74.2	91.0	103.0	100.1	**0.091**
	485	6060	6480	6840	6480	5160	99.8	96.5	90.7	102.5	100.6	6240	6600	6540	5280	5880	63.6	74.8	92.3	103.2	101.8	**0.091**
	316	6000	6480	6840	6720	4860	103.3	101.0	100.3	97.1	100.8	6060	6540	6720	5400	5820	61.4	74.7	89.2	99.6	98.4	**0.094**
	351	5760	6540	6960	6420	4920	96.1	86.8	100.7	101.6	104.3	6120	6540	6900	5280	5520	62.4	75.7	88.8	102.6	96.8	**0.094**
	356	6120	6540	6720	6780	5100	86.3	100.2	94.4	99.9	106.0	6120	6300	6540	5160	6120	57.5	74.8	89.2	102.6	101.9	**0.094**
	438	5700	6780	5820	6660	5160	95.8	90.5	94.7	94.6	104.3	6240	6540	6360	5100	5700	61.4	76.2	93.3	102.3	101.3	**0.096**
	90	6000	6420	6900	6360	5160	102.2	98.1	99.9	95.9	99.2	6360	6660	6600	5400	5820	59.1	69.8	87.6	102.4	102.2	**0.096**
	237	6240	6420	6780	6720	5040	102.4	90.7	95.7	101.1	92.9	6660	6420	6600	5100	6120	56.0	67.9	87.7	101.6	101.9	**0.096**
	Obs.	**6120**	**7380**	**7740**	**7140**	**4800**	**96.8**	**94.2**	**92.9**	**89.5**	**104.3**	**6480**	**8160**	**7140**	**4320**	**6180**	**63.7**	**74.8**	**90.6**	**105.4**	**102.2**	
320	83	5160	4320	5940	5820	5700	87.0	103.6	101.6	99.7	82.8	2340	4860	6420	6600	5640	44.8	72.2	84.5	82.4	84.3	**0.115**
	20	5340	3960	6000	5940	5880	89.5	106.1	97.2	98.2	81.6	2100	5220	5940	5760	6180	35.6	68.6	85.4	87.6	84.5	**0.118**
	18	5220	4200	6120	5820	5580	99.9	105.0	100.5	104.3	82.0	2040	4920	6240	5760	5520	33.3	68.8	86.0	85.0	89.6	**0.130**
	59	5400	4140	6120	5760	5880	92.7	104.8	86.0	95.6	83.2	2100	5040	5880	5820	6540	32.2	70.9	85.0	86.6	83.7	**0.130**
	156	5520	4080	6120	5700	5640	92.3	103.1	96.9	90.5	101.2	2400	5160	5580	5700	5640	42.7	70.3	86.3	87.0	86.1	**0.138**
	75	5280	4140	5880	5760	5880	92.9	102.6	104.1	103.5	91.6	2220	4920	6120	5580	6540	45.7	71.9	85.2	86.0	84.1	**0.141**
	21	5460	4080	6120	5580	5760	100.9	104.8	98.9	97.0	93.1	2400	4440	6240	5880	5580	43.0	71.5	79.0	87.7	87.8	**0.144**
	158	5280	3900	6180	5880	5880	102.9	103.7	100.4	100.6	69.9	2100	4800	6360	6180	6060	37.2	71.4	83.4	83.5	83.8	**0.147**
	65	5340	4140	5940	5820	5760	98.5	95.6	98.0	103.2	84.5	1980	5520	5940	5820	6480	36.0	67.1	85.1	86.2	85.7	**0.147**
	60	5400	3960	6240	5760	5880	99.8	101.9	99.4	103.7	84.5	2100	4740	5880	5940	6600	40.9	68.3	84.1	86.4	87.0	**0.148**
	Obs.	**4920**	**4980**	**6180**	**6120**	**5460**	**68.0**	**94.6**	**95.6**	**89.5**	**78.5**	**2100**	**4380**	**6600**	**5520**	**5220**	**39.1**	**74.2**	**88.5**	**89.7**	**91.9**	

Table C.3: Test 1 and 2 pre-simulation volume/speed RMSP - crash conditions (#371, #405 and #454)

Crash #	Seed	Upstream Flow Rate (vph)					Upstream Speed (km/h)					Downstream Flow Rate (vph)					Downstream Speed (km/h)					RMSP
		0 - 1'	**1 - 2'**	**2 - 3'**	**3 - 4'**	**4 - 5'**	**0 - 1'**	**1 - 2'**	**2 - 3'**	**3 - 4'**	**4 - 5'**	**0 - 1'**	**1 - 2'**	**2 - 3'**	**3 - 4'**	**4 - 5'**	**0 - 1'**	**1 - 2'**	**2 - 3'**	**3 - 4'**	**4 - 5'**	
371	188	4020	5340	4500	3960	4080	101.1	103.9	104.6	106.0	104.4	4440	5160	3900	4320	4080	78.4	90.0	98.4	104.6	102.8	**0.075**
	47	3960	5340	4380	4080	3840	105.1	98.5	99.3	105.2	103.8	4440	5040	4020	4080	4260	80.4	91.2	99.2	104.0	103.6	**0.079**
	9	4080	5400	4260	4080	3840	104.2	103.9	105.1	105.8	101.3	4380	5280	3660	3960	4260	78.8	91.9	101.3	103.6	101.1	**0.079**
	43	4320	5040	4320	4020	3900	100.9	103.6	103.6	104.7	106.0	4740	4980	3960	3780	4380	77.5	91.2	98.2	105.5	103.6	**0.081**
	108	4080	5460	4260	3960	3900	103.7	104.3	103.4	105.7	105.5	4260	5100	3960	4020	3900	81.1	89.9	99.8	104.2	104.9	**0.082**
	101	4020	5400	4380	3960	4020	103.7	104.5	101.7	105.3	104.4	3900	5340	3960	4260	4080	81.6	89.8	101.4	102.9	103.5	**0.082**
	128	3900	5400	4380	4020	3840	104.6	104.6	104.6	104.7	105.6	4500	5100	3960	3900	3960	76.9	90.2	99.2	102.8	103.7	**0.085**
	69	4080	5220	4440	3900	4140	105.2	96.5	105.2	105.9	105.5	4800	4920	3960	3960	4320	76.0	92.8	100.8	104.4	103.4	**0.087**
	41	4140	5160	4380	4200	3780	105.7	104.8	105.2	104.8	105.0	4260	4740	4200	3840	3960	78.0	92.2	99.5	104.8	103.6	**0.090**
	130	4080	5400	4080	4140	3960	104.4	103.1	105.6	105.4	104.2	4920	4740	4020	4140	3900	72.7	91.7	99.0	103.9	101.9	**0.095**
	Obs.	**4140**	**5580**	**4620**	**3960**	**3840**	**80.2**	**97.2**	**96.6**	**100.5**	**100.0**	**4200**	**4980**	**3780**	**4080**	**4320**	**77.8**	**97.4**	**103.5**	**104.2**	**100.1**	
405	4	6480	5940	5520	5520	5880	98.9	101.2	102.9	102.7	100.0	5640	4620	4680	5580	4560	75.8	84.1	90.6	94.3	98.9	**0.051**
	8	6360	6120	6060	5160	5940	101.2	101.7	100.4	103.1	102.5	5400	5100	4920	5160	4440	77.2	81.7	89.3	97.1	98.9	**0.054**
	9	6540	5880	5280	5640	5640	98.2	103.9	103.1	101.8	101.6	5220	4920	4860	5040	4800	75.4	83.7	91.6	97.2	99.1	**0.055**
	1	6660	6000	5820	5820	5340	98.2	100.3	101.7	100.5	103.3	5520	4740	5520	4680	4560	74.5	82.6	88.5	97.1	99.3	**0.055**
	5	6720	5820	5820	5580	5820	95.2	102.7	102.6	103.3	102.3	5340	5100	5100	5100	4920	75.9	83.7	91.1	97.0	100.7	**0.058**
	2	6360	6000	5640	5880	5640	102.4	101.0	101.9	100.7	100.9	5340	5220	4680	5580	4620	76.1	81.0	89.8	93.4	99.2	**0.058**
	6	6900	5880	5340	5760	6000	99.7	100.6	100.5	101.1	103.0	5520	4500	5280	5040	4920	75.7	83.2	88.2	97.4	101.0	**0.058**
	3	6720	6120	5760	5640	5700	98.4	98.9	102.8	100.3	104.3	6060	4860	5460	4800	4500	74.9	82.3	89.6	99.3	101.1	**0.059**
	7	6540	5940	6120	5160	5400	100.8	100.7	102.1	104.0	104.0	5400	5160	5100	5040	4500	75.9	82.0	90.3	96.9	101.6	**0.060**
	10	7260	5880	5520	5340	5520	99.1	99.8	105.5	102.7	100.7	5640	5340	4920	5040	4380	75.5	82.7	91.0	98.6	101.0	**0.061**
	Obs.	**6600**	**6240**	**5580**	**5580**	**5760**	**91.4**	**94.1**	**97.7**	**99.5**	**96.3**	**5340**	**4740**	**4920**	**5040**	**4320**	**75.5**	**81.8**	**83.0**	**91.7**	**96.9**	
454	266	6180	6240	5880	6660	6000	52.7	56.0	51.0	56.3	47.0	5280	6360	6120	6180	6300	38.6	69.9	81.4	77.3	74.8	**0.124**
	576	6540	6060	6120	6000	6060	53.6	53.4	54.4	53.6	49.0	5640	5820	6300	5940	6000	42.7	72.0	80.7	78.6	75.1	**0.127**
	712	6360	6000	6120	6300	5940	59.0	54.3	54.6	55.0	46.6	5760	6180	5940	6300	6180	46.5	70.2	81.0	76.5	74.6	**0.131**
	169	6240	6300	5940	6180	6000	53.1	59.0	52.7	54.6	48.0	5520	6240	6600	5880	6060	41.3	72.4	80.0	78.8	75.5	**0.132**
	464	6060	6240	6120	6000	5880	52.9	51.2	52.8	59.0	50.4	5580	6240	5940	6180	6180	45.2	71.4	80.2	76.5	73.0	**0.133**
	446	6240	6060	6240	6300	5940	50.5	56.9	54.6	54.3	48.5	5400	5340	6240	6180	5880	38.8	73.7	82.3	78.0	76.9	**0.134**
	401	6300	6060	5940	6120	6060	52.4	51.4	53.4	56.5	50.8	5400	5940	5820	6480	6000	41.7	72.5	81.8	77.2	74.2	**0.134**
	265	6120	6180	6360	6240	6000	55.7	55.8	59.4	52.9	47.7	5640	6060	6600	6060	6060	43.1	72.1	81.4	78.6	75.5	**0.137**
	611	6240	6120	6300	6180	6000	60.8	50.1	51.7	55.6	48.7	5400	6240	6180	6120	6180	42.7	71.3	81.0	76.9	75.2	**0.137**
	120	5940	6120	6420	5640	6300	55.4	54.2	57.1	50.5	50.1	5400	6060	6180	6180	5940	42.4	71.5	79.6	76.9	75.2	**0.137**
	Obs.	**6556**	**6439**	**6433**	**6158**	**5558**	**44.4**	**47.0**	**46.6**	**45.4**	**36.3**	**5182**	**6131**	**6339**	**6390**	**6403**	**46.2**	**63.8**	**75.7**	**72.3**	**68.6**	

Table C.4: Test 1 and 2 pre-simulation volume/speed RMSP - crash conditions (#455, #478 and #521)

Crash #	**Seed**	**Upstream Flow Rate (vph)**					**Upstream Speed (km/h)**					**Downstream Flow Rate (vph)**					**Downstream Speed (km/h)**					**RMSP**
		0 - 1'	**1 - 2'**	**2 - 3'**	**3 - 4'**	**4 - 5'**	**0 - 1'**	**1 - 2'**	**2 - 3'**	**3 - 4'**	**4 - 5'**	**0 - 1'**	**1 - 2'**	**2 - 3'**	**3 - 4'**	**4 - 5'**	**0 - 1'**	**1 - 2'**	**2 - 3'**	**3 - 4'**	**4 - 5'**	
	7	6300	6060	6120	6240	6180	66.0	75.6	64.1	52.6	54.6	5640	6060	6120	6060	6060	51.8	58.7	75.4	83.9	84.6	**0.105**
	9	6000	6480	5940	5940	5940	58.1	79.7	61.5	57.7	53.3	5760	5880	5760	6060	6060	56.5	60.9	74.2	84.8	90.0	**0.111**
	4	6480	6420	6060	6240	5760	71.3	82.5	84.5	65.8	49.6	6000	6240	6120	6000	5820	57.2	59.7	74.1	85.6	88.4	**0.111**
	2	6420	6480	5820	5880	6120	59.6	62.9	57.7	56.3	56.8	5640	6000	5760	5880	6060	44.8	55.8	75.9	85.3	86.0	**0.111**
	10	5820	6240	5580	6180	6000	54.1	55.4	68.6	62.8	57.9	6240	5460	6120	5880	6000	61.7	60.8	74.6	84.0	89.0	**0.116**
455	6	6600	6480	6000	6120	6240	99.3	92.0	74.0	72.2	56.2	5880	6120	6180	6240	5940	49.0	59.6	74.2	82.9	90.2	**0.127**
	8	6480	6180	6060	6180	6240	95.4	91.0	79.5	65.0	53.9	5820	5640	6360	6000	5820	45.0	53.0	73.6	86.4	88.7	**0.130**
	1	6120	5880	6300	5580	6180	56.6	74.7	85.2	49.6	56.5	6060	5820	6000	5820	5880	49.5	56.3	75.3	84.6	87.3	**0.133**
	3	6480	6300	6240	6000	5880	77.5	94.9	77.9	60.2	51.8	5940	6060	6180	5940	5700	43.6	59.1	74.3	84.4	90.1	**0.137**
	5	6600	6360	5880	6060	6300	99.4	99.3	98.8	94.4	73.8	5640	6000	6180	6240	6180	42.2	56.7	74.3	86.8	89.5	**0.188**
	Obs.	**5880**	**6480**	**5760**	**6060**	**5940**	**78.0**	**67.4**	**69.8**	**72.6**	**65.7**	**5160**	**5940**	**5640**	**6360**	**5340**	**56.3**	**53.6**	**74.2**	**85.8**	**89.9**	
	9	6060	6180	6660	5760	5880	59.3	73.2	71.3	57.2	46.4	3120	5640	5760	6060	6060	37.9	54.9	64.7	75.7	76.6	**0.094**
	201	5940	6060	6360	6000	5940	52.9	59.8	62.8	76.3	59.3	3420	4260	5940	6240	6000	44.4	44.1	63.0	72.8	78.1	**0.095**
	397	6060	6360	6240	6240	5820	52.9	71.8	74.8	58.7	47.1	3420	4740	6180	6120	6060	36.6	40.6	64.1	73.9	76.4	**0.099**
	6	5640	6180	6360	6180	5820	55.8	47.4	58.2	69.6	59.4	3180	5340	6000	6300	5940	40.2	48.6	64.3	74.2	77.4	**0.107**
	398	6000	6180	6600	6180	5700	51.5	52.4	78.2	79.9	47.3	3420	4800	6060	6120	5940	35.1	52.8	64.2	76.9	77.0	**0.108**
478	370	6360	6180	6300	6180	5760	56.8	48.7	77.1	65.4	45.7	3000	4560	6000	5880	6420	42.3	42.7	66.8	77.8	77.5	**0.110**
	59	5880	6240	6240	6300	5700	42.3	54.3	70.0	75.3	58.8	3420	5100	6360	5880	6000	38.1	43.6	61.4	78.1	78.9	**0.118**
	53	6120	6420	6360	6060	5700	58.9	63.3	55.7	53.9	62.3	3360	5160	5820	6420	5520	33.6	53.5	66.8	74.6	78.9	**0.122**
	94	6180	6000	6180	6000	5820	48.7	45.1	59.7	76.3	52.6	3480	5220	5580	6360	6120	37.2	59.4	70.4	75.0	76.4	**0.123**
	401	6060	5940	6120	6120	5820	56.0	47.5	67.9	64.4	59.0	2640	5040	5820	5820	6120	32.9	45.5	64.0	76.5	75.7	**0.128**
	Obs.	**5580**	**6180**	**6300**	**5760**	**5100**	**53.8**	**66.6**	**65.8**	**67.8**	**48.2**	**3120**	**4860**	**5940**	**6120**	**5400**	**47.2**	**51.0**	**66.2**	**71.1**	**75.1**	
	264	6720	6000	6420	6660	5820	68.0	65.2	55.0	61.1	57.5	6120	6240	6540	5880	6120	50.8	64.9	68.7	73.8	72.9	**0.071**
	739	6120	6300	6840	6600	6060	60.9	65.1	57.0	70.3	54.0	6000	6540	6480	6180	5940	52.3	64.6	68.9	73.6	72.4	**0.074**
	546	6840	6240	6300	6420	6300	70.5	82.2	56.0	58.9	52.1	6000	6480	6420	6120	6420	52.3	62.3	69.7	73.7	72.6	**0.075**
	572	6600	6480	6060	6780	6060	75.1	78.9	57.8	64.4	55.2	6120	6360	6420	6360	6120	52.7	63.8	69.7	73.3	73.0	**0.076**
	118	6540	6240	6240	6300	6120	75.7	68.1	56.7	66.7	56.3	6120	6120	6420	6180	6000	51.6	62.4	70.3	72.3	73.1	**0.077**
521	169	6060	6360	6180	6780	6000	63.1	70.7	56.4	70.8	54.6	6000	6420	6420	6300	6120	51.2	60.9	71.6	73.5	71.2	**0.079**
	820	6540	6360	6240	6240	6180	61.6	72.3	57.5	60.6	54.5	5820	6000	6360	6240	6120	49.3	65.4	70.9	73.7	72.5	**0.080**
	734	6360	6120	6360	6300	5820	55.0	67.2	59.2	55.6	53.5	6180	5940	6240	6420	5940	53.4	64.0	71.8	72.7	73.3	**0.080**
	703	6300	6540	6120	6300	5820	70.1	72.3	56.4	61.4	56.7	5700	6240	6180	6060	5940	51.3	63.6	71.6	72.2	72.6	**0.081**
	251	6480	6120	6300	6180	6000	61.9	64.4	55.9	51.2	50.3	6000	6240	6300	6180	6000	53.0	63.4	70.7	73.8	72.9	**0.081**
	Obs.	**7080**	**6060**	**7140**	**6720**	**5700**	**66.2**	**72.7**	**60.9**	**61.8**	**51.5**	**6480**	**6480**	**7140**	**6240**	**5640**	**56.9**	**58.0**	**64.6**	**73.5**	**72.8**	

Table C.5: Test 1 and 2 pre-simulation volume/speed RMSP - crash conditions (#522, #571 and #595)

Crash #	Seed	Upstream Flow Rate (vph)					Upstream Speed (km/h)					Downstream Flow Rate (vph)					Downstream Speed (km/h)					RMSP
		0 - 1'	**1 - 2'**	**2 - 3'**	**3 - 4'**	**4 - 5'**	**0 - 1'**	**1 - 2'**	**2 - 3'**	**3 - 4'**	**4 - 5'**	**0 - 1'**	**1 - 2'**	**2 - 3'**	**3 - 4'**	**4 - 5'**	**0 - 1'**	**1 - 2'**	**2 - 3'**	**3 - 4'**	**4 - 5'**	
	11	6540	6120	5100	4380	5220	98.6	102.1	100.2	106.1	103.2	5880	5400	4980	5220	5520	96.8	101.9	102.3	103.6	101.1	**0.048**
	19	6480	5820	5280	4560	5340	103.8	95.8	104.0	103.5	103.8	6420	5640	4560	5220	5340	99.1	104.2	104.7	101.6	104.5	**0.051**
	9	6420	6180	4740	4500	5580	100.4	99.3	100.2	104.6	97.8	6240	5820	4020	4920	5640	98.6	102.1	104.7	103.8	97.6	**0.055**
	3	6600	5880	4980	4320	5700	91.9	99.6	104.6	102.4	101.4	6300	5460	4740	4980	5460	98.9	101.8	100.4	100.6	100.5	**0.057**
	1	6120	6000	5040	4560	5340	99.1	101.0	103.8	104.2	102.8	6000	6000	4380	5040	5340	98.5	96.6	102.4	98.3	95.5	**0.057**
522	13	5880	6120	5160	4560	5640	101.6	91.1	97.6	104.2	101.1	5580	6300	4260	4980	5940	102.2	97.9	104.3	101.6	100.3	**0.067**
	7	6180	6060	5100	4380	5460	90.8	90.0	101.3	101.6	96.8	5700	5340	4800	5100	5280	98.6	101.8	100.5	98.0	99.9	**0.069**
	10	6540	6060	5220	4080	5760	102.3	102.6	103.7	105.2	103.2	6300	5520	5160	4200	5160	99.6	100.3	103.9	102.7	103.5	**0.073**
	15	6120	6300	4500	4380	6060	104.1	92.7	103.1	105.4	94.6	6000	5760	3900	5700	6000	100.5	97.0	104.9	97.4	101.5	**0.078**
	6	6360	6120	5040	4440	5700	94.6	95.6	102.4	103.3	94.8	6120	5280	5220	4860	6300	100.1	98.3	100.0	102.0	101.1	**0.078**
	Obs.	**6420**	**6120**	**5100**	**4320**	**5520**	**99.4**	**104.3**	**101.2**	**112.7**	**109.4**	**5880**	**5520**	**4380**	**5220**	**5520**	**99.3**	**101.3**	**108.7**	**113.4**	**107.9**	
	69	4740	5580	5640	5400	4980	41.1	53.5	72.9	52.6	49.9	5220	5220	5400	4740	5460	50.3	52.9	47.1	54.1	56.5	**0.113**
	28	4860	5400	5280	5160	5460	43.4	54.8	56.8	51.6	53.3	5100	5040	5160	5220	5040	41.9	44.7	51.1	54.5	49.2	**0.115**
	3	4980	5040	5460	5340	5160	42.9	44.5	51.1	61.9	61.4	4740	5160	4980	4860	5100	58.5	51.6	50.8	53.0	60.7	**0.121**
	38	4980	4980	5580	5400	5100	42.0	49.9	47.8	48.5	56.5	4560	5520	5220	4860	5880	45.8	52.4	55.6	42.0	56.4	**0.127**
	16	4500	5700	4860	5700	5280	45.1	53.8	40.5	58.7	59.2	5160	5100	5580	4860	5280	38.9	50.0	52.2	46.3	51.1	**0.131**
571	82	5340	5460	5280	5220	5100	44.2	53.6	59.6	48.1	46.7	5400	4980	5340	5220	5100	50.4	55.2	48.5	55.1	54.8	**0.136**
	26	5160	5460	5280	4500	5700	47.4	48.9	59.3	45.4	65.6	5160	5040	5040	5220	4740	47.3	51.8	59.8	52.0	63.1	**0.137**
	12	5340	5160	5520	4500	5460	48.6	51.1	60.3	40.1	67.5	5340	5280	5220	4920	5160	46.6	51.6	55.7	57.7	60.7	**0.140**
	18	4740	5040	4500	5520	5040	42.3	59.9	51.1	54.5	64.6	5520	5100	4620	4860	5220	63.0	57.4	47.9	40.8	52.3	**0.142**
	74	5100	5280	5580	5460	4800	46.7	50.1	67.6	59.2	43.0	5280	5460	5220	4680	4920	53.4	58.4	46.8	46.9	53.8	**0.143**
	Obs.	**4140**	**5100**	**5100**	**5280**	**4800**	**41.2**	**63.0**	**63.2**	**59.7**	**67.9**	**4320**	**4980**	**5040**	**4560**	**5340**	**46.6**	**54.3**	**54.1**	**57.1**	**54.9**	
	446	5940	5820	5640	4500	5520	102.9	102.9	103.0	105.5	89.8	4620	5280	3540	4080	4860	50.0	61.3	44.9	46.6	68.9	**0.098**
	349	5820	6000	5460	4620	5460	105.4	103.9	106.6	106.7	87.5	5280	4860	3480	4140	5340	53.4	59.1	45.7	46.0	70.4	**0.099**
	851	5760	5880	5580	4740	5460	103.3	103.5	104.1	105.5	91.6	4740	4680	4140	3720	5340	52.6	60.4	44.7	46.8	68.9	**0.099**
	523	5640	6180	5400	4620	5460	102.9	104.3	104.2	104.4	89.0	4440	4500	3960	3960	5160	54.2	63.6	44.9	46.2	70.5	**0.100**
	529	5760	6000	5640	4620	5460	103.8	103.9	105.3	104.8	78.0	5100	4980	3660	4020	5280	53.6	61.2	45.4	47.7	69.0	**0.100**
595	15	5760	6060	5580	4620	5520	104.2	103.7	103.9	104.5	91.3	4860	5220	4140	3900	4980	53.7	59.7	45.1	47.3	69.3	**0.101**
	734	5820	5880	5580	4680	5400	105.1	103.8	104.4	104.6	90.0	4860	5280	3540	3960	5280	52.7	59.2	45.1	46.8	69.6	**0.101**
	373	5640	6000	5580	4680	5340	88.6	103.4	104.0	104.1	93.0	4980	4740	4140	3960	5640	54.0	64.9	42.3	47.2	69.9	**0.102**
	787	5880	5880	5520	4440	5340	103.6	102.5	104.0	103.2	85.7	5040	4320	3780	3780	4980	53.2	64.4	44.2	46.5	70.4	**0.102**
	790	5760	5820	5460	4740	5400	104.1	102.6	105.0	104.7	85.6	4980	4500	4020	4260	4800	52.5	64.7	44.2	45.2	70.9	**0.102**
	Obs.	**6120**	**6420**	**5460**	**4500**	**5340**	**81.7**	**95.0**	**103.9**	**104.1**	**82.0**	**4680**	**4560**	**3780**	**4080**	**4860**	**49.8**	**50.3**	**44.4**	**41.2**	**67.7**	

Table C.6: Test 1 and 2 pre-simulation volume/speed RMSP - crash conditions (#647, #688 and #702)

Crash #	Seed	Upstream Flow Rate (vph)					Upstream Speed (km/h)					Downstream Flow Rate (vph)					Downstream Speed (km/h)					RMSP
		0 - 1'	**1 - 2'**	**2 - 3'**	**3 - 4'**	**4 - 5'**	**0 - 1'**	**1 - 2'**	**2 - 3'**	**3 - 4'**	**4 - 5'**	**0 - 1'**	**1 - 2'**	**2 - 3'**	**3 - 4'**	**4 - 5'**	**0 - 1'**	**1 - 2'**	**2 - 3'**	**3 - 4'**	**4 - 5'**	
647	518	4980	5640	6180	6000	5820	90.5	83.9	102.3	102.5	94.6	4800	5640	6000	6420	5880	66.8	73.2	71.6	74.6	73.9	**0.095**
	820	5220	5340	6420	5940	5880	76.5	101.6	101.8	96.7	82.2	5100	6060	5820	6180	6420	64.9	73.0	73.7	72.1	66.4	**0.100**
	285	5040	5940	5820	6000	5640	90.3	82.7	99.9	89.6	102.2	5160	5700	6120	5640	5580	66.5	74.6	74.7	75.0	74.6	**0.104**
	660	4980	5520	6360	5820	5520	97.9	101.6	78.0	96.1	87.5	4440	6180	6240	5940	5220	68.0	75.8	70.8	76.9	74.2	**0.105**
	88	4860	5460	6360	6180	5520	95.9	100.4	101.9	99.7	103.3	4800	5940	5940	5640	5880	67.1	74.6	73.7	75.0	74.4	**0.105**
	119	4920	5520	6180	5760	6000	96.8	99.0	101.1	102.1	79.1	4680	5760	5940	6240	6060	67.9	75.3	72.5	73.3	74.2	**0.106**
	45	5040	5700	6360	5700	5640	95.1	104.1	88.4	100.4	101.2	4860	6060	5820	6300	5940	65.6	73.8	74.1	69.9	73.8	**0.106**
	399	4920	5460	6240	6060	5760	98.4	90.1	100.6	98.1	100.3	4620	6420	6120	5940	4920	66.0	70.1	70.8	75.4	75.0	**0.106**
	607	5040	5460	6300	5940	6000	92.7	103.4	102.8	101.2	101.9	4920	6120	6120	6120	5400	66.9	71.8	71.5	72.6	76.8	**0.107**
	756	5220	5160	6360	6060	5580	98.4	103.8	100.4	100.8	97.6	4500	6360	5940	6240	5040	66.1	75.3	72.7	76.4	75.2	**0.107**
	Obs.	**4920**	**5580**	**6180**	**5940**	**5820**	**73.7**	**91.2**	**92.2**	**90.6**	**90.7**	**3960**	**5820**	**5220**	**5760**	**5460**	**65.8**	**75.0**	**74.5**	**75.3**	**76.1**	
688	14	5880	4500	5460	5580	5280	99.3	86.5	48.4	60.8	46.6	5580	6240	5580	5700	5580	49.5	73.7	57.0	47.7	47.0	**0.145**
	1	4680	5220	4980	5640	4680	88.6	85.5	64.3	54.6	50.1	5280	5880	4980	5760	5280	46.0	72.1	45.1	61.5	41.1	**0.150**
	17	5700	5400	5400	5820	5400	64.0	70.8	53.4	70.8	57.8	5400	5940	5940	5580	5160	46.3	67.4	55.9	48.7	44.8	**0.152**
	6	4500	4740	5400	5700	5100	102.8	85.2	45.3	51.9	49.5	5400	6180	5280	5820	5340	43.2	66.8	50.2	57.1	48.9	**0.153**
	19	5460	5460	4920	5400	5040	61.1	81.5	49.9	55.3	49.4	5640	6060	5100	5760	5280	46.3	72.5	51.6	54.7	46.5	**0.157**
	3	5100	5100	5280	4860	4800	101.5	84.7	57.5	48.8	57.0	5580	6000	5700	5220	4980	43.9	52.6	57.4	44.3	49.9	**0.162**
	18	5760	5580	5280	5580	5220	70.7	51.1	63.1	58.6	44.7	5340	5940	5460	5820	5280	46.3	72.8	56.4	51.5	47.3	**0.162**
	10	5460	5580	5520	5580	4680	83.5	59.9	61.7	63.2	46.3	5580	5640	5640	5400	5340	41.7	61.7	45.7	56.3	43.5	**0.165**
	2	5220	4560	5460	5040	4800	103.2	73.8	71.0	84.8	44.0	5340	6060	5640	5220	5760	41.4	65.9	56.8	51.6	51.4	**0.169**
	4	5220	4920	5820	5400	5040	98.7	53.8	63.2	49.0	47.7	5460	5580	6120	5280	5520	44.3	40.9	65.7	58.1	45.9	**0.169**
	Obs.	**5520**	**4680**	**5640**	**5640**	**5220**	**85.8**	**80.0**	**60.0**	**60.1**	**59.3**	**4800**	**5520**	**5460**	**5160**	**6000**	**47.7**	**73.6**	**79.3**	**72.9**	**58.2**	
702	11	4680	5700	6120	5820	6240	88.1	83.6	60.2	69.2	66.6	5040	5220	5580	6300	6000	39.1	40.6	80.6	87.0	89.2	**0.095**
	5	4620	5520	5820	6480	5880	101.7	96.6	85.6	75.4	85.0	5400	4860	6000	5880	6300	40.8	41.1	78.7	89.3	87.4	**0.105**
	84	4500	5520	5940	6300	6060	103.8	101.0	86.8	58.0	59.4	5160	5100	6360	6060	5760	42.2	42.2	75.2	86.7	87.0	**0.112**
	54	4380	6000	5940	5940	5880	106.1	96.6	94.9	75.8	57.7	4920	5040	6180	5700	6180	40.9	46.4	79.7	90.1	86.7	**0.115**
	3	5100	5340	5760	6120	5340	97.1	96.8	63.1	64.5	83.3	5400	5100	6000	5760	5400	41.6	39.2	78.4	87.5	88.3	**0.117**
	40	4680	5640	5880	5400	6180	104.3	103.1	95.5	96.8	75.9	5100	5160	5460	6120	5820	40.6	43.0	80.5	86.2	88.7	**0.119**
	66	4440	5100	6060	5880	6300	104.8	90.8	58.5	59.1	59.4	5100	5220	5700	6240	5940	41.6	42.0	80.3	86.5	88.3	**0.120**
	4	4860	4980	6600	5940	5820	104.0	92.8	95.9	69.1	57.1	4800	5160	6360	5700	5820	38.1	37.0	76.8	87.6	88.1	**0.121**
	77	4140	5160	5940	6000	5760	103.8	93.2	55.1	57.1	58.5	5040	5160	5700	5940	5640	42.7	45.3	79.8	88.6	89.4	**0.123**
	51	3900	5880	6120	6000	6000	106.4	79.7	68.0	56.4	62.3	5160	5220	6000	5880	5940	40.1	40.9	80.4	88.2	86.3	**0.124**
	Obs.	**4140**	**5280**	**6480**	**5940**	**5880**	**82.0**	**94.5**	**79.8**	**76.2**	**70.8**	**4680**	**4680**	**5520**	**6300**	**5460**	**45.9**	**41.7**	**79.3**	**90.5**	**94.6**	

Table C.7: Test 1 and 2 pre-simulation volume/speed RMSP - crash conditions (#710, #731 and #739)

Crash #	Seed	Upstream Flow Rate (vph)					Upstream Speed (km/h)					Downstream Flow Rate (vph)					Downstream Speed (km/h)					RMSP
		0 - 1'	**1 - 2'**	**2 - 3'**	**3 - 4'**	**4 - 5'**	**0 - 1'**	**1 - 2'**	**2 - 3'**	**3 - 4'**	**4 - 5'**	**0 - 1'**	**1 - 2'**	**2 - 3'**	**3 - 4'**	**4 - 5'**	**0 - 1'**	**1 - 2'**	**2 - 3'**	**3 - 4'**	**4 - 5'**	
710	65	6600	5760	6600	6360	6540	65.8	57.6	73.4	93.6	84.3	4980	6060	6240	6480	6600	38.2	62.1	66.5	79.3	77.8	**0.107**
	22	6180	6120	5940	6300	6360	62.2	53.2	80.9	72.2	67.6	5160	5940	6360	6180	6540	34.6	62.3	67.9	80.5	76.9	**0.117**
	958	6480	6060	6480	6480	6300	57.6	57.4	58.1	83.4	65.5	5220	6240	6120	6480	6300	34.0	60.0	66.5	80.3	80.5	**0.122**
	323	6180	5940	6360	6600	6360	59.0	59.4	56.6	65.1	69.8	4980	6480	6360	6240	6120	38.3	63.2	65.0	77.6	75.2	**0.124**
	798	6180	5940	5940	6720	6360	56.6	61.4	59.5	73.9	94.6	5100	6300	6360	6480	6300	33.5	61.4	65.8	81.2	80.1	**0.128**
	567	6300	6120	6240	6060	6360	53.2	53.4	59.7	72.1	66.9	4980	6180	5820	6600	6540	32.5	63.8	67.9	77.5	76.6	**0.128**
	804	6060	6300	6000	6480	6540	65.8	56.9	78.5	96.3	83.3	5040	6300	6120	6660	6300	35.3	55.9	66.3	73.3	76.4	**0.129**
	797	6660	6000	6060	6060	6180	70.0	64.9	59.8	71.9	66.5	5040	6000	6240	5820	6000	36.9	65.4	64.6	83.3	82.3	**0.131**
	132	6120	5760	6540	6540	6360	66.6	53.9	61.1	68.0	78.8	5160	6120	6300	6180	6180	35.2	58.5	65.8	82.3	83.4	**0.131**
	728	6600	5940	6420	6360	5820	71.2	57.2	63.7	67.1	80.8	4980	6000	5940	6060	6420	35.4	63.2	67.1	79.2	78.8	**0.133**
	Obs.	**6540**	**5760**	**6600**	**6780**	**6120**	**53.5**	**64.1**	**82.1**	**82.2**	**76.9**	**4740**	**6120**	**5760**	**6540**	**6300**	**48.9**	**72.8**	**71.7**	**87.3**	**91.8**	
731	749	6060	6120	5520	6120	5580	83.6	79.7	98.3	88.2	101.0	4440	4380	5700	5640	5700	31.9	35.4	56.0	74.3	80.9	**0.119**
	944	5700	6360	6180	6000	6000	87.9	86.1	79.6	88.2	88.9	4500	4500	5820	6060	5940	31.9	35.4	57.1	74.0	78.4	**0.123**
	99	5640	6300	5880	5760	6060	90.5	88.1	87.6	89.2	94.1	4200	4320	5340	6060	5940	30.8	34.9	58.6	74.0	78.7	**0.127**
	407	5580	6000	5940	5820	5940	85.8	98.5	91.4	90.0	97.7	4440	4500	5640	5940	6060	30.4	35.2	53.1	71.8	67.9	**0.131**
	371	6000	6180	5820	5940	5820	92.9	78.0	89.1	96.4	91.6	4380	4320	5400	5880	6180	31.7	35.0	56.8	74.3	78.7	**0.132**
	198	6060	6240	5880	5220	6240	89.9	89.3	88.7	101.7	98.4	4440	4500	5400	5700	5940	31.7	36.0	58.6	73.7	78.8	**0.133**
	862	5700	5760	6540	5700	6180	86.3	100.3	90.0	94.3	88.7	4380	4320	5400	6240	5820	31.9	35.4	56.5	73.7	80.4	**0.134**
	357	5880	6060	5640	6240	6240	92.2	78.7	93.9	97.8	93.9	4020	4200	5820	6000	6240	31.4	35.8	57.6	73.5	78.2	**0.135**
	727	6300	5520	6480	5580	6360	85.0	97.6	91.7	95.7	87.0	4200	4620	5820	6060	5940	31.7	34.8	55.5	73.2	78.8	**0.137**
	133	6180	5100	6120	6120	6060	86.4	100.7	91.6	94.4	98.8	4440	4440	5760	6000	6060	31.8	34.7	54.0	71.0	78.8	**0.140**
	Obs.	**5134**	**5593**	**5706**	**5703**	**6309**	**62.6**	**75.0**	**81.8**	**89.7**	**93.6**	**4196**	**4546**	**5068**	**5671**	**5885**	**37.4**	**36.5**	**52.8**	**65.4**	**78.3**	
739	78	5520	6780	5580	6360	5220	86.2	94.6	99.4	100.6	101.4	2520	5760	6060	5760	4560	33.2	100.3	98.6	99.7	100.3	**0.126**
	52	5340	6720	5880	6300	5160	100.4	100.7	100.4	98.8	101.7	2280	5700	6540	5640	4920	33.1	100.6	95.2	101.8	99.6	**0.132**
	68	5100	7080	5400	6240	5400	100.5	102.0	102.7	100.9	102.5	2580	5400	6120	5880	5040	32.8	103.5	100.6	92.6	101.3	**0.133**
	97	5220	6960	5280	6900	5220	94.6	100.5	103.7	102.3	102.5	2460	5820	6060	6060	5100	29.0	100.1	97.4	102.1	103.1	**0.136**
	73	5460	6540	5760	6300	5340	95.2	100.5	101.2	98.3	97.4	2640	5880	6300	5640	4800	31.5	101.2	102.7	100.8	101.6	**0.138**
	99	5520	6900	5400	6480	5400	91.7	95.1	101.9	101.6	101.0	2580	5820	6060	5880	4800	30.0	99.4	93.3	99.9	101.3	**0.138**
	85	5520	6660	5220	6720	5160	99.1	98.8	97.1	89.9	102.7	2580	6000	6180	5340	5160	32.6	100.7	97.4	101.1	101.4	**0.140**
	30	5340	7020	5460	6720	5100	100.1	100.6	101.9	97.5	99.4	2520	5640	6480	5400	4380	29.9	103.2	97.1	102.0	102.3	**0.140**
	88	5280	6660	5580	6720	4860	95.0	100.2	96.3	90.7	103.1	2580	5880	6240	5280	4920	31.3	101.1	96.1	98.3	101.8	**0.141**
	60	5460	6720	5580	6540	5160	85.6	100.0	103.8	101.9	105.4	2520	6060	6060	6000	4680	26.7	100.2	97.5	101.0	103.6	**0.142**
	Obs.	**4920**	**7140**	**5340**	**6660**	**5280**	**87.9**	**101.7**	**106.5**	**100.7**	**107.2**	**2215**	**6000**	**5880**	**6120**	**4500**	**66.2**	**102.9**	**104.7**	**104.4**	**106.7**	

Table C.8: Test 1 and 2 pre-simulation volume/speed RMSP - crash conditions (#781, #854 and #858)

Crash #	Seed	Upstream Flow Rate (vph)					Upstream Speed (km/h)					Downstream Flow Rate (vph)					Downstream Speed (km/h)					RMSP
		0 - 1'	**1 - 2'**	**2 - 3'**	**3 - 4'**	**4 - 5'**	**0 - 1'**	**1 - 2'**	**2 - 3'**	**3 - 4'**	**4 - 5'**	**0 - 1'**	**1 - 2'**	**2 - 3'**	**3 - 4'**	**4 - 5'**	**0 - 1'**	**1 - 2'**	**2 - 3'**	**3 - 4'**	**4 - 5'**	
	57	6180	6420	6720	6480	6900	73.3	86.3	81.6	83.4	81.8	6360	6540	6720	6540	6360	66.2	76.5	87.6	85.9	88.1	**0.054**
	916	6540	6300	6300	6780	6780	67.9	77.4	89.3	80.3	77.0	6240	6180	6600	6660	6540	69.6	71.3	93.4	89.4	88.3	**0.062**
	779	6660	6120	6540	7080	6300	89.1	85.4	89.1	82.6	76.0	6360	6480	6720	6360	6300	69.8	76.8	89.9	93.7	88.5	**0.065**
	747	6360	6540	6360	6660	6900	77.7	66.8	83.4	76.9	88.8	6180	5940	6780	6360	5700	66.6	76.8	95.5	85.8	89.7	**0.071**
	978	6480	6360	5880	6720	6720	87.0	77.4	72.7	87.9	90.0	6420	5700	6540	6540	6600	64.4	83.8	97.1	89.1	88.4	**0.072**
781	7	6360	6240	6780	6660	6720	77.6	68.7	83.2	77.6	98.4	5940	6360	6240	6840	6720	57.4	79.5	93.1	86.2	86.8	**0.073**
	447	6420	6540	6300	6780	6720	86.6	70.8	68.7	83.9	89.7	6060	6120	6480	6720	5880	69.2	78.4	88.5	86.3	87.7	**0.074**
	395	6000	6480	6780	6600	6900	87.0	77.5	88.9	97.7	92.4	6180	6420	6780	6720	6480	63.3	73.5	87.1	84.1	85.1	**0.074**
	267	6480	6120	6720	6960	6420	62.5	72.9	90.0	79.5	78.9	6240	6480	6240	6660	6360	64.9	75.8	95.4	90.8	88.7	**0.074**
	709	6420	6420	6480	6600	6900	90.5	84.5	82.9	86.2	93.0	6660	6360	6480	6600	6540	58.5	74.4	85.0	88.5	88.2	**0.076**
	Obs.	**6480**	**6180**	**6720**	**6840**	**6780**	**79.2**	**81.5**	**82.9**	**82.1**	**82.1**	**5580**	**6060**	**7020**	**6900**	**6540**	**64.7**	**78.4**	**92.0**	**90.8**	**82.8**	
	47	5460	6300	5760	4680	4740	91.1	92.8	87.6	105.1	104.0	5940	6540	4380	4620	4680	75.2	95.9	103.5	105.2	102.9	**0.050**
	34	6120	6180	5760	4440	4920	98.8	92.1	100.3	105.5	103.6	6180	6360	4260	4620	4980	72.7	94.9	103.3	103.6	103.0	**0.050**
	26	5880	6420	5880	4440	4740	97.9	97.9	101.1	103.8	103.5	6060	6300	4620	4560	5040	74.4	96.9	103.2	102.3	102.6	**0.057**
	15	5700	6480	5460	4500	5100	103.6	97.9	99.3	106.7	102.7	5940	6120	4260	5460	4680	74.4	95.8	105.1	99.5	103.3	**0.060**
	90	5880	6180	5940	4320	4800	103.6	98.5	100.4	106.2	104.5	6120	6360	4500	4560	4260	74.0	99.9	102.4	102.7	103.2	**0.060**
854	9	5940	6240	5700	4620	4560	95.8	97.3	102.4	105.2	96.8	6000	6300	4560	4740	4800	70.2	100.4	101.3	103.0	102.4	**0.060**
	128	5760	6540	5940	4320	4500	101.3	102.3	100.9	105.9	105.5	5820	6720	4500	4500	4440	74.9	94.4	104.0	102.6	102.7	**0.062**
	105	6000	6240	5760	4500	4500	103.4	102.9	101.9	105.2	104.8	6180	6300	4320	5160	4200	70.4	100.7	103.8	101.5	103.4	**0.063**
	74	5880	6360	5760	4740	4800	99.5	101.1	102.8	103.9	102.1	6420	6180	4620	4740	5040	74.9	101.0	103.7	103.4	100.7	**0.065**
	101	5940	6120	6180	4440	4800	100.3	79.9	102.1	105.2	104.0	6000	6180	4680	4800	4740	75.1	97.2	103.4	102.8	101.5	**0.065**
	Obs.	**5940**	**6300**	**6060**	**4440**	**4620**	**94.4**	**94.4**	**91.2**	**103.0**	**102.2**	**6360**	**6120**	**4080**	**4980**	**4620**	**77.4**	**89.7**	**97.8**	**98.6**	**100.7**	
	120	6420	4560	5280	4740	5280	100.7	105.6	104.6	103.9	103.2	5580	4620	4680	5040	5160	76.9	102.1	100.2	96.6	98.9	**0.058**
	437	6660	4260	5340	4680	5220	100.8	103.9	100.6	105.3	101.6	5880	4320	4620	5580	5340	77.4	99.5	103.1	92.0	98.8	**0.060**
	419	6420	4500	5160	4680	5280	101.9	106.8	98.1	103.6	102.4	5340	4380	4740	4980	4800	77.7	105.5	103.6	96.0	99.2	**0.060**
	661	6180	4920	5160	4740	5340	101.4	103.5	105.2	105.5	100.5	5580	4680	4500	5520	5580	74.8	103.6	105.2	94.3	97.7	**0.063**
	751	6000	4620	5340	4500	5340	96.2	104.7	101.8	102.5	103.5	5400	4680	4560	5340	5280	78.5	102.7	102.5	95.6	98.3	**0.063**
858	614	6420	4500	5400	4500	5220	101.3	103.2	103.7	104.5	101.1	5400	4680	4620	5520	4980	76.1	102.5	100.8	94.4	100.5	**0.063**
	892	6300	5040	5220	4440	5580	102.7	103.3	104.3	107.5	103.2	5760	4620	4800	4980	5400	77.9	102.8	102.5	96.5	98.4	**0.063**
	961	6360	4320	5220	4740	5340	100.0	99.3	104.7	103.2	99.6	5700	4440	4680	4920	5640	76.7	101.2	103.0	95.3	99.1	**0.063**
	592	6480	4380	5460	4800	5100	102.0	106.6	105.1	101.4	103.2	5820	4440	4920	5160	4860	76.3	101.1	104.3	95.9	100.7	**0.063**
	683	6300	4440	5460	4500	5160	104.2	105.8	106.3	102.7	104.1	5460	4800	4680	4920	5040	77.0	103.6	103.4	95.2	101.1	**0.064**
	Obs.	**5415**	**6720**	**4800**	**5580**	**4560**	**105.4**	**101.9**	**105.2**	**108.2**	**106.2**	**5640**	**4020**	**4140**	**5100**	**5220**	**75.6**	**106.0**	**108.6**	**97.6**	**103.9**	

Table C.9: Test 1 and 2 pre-simulation volume/speed RMSP - crash conditions (#884, #888 and #903)

Crash #	Seed	Upstream Flow Rate (vph)					Upstream Speed (km/h)					Downstream Flow Rate (vph)					Downstream Speed (km/h)					RMSP
		0 - 1'	**1 - 2'**	**2 - 3'**	**3 - 4'**	**4 - 5'**	**0 - 1'**	**1 - 2'**	**2 - 3'**	**3 - 4'**	**4 - 5'**	**0 - 1'**	**1 - 2'**	**2 - 3'**	**3 - 4'**	**4 - 5'**	**0 - 1'**	**1 - 2'**	**2 - 3'**	**3 - 4'**	**4 - 5'**	
884	779	5040	5580	6060	5940	5400	58.2	60.9	60.3	56.8	49.7	5160	5340	6060	5340	5460	45.3	39.4	74.7	47.1	49.9	**0.104**
	397	5640	5520	5580	5820	5280	80.0	59.4	59.8	58.1	45.1	5280	4920	5760	5520	5520	45.1	35.4	73.0	59.0	46.9	**0.104**
	179	5580	5400	6180	5700	5220	56.4	57.8	77.0	52.6	44.4	5280	5040	6180	5760	5220	44.0	37.3	69.9	56.8	44.9	**0.109**
	118	5820	5760	5460	5580	5340	48.2	60.0	62.1	57.3	50.9	5100	5220	6060	5700	5760	46.1	39.2	82.0	66.5	46.3	**0.115**
	595	5580	5520	5760	5520	5820	59.6	55.0	63.9	50.4	43.1	5160	5040	5940	5760	5580	38.3	39.9	55.4	44.6	52.4	**0.124**
	987	5580	5340	5820	5580	5280	69.7	46.6	55.2	55.5	47.3	5040	4980	5940	5580	5760	42.7	39.9	47.3	58.5	53.3	**0.127**
	165	6000	5100	5760	5460	5520	88.2	52.4	65.3	60.7	48.3	5160	5040	6120	5580	5340	48.2	36.2	71.0	60.2	41.6	**0.138**
	271	5940	5700	5460	5640	5700	60.9	63.1	59.3	70.9	47.3	4860	5160	5820	5820	5580	38.7	42.2	59.0	59.1	47.5	**0.139**
	369	5820	4740	6120	5580	5460	69.8	52.4	78.4	70.5	45.2	4980	4860	5940	5580	5580	49.0	39.8	65.7	52.8	46.9	**0.139**
	479	5520	5280	6000	5340	6060	62.2	54.2	60.9	59.3	63.9	5040	5520	5940	5760	5520	48.3	43.4	82.7	53.3	44.7	**0.154**
	Obs.	**5220**	**5460**	**5520**	**5400**	**5100**	**63.5**	**59.4**	**61.2**	**51.7**	**42.4**	**4500**	**5040**	**5700**	**6000**	**5100**	**56.6**	**38.1**	**73.4**	**59.6**	**55.8**	
888	282	4920	5880	4080	5940	4320	101.7	102.1	102.9	99.5	103.9	5220	5040	5160	4320	5640	60.0	83.2	99.5	102.5	100.3	**0.051**
	394	5760	5820	4020	6060	4620	100.2	99.8	104.5	101.4	102.7	5400	4800	4980	4560	5640	59.6	83.7	99.2	101.7	100.6	**0.055**
	100	5820	5760	4320	6360	4380	103.0	101.3	102.5	101.4	104.0	5640	4860	5220	4680	5580	59.7	83.4	97.8	100.8	101.4	**0.056**
	411	5220	5940	3960	5580	3960	100.1	95.9	103.7	102.6	103.0	5280	5160	5100	4140	4920	61.5	83.4	92.3	101.5	97.4	**0.056**
	320	5520	5940	4680	6780	4260	100.8	102.3	98.9	97.7	103.6	5040	5340	6240	4440	5340	60.9	81.3	97.5	102.9	102.5	**0.060**
	11	5280	6300	4680	6180	3840	99.8	102.6	103.1	103.0	105.8	5160	5460	5400	4920	4620	58.4	83.9	95.9	102.7	102.9	**0.063**
	87	5460	6420	4680	5820	4320	101.6	102.5	96.6	90.6	106.5	5580	5220	5640	4860	4800	59.1	82.5	101.4	103.9	102.3	**0.063**
	253	4800	6420	4440	6000	4260	104.0	100.2	100.7	93.5	104.0	5580	5460	5220	4800	5220	58.9	84.0	99.7	101.1	99.9	**0.064**
	147	5340	5880	3960	6060	3900	103.6	96.4	105.5	102.1	103.5	5520	5040	5100	4740	4860	59.9	84.7	101.0	103.2	100.5	**0.064**
	263	6120	6240	4800	5580	3900	95.9	91.4	101.6	98.2	106.9	5580	5280	5460	4320	5100	61.0	84.4	99.2	104.6	97.2	**0.064**
	Obs.	**5460**	**6300**	**4440**	**6060**	**4380**	**98.0**	**99.8**	**103.7**	**99.6**	**107.5**	**4980**	**4860**	**5460**	**4380**	**5220**	**58.2**	**80.7**	**92.1**	**104.9**	**93.6**	
903	42	5074	6152	6662	6692	6956	58.7	95.7	102.0	96.1	94.4	2353	4994	6966	7169	6333	39.2	60.5	91.4	91.6	92.0	**0.030**
	46	5074	6278	6793	7142	6377	61.8	102.2	98.4	93.6	92.9	2306	4994	6900	6708	6533	38.7	59.9	86.2	92.5	92.5	**0.035**
	12	5385	6278	6793	6949	6699	56.0	93.6	102.0	96.8	93.5	2494	5271	7033	6972	6000	40.7	65.4	91.5	91.6	94.2	**0.038**
	77	4919	6466	6597	6821	6312	62.2	98.8	98.5	90.2	96.0	2588	5160	6900	6906	5867	35.6	59.7	91.4	92.6	94.8	**0.039**
	26	4919	6403	6858	7014	6634	61.4	104.1	101.2	81.2	86.7	2494	5326	6834	6643	6267	35.0	60.7	91.0	92.7	92.6	**0.044**
	55	5022	6089	6728	7142	6505	65.9	103.9	92.2	96.5	94.8	2400	4994	7232	6972	5867	35.4	61.4	90.8	90.6	95.3	**0.049**
	69	5281	6027	6793	6756	6827	47.9	94.6	95.3	99.2	95.6	2400	5105	6701	7103	6133	36.1	56.4	93.9	91.8	94.0	**0.050**
	47	4867	6340	7054	6499	6827	68.3	104.6	89.1	81.0	91.5	2541	5215	6568	6708	6267	38.1	59.2	94.4	92.6	93.5	**0.062**
	4	5229	6529	6466	6821	6634	50.8	80.7	89.1	85.2	79.7	2165	5326	6900	6840	6400	40.3	66.0	92.5	92.2	94.2	**0.070**
	64	5229	5838	7054	6563	6827	39.5	96.6	94.6	97.4	83.6	2259	5215	6966	6380	6133	37.6	59.4	93.3	94.4	93.6	**0.079**
	Obs.	**5100**	**6240**	**6780**	**6840**	**6660**	**57.3**	**97.5**	**96.3**	**91.7**	**90.9**	**2400**	**5160**	**6900**	**6840**	**6180**	**37.7**	**60.8**	**91.7**	**92.2**	**93.7**	

Appendix D

Pre-simulation Volume and Speed RMSP - Non-crash Conditions

Table D.1: Test 2 pre-simulation volume/speed RMSP - non-crash conditions (#118, #170 and #222)

Crash #	Seed	Upstream Flow Rate (vph)					Upstream Speed (km/h)					Downstream Flow Rate (vph)					Downstream Speed (km/h)					RMSP
		0 - 1'	**1 - 2'**	**2 - 3'**	**3 - 4'**	**4 - 5'**	**0 - 1'**	**1 - 2'**	**2 - 3'**	**3 - 4'**	**4 - 5'**	**0 - 1'**	**1 - 2'**	**2 - 3'**	**3 - 4'**	**4 - 5'**	**0 - 1'**	**1 - 2'**	**2 - 3'**	**3 - 4'**	**4 - 5'**	
118	124	2940	2880	2940	3000	3060	106.5	106.8	107.0	104.0	106.5	2820	3000	3120	2880	3000	105.4	106.7	104.8	107.2	106.6	**0.039**
	125	2880	2940	2940	3000	3000	106.2	106.6	107.4	106.5	104.8	2880	2880	3060	3060	2880	106.1	106.7	105.6	104.3	107.6	**0.040**
	127	3000	2820	2940	3060	2940	106.7	107.5	106.3	106.0	107.5	2940	2880	2940	2940	3120	106.0	104.1	106.3	105.6	106.5	**0.040**
	198	2820	2940	2940	3060	2940	106.0	105.9	105.9	105.2	107.7	2880	2940	3180	2940	2940	103.6	106.4	104.4	107.1	105.5	**0.041**
	197	2940	2880	3000	2880	3060	106.3	105.9	105.1	107.8	107.2	2880	3120	3000	2940	2880	106.1	104.2	106.3	107.5	106.1	**0.043**
	196	2880	2940	2820	3000	3180	105.7	104.2	107.7	106.7	106.8	3120	2880	3000	3000	3000	105.0	106.5	107.4	104.2	105.7	**0.043**
	192	2880	3000	2820	3000	3180	105.2	105.9	107.9	106.2	106.9	2940	2760	3000	3060	3060	106.8	107.5	106.8	104.2	106.2	**0.043**
	194	2760	2880	2940	3120	2940	107.1	107.6	106.8	105.6	107.2	2760	2880	3120	2820	3060	106.8	105.8	106.0	106.4	107.4	**0.043**
	129	2820	2820	3060	2940	3060	106.5	106.9	106.9	106.5	106.1	2880	2760	3000	3000	2940	106.3	105.5	105.3	104.7	104.5	**0.044**
	10	2820	2880	2940	2940	3120	105.5	106.3	106.3	104.1	107.2	2700	3060	3060	2940	3180	106.5	106.5	105.9	104.3	105.6	**0.044**
	Obs.	**2880**	**2929**	**2965**	**3000**	**3071**	**110.3**	**116.8**	**114.1**	**113.2**	**108.4**	**2967**	**3022**	**3136**	**3016**	**3115**	**105.9**	**106.8**	**105.5**	**106.6**	**105.4**	
170	198	6240	6360	6060	5880	6060	85.0	71.8	59.8	76.2	83.7	6240	6300	5640	5880	6420	78.1	77.9	75.1	76.1	73.3	**0.080**
	639	5460	6420	5760	6480	6120	88.4	93.4	85.1	81.6	78.0	5820	6180	5940	6360	6060	77.4	78.8	73.4	75.6	73.6	**0.083**
	784	6420	6240	5760	6060	6360	87.1	71.7	93.3	73.4	60.2	6120	5460	6540	6180	6180	74.7	77.8	73.8	76.6	73.6	**0.086**
	204	6240	6240	5700	6240	6540	90.2	83.5	88.6	81.9	60.3	6180	6060	6660	5940	6120	75.8	73.0	74.6	76.1	75.2	**0.087**
	495	5940	6240	5880	6120	6360	69.1	66.6	80.0	87.7	58.2	6120	5700	6360	6240	6180	74.7	77.4	74.5	76.5	74.3	**0.088**
	995	6240	6600	5880	6060	5760	80.5	89.6	99.1	68.1	69.3	6420	5880	6300	5940	6000	70.5	76.0	75.0	75.9	75.5	**0.086**
	258	6120	6360	5700	6240	6300	95.2	88.4	86.2	79.0	69.4	6660	6480	6360	6180	6180	74.4	75.2	75.2	77.1	73.3	**0.086**
	5	6300	6300	5940	5880	6240	77.0	68.7	99.9	84.9	65.3	6360	5700	6000	6240	6300	75.5	76.1	74.6	74.4	74.6	**0.084**
	710	6240	6240	5880	6180	6240	99.5	75.1	85.5	73.0	59.5	6240	6360	6060	6240	5760	73.9	75.6	74.9	75.4	74.7	**0.086**
	306	6000	6600	5940	5880	5880	84.9	85.3	79.5	83.8	99.6	6360	6660	5640	5880	5460	75.0	74.6	75.6	75.8	74.0	**0.089**
	Obs.	**6270**	**6315**	**5935**	**6020**	**6150**	**76.8**	**76.5**	**74.2**	**75.2**	**71.4**	**5662**	**5836**	**5678**	**5662**	**5689**	**77.4**	**79.1**	**79.0**	**76.0**	**76.8**	
222	197	4200	3840	3780	3780	3960	105.9	104.9	104.4	106.7	106.5	3840	3900	3660	4020	3900	92.4	90.8	92.2	93.2	92.7	**0.022**
	58	4320	3900	3660	3840	4080	105.0	104.7	107.5	105.3	104.8	4080	3960	3660	3960	3840	92.7	91.5	93.4	91.9	91.7	**0.022**
	19	4140	3720	3900	3840	3960	106.8	106.6	105.9	105.6	105.1	4080	3780	3660	4080	3960	91.9	92.2	92.2	91.5	90.8	**0.023**
	123	4320	3720	3840	3900	3900	106.0	106.0	106.8	106.3	104.9	4200	3780	3780	4200	3840	93.2	91.6	92.0	92.0	92.2	**0.024**
	124	4260	3900	3660	3960	3960	105.2	106.4	105.9	104.2	104.1	4020	4080	3780	3780	3960	91.6	92.8	91.5	92.4	92.2	**0.025**
	71	4320	3780	3780	3840	4140	106.0	104.9	105.5	106.3	104.9	4020	3840	3780	4080	3660	93.1	91.9	91.2	92.5	93.8	**0.026**
	125	4200	3840	3840	3780	3960	106.1	106.0	106.6	104.1	105.6	3900	3720	3960	4140	3720	92.0	91.8	93.0	91.9	93.0	**0.028**
	95	4140	3780	3840	3960	3900	105.9	105.0	104.4	105.7	105.6	3960	3660	4080	3840	3900	91.0	92.4	92.4	92.7	92.2	**0.028**
	108	4140	3960	3660	3840	4020	103.5	106.4	105.7	106.2	105.4	3900	3900	3540	4080	3720	93.1	91.6	93.6	92.2	92.0	**0.029**
	5	4320	3660	3840	3840	3840	103.4	103.2	105.7	105.9	106.2	4020	3900	3900	3720	4080	91.8	90.5	90.9	92.8	91.7	**0.029**
	Obs.	**4215**	**3865**	**3740**	**3905**	**3960**	**106.6**	**107.6**	**107.3**	**108.7**	**108.5**	**4045**	**3835**	**3800**	**3945**	**3920**	**94.3**	**89.6**	**92.5**	**91.9**	**91.6**	

Table D.2: Test 2 pre-simulation volume/speed RMSP - non-crash conditions (#223, #239 and #320)

Crash #	Seed	Upstream Flow Rate (vph)					Upstream Speed (km/h)					Downstream Flow Rate (vph)					Downstream Speed (km/h)					RMSP
		0 - 1'	**1 - 2'**	**2 - 3'**	**3 - 4'**	**4 - 5'**	**0 - 1'**	**1 - 2'**	**2 - 3'**	**3 - 4'**	**4 - 5'**	**0 - 1'**	**1 - 2'**	**2 - 3'**	**3 - 4'**	**4 - 5'**	**0 - 1'**	**1 - 2'**	**2 - 3'**	**3 - 4'**	**4 - 5'**	
	666	3780	3240	3420	3480	3660	105.2	106.8	106.4	105.9	102.1	3600	3120	3360	3720	3480	104.1	104.9	104.9	102.9	101.4	**0.037**
	90	3600	3300	3420	3480	3720	105.6	104.9	106.1	106.0	104.6	3720	3300	3240	3480	3420	103.2	104.4	103.5	104.8	105.2	**0.037**
	41	3660	3360	3420	3660	3600	102.9	106.0	106.0	106.0	105.7	3360	3300	3300	3480	3360	104.2	103.9	104.8	105.1	106.1	**0.038**
	322	3660	3360	3420	3660	3780	105.9	106.2	106.6	104.4	104.1	3540	3240	3240	3840	3660	104.3	103.4	103.2	103.5	102.3	**0.040**
	966	3660	3420	3300	3540	3720	105.8	106.2	107.8	107.3	105.0	3540	3240	3420	3660	3660	103.8	105.8	106.0	104.6	101.7	**0.040**
223	671	3780	3480	3420	3360	3720	106.3	102.8	105.0	105.1	106.9	3600	3300	3240	3600	3600	105.5	105.2	104.9	105.1	104.0	**0.041**
	208	3780	3300	3480	3660	3480	106.0	105.9	105.7	106.5	103.7	3720	3000	3480	3660	3420	104.8	106.3	106.3	105.9	102.5	**0.041**
	548	3840	3180	3600	3660	3480	102.5	106.3	105.9	105.9	106.7	3480	3060	3420	3600	3360	103.4	106.6	104.6	103.5	105.2	**0.041**
	947	3660	3240	3600	3540	3540	106.8	104.1	106.5	103.1	105.6	3600	3300	3180	3720	3600	104.6	103.9	106.2	101.3	104.6	**0.041**
	497	3660	3360	3420	3600	3420	107.1	106.0	105.6	105.2	103.9	3660	3240	3360	3720	3480	105.5	105.6	104.7	104.1	102.7	**0.042**
	Obs.	**3670**	**3385**	**3433**	**3575**	**3685**	**107.9**	**109.1**	**109.7**	**108.5**	**108.2**	**3502**	**2929**	**3060**	**3475**	**3453**	**103.6**	**104.5**	**104.2**	**102.2**	**102.6**	
	341	5940	5520	6000	5880	5940	87.0	92.1	98.3	93.2	99.1	5820	5820	5400	6240	5520	102.1	100.3	102.3	98.7	99.3	**0.056**
	525	6000	6000	5880	5760	5940	86.2	92.9	97.5	98.0	91.7	6360	5940	5760	5760	5820	100.3	101.3	101.1	101.4	99.5	**0.056**
	305	6060	6060	5940	5520	5880	87.9	86.8	88.2	103.5	97.6	6300	6060	5580	6000	5700	99.9	101.4	101.7	98.0	98.6	**0.059**
	108	5880	5940	5940	5760	5760	94.7	94.0	90.4	90.8	103.1	5760	6000	5760	5820	5700	101.4	96.7	101.8	101.1	101.5	**0.059**
	444	5880	5940	6060	5760	5820	90.3	92.2	98.9	102.1	99.8	6180	5940	5640	6360	5700	101.4	99.8	100.7	98.6	101.4	**0.060**
239	1	5760	5940	6060	5880	6060	103.2	87.4	87.6	87.5	91.7	5940	6120	5640	5940	5760	100.0	99.0	99.1	98.1	96.1	**0.060**
	528	5760	6180	5880	5880	5760	81.1	101.8	100.2	97.2	93.9	5760	6180	5580	6180	5460	102.0	97.1	101.6	99.7	101.0	**0.062**
	293	5820	5760	6240	5880	5460	90.0	94.0	95.3	96.9	98.4	5700	6060	5760	6180	5580	103.4	101.5	101.1	99.7	98.8	**0.062**
	110	6120	5820	6120	5760	5700	76.6	87.1	102.7	102.3	93.0	6060	5940	5460	6120	5400	98.5	99.2	102.8	89.3	101.9	**0.062**
	195	5700	5820	6180	5640	5940	82.3	90.8	98.4	88.9	92.4	5760	5820	6180	5940	5580	101.8	103.2	101.8	103.9	102.4	**0.063**
	Obs.	**5820**	**6016**	**6060**	**5809**	**5907**	**81.7**	**87.9**	**90.1**	**91.3**	**92.0**	**5865**	**5945**	**5485**	**6050**	**5705**	**90.9**	**91.1**	**92.1**	**95.9**	**95.9**	
	756	5820	5700	5880	6000	6000	94.4	74.7	83.1	75.2	57.0	5700	5580	6240	5940	6060	79.0	79.2	76.9	80.5	76.0	**0.100**
	461	5760	5820	5580	5460	6000	87.6	86.9	93.1	95.7	76.4	5640	5460	5760	6300	5040	80.5	79.8	78.9	76.3	81.0	**0.116**
	744	5760	5700	5880	5940	5580	88.1	99.8	77.9	73.1	99.5	5820	5940	5820	5700	5940	79.1	77.7	79.4	81.0	77.1	**0.118**
	638	5700	5760	6000	5580	6000	104.2	89.2	70.1	93.5	82.9	5760	6060	5940	5640	5520	81.1	77.5	76.7	78.9	79.9	**0.118**
	711	6000	5760	5820	5820	6180	91.1	75.5	62.6	91.0	55.4	6360	6120	5700	6720	6120	78.3	75.3	77.9	74.4	79.3	**0.119**
320	468	5700	5940	5640	6000	5880	98.9	93.4	99.7	83.4	82.0	5880	5760	5880	5760	5940	79.4	80.1	78.8	78.9	79.5	**0.124**
	375	5700	5940	5760	5940	5760	103.2	83.9	91.0	87.3	90.8	5760	5580	6180	5640	5580	79.2	79.0	77.8	78.0	77.1	**0.126**
	451	6000	5580	5940	5820	5880	90.9	74.1	81.7	102.4	102.9	6180	5400	5520	6240	5760	76.3	78.0	82.0	77.4	78.5	**0.126**
	706	5820	5460	5880	5880	5880	87.9	87.3	97.6	88.8	92.1	5520	5760	6060	5760	6420	78.0	79.5	77.1	80.0	76.8	**0.128**
	957	5700	5700	6120	5820	6060	93.9	103.1	86.1	96.4	68.8	5940	6000	5640	6780	5820	79.5	79.1	78.7	73.8	78.1	**0.130**
	Obs.	**5745**	**5765**	**5825**	**5890**	**5660**	**69.3**	**70.1**	**73.0**	**74.5**	**70.0**	**5860**	**5730**	**5700**	**5890**	**5810**	**84.1**	**84.0**	**84.2**	**83.1**	**82.4**	

Table D.3: Test 2 pre-simulation volume/speed RMSP - non-crash conditions (#371, #405 and #454)

Crash #	Seed	Upstream Flow Rate (vph)					Upstream Speed (km/h)					Downstream Flow Rate (vph)					Downstream Speed (km/h)					RMSP
		0 - 1'	**1 - 2'**	**2 - 3'**	**3 - 4'**	**4 - 5'**	**0 - 1'**	**1 - 2'**	**2 - 3'**	**3 - 4'**	**4 - 5'**	**0 - 1'**	**1 - 2'**	**2 - 3'**	**3 - 4'**	**4 - 5'**	**0 - 1'**	**1 - 2'**	**2 - 3'**	**3 - 4'**	**4 - 5'**	
371	364	5580	5340	5220	5580	5040	85.5	88.0	99.9	98.2	102.9	5400	4740	5520	5400	5160	83.7	84.4	82.7	81.5	82.9	**0.106**
	484	5460	5220	5280	5460	5280	103.5	93.5	104.7	81.7	99.9	5100	5340	5340	5580	4680	84.9	83.1	83.4	83.9	82.9	**0.108**
	488	5520	5280	5400	5400	5280	98.0	103.5	103.9	90.5	89.7	5460	4860	5820	5460	4920	84.0	85.7	82.6	82.2	85.6	**0.109**
	254	5520	4920	5340	5520	5160	98.3	104.7	95.3	101.8	80.6	5280	4920	5160	5700	5280	83.5	83.7	83.8	82.2	83.8	**0.111**
	666	5580	5100	5220	5580	5220	100.4	104.3	103.6	86.4	94.4	5280	4980	5340	5520	5220	82.9	84.0	81.8	81.8	80.9	**0.112**
	677	5460	5340	5220	5460	5220	101.0	92.1	92.2	97.9	100.8	5160	5280	5400	5760	4500	81.9	84.2	82.3	82.1	84.9	**0.112**
	114	5340	5220	5400	5400	5340	86.1	96.2	103.0	96.3	100.9	5640	4740	5700	5280	5040	80.5	81.8	82.2	83.5	83.0	**0.113**
	454	5100	5160	5340	5580	5340	91.2	93.5	94.8	102.0	101.4	4860	5640	5100	5460	5220	85.7	83.4	83.9	84.0	83.5	**0.113**
	995	5340	5400	5280	5400	5220	81.9	100.8	94.9	103.5	101.5	5520	5220	5160	5220	5160	82.2	83.4	84.5	80.6	79.9	**0.114**
	583	5460	5280	5400	5100	5280	100.4	103.1	83.0	97.6	102.3	5040	5220	5400	5460	5040	82.8	82.9	81.1	84.5	81.4	**0.116**
	Obs.	**5290**	**5125**	**5110**	**5290**	**5080**	**76.4**	**78.2**	**79.2**	**76.3**	**75.2**	**5145**	**5080**	**5370**	**5300**	**4885**	**85.5**	**86.2**	**84.8**	**84.8**	**86.2**	
405	37	4980	5160	5340	5520	5940	102.9	102.6	100.8	96.0	96.2	4320	5100	4860	5340	5100	84.9	89.9	83.8	78.6	78.2	**0.118**
	52	5100	5280	6480	5160	5100	102.7	101.1	101.4	102.9	105.8	4740	4920	4920	4320	4980	86.8	86.2	85.6	82.2	77.2	**0.122**
	72	6660	5400	5520	4860	5580	93.7	101.3	103.5	103.8	102.8	5340	4800	4380	4260	4800	82.7	86.8	88.7	80.5	76.1	**0.128**
	99	5640	5280	5520	4680	6960	101.4	104.3	103.3	103.4	97.5	5100	5040	4380	4680	6480	86.5	86.3	88.9	80.4	74.0	**0.149**
	15	5700	5640	5220	6300	5520	100.7	103.1	102.4	100.9	103.9	4380	5100	5340	5400	4740	88.2	87.2	84.3	80.5	77.4	**0.135**
	31	6120	5580	5280	5520	5280	101.5	102.0	104.8	102.2	103.5	5940	4560	5220	4080	4860	84.3	86.8	88.2	84.0	78.3	**0.138**
	41	5280	5280	5400	6180	4920	101.6	101.4	101.7	102.5	103.3	4740	4920	4920	5280	5040	86.8	85.7	85.4	81.7	76.6	**0.129**
	44	5220	5640	5040	5280	5700	102.2	103.8	103.3	101.6	100.8	4500	5160	4560	4740	5820	87.8	86.8	87.3	80.8	75.1	**0.130**
	50	6480	5160	5220	4980	5400	101.4	102.9	104.6	103.3	101.2	4920	4320	4380	4740	5160	85.6	87.7	88.5	77.3	75.7	**0.130**
	70	5520	4860	5640	6540	5580	103.5	103.8	102.2	97.2	101.8	4380	4260	5760	5400	4140	88.7	88.1	80.9	76.4	78.9	**0.140**
	Obs.	**5215**	**5190**	**5430**	**5000**	**5300**	**85.5**	**81.5**	**78.4**	**80.5**	**78.7**	**4398**	**4618**	**4625**	**4368**	**4548**	**81.7**	**81.5**	**80.9**	**79.8**	**84.9**	
454	922	6060	5520	5760	5880	6060	54.1	45.4	46.4	52.1	51.4	6120	6240	6060	5940	5700	59.6	60.0	55.4	52.7	47.5	**0.115**
	869	5820	6180	5460	6120	6000	53.2	51.4	45.5	54.7	48.5	6180	6300	6240	5940	5580	56.8	62.8	63.7	54.7	48.3	**0.116**
	854	6120	5700	5520	5940	6180	56.3	46.7	45.8	52.9	60.3	6180	6120	6240	6000	5760	58.3	60.5	58.6	55.5	51.7	**0.116**
	39	5760	5880	5880	5940	6060	46.6	53.6	47.7	54.6	50.9	6240	6420	6060	6060	5640	58.0	64.8	66.0	55.7	47.4	**0.118**
	567	6000	5820	5580	6240	6120	48.3	48.3	43.7	52.1	52.3	6240	5880	6240	6180	6060	60.0	53.9	52.5	56.5	54.9	**0.119**
	858	6000	5700	5880	6240	5940	51.6	45.5	50.3	52.1	56.2	6180	6180	6000	6000	5760	61.6	60.4	52.8	50.8	54.5	**0.121**
	717	6420	6120	5160	6180	5700	54.8	50.2	40.4	55.9	51.6	6060	6420	6120	5880	6000	61.7	60.3	62.7	53.1	57.7	**0.121**
	610	6180	6000	5520	6120	5520	53.3	52.9	42.9	53.7	47.3	6060	5760	6240	5940	6060	58.0	51.4	58.9	60.9	52.8	**0.122**
	366	5820	5760	6180	5880	5640	56.2	46.8	52.1	46.6	52.7	6120	6420	6300	6120	5520	56.3	62.6	66.3	60.7	45.9	**0.122**
	724	5880	5880	5340	6300	5820	54.8	53.2	46.9	53.9	50.1	6180	6180	6060	6000	5940	59.1	64.3	57.2	57.4	47.9	**0.122**
	Obs.	**5975**	**5675**	**5760**	**6095**	**6225**	**46.8**	**41.6**	**43.5**	**46.6**	**47.9**	**4860**	**5051**	**5209**	**5280**	**4947**	**60.5**	**63.4**	**64.6**	**60.8**	**56.3**	

Table D.4: Test 2 pre-simulation volume/speed RMSP - non-crash conditions (#455, #478 and #521)

Crash #	Seed	Upstream Flow Rate (vph)					Upstream Speed (km/h)					Downstream Flow Rate (vph)					Downstream Speed (km/h)					RMSP
		0 - 1'	**1 - 2'**	**2 - 3'**	**3 - 4'**	**4 - 5'**	**0 - 1'**	**1 - 2'**	**2 - 3'**	**3 - 4'**	**4 - 5'**	**0 - 1'**	**1 - 2'**	**2 - 3'**	**3 - 4'**	**4 - 5'**	**0 - 1'**	**1 - 2'**	**2 - 3'**	**3 - 4'**	**4 - 5'**	
455	780	5940	5580	5520	5580	5820	91.0	84.7	96.7	95.4	67.8	5700	5280	5580	5820	5760	59.3	68.7	69.7	73.1	75.2	**0.116**
	907	6120	5580	5760	5100	5700	97.6	100.2	87.0	92.6	80.2	6060	5520	5640	5220	5820	64.3	62.4	65.3	73.8	76.6	**0.122**
	113	5280	5760	5520	5460	5760	76.0	95.0	100.7	87.8	70.5	5280	5760	5280	5940	5580	62.8	64.8	64.3	68.1	74.0	**0.135**
	664	5760	5640	5700	5340	5640	80.8	64.9	101.0	91.3	94.6	5400	5460	5700	6120	4980	68.0	67.0	66.8	69.7	71.6	**0.124**
	703	5580	5820	5520	5460	5760	89.3	94.8	96.4	87.9	68.3	5880	5520	5220	6000	5880	62.2	66.4	67.9	65.8	73.8	**0.126**
	487	6180	5520	5400	5460	5820	90.0	99.2	99.7	89.0	69.0	5640	5460	5640	5940	5940	59.8	64.9	69.8	74.0	76.0	**0.123**
	440	5880	5580	5400	5880	5100	91.9	99.2	98.8	93.4	99.2	5640	5340	5520	5940	4440	69.6	66.2	71.3	75.5	74.3	**0.122**
	765	6120	5760	5280	5400	5580	99.2	86.2	98.2	97.7	98.7	5760	6000	5280	4980	5340	63.3	63.0	70.7	76.3	77.7	**0.132**
	904	6060	5160	5880	5040	6000	90.6	99.9	99.5	96.3	68.3	5160	5460	5460	5700	5640	67.8	63.9	68.5	67.8	72.5	**0.129**
	706	5640	5700	5400	5280	6000	98.7	68.7	81.3	97.6	88.9	6000	5340	5340	5820	5820	61.4	61.5	66.1	68.3	74.7	**0.135**
	Obs.	**5722**	**5531**	**5324**	**5313**	**5258**	**77.5**	**79.0**	**77.4**	**75.5**	**78.3**	**5525**	**5210**	**5335**	**5255**	**5130**	**75.2**	**76.2**	**77.4**	**80.1**	**81.0**	
478	825	6000	6060	6360	6180	6480	69.4	66.0	69.8	84.9	64.6	6000	6180	6600	5760	6420	74.8	74.8	74.0	78.3	74.6	**0.068**
	923	6240	6360	5820	6540	6360	85.9	63.7	61.6	68.9	67.1	6240	6360	5940	6300	5880	73.4	72.8	74.7	76.5	74.8	**0.075**
	982	5940	6420	5940	6540	6480	82.1	60.1	81.2	60.2	74.1	6060	6480	6000	6360	6480	74.2	74.5	75.7	76.5	74.1	**0.076**
	31	6120	6420	6060	6360	6480	67.7	66.2	54.0	66.7	61.2	6300	6480	6360	6060	6300	76.0	74.9	74.8	74.3	75.1	**0.080**
	454	6000	6180	6060	6420	6360	86.4	80.8	82.9	68.5	83.1	6180	5400	6360	6240	6420	75.2	78.3	74.4	75.1	74.2	**0.085**
	875	6060	6120	6180	6300	6420	100.5	76.0	74.5	66.8	77.2	6480	6600	6000	6060	6360	75.3	74.3	73.6	76.8	74.1	**0.086**
	602	6120	6240	6300	6480	6360	77.4	92.6	76.1	60.5	64.1	6180	6660	6180	6540	6060	73.8	73.0	75.1	75.9	75.9	**0.086**
	522	6180	6240	6060	6420	6600	96.0	70.2	73.5	67.4	71.0	6480	6420	6480	6600	5760	74.2	74.1	74.3	71.3	74.8	**0.088**
	45	6240	6180	6240	6180	6480	93.1	62.4	68.2	79.9	74.2	5820	6420	6540	6600	6420	75.7	74.6	74.0	71.6	75.9	**0.088**
	364	6240	6180	6180	6540	6420	82.2	82.0	77.0	72.5	71.1	6120	6420	6240	6840	6060	76.1	74.9	67.9	69.1	75.1	**0.088**
	Obs.	**6080**	**6190**	**6180**	**6385**	**6390**	**70.3**	**70.0**	**68.8**	**67.4**	**70.5**	**6135**	**6135**	**6250**	**6225**	**6425**	**78.2**	**79.9**	**79.5**	**79.3**	**79.0**	
521	633	6000	5880	5640	5820	5280	56.2	51.2	55.8	56.0	50.3	6000	5940	5760	5760	5640	55.4	50.5	51.2	45.8	50.0	**0.068**
	782	5820	5400	5700	5820	5340	53.3	52.0	45.8	49.6	42.0	5940	5880	5700	5580	5940	54.5	50.3	49.4	43.5	48.8	**0.096**
	823	5640	5400	6000	5580	5280	51.2	51.1	55.2	50.2	46.4	5820	5640	5700	5400	6060	51.1	49.0	46.2	44.8	46.9	**0.096**
	711	6000	5580	6060	5880	5700	51.3	50.2	52.4	47.7	48.7	6060	5820	6000	5460	5700	54.4	45.7	50.8	43.6	45.6	**0.096**
	356	5580	5340	5940	5640	5760	54.5	53.6	57.1	47.7	49.7	6000	5580	6120	5520	5880	57.3	43.8	49.8	45.7	45.1	**0.098**
	586	5580	5520	5760	5940	5460	49.0	49.9	53.6	51.4	49.2	5940	5880	5880	5400	5820	51.6	48.0	46.3	45.1	46.2	**0.099**
	731	6000	5700	6000	5220	5160	53.3	59.6	52.3	44.7	47.0	6000	5880	5460	5460	5580	56.2	50.6	46.2	43.6	44.2	**0.101**
	113	5820	5340	5640	5700	5640	54.7	46.0	51.1	53.2	46.8	5820	5640	5460	5520	5520	55.9	45.7	50.6	42.9	47.2	**0.101**
	484	5820	5940	5520	5820	6300	51.2	54.1	48.1	51.4	54.8	6060	5820	5880	5760	6060	51.8	45.1	47.3	47.0	49.1	**0.102**
	955	5340	6120	5820	5400	5700	49.3	55.1	52.5	53.1	48.7	6060	6000	5580	5640	5700	50.6	52.2	46.4	44.9	43.3	**0.102**
	Obs.	**5800**	**5766**	**5660**	**5685**	**5640**	**54.3**	**55.6**	**54.8**	**49.9**	**49.4**	**5790**	**5595**	**5585**	**5460**	**5750**	**59.1**	**56.9**	**57.2**	**51.7**	**53.7**	

Table D.5: Test 2 pre-simulation volume/speed RMSP - non-crash conditions (#522, #571 and #595)

Crash #	Seed	Upstream Flow Rate (vph)					Upstream Speed (km/h)					Downstream Flow Rate (vph)					Downstream Speed (km/h)					RMSP
		0 - 1'	**1 - 2'**	**2 - 3'**	**3 - 4'**	**4 - 5'**	**0 - 1'**	**1 - 2'**	**2 - 3'**	**3 - 4'**	**4 - 5'**	**0 - 1'**	**1 - 2'**	**2 - 3'**	**3 - 4'**	**4 - 5'**	**0 - 1'**	**1 - 2'**	**2 - 3'**	**3 - 4'**	**4 - 5'**	
522	58	5940	5400	4920	5460	5040	101.0	104.2	102.3	99.1	104.1	5460	5400	5160	4980	4800	102.0	102.0	102.7	104.5	102.2	**0.026**
	99	5880	5400	4920	5340	4920	101.6	103.7	103.1	102.8	102.7	5340	5340	5100	5280	5280	103.7	100.5	100.2	101.7	101.2	**0.026**
	189	5580	5640	4740	5460	4980	100.7	102.6	103.0	103.7	104.7	5700	5220	4980	5160	5040	101.3	101.6	101.8	103.4	102.7	**0.029**
	11	5640	5460	5040	5460	4980	95.8	104.4	103.9	101.6	100.3	4980	5460	5160	5580	5040	103.8	102.9	101.8	103.7	102.2	**0.030**
	180	5880	5400	4920	5460	5160	98.8	103.9	105.6	98.9	103.5	5640	5040	5100	5160	5040	103.4	103.2	100.8	102.3	103.6	**0.031**
	190	5760	5460	5040	5220	5220	101.4	103.0	103.9	102.5	102.1	5640	5280	4980	5460	4980	94.8	101.8	101.0	101.2	103.0	**0.031**
	45	5640	5580	5160	5100	5160	100.6	104.5	101.8	103.6	101.3	5040	5340	5160	5460	5280	101.0	101.6	103.2	101.9	101.5	**0.031**
	30	5760	5580	4860	5640	4860	102.6	101.1	104.8	102.5	104.1	5760	5220	5280	4980	4920	99.1	103.4	99.6	104.5	102.4	**0.032**
	97	5640	5460	4860	5700	4920	101.0	102.0	102.6	101.5	104.1	5580	5220	5040	5700	5100	100.5	102.9	100.8	101.7	101.8	**0.033**
	187	5460	5640	5040	5340	4980	101.4	103.4	105.0	102.6	105.4	5580	5280	5220	5220	4620	99.8	101.8	101.5	101.9	103.4	**0.034**
	Obs.	**5716**	**5558**	**4934**	**5405**	**5111**	**98.8**	**100.4**	**100.9**	**100.5**	**101.0**	**5398**	**5485**	**5285**	**5240**	**5090**	**100.1**	**102.6**	**103.0**	**104.4**	**104.5**	
571	399	5040	5100	5460	5340	5220	95.7	90.9	95.1	97.9	101.7	4800	5520	5340	5040	4680	71.8	69.1	73.1	75.7	77.1	**0.124**
	304	5100	5340	5280	5040	5520	95.1	93.7	101.8	102.1	95.7	5340	4980	5340	4800	5340	75.6	76.1	72.7	78.9	74.0	**0.124**
	569	5340	5520	5460	4920	5280	94.8	100.3	90.1	99.9	94.2	5100	5400	5340	5340	5400	73.2	72.6	70.6	69.2	74.5	**0.126**
	235	5640	4920	5640	5160	5160	84.4	103.8	98.0	99.5	96.4	5400	5160	5280	5040	5160	70.1	71.1	74.7	72.9	73.6	**0.127**
	688	5340	5220	5520	5700	4800	97.2	99.3	99.2	92.5	100.4	5160	5400	5400	5460	4920	74.5	74.1	73.5	75.6	74.4	**0.128**
	677	5700	5400	5340	5220	4800	91.5	99.8	97.4	97.6	102.8	5280	5520	5400	5280	4920	71.8	71.9	70.9	72.8	75.4	**0.128**
	233	5580	5220	5100	5340	5640	93.6	98.9	96.4	96.7	98.5	5400	5220	5640	5100	5340	73.6	71.6	69.7	71.4	73.1	**0.128**
	369	5760	5100	5340	5340	4740	95.4	96.8	95.2	99.1	100.7	5460	5340	5400	4980	4920	70.5	73.4	69.2	72.1	76.3	**0.129**
	315	5400	5520	5160	5280	5580	96.6	95.2	98.0	96.8	97.6	5100	5460	5340	5400	5340	73.5	74.2	72.5	69.9	66.6	**0.130**
	225	5580	5340	5100	5100	5400	92.9	100.5	98.7	100.6	100.3	5220	5160	5340	5220	5280	75.0	73.3	72.2	72.3	73.3	**0.130**
	Obs.	**5165**	**5195**	**5205**	**5085**	**5040**	**72.5**	**78.4**	**78.4**	**76.1**	**77.8**	**5145**	**5060**	**5015**	**5160**	**5175**	**80.0**	**79.4**	**77.9**	**79.0**	**81.9**	
595	161	5220	4920	4980	5160	5460	105.2	103.7	103.9	103.3	103.2	4800	4380	3900	4500	4740	105.5	103.6	104.5	102.4	104.5	**0.064**
	40	5100	4920	5040	5340	5400	102.2	104.1	104.1	104.8	102.7	4320	4320	4200	4680	4440	103.6	104.1	103.5	104.6	105.0	**0.064**
	180	5160	5100	4980	5280	5460	105.9	104.8	104.3	104.1	105.1	4440	4440	4260	4440	4560	105.4	104.2	102.9	104.0	104.1	**0.066**
	21	5220	4920	5040	5160	5700	104.4	104.8	105.0	103.6	104.6	4620	4260	4260	4560	4800	105.4	105.6	104.0	104.5	104.9	**0.066**
	127	4980	5040	5160	5220	5340	104.3	103.7	103.5	103.4	103.8	4620	4440	4260	4320	4860	103.4	104.6	103.7	104.6	103.7	**0.067**
	192	5280	5040	4980	5280	5340	105.1	104.2	105.3	104.4	103.7	4860	4080	4140	4680	4320	105.5	103.4	105.6	104.4	104.9	**0.067**
	28	5220	4980	5100	5040	5580	103.8	104.1	104.2	105.5	103.6	4560	4380	4260	4260	4440	104.4	102.8	104.9	105.1	103.7	**0.068**
	137	5160	5040	5160	5220	5280	103.9	103.1	105.5	104.5	104.9	4680	4080	4380	4380	4440	103.7	104.5	103.5	105.3	103.6	**0.068**
	69	5340	4980	5040	5160	5340	104.6	102.8	105.2	106.0	105.0	4740	4500	3840	4740	4500	104.3	104.0	105.8	106.2	103.8	**0.068**
	10	5280	5100	4980	5280	5460	104.0	103.4	104.9	103.6	105.9	4980	4080	4440	4560	4260	102.3	104.8	104.1	104.8	105.5	**0.068**
	Obs.	**5370**	**5085**	**5185**	**5330**	**5480**	**93.1**	**93.7**	**92.2**	**94.7**	**94.4**	**4775**	**4415**	**4190**	**4715**	**4510**	**103.8**	**100.8**	**95.9**	**95.4**	**97.8**	

Table D.6: Test 2 pre-simulation volume/speed RMSP - non-crash conditions (#647, #688 and #702)

Crash #	Seed	Upstream Flow Rate (vph)					Upstream Speed (km/h)					Downstream Flow Rate (vph)					Downstream Speed (km/h)					RMSP
		0 - 1'	**1 - 2'**	**2 - 3'**	**3 - 4'**	**4 - 5'**	**0 - 1'**	**1 - 2'**	**2 - 3'**	**3 - 4'**	**4 - 5'**	**0 - 1'**	**1 - 2'**	**2 - 3'**	**3 - 4'**	**4 - 5'**	**0 - 1'**	**1 - 2'**	**2 - 3'**	**3 - 4'**	**4 - 5'**	
647	829	6480	5940	6480	6420	6060	74.6	83.7	82.5	76.4	79.1	6000	6600	6600	6180	6300	76.9	75.3	75.1	75.1	75.7	**0.056**
	923	6480	6240	6240	6420	6000	85.1	69.6	84.1	77.6	73.5	6360	6240	6120	6480	6180	77.9	75.3	77.3	76.9	76.4	**0.058**
	533	6360	6420	6240	6240	6420	88.5	84.5	73.1	78.2	74.7	6660	6360	6180	6180	5940	75.3	77.5	75.8	77.8	73.2	**0.061**
	279	6360	6240	6660	5940	6660	76.6	86.8	75.9	92.3	83.2	6240	6540	6120	6120	6600	75.9	75.9	77.6	78.6	75.1	**0.063**
	788	6420	6300	6360	6480	6240	75.4	87.1	78.8	87.8	73.9	6420	6300	6480	6360	5880	75.4	73.1	73.6	77.0	76.5	**0.064**
	454	6300	6180	6720	6000	6180	81.5	82.7	77.1	64.5	80.2	6300	6780	6000	5880	6360	72.8	73.8	76.8	76.8	76.1	**0.067**
	579	6240	6420	6300	6360	6240	90.9	69.7	75.8	80.3	94.6	6660	6480	5940	5880	6300	74.8	74.5	77.0	77.7	75.3	**0.071**
	679	6600	6360	6240	6600	6300	83.0	73.4	84.4	77.0	65.6	6420	6660	6360	6180	6060	71.1	74.7	76.2	76.6	76.0	**0.073**
	935	6600	6180	6540	5880	6540	81.5	76.2	84.5	98.1	91.6	5940	6480	6120	5940	6240	74.5	74.0	76.1	75.1	76.5	**0.074**
	70	6360	6360	6000	6480	6300	82.1	73.9	79.9	90.7	67.3	6300	6120	6240	6720	6420	77.8	75.8	79.0	74.7	76.8	**0.074**
	Obs.	**6500**	**6270**	**6525**	**6180**	**6425**	**75.6**	**75.7**	**76.7**	**76.8**	**78.7**	**5986**	**5913**	**5918**	**5793**	**5995**	**78.0**	**77.5**	**79.4**	**80.6**	**79.3**	
688	45	4140	4920	5100	4800	4860	101.0	102.4	102.7	93.0	88.1	4200	4860	4980	5340	4320	90.0	90.6	89.8	82.3	87.2	**0.077**
	29	4320	4620	5100	4500	5520	105.2	105.2	103.3	92.9	102.3	4500	4920	4560	5100	4860	92.0	84.5	89.9	85.4	84.4	**0.078**
	346	4500	4560	4680	4800	5400	103.0	104.5	105.1	103.7	92.9	4380	4800	4980	4620	4920	88.4	89.3	87.3	83.4	84.4	**0.078**
	304	4080	4920	4620	4500	5640	101.1	104.6	106.0	102.3	89.6	4320	4740	4680	4380	5460	92.0	87.3	89.6	88.1	85.8	**0.078**
	415	4140	4680	4980	4740	5340	105.0	104.9	101.4	105.7	87.5	4620	4860	4680	4860	5340	90.4	89.1	91.9	82.7	84.9	**0.078**
	267	4380	4560	5040	4800	5280	104.9	101.1	105.3	97.7	92.2	4680	4800	4620	5340	5100	90.2	87.4	92.0	81.6	84.6	**0.078**
	108	4380	4740	4920	4680	5220	103.0	105.2	101.5	104.0	100.1	4200	5100	4680	4980	4860	92.1	88.2	90.7	82.3	83.7	**0.079**
	324	4260	4680	4860	4800	5280	105.1	102.0	103.6	104.7	96.5	4380	4680	4920	4920	5040	88.9	89.7	89.5	85.3	82.1	**0.079**
	384	4320	4620	5040	4680	5460	106.0	104.9	105.2	104.7	94.8	4800	4800	4500	4980	4920	91.1	89.3	92.6	84.0	85.2	**0.080**
	65	4140	4800	4860	4800	5160	104.0	97.2	102.2	102.2	103.0	4380	5100	4800	5040	4740	85.6	87.1	91.3	84.5	86.4	**0.080**
	Obs.	**4227**	**4380**	**4636**	**4396**	**5100**	**93.4**	**91.6**	**89.5**	**88.8**	**88.6**	**4340**	**4735**	**4485**	**4620**	**4730**	**94.9**	**93.9**	**94.4**	**88.8**	**91.2**	
702	492	5340	4740	5520	5340	5280	101.7	101.1	100.8	97.2	105.1	5160	5040	5520	5100	4980	95.0	93.9	92.6	90.6	89.9	**0.053**
	411	5460	4920	5400	5220	5520	96.7	98.0	95.4	103.5	98.5	5760	4980	5400	5280	4980	94.4	93.8	93.5	87.8	89.0	**0.056**
	442	5220	5100	5040	5460	5700	103.7	99.6	94.8	104.6	98.8	5160	5460	5100	5280	5580	96.4	94.2	93.8	91.8	90.9	**0.056**
	468	5160	5280	5340	5280	5340	100.7	100.4	102.4	97.1	101.7	5100	5280	5160	5400	5400	95.8	93.8	95.3	87.3	88.3	**0.057**
	385	4920	5280	5220	5340	5400	100.6	100.8	102.7	102.4	104.4	5160	5340	5400	4920	4980	95.2	92.5	92.7	92.6	89.0	**0.058**
	136	5220	5160	5340	5340	5340	94.9	102.6	102.6	99.5	96.4	5040	4980	5400	5700	5460	96.4	92.7	92.9	89.5	90.6	**0.058**
	73	5400	4920	5640	5160	5460	101.8	104.6	102.8	99.3	101.4	5040	5160	5100	5520	5220	95.7	92.8	98.2	89.2	88.1	**0.058**
	384	5460	5160	5280	5280	5520	104.6	96.9	101.7	103.5	92.6	5700	5100	4860	5340	4920	95.9	94.3	96.9	90.9	89.3	**0.058**
	467	5700	4860	5280	5280	5520	92.3	98.6	102.4	104.3	103.6	5280	4800	5400	5160	5340	97.4	93.9	95.0	88.3	88.7	**0.058**
	197	5160	5100	5460	5400	5340	104.0	104.1	102.8	99.0	91.8	4980	5460	5460	5340	4860	96.1	93.0	95.0	92.6	91.6	**0.058**
	Obs.	**5045**	**4745**	**5105**	**4936**	**5269**	**95.6**	**95.3**	**93.8**	**96.2**	**95.9**	**5100**	**4985**	**5050**	**5040**	**5080**	**99.5**	**98.1**	**98.5**	**95.7**	**95.1**	

Table D.7: Test 2 pre-simulation volume/speed RMSP - non-crash conditions (#710, #731 and #739)

Crash #	Seed	Upstream Flow Rate (vph)					Upstream Speed (km/h)					Downstream Flow Rate (vph)					Downstream Speed (km/h)					RMSP
		0 - 1'	**1 - 2'**	**2 - 3'**	**3 - 4'**	**4 - 5'**	**0 - 1'**	**1 - 2'**	**2 - 3'**	**3 - 4'**	**4 - 5'**	**0 - 1'**	**1 - 2'**	**2 - 3'**	**3 - 4'**	**4 - 5'**	**0 - 1'**	**1 - 2'**	**2 - 3'**	**3 - 4'**	**4 - 5'**	
710	531	5700	5880	5880	5880	6420	99.6	101.5	94.9	92.6	91.7	6000	5760	5700	6240	6120	88.4	88.1	86.8	86.5	88.9	**0.040**
	828	5940	5820	5940	5760	6240	97.7	95.1	90.7	96.7	83.4	6420	5880	5820	6060	5820	87.7	87.3	86.4	87.6	88.3	**0.041**
	786	5760	6120	5940	5640	5880	93.0	87.2	91.6	86.9	98.0	6300	5820	6000	5580	5640	90.1	87.0	86.7	87.6	91.0	**0.041**
	324	5880	5880	5880	6000	6060	102.6	99.5	92.7	88.9	94.1	5580	6000	6060	5820	5700	88.5	86.0	85.9	86.2	90.3	**0.041**
	282	5940	5880	6060	5820	6060	91.7	102.8	96.7	95.2	95.9	5700	6120	5940	5880	5880	88.7	86.0	86.6	87.9	89.0	**0.042**
	677	6000	5760	5880	6120	5520	90.4	99.3	92.4	89.9	97.6	5820	5760	5940	5820	5640	89.6	86.9	86.0	88.6	90.4	**0.042**
	687	5760	5880	5940	6300	6060	103.7	95.1	98.1	95.0	91.6	6000	6060	6120	5760	6120	87.5	87.4	85.9	87.7	90.3	**0.042**
	830	5760	5700	5760	5820	6060	95.4	95.0	91.7	100.2	97.1	6060	5580	6120	5940	5760	87.5	88.0	85.5	88.2	88.6	**0.042**
	322	6060	5940	5880	5940	6120	96.6	102.9	102.5	97.4	89.0	5940	5820	6180	5880	6000	91.3	87.7	85.6	87.4	89.5	**0.043**
	123	5820	5640	5940	5940	6240	98.5	102.6	92.3	91.9	100.0	5760	5820	6240	6240	5640	91.4	86.9	85.4	89.4	90.8	**0.044**
	Obs.	**5910**	**5975**	**5870**	**5975**	**6105**	**92.9**	**92.6**	**92.4**	**89.5**	**90.1**	**5975**	**5865**	**6025**	**6035**	**5918**	**92.7**	**90.2**	**89.4**	**90.7**	**92.7**	
731	699	5700	5700	6540	6060	5700	89.3	75.1	70.9	90.8	92.6	6120	5880	6180	6180	6240	65.3	63.6	62.2	65.2	67.8	**0.078**
	286	5640	5940	6060	6060	5520	93.2	88.0	89.4	93.6	91.3	6060	5760	5880	5820	5640	69.1	64.6	68.7	69.0	64.7	**0.087**
	60	5820	5880	5640	6000	6360	98.1	80.2	68.5	76.1	72.5	6360	6240	6240	6300	6060	63.9	67.2	68.0	65.6	67.1	**0.091**
	609	6060	5820	6000	5820	6300	94.6	93.7	91.8	85.6	81.0	5820	5760	6060	6120	6180	69.0	69.5	67.8	65.4	68.5	**0.095**
	634	6000	5880	6360	5940	6000	94.6	96.1	86.1	93.1	83.2	6180	6000	6060	5760	6060	67.1	68.2	67.7	69.0	67.6	**0.097**
	146	6000	5640	6360	5880	6060	93.1	99.1	84.9	89.9	86.2	5700	6240	6120	5880	5880	67.1	67.3	70.4	67.6	69.7	**0.097**
	240	6120	5820	5400	6240	5940	85.1	86.6	100.3	92.1	92.7	6180	5520	6240	6180	6120	68.5	67.4	69.6	69.0	67.8	**0.098**
	466	5520	5640	5820	6000	5820	99.8	92.0	79.9	70.7	70.1	6120	5940	6120	6120	6000	70.2	69.1	59.8	63.7	69.8	**0.098**
	154	5100	5880	5700	6240	6180	100.2	89.6	91.2	86.4	82.7	5940	6060	5940	6240	6060	69.0	64.2	61.7	64.5	63.8	**0.099**
	521	6180	5400	6060	6000	6000	93.0	94.5	87.4	92.7	91.5	5580	6060	6120	5640	5940	66.8	61.6	65.2	69.5	67.6	**0.101**
	Obs.	**5610**	**5685**	**5730**	**5770**	**5550**	**74.5**	**75.0**	**75.9**	**80.1**	**79.7**	**5645**	**5700**	**5665**	**5740**	**5730**	**65.7**	**68.3**	**66.8**	**66.4**	**65.4**	
739	31	5820	5760	5520	5160	5220	102.2	101.4	101.4	103.1	101.3	5520	5820	5220	5400	4980	100.3	100.3	101.4	99.2	101.9	**0.025**
	188	5940	5520	5580	5340	5160	103.4	103.0	103.2	100.2	99.4	5760	5580	5160	5220	5220	100.7	100.9	102.3	100.9	102.1	**0.026**
	187	5640	5880	5520	5160	5400	103.1	102.8	102.7	102.2	103.8	5820	5400	5460	5160	5100	101.4	101.0	96.8	101.5	102.3	**0.026**
	189	5880	5820	5280	5340	4860	102.5	102.9	103.1	104.5	105.5	6060	5340	5400	5040	5280	99.1	101.9	101.4	102.4	102.3	**0.027**
	199	5940	5760	5280	5220	5280	100.0	102.2	103.3	103.4	99.6	6120	5640	5100	5220	5400	100.9	101.6	101.0	100.8	101.4	**0.027**
	186	5940	5880	5400	5040	5100	103.3	104.0	101.1	105.1	102.6	5760	5640	5340	5460	4740	101.8	101.2	101.7	100.4	102.8	**0.029**
	136	5760	5820	5400	5160	5040	97.3	100.7	102.4	103.4	104.1	5580	5460	5580	5400	4860	102.3	100.4	100.5	101.6	102.8	**0.029**
	4	5760	5820	5460	5160	5100	99.9	99.3	98.3	102.2	103.0	6240	5580	5280	4980	5520	97.1	100.5	102.1	101.2	102.3	**0.029**
	59	5820	5940	5400	5160	5160	98.1	102.2	105.0	104.7	102.8	6060	5400	5580	5040	5460	98.3	103.0	101.4	103.0	101.5	**0.029**
	117	6060	5520	5640	4980	5160	100.4	102.5	102.7	99.6	100.6	5760	5400	5340	5520	4980	97.2	98.9	99.9	101.0	102.6	**0.029**
	Obs.	**5830**	**5775**	**5470**	**5225**	**5095**	**101.3**	**101.7**	**102.9**	**104.2**	**104.3**	**5920**	**5625**	**5365**	**5288**	**5145**	**96.9**	**98.1**	**100.7**	**98.8**	**102.8**	

Table D.8: Test 2 pre-simulation volume/speed RMSP - non-crash conditions (#781, #854 and #858)

Crash #	Seed	Upstream Flow Rate (vph)					Upstream Speed (km/h)					Downstream Flow Rate (vph)					Downstream Speed (km/h)					RMSP
		0 - 1'	**1 - 2'**	**2 - 3'**	**3 - 4'**	**4 - 5'**	**0 - 1'**	**1 - 2'**	**2 - 3'**	**3 - 4'**	**4 - 5'**	**0 - 1'**	**1 - 2'**	**2 - 3'**	**3 - 4'**	**4 - 5'**	**0 - 1'**	**1 - 2'**	**2 - 3'**	**3 - 4'**	**4 - 5'**	
	697	6540	6060	6060	6120	6360	90.1	83.1	75.5	83.1	78.2	6180	6300	6180	6060	6000	78.4	80.4	74.6	81.6	84.6	**0.049**
	269	6000	6060	6240	6120	6240	81.5	85.2	90.1	76.5	96.0	5940	6420	6300	5880	6060	79.9	79.2	81.8	82.3	85.2	**0.050**
	788	6360	6000	6060	6300	6300	71.0	89.6	88.1	76.6	79.1	5700	6120	6540	6300	5880	79.0	78.2	80.0	83.0	84.6	**0.051**
	691	6360	5760	6420	6120	5880	88.7	81.5	85.1	91.0	80.1	6000	6120	6360	6000	5760	76.7	80.8	78.6	81.5	83.7	**0.051**
	195	5940	5880	6180	6240	6300	82.2	90.2	96.8	85.5	86.4	5700	5820	6540	6300	6180	78.1	82.1	81.4	82.0	82.3	**0.055**
781	27	6180	6180	5880	6060	6360	87.2	75.2	81.3	97.9	96.3	6000	6240	6060	6060	6060	78.3	81.0	81.1	83.2	83.6	**0.062**
	974	6180	6000	6240	6000	6900	75.2	92.7	99.0	83.7	78.4	5580	6240	6600	6660	6000	80.5	81.1	78.6	79.3	84.4	**0.064**
	828	6000	5940	6420	5820	6420	84.2	97.9	86.0	81.4	95.4	6000	6300	6060	6120	5580	76.4	80.0	76.0	81.0	84.9	**0.064**
	596	6060	6060	5700	6660	6240	75.4	78.2	103.9	89.5	82.7	6120	6240	5940	6360	6480	79.9	80.8	81.3	82.2	82.5	**0.065**
	58	6540	5940	6420	5820	6300	93.1	77.1	77.8	94.1	96.0	6180	6000	6120	5940	6300	79.4	81.6	81.3	84.4	83.3	**0.065**
	Obs.	**6310**	**6005**	**6130**	**6128**	**6330**	**80.2**	**82.5**	**82.7**	**81.5**	**82.3**	**5960**	**6185**	**6020**	**6265**	**6044**	**82.3**	**83.3**	**83.0**	**85.4**	**87.0**	
	31	5400	5640	5400	4980	5040	103.8	102.4	102.9	104.2	103.5	5400	5460	5280	5160	4800	103.8	100.2	103.6	100.7	102.8	**0.020**
	188	5520	5400	5400	5040	5100	103.1	101.2	104.1	105.1	101.0	5340	5460	5040	5160	4800	102.0	101.8	103.1	102.7	103.9	**0.022**
	181	5280	5640	5340	5040	4860	100.3	103.3	104.0	103.9	102.6	5520	5340	5100	4980	4740	100.8	102.3	103.8	101.8	102.9	**0.023**
	71	5700	5340	5400	4860	4920	102.0	102.7	102.2	103.7	104.2	5280	5640	5040	5220	4680	103.4	99.0	101.0	103.2	103.6	**0.023**
	3	5400	5580	5220	4980	5100	100.7	102.3	103.8	103.0	102.9	5460	5280	5160	5280	4800	100.3	101.1	101.5	99.7	102.2	**0.024**
854	186	5460	5700	5220	4920	4920	104.2	104.1	100.2	104.6	103.6	5460	5520	5220	5400	4440	102.1	101.0	102.1	101.6	103.1	**0.026**
	179	5460	5580	5400	5100	4740	103.5	102.4	102.5	104.9	103.8	5520	5460	4920	5100	5220	102.1	100.2	102.3	101.7	102.5	**0.027**
	5	5340	5580	5340	5040	4740	100.7	100.2	101.3	102.1	104.1	5460	6000	5040	4920	5100	99.7	97.6	100.6	101.7	101.8	**0.027**
	108	5400	5640	5160	4980	4800	102.4	99.7	101.8	103.4	104.8	5100	5760	4860	4860	4560	102.3	99.1	102.4	102.6	104.5	**0.027**
	76	5520	5460	5220	5040	4740	100.5	103.6	99.6	103.4	105.1	5100	5700	5340	4920	4620	102.7	99.3	102.6	104.0	103.9	**0.028**
	Obs.	**5373**	**5660**	**5325**	**5055**	**4900**	**100.8**	**101.7**	**102.5**	**104.7**	**105.3**	**5345**	**5675**	**5040**	**5220**	**4780**	**100.4**	**99.2**	**102.4**	**102.0**	**104.0**	
	580	5460	5340	5520	5280	5100	99.2	101.0	95.3	85.5	97.4	5760	5040	5580	5100	5040	86.8	88.3	86.8	87.9	89.6	**0.051**
	998	5520	5400	5280	5700	5280	99.0	101.1	92.6	89.3	100.1	5400	5220	5580	5640	4920	88.2	87.8	86.5	86.8	87.9	**0.051**
	702	5580	5460	5280	5580	5760	91.7	102.0	94.5	89.4	96.6	5340	5280	5400	5340	5760	87.6	87.1	86.0	85.9	86.9	**0.054**
	346	6000	5220	5100	5700	5400	91.1	104.2	103.5	97.8	96.4	5340	5340	5580	5040	5040	85.8	88.8	84.7	86.8	87.1	**0.054**
	2	5700	5220	5220	5700	5400	96.6	103.9	97.9	100.6	99.3	5460	5220	5460	5340	5280	86.6	88.5	86.4	87.2	87.7	**0.055**
858	408	5520	5340	5280	5760	5220	99.2	103.4	103.7	98.0	96.8	5400	5220	5460	5280	5040	87.5	86.8	87.4	86.5	86.4	**0.056**
	691	5640	5220	5580	5520	5100	99.8	101.5	86.3	94.6	103.5	5340	5400	5820	5040	5220	86.2	84.4	88.5	86.7	85.9	**0.056**
	364	5880	5340	5280	5760	5100	93.7	90.2	98.7	93.9	99.3	5820	4620	5640	5520	5040	87.8	87.0	86.6	85.9	87.6	**0.056**
	613	5700	5280	5280	5700	4980	101.0	103.7	91.0	97.3	104.2	4980	5400	5760	4980	4920	87.2	86.9	86.2	86.1	86.6	**0.057**
	889	5640	5280	5100	5760	5340	104.6	101.1	96.8	87.0	99.0	5580	5040	5520	5400	5520	87.6	87.1	87.3	88.2	87.9	**0.057**
	Obs.	**5720**	**5420**	**5245**	**5715**	**5300**	**91.63**	**92.13**	**90.37**	**89.63**	**93.96**	**5231**	**5067**	**5264**	**4770**	**4996**	**88.6**	**89.2**	**89.3**	**90.9**	**89.2**	

Table D.9: Test 2 pre-simulation volume/speed RMSP - non-crash conditions (#884, #888 and #903)

Crash #	**Seed**	**Upstream Flow Rate (vph)**					**Upstream Speed (km/h)**					**Downstream Flow Rate (vph)**					**Downstream Speed (km/h)**					**RMSP**
		0 - 1'	**1 - 2'**	**2 - 3'**	**3 - 4'**	**4 - 5'**	**0 - 1'**	**1 - 2'**	**2 - 3'**	**3 - 4'**	**4 - 5'**	**0 - 1'**	**1 - 2'**	**2 - 3'**	**3 - 4'**	**4 - 5'**	**0 - 1'**	**1 - 2'**	**2 - 3'**	**3 - 4'**	**4 - 5'**	
884	768	4800	4260	4020	4980	4440	103.1	102.4	102.9	103.3	102.5	4440	4680	4260	4500	4200	103.1	102.4	101.7	99.4	100.6	**0.053**
	903	3960	4560	3960	4500	4500	103.9	101.1	103.2	102.2	101.7	4140	4680	4140	4800	4380	103.7	101.6	102.1	102.2	102.8	**0.054**
	236	4320	4200	3840	4620	4740	104.6	105.1	104.6	102.3	103.6	3960	4260	4560	4320	4320	103.5	103.9	101.4	99.1	101.5	**0.055**
	133	4800	4200	4260	4560	4560	101.7	103.8	103.3	104.1	104.0	4080	4320	4140	5040	4440	103.1	101.6	102.3	102.3	103.6	**0.055**
	171	4560	4140	3900	4560	4320	104.9	103.7	104.2	102.6	102.3	4320	4500	3960	4260	4560	105.6	102.7	102.1	101.6	102.2	**0.058**
	396	4260	4500	4380	5040	4200	103.3	103.7	105.6	104.4	100.9	4200	4560	4500	4740	4320	102.1	104.5	101.9	100.7	103.9	**0.058**
	802	4860	4020	4020	4800	4800	105.1	104.3	102.2	101.9	102.9	4200	4200	4380	4920	4740	105.0	98.8	104.0	100.9	99.8	**0.058**
	381	4080	4260	4440	4860	4080	101.7	104.9	103.8	102.3	104.1	4260	4380	4320	4560	4680	103.8	100.4	104.0	101.9	100.2	**0.059**
	961	4260	4440	3960	4320	4440	103.6	103.5	106.2	103.7	102.6	4500	4020	4200	4440	4620	102.8	102.3	104.1	101.6	101.8	**0.059**
	183	3840	4320	4380	4320	4800	103.2	102.6	102.1	102.3	100.8	4080	4380	3900	4560	4620	100.4	102.3	102.8	100.2	101.8	**0.060**
	Obs.	**4391**	**4336**	**4151**	**4696**	**4636**	**96.0**	**95.9**	**95.4**	**93.5**	**94.2**	**4175**	**4385**	**4275**	**4530**	**4425**	**101.0**	**100.8**	**101.0**	**98.2**	**98.1**	
888	3	4800	4980	4620	4680	4800	101.7	103.0	101.6	103.2	99.4	4980	4620	4680	5040	4620	100.9	102.4	102.9	100.4	102.2	**0.046**
	31	4920	4740	4800	4560	4920	104.0	100.3	103.4	104.2	100.5	4920	4800	4800	4860	4740	103.2	101.8	104.4	100.7	105.1	**0.051**
	6	4800	4920	4620	4680	4800	104.6	99.2	102.6	102.7	98.3	4920	4560	4980	4860	4380	104.4	101.7	99.3	101.6	102.4	**0.051**
	4	4680	4920	4740	4560	4740	102.9	102.0	99.7	103.9	103.8	5280	4920	4500	4680	4620	98.4	101.1	103.4	101.7	103.9	**0.052**
	28	4740	4920	4680	4740	4620	101.5	104.0	104.4	103.1	104.0	4860	4440	4860	4980	4860	100.6	102.8	102.9	102.7	101.3	**0.053**
	39	4800	4980	4620	4740	4740	102.2	102.9	104.2	102.7	101.1	4980	4560	4380	5160	4560	102.0	104.6	103.9	99.8	103.5	**0.057**
	19	4680	4800	4800	4620	4860	104.0	102.7	104.8	104.3	104.7	4980	4800	4500	4920	4440	102.2	99.2	103.6	102.2	103.0	**0.058**
	29	4860	4800	4860	4500	4860	102.4	104.0	99.6	103.8	102.8	4980	4920	4200	4800	4800	104.0	100.9	104.6	102.2	103.2	**0.060**
	25	4920	4920	4680	4500	4740	102.3	104.8	83.3	101.4	103.5	5040	4680	4500	4740	5100	102.4	103.9	103.0	102.7	101.6	**0.060**
	18	4740	4920	4740	4560	4800	103.8	102.4	104.6	103.8	105.0	4740	4800	4740	4380	5160	103.4	103.7	103.5	105.5	102.8	**0.064**
	Obs.	**4835**	**4870**	**4745**	**4658**	**4750**	**95.1**	**94.9**	**95.0**	**95.3**	**93.4**	**4985**	**4645**	**4745**	**4845**	**4845**	**94.5**	**95.1**	**96.6**	**99.4**	**102.3**	
903	733	6180	6240	6120	6180	5460	82.4	87.5	86.6	91.6	94.4	6300	6060	6000	5700	5940	86.4	85.2	87.5	86.4	86.5	**0.047**
	680	6180	5940	6240	6000	5880	82.7	90.7	91.5	94.9	97.2	6060	6000	6360	5700	6060	87.1	84.9	87.8	85.5	92.2	**0.051**
	417	6060	6180	5940	6000	5940	72.7	82.1	98.5	99.7	100.4	6000	5640	6180	6120	5340	86.0	87.6	86.5	87.1	95.1	**0.059**
	6	6300	6000	6000	6180	5760	75.0	82.4	95.5	99.9	103.0	6300	5640	6420	5940	5940	85.6	85.2	85.2	85.0	93.8	**0.061**
	826	6060	5760	6120	5880	5700	67.3	84.4	88.0	94.1	95.4	5880	5820	6240	5640	6060	85.7	84.7	84.8	84.9	89.3	**0.063**
	721	6240	5880	6240	6240	5520	89.1	96.2	92.8	81.5	98.0	6360	5580	6420	5640	5580	85.3	88.9	87.3	85.8	93.4	**0.065**
	636	6300	5640	6120	5940	5700	73.9	92.2	74.9	91.9	102.2	5940	5880	6120	5640	5460	83.6	86.7	83.4	86.6	94.8	**0.065**
	483	6300	6240	5940	6060	5460	94.0	77.5	98.5	97.6	102.9	6120	6000	6000	5760	5460	86.9	82.4	87.0	87.0	92.2	**0.067**
	581	6000	5940	5820	6360	5400	72.2	96.7	101.0	95.0	99.5	5940	6000	5760	6060	5460	86.6	86.9	87.8	84.7	92.3	**0.068**
	716	6360	5940	5580	6420	5700	70.8	87.0	99.8	99.7	102.5	5580	5940	5940	6120	5520	85.5	86.1	88.6	87.3	91.0	**0.068**
	Obs.	**5858**	**5924**	**5891**	**6120**	**5684**	**80.6**	**81.7**	**85.5**	**90.2**	**91.0**	**5880**	**5755**	**5930**	**5810**	**5685**	**89.2**	**90.8**	**91.4**	**90.3**	**95.0**	

Appendix E

Pre-simulation Volume and Speed RMSP - Test 3

Table E.1: Test 3 pre-simulation number seed and RMSP values - Segment A

Time		Seed	RMSP	Time		Seed	RMSP
6:00	7:00	2	0.172	7:00	8:00	11	0.168
		273	0.173			127	0.170
		230	0.175			742	0.170
		111	0.175			9	0.170
		622	0.175			488	0.170
		695	0.177			912	0.170
		329	0.177			741	0.170
		114	0.177			578	0.170
		231	0.177			434	0.170
		229	0.177			819	0.170
8:00	9:00	376	0.201	9:00	10:00	572	0.189
		574	0.201			695	0.189
		551	0.202			138	0.191
		533	0.202			587	0.192
		358	0.202			726	0.192
		405	0.202			557	0.192
		456	0.202			422	0.193
		85	0.202			465	0.193
		688	0.202			257	0.194
		225	0.202			8	0.194
10:00	11:00	23	0.049	11:00	12:00	3	0.053
		56	0.049			80	0.053
		155	0.049			41	0.053
		38	0.049			12	0.053
		578	0.049			143	0.053
		200	0.049			345	0.054
		137	0.050			765	0.054
		798	0.050			456	0.054
		12	0.050			9	0.055
		70	0.051			13	0.055
12:00	13:00	4	0.053	13:00	14:00	10	0.052
		7	0.053			7	0.053
		5	0.053			5	0.053
		8	0.053			1	0.053
		6	0.053			8	0.053
		2	0.054			3	0.053
		3	0.054			6	0.053
		1	0.054			4	0.054
		9	0.054			2	0.054
		10	0.055			9	0.054
14:00	15:00	5	0.049	15:00	16:00	5	0.051
		2	0.049			3	0.051
		1	0.050			1	0.051
		6	0.050			2	0.051
		4	0.051			6	0.052
		7	0.051			7	0.052
		8	0.051			4	0.052
		9	0.052			10	0.052
		10	0.052			8	0.052
		3	0.052			9	0.055
16:00	17:00	1	0.047	17:00	18:00	8	0.066
		4	0.048			3	0.067
		6	0.048			6	0.067
		9	0.048			7	0.069
		3	0.048			1	0.069
		5	0.048			10	0.069
		7	0.049			4	0.070
		8	0.049			5	0.070
		10	0.050			9	0.070
		2	0.051			2	0.072

Table E.2: Test 3 pre-simulation number seed and RMSP values - Segment B

Time		Seed	RMSP	Time		Seed	RMSP
6:00	7:00	747	0.106	7:00	8:00	317	0.150
		679	0.108			834	0.150
		886	0.108			558	0.151
		963	0.109			398	0.151
		682	0.109			737	0.151
		677	0.110			354	0.151
		931	0.110			584	0.151
		680	0.111			937	0.151
		8	0.111			473	0.151
		610	0.111			818	0.151
8:00	9:00	106	0.149	9:00	10:00	145	0.111
		892	0.151			713	0.113
		935	0.152			678	0.113
		206	0.153			214	0.115
		342	0.153			492	0.116
		155	0.154			505	0.116
		533	0.154			830	0.116
		999	0.154			829	0.116
		802	0.154			345	0.117
		560	0.154			864	0.117
10:00	11:00	5	0.031	11:00	12:00	99	0.030
		4	0.032			71	0.030
		8	0.032			69	0.031
		7	0.033			94	0.031
		6	0.033			54	0.031
		1	0.034			84	0.031
		2	0.034			45	0.031
		10	0.035			78	0.032
		3	0.036			15	0.032
		9	0.036			11	0.032
12:00	13:00	16	0.028	13:00	14:00	71	0.029
		33	0.029			67	0.029
		20	0.029			57	0.030
		31	0.030			61	0.030
		11	0.030			70	0.030
		32	0.030			56	0.030
		25	0.030			55	0.030
		8	0.030			86	0.030
		27	0.030			32	0.031
		5	0.030			31	0.031
14:00	15:00	23	0.025	15:00	16:00	70	0.023
		7	0.025			8	0.023
		72	0.025			58	0.023
		90	0.025			4	0.024
		47	0.026			100	0.024
		27	0.026			57	0.024
		55	0.026			16	0.024
		32	0.026			31	0.024
		66	0.026			5	0.024
		54	0.026			69	0.024
16:00	17:00	86	0.024	17:00	18:00	86	0.024
		65	0.025			65	0.025
		83	0.025			83	0.025
		90	0.025			90	0.025
		5	0.025			5	0.025
		6	0.025			6	0.025
		23	0.025			23	0.025
		77	0.025			77	0.025
		58	0.025			58	0.025
		44	0.026			44	0.026

Appendix F

Case Study 2: ANOVA Tables and Residual Plots

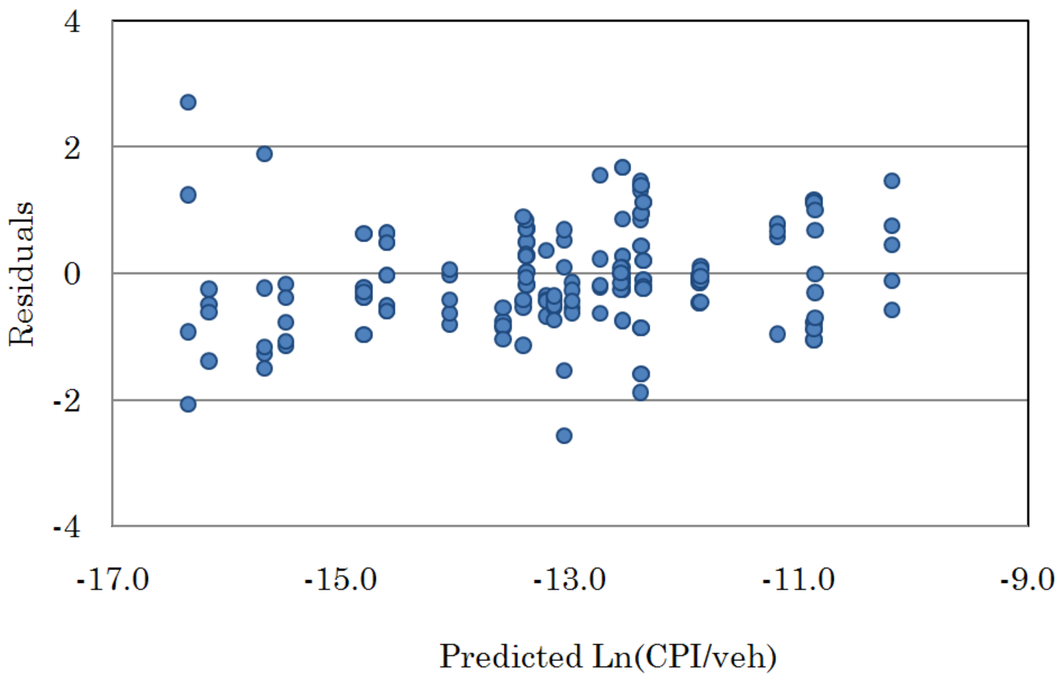

Figure F.1: Residual Plot for Case study 2 - Off-ramp

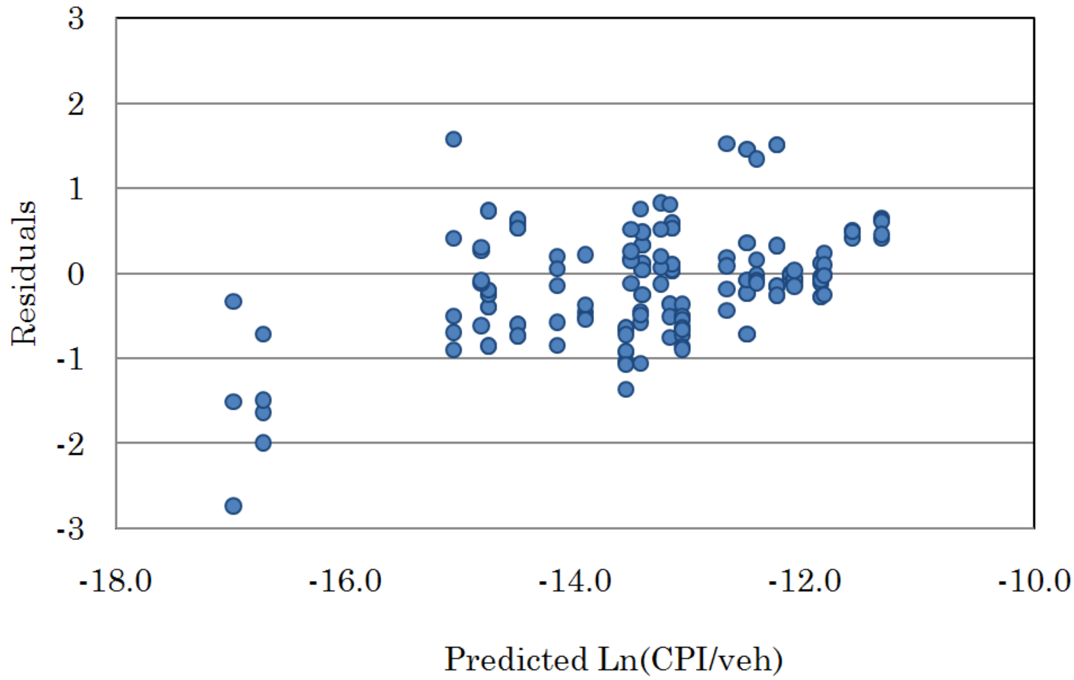

Figure F.2: Residual Plot for Case study 2 - Straight segment

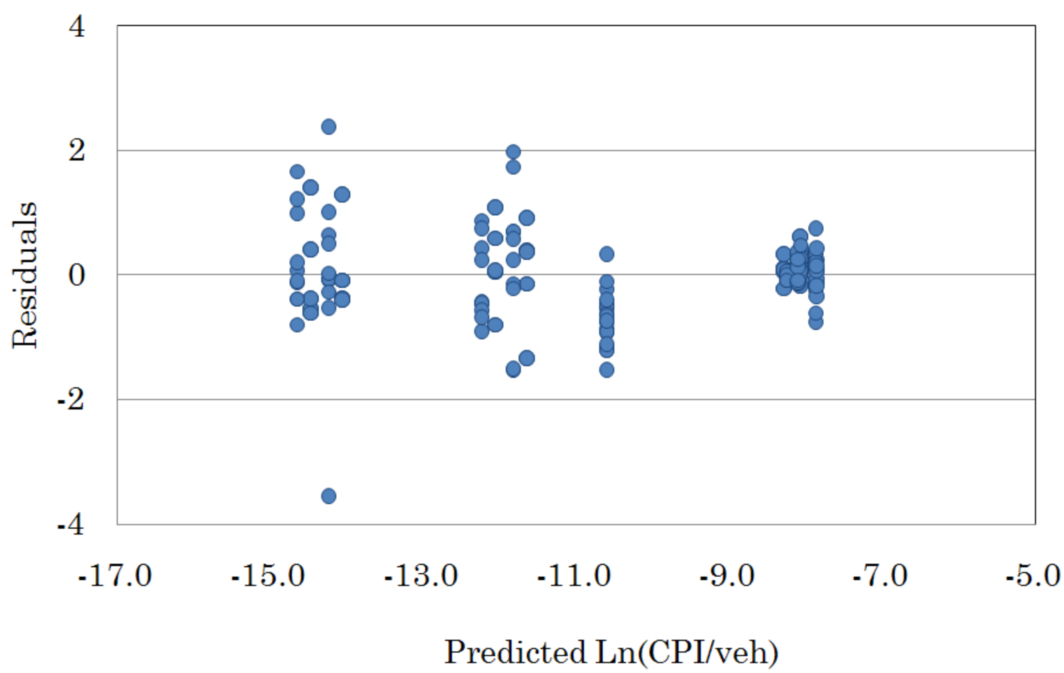

Figure F.3: Residual Plot for Case study 2 - on ramp

Table F.1: N-way ANOVA for 105 km/h Strategy (off-ramp)

Dependent Variable: Ln(CPI/veh)					
Source	Sum of Squares	df	Mean Square	F- value	p-value
A	**142.70**	**1**	**142.70**	**134.10**	**0.00**
B	**197.67**	**1**	**197.67**	**185.76**	**0.00**
C	3.06	1	3.06	2.87	0.09
D	**10.46**	**1**	**10.46**	**9.83**	**0.00**
E	**5.55**	**1**	**5.55**	**5.21**	**0.02**
A * B	**5.48**	**1**	**5.48**	**5.15**	**0.02**
A * C	**4.42**	**1**	**4.42**	**4.15**	**0.04**
B * C	3.67	1	3.67	3.45	0.07
A * B * C	1.69	1	1.69	1.58	0.21
A * D	**6.54**	**1**	**6.54**	**6.15**	**0.01**
B * D	0.46	1	0.46	0.43	0.51
A * B * D	0.09	1	0.09	0.08	0.78
C * D	0.06	1	0.06	0.06	0.81
A * C * D	0.00	1	0.00	0.00	0.95
B * C * D	0.02	1	0.02	0.02	0.90
A * B * C * D	0.06	1	0.06	0.05	0.82
A * E	**7.53**	**1**	**7.53**	**7.07**	**0.01**
B * E	**4.73**	**1**	**4.73**	**4.45**	**0.04**
A * B * E	3.32	1	3.32	3.12	0.08
C * E	3.06	1	3.06	2.87	0.09
A * C * E	**4.42**	**1**	**4.42**	**4.15**	**0.04**
B * C * E	3.67	1	3.67	3.45	0.07
A * B * C * E	1.69	1	1.69	1.58	0.21
D * E	0.17	1	0.17	0.16	0.69
A * D * E	0.32	1	0.32	0.30	0.58
B * D * E	0.41	1	0.41	0.38	0.54
A * B * D * E	0.25	1	0.25	0.23	0.63
C * D * E	0.06	1	0.06	0.06	0.81
A * C * D * E	0.00	1	0.00	0.00	0.95
B * C * D * E	0.02	1	0.02	0.02	0.90
A * B * C * D * E	0.06	1	0.06	0.05	0.82
Pure Error	153.231	144	1.064		

Table F.2: N-way ANOVA for 105 km/h Strategy (straight segment)

Dependent Variable: Ln(CPI/veh)					
Source	Sum of Squares	df	Mean Square	F- value	p-value
A	**65.48**	**1**	**65.48**	**74.87**	**0.00**
B	**181.22**	**1**	**181.22**	**207.19**	**0.00**
C	**4.98**	**1**	**4.98**	**5.70**	**0.02**
D	0.26	1	0.26	0.30	0.59
E	**7.51**	**1**	**7.51**	**8.58**	**0.00**
A * B	**9.32**	**1**	**9.32**	**10.66**	**0.00**
A * C	**3.95**	**1**	**3.95**	**4.52**	**0.04**
B * C	**3.31**	**1**	**3.31**	**3.79**	**0.05**
A * B * C	2.98	1	2.98	3.41	0.07
A * D	2.50	1	2.50	2.85	0.09
B * D	0.22	1	0.22	0.25	0.62
A * B * D	0.12	1	0.12	0.14	0.71
C * D	0.12	1	0.12	0.14	0.71
A * C * D	0.24	1	0.24	0.28	0.60
B * C * D	0.20	1	0.20	0.23	0.63
A * B * C * D	0.33	1	0.33	0.37	0.54
A * E	**6.99**	**1**	**6.99**	**7.99**	**0.01**
B * E	**4.98**	**1**	**4.98**	**5.70**	**0.02**
A * B * E	2.79	1	2.79	3.19	0.08
C * E	4.98	1	4.98	5.70	0.02
A * C * E	**3.95**	**1**	**3.95**	**4.52**	**0.04**
B * C * E	3.31	1	3.31	3.79	0.05
A * B * C * E	2.98	1	2.98	3.41	0.07
D * E	0.31	1	0.31	0.35	0.55
A * D * E	0.50	1	0.50	0.58	0.45
B * D * E	0.26	1	0.26	0.29	0.59
A * B * D * E	0.74	1	0.74	0.85	0.36
C * D * E	0.12	1	0.12	0.14	0.71
A * C * D * E	0.24	1	0.24	0.28	0.60
B * C * D * E	0.20	1	0.20	0.23	0.63
A * B * C * D * E	0.33	1	0.33	0.37	0.54
Error	125.95	144	0.87		

Table F.3: N-way ANOVA for 105 km/h Strategy (on ramp)

Dependent Variable: Ln(CPI/veh)					
Source	Sum of Squares	df	Mean Square	F- value	p-value
A	**1033.12**	**1**	**1033.12**	**2231.63**	**0.00**
B	**69.29**	**1**	**69.29**	**149.67**	**0.00**
C	0.00	1	0.00	0.00	0.99
D	0.08	1	0.08	0.17	0.68
E	0.14	1	0.14	0.31	0.58
A * B	**48.13**	**1**	**48.13**	**103.96**	**0.00**
A * C	0.07	1	0.07	0.15	0.70
B * C	0.03	1	0.03	0.06	0.81
A * B * C	0.05	1	0.05	0.11	0.74
A * D	0.06	1	0.06	0.14	0.71
B * D	**1.91**	**1**	**1.91**	**4.13**	**0.04**
A * B * D	**1.51**	**1**	**1.51**	**3.26**	**0.07**
C * D	0.18	1	0.18	0.39	0.53
A * C * D	0.00	1	0.00	0.01	0.93
B * C * D	0.08	1	0.08	0.17	0.68
A * B * C * D	0.22	1	0.22	0.47	0.49
A * E	**1.38**	**1**	**1.38**	**2.98**	**0.09**
B * E	0.38	1	0.38	0.82	0.37
A * B * E	0.07	1	0.07	0.16	0.69
C * E	0.00	1	0.00	0.00	0.99
A * C * E	0.07	1	0.07	0.15	0.70
B * C * E	0.03	1	0.03	0.06	0.81
A * B * C * E	0.05	1	0.05	0.11	0.74
D * E	0.05	1	0.05	0.12	0.73
A * D * E	0.59	1	0.59	1.28	0.26
B * D * E	0.10	1	0.10	0.21	0.64
A * B * D * E	0.03	1	0.03	0.05	0.82
C * D * E	0.18	1	0.18	0.39	0.53
A * C * D * E	0.00	1	0.00	0.01	0.93
B * C * D * E	0.08	1	0.08	0.17	0.68
A * B * C * D * E	0.22	1	0.22	0.47	0.49
Error	66.66	144	0.46		

Appendix G

Case Study 2 CPI/veh changes with volume and % trucks - On ramp Segments

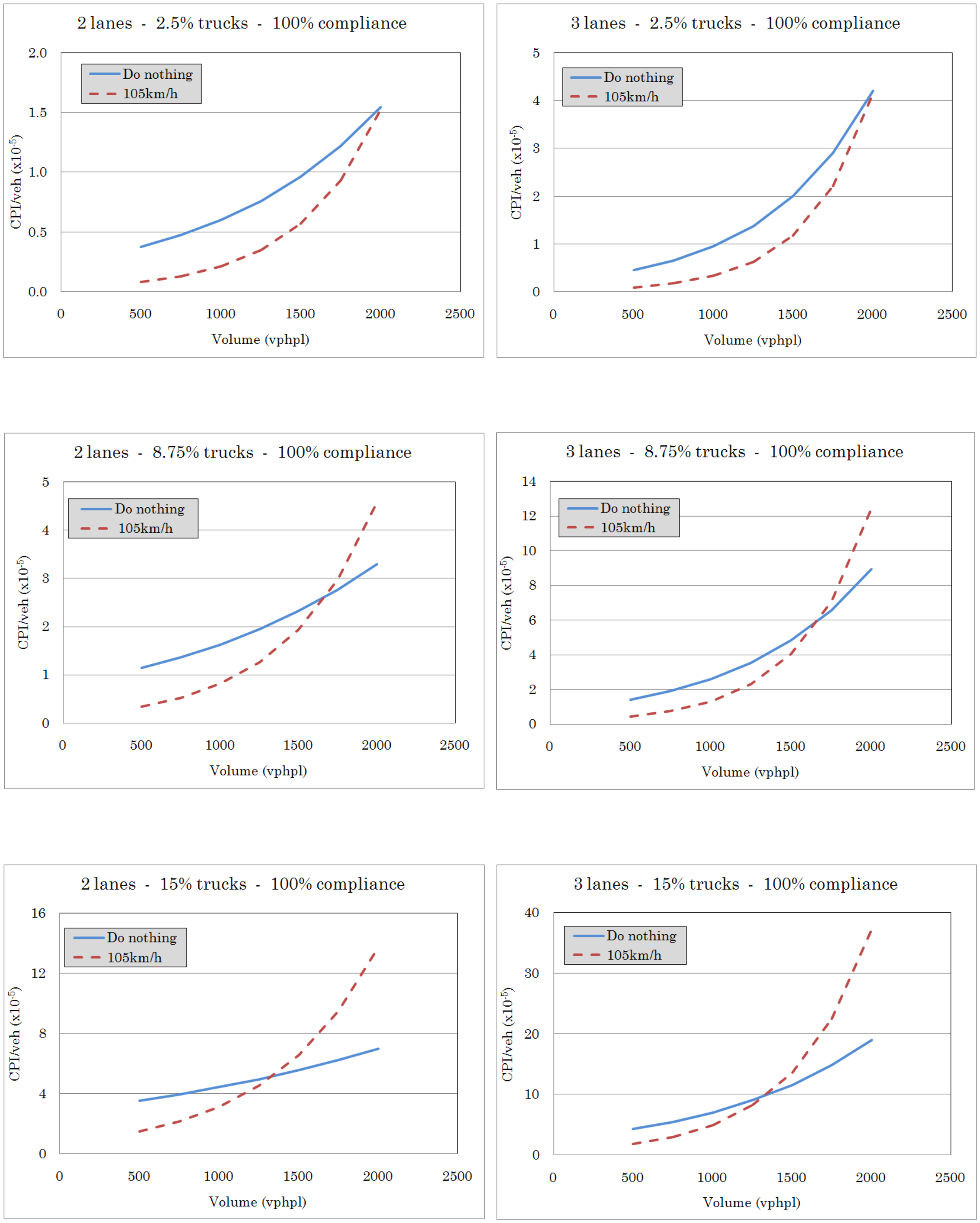

Figure G.1: Estimates of CPI/veh as a function of volume for on ramps.

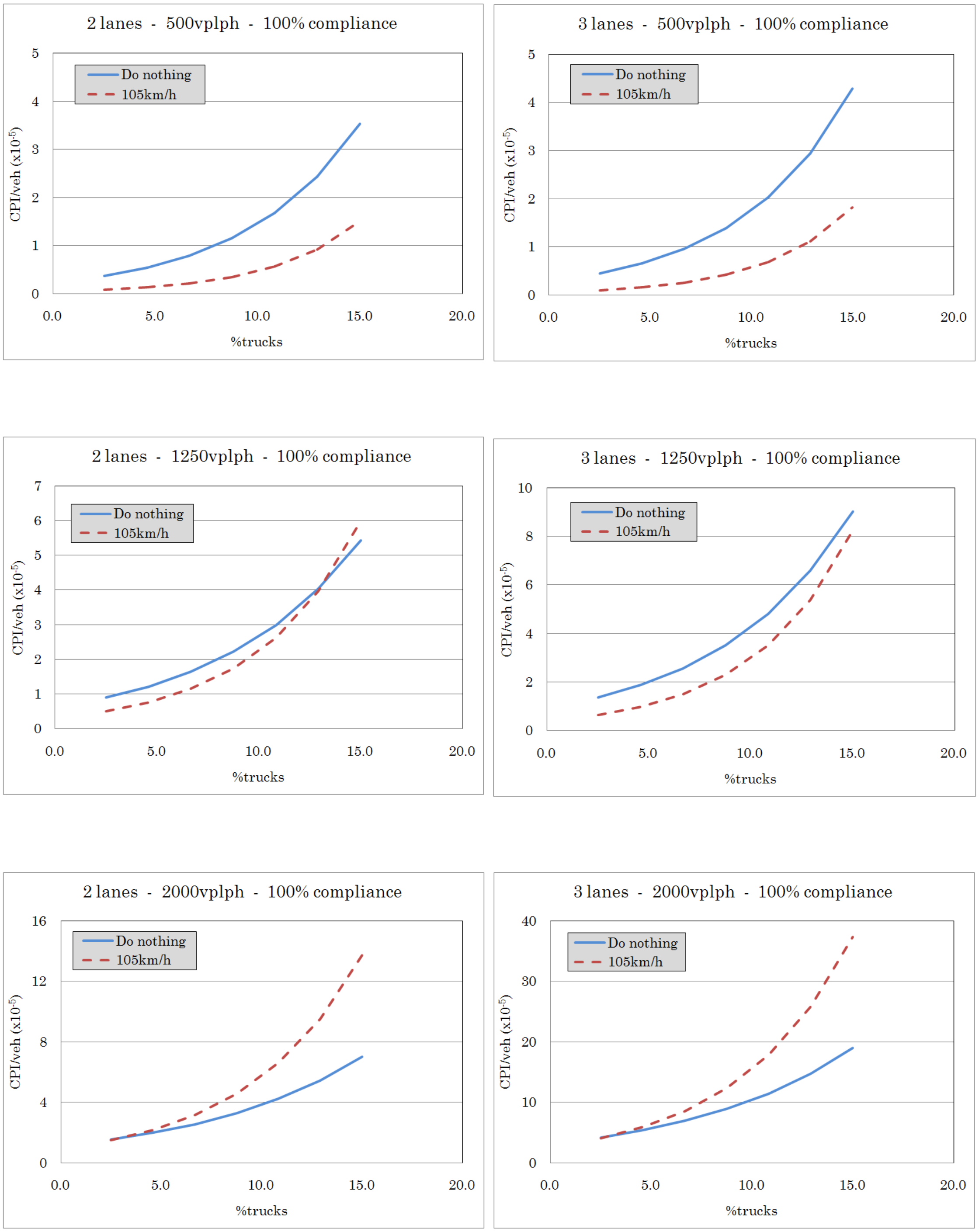

Figure G.2: Estimates of CPI/veh as a function of the percentage of trucks for on ramps.

Appendix H

Case Study 2 CPI/veh changes with volume and % trucks - Straight Segments

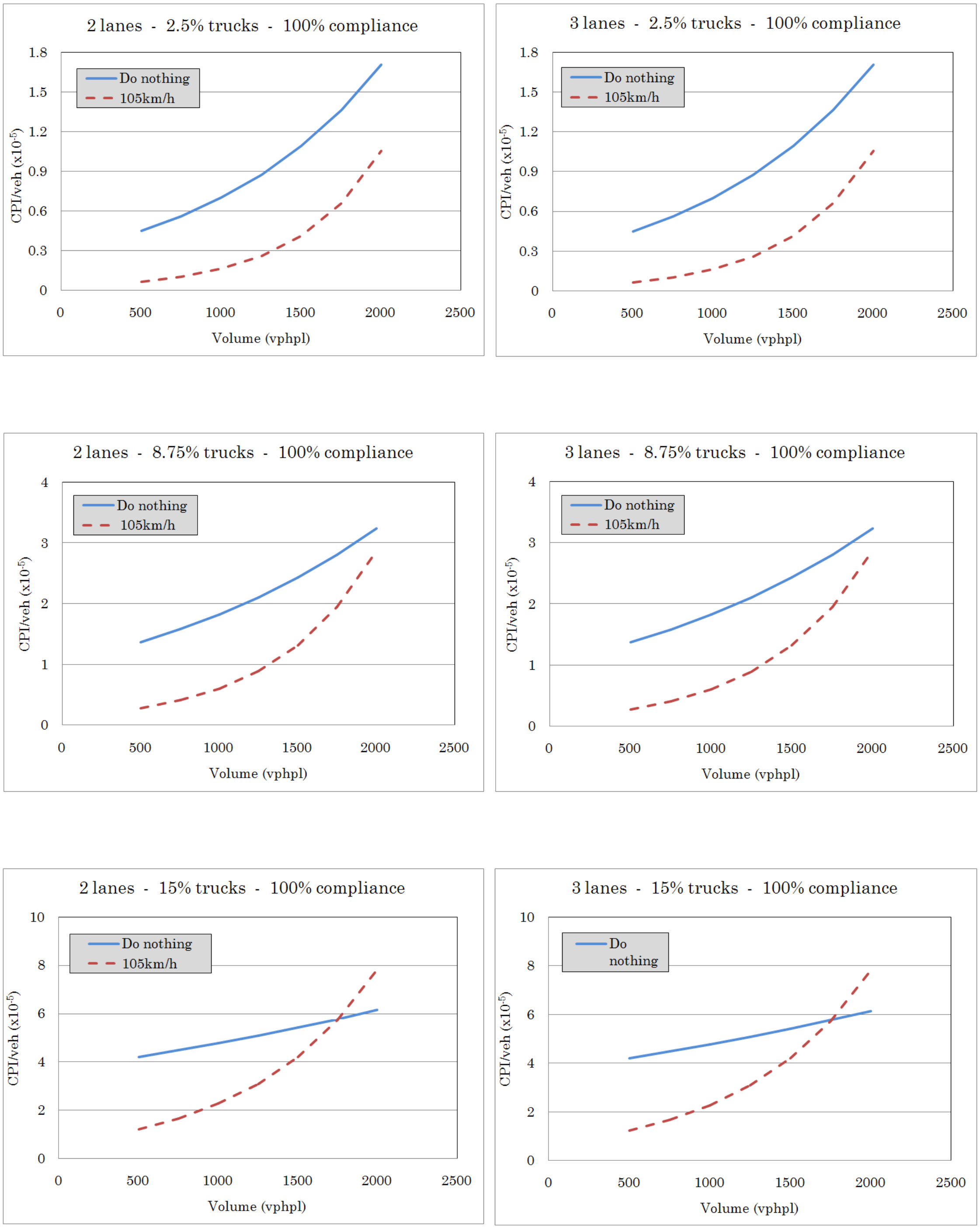

Figure H.1: Estimates of CPI/veh as a function of volume for straight segments.

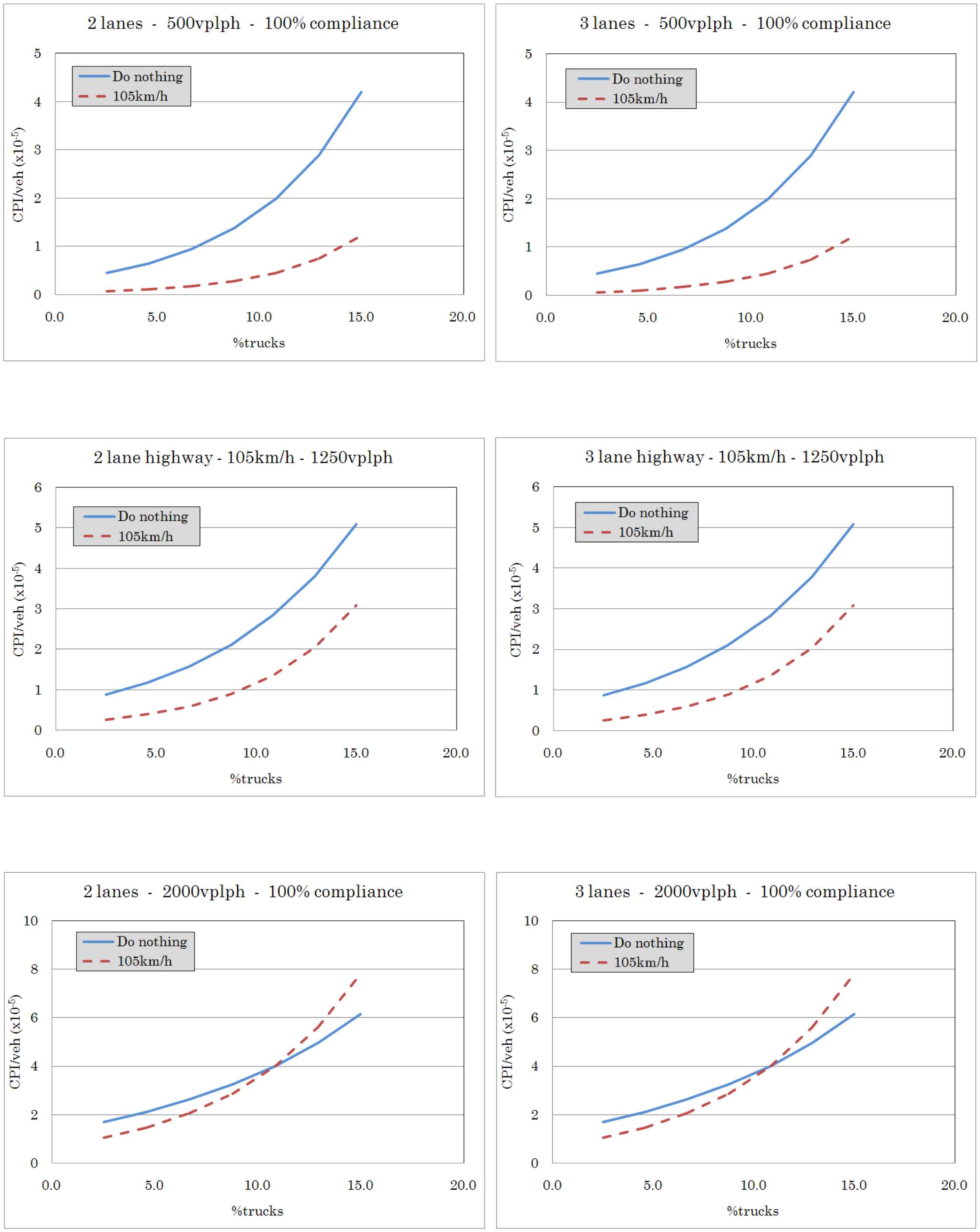

Figure H.2: Estimates of CPI/veh as a function of the percentage of trucks for straight segments.

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