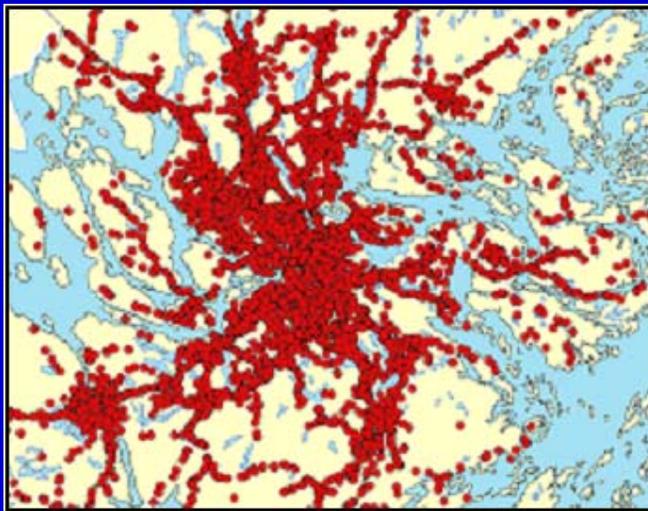


Indicators for traffic safety
assessment and prediction
and their application in
micro-simulation modelling:
A study of urban and suburban intersections

Jeffery Archer



The Greater Stockholm area defined by accident occurrence (from STRADA)

Doctoral Thesis
Stockholm, Sweden 2005



DEPARTMENT OF INFRASTRUCTURE

Division for Transport and Logistics, ToL

Centre for Transport Research, CTR



ROYAL INSTITUTE
OF TECHNOLOGY

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Picture on front cover represents the county of Stockholm defined by accident occurrence (data from STRADA)

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Stockholm, 20th February 2005

Jeffery Archer

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Executive summary

The large number of serious injuries and fatalities resulting from traffic accidents is today recognised as a major health problem around the world. As a result, policies of action have been determined to combat these problems at the international and national level. In Sweden, the long-term political goals for traffic safety concern the development of a sustainable and functional road transport system that results in no serious injuries or fatalities (the ‘*zero-vision*’). In order to achieve these goals, there is a growing need in transportation planning and traffic engineering work for relatively fast, reliable and effective methods to evaluate and predict the impact of new and alternative safety enhancement measures. These methods must assure the quality of traffic system safety and consider other important objectives, such as traffic performance, capacity, and environmental issues. Together, these form essential elements of a sustainable long-term transport infrastructure development.

This thesis is concerned with the many concepts, theories and methods related to effective short-term traffic safety assessment and, more specifically, on the use of proximal safety indicators as an alternative to historical accident data. Safety indicators can be used to measure the spatial and/or temporal proximity of safety critical events and are assumed to have an established relationship with accidents. As an alternative measure of traffic safety, proximal indicators have the advantage of being frequent than accidents, and therefore require shorter period of study to establish statistically stable values. They are also adaptive to the specific characteristics and conditions of particular traffic locations or facilities, making them useful in before-and-after study designs, and other safety assessment strategies. A major drawback associated with proximal safety indicators concerns their validity, i.e. how well they actually represent ‘*safety*’ as a theoretical concept. This is usually measured by the strength of the relationship between safety indicators and traffic accidents and accident outcome severity, and how accurately an expected number of accidents (as an accepted measure of safety) can be predicted. Validity also concerns whether the events measured are representative of the same underlying processes that precede accident occurrence. Other questions concern the reliability of the various measurement techniques, their advantages and disadvantages and their usefulness from a practical perspective.

The relationships between proximal safety indicators and more traditional traffic measures such as traffic flow, and speed, is also an issue that is considered, along with safety-relevant interactive processes such as gap-acceptance in yielding situations and maintaining a suitably safe gap when car-following. Deeper knowledge of these different and complex relationships is expected to provide a solid basis for predictive safety modelling in the future, where the complexities and dynamics of traffic processes can be adequately represented. A particular type of dynamic traffic modelling that has become increasingly popular among transport planners and traffic engineers, is simulation. Microscopic traffic simulation has the potential to provide a safe and flexible test environment for the estimation of traffic safety and performance effects brought about by new and alternative designs and other safety influencing factors that are related to the roadway, road-users and vehicles. Importantly, this type of modelling allows sensitivity testing, is relatively cost-effective and allows effects to be visualised for expert and non-technical audiences. This safety modelling approach is also ‘*proactive*’ and ethically more appealing than statistical modelling based on accident data. Simulation modelling for traffic safety assessment and prediction is an area that is considered to have great potential for transportation planning and traffic engineering in the future.

This thesis focuses on the identification and measurement of safety problems at urban and suburban intersections using safety indicators. To put these safety problems into perspective important and relevant background information is presented. This includes a brief overview of the present day traffic safety problem, and the international and national traffic safety statistics. Statistics are also stated in relation to urban area problems in Sweden, and the types of accidents that occur at roadway intersections. A section is also included concerning different approaches to traffic safety research and modelling. A brief introduction in relation to the causes of accidents is also given, along with some of the more useful safety countermeasures at urban intersections. Statistical predictive modelling is also discussed briefly, before an in-depth review of the many different safety indicators and their associated measurement techniques.

The first two practical studies undertaken as part of the work on this thesis involve safety indicator measurement in the field. The first study is concerned with the usefulness, validity and reliability of the Traffic Conflict Technique in relation to four intersections on a busy city street in central Stockholm. In this study, a comparison of intersection safety is carried out by examining the different types of conflicts that occur at each, and by contrasting the conflict data against police reported accident data. The results are discussed in relation to differences in intersection layout, signalling strategies, and the interactions between vulnerable road-users and vehicles at the pedestrian crossings. It was concluded from this study, that there are important influential factors that have a complex effect on the relationship between accidents and serious conflicts, and that these must be considered for accident prediction purposes.

The second study represents a central part of this thesis. A detailed comparison is made between three different proximal safety indicators (Time-to-Accident, Time-to-Collision, and Post-Encroachment Time) at three unregulated T-junctions during different time-periods including morning and afternoon peak hours. This main purpose of this study was to identify the potential and limitations of the different safety indicator concepts and measurement techniques. Furthermore, it was intended to identify relationships between the safety indicators and other influential traffic parameters and processes with regard to traffic safety. A video-analysis program (SAVA) was developed specifically for the purposes of this study, and was evaluated as part of this work. The results of this study showed that each of the indicator measurement techniques had different limitations. In addition, video-analysis proved particularly time-consuming, and resource demanding, making on-the-spot subjective judgement more practically appealing. Video-analysis is also restricted to the quality and coverage of the imagery, while field observation provides a wealth of additional qualitative and quantitative information that is highly useful for detailed safety analysis purposes.

The relationships between proximal safety indicators and different traffic parameters and processes were investigated further using a methodology based on microscopic simulation modelling. Arguably, the majority of commercial and academic micro-simulation tools have not reached a sufficient level of development to realise the full potential of '*safety simulation*' at the present moment in time. This type of simulation modelling also requires a highly detailed and consistent set of empirical data, as well as more stringent calibration and validation procedures than those used in standard traffic performance and capacity related studies.

Two different simulation experiments were carried out. The first was a continuation of the study based on the evaluation of safety at unsignalised T-junctions. Using the Täby T-junction data, a simulation model was constructed in relation to three different time-periods, each with different traffic patterns. The goal of this modelling was to reproduce the same number of safety critical events in the simulation runs. These were measured by the same three safety indicators used in the original field study. In order to achieve representative gap-acceptance behaviour in the model, a probabilistic function based on binary logistic regression was introduced. This was based on the original field data. Other aspects of the model were also calibrated and validated very carefully to ensure that the simulation model was representative of the corresponding real-world situation. The results of this study indicated the possibilities and potential of safety simulation, but also highlighted a number of modelling issues that need to be resolved before this approach becomes an accepted practice among transport planners and traffic engineers in the future.

The second simulation study took a slightly different approach looking at a suburban signalised intersections and the evaluation of an incident-reduction function used in vehicle-actuated signal controller logic. This function is designed to reduce the incidence of rear-end collisions for vehicle drivers who are faced with a stop-go decision in the so-called '*dilemma zone*' following the onset of an amber signal. For the purposes of this study, empirical field data was collected and analysed using video-analysis. Although the simulation model was strictly calibrated and validated, safety indicator data was not collected in the field and therefore could not be validated against the simulation results. The purpose of this study was to test the potential of the simulation methodology and the pre-programmed vehicle-actuated signal logic (including incident reduction) for future studies in which the performance of traffic signals, traffic performance and safety is an important study issue. The results of the study showed a 22 per cent reduction in the number of unsafe rear-end interactions (measured by the Time-to-Collision safety indicator) when the incident reduction function was active. Furthermore, no detrimental effects on traffic performance were found. The simulation-based safety estimation methodology was found to be useful for similar studies in the future.

From the work conducted in this thesis, it has become increasingly apparent that the use of proximal traffic safety indicators has considerable unrecognised potential in relation to the need for fast, reliable, and accurate traffic safety assessment and prediction. Furthermore, there is distinct need for more research in this area in order to develop standardised methods of application (using field observation and video-analysis) that serve to improve reliability, and establish the acceptability and validity of these measures as both a diagnostic tool and useful predictive instrument for transport planners and traffic engineers in the future. As a first step in achieving these goals, the establishment of proximal safety indicator database is suggested. This will enable large-scale comparisons against accident data and other traffic measures for the purposes of establishing validity, and robust statistical safety prediction models of a more detailed and accurate nature than those that have been developed to date.

Glossary of Terms – Quick Reference Guide

Accident (traffic)	Event between road-users that results in injury, fatality or property damage
Accident causation	Underlying reasons that pre-empt a traffic accident, most usually involving an unforeseen chain-of-events. Accident causation is often attributed to one of the three main components of the traffic system: road-user, vehicle or roadway, or a combination of thereof
Accident outcome	Result of an accident in terms of injury severity, fatality and in some cases also property damage
Accident rate	Number of accidents in accordance with a measure of exposure
Accident risk	Risk for accident involvement (for different road-user classes). Objective risk reflects accident frequency in relation to a measure of exposure or population
Accident severity	Level of injury sustained in a traffic accident: usually categorised as minor, serious or fatal
Calibration	Process used in Traffic Simulation to (statistically) ensure that the functioning and behaviour of a particular model and/or sub-model corresponds with observed empirical measurements or predetermined values
Car-following	Term used to describe the status of a vehicle that has a time/distance gap or headway less than a predetermined maximum value
Collision	Impact event between two or more road-users/vehicles, or a road-user (vehicle) and stationary object
Collision course	Existence of a common projected conflict point in time and space for two (or more) road-users/vehicles, usually based on momentary measures of trajectory, speed and distance
Conflict	A potentially unsafe interactive event that requires evasive action (braking, swerving or accelerating) to avoid collision
Conflict distance	A momentary measurement of (spatial) distance to a common conflict point for a road-user/vehicle in a conflict situation
Conflict observation	Method that is used by trained observers to determine Time-to-Accident values in accordance with the Traffic Conflict Technique. Based on the subjective estimation of speed and distance for road-users/vehicles that are in a conflict situation
Conflict point	Common spatial location of projected trajectories given momentary measures of speed and distance for two or more road-users/vehicles
Conflict zone	Common area used by road-users/vehicles approaching from different trajectories
Conflict severity	Seriousness of a potential collision or near-accident measured by temporal or spatial proximity
Conflict speed	Momentary measurement of velocity for a road-user (vehicle) in a conflict situation
Crash	Term that is sometimes preferred to (traffic) accident due to the fact that it implies an element of causality rather than an unforeseen random occurrence

Critical-gap	Average measure of gap-acceptance in a yielding situation where the probability of acceptance is estimated to be equal to the probability of rejection, mainly used for capacity calculation
Dilemma zone	Area on an approach road to a signal regulated intersection where the driver is indecisive regarding whether to stop or go when faced with the onset of an amber traffic signal
Driver behaviour	Largely misused and over-simplified term used in traffic engineering that is used to describe the actions and/or variability of drivers in different driving situations. Should relate to the study of individual behavioural processes that underlie driver actions (performance)
Driver performance	Generally refers to the skill and ability level of drivers in relation to the driving task
Evasive manoeuvre	Action that is taken by a road-user to resolve a conflict situation and involves braking, accelerating, and/or swerving
Exposure	Measure of spatial or temporal duration in the traffic system in relation to the number of dynamic system objects road-users, vehicles (axles), etc.
Fatality	Death resulting from a traffic accident (usually within a 30 day period after the accident occurrence)
Gap-acceptance	Process that describes and measures interaction between prioritised and non-prioritised road-users. Generally involves spatial or temporal measurement of gaps or lags in prioritised streams that are accepted or rejected in relation to a particular yielding manoeuvre
Incident reduction (IR) function	Function designed to reduce or eliminate the occurrence of accidents. In Swedish vehicle actuated signal control the IR-function uses vehicle detection to reduce the number of rear-end accidents and conflicts in the dilemma zone on a signalled approach
Injury accidents	Traffic accidents that result in minor or serious injury to one or more parties. Some statistical measures and accident risk quotients include accidents that involve both injury and fatality.
LHOVRA	LHOVRA is an acronym where each letter represents a special function that can be applied in vehicle actuated signal control to improve traffic safety and/or traffic performance
Macroscopic (macro-) simulation	Simulation at a less detailed (aggregated, macroscopic) level.
Mesoscopic simulation	Simulation at an intermediate level of abstraction in comparison to microscopic and macroscopic simulation modelling
Microscopic (micro-) simulation	Simulation at a very detailed (microscopic) level
Near-accident	Safety critical event that has close temporal and/or spatial proximity to an accident
Non-serious conflict	Conflict event in accordance with the Traffic Conflict Technique that is not of sufficient severity to be classed as 'serious' according to a specified severity threshold function

Police reported accidents	Accidents that are reported to the police and are recorded in the accident database of accident statistics (in Sweden only accidents involving injury and fatality are recorded)
Post-Encroachment Time (PET)	A safety indicator that represents a measure of the temporal difference between two road-users over a common spatial point or area. This should be below a predetermined maximum threshold value (typically 1 to 1.5 seconds). PET measures do not require the existence of a collision course, but do require transversal trajectories
Process validity	Term used in this thesis to describe the relationship between the processes preceding accidents and those preceding serious conflicts (or other safety indicators)
Predictive validity	Term used in this thesis to describe the relationship between the expected (predicted) number of (police reported) traffic accidents and the expected number of serious conflicts (or other safety indicator measures)
Required braking rate (RBR)	Measure of conflict severity based on a momentary measure speed and distance to a conflict point, that represents the average (linear) braking required to avoid a collision from the point the measure is taken
Safety	Freedom from accident or loss (see also Traffic Safety)
Safety (severity) continuum	Theoretical concept inferred in relation to the use of proximal safety indicators whereby all interactions are placed on the same scale with safe passages at one extreme and accidents involving fatalities at the other
Serious conflict	Conflict event in accordance with the Traffic Conflict Technique that is of sufficient severity to be classed as 'serious' according to a threshold function that takes into consideration the Time-to-Accident value and conflicting road-user speed
Safety critical event	Term used to describe a situation where there is an identified accident potential or where a proximal measure of safety is meets predetermined criteria (including threshold values)
Simulation (traffic)	Abstract imitation of the operation of a real-world process or system over time and event occurrence. Traffic simulation is concerned with the modelling of processes in the traffic system and can be conducted at different levels of abstraction depending of the purpose of the study
Time Extended TTC (TET)	Safety indicator measure based on Time-to-Collision. Represents a measure the period of time during which conflicting road-users are under a maximum TTC-threshold. Can be summated for a specific facility and/or measurement period
Time Integrated TTC (TIT)	Safety indicator measure based on Time-to-Collision. Represents a measure of the integral of a TTC-event while under a maximum TTC-threshold (i.e. difference from threshold multiplied by time-resolution). Can be summated for a specific facility and/or measurement period
Time-to-Accident (TA)	Safety indicator measure determined in accordance with the Traffic Conflict Technique. Based on a subjective estimation of speed and distance by trained observers for conflicting road-users in relation to a common conflict point. The Time-to-Accident measure is recorded only once at the time when evasive action is first taken by a conflicting road-user. TA-values are used in conjunction with speed to determine whether or not a conflict is serious or non-serious event in accordance with a threshold function.

Time-to-Collision (TTC)	Safety indicator measure based on an objective measure of speed and distance (usually involving photometric video-analysis) for conflicting road-users in relation to a common conflict point. The Time-to-Collision measure is recorded continually throughout a conflict event and is not dependent on evasive action by the conflicting road-users. The minimum TTC-measure recorded during a conflict event is usually taken as the defining value. TTC-values above a predetermined threshold are ignored. (See also Time Extended and Time Integrated TTC)
Traffic conflict	An accepted definition is stated as: "...an observable situation in which two or more road-users approach each other in time and space to such an extent that there is a risk of collision if their movements remain unchanged" (Amundsen and Hydén, 1977)
Traffic Conflict Technique (TCT)	Refers here to the Swedish Traffic Conflict Technique based on the developmental work of Christer Hydén at the University of Lund, Sweden (see Time-to-Accident). Other similar but not identical conflict techniques exist, or have existed, in other countries
Traffic safety	Term that is implicitly accepted as being related to the negative performance of the traffic system measured by traffic accident frequency and outcome severity. At the individual level, experienced traffic safety is related to the absence of danger and feeling of security
Traffic system	Systems theory view used to describe the processes of the traffic system as dynamic and complex interactions between and among key elements at various hierarchical levels. The three main elements are usually identified as: the roadway infrastructure, the road-user, and the vehicle
Underreporting	Term used to describe the fact that many accidents are not reported to the police and therefore are not represented in accident statistics. Underreporting increases with higher levels of accident outcome severity. Accidents involving vulnerable road-users are typically underreported
Validation	In simulation, validation refers to the process of ensuring that measures generated by the model correspond (within statistical tolerances) to those measured in the field, thereby ensuring model representativeness
Validity	Validity concerns the accuracy with which a measure represents a theoretical construct (assessed often through consensus)
Vulnerable Road-Users (VRUs)	Term generally used to describe pedestrians and cyclists, but may also include mopeds and sometimes also motorcycles in view of their susceptibility to injury in the event of an accident

PART I:
BACKGROUND

1. General introduction

1.1 Traffic development

The last century has seen vast improvements in the living conditions and economic wealth of the industrialised nations of the world, and consequently a large growth in population, particularly in urban areas. The growth of cities and towns has also led to an increased need for mobility and the volume of vehicles occupying the road infrastructure. Statistics indicate that the volume of road traffic has increased three-fold during the past 30 years, and that the number of road traffic accident fatalities has decreased by half. The increase in the number of vehicles has however, far outweighed the projected capacities and adaptive capabilities of the existing road infrastructure particularly in large cities, leading to deterioration in traffic performance and increasing difficulties in maintaining an acceptable and sustainable traffic safety standard.

This situation demands a better utilisation of the existing road infrastructure and has emphasised the role of transportation planning and traffic engineering as a means to optimise and balance key traffic system objectives concerned with safety, accessibility, capacity, performance and environmental issues, and to meet the needs and demands of different road-user groups given the limited resources available.

The problem appears to be one of global proportions with traffic fatalities rated as the ninth most common cause of death according to statistics presented by the World Health Organisation, and it is one that is likely to increase in the near future as a result of the development of third world countries. The worldwide traffic safety situation has also been described as a “*global catastrophe*” by the Red Cross organisation.

1.2 The scope of the traffic safety problem

According to the statistics from the European Commission based on the 15 member countries ‘*EUR-15*’ that existed prior to the addition of the 10 new countries in May 2004, the safety situation based on 2002 statistics can be summarised as follows:

- 1.3 million road traffic accidents per year
- More than 40 000 fatalities per year (the definition includes deaths that occur within 30 days of a road accident)
- Approximately 1.7 million injuries per year
- Estimated direct and indirect cost: 160 billion Euros (equal to 2 per cent of the EU Gross National Product)

Accident figures from the 10 new countries that joined the EU in 2004, suggest an estimated additional 12 000 fatalities for year 2002.

A closer look at the annual EUR-15 statistics reveals that certain categories of road-users are particularly vulnerable, these include:

- Road-users between 15-24 years (10 000 fatalities)
- Pedestrians (7000 fatalities)
- Cyclists (1800 fatalities)
- Motorcycles and mopeds (6000 fatalities)

Excessive or inappropriate speed is estimated to be involved in 15,000 fatalities, drink, drugs or fatigue in 10,000 fatalities, and the non-use of seat belts or helmets in 7,000 fatalities. Excessive or inappropriate speed is involved in more than one-third of all accident fatalities, and drink, drugs or fatigue in as many as one-quarter. The relative risk of fatality in European traffic is far greater for vulnerable road-users (pedestrians, cyclists, mopeds and motorcycles) than for drivers or vehicle passengers.

The accident statistics elsewhere are equally disturbing. A similar number of fatalities (43 000) is reported by the United States in comparison the EUR-15 member countries, along with a considerable number of injuries (2.9 million) for 2002. The estimated economic cost in relation to road traffic accidents in USA was estimated to be approximately 230 billion US Dollars by the NHTSA (2004), a figure nearly 50 per cent higher than that estimated for the EU. The scope of the problem is illustrated further by a comparison of injury and fatality statistics for 32 OECD member countries (see Figure 1.1 below).

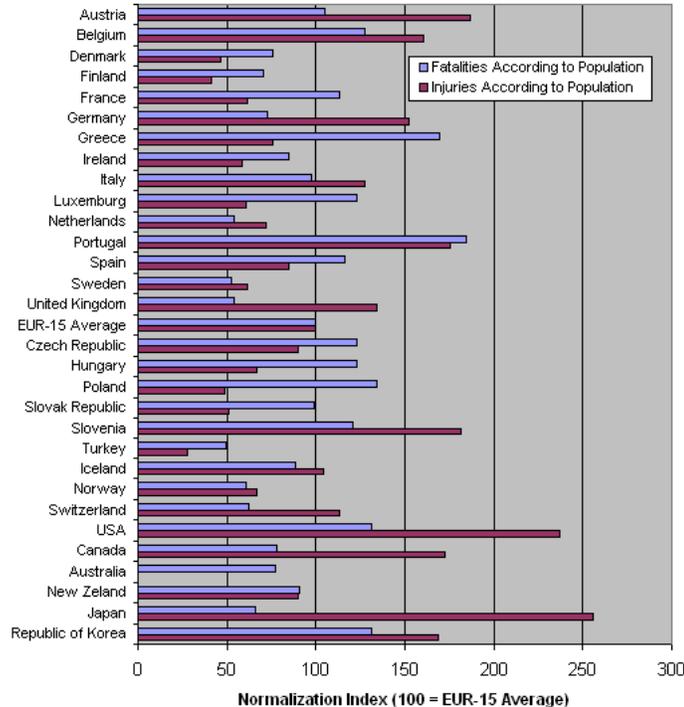


Figure 1.1 Fatality and injury rates in accordance with national population, normalised against EUR-15 average values

To ensure comparability, the numbers of injuries and fatalities have been calculated in relation to national population, and vehicle distance travelled. Furthermore, the statistics have been normalised using an index based on an average for the EUR-15 countries.

A further comparison that can be made concerns the differences in the numbers of accidents occurring inside and outside urban areas. The OECD data indicates that around 30-35 percent of all road traffic fatalities occur in the urban environment. There is however, a large degree of variation among the member countries, ranging from approximately 20 to 50 per cent due to differences in data collection and analysis methods. The statistics for injuries is somewhat different, as many as 68 per cent of the total number of injuries from road traffic accidents are reported to occur in the urban environment. Accident statistics also indicate that the majority of accidents involving injury in urban areas occur at intersections and involve vulnerable road-users to a much greater extent than elsewhere.

1.3 Traffic safety research from a historical perspective

It has been suggested by Goldstein (1963) that successful research in relation to traffic safety studies has two basic and essential requirements: substantive knowledge of the subject under study (i.e. the realm of accidents), and skill in the pertinent techniques of investigation (i.e. scientific research methodology). Since people are rarely experts in more than one scientific area, Goldstein suggests that multi-disciplinary co-ordination and co-operation is a key issue in all traffic safety related scientific research in order to resolve problems of what he described as a “*conceptual methodological*” nature. In his philosophically inspiring report, Goldstein identified a number of conceptual methodological problems that are “*peculiar*” to traffic safety research and which do not become apparent from the study of only one isolated area. These include the following:

- How do we classify safety critical events when accidents almost never occur for the same reasons, but rather a concomitance of many factors?
- How do we deal with the problem of traffic safety studies when accidents are very rare events in relation to traffic exposure? The question of relevant variables, how these are measured and how “relevance” is established must also be asked.
- Must we have full knowledge of accident causation to deal with the problem of accident prevention? Accidents can be prevented by removing known hazards and by redesigning the infrastructure, without knowing the exact nature of real ‘*accident causation*’. Scientifically, this relationship is important, calling for operational prevention countermeasures and the combination of knowledge relation to traffic safety and research methodology.

In another report from this time-period, Blumenthal (1968) describes an approach that he refers to as “*the macrostructure of the traffic safety problem*” that encompassed the ideas of General Systems Theory, political influence and administration policy, recognising also the importance of values at the individual level. Based on this macrostructure model, Blumenthal described traffic safety as a problem with “*technological, behavioural, and sociological and value dimensions*” where accidents were regarded as the result of an imbalance between driver capabilities and the demands of the road transport system. Blumenthal also recognised the responsibility of an “*administrative infrastructure*” for system functionality, and an underlying “*value structure*” that represented the increasing social demand to take active measures.

The macrostructure model of Blumenthal can be compared to the controversial ideas of Smeed (1949), who had earlier suggested that it was society as a whole that determined the accepted level of traffic safety development based on the prevailing needs and demands, and aspects of traffic safety that were most prominent at a particular moment in time. Smeed proposed that traffic safety policy was largely the result of temporary and complex relationships determined by the dynamic forces existing in the current political, social, and economic climate. This is a useful political description of the traffic safety situation existing in most countries of the world today. (Traffic safety policy is described in Appendix 1).

1.4 General Systems Theory as an descriptive approach to traffic safety

Blumenthal (1968) pointed out, the usefulness of adopting a General Systems Theory approach for the scientific and methodological study of *'traffic safety'*. According to the General Systems Theory introduced by biologist Von Bertalanffy in the 1940's (see e.g. Von Bertalanffy, 1968), traffic can be regarded as an *'open system'*. This perspective can be applied in order to describe and explain the inherent properties, hierarchical structure and the complex and dynamic interactive processes that together form the traffic system.

General Systems Theory also provides a means for detailed systematic analysis and the identification of properties and mechanisms such as *'emergence'* that exist as a result of the interconnectivity and relationships of system components at different structural levels (see e.g. Weinberg, 1975; Casti, 1997).

If a General Systems Theory approach is adopted for the study of the traffic system, complexity and dynamic processes can be explained by the interactions and relationships among road-users, vehicles, and roadway components at the highest level of abstraction. Given the main concepts of this theory, an illustrative diagram of the fundamental elements of the traffic system is suggested below in Figure 1.2.

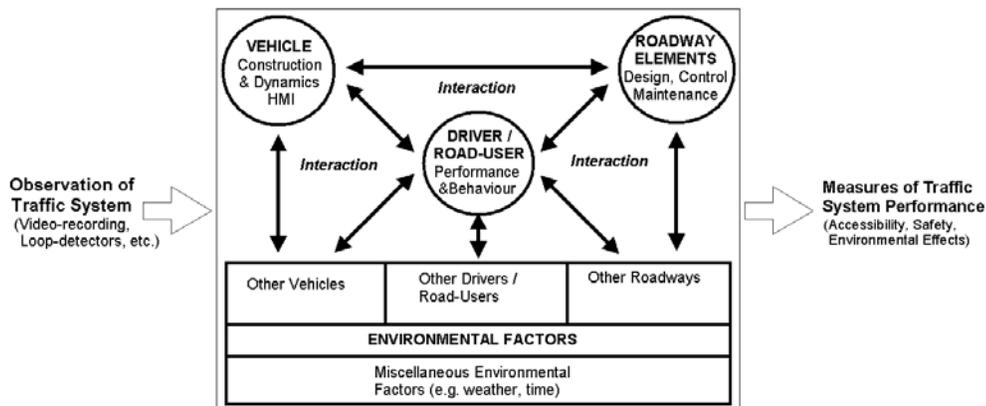


Figure 1.2 A conceptual model of the key elements of the traffic system

Traffic safety and other measures of traffic system performance can be regarded as an emergent property generated by inappropriate (and in many cases unsafe) interactions between or within components as the system transcends from one state to another over time. Furthermore, road accidents can be meaningfully viewed as *"failures of the system rather than failures of any single component"* (Little, 1966).

By focusing on the interactions between and among traffic system entities, it is possible to establish an approach to safety research that is facilitated by the construction of abstract conceptual models and theories. As scientific instruments, these facilitate the discovery of new knowledge and a forum for the generation of new hypotheses that need investigation.

1.5 Traffic safety measurement and analysis

1.5.1 Use of historical accident data

Traffic safety is commonly measured in terms of the number of traffic accidents and the consequences of these accidents with regard to their outcome in terms of severity. While this historical data approach is useful for the identification of specific safety problems at the national and regional level, it is regarded as a *'reactive'* approach implying that a significant number of accidents must be recorded before a particular traffic safety problem is identified and remedied using appropriate safety countermeasures (see e.g. Lord and Persaud, 2004).

A further drawback with this approach concerns the quality and availability of accident data and the time-period required to statistically validate the success of different safety enhancing measures given random and sparse nature of traffic accidents. Furthermore, since accident occurrence is commonly a result of a complex and dynamic chain of events, it is often difficult to perform safety analyses on the basis of statistical counts and poorly documented accident database records that reveal little qualitative information with regard to the underlying causes of accidents.

In order to perform a more qualified and comprehensive form of safety analysis and to assess and predict levels of traffic safety at specific types of traffic facilities, there is a distinct need for faster, more informative, and more resource effective methods that yield valid and reliable safety measures in the short-term without the need for (or in addition to) accident data. Similarly, these alternative safety measures can provide a foundation for predictive modelling in order to be able to estimate safety impact with an acceptable level of statistical accuracy.

1.5.2 Proximal safety indicators as an alternative approach

Arguably, a more effective safety assessment strategy involves the use proximal safety indicators that represent the temporal and spatial proximity characteristics of unsafe interactions and near-accidents. The main advantage of such measures is related to their resource-effectiveness given that they occur more frequently than accidents and require relatively short periods of observation in order to establish statistically reliable results.

Proximal safety indicators are particularly useful for before-and-after study designs where there is an emphasis on the assessment and comparison of safety enhancement measures at specific traffic facilities and, in some cases, the interactions of specific road-user categories. The methodologies used to collect safety indicator data also make the results sensitive to site-specific elements related to roadway design and the dynamic and complex relationships among different traffic variables such as average speeds, traffic flows and proportions of turning movements.

Despite the obvious advantages of an approach to traffic safety assessment based on the use of proximal safety indicators, there have been a number of fundamental questions related to the validity of proximal safety indicators given the underlying theories on which they are grounded and the reliability of associated measurement techniques. As a result, the use of proximal indicators as accepted measures of safety in their own right, has been limited in transportation planning and traffic engineering in many countries throughout the world.

The debate related to the need for proximal safety indicator process or product validity is believed to stem from the long-standing use of accident data as an inverted measure of traffic safety. This has consequently established accident data as *the* accepted measure of the abstract and theoretical concept of ‘*traffic safety*’. The need for this particular type of validity may however, be overly exaggerated, or even unnecessary, in situations where proximal safety indicators serve as a useful evaluative tool and the safety analysis concerns safety prevention rather than accident prediction (see e.g. Chin and Quek, 1997). An interesting finding with regard to these issues, is that proximal safety indicators can in some cases be a better predictor of the expected number of accidents than historical accident data (Migletz, Glauz and Bauer, 1985; Svensson, 1992).

The existence of a ‘*safety continuum*’ is regarded as a prerequisite for most proximal safety indicators suggesting the existence of ‘*safe interactions*’ or ‘*undisturbed passages*’ at one end and ‘*accidents*’ with outcomes of varying severity at the other. This conceptualisation is useful for traffic safety research, providing connectivity between the bottom-up approaches to traffic safety found in the behavioural sciences, and the macroscopic (top-down) perspective of traffic safety as representing accident frequency and outcome severity. This relationship has been described in many different models over the years, such as that of Von Klebelsburg (1982) illustrated in Figure 1.3 below.



Figure 1.3 Traffic safety and the relationship between errors, standard behaviour, traffic conflicts and accidents

With regard to the subject of safety indicators, the ECMT (2002) make a distinction between what they term ‘*direct*’ and ‘*indirect*’ measures. The number of people killed and injured in road traffic is regarded as a ‘*direct*’ safety measure as it is deemed to possess a sufficient degree of validity, reliability and availability to describe the local, national or international safety situation. A number of ‘*indirect*’ safety measures are also recognised that are regarded as indicative of the safety situation, but which do not provide “*a complete picture*”. These include: the number of near-accidents, levels of exposure to road traffic, various behavioural measures, measures related to roadway and vehicle standards, measures of enforcement and related traffic legislation, other systematic traffic measurements and the awareness of safety problems among the general public.

1.6 Traffic safety modelling

1.6.1 Mainstream modelling approaches

In a report published by the OECD the need for more multi-disciplinary and diversified road traffic safety research was recognised in order to overcome the increasing complexities of the current traffic problems, particularly those related to traffic safety (OECD, 1997). The report proposes that the process of formulating and testing scientific models and theories is critical for the improvement and prioritisation of research related to traffic safety and serves to facilitate and promote the establishment of multi-disciplinary research, communication, and the accumulation of knowledge. Four mainstream modelling approaches are identified in the OECD report, including the following:

Descriptive models – These are most commonly based at the system level and are based on two principle sources of information: traffic accident data and exposure data. Problems with such models are often related to the availability and quality of both types of data. An example is the model of Rumar (1985), which describes the traffic safety situation in terms of exposure, risk and accident consequence (see Chapter 2, Section 2.3, and Figure 2.5).

Predictive/Analytical models – These are used to predict how changes in independent variables are expected to influence dependent variables in accordance with mathematical models that describe these relationships. Predictive models are often used to estimate the effects of specific countermeasures and alternative roadway designs as an alternative to before-and-after studies based on accident data that require an unrealistic and impractical period of data collection. This type of modelling is most advantageous when there are a large number of experimental variables in combination with influences from various sources that are difficult to control experimentally. The literature suggests that many models suffer from a lack of flexibility and lack a sound theoretical foundation thereby restricting predictive ability and the possibilities for generalisation. (See e.g. Hakim *et.al.*, 1991; Stewart,1998).

Risk models – The main aim of these models is to identify and quantify risk factors that explain and predict individual road-user behaviour and to make safety assessments based of the risk-reduction effect of various countermeasures. Two main approaches can be identified: an analytical, system-oriented approach that aims at identifying risk factors and determining the mechanisms that act on the occurrence and severity of accidents; and a quantitative approach that attempts to estimate different effects on the basis of risk calculations. A problem with many risk models is that they are often too specific and context dependent, lacking consideration for other important traffic system elements. (See e.g. Michon, 1989; Echterhoff, 1992; Brehmer, 1994; Williams, Paek and Lund, 1995).

Accident consequence models – The main aim of this type of model is to reduce the consequences of accidents by identifying influential factors such as those related to the roadway environment, vehicle safety and emergency services; or alternatively, by promoting safety equipment or influencing driver behaviour. Qualitative in-depth analyses are often conducted for this purpose in accordance with special evaluation methodologies. Accident consequence approaches also include intervention strategies such as the introduction of legislation and policies related to the control of speed, alcohol and drugs, use of seat belts, etc.

It is recognised that one of the biggest problems associated with traffic safety research is the lack of congruency between models and theories at different hierarchical levels of abstraction, particularly those at the macroscopic and microscopic level. The reason for these conceptual differences is believed to be attributable to the way in which top-down and bottom-up research is conducted and the different aims and goals of the two approaches. Similarly, model integration is likely to require the combination of many different scientific disciplines within a unified theoretical framework (OECD, 1997).

1.6.2 Modelling approaches based on traffic simulation

A particular type of predictive/analytical modelling that is becoming increasingly popular for traffic analysis purposes in the field of transport planning and traffic engineering, is simulation modelling. Traffic simulation models are designed to mathematically or logically represent the behaviour of the traffic system at various levels of abstraction in order to generate a quantitative description of system performance. Simulation has become an effective tool for analyzing a wide variety of complex and dynamical traffic-related problems that cannot be studied with sufficient accuracy using other more traditional analytical methods.

According to Lieberman and Rathi (2001), traffic simulation is useful for the following:

- The evaluation of alternative treatments
- The test and visualisation of new designs
- As an important part of the design process
- As an integrated part of other traffic analysis tools
- The training of personnel (e.g. traffic control centres),
- Safety analysis

Lieberman and Rathi (2001) propose that simulation should not be used instead of optimisation models, capacity estimation procedures, demand modelling and design activities but rather as a method to support this type of work and as a tool for visualising the traffic system. Visualisation is considered valuable in order to gain an understanding and insight into how a traffic network or facility functions and behaves under different conditions. Simulation models also represent a means to describe the dynamical and often complex processes of the traffic system, and as means to explain results related to alternative treatments or designs to expert and non-technical audiences.

There are a number of ways in which simulation models can be categorised. While it is possible to have continuous models that describe how the elements of a model change over time in response to continuous stimuli, discrete time-based models are more common. In time-based models, time is segmented into a succession of specific intervals. During each interval, the activities that change the states of various system elements are computed. An alternative to ‘discrete time’, is the use of ‘discrete events’. Discrete event based models respond to changes in state and are generally more economical than those based on time, if the system size is limited, and if the states of the entities change relatively infrequently.

The most common classification terminology refers to the level of detail that each system represents (for a more detailed discussion regarding different levels of traffic network modelling see e.g. Merritt, 2003). The three levels of modelling recognised in the majority of simulation software tools include: macroscopic models (low fidelity), mesoscopic models (mixed fidelity), and microscopic models (high fidelity). Macroscopic models describe entities and their activities and interactions at a relatively low-level of detail. The performance of a link is often represented by a function determined from link attributes (e.g. number of lanes, length, etc.) and established relationships between speed, flow and density. Arguably, macroscopic models should be used when the intended results are not sensitive to microscopic detail, or where the scale of the model is such that the execution time would be unacceptable with a higher level of detail.

Mesoscopic models represent dynamic system entities at a relatively high-level of detail, but describe the activity of entities at lower level of detail than microscopic models. Microscopic models describe entities and activities at a high-level of detail. The actual level of detail can vary from one software implementation to another depending on the ability of the modelling tool to handle detail and the purpose of the simulation study. The performance of individual entities is represented by a number of smaller sub-models that describe elementary behaviour such as: car-following, gap-acceptance, and lane-changing. It is also possible to represent variation in road-user behaviour and vehicle performance. While microscopic simulation offers a higher level of modelling detail, there are also more stringent requirements placed on model calibration and validation. Today, there are also models that combine the advantages of mesoscopic and microscopic models in an integrated environment (see e.g. Burghout, 2004).

While Lieberman and Rathi (2001) state that traffic simulation can be used for safety analysis purposes, this particular area of application has been largely neglected in terms of research and development to date, despite being recognised as an area of great potential. An area of growing interest with regard to the application and use of proximal safety indicators concerns the extent and accuracy with which these can be estimated from dynamic modelling approaches such as those involving microscopic traffic simulation. While the random and sparse nature of traffic accidents does not lend itself to this type of modelling, it may be possible to generate representative ‘near-accidents’ that can be measured by proximal safety indicator techniques with a reasonable level of statistical accuracy in comparison with observed values. This particular area is one that is examined in some depth in this thesis.

Detailed microscopic simulation modelling for safety assessment and prediction purposes is believed to have considerable potential in the field of transportation planning and traffic engineering in the future. The reason for this is that carefully calibrated and validated simulation models provide a controlled and flexible ‘off-line’ test platform that allows the user to experiment with alternative design solutions and different traffic parameter values in order to estimate the effects these will have on both safety and traffic performance. Sensitivity analysis can provide a useful indication of expected safety and traffic performance effects in real-world scenarios at an early stage in the planning and development process. Presently, this particular area of application still requires a great deal of research and development before it becomes an accepted and viable methodology that is readily available to transportation planners and traffic engineers.

1.7 Aims and goals

This thesis is primarily concerned with traffic safety assessment and prediction based on proximal safety indicators and associated measurement techniques. Important issues concern safety indicator validity and measurement reliability, as well as practical issues related to their use in safety assessment studies in the field. An important area of investigation also concerns the identification of relationships between safety indicators and other traffic parameters and processes. Information regarding such relationships is considered useful for predictive safety modelling, and for dynamic simulation modelling aimed at safety impact estimation

A second, and equally important part of this work, concerns the use of dynamic micro-simulation modelling for safety estimation and comparison purposes. This entails an in-depth investigation into the potential and limitations of this approach, and an identification of particular problems related to modelling detail, and the representation of road-user behaviour and vehicle performance. Model calibration and validation are also critical issues that will be considered. It is intended to demonstrate the potential and limitations of “*safety simulation*” through practical example, and further the current level of knowledge in this field. Areas in need of further research will also be identified.

A number of hypotheses have been formulated in relation to the specific aims and goals of this work. These include the following:

- Hypothesis 1:** Different proximal safety indicator concepts and measurement techniques are not equally efficient with regard to the identification and quantification of different safety critical situations
- Hypothesis 2:** The frequencies and severities of near-accidents and accidents are significantly influenced by measures related to exposure, vehicle speed and measures related to the processes of interaction between road-users such as distance-keeping in car-following situations and gap-acceptance
- Hypothesis 3:** Microscopic simulation can be used as a dynamic and complex modelling approach to estimate traffic safety effects based on the application and use of proximal safety indicators with a reasonable level of accuracy provided that the simulation model can be calibrated and validated against empirical data with a high degree of stringency with regard to safety-relevant parameters, and the behaviour of road-users can be sufficiently represented

Each of these hypotheses will be tested in various parts of the research presented in the following chapters of the thesis. They also play an important role in determining the methodological approaches that are adopted in the each of the studies and simulation experiments, and the content and order of the results that are presented.

2. Swedish traffic safety statistics and the identification of urban area problems

Introduction

This chapter highlights several important and relevant issues related to Swedish traffic safety statistics and the safety problems relative to urban areas. The main intention is to demonstrate the use of historical accident data for the purposes of identifying safety problems to discuss the collection of accident and exposure data and the problem of underreporting. Furthermore, background information is provided in relation to the occurrence of different types of accidents in urban areas with particular emphasis on intersections. This information is relevant given the type of traffic environment and facility chosen for the experimental studies described in later chapters. A more detailed statistical review of the traffic safety problems in urban areas is given in Archer and Vogel (2000).

2.1 Traffic safety statistics for Sweden

2.1.1 General accident and exposure data

Presently, Sweden has a population of approximately 9.0 million people and 5.6 million of these hold a valid driving licence. The road infrastructure consists of 138,000 kilometres of roadway and there are some 4.5 million vehicles in use in the traffic system (9.2 million vehicles registered). According to statistics published by the Swedish Road Authority (SRA), 58 billion kilometres were travelled by private vehicles and 13 billion kilometres were travelled by heavy goods vehicles during 2002. Furthermore, it is estimated that an average Swedish person travels 44 kilometres per day, 29 of these by private vehicle.

Road traffic accident statistics for Sweden during 2002 show that there were 16,947 road traffic accidents involving personal injury and/or fatality. In these accidents, 560 road-users were killed, 4,592 were seriously injured and 20,155 suffered minor injuries*. This represents a four per cent decrease in the number of fatalities compared to the previous year, but also a 12 per cent increase in the number of serious injuries and a 9 per cent increase in minor injuries. From a longitudinal perspective, the number of fatalities and serious injuries has shown an overall decline of around 25-35 per cent since 1980 whereas the number of minor injuries has increased by almost 50 per cent.

This development is illustrated graphically in Figure 2.1 below, where year 1980 serves as an index value of 100 for the numbers of fatalities, serious injuries and minor injuries (848, 6064 and 13,182 respectively for this base year). The same picture is also found if the number of accidents involving fatality or injury is considered instead of the numbers of fatalities and injuries.

* Serious injuries are defined by SIKA as those that involve traumatic injuries to the body such as broken bones, head injuries, internal injuries, serious wounds etc., and any injuries that involve hospitalization; all other injuries are classed as minor.

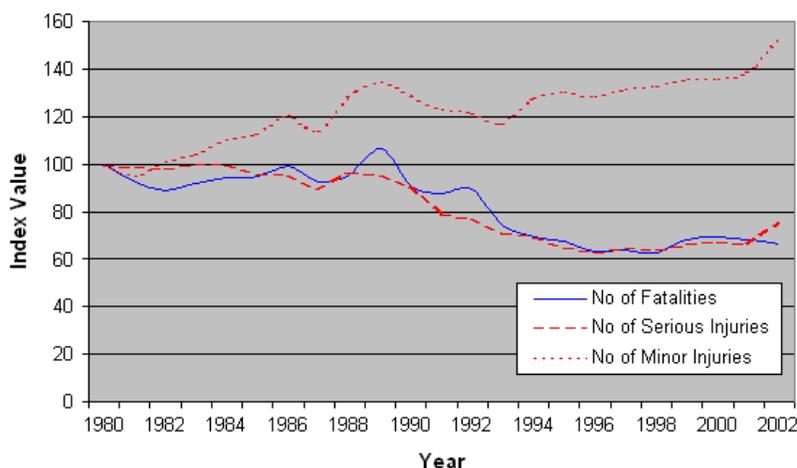


Figure 2.1 Traffic safety development in Sweden (1980 as base year with index value 100)

Accident statistics show that the number of fatalities per 100,000 vehicles in traffic has decreased from 28 in 1980 to 13 in year 2002. This figure has remained relatively stable since the mid-nineties. For serious injuries, the value has dropped from 197 in 1980 to 103 in 2002. Again, there has been little improvement since mid-1990, with the exception of 2001 with a figure of 92. The number of minor injuries per 100,000 vehicles in traffic has actually increased from 428 in 1980 to 451 in 2002, reaching a low of 409 in year 2000. For safety statistics compared to the population, the development trend has been very similar.

The number of fatalities per million vehicle kilometres has only been estimated in Sweden during the past three years. The figures for the first two years 2000 and 2001 are quite similar showing 9 and 8 fatalities, 61 and 58 serious injuries, and 267 and 263 minor injuries per million vehicle kilometres, respectively. In 2002 there was a similar fatality rate (8 per million vehicle kilometres), but a notable increase in the number of serious and minor injuries (66 and 289 per million vehicle kilometres respectively).

The traffic safety statistics for year 2002 indicate a slight but noticeable increase in terms of the safety development trend in Sweden, despite a small reduction in the number of fatalities. This was largely unexpected following the introduction of the Swedish 'Vision Zero' safety strategy a number of years earlier (see Appendix 1).

2.1.2 Accident types and road-user risk levels

Road accident statistics show that nearly one-third of all fatality or injury accidents in Sweden are 'single' accidents, i.e. accidents that involve only one motorised vehicle and no other types of road-users. The 1,198 accidents resulted in 161 fatalities and a larger number of serious injuries than any other specific accident type. Approximately one-third of all accidents involving fatality or injury are between motorised vehicles: The statistics in relation to vehicle-vehicle accidents, show that more than 25 per cent occurred at crossroads, and that another 24 per cent were the result of head-on collisions. Turning and rear-end collisions account for a further 35 per cent (SIKA, 2003).

The level of accident risk for different classes of road-user have also been estimated by SIKKA in accordance with data from a large-scale national travel-behaviour survey conducted in 2001. The risk of death or serious injury per 1 billion kilometres of travel was found to differ significantly between different road-user groups. For those travelling by private car, the probability of being involved in a fatal accident was found to be 4.6 per 1 billion kilometres of travel. Using this value as an index, the relative fatality risk for other road-user classes could be compared. It was found that pedestrians and cyclist have nearly a 5.0 times greater fatality risk and that motorcycle and moped riders have a 14 times greater risk.

The accident statistics for 2002 also show that 7.4 per cent of all fatality or injury accidents reported by the police were suspected of involving the use of alcohol or other drugs. This figure is representative of a steady incline since the mid-1990s when levels of only 5.8 per cent were recorded. It is also possible that these differences are due to changes in the accident data collection process.

2.1.3 Accidents in urban areas vs. rural areas and motorways

The accident statistics for Sweden in 2002 show that 146 of the 560 accidents involving fatality, and 2,046 of the 4,592 accidents involving serious injury occurred in urban areas. The statistics also indicated that unprotected road-users were involved to a much higher extent than in other areas. During 2002, 33 pedestrians, 27 cyclists and 4 moped riders were killed in traffic accidents in urban areas compared to 25 pedestrians, 15 cyclists and 8 moped riders elsewhere. Similar ratios are also found for the differences in numbers of serious injuries.

The 142 traffic accidents involving 146 fatalities represent a significant drop in comparison to earlier years (the only exception being 1996). This represents a significant break in the statistical trend, and time will reveal if this can be sustained. A look at the injury data shows a different trend, with increases in numbers of accidents involving serious and minor injuries (1,653 and 7,402 for year 2002 respectively) and the actual numbers of injuries (2,046 serious and 10,637 minor) resulting from these accidents. Data indicates that the frequency of injuries and accidents involving injury has shown a steady increase since the mid-1990's.

If the number of fatalities and serious injuries are expressed as a percentage of the number of accidents involving fatalities and injuries some interesting results emerge. These figures indicate that, given the occurrence of an accident involving injury or fatality, there is a 1.6 per cent probability of fatality and a 22.4 per cent probability of serious injury in the urban environment, and a 5.5 per cent probability of fatality and a 32.9 per cent probability of serious injury elsewhere.

Further differences can be found if the various types of accidents that involve vehicles are examined in more detail with regard to urban and non-urban areas. This comparison is shown in Figure 2.2 for the number of fatalities. The diagram shows that the numbers of fatalities is greater outside urban areas for almost all types of vehicle accidents except those that involve pedestrians and cyclists.

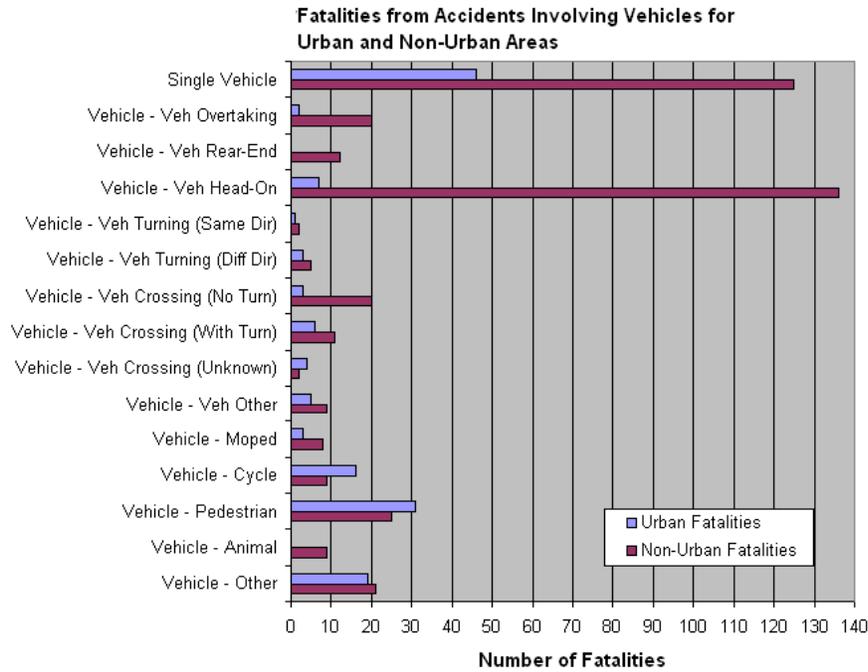


Figure 2.2 Differences in fatalities for various accident types involving vehicles for urban and non-urban areas during year 2002

A similar diagram is also shown for serious and minor injuries (see Figure 2.3).

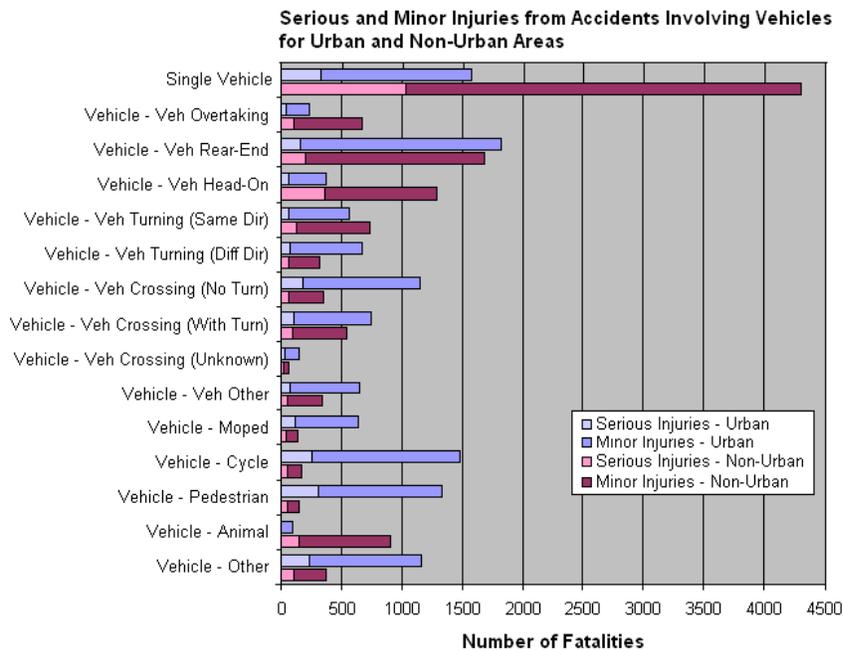


Figure 2.3 Differences in injuries for various accident types involving vehicles for urban and non-urban areas during year 2002

The diagrams indicate a number of important differences, including a greater number of injuries resulting from rear-end collisions in the urban environment. Furthermore, there appear to be more serious and minor injuries from vehicle turning and crossing accidents in urban areas than elsewhere, this is expected given the greater density of junctions. There are also considerably more serious and minor injuries in relation to vehicle accidents involving pedestrians and cycles (as there were for the numbers of fatalities).

2.1.4 Accidents at intersections

The safety statistics for both Sweden and those at the international level suggest that most accidents involving injury occur in the urban environment and that these accidents are most frequent at roadway intersections and involve one or more vehicles. Unfortunately, the accident statistics for intersections in Sweden have not until quite recently been defined in accordance with area (i.e. urban, rural, motorway). The statistics for intersections are illustrated below in Figure 2.4.

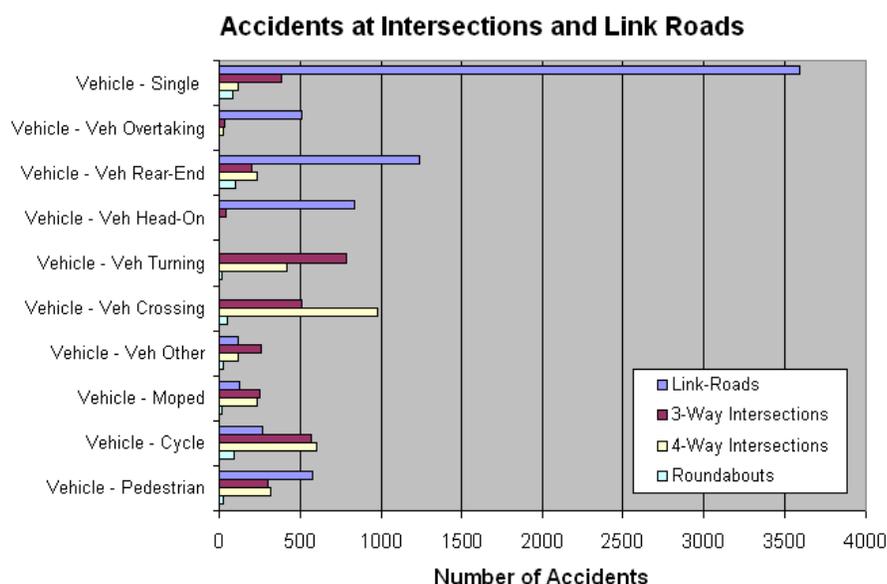


Figure 2.4 Accidents at intersections and link-roads for year 2002

The statistics show a proportionately higher number of vehicle-turning and vehicle-crossing accidents at 3-way intersections (T-junctions) and 4-way intersections as expected, but also higher numbers of accidents involving vulnerable road-users. Rear-end accidents are also a frequent occurrence at intersections and are often (incorrectly) classed in conjunction with link-roads despite occurring on an intersection approach. Presently, there are relatively few roundabouts in Sweden and therefore an over-proportionately low number of accidents.

In total, there were 3,564 accidents at 3-way intersections in Sweden during 2002. These resulted in 82 fatalities, 730 serious injuries and 2,752 minor injuries. For 4-way intersections, 3,223 accidents were recorded; these resulted in 57 fatalities, 584 serious and 2582 minor injuries. For the 435 accidents occurring at roundabouts, there were only 5 fatalities, 68 serious injuries and 362 minor injuries. The figures for link-roads are considerably different with a figure of 8,744 accidents that resulted in 328 fatalities, 1,877 serious and 6,538 minor injuries.

Safety levels at intersections are largely influenced by the design details and type of regulatory control that is used (see e.g. Englund, *et.al.*, 1997). It is however, generally recognised that signal control has a positive safety effect by temporally separating conflicting flows of traffic. This safety effect is reduced considerably however, as a direct result of accidents caused by red-light violations. While a breakdown for intersection and area type statistics is not available, it can be assumed that safety problems at intersections are more prominent in the urban environment given that they are more frequent in this type of area. This is also suggested by the incidence of vehicle-vehicle accidents and accidents between vehicles and vulnerable road-users that result in injury in relation to vehicle-turning or vehicle-crossing manoeuvres in urban areas (see Figure 2.3).

2.2 Safety data collection and analysis

2.2.1 Accident and exposure data sources in Sweden

The most comprehensive set of annual statistics related to traffic safety is assimilated each year by the Swedish Institute for Transport and Communications Analysis (SIKA). Each year a report is published concerning ‘road traffic injuries’ as part of the *Official Statistics of Sweden* series. The road traffic accident statistics prepared annually by SIKA are based on police-reported injury accidents that have been registered in the SRA accident database (STRADA). The aim of the SIKA report is to provide a broad overview of the traffic safety situation in Sweden and its development, for a wide spectrum of interested parties including the general public, the media, government or authority officials, and research institutes. The SIKA report provides a useful analytical breakdown of accident statistics in accordance with road-users, accidents type and location and other relevant demographical data.

The SIKA report is also prepared in a way that indirectly reflects existing problems in identified areas of interest (by the SRA) and indicates changes that are important as a measure of development in relation to the political goals of the traffic system. Accidents and traffic safety data is also collected and analysed by many local authorities. Presently, accidents involving injury or fatality that are reported by the police or medical institutions are recorded in a specially designed database system – STRADA, maintained by the SRA. It is intended that this database should contain detailed information regarding both the circumstances of the accident and details of personal injuries when fully functional. This system is designed as a geographical information system (GIS) that is available to researchers, SIKA, insurance companies, local authorities and the police. Presently, there are still problems related to the exchange of information with other database systems and in particular the classification of accidents. STRADA will eventually provide a comprehensive basis for the majority of traffic safety analyses based on historical accident data.

Exposure data is also collected mainly for the purposes of providing a suitable foundation for the further development and maintenance of the road infrastructure. The SRA has a traffic measurement system for the estimation of annual average daily traffic (AADT) based on a large number of sample-measurements at randomly selected locations in the state-administered road network. This work is carried out several times each year. Each AADT value is stated with error margins to ensure that the estimated values correspond to actual values with a 95 per cent level of confidence.

A large number of local authorities (65-70 per cent) throughout Sweden measure traffic flow on their road and street network. These measurements are carried out mainly on major roads. In a survey conducted in 1998, the local authorities estimated that approximately 37 per cent of major roads were covered by their annual measurements, and approximately 11 per cent of all other roads.

Other data is collected by the Statistics Sweden organisation (SCB) who have conducted an ongoing survey (since 1994) that investigates travel patterns among the Swedish population. This survey (RES) is carried out through interviews and highlights all trips and movements in the traffic environment. The questions in the interviews concern modal choice, trip distance and length, reason for travel, start and end-points, time of travel etc. Other demographic information related to the interviewed party is also recorded. The main purpose of this survey is to measure travel in the traffic environment in order to estimate traffic activity and its constitution, calculate risks in the traffic system, analyse environmental effects related to traffic, and develop and validate models for forecasting.

In addition to the SCB:RES surveys, the Swedish National Road and Transport Research Institute (VTI) conduct an annual investigation of travel behaviour among the Swedish population using a postal questionnaire. The main purpose of this survey is to obtain relevant traffic safety information regarding road-user exposure. The questionnaire is specially adapted to obtain information from unprotected road-users (pedestrians and cyclists) and the type of traffic environment.

2.2.2 Accident data quality and the problem of underreporting

The quality of accident data usually refers to the relationship between the number of police reported road traffic accidents and the actual number of road traffic accidents. Validity and reliability of data is affected by a number of factors from the time when the accidents are first recorded. A particular problem already at the scene of an accident, is the fact that the police do not have the expertise required to classify the injuries.

Other problems have been found with regard to the accident description and location, and lack of important information from the accident scene that can be used to help derive the reasons underlying the accident. Many of the problems related to data quality have been rectified during manual and logical control checks at the time the data is registered into the accident database. Comparisons have also been made between the police reported data and hospital data to assure data quality (see e.g. Englund, *et.al.*,1998; SIKÅ, 2003).

The biggest problem with regard to the quality of accident statistics is related to the problem of underreporting. Presently, Swedish accident statistics include only police reported accidents that involve personal injury. However, statistics are needed at the national and regional levels that can provide a more accurate description of the total number of injury accidents during a specific time-period. For this purpose, a number of complicated and expensive nationwide surveys have been conducted in Sweden.

In a surveys conducted during the early 1980's by Statistics Sweden (SCB), the total number of people injured in traffic accidents was found (as expected) to be considerably higher than the police reported statistics suggested (SIKA, 2003). The coverage of police reported accidents was also found to be considerably higher with increasing levels of injury (see Table 2.1 below).

Table 2.1 *Level of underreporting in relation to different classes of injury sustained in traffic accidents (SIKA, 2003)*

Injury Class	Estimated Number (Age 16-74 years)	Level of Coverage (per cent)	Confidence Interval (30 per cent level of risk)
Severe Injuries	8,180	59	± 11
Minor Injuries	34,661	32	± 3
Total	42,841	37	± 3

The coverage of police reported accidents was also found to vary considerably among different classes of road-user (see Table 2.2 below).

Table 2.2 *The level of underreporting in relation to different road-user classes for injuries sustained in traffic accidents (SIKA, 2003)*

Road-user Class	Estimated Number (Age 16-74 years)	Level of Coverage (per cent)	Confidence Interval (30 per cent level of risk)
Car Driver	13,796	51	± 7
Car Passenger	8,006	46	± 8
Motorcyclist	2,979	49	± 15
Moped	1,661	32	± 13
Cyclist	13,088	15	± 2
Pedestrian	2,067	54	± 15

In a further survey conducted by Statistics Sweden in 1997, accident data recorded in the patient register maintained by the National Board of Health and Welfare was made available for comparison against traffic accident data. This data provided useful information regarding injuries and diagnoses, how injury types varied according to accident type, road-user category, and the age of those involved. In particular, it was found that the categorisation between severe and minor injuries made by the police authorities was relatively accurate (approximately 84-92 per cent for serious injuries, and 73-80 per cent for minor injuries).

Underreporting represents a major problem with regard to establishing the full-extent of the traffic safety problem. It is also a problem that is particularly relevant to the urban environment due to the lack of adequate coverage of accidents that involve the injury of vulnerable road-users.

2.3 Accident data and the dimensions of traffic safety

Historical data is used for many different types of models and modelling approaches. A useful descriptive model has been proposed by Rumar (1988) to highlight the relationship between what he referred to as the “*three basic dimensions of traffic safety*”. These dimensions include: risk, exposure, and consequences (i.e. accident outcomes). Each is considered relevant given the fact that changes in any one particular dimension will have an influence on the overall traffic safety situation represented by the total area in Figure 2.5 below.

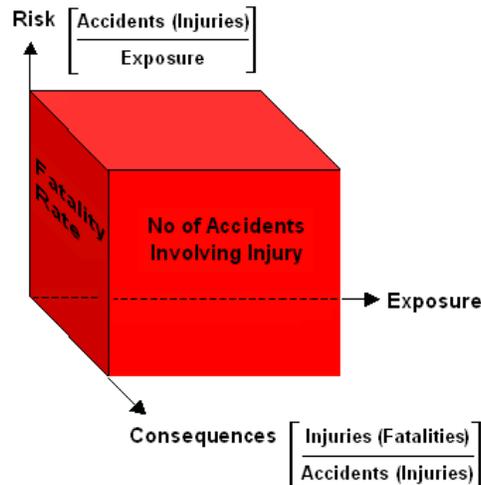


Figure 2.5 The three dimensions of traffic safety proposed by Rumar (1988).

The model suggested by Rumar is indicative of the fundamental principles used in descriptive models that are based on historical accident and exposure data. These types of models are commonly used to express meaningful comparative measures of risk at the international and national level. Typical examples of traffic safety risk include:

- Health risk in traffic** – Number of fatalities/injuries per million hours in traffic
- Accident risk** – Number of accidents per million kilometres travelled per person
- Injury risk** – Number injured per million kilometres travelled per person
- Death risk** – Number of fatalities per million kilometres travelled per person
- Accident ratio** – Number of accidents per million kilometres travelled per vehicle
- Injury ratio** – Number injured per million kilometres travelled per vehicle
- Death ratio** – Number of fatalities per million kilometres travelled per vehicle
- Vehicle/accident ratio** – Number of vehicles involved in accidents per million kilometres travelled per vehicle
- Injury consequence ratio** – Number of injured per police reported accident
- Death equivalence ratio** – Number of fatalities plus number of serious injuries plus number of minor injuries

Risk models represent a useful instrument for descriptive and comparative traffic safety analysis. Other modelling approaches are discussed in the following chapters.

3. Understanding traffic accidents and the reasons for their occurrence

Introduction

As a further important and relevant part of the introduction to this thesis, the topics of accident causation and safety countermeasures are briefly discussed. These topics are included in light of their relevance to safety analysis techniques and the use of various measurement techniques such as those based on proximal indicators that involve the identification and quantification of ‘near-accidents’ as precursors to accidents. A review of the literature and various techniques used for obtaining causation data is therefore considered relevant in order to gain deeper understanding of the underlying processes related to accident occurrence.

3.1 Accident analysis

Generally, accident analysis is a term used to describe the many different methods and theoretical frameworks that are used to investigate accidents in order to find the main cause or causes. According to Hollnagel (2001) the cause is associated with the identification of a limited set of aspects of the situation seen after the fact, that are necessary and sufficient conditions for the effects to have occurred. The process of obtaining empirical accident data is difficult. Police reports and insurance company reports rarely provide a detailed account of the chain of events preceding an accident, and ‘cause’ (i.e. responsibility), is usually assigned to one of the involved parties without any in-depth investigation. In recent years, in-depth accident analyses have become increasingly popular.

In Sweden, there is presently a policy to conduct this type of investigation in relation to all accidents that result in fatality and serious injury. This type of analysis involves the use of experts with different disciplinary backgrounds who perform a qualitative in-depth investigation in accordance with a predetermined theoretical reference frame. There is also a project called FICA (Factors Influencing Causation of Accidents) that involves the in-depth study of vehicle accidents and the establishment of an accident databank. This project is aimed at vehicle safety and the development of in-vehicle ITS, and is jointly financed by Swedish vehicle manufacturers and the Swedish Road Authority, involving leading research institutes.

Typically, this type of analysis divides the accident process up into three temporally separated phases: ‘pre-crash’ which focuses on the interaction between the different elements of the traffic system and tries to establish the information available to road-users, and how this was used and acted upon; ‘crash’ which looks at environmental factors, vehicle construction and the effect of various safety systems; and ‘post-crash’ which focuses on the effectiveness of the emergency services, medical care and rehabilitation. The knowledge gained from studies such as these can be usefully used for active safety countermeasures in relation to the different elements of the traffic system, i.e. road-users, vehicles and the roadway infrastructure.

3.2 Large-scale longitudinal accident studies

A number of longitudinal accident studies can be found in the literature. Three of the more interesting are described below.

3.2.1 The UK study

One of the most comprehensive studies concerning the underlying causes of accidents was carried out in a study in the Greater Leeds area in England in the late 1980's (Carsten, *et.al.*,1989). During a one-year period, 1254 accidents involving injury or fatality were investigated on roads with a speed limit of 40 mph (approx. 60 km/h) or less. Two per cent of the accidents involved fatalities and approximately 20 per cent involved serious injuries. In addition to the police accident reports, questionnaires were administered and accident sites were visited in order to obtain as much relevant information as possible regarding each accident.

An innovative '*chain-of-factors*' approach was used for determining accident causation based on a multi-level coding scheme comprising of approximately 150 different items. The results of the study indicated that being '*unable to anticipate*' accounted for 29 per cent, '*failure to yield*' for 16 per cent, and '*failure to anticipate*' 10 per cent of the first level factors stated as '*immediate failures that precipitated an accident*'. Results also show that as many as 44 per cent of drivers considered themselves to be the '*innocent victims of others' mistakes*'. Failure to yield was also identified as a major factor for adult and child-pedestrians (66 and 78 per cent, respectively).

At the second level that concerned '*failures that increased the likelihood of an accident*', findings suggested that as many as 62 per cent of the predisposing factors were situational problems. For drivers, the most important factors were '*driving too fast for the situation*' (29 per cent) and '*following too close*' (8 per cent). At the third level regarding '*road-user behaviour or lack of skill leading to a failure*', different road-user skills were considered. The greatest problem for motor vehicle drivers was found to be attributable to a misinterpretation of other road-users intentions, while pedestrians were more susceptible to problems described as a '*failure to look*'. Both groups also indicated a '*lack of judgement*' in the estimation of speed or trajectory of other road-users.

The most common problem at the fourth level, which concerned '*explanations for failure or behaviour*', indicated that drivers often experienced obstructed vision by objects inside or outside the vehicle. Furthermore, '*impairment*', particularly the influence of alcohol, was found to be a problem among both drivers and pedestrians involved in accidents.

3.2.2 The French study

Another major study that looked at some of the reasons behind accidents in urban areas, and the differences between these accidents and those occurring outside urban areas, was conducted by the French traffic researchers Malaterre and Fontaine (1993).

Their investigation was primarily aimed at identifying the safety needs of drivers and the possibility of satisfying these needs through the use of Intelligent Transport Systems. As a starting point, the authors identified 17 different basic needs in relation to the driving task. That were grouped into the road-user skills related to: '*control*', '*prediction*', '*estimation*', '*detection*', and '*status*'.

A total of 3,179 accidents involving 6,049 road-users were investigated. The results of this study identified the need for better detection in urban areas and particularly at junctions, and the need for better prediction regarding the intended manoeuvres of road-users. Detection problems were identified in 61 per cent of all accidents analysed in the urban environment, and 45 per cent in other types of areas.

On the basis of these findings the authors suggested that many accidents in urban areas could be avoided by the introduction of Intelligent Transportation Systems (ITS) that could support the driver through: '*critical course determination*', '*obstacle detection*', '*vision enhancement*', and '*safety margin determination*'.

3.2.3 The US study

In the USA, researchers Retting, Williams, Preusser, and Weinstein (1995) conducted a major longitudinal study based on 4,526 police reported accidents from three cities and one urban county. Their study focused specifically on traffic safety problems particular to the urban environment and was aimed at developing a classification system based on pre-accident driver/vehicle behaviour that could be used by planners and policy makers in an attempt to reduce the most common types of urban accidents and find suitable countermeasures.

Results indicated that 56 per cent of all accidents occurred at intersections, and that 31 per cent of these accidents resulted in injury. Pedestrian and cycle accidents were not included. Five of the thirteen different types of accidents accounted for 76 per cent of the total number that occurred in the four urban areas, these included: '*ran traffic control*' (22 per cent), '*stopped or stopping*' (18 per cent), '*ran-off road*' (14 per cent), '*lane-change*' (13 per cent), and '*left-turn oncoming*' (9 per cent).

These five accident types also accounted for 83 per cent of all accidents involving injury. Differences between the three cities and county were noted with regard to the rank order of accidents. The authors proposed that the most common types of accidents, could be resolved by a combination of better signal timing, increased visibility for traffic signals and signs, reduced speeds near intersections, red-light cameras, or intersection redesign.

3.3 Accidents and traffic system complexity

It is often suggested that the underlying causes of accidents in the traffic system emanate primarily from *exogenous* rather than *endogenous* sources. This implies that the complexity of the traffic environment will at certain times and in certain places, exceed the adaptive capabilities of the road-user and result in errors. Complexity is a concept that implies limitations in information processing ability, more specifically in relation to perception and cognition. From a socio-technical point of view, this suggests that the traffic system is improperly designed with regard to the limitations of road-users. (Adapting the traffic system to meet the needs and requirements of road-users is also recognized as an important issue in the Swedish '*Vision Zero*', see Appendix 1) The problem of understanding complexity, how it can be defined, and how it affects human performance has been approached from a number of different theoretical perspectives in the past, although most investigations have been conducted in relation to specific situational contexts and therefore cannot be generalised.

Complexity has been investigated by, amongst others, Woods (1986) who identified factors that contribute to complexity in problem-solving domains and the effects these have on human performance. In particular, four dimensions related to the world itself have been identified to define the cognitive demands of any particular problem solving domain. These dimensions include ‘*dynamism*’, which refers to the fact that events can occur and change at indeterminate times; ‘*the number of parts and extensiveness of interconnections between parts and variables*’ (that can be complex in their own right); ‘*uncertainty*’, suggesting that the available data can be ambiguous incomplete, erroneous or imprecise with regard to the true state of the world; and ‘*risk*’ in terms of an understanding of the nature of different outcomes and their relative frequencies.

The level of complexity is also dependent on the interactions of the agent, the problem-solving domain, and the agent’s representation of this domain. The complexity of any particular situation is believed to heighten the potential for cognitive or perceptual errors, and can therefore be considered as a temporary unstable state of the traffic system (in accordance with General Systems Theory), that has an elevated accident risk. Complexity is often mentioned in relation to the traffic system, although systematic scientific investigations that focus specifically on measures or dimensions of complexity in relation to the causes of traffic accidents are very rare.

3.4 Accident causation and the human element

Literature from the field of psychology and human factors shows that the relative proportion of accidents attributed to human error has increased during the past 40-50 years. In the 1960’s roughly one-third of all accidents were believed to be the direct cause of human error. In the 1970’s a comprehensive study by Treat *et.al.* (1977). Identified the human element as the main cause in 57 per cent of the traffic accidents that were studied. In the 1990’s, this figure was reported to be as high as 90 per cent in a study covering 420 in-depth and 2,258 on-site accident investigations by Sanders and McCormick (1992). Accident causation in accordance with the relative proportions of human, environmental and vehicle elements are illustrated graphically in Figure 3.1 below.

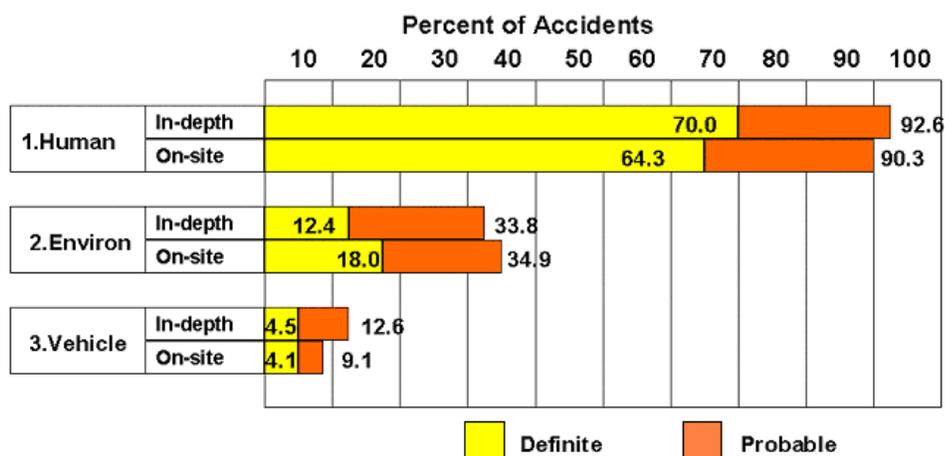


Figure 3.1 Causes of accidents shown according to with the relative proportions of different traffic system elements (Sanders and McCormick, 1992)

The reasons for this increasing attribution of accident cause to the human element are many. According to Hollnagel (2001), many factors are related to:

- The complexity of modern technological systems
- The development of improved models and methods for human error analysis
- The increased reliability of technological systems which has the effect of increasing the relative probability for other types of errors
- The fact that it is often cheaper to assign blame to the human element rather than having to redesign an entire system

Literature from areas such as Human Factors (Human Engineering) and Systems Safety, suggests that human involvement in accidents is often oversimplified in many methods of analysis. Leveson (1995) suggests that accident data is commonly biased and incomplete, being based heavily on the type of sub-optimal human performance that occurs in emergency situations. Furthermore, she states that assigning blame solely on the human element disregards the true underlying multiple causes of accidents and does not account for important aspects related to the situational contexts. It is also important to realise that human actions are capable of preventing accidents as well as being a potential cause. Research today identifies the contribution of many other factors in relation to accident causation including; poor engineering design, poor man-machine interface design, inadequate training, poorly worded instruction manuals (see e.g. Wickens, 1992; Leveson, 1995; Hollnagel 2001).

There are a number of well-recognised error classification systems or error taxonomies that have evolved over the years. In particular, the work Norman (1981) and Reason (1990) has been influential in identifying and predicting various different types of human error according to a classification system that distinguishes between knowledge-based, rule-based, and skill-based errors, as well as slips, and lapses. This work is largely grounded in the theories of Rasmussen (1984; 1987), who earlier identified different stages in the process of learning tasks and different steps in the decision-making process.

Reason and Rasmussen's theories were utilised by Parker *et.al.* (1995) who constructed a Driver Behaviour Questionnaire to discover knowledge related to different types of error in relation to the task of driving. Parker and colleagues found amongst other things, that '*intentional rule breaking*' was highly correlated to traffic accidents. Researchers Åberg and Rimmö (1998) conducted a study similar to that of Parker and colleagues using Swedish data. Their analysis was based around the '*Theory of Planned Behaviour*' suggested by behavioural psychologists Fishbein and Ajzen (1975), and revealed a four-factor structure over different error types that included: intentional violations, serious misjudgement failures, attentional errors, and failures largely attributed to inexperience.

Other research in relation to driver errors has been carried out by Brehmer (1990) who found significant differences in what he termed '*systematic errors*' representing the discrepancy between desired and taken action bearing in mind important perceptual and cognitive limitations, and '*unsystematic errors*' that represented the normal random variation in road-user behaviour that are generally difficult to predict and quantify.

3.5 Driver performance and error frequency

Driving is regarded by behavioural researchers as a highly complex task, requiring continual adaptation to meet the needs and demands of the prevailing traffic situation. An idea of the level of complexity is suggested in relation to driver performance and exposure in a novel and interesting report by researchers Häkkinen and Luoma (1991)*. According to their statistics, based on data from Finland and the United States (see Table 3.1), average drivers are responsible for approximately 30 errors per hour, as a result of approximately 7,200 observations, 2,400 decisions and 1,800 actions. If these statistics are taken literally, it could be suggested that only one out of every 60 errors on average is likely to result in a risky situation, and similarly that each accident is preceded by approximately 75,000 errors.

Table 3.1 Events of an average driver, based on an average speed of 60 km/h and annual mileage of 200,000 km (Häkkinen and Luoma, 1991)

Event	Frequency per time-unit	Frequency per kilometre
Pieces of traffic information	5 in 1 sec	300 per km
Driver observations	2 in 1 sec	120 per km
Driver decisions	40 in 1 min	40 per km
Driver actions	30 in 1 min	30 per km
Driver errors	1 in 2 min	1 per 2 km
Risky situations	1 in 2 hrs	1 per 120 km
Near accidents	1 in 1 month	1 per 2,000 km
Accidents	1 in 7.5 years	1 per 150,000 km
Injury accidents	1 in 100 years	1 per 2 million km
Fatal accidents	1 in 2,000 years	1 per 40 million km

3.6 Perceptual and cognitive limitations and information-processing

Perceptual and cognitive research in relation to the driving task is now a predominant area of multidisciplinary research in Human Factors (Human Engineering) and Human-Machine Interface (HMI) design. The information-processing approach emerged with the advent of cognitive psychology in the 1970's and has identified and quantified many different limitations in relation to human perception and cognition, and the propensity for different types of human error to occur as a result of these limitations.

Among the many concepts that are applicable to the driving task are various psycho-physical limitations with regard to the judgement of speed and distance and the effects of pre-attentive selective sampling (see e.g. Evans, 1970, Shinar, McDowell and Rockwell, 1974; Haglund and Åberg, 1990).

*The results of this report were interpreted in the academic thesis presented by Åse Svensson in 1997 and are restated here in light of their relevance and interesting nature (Original report in Finnish)

Similarly, higher-level cognitive processing abilities such as problem-solving and decision-making has been found to be limited with regard to: short-term or working memory; long-term memory; attentional resources and the ability to divide these among several different tasks; and *'workload'* i.e. the ability to deal with several tasks concurrently (see e.g. Alm & Nilsson, 1995; Hancock *et.al.*, 1990).

Rockwell (1972) has suggested that visual information constitutes as much as 90 per cent of the total information input required for the driving task. It has also been suggested that as many as 50 per cent of all accidents are attributable to perceptual failures such as the judgement of speed and distance (Englund *et.al.*, 1998). Other behavioural phenomena that are known to affect driver performance include *'inattention blindness'* (Mack and Rock, 1998) and *'perceptual fixation'* (Muller and Rabbitt, 1989). There are also a number of internal and external factors that are known to influence decision-making. These include: temporary debilitating factors such as stress, fatigue, and alcohol (or drugs); social psychological factors such as attitudes, social cognition, biases, and norms; personal demographic factors such as age, gender, and experience; and long-term personality factors such as a high level of aggressiveness, a propensity for risk-taking, and a general lack of conformity to rules and regulations (see e.g. Tränkle *et.al.*, 1989; Wickens, 1992; West, Elander and French, 1993; Englund *et.al.*, 1998. Parker and Lajunen, 2001).

While the importance of this type of research is recognised in relation to traffic safety, there has also been some criticism attributed to the use of these research findings for modelling purposes. This criticism stems largely from the fact that many of these models are not sufficiently supported by empirical research to enable them to be generalised to other situational contexts (and sometimes also lack a solid theoretical framework). This view is shared by Hollnagel (2001) who argues that this type of modelling is useful in enabling the formulation of predictions concerning certain types of error occurrence, but also suggests that the extent to which these are representative of the real-world context remains unclear.

The human information processing approach is also recognised by the Swedish Road Authority (SRA, 1996), who have identified human functions/error mechanisms that are critical for safe driving. These functions include:

- The timely detection of relevant information
- The identification and selection of information for decision-making
- The interpretation of relevant information
- The ability to turn decisions into correct action
- The evaluation and modification of actions taken
- The evaluation of own abilities and limitations
- The evaluation of vehicle performance and limitations
- The motivation to drive safely

In their report, aimed at identifying ways through which the *'Vision Zero'* could be achieved (see Appendix 1), the SRA identified stress and strain, tiredness, alcohol, and medication, as factors which can have a serious negative effect on driver performance. They also identified inexperience and incorrect attitudes as potential problem areas with regard to safety.

One of the most comprehensive information-processing models in relation to driver behaviour and performance has been suggested by Rumar (1985). This model (depicted in Figure 3.2) has also found support in a number of empirical studies. Rumar's model describes the processes in which decisions are made on the basis of perception and comprehension of the traffic environment, and how these decisions are influenced by attentional factors, motivation, previous experience, and expectations. Perceptual and cognitive filters are also provided to show how important information may be lost or misinterpreted during the different stages of processing. Another important aspect of this model is the feedback loop, suggesting the iterative and concurrent nature of the driving task.

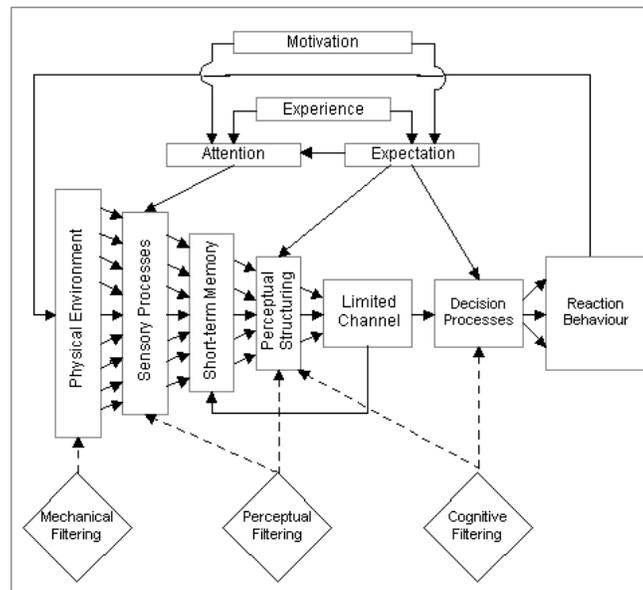


Figure 3.2. Rumar's model of driver information processing

3.7 Traffic safety and the concept of risk

Another approach to modelling in relation to driver behaviour and traffic safety concerns perception of accident risk or danger. One of the main paradigms in driver behaviour modelling has focused on the driver as a self-regulating entity, where the level of difficulty and risk in the driving task is determined solely by the individual driver in relation to the traffic environment. In the theory of '*Risk Homeostasis*' proposed by Wilde (1988), an equilibrium is maintained between estimated risk and acceptable risk as safety levels fluctuate in accordance with the situational context. Similarly, Näätänen and Summala (1976) suggest a '*Zero-Risk*' theory in which the subjective perception of risk in accordance with the conditions of the traffic environment is maintained at a level of zero. Several other risk or danger-based theories have also been presented including the '*Threat-Avoidance*' theory of Fuller (1984). In an interesting study by Svensson (1981), drivers were found to perceive themselves less of a risk threat than other road-users.

The main criticism levelled against risk models is that they are often too simplistic and less useful as a basis for empirical investigation (Rothengatter and de Bruin, 1988; Rumar, 1988). The risk concept is, however, one of the few approaches that take into consideration the motivation of road-users to behave safely.

3.8 Other models and theories of driver behaviour and performance

For a more comprehensive overview of the many different models and theories that are related to driver behaviour, the reader is referred to the now dated, but highly relevant meta-study by Michon (1985), and the work of Ranney (1994). An in-depth review of different models with relevance to driver behaviour and performance from the world of psychology, sociology and psychophysics has also been prepared by Archer (1999). Other mainline approaches, in addition to those that fall into the realm of human factors and information processing, include cognitive systems engineering and socio-technical approaches. For more information regarding these alternative approaches, the work of Hollnagel, (2001), Wickens (1992), and Leveson (1995) is recommended.

3.9 Accident causation and safety countermeasures

Knowledge related to accident causation and the existence of traffic safety problems at various locations or facilities is also useful for determining appropriate safety strategies and countermeasures. This includes the improvement of driver education and training through approaches such as *'graduated licensing schemes'* and *'inverted licensing'* that have been shown to have beneficial effects in terms of reducing the risk for accident involvement (Smith, 1994; Klyve, 1998). The use of public safety campaigns and education programmes, on the other hand, results in only a limited short-term effect (see e.g. Järmark, 1992; Linderöth and Gregersen; 1994; Englund, Nyberg and Thiseus, 1997). Devices that help improve visual detection such as reflexes and better lighting have also been found to have beneficial safety effects (OECD, 1998).

The subject of accident causation has also been of key interest to vehicle manufacturers. Modern vehicles undergo rigorous testing to ensure stability and handling, a high level of driver visibility, suitable control and warning systems, and a high level of injury protection for those inside and outside the vehicle (see e.g. Evans, 1991; Neilson and Condon, 1998). Nowadays there are also international and national standards such as the EuroNCAP to ensure that minimum levels of safety are upheld. Other devices that have had a significant effect on safety are: high-mounted brake lights, daytime running lights, anti-locking braking systems (ABS), and Intelligent Transportation Systems (ITS) that involve driver monitoring and support in relation to perception and decision-making tasks. Other functions for the enhancement of driver performance are also under development.

Making improvements in the design of the roadway to reduce accident risk is a recognised approach to improving traffic safety used by transportation planners and traffic engineers. Towliat (1997) has formulated a number of fundamental principles for safety improvement in urban areas based on factors that are directly based on theories related to road-user behaviour and knowledge concerning the effects of applying different measures. The main principles suggested include: ensuring correctly adjusted speed levels, removing the possibility for implicit yielding, improving visibility, ensuring simplicity and clarity, and better integration between vulnerable road-users and other traffic. These principles are fundamental to the strategies of *'traffic calming'*, *'verkehrsberuhigung'* and *'environmental prioritisation'* that have had positive effects on traffic safety (see e.g. Englund *et.al.*, 1998; Kjemtrup and Herrstedt, 1992). The Swedish Road Authority has integrated these principles and existing knowledge into the TRAST (*'Traffic in Cities'*) and VGU (*'Road and Street Design'*) guidelines and recommendations for traffic planning purposes.

In Chapter 2, statistics were shown to suggest that a large of traffic accidents in the urban environment occur at intersections. Safety levels at intersections are largely influenced by the design and type of regulatory control used which affect the level of complexity and degree of interaction at this type of facility. Generally, the use of designated turning lanes, local speed restrictions, the removal of sight restrictions, and more restrictive forms of control such as stop signs instead of yield signs, and traffic signals instead of stop or yield signs, have been found to have a positive effect on safety (Elvik, Mysen and Raa, 1997; Englund *et.al.*, 1998, SRA, 2001).

The study of accident causation is also useful for identifying safety problems that can be resolved using Intelligent Transportation System (ITS) solutions (Malaterre and Fontaine, 1993). ITS applications represent an integration of research from many different scientific areas and can provide economically viable technological solutions to many simple and complex transportation problems. ITS is expected to have a significant impact in most countries by: increasing the overall efficiency of the traffic system, making significant contributions to environmental quality and energy savings, increasing the productivity of transport systems, and perhaps most importantly, by improving the traffic safety situation (see e.g. FHWA, 1997; ERTICO, 1997; ETSC, 1999a). Particularly for traffic safety related purposes in Europe, the EU has launched the '*eSafety*'-initiative which takes an integrated approach to improving road safety through the use and accelerated introduction of ITS.

An ITS-concept that has received a great amount of attention internationally is Intelligent Speed Adaptation (ISA). This has become a major area of research in many countries including: Sweden, Great Britain, Holland and Australia. The testing of various types of ISA-system has suggested considerable safety improvements in relation to reduction in accidents involving injury and fatality (Carsten and Fowkes, 1998; SRA, 2001). Other applications with high potential in the urban environment include traffic management and control systems (see e.g. Lind, 1997; 1998), and the use of more diverse applications such as '*intelligent*' pedestrian crossings (Carsten, 1995; ETSC, 1999b).

The world of ITS is one of constant development and rapid expansion, and is beyond the scope of this thesis. The interested reader is referred to the various '*online*' and up-to-date information sources, electronic newsletters and '*links*' that are available from the internet websites of the ERTICO organisation (<http://www.ertico.com>) and the ITS-America organisation (<http://www.itsamerica.org>).

3.10 Implications of accident causation for safety analysis work

Understanding the causes of accidents and related theories regarding human behaviour and performance is without doubt, represents important background knowledge for the analyst who intends to study traffic safety through the use of techniques based on the measurement of '*near-accidents*', i.e. failures in the interactive processes between road-users in the traffic system that are regarded as precursory to accidents. The brief and limited coverage of background data regarding accident causation that is presented here, also highlights a number of important issues that are fundamental to the theories on which proximal safety indicators and their associated measurement techniques are based.

PART II:
PREDICTIVE MODELLING
AND
SAFETY MEASUREMENT
CONCEPTS AND TECHNIQUES

4. Traffic safety and predictive modelling

4.1 Predicting safety impact: SRA “effect-relationship” models

For traffic planning purposes, most models that predict expected levels of traffic safety for a given traffic site are based on historical accident data. In Sweden, the Swedish Road Authority’s so-called ‘*effect-relationship*’ models are used to estimate safety effects in the form of normalised average accident ratios (number of fatalities and serious injuries per million axle-pair kilometres), and other ratios based on the seriousness of the resulting injuries. The models are adapted to specific facilities using parameters that define road or intersection type, aspects related to road function and environment, traffic volumes, and the posted speed limit (SRA, 2001; Matstoms and Björketun, 2003).

The SRA have specified effect-relationship safety models for different types of link-roads, and intersections for vehicle traffic. Models are also provided in relation to vulnerable road-users at road-crossing facilities. These models are used by traffic planners for project feasibility studies where cost-benefit analyses are used to help determine roadway design solutions that provide an optimum level of traffic performance and safety in relation to the resources available. Cost-benefit analyses usually entail the calculation of socio-economic costs associated with the estimated reduction of fatalities and serious injuries in relation to investment, drift, and other costs (see e.g. SRA, 1997; SIKÅ, 2002; ICF, 2003)

In the SRA intersection safety models, ‘*safety*’ is initially calculated as an estimated number of accidents based on a non-linear regression model that takes into consideration the traffic volume on primary and minor approach roads of the intersection expressed as average annual daily traffic counts (AADT). The constant-values used in the model are specified according to junction type, posted speed and the type of environment in which they are situated. These values are, determined by expert evaluation with regard to relevant historical accident data and measures of exposure (see Equation 4.1 below).

$$\text{Estimated number of accidents per year, } E = a * (Q_t)^b * (Q_s / Q_t)^c \quad \text{(Equation 4.1)}$$

Where: a , b , and c are constants specific to the intersection type, posted speed and location, and Q_s and Q_t represent primary and secondary road traffic volumes.

The SRA Effect-Relationship manual and models enable the evaluation of socio-economic costs related to the estimated number of accidents. This includes both material-based and risk-based costs for fatalities, severe and minor injuries and property damage. Provision is also made for the estimated costs of unreported accidents (SRA, 2001). The various types of models have also been integrated into computer software application (EVA) and are documented in the Effect-Relationship publication series. This series represents an important collection of knowledge and foundation for all transportation planning related work in the road transport sector in Sweden and are closely related to the high-level political goals and strategies for sustainable development (see Appendix 1).

4.2 Predictive safety modelling approaches

A large number of statistical predictive safety models are described in the literature that attempt to establish a relationship between various traffic parameters and the number of accidents at traffic facilities or in network areas (e.g. Hight and Witowski, 1988; Lau and May, 1988; Brüde, 1991; Brüde and Larsson, 1993; Mensah and Hauer, 1998, Lord and Persaud, 2004; Abbas, 2004). In the discussion regarding statistical safety prediction models, it is often suggested that accident occurrences are discrete, sporadic and random in nature thereby suggesting the suitability of Poisson regression models (see e.g. Haight, 1967, Kulmala, 1994, 1995). The variation in accident occurrence is also considered to be due in part to the systematic variation in identified traffic measures such as traffic flow rates, measures of speed, and intersection design factors.

Discrete, Poisson or negative binomial distributions are usefully applied to estimate the number of accidents that occur at a traffic facility over a particular period of time (see e.g. Chin and Quddus, 2003). If Y is a random variable that describes actual accident occurrence over time and y represents the observed number of accidents over a given time-period, then the mean of Y is Λ (also the random variable), and where $\Lambda = \lambda$, Y is Poisson distributed with parameter λ . The Poisson error structure also implies that the mean and variance are equal, which while simplifying some statistical models, also shows accident data to be over-dispersed with a level of variation that is greater than the mean value. This is considered by some to imply that the negative binomial distribution is a more realistic assumption for the representation of accident occurrence data.

For accident prediction modelling, the Generalised Linear Modelling (GLIM) approach has been found to be particularly useful. This approach accounts for the fact that the dependent variable (i.e. the number of accidents) does not need to be normally distributed, as is often the case with linear modelling approaches. Hauer and Lovell (1988) have used the GLIM approach to describe the relationship between accident frequency and traffic flows on prioritised and secondary roads at intersections (see Equation 4.2).

$$\text{Estimated accident frequency model, } E(\Lambda) = a * Q_s^b * Q_t^c \quad \text{(Equation 4.2)}$$

Where: a , b , and c are constants specific to the intersection type, posted speed and location, and Q_s and Q_t represent the primary and secondary traffic volumes (AADTs).

Kulmala (1995) and Maher and Summersgill (1996), have proposed an addition to the basic GLIM model suggested earlier by Hauer and Lovell, in order to include the effects of other influential variables (see Equation 4.3).

$$\text{Expanded accident frequency model, } E(\Lambda) = a * Q_s^b * Q_t^c * e^{\sum dx} \quad \text{(Equation 4.3)}$$

Where: a , b , and c are constants specific to the intersection type, posted speed and location, and Q_s and Q_t represent the primary and secondary traffic volumes, and x represents any additional variable and d a model parameter.

In a related article by Wood (2004), the use of GLIM (generalised linear models) is discussed in relation to the prediction of accidents of specific types given explanatory variables such as vehicle flows. Wood suggests that, for a single flow model, the true mean number of accidents μ can be modelled as: $\beta_0 x^{\beta_1}$, where x denotes the flow. In this calculation, accidents are assumed to be distributed according to the Poisson assumption or (more commonly) a negative binomial distribution. Wood states that, once the goodness-of-fit for a specific accident model has been established, it is important to specify confidence intervals for both the model parameters and prediction intervals for the dependent variables. This is a standard course of action when working with linear models, and provides useful information regarding the extent of the variation. For accident prediction, the distinction between confidence intervals and prediction intervals is important. The intervals that are usually of interest are those for the true accident rate and those for the predicted accident rate.

For the Poisson model, the following equations can be used to estimate the 95 per cent confidence interval around the true accident rate μ , and the predicted number of accidents y : In these models, the variances of model parameter estimates, which are usually estimated during the regression calculation in statistics package are required:

$$\text{Predicted number of accidents, } y = \left[\hat{\mu}/e^{1.96\sqrt{\text{Var}(\hat{\eta})}}, \hat{\mu}e^{1.96\sqrt{\text{Var}(\hat{\eta})}} \right] \quad \text{Equation (4.4)}$$

$$\text{True accident rate, } \mu = \left[0, \lfloor \hat{\mu} + \sqrt{19}\sqrt{\hat{\mu}^2\text{Var}(\hat{\eta})} + \hat{\mu} \rfloor \right] \quad \text{Equation (4.5)}$$

Where: $\hat{\mu}$ = the $\hat{\mu}e$ estimator of the true mean accident rate, and $\text{Var}(\hat{\eta})$ = the variance around the model parameter estimates, and $\lfloor x \rfloor$ = the integer value that is less than or equal to x .

Similar values can be calculated for the negative binomial model, for the true accident rate μ , the prediction interval for the underlying site safety m (according to Hauer, 1988), and the predicted number of accidents y :

$$\text{Predicted number of accidents, } y = \left[\hat{\mu}/e^{1.96\sqrt{\text{Var}(\hat{\eta})}}, \hat{\mu}e^{1.96\sqrt{\text{Var}(\hat{\eta})}} \right] \quad \text{Equation (4.6)}$$

Prediction interval for the underlying site safety,

$$m = \left[\max \left\{ 0, \hat{\mu} - 1.96\sqrt{\hat{\mu}^2\text{Var}(\hat{\eta}) + \frac{\hat{\mu}^2\text{Var}(\hat{\eta}) + \hat{\mu}^2}{k}} \right\}, \hat{\mu} + 1.96\sqrt{\hat{\mu}^2\text{Var}(\hat{\eta}) + \frac{\hat{\mu}^2\text{Var}(\hat{\eta}) + \hat{\mu}^2}{k}} \right] \quad \text{Equation (4.7)}$$

$$\text{True accident rate, } \mu = \left[0, \lfloor \hat{\mu} + \sqrt{19}\sqrt{\hat{\mu}^2\text{Var}(\hat{\eta}) + \frac{\hat{\mu}^2\text{Var}(\hat{\eta}) + \hat{\mu}^2}{k}} + \hat{\mu} \rfloor \right] \quad \text{Equation (4.8)}$$

Where: $\hat{\mu}$ = the $\hat{\mu}e$ estimator of the true mean accident rate, and $\text{Var}(\hat{\eta})$ = the variance around the model parameter estimates, and \hat{k} = a parameter for fitting a Gamma distribution to obtain an estimated prediction interval given μ .

Usefully, Wood (2005), provides examples for the calculation of these two types of intervals suggesting how different model parameters and variances can be estimated.

An adaptive accident prediction model for estimating safety in terms of accident occurrence at unsignalised urban junctions using the GLIM approach has also been suggested by Sayed and Rodriguez (1999). In their model, the estimation of model parameters is based on a methodology suggested in the work of Bonneson and McCoy (1993), this entails estimating model parameters using a Poisson error structure and calculating a suitable dispersion parameter based on Pearson's χ^2 , the number of observations, and the number of model parameters. Pearson's χ^2 was also used to assess the goodness-of-fit for the model. Sayed and Rodriguez' models proved useful for: identifying and ranking accident-prone-locations, developing critical accident frequency curves, and evaluating before-and-after studies.

In a recent study, a random effect negative binomial model has been developed by Chin and Quddus (2003). The authors state that this model can be used in situations where there are unobserved temporal and spatial effects. The results of their Singapore-based study indicated that the model was useful in identifying the influence of geometric elements, traffic factors and traffic control measures. In a similar study by Greibe (1993), more simple and practical accident models were developed to predict the expected numbers of accidents at urban intersections and roadway sections. The main aim of this study was to identify factors that affect roadway safety in relation to black-spot identification and network analysis. Generalised linear models were found to describe more than 60 per cent of the systematic variation. Greibe found that less variation could be explained for intersection models, and that these demanded more complex explanatory variables that were less likely to be related to roadway design factors. Traffic flow rates were found to be the most powerful variable in all models.

Qin and Colleagues (2003; 2004) have also described a new approach that relates (non-linearly) traffic volume to crash incidence. This involves a process referred to as zero-inflated-Poisson (ZIP) modelling to estimate models for predicting the numbers of various accident types as a function of average annual daily volume (AADT), segment length, speed limit and roadway width. It is suggested that these models can be used for a meaningful comparison of safety on US highways. This type of modelling has also been used by Lee (2002) to estimate the number of crashes among young drivers. Other modelling approaches that have considered measures of traffic volume, include the study by Lee and Colleagues (1992), which identified short-term turbulence of traffic flow as an accident precursor in a log-linear regression analysis that included traffic density and control factors related to roadway geometry, time of day and weather.

In a slightly different approach, Norwegian researchers Jones and Jorgensen (2003) used multilevel models for the analysis of road traffic accident outcome data. Based on the data from 16,332 cases a logistic regression function was used that could predict the probability of surviving a traffic accident given the type of accident and location in which it occurred.

Many accident prediction models are based on the use of incoming traffic volumes (AADTs) on major and minor roads, particularly those related to intersections or motorway on or off-ramps (see e.g. Abdel-Aty and Abdalla, 2004). There are, however, also a number of established models that are based on '*speed-difference*', measured in '*before-and-after*' study scenarios. The results of a comprehensive study by Elvik and colleagues (1997) have now been incorporated into the Norwegian Traffic Safety Manual. Here it is stated that a 1 per cent change in speed corresponds to a 2 per cent change in the number of people injured and a 4 per cent change in the number of fatalities.

In the UK, studies by Webster and Mackie (1996) at TRL suggest that each 1 mph (1.6 km/h) change in speed reduces the number of accidents involving injury by 5 per cent. This calculation has been adapted to different environments, being modified to 6 per cent in low speed areas, 4 per cent on rural roads and 3 per cent on high-speed roads.

Similarly, the ‘power’-model of Swedish researcher Nilsson (2000, 2004), suggests that the number of accidents involving fatalities, injuries, or a combination of both following the introduction of a speed-reducing measure is proportionate to the change in speed raised to a particular index or power value (see Equations 4.9-4.11). Similar equations also exist to calculate the number of fatalities or people injured, rather than the number of accidents. In fact, there is little difference between the model of Nilsson and that proposed by Elvik (1997) mentioned earlier.

$$\text{Accidents involving fatality, } y_1 = \left(\frac{v_1}{v_0}\right)^4 * y_0 \quad \text{(Equation 4.9)}$$

$$\text{Accidents involving fatality and serious injury, } y_1 = \left(\frac{v_1}{v_0}\right)^3 * y_0 \quad \text{(Equation 4.10)}$$

$$\text{Accidents involving injury, } y_1 = \left(\frac{v_1}{v_0}\right)^4 * y_0 \quad \text{(Equation 4.11)}$$

Where: y_1 = estimated number of accidents, y_0 = number of accidents prior to speed change, v_0 = velocity before, v_1 = velocity after.

4.3 Accident prediction based on ‘near-accidents’

While the use of statistical models based on historical accident data are most common in traffic engineering today, there are availability and quality problems associated with the data on which they are based, as discussed previously in Chapter 2. This approach is also considered ‘reactive’ in nature rather than ‘proactive’, where a significant number of accidents must occur before the problem is identified and suitable corrective measures are implemented (see e.g. Lord and Persaud, 2004). Understanding these problems, DeLeur and Sayed (2002) have recently proposed a framework for *proactive* safety planning, i.e. planning that is not entirely based on historical accident data, but uses other measures such as the use of safety indicators and predictive models.

An alternative and/or complementary approach to safety prediction is to measure the more frequent occurrence of near-accidents using proximal safety indicators where these are believed to have an established relationship to accident occurrence. In a study by Sayed and Zein (1999), traffic conflict safety indicator measures from 94 unsignalised intersections were used to establish conflict frequency and severity standards in the form of an Intersection Conflict Index that could be used to compare the relative rates of conflict risk among different intersections. Regression analyses were also performed to develop predictive models that related the relative frequencies of the safety indicator to traffic volumes and accident occurrences.

The results of this study indicated that average hourly conflict rates were well correlated with traffic volume at both signalised and unsignalised intersections. While statistically significant relationships were found between accidents and conflicts at signalised intersections ($R^2 = 0.70 - 0.77$), this was not found to be the case at unsignalised intersections. The reason for this difference was believed to be attributable in part to the quality of the accident data and the randomness associated with low accident frequency. (The subject of proximal safety indicators and the ability to use such measures as predictors of traffic accidents are discussed in more detail in the following chapters).

Other research has considered the relationship between opposing traffic volumes at intersections and the frequency of proximal safety indicators for accident prediction purposes. Spicer *et.al.* (1979), found evidence to suggest that conflict frequency was proportional to the square root of the product of the conflicting traffic volumes at different types of intersections. In a similar approach, Salman and Al-Maita (1995) found that both the sum of primary and secondary traffic volumes and the square root of the product of these volumes correlated well with the numbers of traffic conflicts in a study based on 18 unsignalised T-intersections located in Amman, Jordan. Their study also showed that daily conflict rates were significantly higher in Jordan at this type of intersection than those reported earlier from studies in the US reported by Crowe (1990).

5. Proximal safety indicator concepts and measurement techniques

5.1 Proximal traffic safety indicators as an alternative to accident data

Safety in the traffic system is most usually measured in terms of the number of traffic accidents and the consequences of accidents in terms of fatalities and injuries of varying severity. This is a traditional and long-standing approach that has established the use of accident data as an accepted measure of safety. Statistical accident data has proved useful for a wide range of purposes, including the identification of accident black-spots and problems associated with particular types of facility or different groups of road-user. This type of statistical data also forms a foundation for many types of models used in transportation planning and provides a means to evaluate the success of safety programs, strategies and policies at many different levels of interest.

While the general use of accident data in relation to traffic safety work is beyond question, there are a number of recognised limitations that are directly related to the quality and coverage of data, and the fact that accidents are rare events that occur randomly in both time and space. The collection of accident data is impractical for short-term safety assessment purposes where, for example, there is a need to evaluate the effectiveness of a particular type of safety measure at a specific location or facility. Furthermore, this type of data is less useful for determining accident causation since it is rarely recorded in sufficient detail to draw conclusions regarding the complex chain of events preceded an accident occurrence (see e.g. Carsten *et.al.*, 1989; Elvik, 2003). Factors such as this, limit the use of accident data for the purposes of determining suitable countermeasures.

Traffic safety analyses based on accident data implies an '*after-the-fact*' or '*reactive*' approach, whereby accidents must actually occur before preventive measures are taken. This approach is regarded by many as unethical.

Proximal safety indicators have been suggested as an alternative to the use of accident data. These are defined as measures of accident proximity, based on the temporal and/or spatial measures that reflect the '*closeness*' of road-users (or their vehicles), in relation to projected point of collision. The actual measure of accident proximity depends on the safety indicator concept or technique used.

A key advantage (and prerequisite) of proximal safety indicators is that they occur considerably more frequently than accidents. This suggests the need for a significantly shorter study period to establish statistically reliable results. Furthermore, the use of proximal safety indicators is also a more resource-efficient and ethically appealing alternative for fast, reliable and effective safety assessment. Safety indicators also imply a '*proactive*' approach to traffic safety (i.e. identifying safety problems before they result in accidents), which is more in line with political traffic safety policies such as the Swedish '*Vision Zero*' that call for preventative measures and the development of a traffic system infrastructure that is adapted to the needs and limitations of all types of road-user (see e.g. Tingvall, 1995).

Despite the many advantages related to the use of proximal safety indicators, a number of fundamental problems have been identified. These concern the lack of a consistent definition, their validity as a measure of traffic safety, and the reliability of their associated measurement technique. According to Chin and Quek (1997). These problems are largely responsible for a general lack of understanding and support for this type of method. Arguably, this has hindered the general development and acceptability of proximal safety indicators by traffic safety analysts.

The intention of this chapter is to discuss many of the theoretical and practical problems associated with different proximal safety indicators and their associated measurement techniques. Particular attention is given to the Traffic Conflict Technique and the Time-to-Accident measure, and the Time-to-Collision measure and various derivatives including Post-Encroachment Time. These concepts and techniques are widely recognised as established proximal safety indicator measures by researchers and safety analysts in many different countries. Furthermore, various traffic measures and processes that are known to influence safety (i.e. '*safety-influencing factors*'), are discussed. A number of these are considered indicators of safety in their own right due to their use in predictive models. However, such measures usually have a limited area of application do not meet the defining safety indicator criteria suggested below.

5.2 Defining criteria for proximal safety indicators

Svensson (1998) has identified a number of related criteria that can be used to identify the usefulness of proximal safety indicators, suggesting that they must:

- (i) complement accident data and be more frequent than accidents
- (ii) have a statistical and causal relationship to accidents
- (iii) have the characteristics of '*near-accidents*' in a hierarchical continuum that describes all severity levels of road-user interactions with accidents at the highest level and very safe passages with a minimum of interaction at the lowest level

The first criterion is quite obvious and does not represent a problem for the many different safety indicator concepts and techniques that exist. The second criterion is related to the question of process or product validity and the predictive ability of the proximal safety indicator in relation to accidents. The term '*causal*' also implies that a proximal safety indicator exists prior to the occurrence of an accident, and that accidents and proximal safety indicator occurrences represent measures of the same situational process. This has been disputed by a number of researchers in relation to the Traffic Conflict Technique and is discussed further in the next section.

The third and final criterion, relating to the existence of a '*hierarchical continuum*' of road-user interaction is related to the statistical and causal relationship criterion. Importantly, the notion of proximal safety indicators as measures of '*near-accidents*' makes a clear distinction between these from other recognised traffic parameters that display predictive ability in relation to accident occurrence (e.g. measures related to traffic flow or speed). The concept of '*severity*' is also introduced by the third criterion, suggesting a qualitative and comparative measure in addition the quantitative measure of frequency.

5.3 The Traffic Conflict Technique (TCT)

The Traffic Conflict Technique (TCT) has its origins in the research conducted at the Detroit General Motors laboratory in the late 1960's for identifying safety problems related to vehicle construction (Perkins and Harris, 1967; 1968). The approach adopted was to observe and record unsafe interactions between vehicles, determined by the use of evasive action to avoid a potential collision. The potential of this technique was received enthusiastically by researchers in different parts of the world who sought to find ways to establish the relationship between conflicts and accidents. However, research soon revealed a number of fundamental weaknesses, which cast doubt and scepticism on this approach as a study of traffic safety (Cooper, 1977; Williams; 1981; Chin and Quek, 1997).

Despite the many problems related to validity and measurement reliability, a number of other researchers proceeded with conflict experiments to establish definitions and methods for conflict measurement and analysis (Grayson *et.al.*, 1984). To this end, many international conferences and workshops were held, along with large-scale experiments involving international research groups to establish conflict standards. There were also a great many international publications. In spite of these efforts, the questions surrounding validity and reliability proved too inconclusive for some national transportation research institutes and authorities and the use of the adopted conflict technique (usually referred to by country of origin) was largely discontinued.

The development of the Swedish Traffic Conflict Technique was based at the University of Lund where it was refined in a number of different projects during the 1970's and 1980's before finally reaching its present level of development (Hydén, 1987). The Swedish technique, which is now generally accepted as a *de facto* standard in many other countries, defines a conflict as: "*An observable situation in which two or more road-users approach each other in time and space to such an extent that there is risk of collision if their movements remain unchanged.*" (Amundsen and Hydén, 1977)

As with the original definition by Perkins and Harris (1967), the conflict measure is determined at a point in time and space when evasive action is first taken by one of the conflicting road-users. The '*Time-to-Accident?*' (TA) measure is calculated using estimations of speed and distance made by trained conflict observers. As it is based on the point at which evasive action is taken, this measure does not take reaction-time into account (the Time-to-Collision measure described in the next section does consider reaction-time). In order for the TA-measure to be valid, a collision course (or actions that suggest a collision course) must be established between conflicting road-users based on the estimated speed and distance values at the point when evasive action is first taken by either party (Hydén, 1987).

On the basis of the determined TA-value and the speed of determining road-user, the conflict event is described as '*serious*' or '*non-serious*' in accordance with a non-linear function that takes into consideration the average rate of deceleration needed to avoid a collision at different speeds and a standard friction coefficient (Hydén, 1987). Thus, for the purposes of determining severity, speed-proximity, time-proximity and deceleration power are considered. It should also be noted that for predictive and comparative purposes only the conflicts classified as serious are usually considered. An illustration of the function separating serious and non-serious conflicts is illustrated in Figure 5.1 below.

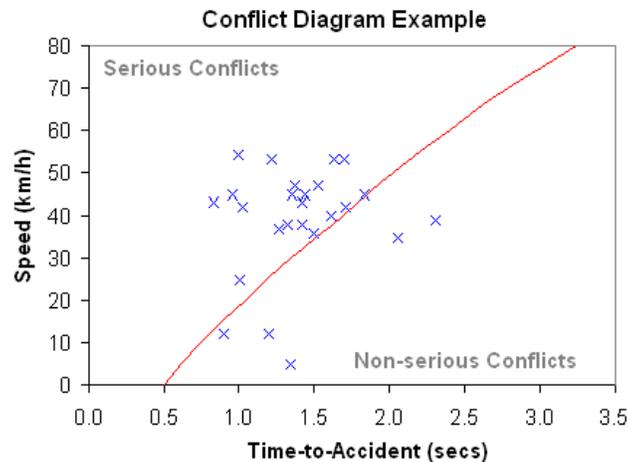


Figure 5.1 Distinguishing between serious and non-serious conflict events in accordance with the Traffic Conflict Technique.

The various problems associated with the Traffic Conflict Technique are described in more detail below. Most problems are related to the way it is defined, different types of validity and measurement reliability.

5.3.1 Concepts, definitions and underlying theories

Researchers Chin and Quек (1997), suggest that the insistence of regarding conflicts in terms of evasive actions has resulted in a variety of different ways of defining, identifying and interpreting traffic conflicts. They propose that an exhaustive list of evasive actions in all situations might be needed in order for conflict observers to understand what it is they are actually looking for. Despite the obvious overhead that such a list places on the observer, such a listing has been prepared in the user-manual for the US conflict technique (FHWA, 1989).

More importantly, Chin and Quек suggest that not all driver actions taken are necessarily 'evasive' in nature, and may in some cases be 'precautionary'. This has important implications with regard to the relationship between conflicts and accidents and the assumption that they are measures of the same fundamental processes according to a hierarchical continuum of interaction event safety. It has been suggested that some accidents and 'near-misses' may occur as the result of drivers having failed to take any evasive action (Glauz and Migletz, 1980; Gårder, 1989).

The issue of process validity has been addressed by Hydén (1987) who provided evidence to suggest that 'braking-only' was by far the most common form of evasive action in both accidents and conflict observations (68 and 79 per cent, respectively). This was closely followed by 'braking and swerving' (20 and 14 per cent for accidents and conflicts respectively), 'swerving only' (10 and 5 per cent, respectively), and 'accelerating' which was only found in 2 per cent of all accidents and conflicts. From this and other information, Hydén concluded, that conflicts and accidents shared the same approximate severity distribution. It was also found that accidents had on average 0.5 second higher (i.e. less-severe) TA-values and speeds 10-20 km/h lower than serious conflicts.

The accepted conflict definition (stated earlier) does not mention evasive action and leaves some ambiguity with regard to what is ‘*observable*’ and what is a ‘*sufficient*’ level of risk to distinguish between conflict and non-conflict situations. This also has important implications for the severity construct which implies ‘*nearness to collision*’, and the relationship between safe passages, conflicts and accidents. This relationship was originally defined by Hydén (1987) as a three-sided pyramid (see Figure 5.2 below). Others have since preferred to describe the relationship graphically in the form of a severity-frequency distribution as suggested by Glauz and Migletz (1980).

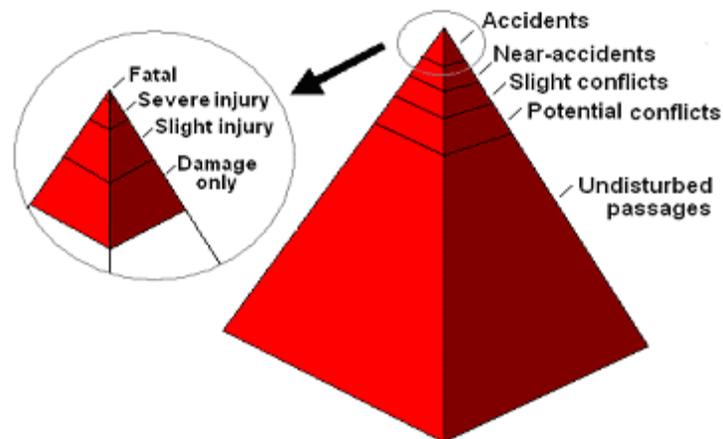


Figure 5.2 The safety pyramid according to Hydén (1987).

A number of studies have been conducted with regard to resolving the problem of differences in general conflict definitions and severity levels. Most notably, the study by Grayson and colleagues (1984) investigated eight different conflict techniques (including the Time-to-Collision and Post-Encroachment Time measures discussed in the following paragraphs). This study was carried out using international teams of observers that registered conflicts from a common data set in accordance with their own definitions and methods of measurement. Although this study showed a good level of agreement in the rank ordering of conflicts according to severity, variations were found in the comparison of conflict frequencies due to the differences in determining a suitable severity level to distinguish between ‘*serious*’ and ‘*non-serious*’ events.

The distinction between serious and non-serious conflicts has also been the subject of criticism. Chin and Quek (1997) suggest that discounting the information from ‘*slight*’ and ‘*moderate*’ conflicts is contrary to the main intention of proximal safety indicators, which is to provide a more comprehensive source of information than accident data. Swedish researcher Svensson (1998) has studied the frequency patterns of both serious and non-serious conflicts and concluded that there may be significant differences in the shape of the ‘*safety pyramid*’ with regard to the relationship between events of a less-serious nature and conflicts at different traffic facilities. This suggests the importance of including more comprehensive conflict information for the purposes of safety analysis.

5.3.2 The validity of the Traffic Conflict Technique

The validity of the TCT is most often determined by the level of statistical correlation between observed conflicts and accident data (i.e. product or predictive validity). This was considered particularly important in the early years of development in order to establish the technique as an alternative to the use of accident data. During this time, however, there were as many studies that indicated poor levels of correlation as there were studies that suggested the existence of acceptable levels of correlation (see e.g. Williams, 1981).

Chin and Quek (1997) suggest that these validity problems were at least partially due to the quality and coverage of accident data. In order to resolve the validity issues, two different approaches were suggested, the first involved limiting the use of the technique to only those cases where accident data was insufficient to be of use in accident analysis, and the second involved attempts to redefine conflict concepts and measurement techniques to ensure better correlation or finding suitable explanations for the lack of correlation (Amundsen and Hydén, 1977; Zimolong, *et.al.*, 1980; Hyden *et.al.*, 1982).

There are a number of studies that question some of the fundamental issues related to the need for validity. Hauer (1979) opposed the very idea of predicting accidents, suggesting instead that there was a greater need to prevent accidents rather than predict them. In a later report by Hauer and Gärder (1986) it is argued that the validity of the TCT should be assessed by comparing levels of variance in the estimates of conflict and accident rates. It is suggested that the method producing the most unbiased estimate with the smallest amount of variance is that with the greatest degree of validity.

Grayson and Hakkert (1987) suggest that the question of validity should not only be confined to establishing a statistical relationship between accidents and conflicts and propose that construct validity should be established in relation to a “*common causation process*” that can lead to different outcomes for conflicts and accidents rather than measures of validity based on a comparison between these two data-sets. This suggests that validity should be determined by how well safety analysis based on the TCT can identify and evaluate operational deficiencies and improvements. Oppe (1986), has further suggested the need to classify conflicts and accidents according to manoeuvre type and severity level in order to make comparisons relevant to validity.

In light of the uncertainties in relation to the quality of accident and conflict data, Chin and Quek (1997) suggest that it may be a futile and unnecessary exercise to establish a statistically significant relationship to justify the use of the TCT, particularly where it is used as a diagnostic and evaluative instrument rather than for accident prediction. This argument emphasizes the need for proximal safety indicators, to be useful in their own right without the need for validation against measures of accident occurrence. Arguably, the long-standing tradition of using accident data as a measure of safety has established its general acceptability and largely unquestioned validity. While this situation prevails, studies by Migletz and colleagues (1985) and Svensson (1992), have indicated that conflict studies can produce estimates of accident occurrence that are as good as, or better than, those based on accident data (and require a considerably shorter data-collection time-period).

5.3.2.1 Calculating the expected number of accidents from conflict data

Hydén (1987) states the importance of establishing how accidents and serious conflicts are related. This implies the need for both process and predictive validity. An underlying hypothesis in what Hydén termed the ‘*first generation approach*’, suggested that the variation in the relationship between accidents and conflicts could be explained by a number of variables, and secondly that after grouping the data in accordance with these variables that there was one real value in the relationship between serious conflicts and accidents for each group.

It is important to emphasise that Hydén considered not only police reported accidents, but also property damage accidents for the purposes of calculating suitable “*conversion factor*”. Stepwise regression was used to determine the factors influencing the variation in the relationship between accidents and conflicts. The calculations were based on data from more than 50 conflict studies at intersections in Malmö and a similar number in Stockholm. Variables included: speed-level and form of regulation (signal control, no signal control low-speed, and no signal control high-speed); existence of traffic island (no island or island in some approaches), sight distance (good or poor), interacting road-user types (car-car, car-cycle, car-pedestrian, car-moped), time-period (09:00-16:00 or 16.00-18:30), and lastly a variable related to the direction of travel.

The results of this analysis resulted in an initial 3 by 4 matrix classification system for the parameter values used to describe differences in the relationship between conflicts and accidents. The three-factor dimension consisted of interacting road-users (car-car, car-cycle, car-pedestrian), while the four-factor dimension consisted of the following:

Traffic class 1: Situations at low-speed intersections or situations at high-speed intersections for turning vehicles only

Traffic class 2: Situations at signalised intersections for turning vehicles only

Traffic class 3: Situations at high-speed intersections with one or more non-turning vehicles

Traffic class 4: Situations at signalised intersections with one or more non-turning vehicles

The statistical model proposed by Hydén for the conversion factors relating to each item in the matrix is as follows:

$$\text{number of recorded accidents, } x_i \in Po(\lambda_i \pi_i B_i) \quad \text{(Equation 5.1)}$$

$$\text{number of observed conflicts, } y_i \in Po(\lambda_i A_i) \quad \text{(Equation 5.2)}$$

Where: x_i represents the number of recorded accidents, y_i represents the number of observed conflicts. For x_i , Po represents a Poisson-process with mean intensity defined by the conflict frequency λ_i , and the product of the intersecting flows determined by B_i for conflicts and a π_i factor that specifies the probability that element i will result in an accident. For y_i , Po represents a Poisson-process with mean intensity defined by the conflict frequency λ_i , and the product of the intersecting flows determined by A_i .

Using the main principals of this model, and a good deal of statistical testing and refinement, the original 12-cell matrix was summarised by a 2 by 2 matrix (car-car and car-vulnerable road-user, versus traffic class 1-2 and traffic class 3-4) for the data. Conversion factors were determined with suitable confidence intervals in accordance with the Poisson assumption for the Malmö and Stockholm data (see Tables 5.1 and 5.2). It is interesting to note that there is a good level of agreement between the two data sets, and that there are a number of more subtle differences attributed to differences in driver behaviour, frequencies of accident/conflicts types and the quality and coverage of data.

Table 5.1 Final Conversion factors (values divided by 10^5) and confidence intervals (at $1-\alpha=0.05$ level, values divided by 10^5) between conflicts and accidents according to Hydén (1987) based on Malmö data

	Interaction Type: Car-Car	Interaction Type: Car-Vulnerable Road-User
Traffic Class 1+2	3.2 (2.0-6.9)	15.3 (12.2-19.6)
Traffic Class 3+4	11.1 (8.2-16.1)	89.2 (70.5-113.3)

Table 5.2 Final Conversion factors (values divided by 10^5) and confidence intervals (at $1-\alpha=0.05$ level, values divided by 10^5) between conflicts and accidents according to Hydén (1987) based on Stockholm data

	Interaction Type: Car-Car	Interaction Type: Car-Vulnerable Road-User
Traffic Class 1+2	3.1 (1.8-8.7)	12.8 (9.3-18.7)
Traffic Class 3+4	14.1 (11.6-17.6)	62.1 (44.7-85.7)

As a further part of the validation process, a comparison was made between the relative frequencies of different types of safety critical situations in which accidents and conflicts occurred. This comparison showed a tendency for both an under- and overestimation of accidents based on different conflict situations such as left-turning manoeuvres, rear-end interactions or perpendicular interactions. Many of these differences were exaggerated further in relation to certain types of intersections.

Hydén (1987) also compares the results from a number of before-and-after studies conducted at intersections in conjunction with the introduction of safety enhancement measures (speed-humps, traffic signals, and cycle-paths). The recorded number of conflicts and accidents are both used to predict the number of accidents both before and after the safety countermeasure is introduced. This comparison reveals a considerable overestimation of the number of accidents. These findings are attributed to differences in the conflict observation period and their representivity for the purposes of calculating the estimated number of accidents per year. It is also suggested that the time-period for the studies were unsuitable being immediately before and after the introduction of a safety measure. Similarly, the possibility of a 'regression-toward-the-mean' effect is suggested.

Following many years of practical application and a good deal of research a number of potential areas of improvement related to validity and reliability were identified. Hydén (1987) also pointed out the need for validation in relation to the diagnostic qualities of the Traffic Conflict Technique instead of the more typical *'first generation'* approach that was mainly directed at establishing predictive ability. This provided an improved approach for calculating conversion factors.

One of the main improvements to the Traffic Conflict Technique at this time was the introduction of a *'uniform severity level'* and *'uniform severity zones'* based on the relationship between Time-to-Accident and approach speed (see Figure 5.3 below). Previously, a fixed-threshold value (usually 1.5 seconds) had been used to distinguish between serious and non-serious Time-to-Accident values. This new approach distinguished between serious and non-serious conflicts in accordance with a function based on vehicle speed and distance to a conflict point, the amount of braking power required, and a friction coefficient (making the function non-linear). Similar functions could be established to determine equidistant parallel severity zones. One of the basic concepts underlying the Traffic Conflict Technique is that serious conflicts should reflect the probability of a collision; therefore, the use of a uniform severity level such as this was believed to significantly improve the validity of the technique.

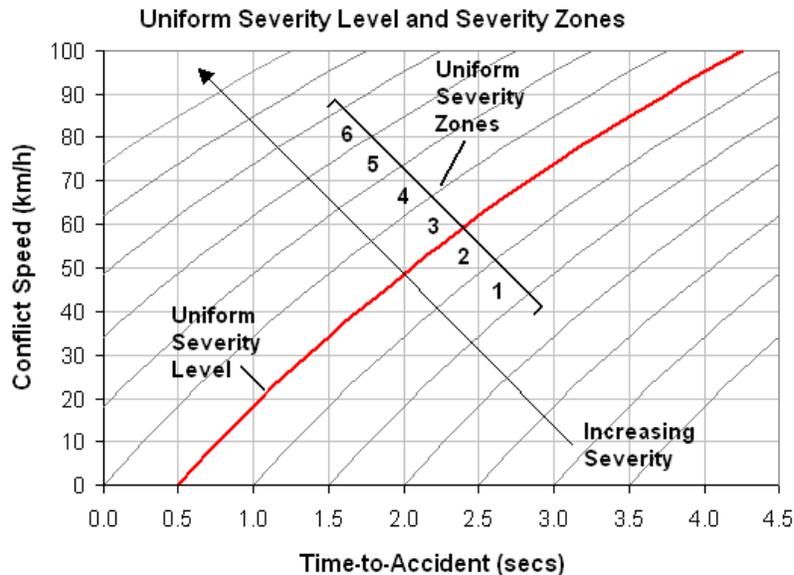


Figure 5.3 Uniform severity level and severity zones according to Hydén (1987)

Following the application of the uniform severity level concept, much of the validation work concerned comparing the processes underlying conflicts and accidents. Hydén (1987) investigated 312 accidents and compared the data with that of 761 conflicts data taking into consideration important factors such as conflicting speeds and distances to the collision point, type of evasive manoeuvre and type of road-users involved. Interviews with accident victims and on-the-scene measures were also recorded. This comparison led to the conclusion that conflicts and accidents were based on a common underlying process and had a fundamental similarity.

Hydén (1987) also suggested that accidents were a type of conflict (according to the definition made) and therefore that the severity distributions of conflicts and accidents could be combined to produce a more reliable estimate for a conflict distribution. In such a distribution, the tail with high severity represents an area of accident occurrences only (see Figure 5.4 below). Estimations based on the data collected showed that approximately one accident event occurred per 5000 hours of conflict observation thereby making reliable estimations of the size of the tail area very difficult.

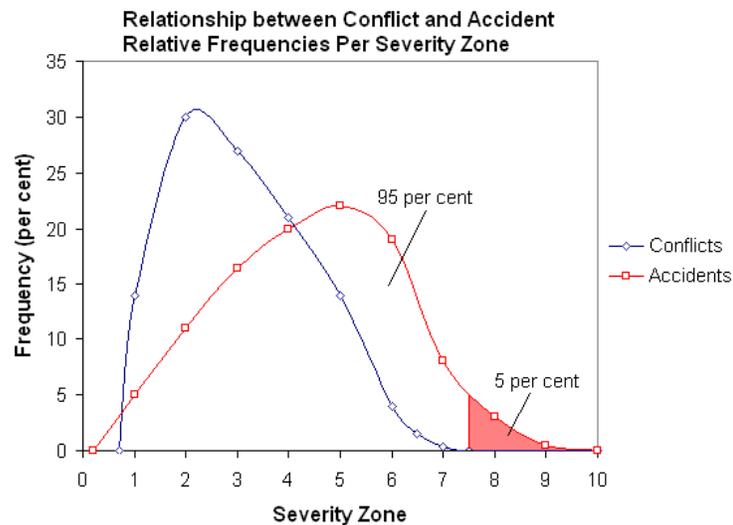


Figure 5.4 Example of relationship between conflict and accident relative frequencies per severity zone according to Hydén (1987).

From this new line of reasoning, it was concluded by Hydén (1987) that the proportional distributions of conflicts and accidents per severity zone could be used as a basis for calculating ratios between accidents and the sum of accidents and conflicts in absolute numbers. For this particular calculation, the relative numbers of accidents and conflicts were required along with details regarding the period of recording or observation, and the number of sites at which these occurred. Importantly, this data could be used to derive the probability that a conflict of a particular severity would lead to a police reported injury accident. In the cases studied by Hydén, these probability values clearly indicated the higher level of accident potential for vulnerable road-users (cyclists and pedestrians) at lower levels of severity in comparison to car-car conflicts. These findings suggested that future approaches to predicting the numbers of accidents at different traffic facilities based on observed conflicts should consider conflict severity frequencies where higher numbers of more severe conflicts suggest significantly higher risk for accidents involving injury.

5.3.2.2 The CD-base software program

There is a small software program that has been developed at the Department of Traffic Engineering at the University of Lund for recording conflict data in a computerised database, presenting the data in graphical form. There is also a function for calculating the estimated number of police reported accidents per year, based on different types of conflict observation data. This software program is freely available can be downloaded freely from the Department of Traffic Engineering website.

The calculation for the estimated number of police reported accidents is broken down into three specific types of situation: interactions for vehicles that are on different trajectories, interactions for vehicles with the same final trajectory (rear-end and merging conflicts), and vehicle-vulnerable road-user interactions. For each of these three cases, a different conversion factor is used. The calculation considers the number of conflicts observed for a given interaction type, the numbers of hours of conflict observation, as well as the numbers of hours per day and the number of days per year that the observation period represents.

According to the calculations performed by this software, each serious conflict between two vehicles with opposing trajectories during a normal conflict observation period of 6 hours per day (representing 300 days per year) will increase the estimate for the number of police reported accidents by 0.0357. Similar calculations for vehicle-vehicle interactions with the same final trajectory show an increase in the estimate for the number of police reported accidents by 0.0084, while vehicle-vulnerable road-user interactions result in an increase in the estimate for the number of police reported accidents by 0.1017. There are no confidence levels expressed in relation to this data. Representatives at Department of Traffic Engineering also state that the program is in need of updating with regard to the conversion factors used, and furthermore, that the calculations of police reported accidents are only intended as very approximate estimations.

5.3.3 The reliability of the Traffic Conflict Technique

The methodology of the Traffic Conflict Technique has been heavily criticised for relying on the subjective judgement of speed and distance by trained observers (Hauer and Gårder, 1986). This subjectivity allows for the possibility of unreliable measurements, although it has been suggested that such uncertainties can be accounted for by the use of various statistical techniques (Chin and Quek, 1997).

Two types of reliability problem have been identified. The first, intra-observer reliability, is related to the variability in the recordings of an individual observer, and the second, inter-observer reliability, is related to the variability between different observers. The inconsistencies of an individual observer can be attributed to a number of factors including: lack of training, inadequate definitions of the situations to be observed, fatigue, excessive numbers of conflicts, and the occurrence of complex conflict types (Older and Spicer, 1976; Chin and Quek, 1997). The use of manuals and adequate training programs can be used to remedy some of these problems, and video-recordings can be used to verify more difficult conflict scenarios (see e.g. Hauer, 1987; Glauz and Migletz, 1980; FHWA, 1989). Research has shown, that observers can provide good estimates of speed and distance with small margins of error (Hydén, 1987).

The problems found at the individual level are likely to be emphasised in comparisons between individuals or groups of observers. In the large-scale comparison of different Traffic Conflict Techniques reported by Grayson and colleagues (1984), on-site video-recordings were made in addition to the conflict observations. As mentioned previously, the results of this study showed variations in the frequencies of conflicts observed by different teams although the rank ordering according to severity was found to be consistent.

Differences in conflict detection rates were found in the comparison study by Grayson and colleagues (1984) that were affected by the way in which the conflicts were defined and observed. In particular, detection was found to be more difficult and therefore also more variant in relation to conflicts with lower levels of severity. Chin and Quek, (1997) suggest that even where conflicts are well defined and observers are well trained, the subjective observations of conflicts may still result in a good deal of variation among observers.

The reliability of conflict measures can be improved by the use of objectively defined measures to verify difficult and complex conflict situations, for example, through processes involving video-analysis. A number of alternative proximal safety indicators such as Time-to-Collision and Post-Encroachment Time (discussed below) are largely dependent on photometric techniques rather than on-site observation. The use of video-analysis, while allowing events to be repeatedly observed, has certain disadvantages related to the limited coverage and quality of the two dimensional imagery, which makes the identification of safety critical events considerably more difficult (see e.g. Hallert, 1964; van der Horst, 1990; Hydén 1996, Hupfer, 1997).

5.3.4 Suggested improvements in the literature

Having identified a number of limitations in relation to the Traffic Conflict Technique, Chin and Quek (1997) suggest the use of an improved framework for studies aimed at the investigation of road-user interaction. The proposed framework involves using quantitative definitions that correctly reflect the intended purpose of the study in order to achieve more objective evaluations. This type of definition involves measures of time or space accident proximity without the need for elaborated severity structures. The use of photometric measurement is also advocated in order to achieve good precision and measurement reliability. Chin and Quek also state the need to specify a threshold value for the conflict measure in accordance with the nature of the safety problems that are to be investigated.

Furthermore, it is considered useful to establish a statistical distribution of the conflicts so that the proportion of critical situations are not merely counted but also derived mathematically. Chin and Quek (1997) suggest that the conflict measures recorded can be used to derive a probability function representing generalised conflict severity as shown in Figure 5.5.

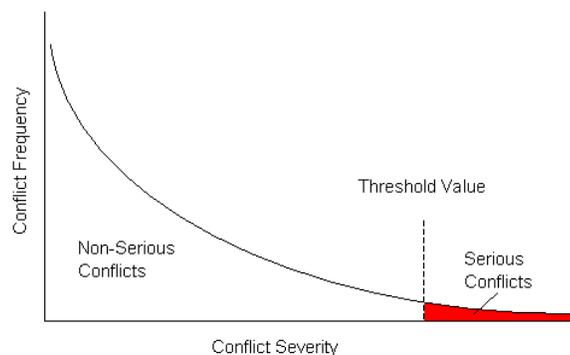


Figure 5.5 *Distribution of conflict events indicating probability for critical situations according to Chin and Quek (1997)*

Using a suitable threshold, the proportion of critical conflict events from such a distribution can be determined by size of the area (i.e. the integral) under the conflict curve beyond a severity threshold value. Chin and Quek propose the use of a mixed Weibull density function for the purposes of deriving a suitable statistical distribution based on conflict observations. This function can be used to derive the probability of a conflict occurring that is greater than a predetermined severity threshold. The actual severity scale used is dependent on the main intentions and purpose of the conflict study, which should also dictate the choice of conflict definition and the measurement technique applied.

5.3.5 Alternative representations of conflict severity

The actual outcome severity of an accident is directly related to the impact force of the colliding objects, which is defined proportionate to changes in acceleration and mass (i.e. momentum) in accordance with Newton's third fundamental law of physics. Thus, conflict situations with 'close' accident proximity levels but relatively low speed may indicate a high accident risk level but a low risk for personal injury (i.e. outcome severity). Generally, higher speed is related to higher risk for injury and fatality (i.e. speed is a good indicator of accident outcome severity). For this reason it is useful to use values of speed, or more preferably acceleration, in order to establish suitable levels of severity.

In the Traffic Conflict Technique, speed is used to distinguish serious and non-serious conflicts in accordance with a function based on the amount of required deceleration to avoid a collision and the level of friction between the vehicle and roadway. In the commonly used Time-to-Accident – Speed graph (see Figures 5.1 and 5.3) the severity level of the individual conflicts is not easily interpreted, and is represented by the perpendicular distance from the line that distinguishes between serious and non-serious conflicts. This 'distance' is however, proportional to speed rather than the average deceleration required to avoid a collision, and therefore the seriousness of conflicts may be underrepresented. For the purposes of this thesis, the required deceleration rate (RBR) is therefore considered a more appropriate predictor of accident severity risk and one that can be applied to most proximal safety indicator measures.

According to Hupfer (1997) a conflict severity scale based on braking rates has previously been proposed by the Zimolong and colleagues in the late 1970s in relation to the German Conflict Technique (see e.g. Zimolong, Gstalter and Erke, 1980). In the definition proposed, four different conflict severity levels were specified: the first of these suggests a controlled use of brakes or controlled change of lanes to avoid collision; the second a severe use of brakes and/or an abrupt change of lanes; the third level involves emergency braking and fast driver reaction; and fourth level involves collision. Interestingly, this concept and alternative definition of conflict severity was not developed further despite a study by Zimolong (1982) in which the total sum of conflict values according to levels 1 to 3 were found to correlate well with statistical accident data. Hupfer (1997) states that the German Conflict Technique was discontinued after receiving considerable criticism in the mid 1980's regarding validity issues.

In a report by Hydén (1996), the ideas concerning the braking rate severity scale were brought back into use in connection with the development of video-image processing software (ViVa-traffic,) that was to be used for the determination of traffic safety indicator values. In this report, the severity levels suggested earlier by Zimolong and colleagues were assigned deceleration values.

The braking rate definitions were stated in the definition of an alternative proximal safety indicator - Deceleration-to-Safety (DST) - which was intended to overcome a number of conceptual problems associated with the use of Time-to-Collision and Post-Encroachment Time in video-analysis processing. The braking rate values used in association with the DST-indicator and the original conflict levels of Zimolong and colleagues are listed below along in Table 5.3. Since Hydén's report in relation to the use of the VIVA-traffic video-analysis software, there has been little mention of the use of braking rates as a conflict severity measure in the literature.

Table 5.3 Deceleration-to-Safety braking levels proposed by Hydén (1996)

Conflict Level	Deceleration-to-Safety	Description
No Conflict	Braking rate ≤ 0 m/s ²	Evasive action not necessary
No Conflict	Braking rate 0 to -1 m/s ²	Adaptation necessary
1	Braking rate -1 to -2 m/s ²	Reaction necessary
2	Braking rate -2 to -4 m/s ²	Considerable reaction necessary
3	Braking rate -4 to -6 m/s ²	Heavy reaction necessary
4	Braking rate < -6.00 m/s ²	Emergency reaction necessary

The alternative use of required braking rates as a measure of severity is illustrated below in Figure 5.6 based on the same conflict data as the standard diagram shown in Figure 5.1 above. For comparative purposes, the function used to distinguish between serious and non-serious conflicts is also included, both as a linear function (without the curvature added by the friction coefficient) and in its original form. If the relative frequencies of conflicts are summated for the different conflict level categories proposed above in Table 5.3, it is possible to derive a conflict probability function, as suggested by Chin and Quek (1997). Similarly, actual frequencies per severity zone could also be used to estimate the expected number of police reported accident occurrences, as originally suggested by Hydén (1987).

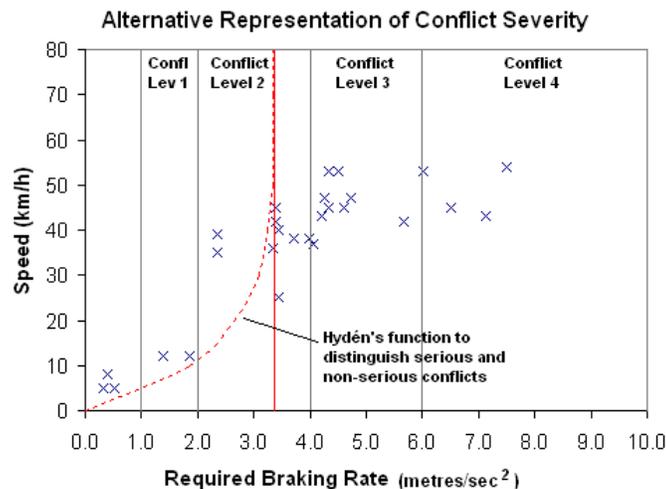


Figure 5.6 Alternative representation of conflict severity as required braking rate

5.3.6 Effect size and Traffic Conflict Technique studies

In an interesting report by Swedish researcher Brundell-Freij (1991) the necessary size of accident or serious conflict data to see an indication of improvement or to ensure statistical significance in before-and-after study designs has been calculated based on the Poisson assumption (see Table 5.4 below).

Table 5.4 Necessary size of accident or serious conflict data to see an indication of improvement or to ensure statistical significance in before-and-after study designs Brundell-Freij (1991)

Expected Effect (per cent)	Number of Accidents or Serious Conflicts need in order to:	
	(a) See an indication of improvement in 9 of 10 studies	(b) Obtain a 90 per cent level of significance in 8 of 10 studies
10	315	710
20	75	198
30	32	82
40	17	41
50	10	23

5.3.7 Example: Calculation of Time-to-Accident in a safety critical event

An example representing a typical conflict situation and the calculation of Time-to-Accident is illustrated below in Figure 5.5. In the example shown, the conflict situation is measured at the time the right-of-way vehicle begins to brake in order to avoid collision with a duty-to-yield vehicle that has accepted a short time-gap. A collision course exists in this example. This is not essential according to the definition; it is sufficient that the behaviour of the road-users suggests the existence of a collision course. The resulting Time-to-Accident is 1.04 seconds which at speed 38 km/h is considered a serious conflict.

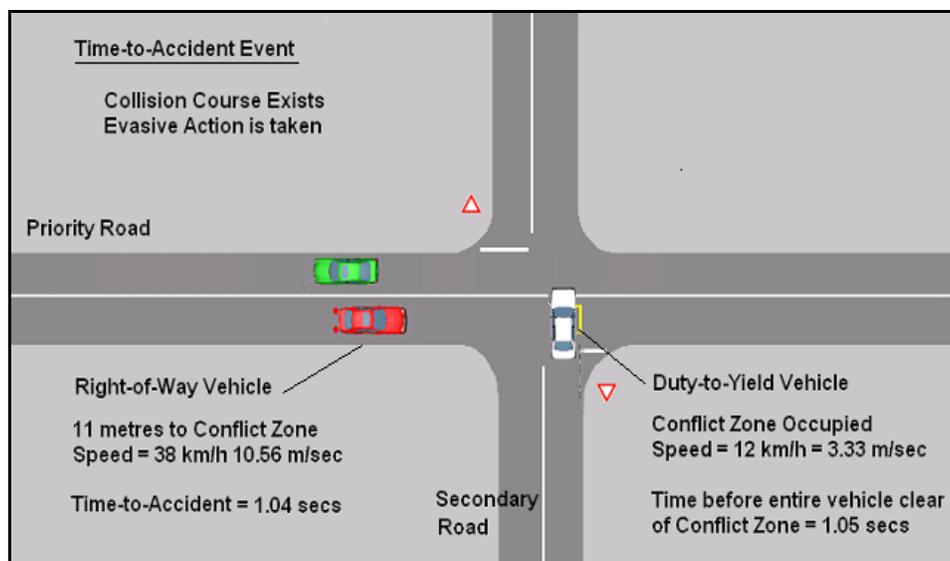


Figure 5.7 Example of a conflict situation and the calculation of Time-to-Accident

5.4 Time-to-Collision (TTC)

An alternative proximal safety indicator to that described above is Time-to-Collision (TTC). TTC is usually regarded as a more objectively determined measure of accident proximity in comparison to Time-to-Accident, and generally involves the use of photometrically determined measures. This particular indicator was originally suggested by Hayward (1972) who described a TTC event as:

"...the time that remains until a collision between two vehicles would have occurred if the collision course and speed difference are maintained."

Typically, the actual TTC-value used represents the minimum Time-to-Collision recorded during the entire interactive process of the safety critical event, rather than the value recorded at the time evasive action is first taken as in the TCT. There are however, other measures noted in the literature, such as the duration of the entire TTC-event (see e.g. Hydén, 1987). The general TTC definition implies that the reaction time of the road-user is also considered, which in some cases may be important with regard to the intention and purpose of safety study (Chin and Quek, 1997).

A prerequisite, as for the TCT, concerns establishing the existence of a collision course. When a collision course is determined, the TTC-value becomes finite and decreases with increasing accident proximity. In safety studies based on the use of TTC, a suitable threshold level must also be determined in order to distinguish between serious or *'relevant'* safety critical events, and those events that are not of interest. The threshold is represented as a fixed value rather than a function that is dependent on measures related to speed, deceleration and vehicle-roadway friction.

The severity of a particular TTC-event is implicitly represented by the time-value derived from measures of speed and distance. This implies that all minimum TTC-values of, for example, 1.00 second are regarded as having an equal level of severity irrespective of whether the speed used in the calculation is 10 km/h or 100 km/h. The TTC-concept may therefore be less useful as a comparative measure of conflict severity. To overcome this problem an additional severity structure, such as the required braking rate measure mentioned above, can be usefully applied.

Arguably, the widespread use of the TTC concept has been largely neglected due to the problems associated with the data-extraction process. Most often, this entails photometric video-analysis that is both resource-demanding and laborious. The use of video-analysis also limits the quality and scope of a safety study, where safety critical events can be difficult to detect in two-dimensional imagery, and subject to problems related to the relative positioning of the camera and the coverage this provides. TTC distributions have however been determined and applied in several studies to identify traffic safety impacts (Fancher *et.al.*, 1997; Van Arem and De Vos, 1997). The TTC-concept has also been used as an integral part of the Dutch Conflict Technique (see e.g. van der Horst, 1982)

5.4.1 Example: Calculation of Time-to-Collision in a safety critical event

An example representing a typical conflict situation and the calculation of Time-to-Collision is illustrated below in Figures 5.8a and 5.8b. The figures show the calculation of TTC on two separate occasions, although it should be remembered that these calculations are made continually at regular time-intervals during the course of a safety critical event for the purposes of determining a 'minimum' TTC-value.

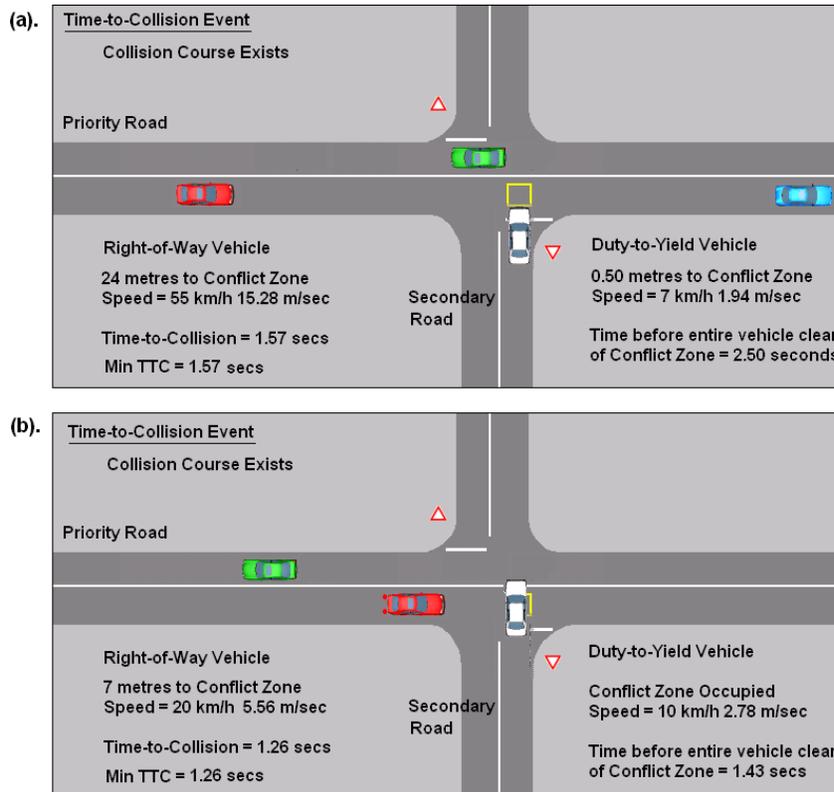


Figure 5.8(a,b)

Example of a conflict situation and the calculation of Time-to-Collision

5.5 Extended Time-to-Collision (TET, TIT)

The Dutch researchers Minderhood and Bovy (2001) have proposed two alternative proximal safety indicators that are based on general principles of the Time-to-Collision concept. The first of these is referred to as Time Exposed TTC (TET) and represents a measure of the length of time a TTC-event remains below a designated TTC-threshold. The second indicator, referred to as Time Integrated TTC (TIT), is similar to the first but represents a measure of the integral of the TTC-profile during the time it is below the threshold. Both measures are illustrated in Figure 5.9 below.

Minderhood and Bovy suggest that these values can be summated for a particular time-period and traffic facility, and used to derive average values that represent the probability of being involved in a safety critical situation per vehicle and time unit. These measures are also regarded as suitable for use in simulation studies.

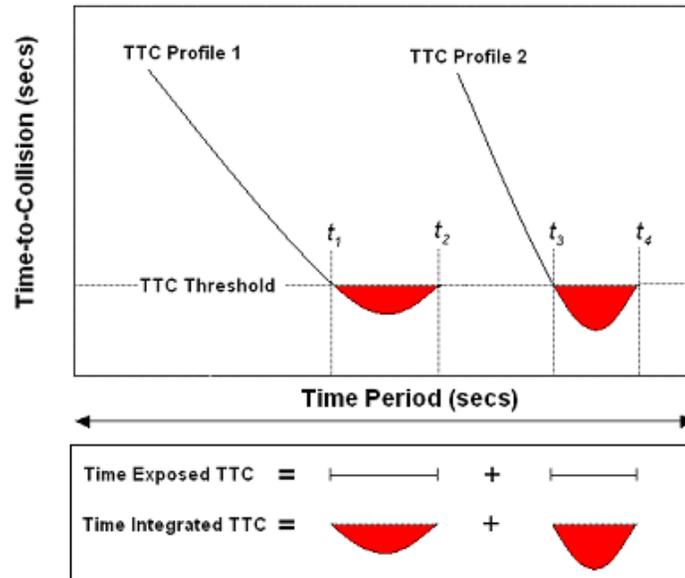


Figure 5.9 The Time Exposed and Time Integrated TTC proximal safety indicator measures proposed by Minderhoud and Bovy (2001)

5.6 Time-to-Zebra (TTZ)

A further variation of the Time-to-Collision concept has been developed for the purposes of estimating traffic safety at pedestrian (i.e. zebra) crossings. The TTZ value has been used by, amongst others, Varhelyi (1996) to assess the frequency and severity of critical encounters between vehicles approaching a pedestrian crossing and pedestrians who cross from either the left or right side of the road. In this study, critical time and distance intervals were identified in relation to the approaching speed of vehicles and a classification scheme was developed to record the different possible outcomes between vehicles and pedestrians. On the basis of this study, it was concluded that many drivers do not adapt their speed to the posted limit at pedestrian crossings, and regard pedestrians not on the crossing as a potential danger risk. The study showed that only one out of every four drivers stopped or braked to allow pedestrians to cross, and pedestrians were in many cases forced to actively 'take' priority on the crossing. (These studies were conducted before the pedestrian-crossing reform in Sweden, which now insists that drivers stop to allow waiting pedestrians and cyclists to cross).

5.7 Post-Encroachment Time (PET)

A further variation of the Time-to-Collision concept is Post-Encroachment Time (PET). This measure is used to measure situations in which two road-users that are not on a collision course, pass over a common spatial point or area with a temporal difference that is below a predetermined threshold. The PET concept has been used as part of the Dutch and Canadian Conflict Techniques (see e.g. Cooper, 1983; van der Horst & Kraay 1986; Hydén, 1987; 1996; Topp 1998). An important question related to the PET-concept concerns its convergent validity and whether or not PET-events can be regarded as representative of the same traffic processes that precede accidents.

The main difference between PETs and TTCs is the absence of the collision course criterion. PETs are easier to extract using photometric analysis than TTC as no relative speed and distance data is needed. The measure represents the difference in time between the passage of the “offended” and “conflicted” road-users over a common conflict zone (i.e. area of potential collision). This makes PET not only a useful ‘objective’ measure, but also one that is less resource-demanding than TTC with regard to data-extraction process, not requiring constant recalculations at each time-step during a safety critical event duration.

There are a number of recognised drawbacks with the PET-measure. Severity is implied directly by the PET-value, thereby subjecting it to the same criticism as that of the TTC-concept. Furthermore, the fact that speed and distance are not measured for the purposes of determining this value, infers that there is no possibility to accurately compare the relative severities of PET events, or to calculate a more useful severity measure. More importantly, the PET-concept is only useful for measuring safety critical events where there are transversal (i.e. crossing) trajectories for the road-users involved. Events with similar (final) trajectories are better suited to the TTC-concept discussed earlier. The reason for this is that there will always be a collision course if the speed of the following vehicle is higher than that of the preceding vehicle. PET-measurement requires a fixed projected point of collision, rather than one that changes with the dynamics of the safety critical event (as is the case in an unsafe rear-end or merging interaction).

5.7.1 Example: Calculation of Post-Encroachment Time in a safety critical event

An example representing the calculation of Post-Encroachment Time is illustrated below in Figures 5.10a and 5.10b. The example shown below indicates the position of the two vehicles involved in the safety critical event at the start and end of the PET-measurement.

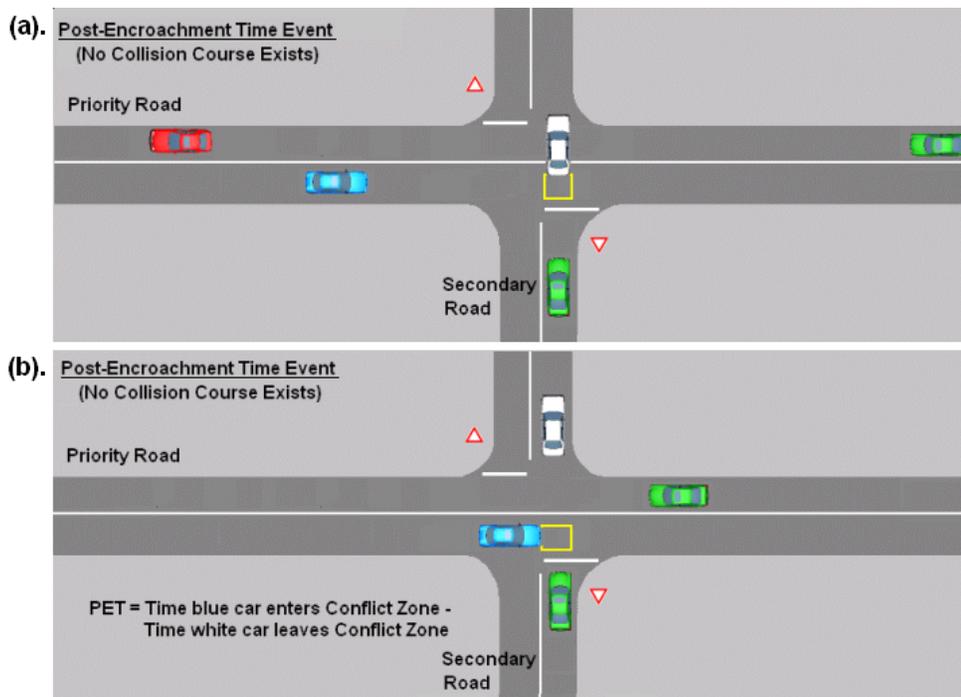


Figure 5.10(a,b) Example of the calculation of a Post-Encroachment Time event

5.8 Derivatives of Post-Encroachment Time

In a recent report by the Federal Highway Administration of the US Dept. of Transport regarding traffic simulation and surrogate safety measures, several variations of the PET concept are described (FHWA, 2003).

These include the following:

Gap Time (GT) – The time lapse between the completion of an encroachment by a turning road-user and the arrival time of a crossing road-user if they continue with the same velocity and trajectory

Encroachment Time (ET) – The time duration during which the turning of one road-user infringes the right-of-way of a mainline road-user

Initially Attempted Post Encroachment Time (IAPT) – The time lapse between the commencement of an encroachment by a turning road-user plus the expected time for the mainline road-user to reach the common conflict point, and the completion time of encroachment by the turning road-user

These variations show a number of subtle differences in comparison to the generic PET concept from which they are derived. The ‘Gap Time’ concept is based on an estimated time of arrival at the potential point of conflict rather than the actual time difference. This proximal safety indicator is similar in nature to the Traffic Conflict Technique, relying on a measure at the point when evasive action is first taken. While this accounts for the effect of braking by a secondary vehicle the elementary nature of the original PET concept is lost as resource-demanding measures of both speed and distance are required during data extraction process (FHWA, 2003).

The Encroachment-Time concept is similar in some respects to that of the Time-Integrated TTC, and may be useful as method that provides slightly more information with regard to the severity of encroachment-events where more serious interactions result in longer right-of-way infringement times. This concept is not subject to the limitation of transversal crossing manoeuvres and preserves the intuitive simplicity of the fundamental PET concept making the extraction process relatively resource-effective. Problems with this technique are related to the need for suitable definitions where right-of-way infringements can be complex and difficult to detect and quantify. The third and final PET-derivative, Initially Attempted Post Encroachment Time, is related to conflicting turning manoeuvres and is a simplistic measure of several related time-differences between two road-users. This particular measure has the same advantages and disadvantages as the fundamental PET-concept.

5.9 Other safety indicators

There are many other safety indicators that are less well known and less widely used. Many of these indicators do not have an established statistical relationship to accident frequency and outcome severity and/or lack sufficient experimentation and scientific investigation to qualify as safety indicators in accordance with the fundamental requirements that have been suggested by Svensson (1998).

The list of alternative safety indicators includes, amongst others, the following:

Deceleration Rate (DR) – This measure is quite simply a measure of the highest rate at which a vehicle must decelerate to avoid a collision (FHWA, 2003). Deceleration power is mentioned by Hydén (1987) as an important aspect in determining the severity of a conflict. In similarity to the extended TTC measures suggested by Minderhoud and Bovy (2001), it is theoretically possible to measure the time spent under a specified deceleration threshold rate and the integral (e.g. -2.0 metres/sec²). However, the measurement of actual deceleration rates using, for example, photometric analysis is difficult and resource demanding.

Deceleration-to-Safety Time (DST) – Similar to the above this indicator is defined as the necessary deceleration (where this is the primary evasive action) required to reach a PET that is greater than zero seconds. This measure has been used in conjunction with photometric analysis to determine levels of safety in the interactions between vehicles and pedestrians as a complement to the TA-measure used in the Traffic Conflict Technique and PET (Topp, 1998).

Proportion of Stopping Distance (PSD) - This measure represents the ratio of the distance available for a manoeuvre to that of the necessary braking distance to a projected point of collision (FHWA, 2003).

'Jerks' (composite *g*-force and speed) - A study by Wählberg (2000) investigated how left/right, accelerate/decelerate and composite *g*-force and mean speed were related to the frequency of accidents for bus drivers during different time-periods. Results showed a weak tendency for left/right *g*-force and mean speed to predict bus accidents. This study was followed the earlier work of Gully *et.al.*, (1995) that identified a relationship between accident frequency and observable driver behaviour such as abrupt lane changes and sharp deceleration.

Shock-Wave Frequency – A study by Van Arem and DeVos (1997) in relation to the effects of a special lane for intelligent vehicles on traffic flows showed that the frequency of shock waves could be applied as a useful indicator of safety.

Time-to-Line Crossing (TLC) – This measure is used to determine the remaining TTC in a conflict situation before a vehicle crosses a lane boundary. Vogel (2003) points out that this indicator is a useful measure in comparative driving simulator studies, but is otherwise difficult to ascertain in field measurements without the use of an advanced instrumented vehicle

Standard Deviation of Lateral Position (SDLP) – This measure is similar in nature to the above reflecting the degree of vehicular control a driver exerts in any particular driving situation and is allegedly related to the probability of running-off the road (see Vogel, 2003). This indicator is again mostly applicable to driving simulator or instrumented vehicle studies and is less suitable as an indicator of safety in static field measurement.

5.10 Safety-influencing factors

Before leaving the topic of safety indicators it is important to consider a number of other traffic parameters and processes that are known or assumed to have a direct influence on traffic safety measured by proximal indicators or accidents and accident outcomes. These ‘*safety-influencing factors*’ do not qualify as proximal indicators according to the definitions and criteria mentioned earlier. Many are also standard measures of traffic performance or effectiveness that are used for various types of traffic system analyses. A number of these also have well-documented relationships with accident frequency and outcome severity serving as predictor variables in traffic models. These safety-influencing factors include, amongst others, the following:

- Speed and speed variance
- Gap-acceptance in yielding situations
- Gaps/Headway between vehicles in traffic streams
- Traffic flow rates (including derived measures such as saturation, density, etc.)
- Frequency of red-light violations
- Relative frequencies of turning manoeuvres or numbers of vehicles in simultaneous conflicting streams at intersections
- Aspects related to roadway design and traffic regulation (e.g. possibility to make left-turn manoeuvres across oncoming streams of traffic)

5.10.1 Speed and speed variance

Measures of speed and speed variation and their relationship to accidents have received much attention in traffic safety literature. Speed has been cited as a significant contributing factor in more than 30 per cent of all fatal accidents and 12 per cent of all accidents in general (Bowie and Walz, 1994). An in-depth review of some 2000 vehicle crashes in the United States of America has implicated excessive speed for the roadway conditions as the second most frequent causal element out of a list of 50 different driver, vehicle and environmental factors (Treat *et.al.*, 1977). Similar findings have also been reported in other many countries (e.g. Munden, 1967; Salusjärvi, 1981; Nilsson, 1982; Kloeden *et.al.*, 1997; 2001).

It is often stated that speed is related to traffic safety in two particular ways. Firstly, higher vehicular speed gives the operator proportionately less time to react to a potential hazard in the roadway, and allows other road-users such as pedestrians less time to react. Secondly, the relationship of mass and speed to kinetic energy infers that the risk of fatality and serious injury increases with increasing speed. This is confirmed by the literature. According to Carlsson (1996) the risk for fatality for a pedestrian that is hit by a vehicle at 30 km/h is approximately 6 to 16 per cent, however if the speed of the vehicle is raised to 50 km/h the risk of fatality increases to between 40 and 85 per cent. Similar findings to these are reported by Joksch (1993) who suggests that the probability of fatality from an impact speed of 80 km/h is 15 times that of an impact speed of 40 km/h for a vehicle occupant.

In a recent report by Várhelyi, Hjalmdahl and Hagring (2003) concerned with speeds in critical situations, it is suggested as a rule of thumb, that each 1 km/h reduction in speed results in a reduction in the number of accidents involving injury by up to 3 per cent. There is also a substantial amount of literature concerning the effects of raising or lowering speed limits on the resulting numbers of accidents involving fatality and serious injury from many different countries (see e.g. Nilsson, 1990; Peltola, 1991; Finch, *et.al.*, 1994; Garber and Graham, 1990; Thulin, and Nilsson, 1994); Newstead and Mullen, 1996). Predictive models based on this relationship have been discussed earlier in Chapter 4.

The relationship between speed and traffic safety in terms of accidents and outcome severity has been a driving force behind work on speed adaptation devices. Recent trials in Sweden, Great Britain, Holland and several other countries with Intelligent Speed Adaptation (ISA) have shown positive trends with regard to traffic safety improvement (Várhelyi, 1996; Carsten and Comte, 2000; Jozwiak, 2000; SRA, 2002a).

A study by Spolander, Laurell, Nilsson, and Pettersson (1979) identified a large number of factors that were believed to influence the choice of speed in a given traffic situation. These factors included amongst others: weather and visibility, time of day, subjective risk assessment, risk of being caught and punished for speeding, evaluation of costs associated with travel, desired level of comfort, and personal characteristics such as experience and desired speed., Research has also shown that vehicle characteristics, roadway quality, posted speed, and prevailing traffic conditions all have a significant influence on speed choice (Haglund and Åberg, 1990).

Speed variation has also been found to have an important influence on accident risk. One of the pioneers in this field was the US researcher Solomon who quantified the relationship between speed and accident involvement after examining an extensive number of accident records and comparing these with speed measurements and interview data in the late 1950's (Solomon, 1964). In the now infamous U-shaped curve that described the relationship between the frequency of accidents and speed, actual accident rates were found to be lowest where these were closest to the mean and increased with greater deviation above and below the mean. Since the early work of Solomon, there has been some debate with regard to the effect lower than average speeds have on accident risk.

Frith and Patterson (2002) have since demonstrated that the findings of Solomon were most probably due to factor related to the way in which speeds and accidents were measured. Nevertheless, there are other studies that suggest the effect increased speed variance has on accident risk (see e.g. Garber and Gadiraju, 1988; Evans, 1991).

5.10.2 Gap-acceptance

The gap-acceptance behaviour of road-users on yielding is undoubtedly one of the most important determinants of traffic safety at intersections. A great deal of research has been conducted in this area and there appear to be many different approaches to the scientific investigation and modelling of such behaviour (see e.g. Darzentas *et.al.*, 1980; Adebesei and Sama, 1989; Abou-Henaidy, Temply, and Hunt, 1994; Hagring, 1998; Brilon *et.al.*, 1999; Pollatschek, Polus and Livneh, 2002).

Many statistical models for the calculation of capacity at unsignalised intersections assume the use of an average ‘critical gap’ to describe the process of yielding from secondary roads. This assumption implies that gaps or lags in the priority stream of traffic are accepted if they are greater than the ‘critical gap’ value. The critical time-gap value is usually defined statistically at the intersection point between frequency distributions representing the probability of accepting and rejecting time-gaps of differing sizes (see e.g. Drew, 1968). Other statistical methods include the use of Maximum Likelihood to determine the probability that a distribution of empirically observed critical gaps falls between established distributions of accepted and highest-rejected gaps (see e.g. Brilon *et.al.*, 1999; Hagrings, 1998).

Pollatschek and colleagues (2002) suggest that the behaviour of drivers, such as gap-acceptance behaviour, is not homogenous or consistent over time, and also that different levels of driver-risk in the acceptance of gaps are an important factor in determining intersection capacity. This has also been suggested by Ashworth (1968) who found that replacing the average critical gap with a distribution of critical gaps resulted in a large reduction in intersection capacity. The modelling approach used by Pollatschek and colleagues is unique as a microscopic decision model. It is based on a risk-reward loop process that suggests entry into a priority traffic stream occurs when the perceived benefit is greater than the associated risk. Arguably, this type of approach is more representative of real-world situations and could be usefully applied in dynamic modelling related to safety assessment.

Other research in this area has shown that many drivers experience difficulty estimating the speed of oncoming vehicles in the gap-acceptance process (Parsonson, Isler and Hansson, 1996). A Canadian study by Abou-Henaidy and colleagues (1994), found a number of factors that influenced the gap-acceptance process including: age, gender, the existence of passengers in the vehicle, and time spent waiting at the head of a queue. An interesting finding with regard to waiting time, was that the probability of accepting a gap during the first 30 seconds actually declined and only began increased after this period. Abou-Henaidy and colleagues (1994) also found that higher speed on a primary road caused shorter gaps to be accepted.

The probability of accepting a smaller gap was also found to increase in accordance with increasing traffic flow and the type (and size) of the vehicles in the primary traffic stream. Other research has also pointed to the effect of sight-distance on the gap-acceptance process and the geometric design of the intersection (e.g. Strömngren, 2002, Darzentas *et.al.*, 1980).

The subject of gap-acceptance is too extensive and diverse to be described in any detail in this thesis. Furthermore, the literature suggested here is mostly related to traffic performance issues and modelling approaches that are less concerned with traffic safety. There is a distinct need for future research that looks at road-user behaviour in gap-acceptance situations from a traffic safety modelling perspective.

5.10.3 Red-light violations

Red-light violations are often reported to be one of the main causes of accidents at signalised intersections. Safety statistics from the United States for year 2000 suggest that as many as 106 000 vehicle accidents, 89 000 injuries and 1036 deaths can be attributed to red-light violations (FHWA, 2004). This particular type of safety deviant behaviour is often the result of driver impatience, poor speed adaptation, and lack of judgement. It has, however, also been correlated with personality traits such as thrill-seeking (Porter and Berry, 1999).

The use of red-light cameras has been found to be an effective deterrent in many countries, including: the United States of America, the Netherlands, Great Britain and Australia. Studies from these countries indicate that red-light cameras reduce the number of violations by up to 55-60 per cent, and the number of accidents by up to 25-30 per cent (see e.g. Andreassen, 1995; FHWA, 1999).

5.10.4 Traffic flow, composition, turning movements, and traffic regulation

The relationship between traffic volume on primary and secondary roads and safety has been described previously in relation to predictive modelling (see Chapter 4). Elevated traffic volumes are known to increase the accident risk, mainly by increasing levels of exposure and by placing higher demands on road-user interaction at different types of intersection. The relationship between traffic-flow and safety is not always as uncomplicated as might be expected. This was pointed out by Ekman (1996), who found complex safety effects in relation to the interaction of vehicles and vulnerable road-users.

Different forms of traffic regulation have also been shown to have safety related effects, where it is generally found that more restrictive forms of regulation result in fewer accidents (Elvik, Mysen and Vaa, 1997; SRA,2001). According to Scandinavian literature, the introduction of a two-way stop could reduce the number of traffic accidents involving injury by 25 per cent, and the introduction of signals could give a reduction of 15 per cent (Englund *et.al.*, 1998). This research suggests that allowing simultaneous or conflicting streams of traffic at intersections often increases the number of accidents by increasing exposure and the need for road-user interaction. The statistics related to the many type of accidents occurring at intersections were presented earlier in Chapter 2.

Traffic composition also has the potential to influence safety, although there is little mention of such effects in the literature. An increase in the relative number of heavy goods vehicles can be hypothesised to have an influence on the amount of variation in average speed therefore causing greater friction and higher accident risk (see e.g. Garber and Gadiraju, 1988; Evans, 1991). Composition factors are also used to reflect different penetration levels in relation to various ITS devices such as Intelligent Speed Adaptation (ISA). A report by Archer and Åberg (2001) proposes that different levels of ISA-penetration may have a negative impact on safety due to greater levels of speed variance along with other adaptive behaviours such as driving faster through intersections. There is currently a large international research project (PROSPER) that is part of the European Union 6th framework program that uses of traffic simulation to estimate the traffic safety and performance effects related to the use of ISA.

There are also a great many aspects related to roadway design that are known to have an great impact on safety. The safety influence in relation to many measures such as: adding extra lanes or specific turning lanes, better lighting, changing three or four-way intersections to roundabouts, adding special signalling functions to reduce both dilemma zone problems and red-light violations have been documented in the ‘*effect-relationship*’ report series and knowledge base in Sweden and other related literature (see e.g. SRA, 2001, Englund *et.al.*, 1997). Other documented guidelines also exist for studies exist (e.g. the Swedish ‘*TRAST*’ manual for developing safer and more accessible city streets for all types of road-user). Developing and evaluating these, and other solutions, is the domain of the transport planner and traffic engineer. A more detailed account of all different safety-influencing factors related to the roadway is outside the scope of this thesis.

Case study 1:

6. The traffic conflict technique as a method for assessing and predicting safety at signalised intersections on a major city street

Summary

This study represents a practical application of the Traffic Conflict Technique at several signalised intersections along a busy city street in Stockholm. The safety study was part of an initial inventory phase of a project entitled: “*Hornsgatan – Demonstration project for the development of a safe city street*” (own translation). This demonstration project has been initiated by the Stockholm City Real Estate and Traffic Administration (Swedish: ‘*Stockholm stads Gatu- och Fastighetskontor*’, abbreviated ‘*GFK*’), and is concerned with the improvement of traffic safety and accessibility on major city streets for all road-user categories, using traditional and innovative traffic planning and design measures*. Work on this project is also co-ordinated with the Swedish Road Authority (SRA). The main results of the initial inventory, including the safety study on which this chapter is based, have been published in a report by the Stockholm City Real Estate and Traffic Administration (GFK, 2004).

For the purposes of this thesis, the main results of the conflict study are discussed from a scientific perspective in relation to important issues concerning the usefulness of the Traffic Conflict Technique for safety assessment, and various aspects related to validity (predictive validity and process validity) and measurement reliability.

6.1 Background of the Hornsgatan-demonstration project

Traffic safety and accessibility are important and often conflicting objectives with regard to the city street environment. In the past, the needs and demands of vehicle traffic have been prioritised to a far greater extent than those of pedestrians and cyclists. This is reflected in the design of the roadway and the way in which vehicle and vulnerable road-user traffic is regulated at intersections and pedestrian crossings. Research has shown, for example, that badly adapted traffic signals have the potential to increase the risk for accidents rather than providing a safety benefit (SRA, 2004). Similarly, overly complicated traffic intersection design and badly adapted speeds are known to have an undesirable safety impact, particularly for vulnerable road-users (see e.g. Englund *et.al.*, 1997). The lack of integration between and among all types of road-user in this complex and intense environment is reflected in the accident statistics, which indicate an unacceptably high numbers of injuries. Particular safety problems can be identified at intersections, often involving involve pedestrians and cyclists.

* The work presented here in conjunction with the Hornsgatan project, has been carried out at SWECO VBB, under the leadership of Patrik Wirsenius. Important contributions to the conflict observation study were made by Malin Rosén and Jessica Fellers. Archer, Rosén and Fellers co-authored the conflict study chapter of the inventory phase report published by Stockholm City Real Estate and Traffic Administration (GFK, 2004)

A problem faced by transport planners and traffic engineers, concerns the identification of effective traffic safety and accessibility solutions that are equally representative of the needs and demands of all road-users categories. Specifically for this purpose, a demonstration project has been initiated by the Stockholm City Real Estate and Traffic Administration (GFK) in close co-operation with the Swedish Road Authority (SRA). This project is based on an existing major arterial city street in Stockholm with high vehicle and vulnerable road-user volumes. The aim of this project is to identify and integrate new and alternative solutions that serve to promote safety and accessibility in this type of environment, bearing in mind the need for sustainable city development and the guidelines, principles and goals stated in the local Traffic Safety Program TSP-2000 (GFK, 2001) and the Swedish 'Zero Vision' (requiring that the traffic system is developed to meet the needs and limitations of all road-users, see Appendix 1). As a demonstration project, it is hoped that the solutions that are suggested and implemented will serve as an example for other city streets, both in Stockholm and elsewhere.

6.2 Hornsgatan

The city street chosen by for the purposes of this project was Hornsgatan, a typical city street that serves as an arterial road and shopping area with high volumes of vehicle traffic, and large numbers of cyclists and pedestrians. The street is described by GFK as having a robust structure that will tolerate smaller changes to the roadway environment without imposing on the overall quality. For descriptive purposes, the street can also be divided into an Eastern and Western section. The Western section has fewer shops and a higher volume of traffic, while the Eastern section has more shops and a higher proportion of unprotected road-users.

The posted speed along Hornsgatan is 50 km/h. Spot speed measurements in conjunction with this project at all pedestrian crossings indicated average speed of between 30-35 km/h throughout daytime hours. The 85th percentiles were well below the posted limit at all measurement locations along the eastern section. Most intersections along Hornsgatan are regulated by traffic signals due to the large traffic volumes and the needs of pedestrians to cross the road. The traffic volume levels (estimated AADTs) along Hornsgatan are illustrated below in Figure 6.1 for the Eastern section (the main conflict study area).



Figure 6.1 Average daily traffic flow along the eastern section of Hornsgatan

Average daily traffic volumes on the Eastern section of Hornsgatan vary between 19,000-26,000 vehicles per day. Traffic flow counts suggest that peak flows occur between 17:00-18:00 p.m. although high flow rates (corresponding to approximately 70 per cent of the peak, or higher) are found during most daytime hours.

There are large numbers of pedestrians crossing Hornsgatan and intersecting side-roads. Pedestrian counts at the crossings along Hornsgatan show figures in excess of 500 people per hour during peak periods. All pedestrian crossings except two are regulated by traffic signals. GFK estimate that as many as 28,000 pedestrians cross the entire length of Hornsgatan during the peak time-periods (07:00-09:00 a.m., 12:00-14:00 p.m. and 16:00-18:00 p.m.) The total volume along the entire length of Hornsgatan is estimated to exceed 80,000 people. For cyclists, there are physically separated cycle-paths along the Western section, and a smaller part of the Eastern section. Where separated cycle-paths do not exist, cycle-lanes are marked on the main roadway. Cycle counts indicate flows of approximately 1,200-3,400 cyclists per day, with a majority in the Eastern section. The volume of cycle traffic is prone to seasonal variation with considerably less cycle traffic during winter months.

Accident statistics for Hornsgatan, for the six-year period between 1997-2002, show a total of 164 police reported accidents. These resulted in 41 serious injuries, 170 minor injuries and no fatalities. This suggests an average of approximately 35 minor injuries and 7 serious injuries per year. It is important to note that more than two-thirds of the traffic accidents for this period occurred in the Eastern section, the vast majority at intersections.

The accident statistics also indicate that the majority of injury related accidents occurred during the main afternoon peak hours (between 16:00 to 19:00 p.m.) when traffic volumes were at their highest (see Figure 6.2a). This suggests that the conflict studies should be conducted from approximately 07.00 a.m. to 19:00 p.m., and that there is a significant elevation in the number of accidents in the three hours before midnight. A closer look at the monthly variation in accidents also indicates that there is a peak in June during the warmest part of the year and immediately prior to the main holiday season (see Figure 6.2b). The monthly data also indicates that accidents are quite common in October, the time when the conflict studies described in this report were carried out.

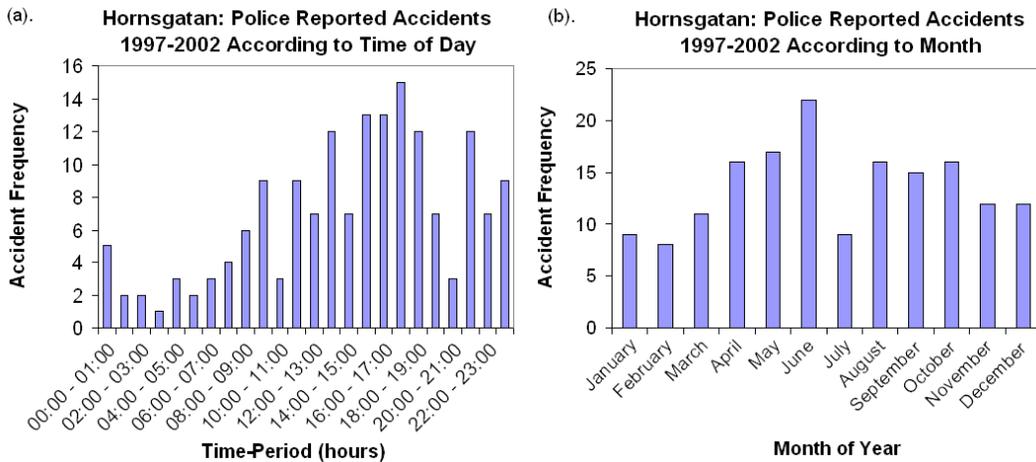


Figure 6.2(a,b) Police reported accidents 1997-2002 according to time of day (a) and month of year (b)

The most common types of traffic accident that occur on Hornsgatan involve interaction between two private vehicles, or between private vehicles and pedestrians or cyclists (see Figure 6.3 below). Accidents involving pedestrians and cyclists account for approximately one-third of the total number, although the total proportion of serious injuries is significantly higher for these two classes of road-users (in excess of 50 per cent). The most common types of vehicle accidents include: rear-end collisions, accidents involving left-turn manoeuvres (i.e. across opposing streams of traffic), and single vehicle accidents.

Hornsgatan: Injuries in Police Reported Accidents 1997-2002 According to Road-User Category and Accident Outcome Severity

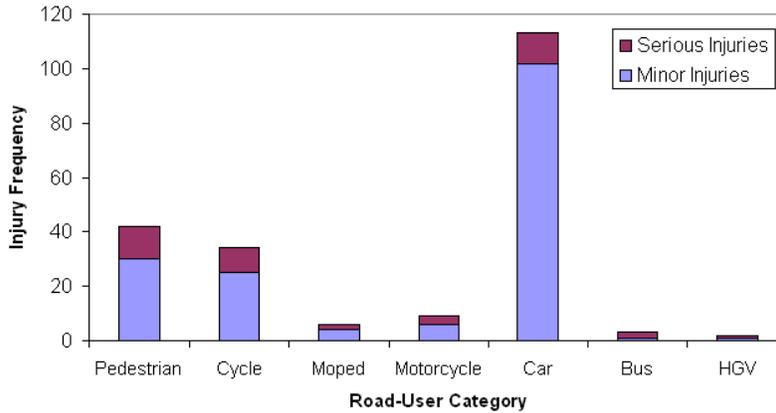


Figure 6.3 Police reported accidents 1997-2002 according to road-user category and accident outcome severity

The location of accidents shown in accordance with road-user category and accident outcome severity for the eastern section is shown below in Figure 6.4. A clear tendency for accidents to occur in and around intersections can be observed in this figure.

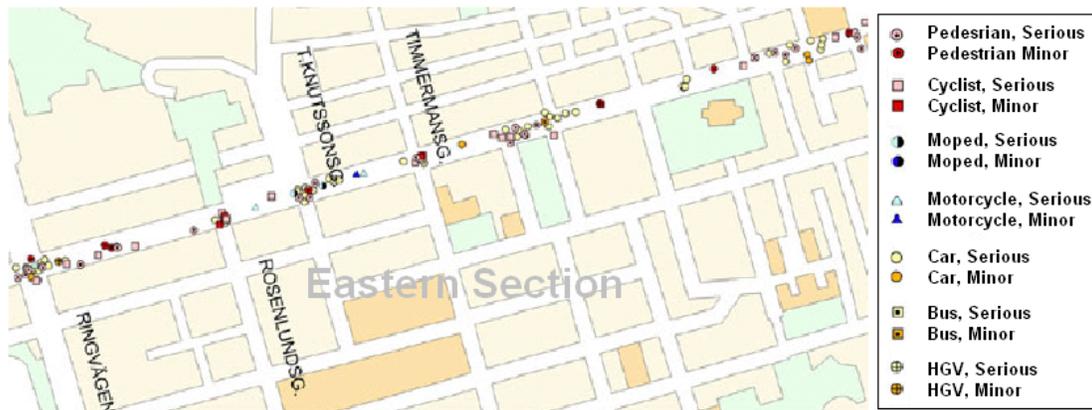


Figure 6.4 Location of police reported accidents in the eastern section of Hornsgatan 1997-2002 according to road-user category and accident outcome severity

6.3 Objectives of this study

This study focuses on the application and use of the Traffic Conflict Technique as a method for short-term safety assessment and comparison at four intersections along the Eastern Section of Hornsgatan. The original conflict study on which this chapter is based was conducted during the autumn of 2003 as part of an initial safety inventory in the Hornsgatan project. A follow-up study is planned in 2006 after the major redevelopment work has been completed, and will enable a before-and-after comparison.

The conflict data provides a useful opportunity to perform a comparison of conflict and accident data among the four intersections, and to identify important factors that influence the relationship between conflicts and accidents in light of the earlier work of Hydén (1987) discussed in Chapter 5. The extent of the conflict study is not sufficient to conduct an in-depth investigation of the predictive ability of the Traffic Conflict Technique, however, it is expected that the numbers of conflicts and accidents should follow a similar order across the studied intersections.

The predictive ability of the CD-Base program is also reviewed in relation to the estimates of the expected number of accidents based on accident data at each intersection. Furthermore, the predictive ability of the traffic flow-based models based on traffic conflict frequency, proposed by Spicer and Colleagues (1979) and Salman and Al-Miata (1995) are considered. Given the limited set of data, it is expected to find an appropriate rank-order for the intersections with regard to estimated conflict frequency in comparison to observed frequency levels.

Lastly, the issue of measurement reliability will be addressed with regard to the Traffic Conflict Technique. Given that the data set is relatively limited, consisting of only four intersections and three observers with equal numbers of hours of observation at each, the comparison of inter-observer reliability is restricted to a contingency test that is expected to show a significantly similar order among observers with regard to conflict frequency.

6.4 Method

A review of the accident data revealed four intersections along Hornsgatan with a comparatively poor safety record. The location of these sites, and the occurrence of police reported accidents involving serious or minor injuries, is shown below in Figure 6.5.

Three trained and experienced conflict observers participated in this study. A rotation scheme was designed whereby each observer spent one observation day, consisting of three two-hour periods of observation between the hours of 07:00 a.m. and 19:00 p.m., at each of the four sites. This was intended to minimise inter-observer bias in the comparison between intersections. This resulted in a total period of 18 hours of conflict observation at each sites. The time-periods for observation studies at each site were varied from day-to-day in order to include both morning and afternoon peak periods. The observation studies were all carried out during mid-week (i.e. Tuesday to Thursday) to avoid known irregularities in traffic volumes on Mondays and Fridays. Prior to conflict observation, observer-accuracy in relation to speed and distance judgement was tested using a calibrated speed-radar device. All conflicts were recorded on video-film to allow post-analysis and the verification of speed and distances.

Other safety relevant observations were also noted at each site, including: red-light violations, problems with parked vehicles, illegal turning manoeuvres, or other safety relevant events. During the observation period, there was a great deal of variation in weather with temperatures ranging between 12-17 degrees Celsius and sunny, overcast, wet and dry periods.

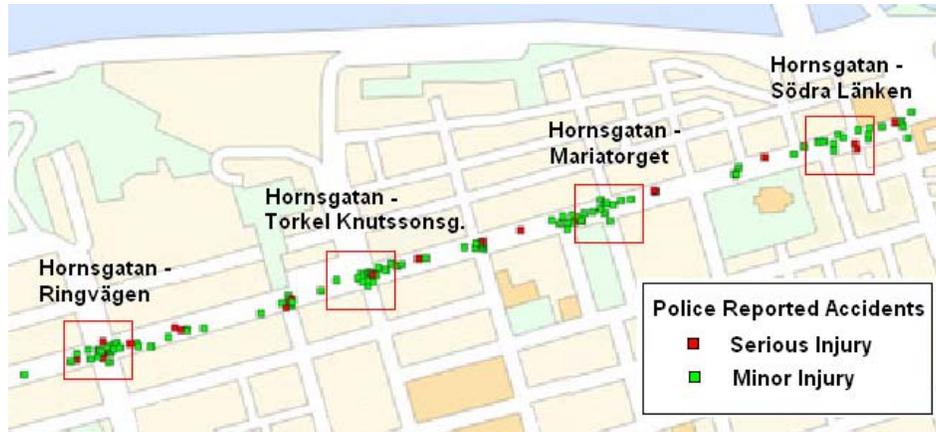


Figure 6.5 Location of conflict observation sites on Hornsgatan and incidence of accidents involving serious or minor injury

Aerial photographs indicating the layout of the four intersections are also shown below in Figure 6.6(a-d).



Figure 6.6(a-d) The intersections on Hornsgatan at which conflict observation was carried out, (a) Hornsgatan-Ringvägen; (b) Hornsgatan-Torkel Knutssonsgatan; (c) Hornsgatan-Mariatorget; (d) Hornsgatan-Söderledstunnel

The flow rates for vehicles (AADTs), and pedestrian and cycle volumes measured during the peak time-periods (07:00-09:00 a.m., 12:00-14:00 p.m. and 16:00-18:00 p.m.) are shown below in Table 6.1. Unfortunately, no information is available in relation to the pedestrian crossing flows or cyclists on the northern and southern approaches at the intersections.

Table 6.1 Vehicle AADT estimates, pedestrian and cyclist flows on the Eastern section of Hornsgatan

Intersection	Direction	Vehicles (AADT)	Pedestrians ¹	Cyclists ²
Hornsgatan - Ringvägen	East - West*	36,000 - 22,000	2,480 - 2,500	470 - 470
	North - South	8,000 - 20,000	----	----
Hornsgatan - Torkel Knutssonsgatan	East - West*	26,000 - 21,000	2,090 - 3,960	470 - 890
	North - South	12,000 - 5,500	----	----
Hornsgatan - Mariatorget	East - West*	20,000 - 19,000	2,600	890 - 1,360
	North - South	1,400 - 2,000	----	----
Hornsgatan - Söderledstunneln	East - West*	19,000 - 21,000	2,260	1,360 - 1,360
	Entry - Exit	8,000 - 13,000	----	----

* = East-West direction represents Hornsgatan; 1, 2 = Measured during 6 hours of peak traffic on Hornsgatan

6.4 Conflict observation results

Results from the 18 hours of conflict observation for each intersection are shown below in Figure 6.7(a-d) in standard conflict diagrams (Time-to-Accident plotted against speed).

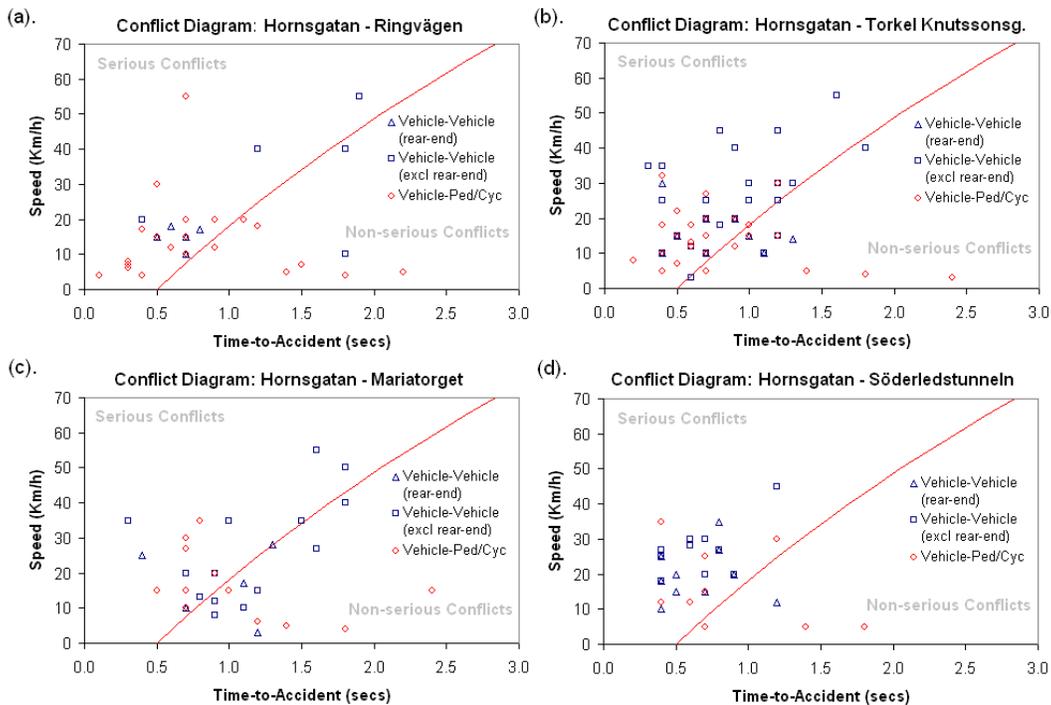


Figure 6.7(a-d) Conflict diagrams for each of the intersections, (a) Hornsgatan-Ringvägen; (b) Hornsgatan-Torkel Knutssonsgatan; (c) Hornsgatan-Mariatorget; (d) Hornsgatan-Söderledstunneln

The locations of each conflict and types of road-users involved are shown below in Figure 6.8(a-d) for each of the four junctions.

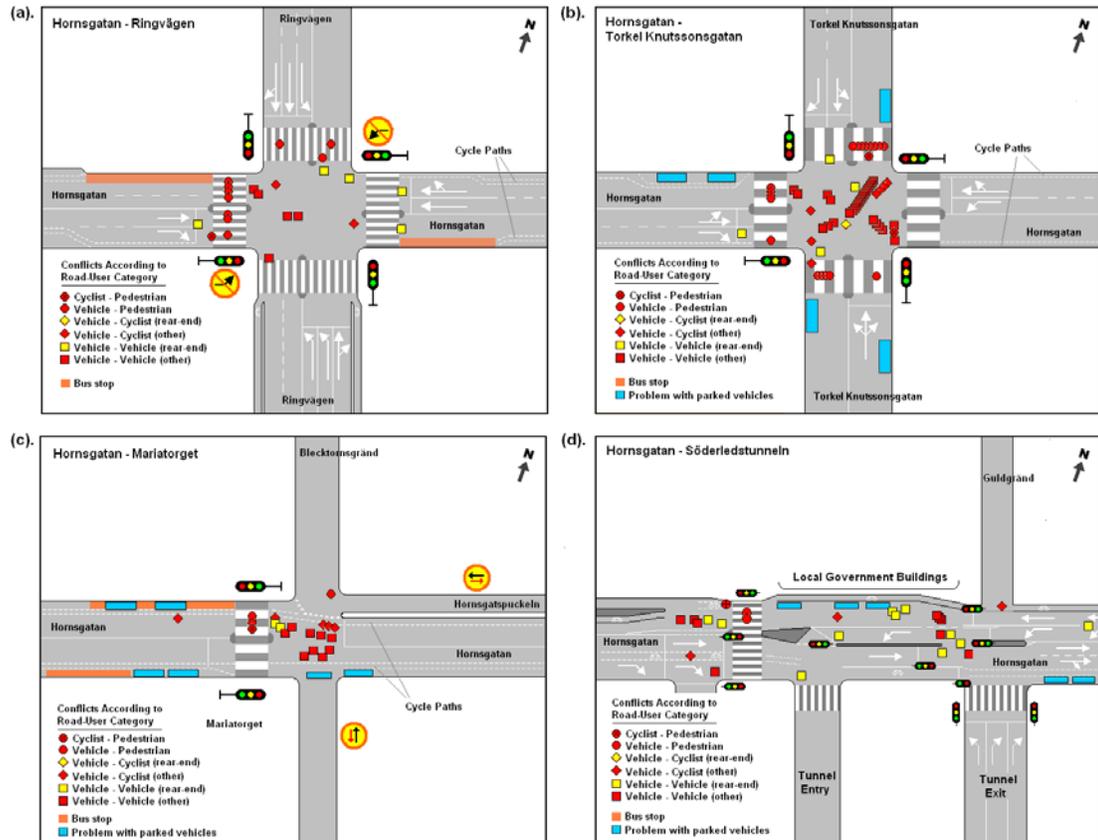


Figure 6.8(a-d) Conflict location and road-user type diagrams for each of the intersections, (a) Hornsgatan-Ringvägen; (b) Hornsgatan-Torkel Knutssonsgatan; (c) Hornsgatan-Mariatorget; (d) Hornsgatan-Söderledstunnel

At the four-way signalised Hornsgatan-Ringvägen intersection, there were a total of 25 serious and nine non-serious conflicts. The serious conflicts included 15 incidents with vulnerable road-users, five vehicle-vehicle rear-end conflicts and five vehicle-vehicle conflicts between vehicles with different trajectories. A number of conflicts were also reported as a direct result of forbidden left-turn movements from each Hornsgatan approach into Ringvägen. Other conflicts occurred during the afternoon peak hours when the intersection failed to clear between signal cycles. The conflict diagram indicates the generally low speed involved in most conflicts, with the majority under 20 km/h. A number of pedestrian conflicts were also caused by wrongly anticipating signal phases (particularly a phase that allowed right-turns from eastbound vehicles on Hornsgatan into Ringvägen). This intersection also had the highest traffic volume of the four studied.

The Hornsgatan-Torkel-Knutssonsgatan intersection is also a relatively standard four-way intersection. At this site a total of 57 serious, and 30 non-serious conflicts were observed a figure more than twice that of the previous intersection. Vulnerable road-users were involved in 26 of the serious conflicts. Furthermore, there were six vehicle-vehicle rear-end conflicts, and 25 vehicle-vehicle conflicts between vehicles with different trajectories.

Conflicts involving vulnerable road-users at the Hornsgatan-Torkel-Knutssonsgatan intersection were predominant as they were for Hornsgatan-Ringvägen. Many of the 18 conflicts involving vehicles and pedestrians were the result of pedestrians crossing on red. Seven vehicle-cyclist and two serious cyclist-pedestrian conflicts were also recorded.

A particular problem at the Hornsgatan-Torkel-Knutssonsgatan intersection was found to be left-turning vehicles from Hornsgatan in the eastbound direction into Torkel Knutssonsgatan. This resulted in a large number of serious conflicts with other vehicles from the opposite Hornsgatan direction, and pedestrians on the Torkel-Knutssonsgatan crossing immediately north of the intersection. This was largely due to the combined vehicle and pedestrian signal phase, and the lack of space between this crossing, and mainline Hornsgatan traffic. In many cases, vehicles that braked for pedestrians were found to be in conflict with oncoming westbound vehicles on Hornsgatan.

A major difference between this intersection, and the Hornsgatan-Ringvägen intersection discussed above, concerns signal regulation and the fact that simultaneous left-turn manoeuvres were allowed from opposing directions of traffic. The level of accident risk appeared to be exaggerated further by the relatively small size of this intersection, which limited visibility and increased situational complexity during periods of intense traffic. As for Hornsgatan-Ringvägen there were a large number of pedestrians that crossed on red, and a number of cyclists that ignored the traffic signals.

The Hornsgatan-Mariatorget intersection is notably different to the two previously discussed. The studied area is that to the left of the pedestrian crossing in Figure 6.6(c). Traffic movements at this intersection are largely regulated by the activation of the signalised pedestrian crossing on the eastbound approach to the junction. The stop line for vehicles travelling in a westbound direction on Hornsgatan is placed 25 metres upstream, thereby allowing vehicles to enter from the two adjoining roads. Sight is also restricted for vehicles turning out from the northern arm of the intersection into Hornsgatan.

A total of 20 serious and 15 non-serious conflicts were observed at the Hornsgatan-Mariatorget intersection. Nine of the serious conflicts involved vulnerable road-users, five of these between vehicles and cyclists. This is believed to reflect the unusual intersection design at this location, where the cycle path rejoins the main roadway in the westbound direction and cuts diagonally in front of the adjoined side road. Most of the more serious vehicle-vehicle conflicts were the result of left-turn manoeuvres from the smaller secondary approach roads. A particularly serious conflict was noted for a motorcycle turning right from the northbound (Mariatorget) approach into the westbound stream of traffic on Hornsgatan. The lack of turning opportunities for vehicles along Hornsgatan was also reflected by the number of vehicles performing U-turns at this intersection, which led to several serious conflicts.

A major safety problem at the Hornsgatan-Mariatorget intersection was found to be the number of vehicle red-light violations at the pedestrian crossing. This was particularly evident in the westbound direction where nearly 80 cases were recorded during 12 hours of observation. This is most probably due to the distance between the stop line and the pedestrian crossing. Interestingly, the number of pedestrian red-light violations was found to be lower than at many other pedestrian crossings along Hornsgatan, perhaps as a result of the imminent danger caused by red-light driving. A further problem regarding red-light violation was found for cyclists, who frequently ignored the pedestrian crossing signal.

The Hornsgatan-Söderledstunnel intersection is perhaps the most complex of the four studied. This is due to the fact that the major arterial tunnel (Söderleden) can only be accessed from one side of Hornsgatan. A total of 25 serious and four non-serious conflicts were observed at this intersection. Six of the serious conflicts involved vulnerable road-users. Two of these were the result of pedestrians going against red. More than half of the vehicle-vehicle conflicts were rear-end events (11) often as a result of vehicles stopping in front of the local government offices after having left the tunnel exit. The remaining eight conflicts were between vehicles with different trajectories, a number of these were the result of the relatively short safety time between signal phases, which caused conflicts between eastbound Hornsgatan traffic and vehicles exiting the tunnel on amber (or red). Only a few red-light violations were actually observed, although there were many suspected cases for vehicles exiting the tunnel. There were also relatively few pedestrian and cycle red-light passages recorded at this intersection.

A number of unusual and dangerous manoeuvres were also recorded at this intersection including U-turns from the eastbound to westbound direction, and vehicles driving directly from the tunnel into the small access road directly opposite.

6.5 Police reported accident data

The STRADA database was used to obtain information regarding the details of each accident, including: the type of accident (e.g. rear-end, crossing, turning, single), the number of people injured, the exact location of the accident in X,Y, and Z co-ordinates, and a short description of the event. Unfortunately, many of the accident types were unspecified, and the descriptions were often extremely brief making more precise classification difficult. The accidents occurring at each intersection during the six-year period between 1997-2002 are described briefly below.

At the Hornsgatan-Ringvägen intersection, 25 police reported accidents have been recorded. These accidents resulted in 30 minor injuries and four serious injuries. Only one accident involving a vulnerable road-user was classed as serious. Vulnerable road-users were otherwise involved in nine of the accidents. For the 16 accidents involving only vehicles, eight were classed as rear-end. A further four were result of left-turning manoeuvres, and two were recorded for vehicles on crossing trajectories. Two of the remaining accidents were the result of illegal manoeuvres.

Similarly, the Hornsgatan-Torkel-Knutssonsgatan intersection showed 14 police reported accidents resulting in 17 injuries (one serious, and 16 minor). Vulnerable road-users were involved in seven accidents (one moped). For the accidents involving vehicles, one was classed as rear-end, four others were recorded as being the result of left-turn manoeuvres, and one further accident occurred between vehicles on crossing trajectories. The remaining accident appears to be the result of an overtaking manoeuvre in the intersection.

For Hornsgatan-Mariatorget, 12 police reported accidents and a similar number of injuries have been recorded. Only one of the injuries (as the result of a rear-end accident) was classed as serious. Vulnerable road-users were involved in three accidents. The vehicle-vehicle accidents included six rear-end collisions, and two turning manoeuvres (one left-turn, and one right-turn). One further accident was the result of an incident with a parked vehicle.

For the fourth intersection, Hornsgatan-Söderledstunnel, the database revealed 18 police reported accidents. These accidents resulted in 25 injuries (three serious, and 22 minor). One of the serious injuries involved a pedestrian, the other two were the result of a single vehicle accident and a rear-end accident. Vulnerable road-users were involved in eight of the 18 accidents. The remaining 10 cases include five rear-end events, and four single vehicle accidents. One further accident is reported only as a “collision between two vehicles”. The positioning of this incident suggests that that it is the result of conflict between a left-turning vehicle from the tunnel exit and a vehicle in the westbound Hornsgatan traffic stream.

6.6 Comparison of conflict data and police reported accident data

In order to make a quantitative and qualitative comparison between the conflict observation data and police reported accident data for each of the four intersections studied, the conflicts and accidents were divided into three main categories: vehicle-vehicle rear-end; vehicle-vehicle other; and vehicle-vulnerable road-user. This comparison is shown below in Table 6.2 for each of the four intersections.

Table 6.2 Comparison of serious conflicts (18 hours observation per site) and police report accidents (period 1997-2002) at each intersection in accordance with conflict/ accident type

		Conflict / Accident Event Type			Total
		Vehicle– Vehicle (Rear-End)	Vehicle– Vehicle (Other)	Vehicle– Vulnerable Road-Users	
Hornsgatan - Ringvägen	Conflicts* (18hours Obs)	7	3	15	25
	Accidents** (6 years)	8	8	9	25
Hornsgatan – Torkel Knutssonsgatan	Conflicts* (18hours Obs)	6	25	26	57
	Accidents** (6 years)	1	6	7	14
Hornsgatan - Mariatorget	Conflicts* (18hours Obs)	2	9	9	20
	Accidents** (6 years)	6	3	3	12
Hornsgatan – Söderledstunnel	Conflicts* (18hours Obs)	9	10	6	25
	Accidents** (6 years)	5	5	8	18
Total	Conflicts* (18hours Obs)	24	47	56	127
	Accidents** (6 years)	20	22	27	69

* = Serious conflicts only; ** = Only Police Reported Accidents

In theory, the accident data should be corrected to include only those events that occurred during the conflict observation period (07:00 a.m.-19:00 p.m.), and perhaps also other factors for strict comparison purposes. The accident database does indicate that approximately 10 per cent of all accidents occurred during evening and early morning hours for the intersections in question (see Figure 6.2(a)). Furthermore, to be strictly comparable the estimated (or expected) number of conflicts and the expected number of accidents, based on the variance in the two data sets, should be used (see Chapter 4, Section 4.2, Equations 4.4 to 4.8). As an initial assessment, however, the numbers of police reported accidents over the six-year period between 1997-2002, and serious conflict frequencies based on 18 hours of observation at each intersection are directly compared (bearing in mind the levels of variance in the data).

The data shown in Table 6.2 indicates a number of interesting differences in the accident and conflict data for each intersection. An initial observation is that the total numbers of conflicts and accidents show a similar ratio for vehicle-vehicle(other) and vehicle-vulnerable road-user event types (approximately 2:1), while the ratio for the vehicle-vehicle(rear-end) event type is more even. This dissimilarity may reflect difficulties in identifying and recording rear-end events for the conflict observer. Among each intersection individually, there appears to be dissimilar patterns for the frequencies of conflicts and accidents according to event type. The only exception appears to be the Hornsgatan-Torkel Knutssonsgatan intersection, where there is good correlation.

Interestingly, vehicle-vulnerable road-user events are the most frequent of the three event types for three of the four intersections with regard to serious conflicts (the exception being Hornsgatan-Söderledstunnel), and for the accidents although here the exception is the Hornsgatan-Mariatorget intersection. Generally, the serious conflict data also identifies vehicle-vehicle(other) events as more common than vehicle-vehicle(rear-end) with the exception of the Hornsgatan-Ringvägen intersection, while the accident data shows a slightly different picture where vehicle-vehicle(rear-end) events are greater than or equal to vehicle-vehicle(other) events in all cases but the Hornsgatan-Torkel Knutssonsgatan intersection. Again, that can be taken as indicative of the problems related to identifying rear-end conflict events for an observer in the field.

A further comparison can be made in relation to the total accident and conflict frequencies for each intersection regardless of event type. This comparison reveals large differences in the relative proportions of accident and conflicts among the intersections. Most interesting is the relatively large number of serious conflicts at the Hornsgatan-Torkel Knutssonsgatan intersection and the relatively low number of accidents. This data indicates a ratio of approximately 4:1 for conflicts and accidents, which is in direct contrast to the Hornsgatan-Ringvägen intersection where the corresponding ratio is 1:1. The Hornsgatan-Torkel Knutssonsgatan intersection appears to have slightly more than twice the number of conflicts and slightly more than half the number of accidents, in comparison to the Hornsgatan-Ringvägen intersection. This finding suggests that the relationship between accidents and conflict is subject to other influences, such as the form of traffic regulation (and whether or not simultaneous left turn manoeuvres are allowed from opposing directions) and perhaps factors related to traffic flow and speed.

Among the vehicle-vehicle(other) category, turning accidents (particularly left-turning manoeuvres) were well represented both in the accidents and serious conflict data for all but the Hornsgatan-Söderledstunnel intersection. The same is also true for crossing accidents (i.e. accidents involving vehicles with different trajectories). Turning and crossing accidents amounted to approximately one-third of the total number for all but the Hornsgatan-Söderledstunnel intersection. The serious conflict data suggested a similar proportion for the Hornsgatan-Ringvägen intersection, but a ratio of slightly more than 50 per cent for the Hornsgatan-Torkel Knutssongatan and Hornsgatan-Mariatorget intersections. Turning and crossing serious were found for the Hornsgatan-Söderledstunnel intersection, amounting to approximately 40 per cent of the total number.

The numbers of serious conflicts involving pedestrians and cyclists appear to follow a trend that varies in approximate accordance with the numbers of pedestrians crossing at each of the intersections on Hornsgatan, with greater numbers found for the Hornsgatan-Torkel Knutssongatan intersection, closely followed by Hornsgatan-Ringvägen. For the accident data, this trend is less obvious with relatively similar numbers of accidents at all but the Hornsgatan-Mariatorget intersection (which shows a much lower accident rate by comparison). For cyclists, the flow rates are highest toward the eastern end of the street (from the Hornsgatan-Söderledstunneln intersection to Hornsgatan-Torkel Knutssongatan), this also appears to be reflected in the serious conflict data and to a lesser extent in the accident data, although the actual numbers are too low to draw any solid conclusions.

The relationship between the estimated number of serious conflicts per year and the expected number of accidents for each intersection are shown below in Figure 6.9. These figures are shown with 95 per cent ($1 - \alpha = 0.05$) prediction intervals, calculated in accordance with the Poisson assumption and principles used in Equations 4a and 4b (see Chapter 4, Section 4.2). The average yearly serious conflict frequency is based on a total of 300 days per year, where the data from 12 hours of conflict recording is taken as representative for one day between the time-period 07:00 a.m to 19:00 p.m. Accidents that were known to have occurred outside this time-period have been eliminated from the accident data for this calculation.

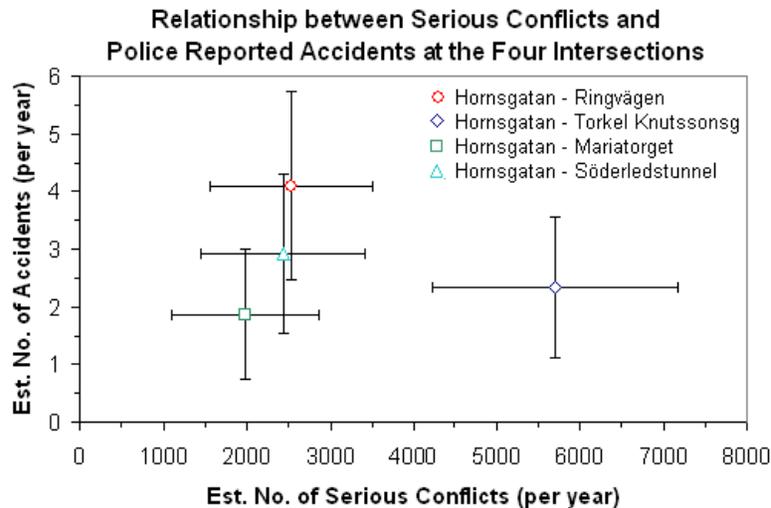


Figure 6.9 The relationship between the estimated numbers of serious conflicts and accidents per year shown with 95 per cent level of confidence (prediction) based on the Poisson assumption

While the level of variation is understandably high (given that the estimates of traffic conflicts are based on only one sample), a curvilinear trend can be discerned in the relationship between the serious conflicts and accidents for three of the four intersections. The exception to this trend is the Hornsgatan-Torkel Knutssonsgatan intersection, which showed an unusually high number of serious conflicts in proportion to the number of accidents, compared to the other three intersections. As suggested earlier, this difference is due to other important factors than influence the relationship between accidents and conflicts. Introducing other factors into a generalised linear model may explain more of the variance in this relationship and improve predictive power.

6.6 Predicting accidents

The CD-base software program developed for the analysis of conflict observation studies, provides a special function for the estimation of the expected number of police reported accidents based on serious conflict data. The program generates three estimates for: vehicle-vehicle(rear-end), vehicle-vehicle(other), and vehicle-vulnerable road-user accidents (the same event classifications used previously in this chapter). As mentioned in Chapter 5, this software is recognised as being outdated with regard to the conversion coefficients (also referred to as π -values) that are used for calculating the expected numbers of police reported accidents. It is also important to remember that these values were originally intended as a rough approximation of expected accident occurrence rates. This is also reflected by the fact that no prediction intervals are expressed in relation to the figures calculated by the program.

While the need for a major update of this software is recognised, it is useful to compare the values obtained from the CD-base software, against estimates based on the accident data for the period 1997-2002. This comparison is shown below in Table 6.3. The estimates based on accident data are shown in accordance with a 95 per cent prediction interval using the Poisson assumption and principles used in Equations 4a and 4b (see Chapter 4, Section 4.2).

Table 6.3 Comparison of predicted annual police reported accident rate using CD-Base software and accident data for period 1997-2002 for each intersection and conflict/accident type

		Predicted No. of Accidents per year			Total
		Vehicle– Vehicle (Rear-End)	Vehicle– Vehicle (Other)	Vehicle– Vulnerable Road-Users	
Hornsgatan - Ringvägen	CD-Base	0.11	0.06	1.52	1.69
	Accid Data*	1.33 ±0.92	1.33 ±0.92	1.50 ±0.98	4.17 ±1.63
Hornsgatan – Torkel Knutssonsgatan	CD-Base	0.89	0.05	2.64	3.58
	Accid Data*	0.17 ±0.33	1.00 ±0.80	1.17 ±0.86	2.33 ±1.22
Hornsgatan - Mariatorget	CD-Base	0.32	0.02	0.92	1.26
	Accid Data*	1.00 ±0.80	0.50 ±0.57	0.50 ±0.57	2.00 ±1.13
Hornsgatan – Söderledstunnel	CD-Base	0.29	0.09	0.61	0.99
	Accid Data*	0.83 ±0.73	0.83 ±0.73	1.33 ±0.92	3.00 ±1.39

* = includes 95 per cent prediction interval

The data shown above in Table 6.3 indicates evidence of over-dispersion for the prediction intervals for the estimated annual average accident rates based on the accident data. This is largely due to the sparse nature of the data when it is divided among the different accident event types. The CD-Base estimates for the numbers of police reported accidents show a moderate level of agreement (i.e. within the confidence intervals) when compared to the estimates based on accident data for Hornsgatan-Mariatorget and Hornsgatan-Söderledstunnel, but not the other two intersections.

A reasonable level of consistency for the majority of vehicle-vulnerable road-user accident estimates is also shown. This is however, not the case for the two vehicle-vehicle event types, where there is consistent underestimation in all but one case. The total numbers of predicted police reported accidents for each intersection also appear to be less consistent for the CD-Base data when compared to the estimates based on accident data.

Given the fact that only four intersections have been studied, and that no actual data for 2003 is available for a comparison of the predicted numbers of accidents, it is difficult to make any conclusions regarding the level of statistical accuracy for the predicted numbers of yearly police reported accidents made by the CD-Base program, or for those based on accident data. It is clear however, that the ability to predict the expected number of accidents based on serious conflict frequency at a level that is within projected confidence intervals at specific traffic facilities, would be a useful contribution for most forms of safety analysis.

On the basis of the data available, it is also possible to estimate the number of accidents at each intersection using the intersection safety model suggested by the Swedish Road Authority in the comprehensive ‘*effect-relationship*’ knowledge base for transport planning purposes. These types of models are intended for cost-benefit analysis in relation to roadway infrastructure investments aimed at maintenance and development. The intersection safety model can be adapted to a specific intersection using input variables related to: intersection type, posted speed, intersection location and area, and traffic flow levels on primary and secondary roads. A comparison of the output data generated by this model in relation to the four studied intersections is shown below in Table 6.4. This data is again contrasted against estimates based on the accident data from 1997-2002.

The intersection safety model is not intended for diagnostic safety analysis and is presented here for comparison purposes only. It might be expected however, to achieve a similar ordering for the intersections as that suggested by the predictions based on accident data. Given the veritable limitations of generalised models such as these, and the nature of the input on which they are based, it is useful to investigate the degree of accuracy that can be achieved. Arguably, methods based on the use of safety indicators such as the Traffic Conflict Technique should be able to predict numbers of accidents at specific traffic facilities with greater statistical precision in light of the underlying theories on which they are based, and their hypothesised relationship with accidents.

Table 6.4 Comparison of predicted annual police reported accident rate using the SRA intersection safety model and accident data for period 1997-2002

	Yearly Estimates based on Police Reported Accidents (STRADA 1997-2002)			Yearly Estimates based on SRA Effect-Relationship Intersection Safety Model (does not include accidents with VRUs)			
	Accidents*	Fatalities / Serious Injuries*	All Injuries*	Accidents	Fatalities / Serious Injuries	All Injuries	Property Damage Accidents
Hornsgatan-Ringvägen	4.17 ±1.63	0.67 ±0.65	5.67 ±1.90	6.72	0.24	1.48	5.58
Hornsgatan-T. Knuttsongsg	2.33 ±1.22	0.16 ±0.33	2.83 ±1.35	5.50	0.19	1.21	4.56
Hornsgatan-Mariatorget	2.00 ±1.13	0.16 ±0.33	2.00 ±1.13	3.63	0.10	0.80	3.08
Hornsgatan-Söderledstunn	3.00 ±1.39	0.50 ±0.57	4.17 ±1.63	2.08	0.05	0.42	1.76

* = includes 95 per cent prediction interval

The data shown above in Table 6.4 indicates that intersection safety model predictions are generally inconsistent with those based on accident data. A match is found only for the intersection with the worst predicted safety level. The estimates of accidents made by this statistical model are, in most cases, also well outside the prediction intervals suggested by the accident data in all but one instance (Hornsgatan-Söderledstunnel). This is not the case for the number of fatalities and serious conflicts, although the data values are too low to represent comparable measures in this instance. The estimated numbers of all injuries resulting from the predicted numbers of accidents also appear much lower than the accident data prediction intervals. It is not possible to draw any specific conclusions based on this comparison without considering the actual accident outcomes. Furthermore, such a comparison would be unjustified given the purposes for which the intersection safety model is intended and the nature of this particular study.

Traffic conflicts have also been used to estimate accident occurrence in a study by Sayed and Zein (1999). The authors found that conflicts of specific severity ranges were significantly related to the numbers of police reported traffic accidents at the majority of intersections studied. This relationship was established using linear-regression models based on hourly traffic conflict rates, and accident data for different intersection types. Although, the models are not specific with regard to the conflict and accident event types studied, and do not mention the inclusion or elimination of conflicts and accidents involving vulnerable road-users, these models are of interest from a practical application perspective and might be useful for estimating accident frequencies at Swedish intersections in the future.

Using the regression models suggested by Sayed and Zein (1999), the numbers of accidents for the four intersections along Hornsgatan were estimated. These calculations revealed however, that estimated numbers of accidents were greatly over-estimated (by a factor of 10) given the accident frequency predicted by the accident data for 1997-2002. While it is perhaps not unexpected to find that the regression models based on Canadian data are not directly suited to the conditions that prevail at Swedish intersections, the general principles suggested by this type of approach do appear to be of value.

6.7 Predicting conflicts

Similar regression models to those discussed above have been suggested by Sayed and Zein (1999) for predicting the number of conflicts based on the product of traffic volumes on primary and secondary roads. The regression model based on Canadian data specifically for urban signalised intersections is shown below in Equation 6.1. Similarly, the calculation of variance that is used to represent the accuracy of this estimation and determine suitable prediction intervals is shown below in Equation 6.2:

$$\text{Average Hourly Conflict Rate (AHC)} = 5.58 + 2.48 * \sqrt{PEV} \quad \text{(Equation 6.1)}$$

$$\text{Variance } [AHC_{\text{predicted}} - AHC_{\text{actual}}] = s_a^2 \left(1 + \frac{1}{n} \right) + s_a^2 (x_i - \bar{x})^2 \quad \text{(Equation 6.2)}$$

Where: PEV is the product of the hourly entering traffic volumes in thousands; s_a^2 is the standard error of the AHC estimate; and s_a^2 is the standard error of the coefficient of the variable x (as obtained from the regression analysis).

The estimated number of conflicts estimated using the regression model of Sayed and Zein (1999) are shown in accordance with the actual numbers of recorded serious conflicts in Table 6.5 below. The estimated hourly conflict rate is shown with a 95 per cent confidence interval calculated in accordance with Equation 6.2 as a measure of accuracy of the estimate. The products of the estimated daily incoming traffic flows on primary and secondary roads, and the square roots of these products, are also shown in Table 6.5 for each intersection. These calculations are made in accordance with the suggestions by Spicer and colleagues (1979), and Salman and Al-Maita (1995), that such values are highly correlated with conflict frequency.

Table 6.5 Comparison of actual and predicted serious conflict rates according to the regression model of Sayed and Zein (1999), and measures of flow that are believed to be correlated with conflict frequency (Spicer, et.al., 1999; Salman and Al-Maita, 1995)

Intersection	Actual Hourly Conflict Rate	Est. Hourly Conflict Rate (Sayed & Zien)	Product of Traffic Flows (AADTs) (Multipl by 10 ⁻⁷)	Square Root of Product of Flows
Hornsgatan-Ringvägen	1.39	1.15 ±0.37	10.02	3.19
Hornsgatan-Torkel Knutssonsgatan	3.16	0.92 ±0.39	5.14	2.27
Hornsgatan-Mariatorget	1.11	0.64 ±0.42	1.56	1.25
Hornsgatan-Söderledstunnel	1.39	0.79 ±0.41	3.17	1.78

As the data in Table 6.5 indicates, the hourly serious conflict rates predicted by the regression model of Sayed and Zein (1999) are slightly lower than the actual rates found, and in most cases fall outside the confidence intervals provided. The exception to this rule is the Hornsgatan-Ringvägen intersection. As for the regression model for predicting the number of accidents, these findings are not unexpected given that the original model is based on Canadian data and therefore requires adaptation to be useful in conjunction with Swedish intersections.

Statistically stable correlation coefficients cannot be calculated for the relationship between hourly conflict rates and the measures of traffic flow that have been suggested by Spicer and colleagues (1979) and Salman and Al-Maita (1995). However, a consistent order is expected among the intersections for these measures. The data shown in Table 6.5 shows some degree of consistency, the exception being the ordering of the Hornsgatan-Ringvägen and Hornsgatan-Torkel Knutssonsgatan intersections, where the latter was found to an unexpectedly high number of conflicts in proportion the number of accidents.

6.8 Inter-observer reliability

The Traffic Conflict Technique is often criticised for the fact that the indicative Time-to-Accident values are based on subjective estimates of speed and distance by trained observers. In this study, significant differences were identified in the frequencies of serious and non-serious conflicts recorded by the three observers during the six-hour study period at each intersection (see Table 6.6 below). The inter-observer reliability results indicate that a higher number of conflicts were identified by observers A and B, in comparison to observer C. Only one intersection (Hornsgatan-Ringvägen), showed a reasonable level of consistency for all three observers, at the other intersections consistency was found only for observers A and B.

Table 6.6 Comparison of the numbers of observed serious and non-serious conflicts for the three observers at each of the four different sites (6-hours observation per observer and site)

	Observer A No of Conflicts Serious / (Non-serious)	Observer B No of Conflicts Serious / (Non-serious)	Observer C No of Conflicts Serious / (Non-serious)	Average Number Per Site
Hornsgatan-Ringvägen	11 (3)	6 (7)	8 (2)	8.33 (4.00)
Hornsgatan-Torkel Knutssonsgatan	24 (3)	30 (9)	3 (11)	19.00 (7.67)
Hornsgatan- Mariatorget	9 (1)	9 (10)	2 (4)	6.67 (5.00)
Hornsgatan- Söderledstunneln	11(0)	12 (4)	2 (2)	8.33 (2.00)
Average Number Per Observer	13.75 (1.75)	14.25 (7.50)	3.75 (4.75)	10.58 (4.67)

Despite the differences between the three observers, a statistical test the form of the contingency coefficient indicated a reasonable (though non-significant) level of inter-observer reliability with a figure 0.87. A significant correlation (Pearson) could however, be determined for observers A and B ($r = 0.965$) at the 95 per cent ($1 - \alpha=0.05$) level of significance, despite the fact that this calculation was based on only four pairs of values. Arguably, the results of observer C should have been eliminated. The consequences of removing this data would however, have had only minor implications for the main findings of this study.

6.9 Final discussion and conclusions

The results of this study have indicated the practical value of the Traffic Conflict Technique as a quantitative and qualitative method for identifying and comparing safety problems at intersections in the city street environment. On-site conflict observation proved also useful for gaining a valuable understanding and insight into the practical functioning of the different intersections, and the influence of other important factors on traffic safety.

With regard to the consistency of the serious conflict data and the historical accident data for the period 1997-2002, it can be said that there was a reasonable level of agreement. Both sets of data suggested that vehicle-vulnerable road-user events were generally the most frequent types of safety critical events to occur at the four intersections. A lower level of consistency was found for rear-end vehicle-vehicle accidents and serious conflicts among the intersections. For this particular type of event, the number of conflicts was found to be lower in proportion to the number of police reported accidents. This may suggest that rear-end conflicts are more difficult to identify and quantify for observers in comparison to other types of conflicts that involve crossing road-user trajectories.

A more detailed comparison of the vehicle-vehicle (excluding rear-end) accident and serious conflict data revealed that left-turning manoeuvres were a particular problem at three of the four intersections (the exception being Hornsgatan-Söderledstunneln). This type of manoeuvre was evident in approximately 30 per cent of all vehicle-vehicle accidents, and in as many as 50 per cent of the corresponding serious conflicts.

At the Hornsgatan-Torkel Knutssonsgatan intersection, a considerably higher conflict to accident ratio was found than at the other intersections. A comparison between this data and that of the Hornsgatan-Ringvägen intersection indicated a significantly higher number of conflicts (nearly twice as many), yet also a considerably lower number of accidents (just over half the number). These findings were believed to be due to differences in the forms of traffic regulation used at the two junctions.

At the Hornsgatan-Torkel Knutssonsgatan intersection, left-turning manoeuvres are allowed simultaneously for opposing streams of traffic, despite the relatively high traffic volumes and the small size of the central intersection area. Furthermore, left-turn manoeuvres were made more difficult by pedestrian crossings on adjacent roads that are given green during the same signal phase. The placement of these crossings causes conflicts between left-turning vehicles, and vehicles in the oncoming direction, when the turning vehicle is forced to brake for crossing pedestrians. This situation also resulted in a number of serious vehicle-pedestrian conflicts. This situation did not appear to be represented in the accident data.

The Hornsgatan-Ringvägen intersection was found to have higher volumes of traffic, and was larger in size. Most importantly, however left-turning manoeuvres from either of the two Hornsgatan approaches were not allowed. Furthermore, the two adjoining Ringvägen approaches have separate signal cycles thereby removing the possibility of left-turn conflicts from these directions. Interestingly, this signalised intersection caused problems for pedestrians who wrongly anticipated the signal phases and began crossing too early.

Estimations of the number of expected police reported accidents based on the number of serious conflicts proved quite inconsistent for each of the intersections. This was due to a number of reasons. Most importantly, the accident data averaged per year and per conflict/accident type was relatively sparse, even for the intersections on this busy city street with high volumes of vehicle traffic, and large numbers of pedestrians and cyclists.

The CD-Base software used for analysing conflict data and providing a rough estimate of the expected number of police reported accidents, showed little consistency with corresponding estimates based on historical accident data. Similarly, estimates in accordance with the SRA 'effect-relationship' intersection safety model used for cost-benefit analysis in transport planning purposes, also indicated a low level of consistency with the estimates based on historical accident data. A regression model suggested by Sayed and Zein (1999), used to estimate accident frequency on the basis of hourly conflict rates, was also tested with little success although the general modelling approach showed considerable promise.

Regression models for the estimation of serious conflict frequency based on traffic volume data was also suggested by Sayed and Zein (1999). This model proved slightly more accurate than the corresponding model for accident prediction, and again suggested the usefulness of this modelling approach. The theories suggesting that there is a high correlation between serious conflicts and products of opposing traffic volumes, and the square roots of these products, were also tested (Spicer *et.al.*,1979; Salman and Al-Maita, 1995). Based on a rank ordering according of actual conflict rates and these flow-based measures, some evidence was found for the existence of such a correlation. Differences were found, however, for the Hornsgatan-Ringvägen and Hornsgatan-Torkel Knutssongatan intersections, where the latter was found to have an unusually high conflict rate in proportion to the number of accidents and opposing volumes of traffic.

Reliability tests were also performed on the data collected by the different observer participating in this study. Significant differences were noticed in the numbers of serious conflicts recorded. A contingency coefficient statistic indicated an overall lack of statistically significant similarity between observers. However, a good level of consistency (and statistically significant correlation) was found between two of the three observers, both in absolute and relative terms.

The Traffic Conflict Technique proved to be a useful diagnostic instrument to identify and compare existing and potentially different safety problems at four intersections along Hornsgatan. The qualitative and quantitative traffic safety data resulting from this technique allowed a detailed comparative analysis to be made. The relationship between accident data and serious conflict data could also be investigated on the basis of this data along with the possibilities to use this type of data for predictive modelling, taking into account other important traffic variables and processes.

This study also shows that the validation of conflicts against traffic accident data is a particularly difficult affair, given the sparse data available, and is of little practical value in studies such as this that are aimed at a comparison of existing safety levels at traffic intersections. There is however, a distinct need to develop valid and useful statistical predictive models of the type suggested by Sayed and Zein (1999). This will provide a better foundation for detailed transport planning work related to traffic safety.

Case study 2

7. The potential and limitations of different proximal safety indicators and their associated measurement techniques: A study of three T-junctions

Summary

This study forms a critical and central part of the main thesis structure. The work presented here represents an evaluation of safety based on different proximal safety indicators at three unsignalised T-junctions in the Stockholm urban and suburban environment. The safety indicators tested include Time-to-Accident in accordance with the Traffic Conflict Technique, Time-to-Collision and Post-Encroachment Time. An important objective in relation to this work concerns the identification of strengths and weaknesses among the proximal safety indicators to determine their suitability and potential for fast reliable and effective safety assessment. In accordance with this aim, a number of important practical and theoretical issues are considered in relation to the indicators and their associated measurement methods or observation techniques. Relationships are also investigated between safety indicator frequency and severity, and other traditional measures of traffic performance including: traffic flow rates on priority and secondary roads, and various measures of speed.

This study also looks at the use of specially developed semi-automated video-analysis (SAVA) software program as a method with which to derive different types of data relative to traffic performance and the safety. Collecting detailed data enables some of the important relationships between traffic variables and behavioural processes such as gap-acceptance to be contrasted against proximal safety indicators. A further reason for collecting data at this level of detail is to provide a suitable foundation for a follow-up study that is concerned with evaluating the potential of micro-simulation as a method for safety assessment and safety impact estimation.

7.1 Introduction

The primary goals transport planning and traffic engineering are concerned with maintaining and improving the traffic system and achieving an optimal balance between key objectives related to safety, performance and environmental issues. For the purposes of optimising and assuring the quality of traffic safety in the future, there is an identified need for faster and more efficient standardised methods and measurement techniques that can be used to compare, evaluate and predict the impact of new and existing safety measures. Presently, most traffic safety assessment and prediction related work is based on the use of historical accident data that has known drawbacks related to the quality and coverage of data. For the assessment of roadway solutions in the future, it is impractical and unethical to wait for accidents to occur before being able to draw statistically sound conclusions regarding safety impact. Alternative measures are therefore required that can be used for safety assessment and prediction.

As mentioned previously, a more effective short-term safety evaluation strategy involves the use of safety indicators that represent the temporal and spatial proximity characteristics of unsafe interactions (see Chapter 5). The main advantage associated with the use of safety indicators is that they occur considerably more frequently than accidents, thereby implying a faster, more efficient and more statistically reliable proximal measure of traffic safety. A major disadvantage is related to their validity as predictors of traffic accidents (i.e. the accepted measure of traffic safety). Proximal safety indicators also have the advantage of being adaptive to the prevailing traffic conditions at a particular location or traffic facility, and therefore do not suffer from the rigidity of many statistical safety estimation models, particularly where they are used as a diagnostic evaluation tool in before-and-after experimental designs.

7.1.1 Traffic safety at urban T-junctions

Safety statistics for Sweden and many other countries indicate that the vast majority of traffic accidents (as many as 70 per cent) occur in the urban environment rather than on rural roads or motorways (see Chapter 2, Section 2.1.3). However, while the overall number of accidents is higher in the urban environment, the fatality rate is considerably higher in rural areas and on motorways. A large proportion of the accidents that do occur in the urban environment are found at intersections and involve vulnerable road-users such as cyclists and pedestrians to a much higher extent than elsewhere.

The accident statistics specific to urban T-junctions in the Greater Stockholm area with a posted speed limit of 50 km/h (the main focus of this study) have indicated a steady increase over the past five years. A larger than average number of fatalities, has been noticed for 2002 (see Table 7.1 below). Unfortunately, a breakdown of data between signalised and unsignalised T-junctions is not available.

Table 7.1 Accident data in relation to T-junctions in the Greater Stockholm Area during period 1994 to 2002

	Year								
	1994	1995	1996	1997	1998	1999	2000	2001	2002
Accidents	349	366	299	363	403	422	414	452	434
Fatalities	7	7	3	2	5	5	3	5	9
Serious Injuries	68	46	35	53	40	65	83	95	144
Minor Injuries	362	413	338	399	473	495	458	563	515

A further breakdown of the accident data for these T-junctions in accordance with accident type is shown in Table 7.2 below. The data shows that there are a great many accidents between vehicles and pedestrians, and vehicles and cyclists at T-junctions that result in a fatalities and injuries. Fatalities and injuries resulting from single accidents also appear to represent a problem at this type of junction. The data also indicates a great many turning and crossing accidents, and a large number of rear-end accidents that often result in minor and serious injuries. These statistics do not consider the problem of underreporting that is particularly common in relation to minor accidents involving vulnerable road-users.

Table 7.2 Accident data according to type for T-junctions in the Greater Stockholm Area during period 1994 to 2002

	Personal Injuries/Fatalities	Accidents	Fatalities	Severe Injuries	Minor Injuries
Single	398	317	8	72	318
Rear-end	571	355	1	32	538
Overtaking	31	24	1	8	22
Turning	897	577	2	96	799
Crossing	1009	665	3	119	887
Meeting (oncoming)	100	56	4	17	79
Pedestrians	519	454	18	110	391
Cyclists/Mopeds	743	704	4	121	618
Others	423	350	5	54	364
Total	4691	3502	46	629	4016

A large number of strategies and policies have been applied over the years to improve the traffic safety situation in the urban environment. Most significantly, these have involved various principles and guidelines aimed at reducing traffic speed and volume, and generally promoting better forms of interaction between different road-user classes. For unsignalised T-junctions (the focus of this study), the Scandinavian literature suggests that the introduction of a two-way stop can reduce accidents involving injury by up to 25 per cent, and that the introduction of signals can give a similar reduction of up to 15 per cent. Furthermore, redesigning the T-junction to a roundabout is estimated to reduce accidents involving injury by up to 30 per cent (see e.g. Elvik *et.al.*, 1997; Englund *et.al.*, 1998; SRA, 2001). The proposed improvements depend substantially on the potential of intersection or facility in question.

For vulnerable road-users the idea of moving pedestrian/cyclist crossings closer to intersections to improve interaction has been debated, while the strategic use of traffic islands/central refuges in roadway design and physically raised pedestrian/cyclist crossings has been shown to have significant safety effects. In particular, the use of elevated pedestrian/cyclist crossings have been found to greatly improve driver's willingness to stop for waiting road-user, and have been shown to significantly reduce vehicle speed by up to 15 km/h. Furthermore, elevated pedestrian/cyclist crossings are estimated to reduce the number of accidents involving pedestrian injury by up to 33 per cent (see e.g. Elvik *et.al.*, 1997; Englund *et.al.*, 1998; SRA, 2001).

7.1.2 Scope and objectives

There are a number of key objectives related to this work. Firstly and most importantly, an evaluation and comparison of three different proximal safety indicators is carried out which considers important theoretical and practical application issues in relation to their suitability for short-term safety assessment at specific traffic sites. The chosen indicators include: Time-to-Accident, Time-to-Collision and Post-Encroachment Time. This evaluation and comparison is based on an empirical investigation and safety analysis of three T-junctions. Relationships between safety indicator frequency and severity, and recognised traffic parameters such as traffic flow rates on priority and secondary roads, and measures of speed are also examined. The validity of the safety indicators with regard to police reported accidents is also considered where such data exists.

Further objectives of this study concern the application of a specially developed semi-automated video-analysis software program (SAVA) for deriving measures of proximal traffic safety and performance. The use of this video-analysis methodology is also intended to provide suitably detailed data for a follow-up study that assesses the possibilities and limitations of micro-simulation as a method for estimating safety impact.

7.2 Data collection and analysis

7.2.1 Selection of T-Junctions

Three unsignalised T-junctions were chosen for the purposes of this study. All of the junctions were yield-regulated with a posted speed limit of 50 km/h. A further condition for selection was that there should be relatively high average annual daily traffic volumes (AADTs) on both the priority and secondary approach roads. It was also decided that there should be an element of vulnerable road-user activity (preferably pedestrian crossings situated close to the junction), and preferably some accident history. The condition regarding accident history proved very difficult to satisfy, given the relatively low frequency of police reported accidents occurring at unsignalised T-junctions with posted speed limits of 50 km/h. The STRADA database also indicated that that accidents at T-junctions rarely occurred at the same location. The T-junctions included in this study are as follows:

- The Täby T-junction – (suburban, Swedish standard intersection type C)
- The Södermalm T-junction – (urban, Swedish standard intersection type A)
- The Vasastan T-junction – (urban, Swedish standard intersection type A)

Standard Swedish intersections are type-denoted from A to F, where Type-A junctions represent the simplest form with relatively low traffic volumes on priority and secondary roads with no queuing and Type-F represents the most complex intersection design with grade-separation to accommodate high traffic volumes on both roads (SRA, 2001). The choice of intersection design is made largely in accordance with the size and relative proportions of traffic volumes on priority and secondary roads, and the intersection location and posted speed limits. The Täby intersection is a Type-C junction that has central refuges separated directional flows within the main junction area and a designated left-turning lane. The two urban junctions are both Type-A. The T-junctions are illustrated below in Figures 7.1 to 7.3:



Figure 7.1 The Täby T-junction (suburban)



Figure 7.2 The Södermalm T-junction (urban)



Figure 7.3 The Vasastan T-junction (urban)

7.2.2 Terminology

An explanatory diagram is presented below (see Figure 7.4) which clarifies the terminology used in this report. The figure also shows the order of priority for yield regulated T-junctions.

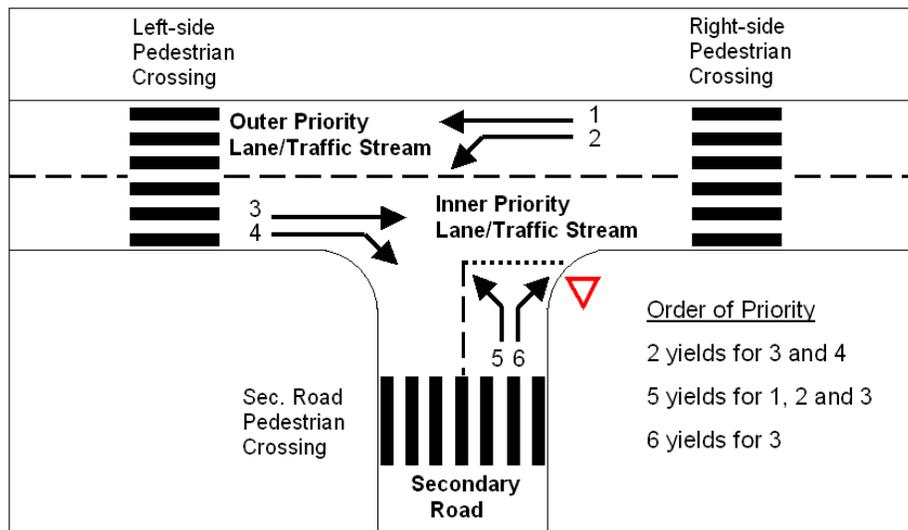


Figure 7.4 Definition of T-junction terminology and order of priority at the test sites

7.2.3 T-Junction regulation

In Sweden, there is a further form of traffic regulation that exists as a *de facto* standard at junctions when no stop or yield sign is posted. This form of regulation, literally translated as the '*right-side rule*' infers that a vehicle must yield for other vehicles that approach from the right-hand side. In many cases, this rule is subject to misinterpretation and yielding occurs as if a yield sign had been posted. This was the case at the Södermalm T-junction, which functioned as if the perpendicular adjoining road was yield-regulated.

7.2.4 Traffic measurement

Traffic Measurements were made at each T-junction during the September-October period with temperatures ranging from 5-12 degrees Celsius. Data was collected for the time-period between approximately 07:00 am to 18:00 pm. For the main data-analysis, three separate two-hour test periods were chosen including the following:

- A morning peak period – 07:00 to 09:00 am
- An off-peak traffic – two hours between 10:00 am and 15:00 pm
- An afternoon peak traffic – 16:00 to 18:00 pm

Measurement included video-film recording using digital video cameras mounted on a 15 metre high mast overlooking the junction. Traditional vehicle logging using pneumatic tubes (loops) was also carried out in order to collect data regarding the number, types and speeds of vehicles immediately prior to the intersection on each approach.

Loop counters were placed on the priority road lanes at a distance of approximately 20 metres from the centre of the intersection, and at a distance of 50-100 metres from the centre of the intersection on the secondary road. At the Täby T-junction, tubes were also placed at a distance of 100 metres from the centre of the intersection on the priority approaches. The vehicle log-data was intended to complement the video-analysis data and ensure correct speed calibration when generating output data based on video-analysis data.

7.2.5 Application of the Traffic Conflict Technique

Conflict observation in accordance with Traffic Conflict Technique was carried out at each T-junction during the period following the original data collection. Practical issues ruled out the possibility of performing conflict observation at the same time as the other measurements. Furthermore, the recommended application of the Traffic Conflict Technique involves a total study period of 18 hours, divided among several days.

For the purposes of this study, the recommended 18 hours of observation at each T-junction were planned to include 4 hours during the morning peak (07:00-09:00am), 4 hours during afternoon peak (16:00-18:00pm) and 10 hours in off-peak hours (10:00am to 15:00pm).

7.2.6 Photometric video-analysis

Video-analysis was carried out using a special software tool developed by the author (see Archer, 2003). A review of existing video-analysis tools for traffic analysis, including ViVa-Traffic (Hydén, 1996; Nilsson, 2000) and Trajex (Andersson, 2003; Nilsson, 2003) indicated that there was no fully-automated software was available for traffic safety related analysis, and also that the semi-automatic software was not suitable for the purposes of this study.

The software developed for the purposes of this study is semi-automatic (i.e. requires a good deal of input from the user to record events of interest) and enables spatial events, such as road-user passages, to be recorded with a temporal accuracy of 40 milliseconds. Road-user passage events are recording in conjunction with virtual line markings and/or positional co-ordinates. These are recorded in a special output file that includes the vehicle type denotation, vehicle identity number, virtual line number or X and Y co-ordinates along with the time of the actual event in milliseconds.

The software utilises a complex orthogonalisation function (involving backward substitution, pivoting and Gaussian elimination, see e.g. Hallert, 1964; Andersson, 2003) to map the X and Y screen-coordinates to real-world X and Y co-ordinates. When this calibration has been made, the distances between any two points on the two-dimensional screen image can be measured in corresponding three-dimensional real-world distance.

The basic layout of passage lines that were used for collecting vehicle and road-user passage data using the semi-automatic video analysis (SAVA) software is shown below in Figure 7.5 for the Täby T-junction. The other two (urban) intersections had a slightly different layout of passage lines

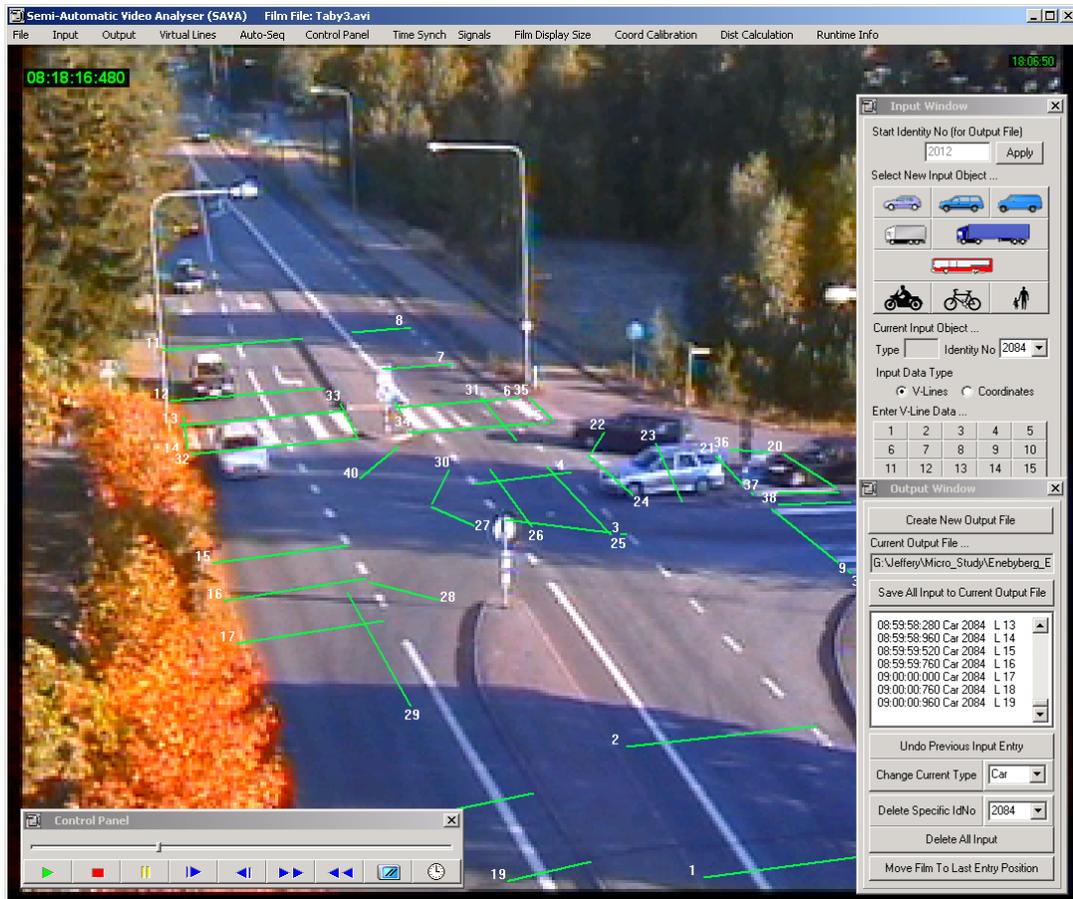


Figure 7.6 Using the semi-automatic video analysis (SAVA) software to acquire test site data for further processing in this study

Video-analysis was used to generate the following data:

- Traffic flow rates
- Origin-destination data
- Traffic composition data
- Average speed and standard deviation of speeds for priority directions, and numbers of speed violations
- Free-flow speed distribution data for priority directions
- Vehicle arrival (time-gap) distribution data for priority directions and numbers of vehicles in car-following mode
- Gap-acceptance (time-gap) and gap-rejection distribution data for all turning manoeuvres from the priority and secondary road
- Safety data including: Post-Encroachment Time values (PET's) and Minimum Time-to-Collision values (TTCs)

7.2.5.1 Video-analysis and the determination of gap-acceptance data

For each T-junction there were three different yielding situations (see Figure 7.7 below, exemplified using the Täby T-junction). These include: left-turning vehicles from the primary road outer lane into the adjoining secondary road; right-turning vehicles from the secondary road merging into the inner lane of the primary road; and left-turning vehicles that cross the inner lane and merge into the primary road outer lane.

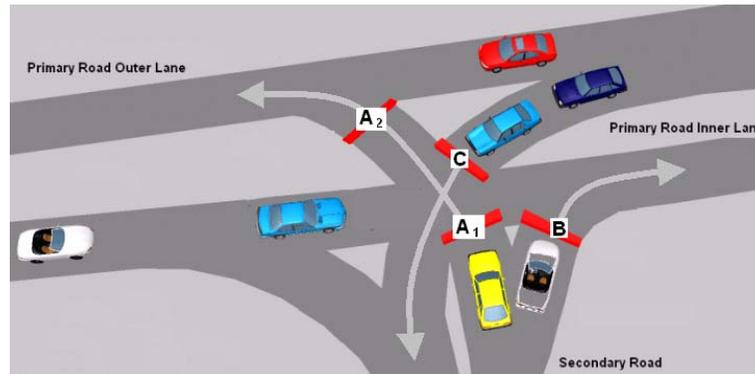


Figure 7.7 Three yielding scenarios at the Täby T-junction: left-turns from the secondary road from a primary (A_1) and secondary yield point (A_2), right-turns from the secondary road from yield point (B) and left-turns from the primary road outer lane from yield point (C)

The most difficult accepted gaps to evaluate were those involving left-turns into outer priority stream. This is because the driver must estimate the time required to reach a secondary yield point after having first crossed the inner priority stream. This particular manoeuvre is less complex for the two urban T-junctions where the distance to the secondary yield point is equal to the width of the inner priority lane. In the software analysis, the accepted gaps for the left-turn manoeuvre were calculated by deducting the time taken between primary and secondary yield points from the estimated arrival time of an approaching vehicle (see Figure 7.8, exemplified for the Täby T-junction). This situation does not present a problem with regard to the registration of rejected gaps.

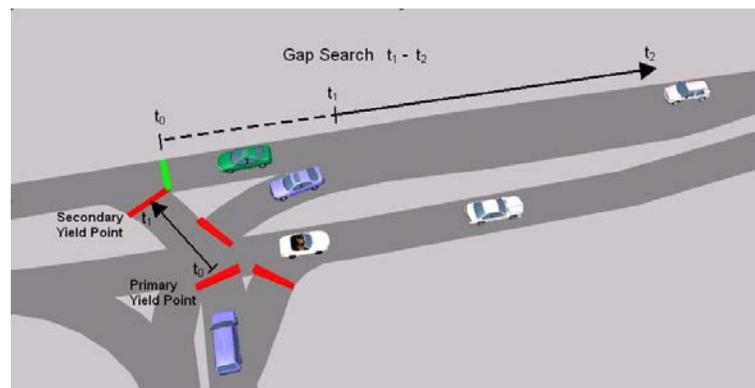


Figure 7.8 Calculation of the accepted time-gaps for left-turns from the secondary road shown for the Täby T-junction

All accepted time-gaps were registered in relation to the point in time when the yielding vehicle crossed the yield line (or began a manoeuvre if the yield line has already been passed). Furthermore, the size of the time-gap is calculated on the estimated time of arrival at a point perpendicular to the yielding position. This estimate is based on a speed and distance measure taken upon entering the intersection (15-20 metres upstream) and is intended to remove some of the bias that would otherwise be present if priority vehicles slowed down when yielding vehicles accept short gaps.

7.2.5.2 Video-analysis and the determination of safety indicator data

The analysis of Time-to-Collision and the Post-Encroachment Time safety indicator data was based on a procedure that included both automatic detection using post-processing software and manual observational detection. The registration of road-user passages across the virtual line markings was used to identify '*potential*' safety critical events through a special function in the post-processing analysis software. Approximately 90 per cent of all vehicle-vehicle safety-critical events could be identified using this approach. There were, however, a number of more complex and irregular safety-critical events that were not identified and a great number of '*false-alarms*' were generated.

As stated in Chapter 5, the PET proximal safety indicator is less suitable for conflict events between vehicles that have the same (final) trajectory. This includes merging and rear-end conflicts, and conflicts between right-turning vehicles from the inner priority lane and left-turning vehicles from the outer priority lane (both into the secondary road). Other problems were also found for the PET indicator. The general PET concept makes no specific distinctions with regard to the order of passage over a common conflict point. The order of passage can be of some importance, however, in certain types of safety critical events. For example, where a vehicle turns left from the outer priority lane into the secondary road and can cross a common conflict point on the inner priority lane closely *before* an approaching vehicle, or immediately *after* a passing vehicle.

In most circumstances, passing *before* is potentially more dangerous requiring adaptive behaviour on behalf of the driver with right-of-way. Passing *after* may however, also be dangerous if the non-prioritised vehicle turns without stopping at high speed, on the assumption that the vehicle in the priority traffic stream will not stop or slow down. This situation is exaggerated further in relation to vehicle-pedestrian interactions.

PET events may also be misrepresented in situations where drivers proceed at low speeds before a pedestrian crossing to allow pedestrians to pass, and then accelerate rapidly passing the common conflict point with a sub-threshold value. In cases such as this, the driver exercises control over the situation suggesting that the interaction is one without accident risk. This situation also exists between left-turning vehicles from the outer priority lane and left-turning vehicles from the secondary road where a common conflict area may be passed within the PET threshold, despite the exercise of control by one or both drivers.

7.2.7 Safety indicator thresholds

The maximum threshold value for the Time-to-Collision safety indicator is set to 3.50 seconds for the purposes of this study. This value represents a compromise between the 3 and 4 second threshold values suggested in the literature (see e.g. Hirst and Graham 1997; Minderhoud and Bovy, 2001). The PET maximum threshold is set to a value of 1.5 seconds. This is slightly higher than the threshold value suggested by Hydén (1996) to distinguish between severe and non-severe PETs. Given the investigative nature of this study, it is considered more appropriate with a slightly higher maximum threshold value in order to obtain sufficient data for safety indicator comparison purposes.

7.2.8 Safety indicator severity

In order to summarise the relative severity of different safety indicators recorded or observed at each T-junction, the average required braking rate measure (RBR) described in Chapter 5 (Section 5.3.5) is used to provide a comparative indication of the levels of severity for the different types of conflicts occurring at each T-junction.

7.2.9 Classification of safety critical events

To enable comparison between the safety critical events recorded by the different indicator measures, a conflict type classification scheme was used. This is illustrated in Figure 7.9 below. In light of the conceptual problems associated with Post-Encroachment Time measurements mentioned above, conflict types 3, 4, 6 and 7 will not be recorded for this particular proximal safety indicator. Similarly, sub-threshold PET events where there is an obvious level of control exerted over the traffic situation are excluded from the results.

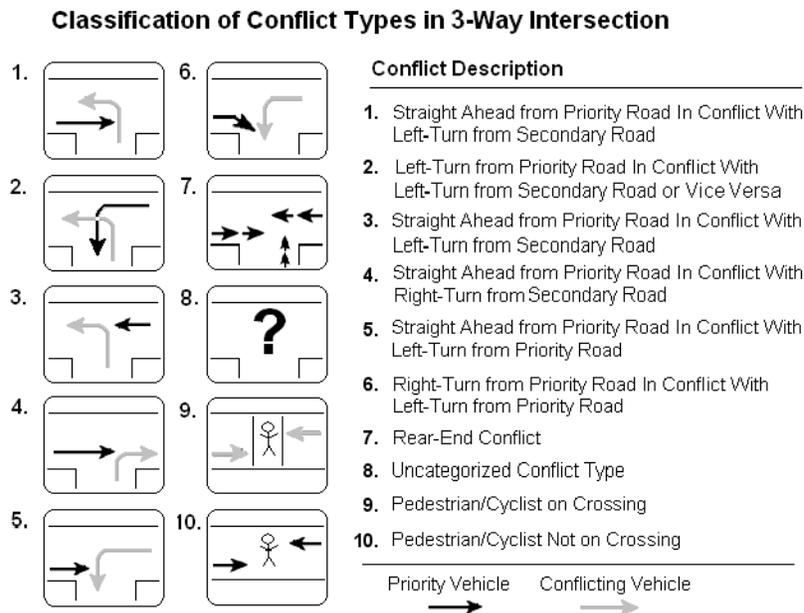


Figure 7.9 Classification of possible conflict types that can occur at T-junctions

7.2.10 Estimating critical gaps for gap-acceptance situations

Since gap-acceptance is recognised as a critical process with regard to traffic safety at yield or stop regulated intersections, it is important to obtain a useful and valid measure in order to be able to make comparisons among different yielding situations and T-junctions. For this purpose, an estimate of critical-gap is made which represents an equal probability for gap-acceptance and rejection. In order to estimate the size of the critical gap in this study, binary logistic (logit) regression analysis is used in accordance with the literature (see e.g. Troutbeck and Brilon, 2000).

Binary logistic regression is useful when the dependent variable is dichotomous and the independent variables are categorical. Furthermore, this statistical analysis is not dependent on distributional assumptions. Logistic regression analysis represents a non-linear transformation of linear regression where the logistic distribution is an ‘S’-shaped distribution function from which probabilities can be derived. The analysis process uses an iterative stepwise procedure to find the best fit. Statistical tests can be performed to test the significance of the function parameters, and the Hosmer-Lemeshow statistical test can be used as a suitable goodness-of-fit measure. In logistic regression analysis it is also useful to consider the predictive ability of the resulting functions.

7.3 Results

7.3.1 Historical accident data

Only two police reported accidents have been recorded at the Täby T-junction during the period 1995-2003. The first of these is registered as a vehicle-vehicle turning accident and resulted in serious injuries for two of the vehicle occupants. The second accident involved a collision between a vehicle and a cyclist and resulted in minor injuries for the cyclist. No accidents are reported at the other two intersections. As a result of the low level of accidents, it is not possible to make comparisons between the various types of accidents and conflicts, or draw any conclusions regarding the predictive ability of the different proximal safety indicators in this study.

7.3.2 Traffic flows, compositions, and turning percentages

The estimated annual average daily traffic (AADT) counts are shown below in Table 7.3. This data indicates that the suburban Täby T-junction has the highest volumes of traffic on both primary (priority) and secondary roads.

Table 7.3 *Estimated annual average daily traffic (AADT) on primary and secondary roads at each of the three T-junctions*

	Täby	Södermalm	Vasastan
Primary Road AADT	14,800	11,000	11,000
Secondary Road AADT	7,600	6,000	3,500

The measured traffic flows for each T-junction are shown below in Figure 7.10(a-c).

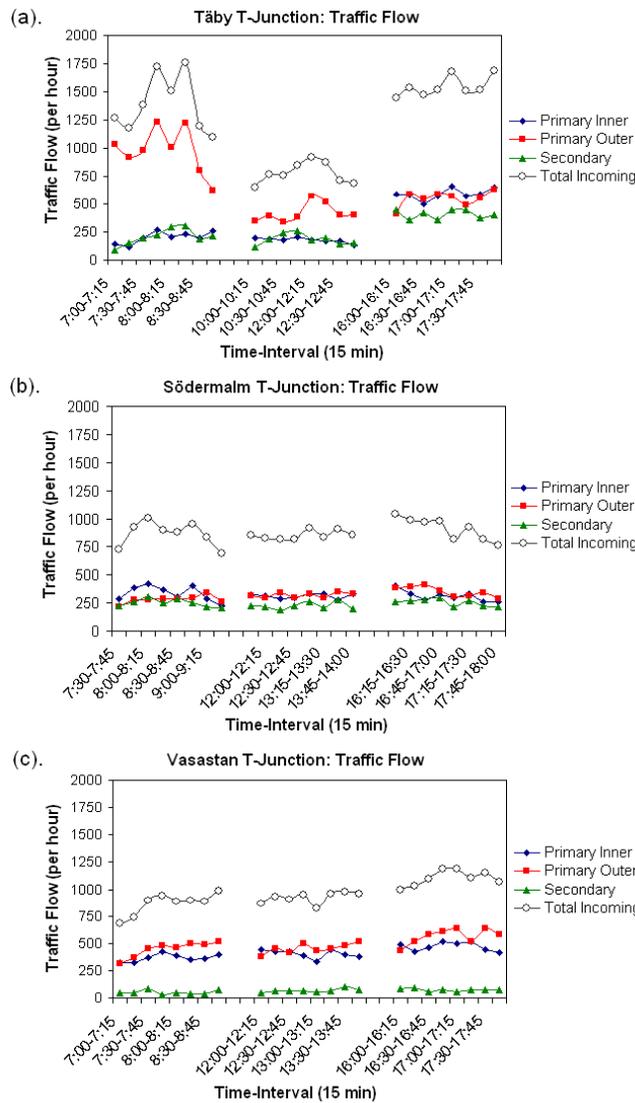


Figure 7.10(a-c) Traffic flow measured for each of the T-junction approach roads during the three different time-periods studied

The graphs representing the flows at each junction suggest a degree of similarity between the two urban T-junctions. The flows at the suburban Taby T-junction are significantly different with higher flows during the morning and afternoon peak periods when people are travelling to and from their place of work. The turning movements and traffic compositions for each T-junction and time-period, are shown below in Figure 7.11(a-i). The tidal traffic at the Taby T-junction is clearly shown during the morning and afternoon peak periods in diagrams (a) and (c) in Figure 7.11. Other major differences between the T-junctions concern the numbers of pedestrians and cyclists. There are also a higher number of pedestrians crossing the roads in the two urban T-junctions, and a larger proportion of cyclists on priority and secondary roads in comparison to the suburban junction.

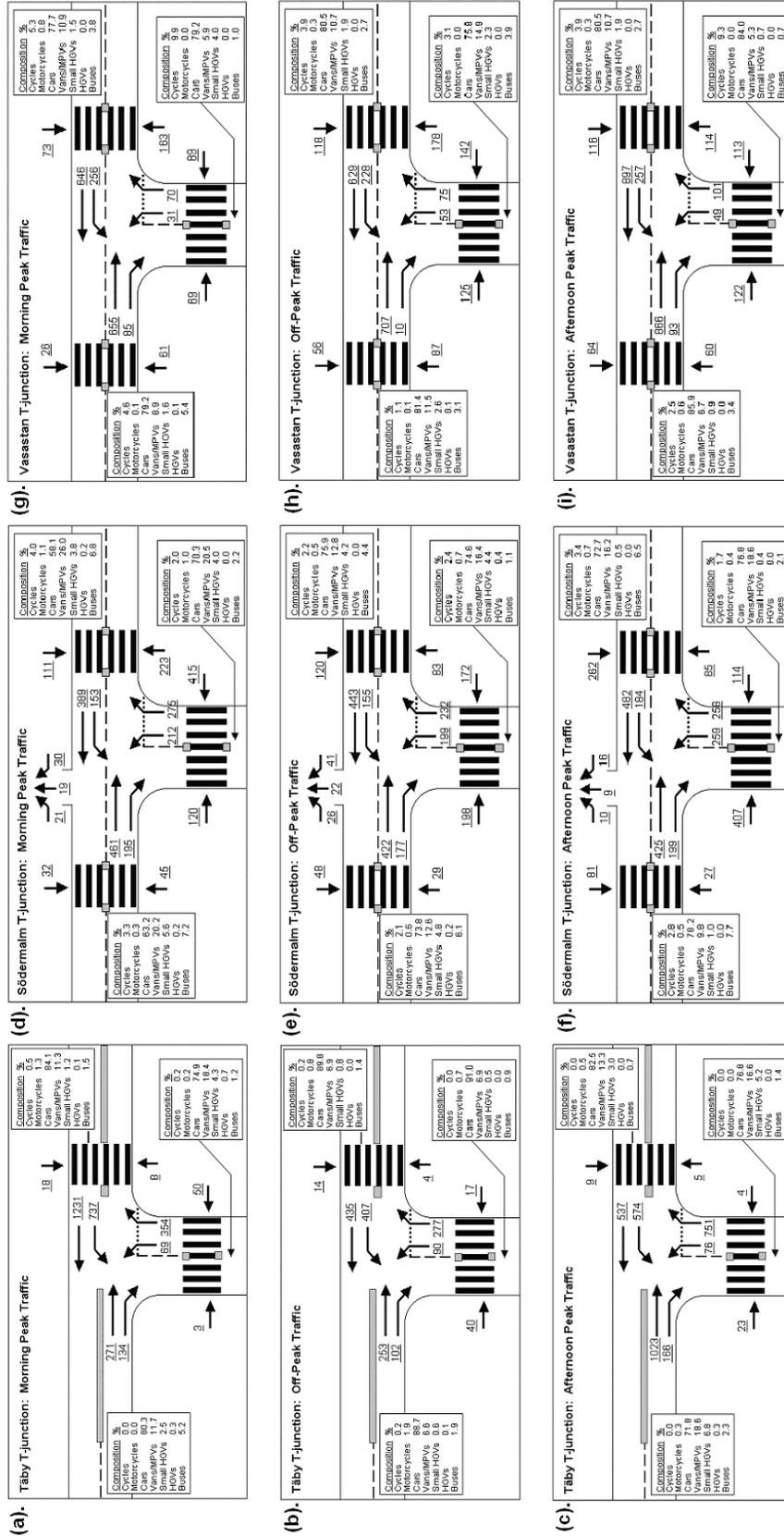


Figure 7.11(a-i). Numbers of turning road-users and traffic composition for the three different time-periods at each T-junction: Täby (a-c), Södermalm (d-f), Vasastan (g-i)

7.3.3 Measures of speed

Different vehicle speed measures for the two priority lanes of traffic during each two hour time-period and T-junction are presented below in Table 7.4.

Table 7.4 *Speed measures for the inner and outer priority lanes during each of the three time-periods at each T-junction*

		Täby			Södermalm			Vasastan		
Measure	Lane	Morn. Peak	Off-Peak	After. Peak	Morn. Peak	Off-Peak	After. Peak	Morn. Peak	Off-Peak	After. Peak
Harmonic Mean	Inner	51.07	51.14	31.80	17.81	20.84	16.80	21.87	20.55	20.76
	Outer	47.19	52.12	47.87	19.14	13.40	22.33	25.10	23.29	17.66
St. Deviation	Inner	9.15	9.25	12.20	8.13	6.88	8.20	7.80	8.33	22.78
	Outer	6.96	7.20	7.58	9.35	9.99	8.44	7.05	7.56	7.00
85th Percentile	Inner	58.26	57.32	49.92	27.89	27.49	28.01	30.87	30.64	29.52
	Outer	52.44	57.60	54.05	33.22	33.56	32.10	32.31	30.06	30.33
Max. Speed	Inner	81.00	90.00	74.93	45.20	43.24	46.26	51.09	54.90	51.07
	Outer	70.04	74.93	72.38	53.76	54.66	56.83	47.20	55.89	60.69
Speeding Vehicles (%)	Inner	63.84	67.19	22.87	0.00	0.00	0.00	0.15	0.28	0.12
	Outer	40.78	68.05	48.42	0.26	0.45	0.83	0.00	0.44	0.11

Speeds were measured using video analysis and verified against log-data based on pneumatic tubes. Speeds were measured at the point of entry to each T-junction (approximately 15-20 metres from a central point perpendicular to the adjoining secondary road) and only for vehicles travelling straight ahead on either of the two priority road lanes.

Again, a considerable difference can be noted for the suburban T-junction (Täby) in comparison to the two situated in the urban environment. At the Täby site the average spot speed is close to the posted limit and shows a large amount of variation on the inner priority lane due to vehicles entering from the secondary road. There is also a large proportion of vehicles at this intersection driving over the speed limit, most noticeably during the off-peak period when there is less friction due to lower traffic volumes.

At the two urban intersections, speeds rarely exceed the speed limit and there is a great deal of friction caused by people crossing the road at each of the pedestrian crossings, this factor and the constant flow of traffic throughout the different time-periods has the effect of keeping the speed level relatively low and constant on average. The relatively large standard deviations also indicate the extent of the friction caused by the use of the pedestrian crossings and, to a lesser extent, the vehicles that enter the T-junctions from the secondary road.

7.3.4 Car-following and vehicle arrival patterns

A value of 3.00 seconds was used as a threshold to determine whether a vehicle was in a state of car-following. This is considered a suitable level for traffic studies in urban and suburban environments (see e.g. Pasanen and Salmivaara, 1993; TRB, 2000; Vogel, 2003). The distribution of time-gaps or headways on the two priority road lanes has an important influence on gap-acceptance for drivers on the secondary road. Higher traffic demand on the priority lanes places greater cognitive and perceptual demands on drivers in yielding situations, thereby increasing the probability for a safety critical event to occur.

For safety evaluation purposes, it is useful to assess the distribution of time-gaps in the priority lane traffic streams to examine the number of shorter (i.e. unsafe) time-gaps that are accepted. Gaps or lags in the arriving traffic streams are largely determined by the traffic demand and driver's individual preferences with regard to maintaining a suitably safe gap. The time-gap distribution also indicates the number of vehicles in car-following state, and can be used to determine the proportion of vehicles that were following with an unsafe (i.e. very close) time-gap. Close following is recognised as a major safety problem (see e.g. Carsten *et al.*, 1989; Evans, 1991; Hiramatsu and Obara, 2000). In this study, time-gap distributions (i.e. bumper-to-bumper measures rather than headway) have been determined in both priority streams at a central position close to the point where vehicles enter from the secondary road (see Figure 7.12a-i). The time-gap distributions represent the gaps that are available to yielding vehicles during the gap-acceptance process.

The time-gap distributions for the Täby T-junction in Figure 7.12 suggest as expected, a large proportion of vehicles driving with a short gap during the morning peak in the outside priority lane (towards the city), and in the opposite direction during the afternoon peak. This is also emphasised by the number of vehicles in car-following state during these two periods (see Table 7.5 below). Similarly, the urban Vasastan T-junction shows relatively high proportions of close-following vehicles in both priority lane directions for all time-periods. The percentages of vehicles in car-following state for this particular T-junction are in some cases double that found for the other urban T-junction (which also has considerably lower traffic flow rates).

Table 7.5 Number and percentage vehicles in car-following state during each of the three time-periods at each T-junction

		Täby			Södermalm			Vasastan		
Car-Following Measure	Lane	Morn. Peak	Off-Peak	After. Peak	Morn. Peak	Off-Peak	After. Peak	Morn. Peak	Off-Peak	After. Peak
No of Vehicles	Inner	48	49	558	77	110	133	290	320	430
	Outer	503	72	143	127	117	103	233	248	449
Percentage	Inner	17.78	19.44	54.76	20.21	25.00	27.94	44.82	45.33	49.77
	Outer	40.89	16.59	26.68	27.79	27.92	24.52	36.41	36.85	50.51

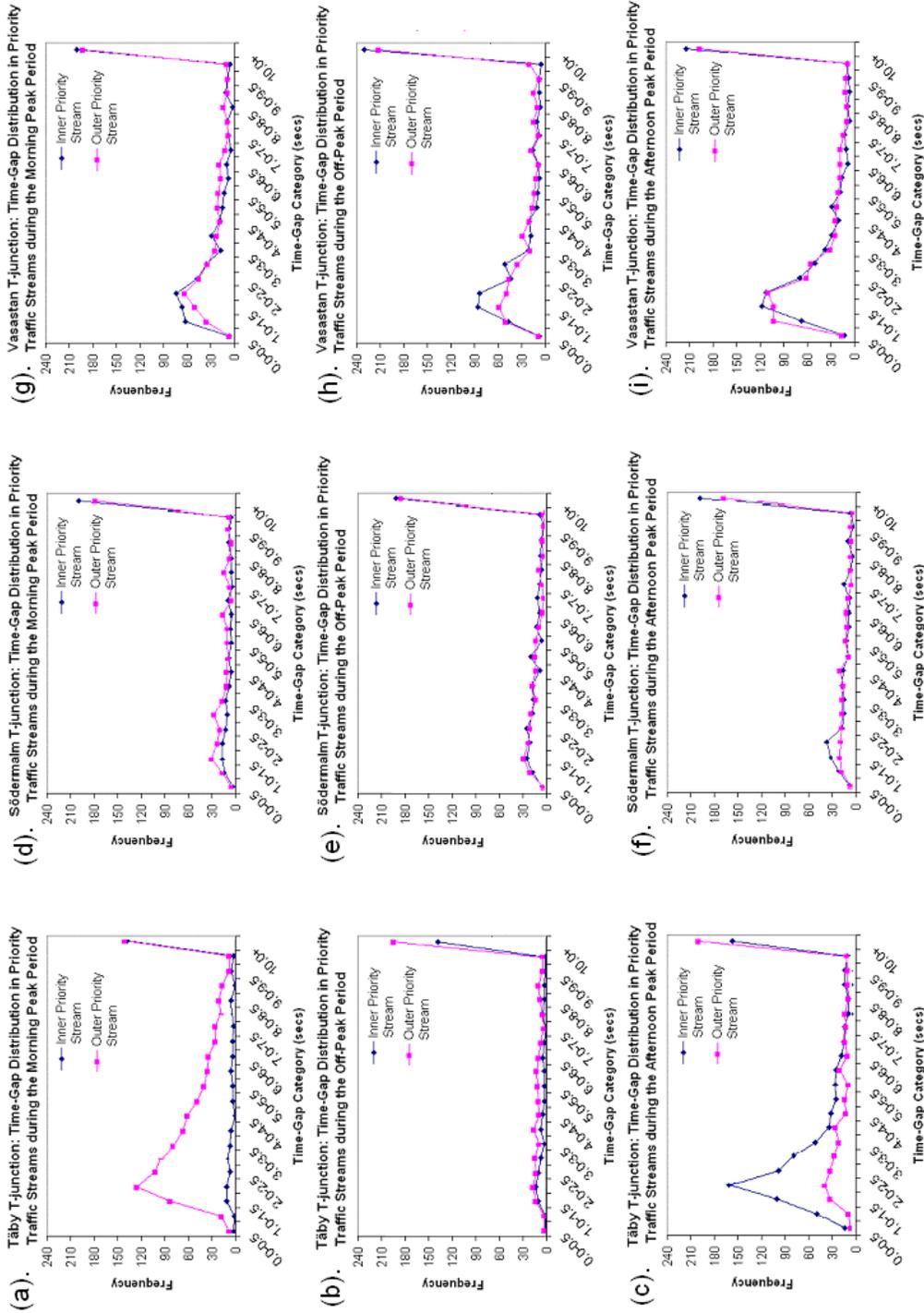


Figure 7.12(a-i). Distribution of time-gaps for the outer and inner priority traffic streams during each time-period for the three T-junctions: Täby (a-c); Södermalm (d-f); Vasastan (g-i).

7.3.5 Gap-acceptance measures

Estimates of critical gap size were made using binary logistic (logit) regression analysis based on empirical data derived from video-analysis for each of the three time-periods at each T-junction. All regression functions were found to have statistically significant parameters (at the $p=0.01$ level of significance) and provided in most cases a good fit against the data as indicated by the Hosmer-Lemeshow statistical test (0.05 level of significance). The goodness-of-fit measures were not particularly good for the majority of the off-peak periods due to the relatively low numbers of yielding vehicles (and therefore also the numbers of accepted and rejected gaps). The predictive ability of the models was in all cases over the 80 per cent mark in relation to the data from which they were determined. Details regarding gap-acceptance at each of the yielding situations for the different time-periods are shown in Table 7.6 below.

Table 7.6 Gap-acceptance data during the three time-periods at the three T-junctions

		Täby			Södermalm			Vasastan		
Measure	Yield Pos*	Morn. Peak	Off-Peak	After. Peak	Morn. Peak	Off-Peak	After. Peak	Morn. Peak	Off-Peak	After. Peak
Number of Accepted Gaps	LT sc	69	90	75	212	199	259	31	53	49
	RT sc	354	277	751	273	232	258	70	75	100
	LT pr	734	407	575	150	155	183	256	228	257
Number of Rejected Gaps	LT sc	269	112	340	215	231	268	92	158	147
	RT sc	42	26	739	54	42	50	31	32	80
	LT pr	117	65	548	46	40	60	165	159	202
Estimated Critical Gap (secs)	LT sc	5.6	5.9	5.7	4.1	4.5	3.5	4.3	4.4	4.6
	RT sc	4.1	3.5	3.5	3.9	3.4	3.8	3.6	4.0	3.3
	LT pr	4.8	5.1	5.1	4.5	4.1	4.9	4.7	4.7	4.8
Shortest Accepted Gap (secs)	LT sc	0.7	2.6	2.2	0.8	1.0	1.2	1.3	1.3	1.4
	RT sc	2.3	2.9	2.1	1.8	2.2	2.2	2.8	2.7	2.0
	LT pr	3.0	2.8	1.6	3.5	1.8	3.3	3.2	3.3	3.0
Largest Rejected Gap (secs)	LT sc	9.8	10.5	10.3	11.5	11.6	10.1	7.5	10.6	7.9
	RT sc	7.0	4.1	8.4	10.8	5.1	9.9	6.5	6.7	7.1
	LT pr	11.5	8.9	9.0	6.8	7.3	8.7	8.2	6.9	8.9

* LT sc = Left-turn from secondary road into priority lane; RT sc = Right-turn from secondary road into priority lane; LT pr = Left-turn from priority road into secondary road

Gap-acceptance problems can be identified in the data in Table 7.6 by comparing the relative proportions of accepted and rejected gaps. The data suggests that left-turn manoeuvres were particularly difficult at the suburban Täby T-junction during morning and afternoon peak hours where the relative ratios of accepted to rejected gaps is approximately 1:10 and 1:8 respectively. This is also indicated by the excessive waiting time at the head of the queue for this manoeuvre (see Table 7.7 below). This yielding manoeuvre is also a problem at the urban Vasastan junction where the relative ratios of accepted to rejected gaps is approximately 1:3 during all time-periods. Longer than average waiting times are also noticed for this manoeuvre (see Table 7.7 below). Yielding at the urban Södermalm T-junction proved to be less of a problem due to the relatively low volume of traffic on the priority road.

An interesting finding was that the left-turn manoeuvre from the secondary road shows both the shortest accepted and the longest rejected time-gaps compared to the other yielding situations. The estimated critical gaps suggest larger times for both types of left-turn yielding situations. This is not expected, given that these manoeuvres both involve crossing an oncoming stream of traffic whereas the right-turn situation does not. A number of the shortest gaps accepted also resulted in safety critical events, particularly left-turns from the secondary road. These findings support the notion that traffic streams consisting of shorter gaps (usually as a result of higher flow rates) cause problems for yielding vehicles, and result in traffic safety problems.

As mentioned above, yielding problems can be identified by examining the relative proportions of accepted and rejected gaps, but also by the time spent waiting at the head of the queue, and the percentage of vehicles that did not stop when negotiating a yielding situation. A closer examination of the data revealed no effects related to the acceptance of shorter and riskier gaps after long periods of time spent waiting at the head of the queue as suggested by Ashworth and Bottom (1977) and Tudge (1988).

Table 7.7 Details of driver gap-acceptance for the different yielding situations in each of the three different time-periods

		Täby			Södermalm			Vasastan		
Measure	Yield Pos*	Morn. Peak	Off-Peak	After. Peak	Morn. Peak	Off-Peak	After. Peak	Morn. Peak	Off-Peak	After. Peak
Average Wait Time at Head of Queue (secs)	LT sc	13.6	7.1	15.3	4.1	4.5	4.0	9.1	8.8	7.9
	RT sc	0.8	0.9	2.9	1.7	1.5	1.8	2.9	4.1	3.4
	LT pr	1.0	0.8	3.2	1.6	1.5	1.8	2.2	2.7	3.1
Percentage of Non-stopping Vehicles	LT sc	21.7	36.7	26.7	53.8	55.3	49.4	19.4	11.3	12.2
	RT sc	83.3	79.8	65.7	63.4	65.5	68.7	48.6	30.7	39.0
	LT pr	80.2	83.8	67.7	68.0	72.3	72.7	66.8	53.9	56.0

* LT sc = Left-turn from secondary road into priority lane; RT sc = Right-turn from secondary road into priority lane; LT pr = Left-turn from priority road into secondary road

7.3.6 Proximal safety indicator data

7.3.6.1 Conflict observation according to the Traffic Conflict Technique

Conflict observation was performed for a total period of 18 hours (6 hours per day) at each of the three T-junctions. The conflict observation included 4 hours during morning and afternoon peak periods, and 10 hours during off-peak periods. Conflict observation was not conducted during the main data-collection period used for all other results presented above, or the following results for Time-to-Collision and Post-Encroachment Time. Standard conflict diagrams (plots of Time-to-Accident against speed) are presented below in Figure 7.13(a-c) for the safety critical events observed at each of the three T-junctions during 18 hours of conflict observation.

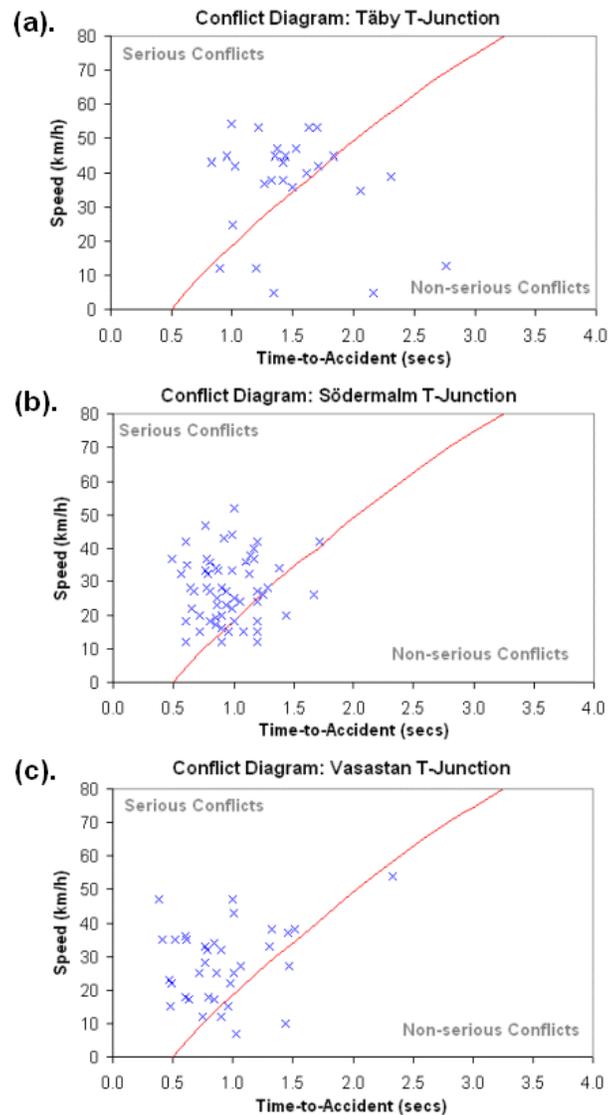


Figure 7.13(a-c) Conflicts recorded at each of the three T-junctions during 18 hours of observation, Täby(a), Södermalm(b); and Vasastan(c)

Data regarding the frequency and severity of observed conflicts in relation to conflict type for each of the three time-periods is shown below in Table 7.8.

Table 7.8 Frequency and severity of observed serious conflicts (TA-values) shown in accordance with time-period and conflict type (non-serious conflict frequencies are shown in brackets)

Confl. Type*	Täby					Södermalm					Vasastan				
	Mrn. Peek	Off- Peek	Aftn Peek	Tot No	RBR Svr**	Mrn. Peek	Off- Peek	Aftn Peek	Tot No	RBR Svr**	Mrn. Peek	Off- Peek	Aftn Peek	Tot No	RBR Svr**
1.	1 (0)	3 (2)	1 (0)	5 (2)	23.4	5 (0)	11 (9)	6 (1)	22 (10)	104.7	1 (1)	7 (1)	2 (0)	10 (2)	47.6
2.	0 (0)	0 (1)	1 (0)	1 (1)	4.0	1 (0)	0 (2)	2 (0)	3 (2)	9.3	0 (0)	0 (0)	1 (0)	1 (2)	4.3
3.	2 (1)	1 (1)	2 (0)	5 (2)	22.9	2 (1)	6 (2)	3 (0)	11 (3)	58.7	0 (0)	1 (0)	5 (0)	6 (2)	24.4
4.	1 (0)	4 (0)	2 (1)	7 (1)	35.4	0 (1)	4 (1)	4 (0)	8 (2)	36.3	0 (1)	1 (0)	1 (1)	2 (1)	8.3
5.	0 (0)	0 (0)	0 (0)	0 (0)	0.0	0 (0)	0 (0)	0 (0)	0 (0)	0.0	0 (0)	0 (0)	0 (0)	0 (0)	0.0
6.	0 (0)	0 (0)	1 (0)	1 (0)	3.4	0 (0)	0 (0)	0 (0)	0 (0)	0.0	0 (0)	1 (0)	0 (0)	1 (0)	3.1
7.	0 (0)	2 (0)	0 (0)	2 (0)	10.0	0 (0)	2 (0)	2 (0)	4 (0)	19.0	1 (0)	4 (0)	0 (0)	5 (0)	26.6
8.	0 (0)	0 (0)	0 (0)	0 (0)	0.0	0 (0)	1 (3)	1 (0)	2 (3)	13.6	0 (0)	3 (0)	2 (0)	5 (0)	32.5
9.	0 (0)	0 (0)	0 (0)	0 (0)	0.0	0 (0)	0 (0)	0 (0)	0 (0)	0.0	0 (0)	0 (0)	1 (0)	1 (0)	6.8
10.	0 (0)	0 (1)	0 (0)	0 (1)	0.0	0 (0)	1 (0)	1 (0)	2 (0)	12.1	0 (0)	1 (0)	0 (0)	1 (0)	17.0
Total	4 (1)	10 (5)	7 (1)	21 (7)	99.1	8 (2)	25 (17)	19 (1)	52 (20)	253.7	2 (2)	18 (1)	12 (4)	32 (7)	170.7
Hourly Rate**	1.0	1.0	1.7	1.2	5.5	2.0	2.5	4.7	2.9	14.1	0.5	1.8	3.0	1.8	9.5

* = See Figure 7.9 for a description of different conflict types; ** = Serious conflicts only in average required braking rate (RBR) severity and Hourly rates

The data in Table 7.8 indicates that the largest number of serious conflicts were found at the urban Södermalm T-junction, and furthermore that the majority of conflicts at this site occurred during the off-peak period (data for the off-peak was collected during 10 hours in total compared to 4 hours for the other two time-periods). These results were largely unexpected given the traffic data which shows that the lowest traffic volumes and lowest average speed levels for this particular T-junction, in addition to few small time-gaps in priority streams, and no evidence of any gap-acceptance problems.

The second largest number of serious conflicts was found at the other urban T-junction (Vasastan), and consequently the smallest number at the suburban Täby T-junction where the speed levels and traffic flows were highest. The summated required braking rate severity measure showed the same order as the serious conflict frequency data.

A closer look at the different type of safety critical events showed that the left-turn manoeuvre from the secondary road was over-represented in the serious conflict data. This manoeuvre caused problems with vehicles approaching on both the inner and outer priority lanes (conflict types 1 and 3). These types of conflicts were evident at all three of the T-junctions. There was also a small tendency noticed for higher frequencies during the afternoon peak hour.

A further type of conflict that was more frequent than many others, involved right-turning vehicles from the secondary road in conflict with vehicles approaching from the left on the inner priority lane (conflict type 4). This suggests that both types of merging manoeuvres into priority streams (conflict types 3 and 4), result more frequently in conflicts than transversal crossing-type manoeuvres. Surprisingly, no conflicts were observed for vehicles turning left from the priority road into the secondary road (conflict type 5). This may be the result of the less complex nature of this manoeuvre. As expected, several rear-end conflicts were noted at each T-junction (conflict type 7).

An interesting finding was also that there were relatively few conflicts between vehicles and vulnerable road-users. This had been expected given the relative volumes of pedestrians recorded at the two urban T-junctions in the video-analysis data. While no such conflicts were observed at the Täby T-junction, several were recorded in the off-peak and afternoon peak periods at the two urban intersections.

The average hourly conflict rates at each T-junction consistently indicated that conflicts were more frequent during the afternoon peak period followed by the off-peak period. This was an interesting finding given the high volume of tidal traffic, and the high average speeds at the Täby T-junction during the morning peak period.

The summated average RBR-severity values for serious conflicts provide a useful comparative indication of the levels of unsafe interaction between different time-periods and intersections. If the average severity rate per serious conflict event is calculated for each T-junction, similar values are found (range 4.72 to 5.33). This suggests a considerable degree of braking where these values are considered as representative of an average negative acceleration rate.

An interesting finding is also that the average RBR-severity values for serious conflicts involving vehicles and vulnerable road-users are higher per event (by approximately 30 per cent) than those found for serious conflicts involving only vehicles. This may suggest the occurrence of situations where pedestrians are not immediately detected by drivers, or where pedestrians display a tendency to cross on the assumption that a vehicle will stop before any form of interactive acknowledgement is established.

7.3.6.2 Time-to-Collision

The Time-to-Collision data derived from a process involving video-analysis is shown below in Table 7.9. A breakdown of data is again given in relation to each time-period and conflict type. It should be noted that the values for each separate time-period are based on 2 hours of video-analysis (i.e. 6 hours in total per T-junction).

Table 7.9 Frequency and severity of TTC-events determined from video-analysis shown in accordance with time-period and conflict type

Confl. Type*	Täby					Södermalm					Vasastan				
	Mrn. Pk	Off-Pk	Aftn Pk	Tot No	RBR Svr	Mrn. Pk	Off-Pk	Aftn Pk	Tot No	RBR Svr	Mrn. Pk	Off-Pk	Aftn Pk	Tot No	RBR Svr
1.	0	0	0	0	0.00	3	6	8	17	28.5	0	1	1	2	3.4
2.	2	0	3	5	14.0	2	0	0	2	2.2	0	1	1	2	4.3
3.	2	0	3	5	11.9	3	3	8	14	29.8	4	1	0	5	6.8
4.	3	2	12	17	56.7	2	6	2	10	15.9	1	0	0	1	2.1
5.	0	0	0	0	0.0	1	1	0	2	2.4	0	3	2	5	5.8
6.	0	0	0	0	0.0	0	0	0	0	0.0	0	0	1	1	2.0
7.	0	0	3	3	7.2	1	0	0	1	1.3	4	6	3	13	22.8
8.	1	0	1	2	5.0	4	0	3	7	12.2	1	4	2	7	12.7
9.	0	0	0	0	0.0	0	0	0	0	0.0	0	0	0	0	0.0
10.	0	0	0	0	0.0	0	1	0	1	0.0	0	1	0	1	0.8
Total	8	2	22	32	94.9	16	17	21	54	95.0	10	17	10	37	60.8
Hourly Rate	4.0	1.0	11.0	5.3	15.8	8.0	8.5	10.5	9.0	15.8	5.0	8.5	5.0	6.2	10.1

* = see Figure 7.9 for a description of different conflict types

The frequencies of the minimum (and sub-threshold) TTC-values follow the same pattern as that found for the serious conflict data discussed previously. Furthermore, a relatively large number of TTC-events were again found to occur during off-peak periods for the two urban T-junctions (Södermalm and Vasastan). An interesting difference between the serious conflict data and the TTC data is that the frequency of the latter appears to be higher. This might be expected given the definition and conceptual basis of this proximal safety indicator, which can include essentially non-severe events that have low speed values but high spatial proximity (see Chapter 5, Section 5.4). This suggests that sub-threshold TTCs may be more frequent than serious conflicts. It should also be remembered that the latter does not strictly require a collision course. It should also be remembered that the TTC data and serious conflict data are not representative of the same time-period.

The frequencies of the different safety critical event types are similar to those found for the serious conflicts. The left-turn manoeuvre from the secondary road was once again found to be the underlying cause of many TTCs (i.e. conflict types 1 and 3). These two safety critical event types were particularly evident at the Södermalm T-junction, and to a lesser extent at the Vasastan T-junction. At the Täby T-junction, no conflict type 1 TTC-events were recorded (i.e. conflicts between left-turning vehicles from the secondary road and vehicles approaching on the inner priority lane) in contrast to the serious conflict data.

TTC-events involving right-turning vehicles from the secondary road in conflict with vehicles on the inner priority lane (conflict type 4), appeared to be most frequent at the Täby T-junction, and were well-represented at the Södermalm T-junction. These findings emphasise once again the problems in relation to left and right-turn merging manoeuvres (i.e. conflict types 3 and 4). An interesting finding that was not evident in the serious conflict data, was the existence of a number of TTC-events between vehicles turning left from the outer priority lane and vehicles approaching on the inner priority lane (conflict type 5). The TTC indicator also identified an unusually large number of rear-end conflicts at the Vasastan T-junction (conflict type 7). The TTC indicator also identified a larger number of safety critical events per hour between vehicles and pedestrians (conflict type 8) at the two urban T-junctions in comparison to the Traffic Conflict Technique.

The frequencies of TTCs among the three different time-periods at each of the T-junctions appear to follow a pattern that is consistent with relative changes in volumes of traffic. This is particularly noticeable at the Täby T-junction where the frequency of TTCs is highest during afternoon peak, closely followed by morning peak. Similarly, few TTCs are recorded during the off-peak period. At the other two intersections, the flows are relatively stable throughout the different time-periods as are the TTC-frequencies. The exception to this rule appears to be the off-peak period at the Vasastan T-junction, where an unusually high number of rear-end and vehicle-vulnerable road-user TTC-events were recorded.

The average RBR-severity rates per TTC-event for the different T-junctions, show some interesting differences. The values for the Södermalm and Vasastan T-junctions are relatively similar (1.76 and 1.64, respectively), while the value for the suburban Täby T-junction is considerably larger (2.79). This could reflect the difference in average spot speed at this junction in comparison to the other two, which should be reflected in increased severity if the measure is accurate and valid. The greater average level of severity at the Täby T-junction also causes the total value for the 6-hour period to be as high as that for the Södermalm T-junction despite large differences in relative frequency.

It is interesting to note that the RBR-severity values are considerably smaller than those for the serious conflicts, suggesting that a number of the recorded events may not be as 'serious' as the TTC-value suggests. A related finding that is most probably the result of chance given the major conceptual differences between the indicators, is that the total RBR-values per hour in relation to serious conflicts and TTC-events are very similar for each of the two urban intersections.

7.3.6.3 Post-Encroachment Time

The frequency and severity data in relation to the PET proximal safety indicator is shown below in Table 7.10. Similar to the two safety indicators discussed previously, a breakdown of this data is given in accordance with the three time-periods and safety critical event types. The PET-values for each separate time-period are based on 2 hours of video-analysis (i.e. 6 hours in total per T-junction). PET values have only been determined for safety critical event types 1, 2, 5, 8, 9 and 10 (i.e. those involving transversal road-user trajectories).

Table 7.10 Frequency and severity of PET-events determined from video-analysis shown in accordance with time-period and conflict type

Confl. Type*	Täby					Södermalm					Vasastan				
	Mrn. Pk	Off- Pk	Aftn Pk	Tot No	RBR Svr	Mrn. Pk	Off- Pk	Aftn Pk	Tot No	RBR Svr	Mrn. Pk	Off- Pk	Aftn Pk	Tot No	RBR Svr
1.	2	1	3	6	32.0	8	2	4	14	34.5	1	3	2	6	17.0
2.	0	0	4	4	16.0	4	1	1	6	11.2	0	1	0	1	2.1
5.	0	0	2	2	1.3	2	0	0	2	6.1	3	1	3	7	16.1
8.	4	6	3	13	24.3	20	19	40	79	138.9	4	8	18	30	61.6
9.	0	0	0	0	0.0	0	0	0	0	0.0	0	0	0	0	0.0
10.	0	0	1	1	3.7	2	1	1	4	16.3	0	0	0	0	0.0
Total	6	7	13	26	77.2	36	23	46	105	207.0	8	13	23	44	96.8
Hourly Rate	3.0	3.5	6.5	4.3	12.9	18.0	11.5	23.0	17.5	34.5	4.0	6.5	11.5	7.3	16.1

* = see Figure 7.9 for a description of different conflict types

The frequencies of the sub-threshold PET-values follow the same order among the three T-junctions as that found for the serious conflict and TTC-data, despite the limited number of conflict types measured by this particular safety indicator. The Södermalm T-junction was found to have the highest number of PET-events, the majority of these involving vehicle-pedestrians interactions. Furthermore, the afternoon peak was again found to generate the largest number of safety critical events, followed closely by the morning and off-peak periods. The PET-safety indicator appears to be more sensitive (but not necessarily more valid) than the other safety indicators with regard to pedestrian-vehicle interactions. The problems associated with left-turning vehicles from the secondary road are again highlighted by the PET-data, as for the indicators discussed previously.

The average RBR-severity rates per PET-event for the different T-junctions show some interesting differences. The values for the Södermalm and Vasastan T-junctions are relatively similar (1.97 and 2.21, respectively), while the value for the suburban Täby T-junction is noticeably larger (3.00). As for the TTC-data, this finding is believed to be attributable to the higher levels of average speed on the priority roads at the Täby T-junction, which has the effect of increasing the severity of the safety critical event.

7.3.7 Safety indicators and their relationship with traffic flow

It has been suggested by Spicer and Colleagues (1979) and Salman and Al-Maita (1995) that the occurrence of traffic conflicts is correlated with the product and/or square root of the product of priority and opposing traffic volumes. These values are contrasted against the hourly frequencies for each safety indicator during the different time-periods at each of the three T-junctions in Table 7.11 below.

Table 7.11 Traffic flow measures and their relationship with the safety indicator frequency during the different time-period scenarios

Measure	Täby				Södermalm				Vasastan			
	Morn. Peak	Off-Peak	Aftn Peak	Total	Morn. Peak	Off-Peak	Aftn Peak	Total	Morn. Peak	Off-Peak	Aftn Peak	Total
Product of Flows	1.0	0.4	1.9	9.5	0.6	0.5	0.7	5.3	0.2	0.2	0.3	2.0
Square Root of Product	1.0	0.7	1.4	3.1	0.8	0.7	0.8	2.3	0.4	0.5	0.6	1.4
Hourly TA-Event Frequency	1.0	1.0	1.8	3.8	2.0	2.5	4.8	9.3	0.5	1.8	3.0	5.3
Hourly TTC-Event Frequency	4.0	1.0	11.0	16.0	8.0	8.5	10.5	27.0	5.0	8.5	5.0	18.5
Hourly PET-Event Frequency	3.0	3.5	6.5	13.0	18.0	11.5	23.0	52.5	4.0	6.5	11.5	22.0

The ordering indicated by both the product, and square root of the product, of priority and opposing traffic flows is consistent with the safety indicator frequencies for the Täby T-junction, but not the other two. In all cases, these traffic volume-based calculations suggest the afternoon peak as the period in which most safety critical events are likely to occur, closely followed by the morning peak. This order is not followed by the two urban intersections where the off-peak period, despite slightly lower volumes of traffic, is second highest in the rank order suggested by the safety indicator frequencies. Arguably, these two volume-based measures do not take into consideration the volumes of pedestrians that tend to have an impact on both traffic performance and safety.

7.4 Comparison of safety indicator data collection and analysis methods

There are some notable differences in the methods and techniques used to collect safety indicator data. The Time-to-Collision and Post-Encroachment Time safety indicator values are derived using video-analysis and post-processing software, while serious conflicts are determined from estimates of speed and distance during on-site observation (and may be validated against video-recordings at a later point in time). The use of semi-automated video-analysis software has both advantages and disadvantages. Given the current state-of-the-art in automated video-analysis software, the greatest disadvantage is related to cost-effectiveness.

The time required to analyse video-recordings is ultimately dependent on many different factors including:

- The intended purpose of the study
- The variables measured and the analysis approach used
- The level of sophistication of the video-analysis software
- The size and quality of the video-recording
- The camera position and angle of the camera with regard to the study area
- The volume of traffic, pedestrians and cyclists

In the approach used in this study, all road-user passages over strategically placed virtual lines were registered in a process that involved stepping the film forwards and backwards. Adjustments were made in accordance with the film-resolution of 40 milliseconds (i.e. 25 frames per second). While the recorded data represented a very detailed data set, there was undoubtedly a large degree of redundancy, where many unimportant events were unnecessarily recorded in detail. An alternative approach, such as the study of safety critical events *only* would be more resource-effective. Similarly, changing the time-resolution from 40 milliseconds to a 500 milliseconds would greatly reduce processing time.

Ideally, a combination of automated and observational safety critical event detection should be used. Once detected, the calculation of safety critical event values, such as Time-to-Collision and Post-Encroachment Time, must be performed manually. For the Time-to-Collision safety indicator, a particularly large number of calculations are required to obtain the minimum value and to ensure the existence of a collision course given the length and breadth of vehicles, their speed and acceleration, and relative distances. An interesting point in relation to the use of automated video-analysis for the identification of safety critical events, is that many conflicts are related to actions that display the underlying intentions of road-users. Small momentary lapses of attention or other perceptual or cognitive failures may result in a sudden initiation of action such as acceleration, and an equally fast revocation, within a limited spatial area and time-span. This type of event represents a conflict situation that may well go unnoticed in automated analysis. Situations such as these emphasise the need for an individual evaluation of each conflict situation in accordance with the prevailing traffic conditions.

The methodology used for identifying TA-values in accordance with the Traffic Conflict Technique has been subject to a great deal of criticism and has been discussed in detail in Chapter 5. Experience with this technique suggests that there are difficulties related to speed and distance estimation, but also that these are largely dependent on the observers location, and the complexity and frequency of the conflicts that actually occur. Other problems related to this technique involve identifying the '*conflict-determining*' road-user for a particular event. Furthermore, it may be difficult to determine exactly where and when evasive action first took place given the positioning of the conflict observer relative to the approaches of an intersection and the possibility to observe brake lights, vehicle braking movements, or changes in trajectory.

Although there may well be problems related to what is usually referred to as the ‘*subjective*’ nature of this methodology, it is presently far more resource-efficient than any of the methods that rely on video-analysis and post-processing procedures. On-site observation also has a number of advantages related to the collection of other qualitative and quantitative data such as red-light violations, excessive vehicle speeds, pedestrians that cross on red or at undesignated places, and situations such as queues and blocking that may have relevance in the final safety assessment relative to a particular site.

7.5 Safety indicators: Strengths and weaknesses

Each of the safety indicators tested in this study has different strengths and weaknesses related to their potential areas of application and suitability for different types of conflicts. As already discussed, the PET-safety indicator is not useful for longitudinal conflict trajectories and is arguably, most useful for safety critical events involving vehicles and vulnerable road-users at pedestrian/cyclist crossings and certain types of vehicle-vehicle interactions. Given the elementary nature of this safety indicator, and the relative ease with which values can be determined using video-analysis, it is a more resource-effective but less informative and more limited alternative to the Time-to-Collision measure. There are also questions regarding the fundamental construct validity of this indicator as a measure of safety, given that there is no collision course and often no evasive action taken.

The TTC-safety indicator, as mentioned above, is particularly resource demanding and requires a considerable calculation for each potential safety critical event. This particular safety indicator would benefit significantly from a fully automated video-analysis procedure and is unlikely to become accepted or used as standard safety indicator before such technology is readily available. The main advantage of this indicator is that it is less ‘*subjective*’ than the Traffic Conflict Technique as the measures of speed and distance are derived directly from video-imagery in the cases where a collision course actually exists.

As the TTC-safety indicator is continually measured throughout each safety critical event, the most dangerous part (i.e. the minimum value) is supposedly identified. This is not the case for the Traffic Conflict Technique where the initial evasive action is the determining moment for a safety critical event. A further difference between these two safety indicators is related to severity. The Time-to-Accident measure is distinguished between serious and non-serious conflicts for the purposes of estimating accident occurrences. The TTC-value is considered as a direct measure of severity, and does not consider speed in relation to the outcome variable. Thus, two TTC events with similar outcome values have the same severity level regardless of speed. As a result, there may be a number of events that are sub-threshold, but which have low severity when measured by other more representative variables such as, the average required braking rate. A comparison of the average required braking rate per serious conflict and per TTC shows significantly different levels, with Time-to-Accident measures twice the size of that found for Time-to-Collision.

Interestingly, the TTC-safety indicator and derivatives such as the Time Extended TTC and Time Integrated TTC concepts (see Minderhoud and Bovy, 2001) are regarded as useful for traffic simulation purposes where the required measures of speed and distance are readily available for (automated) calculation (see Chapter 10). Arguably, these measures are of little use if they cannot be verified.

The Time-to-Accident measure is, as mentioned previously, the most resource effective safety indicator with regard to data collection. The subjective nature and possibility for error in the estimations of speed and distance used to determine the Time-to-Accident value have been discussed earlier. Arguably, however, these problems are more apparent for particular types of conflicts, and safety critical traffic situations. The speed and distance values for vehicles in longitudinal *merging* and *rear-end* type conflicts are particularly difficult to judge where the conflict point is dependent on the relative speed difference and the distance between vehicles that are in conflict.

Furthermore, in situations that involve turning and merging vehicles from secondary roads into priority streams, it is often necessary to consider vehicle acceleration in order to estimate where the point of collision would have occurred had not one of the vehicles taken evasive action. This situation is complex even for a trained observer, and occurs quite regularly in conflict studies at junctions. Situations such as these should be subjected to careful video-analysis to determine speeds, accelerations, and distances more accurately, and to establish the existence of a common collision course, or to ensure that there was behaviour suggesting the existence of a collision course.

Problems with merging manoeuvres may also be more obvious to the observer at junctions where there are higher levels of speed on the priority approaches. When the speeds are relatively low, the distance proximity of the vehicles required for a serious conflict is small and the turning vehicle often does not manage to complete the turning or merging manoeuvre before the conflict situation is determined (and resolved). In these low-speed situations, the conflict is far easier to observe and estimate than it is in cases where there is high speed and longer distance.

As mentioned in the previous section, other difficulties related to this technique concern the identification of the '*determining*' road-user. If, for example, a pedestrian runs across a pedestrian crossing to avoid being hit by a vehicle, should the speed and distance of the vehicle be used to calculate the TA-value, or that of the pedestrian? Although the pedestrian is the road-user who first took evasive action, the real danger and severity potential is related to the speed and distance of the vehicle. These and many other definitional dilemmas generally require a common sense approach.

7.6 Towards a methodology for safety assessment based on indicators

The general methodology applied in this study with regard to the different T-junctions has been quite comprehensive. Not only has the study included the analysis of proximal safety based on three different safety indicators, it has also considered fundamental measures of traffic performance that are hypothesised to have an important influence on the frequency and severity of safety critical events.

It is proposed that a comprehensive safety study at a specific traffic facility should also consider measures related to traffic performance and road-user behaviour in order to be able to identify important relationships between these, and the proximal measures of safety. This is likely to be useful in order to propose suitable safety countermeasures.

The measures suggested include:

- Measures of traffic flow, turning percentages and vehicle composition
- Spot measures of vehicle speeds in and around the junction
- Pedestrian/cyclist movements at pedestrian crossings and elsewhere
- Measures related to gap-acceptance for all yielding situations
- Measures related to the arrival patterns of vehicles (time-gap distributions) on priority road lanes near the yielding situations
- Traffic observation to identify problems related to design and geometry
- Measures related to traffic signalling if this form of regulation is used

In all safety assessment methods, it is also useful to obtain detailed accident data and to compare the types of accidents and road-users involved against safety indicator data. Ideally, accidents and conflicts should use or the same definitions. The comparison of accidents and conflict types can provide useful information regarding particular safety problems at a particular traffic site. In many cases, however, there may be little or no accident data available.

7.7 Final discussion and conclusions

Many of the issues relating to the use of the three safety indicators as measures of proximal safety have been discussed. In particular, there are important differences in the methodologies used to establish the safety indicator values, and limitations regarding the types of safety critical situations that can be accurately and reliably recorded by each. The comparisons and analyses that have been made regarding the use of these indicators suggests that Time-to-Accident (serious conflict) is the most useful and resource effective of the three tested, providing both qualitative and quantitative information.

The comparison of the suburban and urban T-junctions revealed a number of interesting findings not only with regard to the relative frequencies and severities of different conflict types during the different time-periods, but also with regard to the relationship of the safety indicators to other traffic parameters suggested in the literature. The product of primary and secondary approaching traffic volumes and the square root of this product, were believed to be correlated with safety indicator frequency and severity (see e.g. Spicer *et.al.*, 1979; Salman and Al-Maita, 1995). However, the data suggested only a moderate tendency for the existence of such relationships.

A comparison of the three T-junctions revealed a number of common problems. In particular left and right-turns from the secondary road into the outer and inner priority streams (merging manoeuvres) resulted in a large number of safety critical events recorded by both the TA and TTC-safety indicator measures with comparatively high severity levels. The more complex left-turn manoeuvre from the secondary road also resulted in an over-representative number of conflicts with the inner priority road traffic stream particularly at the two urban T-junctions.

The majority of vehicle-pedestrian safety critical events were recorded at the urban T-junctions. For this type of event, the frequencies for the TA and TTC-safety indicators were reasonably consistent, while relatively large frequencies were found for PETs. These differences were found to be consistent with higher priority road traffic volumes at the Vasastan T-junction, and higher pedestrian volumes at the Södermalm T-junction.

Other measures recorded at the sites, indicated the importance of the time-gaps in the arrivals of vehicles on the priority traffic streams for yielding vehicles. Short gaps and long waiting times were found for the left-turn manoeuvre from the secondary road. This resulted in a large number of safety critical events at all three of the T-junctions. Speed was not found to be a problem at the two urban junctions, although a high proportion of speeding vehicles was identified at the Täby T-junction. Increased speed was found to cause a higher number of conflicts resulting from right-turn manoeuvres into the inner priority stream of traffic at this T-junction, and a higher than average level of RBR-severity. Unfortunately, there was insufficient police reported traffic accident data in relation to the sites to compare and discuss issues related to safety indicator validity.

Further objectives relative to this study concerned the use of the specially developed semi-automated video-analysis (SAVA) software as a method with which to derive different types of data relative to traffic performance and safety indicators. Arguably, the video-analysis approach used in this study was exaggerated with regard to level of accuracy and data-coverage. This was also reflected in the excessive amount of time required for the analysis procedure. The SAVA software program and the additional post-processing output-analysis software proved reliable and useful for the task of aggregating detailed road-user data in relation to various measures of speed, traffic flow, road-user composition, turning movements, time-gap distributions and gap-acceptance data. The software also proved very useful for the initial identification of safety critical events. The use of both automated and manual safety critical event detection was used and was found to be useful in order not to overlook more subtle and complex events that may otherwise be overlooked if either one of the approaches is used individually.

Finally, important aspects of the methodology adopted in this study have been considered in relation to their potential and use for the development of fast, valid and reliable safety assessment method in the future. A key issue concerns the validity of the safety indicators and their relationship with accident data that is often lacking or non-existent. Arguably, this type of validity should not come into question unless the purpose of the study is specifically aimed at accident prediction. In situations, where comparisons are made between similar facilities or where before-and-after studies are conducted, the indicator should serve as a diagnostic tool for relative measurement rather than absolute as proposed by Chin and Quek, (1997).

For purposes such as transport planning, accident estimates are required for cost-benefit analysis. Here it would be useful to have established statistical models based on empirical data that can predict the number of accidents on the basis of a safety indicator data with an acceptable degree of accuracy. Regression models of this character have been proposed by Canadian researchers Sayed and Zein (1999) and have been shown to have a good level of predictive power. Arguably, similar models should be developed in Sweden for more accurate accident prediction, and for the purposes of identifying complexities in the relationship between serious conflicts and accidents.

PART III:
SIMULATION AS A DYNAMIC APPROACH
TO SAFETY ESTIMATION

8. The potential and limitations of micro-simulation modelling as an methodological approach to safety assessment and prediction

8.1 General background

The use of traffic simulation models for the study of traffic operations and traffic system impact has increased dramatically among transportation planners and traffic engineers during recent years. Simulation software is becoming increasingly more detailed and flexible, it is generally also better documented and easier and more intuitive to use (see e.g. Algiers, *et.al.*, 1997; Lieberman and Rathi, 2001). It is suggested that traffic simulation provides a number of clear advantages over more traditional traffic analysis tools in that it can provide comprehensive results for an entire study area and allows also the on-line visualisation that is often valuable as a preliminary form of validation (Milam and Choa, 2000).

The majority of traffic simulation tools have been developed specifically for traffic performance analysis where the primary focus is related to capacity. This is reasonable since capacity is often identified as the most common objective of transport planning and traffic engineering related work (Akcelik and Besley, 2001b). More recently, there has been an interest in obtaining traffic system impact related to other objectives, such as traffic safety and environmental issues. While some existing commercial micro-simulation tools have provided support for environmental issues, such as vehicle emissions to assess the impact of traffic on air-pollution, the issue of traffic safety continues to be largely neglected. The predominant lack of safety evaluation measures was identified as a significant deficit in the review of 58 micro-simulation models undertaken several years ago as part of the SMARTTEST project funded by the EU (Algiers, *et.al.*, 1997). Later reviews and comparisons have also found little progress in this area (Bloomberg, Swenson and Haldors, 2003; Brockfield *et.al.*, 2003).

Given the scope of the traffic safety problem in terms of accident fatalities and injuries and their related socio-economic values at the national and international level, it is difficult to substantiate the lack of investment and allocation of resources in developing methods, tools and techniques for valid and reliable safety assessment. This type of assessment is often required for comparative before-and-after type study scenarios to establish the effects of new and alternative safety enhancement or safety influencing measures in the roadway environment at specific locations and in relation to specific road-user groups.

In theory at least, micro-simulation has the potential to provide a useful platform for many different types of evaluative and predictive safety analysis, and represents an alternative to more traditional measures based on statistical modelling. The main potential a simulation-based methodologies, is likely to be recognised as a preliminary form of analysis in the early stages of research, development, and design (see e.g. Archer and Kosonen, 2000).

A major problem in the development of what might be termed '*safety simulation*' concerns the differences in the levels of detail that are required for modelling aimed at traffic performance impact, and that related specifically to traffic safety. Arguably, simulation models that are constructed exclusively for the purposes of traffic performance and capacity analysis often require less attention to detail with regard to individual road-user behaviour and forms of interaction, despite the importance of these processes for estimating intersection capacity.

For safety analysis in particular, the accurate representation of interactive behaviour between road-user entities (e.g. gaps accepted when yielding, distance kept when following a preceding vehicle) and road-user interaction with the environment (e.g. how fast a bend is negotiated, sight distance, etc.) is of critical importance. It is also important to ensure that there are appropriate levels of variation in road-user behaviour and vehicle performance. Models that assume a similar normative behaviour for all road-user entities are unlikely to be of much use for safety assessment and prediction purposes. The representativeness of largely invariant models for capacity and traffic performance assessment may also be questioned (see e.g. Ashworth, 1968).

It is generally recognised that a significantly higher level of modelling detail is required for safety assessment than for other traffic system objectives. This is particularly evident with regard to the relatively simplistic behavioural sub-models that describe interactive processes such as: '*car-following*', '*gap-acceptance*' and '*lane-changing*'. Higher levels of modelling fidelity also require the collection of more detailed empirical data and demand greater stringency in the processes of model calibration and validation. Ultimately, this makes simulation modelling aimed at safety assessment far more complex and resource-demanding than is generally the case in traffic performance and capacity analysis. The question that must then be asked is: "*is it really worth it?*" i.e. are there other methods that are less resource-demanding that can be used to produce results of sufficiently validity and reliability?

While statistical models based on historical data may be able to predict the occurrence of accidents using average annual daily flow rates, aspects related to the roadway design, location and posted speed limit, they are not always able to consider other important features that are influential in determining of the overall level of safety at a particular traffic facility. A major advantage related to the use of simulation, is the possibility to '*tailor*' a model to meet the specific criteria of an existing real-world traffic situation and to incorporate those factors that have been identified as having a direct or indirect influence on traffic safety. This includes, amongst others, factors related to:

- the exact geometric layout of the traffic site including the correct width of lanes, traffic islands etc, and the precise positioning of stop and yield lines
- the accurate representation of traffic signal control strategies including vehicle actuated signalling and co-ordinated signalling
- the interaction between vehicles other classes of road-users including pedestrians and cyclists (this is sometimes referred to as '*interference*')
- the precise representation of traffic flows, turning movements (origin-destination matrices) and traffic compositions over time and specific to link roads

- accurate levels of speed and speed variation over time, and specific to certain link roads, in addition to turning manoeuvres, and speed influencing objects (e.g. speed signs, speed humps etc.)
- differences in vehicle characteristics between and within specific vehicle classes and types (e.g. length, weight, engine-power, braking and acceleration ability, power-to-weight ratios, etc.)
- differences in behaviour and performance between and among different classes of road-user (e.g. choice of speed and various aspects related to car-following, gap-acceptance and lane-changing behaviour)
- dependencies among different factors (e.g. designated public transport lanes for buses, speed limits for heavy goods vehicles, etc.).

This list is not exhaustive, but does highlight the level of detail required in simulation modelling for safety estimation at specific traffic facilities.

While there are clearly a number of important obstacles that need to be overcome with regard to this type of simulation modelling, it is evident that there are also a large number of potential benefits particularly in relation to the work of the transportation planner and traffic engineer. A very useful aspect with regard to methodologies that involve simulation is the possibility to perform sensitivity analyses based on standard roadway designs where the safety influence of various traffic parameters (such as changes in averages speeds, speed variation or flow-rates) can be estimated.

Simulation can also be used to generate all types of data simultaneously (safety, traffic performance and capacity). This allows the analyst to get a more complete and comprehensive picture of the many different operational effects related to a particular area of study. Furthermore, modelling allow the effects of various safety influencing measures to be preliminarily tested in a safe off-line environment. This is particularly useful for various in-vehicle or roadside ITS-applications, and alternative traffic signalling strategies and new signalling functionality (see e.g. Liu and Tate, 2000; Archer and Al-Mudhaffar, 2004).

8.2 Simulation modelling and traffic safety

Despite the fact that simulation has been identified as having a potential for various forms traffic safety analysis (e.g. Liebermann and Rathi, 2001), there are very few studies reported in the current literature that have actually used this type of dynamic modelling.

One well-known ‘*safety simulation*’ study has been carried out by Sayed, Brown and Navin (1994). According to the authors, the main purpose of this study was to study traffic conflicts as ‘*critical-event traffic situations*’ and the effects of various driver and traffic parameters on conflict occurrence. The study focused particularly on the gap-acceptance process at T-junctions and four-way intersections and how it was affected by behavioural characteristics such as: age, gender and waiting time at the head of the queue. Furthermore, the effect and relationship of traffic parameters such as traffic volume and speed were examined in relation to the number and severity of conflicts. The simulation method used in this study was event-based and a number of limitations were noted in relation to both driver behaviour and model performance. The numbers of conflicts generated in the simulation study were found to correlate well with the field data for four unsignalised junctions, and the previous literature.

Sayed and colleagues (1994) suggest the usefulness of simulation in studies such as this to overcome problems related to the uncertainty and complexity of human behaviour and the lack of control, which makes other forms of less or non-dynamic statistical modelling highly difficult. They also refer to the inadequacies of the few previous attempts at safety-related simulation that neglect the importance of such diverse behaviour (see e.g. Cooper and Ferguson, 1976; McDowell *et.al.*, 1983). The authors also state that, for use in simulation: “... a traffic conflict needs to be described and scaled as an unequivocal, observable measure of the systematic variability of risk as perceived by the driver in a given traffic situation?”. The application of the TSC-sim model by Sayed and colleagues represents the first qualified attempt at safety estimation, based on proximal safety indicator measures in a simulation methodology.

More than a decade has now passed since the use of TSC-sim was reported. During this time, a great deal of research and development has occurred in the field of micro-simulation modelling. Similarly, data collection techniques have improved dramatically, suggesting that safety-related simulation could be improved further by the addition of more detailed and diverse models that are more representative of complex and variant driver behaviour and vehicle performance.

Interest in the potential of micro-simulation modelling for deriving indicative measures of safety at signalised and unsignalised junctions for traffic engineering and transportation planning purposes has recently been renewed at the US Federal Highway Association (FHWA, 2003). In the report from the first stage of this project, the processes associated with computing safety indicator measures and extracting and analyzing simulation output data are outlined in what is termed a Surrogate Safety Assessment Methodology (SSAM).

The main objective of this project concerns the development of an integrated tool that allows traffic engineers to perform comparative safety analyses based on traffic simulation tools that are compatible in the general SSAM-framework. It is intended that the analysis of safety should include the most useful surrogate safety measures, and that there should be support for a highly flexible analysis of results including statistical aggregation and the visualisation of safety critical events.

Work reported to date on this project has included a short literature review including different surrogate measures and techniques, a short review of several different micro-simulation tools, and a description of the planned SSAM environment and general ideas related to how surrogate measures can be derived from various micro-simulation tools such as: CORSIM, TEXAS, PARAMICS and VISSIM. Some work has also been carried out with regard to the identification of suitable methods that can be used for the validation of the surrogate safety measures suggested (FHWA, 2003).

A number of other smaller studies can be found in the literature that use a methodology based on micro-simulation modelling to investigate safety-related effects. These include: studies by Liu and Tate (2000), and Kosonen (1999), that are concerned with the evaluation of vehicle-based Intelligent Speed Adaptation (ISA) devices in small urban networks; a study by Brackstone McDonald and Sultan (1999), which looked at the safety effects of an Automatic Cruise Control (ACC) system on the incidence of rear-end collisions; and a study by Sala and Mussone (1999) that investigated the effect of a collision avoidance system on motorways. There is also an early simulation study by Carlsson and Nilsson (1988) that looked at the effects of harmonised speed on traffic safety and efficiency.

In each of these simulation studies, the before-and-after experimentation showed significant and interesting results in relation to the in-vehicle device tested. However, it is also true that little attention had been given to more intricate details related to road-user behaviour and the effects such devices have on the interactive processes between drivers, their vehicles and the roadway. Consequently, the true validity of the results is questionable although they do serve as a preliminary indicator of the effects that might be expected.

A useful example is the experiment by Liu and Tate (2000), where different ISA penetration levels were found to have a contagious effect on unrestricted vehicles causing average speed levels and speed variation to be notably reduced. This reduction could be interpreted as a significant improvement in safety given the nature of the speed-accident relationship and the existence of predictive models such as those of Nilsson (1984) suggested earlier (see Chapter 4). Other research suggests however, that there are complex effects at different penetration levels and also that there are effects related to factors such as '*behavioural adaptation*', that have a significant effect on the safety margin such devices are expected to generate (Carsten, 2000; Archer and Åberg 2001).

In the SINDI project (SINDI is an acronym for *safety indicators*) at the Royal Institute of Technology in Stockholm, work was carried out to the develop a simulation model that could be used for safety assessment based on detailed behavioural modelling (Archer and Kosonen, 2000). A specially adapted version of the HUTSIM micro-simulation software program (Kosonen, 1999) was developed that could identify and record traffic conflicts. The software included the representation of numerous behavioural aspects that were identified in the literature, and to a lesser extent through experimentation, as factors that increased the risk of accidents at intersections including: visibility restrictions, inattention, impatience and varying levels of driver aggressiveness. While some interesting research and development was carried out, this project was discontinued due to a lack of resources before any substantial verification of the modelling approach could be performed.

8.2.1 Micro-simulation software programs

There are a great many micro-simulation software programs in existence at the present time. Many of these are commercial products providing regular support and upgrading (i.e. functional improvements) as a result of ongoing research and development work that is necessary to meet the needs and demands of users and maintain market standing. Typical for this type of simulation package are: PARAMICS, VISSIM, SISTM, AIMSUN and CORSIM.

Arguably, the two most widely used and commercially available micro-simulation software tools in European countries are PARAMICS and VISSIM. A general consensus appears to point to the fact that PARAMICS is more suitable to larger networks and motorways while VISSIM is better suited to more detailed urban driving conditions (TfL, 2003, FHWA, 2003). PARAMICS and VISSIM (and most other commercially available simulation tools) are under constant development with additional functions and features added in each new version.

In addition to these commercial packages, there are academically maintained software programs that are often widely used in different regions or research networks, but which often lack comprehensive support, adequate documentation, regular upgrades, and continual research and development of a general rather than specific nature. Applications such as these also display a tendency to branch into specialised areas.

Examples of these more academically oriented packages include: HUTSIM developed at Helsinki University of Technology in Finland by Kosonen (1999) which is actively used in Scandinavia and some other countries; and DRACULA developed at the University of Leeds, which is used in the UK and internationally. Both of these micro-simulation tools have also been marketed commercially.

Presently, it is recognised that micro-simulation packages have limited functionality in relation to: the modelling of pedestrian behaviour, the modelling of overtaking on single lane carriageways, the optimisation of signal control settings, vehicle arrival patterns in near-capacity conditions, the representative modelling of car-following and gap-acceptance behaviour, and more generally the evaluation of safety and environmental impact (Brackstone and McDonald, 2003; Akcelik and Besley, 2001b; Pollatschek, Polus & Livneh 2002; TfL, 2003). For a review of existing traffic micro-simulation software the user is referred to the comprehensive but now outdated report of the SMARTEST project funded by the European Union (Algers, *et.al.*, 1997), and more recent reviews by Bloomberg, Swenson and Haldors (2003) and by Brockfield, Kühne, Skabardonis, and Wagner (2003).

8.2.2 Safety-related parameters and processes in micro-simulation software

In an interesting report by Bonsall, Liu and Young (2001), many underlying assumptions made by micro-simulation software programs are discussed with regard to road-user behaviour, and the effect that various parameters and parameter values have on traffic safety. The authors suggest that many key parameter values with an implicit safety-relevance have been based on informed guesswork rather than theory. Furthermore, it is stated that some empirically grounded parameter values might be generalised to situations other than those from which they were originally determined, thereby making them contextually irrelevant. The central theme around which this report is based, concerns the ethical dilemma of whether or not parameter values that represent actual observed behaviour should be used in a simulation model even though the behaviour in question might be unsafe, and whether or not the use of such unsafe parameters might contribute to the adoption of unsafe designs and misused resources.

Bonsall and colleagues identify a number of important simulation parameters that have implications for safety, the majority of these are related to standard behavioural sub-models (car-following, gap-acceptance and lane-changing), as well as those related to traffic regulation compliancy, and the preferred or desired speeds adopted by drivers in free-flow conditions. The consequences of unsafe driving in real-world scenarios are also considered in relation to capacity, traffic performance and safety impact, as are the consequences of adopting safe-but-unrealistic, or realistic-but-unsafe parameter values.

The authors suggest that errors in parameters reflecting fundamental issues such as those related to physiology, vehicle performance or system components may have serious implications for system design leading to under or overestimation of performance. For parameters reflecting policy or behaviour, the situation was identified as more complex. If, for example, compliancy rates are overestimated the operational performance is likely to be underestimated, and vice versa. It is also suggested that the consequences of using incorrect parameter values are dependent on the actual use of the model and that a fundamental contributor to these problems lies in the imbalanced concentration of indicators related to operational performance and lack of safety-related parameters in micro-simulation models.

The majority of discrete time-based micro-simulation models use various sub-models to represent the interactive behaviours of road-users in different situations. It is the associated parameter and variable values, their inherent structures and forms of representation (e.g. various types of distributions), and the relationships between and among these that define the individual variant behaviour of road-users. These issues are important and relevant in light of the suggestions made by Bonsall and colleagues, and are central to the concept of safety-related simulation modelling and the work in this thesis.

A number of the main behavioural sub-models used in micro-simulation are described below with regard to their safety relevance.

8.2.2.1 Car-following behaviour

Car-following behaviour is of particular importance to traffic safety. Not only because close following with excessive speed is known to increase the risk for rear-end collisions, but also because car-following behaviour determines the distribution of gaps that exist at any particular point of measurement in a traffic stream. Consequently, the distribution of available gaps influences the gap-acceptance behaviour of yielding vehicle drivers on secondary roads, and in a similar way influences the behaviour of other road-user groups such as pedestrians and cyclists when crossing the road.

In a simulation model designed for safety assessment, it is essential that the car-following model parameters are calibrated to provide a close replication of observed time-gap distributions measured near the yield or stop line in relation to priority traffic streams. The car-following models and parameters available for calibration differ considerably to the early models of, for example, Gipps (1981). Today these models often have a multitude of ‘open’ parameters that require careful calibration (see e.g. Brackstone and McDonald, 1998; Janson Olstam and Tapani, 2003).

In most car-following models, the interaction between vehicles in a car-following situation can be described as a stimulus response mechanism similar to the following (Lieberman and Rathi, 2001):

$$\textit{acceleration response of the following vehicle, } a_f = F(v_l, v_f, s, d_l, d_f, R_f, P_i) \quad \textbf{(Equation 8.1)}$$

where: a_f represents the acceleration response of the following vehicle that is dependent on a function F that is in turn, based on various stimulus factors including: v_l, v_f representing the speeds of the leader and follower vehicles, s representing the separation distance, d_l, d_f representing the projected deceleration of the leader and follower vehicles, R_f representing the reaction time of the following vehicle, and P_i representing additional factors.

Other models, such as the psycho-physical Wiedemann '99 model, have as many as many as ten different parameters that can be adjusted to provide representative car-following behaviour. In addition, there is a definable look-ahead distance and probabilistic level of inattention in the current form of implementation in VISSIM. It is however, questionable whether all such values can actually be observed in field studies (using e.g. specially instrumented vehicles) and whether the many relationships among these variables are known and documented for all possible scenarios. Given the normative and overly simplified nature of many car-following models, it is important to compare time-gap distributions at various measurement points to ensure a representative proportion of shorter and larger gaps.

In a report by Brackstone and McDonald (2003) regarding the modelling of car-following behaviour, the fundamental '*safe-following-distance*' concept is questioned with regard to its relevance and the possibility for misconception. The authors suggest that there are important '*chaotic patterns*' and '*asymptotic behaviours*' in car-following that are not represented in many models. Given the current modelling paradigm, Brackstone and McDonald also raise the question of "*...when is enough (calibration) data enough?*" with regard to the natural variability between and within driver behaviour, differences in situational contexts, and the need for modelling that is representative of the real-world.

8.2.2.2 Gap-acceptance behaviour

The gap-acceptance behaviour of road-users (including pedestrians and cyclists) in yielding situations is perhaps the most critical form of safety-related interactive behaviour. In real-world situations, any misinterpretation of speed or distance can have serious consequences. In both traditional capacity analysis and simulation, there are many different approaches to gap-acceptance modelling behaviour (see e.g. Adebisi and Sama, 1989; Abou-Henaidy, Temply, and Hunt, 1994; Hagring, 1998; Brilon *et.al.*, 1999; Pollatschek, Polus and Livneh, 2002). Typically, micro-simulation uses the concept of a fixed critical-gap value which is derived either from empirical observation, or alternatively from relevant literature. Critical time gaps according to the Swedish capacity manual are indicated below in Table 8.1 (SRA, 1995).

Table 8.1 Base-values for critical time-gaps according to the Swedish CAPCAL Manual

Traffic Flow		Primary Road Speed					
Road	Direction	50 km/h		70 km/h		90 km/h	
		Yield	Stop	Yield	Stop	Yield	Stop
Primary	Left-Turn	4.8	4.8	5.7	5.7	6.7	6.7
Secondary	Left-Turn	5.3	6.0	6.2	6.9	7.2	7.8
	Str.-Ahead	5.1	5.8	6.0	6.7	7.0	7.6
	Right-Turn	5.0	5.7	5.9	6.6	6.9	7.5

This modelling approach is known to have implications for capacity analysis where the lack of sufficient variation can cause an underestimation of capacity (Ashworth, 1968). Similarly, in a simulation model, the use of a fixed value will have the effect of allowing all vehicles to pass a yield or stop line if they encounter a gap or lag that is greater in size. As with the car-following behaviour, it is unlikely that such strictly deterministic and invariant behaviour is representative of actual gap-acceptance behaviour.

Given that there are individual differences in the qualitative estimation of a ‘safe’ gap, it is not unreasonable to suggest the need for a modelling approach that is more probabilistic in nature. This would allow some drivers to accept slightly shorter gaps and some drivers to accept slightly longer gaps with the vast majority distributed closely around the central ‘critical’ gap value. When calibrating the gap-acceptance behaviour of drivers in a simulation model, it should be possible to compare the distributions of accepted and rejected gaps in the model with those observed in the real-world.

A probabilistic (statistical) microscopic decision model has been proposed by Pollatschek, Polus and Livneh (2002) which not only takes into consideration the individual differences among different types of drivers (cautious, normal, aggressive) and their prevalence for risk-taking, but also the effect of waiting time at the head of the queue. This model showed good predictive value in the estimation of capacity based on the probability of accepting a random gap generated in accordance with an exponential gap distribution based around a mean gap value.

The modelling approach used by Pollatschek and colleagues (2002) was based on a risk-reward loop process, where entry into a priority traffic stream occurs when the benefit from entry is greater than the associated risk. The estimation of the conflicting traffic is denoted by a parameter β that is updated after each rejected gap. Similarly, the individual preferences of each driver are characterised by a parameter denoted α where larger values show increasing levels of risk. The proposed model demonstrates the differences in the driver population and the effect these have on entry capacity. Arguably, this model presents a means to custom fit a capacity model to a given traffic situation.

The probability $pi(\alpha)$ that i vehicles will enter a random gap is given by the following equation:

$$probability, pi(\alpha) = \exp[-it_{ig}(\alpha, \bar{\beta} / \beta)] - \exp[-(i+1)t_{ig}(\alpha, \bar{\beta} / \beta)] \quad \text{(Equation 8.2)}$$

where: t_{ig} represents an individual critical gap, α represents the smallest accepted gap by an individual driver, and $\bar{\beta}$ represents the expected gap value from a stream of gaps.

Models such as that of Pollatschek and colleagues (2002) could be usefully incorporated into micro-simulation tools to adequately represent the intricacies and complexities of variant gap-acceptance behaviour

8.2.2.3 Lane-changing behaviour

The modelling of lane-changing behaviour in most micro-simulation models is at present restricted to dual carriageways and multi-lane motorways. The modelling of urban networks and isolated intersections therefore generally lacks this potentially unsafe form of behaviour. Similarly, problems related to the process of parking and parked vehicles on urban link roads are very rarely modelled.

Modelling lane-changing behaviour is particularly difficult due to the following factors amongst others:

- the inherent differences in discretionary and mandatory lane-changing behaviour, the effect of close following vehicles and the identification of thresholds over and above which a driver will be triggered to change lanes if a suitable gap exists
- the anticipation of gaps in right and/or left-hand traffic streams
- courtesy yielding and ‘pushing’ into gaps
- the urgency of a lane-changing manoeuvre due to the need to turn off a motorway or due to slow-moving vehicles that have an experienced delaying effect on the driver
- the tendency to keep to the right (in right side traffic) depending on prevailing speed levels and individual speed preferences in normal driving conditions, and the tendency to fill all lanes in queue situations
- the compliancy of drivers with regard to the speed limit and traffic regulations such as overtaking on the inside

Arguably, lane-changing is the most complex interactive and adaptive behaviour to model as it involves elements of both car-following and gap-acceptance while travelling at speed. Furthermore, in complex motorway environments, a lane-changing vehicle must interact with vehicles travelling both in-front and behind, and vehicles to the left and right.

8.2.2.4 Reaction time, inattention, and non-compliancy

Many micro-simulation models also include variables that are designed to reflect road-user reaction time and/or inattention, and compliancy with existing traffic rules and regulations (e.g. adherence to the speed limit, driving against a red traffic signal). There is a wealth of evidence to suggest that inattention, delayed reaction and red-light driving have a negative safety impact (see e.g. Evans, 1991, Englund *et.al.*, 1998).

The reaction time and inattention parameters are often misused in simulation modelling. This is due to the fact that they are often applied irrespective of the situational context in which they were originally recorded. In some cases, these measures introduce an element of driver variability and are therefore inappropriately used for the purposes of model calibration or validation. The misuse of such parameters inevitably results in unrealistic road-user behaviour and unduly influences measures related to traffic safety.

For red-light violations, some simulation models have inbuilt probability functions, such as a ‘reaction-to-amber’ function, that can be used to define stop or go behaviour when faced with the onset of amber while in a potential dilemma zone situation. This type of probability function is usually based on empirical measures of vehicle speed and distance in relation to the signalled stop line (see Archer and Al-Mudhaffar, 2004).

8.2.2.5 Variation and the cautious-aggressive continuum

Some micro-simulation models also incorporate an index-variable related to an assumed 'cautious-aggressive' continuum. This is used in order to introduce a representative degree of variability among road-users. In its simplest form, this index divides a population of drivers into a number of categories with varying levels of aggressiveness. Thus, along a continuum between 0.00 and 1.00, drivers that are randomly assigned a value of 0.95 are assumed to have a high level of aggression and those assigned a value of 0.05 are assumed to be overly cautious. These values can be used as a percentile or index to sample behaviourally divergent distributions such as those for desired speed or car-following safety distance. The index value thereby allows suitably 'aggressive' or 'cautious' parameter values to be consistently sampled and used during the simulation.

While the general concept of behavioural clustering is sound, there is often little empirical support for this type of behavioural indexing. This is probably due to the fact that large-scale resource-demanding experimentation, probably involving the use of driving simulators and instrumented vehicles, would be needed in order to establish such relationships. Consequently, it is possible (if not likely) that the behavioural variance introduced by the use of parameters such as this is misrepresentative. There are other approaches that can be used to introduce representative amounts of behavioural variance in simulation models, such as the use of fuzzy logic and genetic algorithms (see e.g. Kosonen, 1999).

As for reaction time, inattention, and non-compliance, there is also a danger of misuse with the use of index-variables. It might be possible, for example, to increase aggressiveness for the purposes of model calibration. While this might be disregarded in simulation models that are concerned primarily with traffic performance or capacity assessment, such measures are likely to lead to greatly distorted and inaccurate results in simulation modelling related to safety assessment and prediction.

8.2.3 Other variables with an identified safety influence

Besides the behavioural sub-models that can be applied to different road-users, there are a great many other important variables used in simulation models that have an important influence on safety. Many of these are obvious, given that they are also recognised as safety influencing factors in real-world scenarios (see Chapter 5).

8.2.3.1 Speed (desired, average) and speed variation

Desired speed, actual average speed, speed variance and speed compliance are also of considerable importance in safety related simulation modelling. Desired speed is essentially an individual (behavioural) attribute that is often assigned randomly to drivers from an observed or hypothesised distribution. Some micro-simulation modelling environments allow the user to define a distribution of desired speeds, occasional in relation to particular stretches of roadway or network areas, or in relation to different road-users.

Essentially, desired speed represents the speed at which drivers will travel if they are not restricted by other road-users, restrictive objects in the roadway, or various forms of traffic regulation. The distributions of desired speed used in simulation models are ideally based on empirical measurements that reflect speed in free-flow conditions.

The effect of a desired speed distribution can be measured at particular points in a model where a similar average speed and a similar level of speed variance should be obtained in comparison to measures observed in the field. For simulation models aimed at traffic safety estimation, attention to detail with regard to different measures of speed is a particularly critical issue. According to prevailing theory, increased average speed may show a tendency to increase the severity of accidents and the severity values of proximal safety indicators, while increases in speed variation may cause an increase in the number of safety critical events.

8.2.3.2 Traffic flow, composition and origin-destination data

The relationship between traffic flow and safety has been described earlier, both with regard to predictive modelling (see Chapter 4), and with regard to their influence on safety (see Chapter 5). It is generally assumed that elevated traffic volume increases the risk for accident involvement by increasing levels of exposure, and by placing higher demands on road-user interaction at intersections. At intersections in particular, greater volumes of traffic on the primary road make the process of gap-acceptance more difficult. However, it is also true that greater traffic demand and higher flow rates reduce average speed thereby resulting in accidents of less severity, where and when they actually do occur. This is also suggested by the accident statistics in and around the Stockholm area, which show higher numbers of police reported accidents (and therefore elevated accident risk levels for drivers) during the morning and afternoon peak hours when the traffic demand is at its peak (GFK, 2000).

The possible safety influence of different turning movements, variations in origin-destination data and the effect of different forms of traffic regulation have been discussed previously in Chapter 5.

A further related issue of relevance in traffic simulation, concerns the correct representation of traffic demand at model boundaries. Generally, it is useful if traffic flow rates, turning-percentages and/or origin-destination matrices, and traffic compositions are made to vary in accordance with time in order to capture an appropriate level of detail. It is also important to use a suitable time-resolution in order to capture peaks within peaks in traffic volume, and the movement and composition of tidal traffic during morning and afternoon peak periods. A number of other problems associated with model boundaries in simulation modelling are discussed by Burghout (2004)

8.2.3.3 Vehicles performance characteristics

There are also a number of safety-relevant vehicle performance characteristics that are vehicle class or vehicle type dependent. These include amongst others desired and maximum acceleration and deceleration rates. In detailed models, the functions that describe acceleration and deceleration characteristics should include a degree of variation among vehicles of a similar class and should be related to speed (acceleration is generally slower at higher speed). For heavy goods vehicles, it can also be useful to consider power-to-weight ratios. The concept of (varied) desired acceleration and deceleration distributions in addition to maximum rates is also useful in that there is a distinction between emergency braking and normal braking. Variation in the physical dimensions (length and breadth) of vehicles within different vehicle class categories is also important in order to achieve a representative vehicle composition in a simulation model.

8.2.3.4 Simulation time-resolution

An important global simulation parameter that has been shown to have a significant effect on the performance of any discrete time-based simulation model is the time-resolution or update-cycle frequency. The sub-models that govern the interaction between vehicles are likely to be more effective and representative of real-world behaviour if they are allowed to operate at a higher time resolution (i.e. tenths of seconds). A side-effect related to the use of high time-resolutions is the increased demand on processing power. Some older models also have implicit dependencies between the time-resolution used and behavioural models. This was previously the case with the conceptualisation of reaction time in some car-following models, where the reaction time was supposedly equal to the time-resolution.

In a study by Brackstone and McDonald (2003), it is recognised that smaller time-steps can provide flexibility in the modelling of certain traffic processes, but also that some human based control processes might be more realistically modelled using a lower resolution. A lower resolution (e.g. 1 second) might allow for the occurrence of road-user errors and the division-of-attention between different driving tasks. Young, Taylor and Gipps (1989) also recognise the potential of this parameter to affect interactive processes in simulation models, and therefore also safety.

8.2.4 Calibrating and validating simulation models for safety estimation

Simulation model calibration generally refers to the process in which the individual components of a simulation model are adjusted or finely tuned so that the model accurately represents the data collected from field measurements according to predefined statistical tolerance levels. The components or parameters of a simulation model that require calibration most frequently include the following: (see e.g. Milam & Choa, 2000; Chu *et.al.* 2004):

- Traffic control operation
- Traffic flow characteristics
- Driver behaviour

Validation on the other hand, is concerned with testing the accuracy of the model by comparing traffic parameter values generated by the simulation model with values derived from relevant empirical data that has been collected in the field. Validation is often described as being “*unequivocally linked*” to calibration in an iterative process where successive adjustments aim to improve the ability of a model to replicate qualitative and quantitative aspects of behaviour and performance measured in the field (see e.g. Milam & Choa, 2000; Chu *et.al.* 2004).

Quite often simulation models contain a wealth of variables to describe traffic control operation, traffic flow characteristics and driver behaviour. Usually, the default values that are provided in a simulation software tool are based on empirical background work in relation to specific traffic conditions and environments. These values usually require adjustment as a normal part of the calibration process. Calibration variables have the ability to influence an entire modelled network or particular parts, such as different types of link roads or intersections, or different classes of vehicles. All changes to the model parameters should (at least in theory) be based on relevant measurements and should be justifiable by the modeller.

Typically, calibration parameters from the simulation runs should be within five per cent or one standard deviation of actual observed values, for the observed and simulated time-periods in question (Milam & Choa, 2000). To compare the accuracy of the simulated values against those for a particular traffic variable there are many different standard statistical methods (e.g. t-tests, Chi-2 tests, various forms of Analysis of Variance, etc.) and special statistical models such the GEH-statistic that has become a standard for British traffic engineers to compare traffic flow rates (UK Highways Agency, 1996).

The GEH statistic is recognised as a useful measure as it considers both the absolute values of the values being compared, and their relative differences. A general rule of thumb is that the GEH-value resulting from a flow rate comparison calculation should be around 1.00 and less than 5.00 in a predetermined number of cases. If this is not the case, the modeller must investigate the causes for the discrepancy and recalibrate the model.

The equation for the standard GEH-calculation is shown below:

$$GEH = \sqrt{\frac{(Fl_{sim} - Fl_{obs})^2}{(Fl_{obs} + Fl_{sim})/2}} \quad \text{(Equation 8.3)}$$

Where: Fl_{obs} represents observed flow , and Fl_{sim} represents simulated flow.

Another important consideration concerns the number of simulation runs that are required to ensure statistically reliable results. In stochastic simulation models such as VISSIM, random numbers are used to generate traffic, and to assign different parameters values to routing choices, and various aspects of driver behaviour and vehicle performance. To ensure that there are no undesirable effects related to the use of one particular random number, multiple simulation runs using different random seeds are required. Results are then based on a median simulation run or averaged across a number of runs for each simulation scenario.

The number of required simulation runs can be determined using the mean and variance for one or several traffic performance measures. In the process of determining an appropriate number of runs, the means and standard deviations of chosen performance measures are examined following several runs in order to determine the number actually required. This process is continued until the means and standard deviations from all of the simulation runs are within certain predefined tolerance levels (see e.g. Hourdakis *et.al.* 2002). The equation used in this process is shown below:

$$N = t_{\alpha/2} * \left(\frac{\delta}{\mu * \epsilon} \right)^2 \quad \text{(Equation 8.4)}$$

Where: μ and δ represent the mean and standard deviation of the performance measure, ϵ denotes the allowable error specified as a fraction of the mean and $t_{\alpha/2}$ is the critical value of the t-distribution at the confidence interval of $1-\alpha$.

Models designed to estimate effects related directly or indirectly to traffic safety are likely to require a much more stringent criteria for calibration and validation than models that focus only on measures of traffic performance. Since traffic safety is related to the processes of interaction between road-users, it is important to ensure that the behavioural models related to car-following, gap-acceptance and lane-changing reproduce measures, and distributions of measures, that are similar to those observed and measured in the field.

Other parameter values that require careful calibration for modelling related to traffic safety, are those related to vehicle characteristics and performance (e.g. average and maximum acceleration and deceleration distributions)..

8.3 Summary: Simulation modelling and safety assessment

Many of the potential limitations and possibilities related to constructing micro-simulation models for safety assessment and prediction have been highlighted in this chapter. Presently, there are few micro-simulation modelling environments that are capable of representing the high level of detail and flexibility required for this type of work, and even fewer that incorporate functions to identify and record safety relevant output.

In order to be able to conduct safety-modelling simulation experiments, many different types of detailed and consistent data are required in relation to the studied traffic site, along with measures of proximal safety to compare against simulation output. Similarly, it appears to be of critical importance to achieve representative levels of variation in fundamental driver behaviour models and parameters, particularly those that have an identified safety relevance (e.g. desired speed, desired average deceleration, and parameters in car-following and gap-acceptance sub-models). This is the approach adopted in the simulation studies presented as part of this thesis. Given that appropriate and realistic levels of variance are achieved, safety-relevant behaviour is expected to emerge from the simulation model. The quality of this behaviour will however, will be greatly dependent on quality of the input data and many aspects related to the quality of the simulation tool with regard to the internal structuring and representation of the input data with which it is provided.

There are a great many conceptual problems with this type of modelling. Many of these arise from the lack of representation of covariance and dependencies between different sets of data, particularly with regard to behavioural variance. These factors intrinsically structure data in ways that are difficult to represent in abstract models. From a scientific point of view, the increasing levels of detail in simulation models and new modelling approaches present a potential for '*safety simulation*' that must be investigated and systematically studied in order to generate new knowledge and further this particular line of research.

Case study 3:

9. Estimating levels of safety at a suburban T-junction using dynamic micro-simulation modelling

Summary

This work is a continuation of the study presented earlier in relation to the use of different proximal safety indicators at three T-junctions in the urban and suburban environment (see Case Study 2 in Chapter 7). The present study investigates the possibilities and limitations of a micro-simulation modelling approach for safety impact assessment based on proximal safety indicators. The detailed data that was collected and analysed in relation to the Täby T-junction is used as a basis for this simulation study. An abstract representation (i.e. a model) of this junction has been designed in the VISSIM simulation environment using an aerial photograph and knowledge regarding the layout and functionality of the traffic site.

A key issue in this work concerns the modelling of gap-acceptance behaviour. The data collected suggests that the standard fixed critical-threshold approach adopted by many simulation models is inappropriate for safety modelling purposes. A probabilistic gap-acceptance function has therefore been developed. This is based on probability functions determined through the analysis of empirical gap-acceptance data using binary logistic regression. A further critical issue concerns the passage of traffic through the junction, and the distribution of time-gaps in the main priority traffic streams. An unrepresentative time-gap distribution and arrival process in relation to the various yielding points would result in too many longer or shorter time-gaps, thereby unduly influencing the gap-acceptance process. A detailed calibration of the car-following model is therefore a critical requirement in order to ensure that the time-gap distributions accurately represent those recorded at the studied T-junction site.

This simulation study evaluates model performance with regard to three different scenarios, each representing a time-period with different traffic conditions. These scenarios represent: morning-peak, off-peak and afternoon-peak traffic. The main objectives of the study are related to the practical application of dynamic time-based simulation modelling for safety impact assessment and prediction purposes, where safety is measured in terms of the frequencies and severities of proximal safety indicators. Presently, there are few examples of safety estimation based on micro-simulation modelling in the literature. The work presented here is based on the assumption that the use of sufficiently detailed data, and an accurate representation of important safety relevant interactive processes in a dynamic modelling environment, will result in similar frequencies and severities of proximal safety indicators to those obtained from real-world studies. This type of dynamic and complex traffic system modelling has major implications for transport planning and traffic engineering work in the future, particularly for the preliminary estimation of safety and traffic performance impact at specific facilities where alternative designs and safety-influencing measures are to be implemented.

9.1 Background, aims and limitations

An in-depth discussion regarding the use of micro-simulation modelling for safety impact assessment and prediction was given in the last chapter along with a description of some of the more important parameters and processes that need to be considered. Past and present literature reveals only a handful of attempts at “safety simulation”, many of these reveal inconclusive results and suggest the need for further research. However, the potential of this particular area of application is well recognised (see e.g. Cooper and Ferguson, 1976; McDowell *et.al.*, 1983; Sayed, Brown and Navin, 1994; Algiers, *et.al.*, 1997; Bloomberg, Swenson and Haldors, 2003; Brockfield, Kühne, Skabardonis, and Wagner, 2003). Currently, attempts are underway at the FHWA to develop an integrated framework (SSAM) for the derivation of proximal safety indicators from simulation models (FHWA, 2003).

The present simulation study can be regarded as experimental in nature, representing an attempt to put many of the recognised theoretical issues into perspective through an approach based on practical application. A precondition of this study, in light of the discussion regarding the use of simulation parameters and modelling presented in the last chapter (Chapter 8), is that the simulation should be based, as far as possible, on empirical data collected from site that is modelled. Furthermore, as few unvalidated assumptions as possible should be made regarding road-user behaviour. The detailed data collected and analysed in relation to the Täby T-junction (see Chapter 7) is used as a empirical foundation for this work, and a suitable model of this particular site is developed for simulation purposes.

The main aim of this study concerns the development of a functional and representative approach to ‘*safety simulation*’, where the dynamic and complex interactive behaviour of modelled entities (i.e. road-users, vehicles and the traffic environment) reproduces similar frequencies and severities of proximal safety indicator measures to those found in a corresponding real-world situation. This is to be achieved by the use of detailed empirical data and a stringent calibration and validation process that considers critical safety relevant processes and traffic parameters. It is expected that this work, whether successful or not, will reveal many of the potential limitations and possibilities associated with this type of modelling, and will serve to identify and recommend improvements specific to the modelling approach adopted and actual simulation tool used.

This type of modelling has also important implications for transportation planning and traffic engineering work in the future, where there is an increasing need for methods and modelling approaches to support site-specific safety impact assessment. Simulation allows specific traffic facilities to be modelled dynamically in great detail in a safe off-line environment. A large number of factors that have a direct or indirect influence on traffic safety and performance can be represented and varied in a model, including: flow rates, turning movements, average speeds and speed variance, signalling, various aspects of road-user behaviour, and aspects related to traffic site geometry and design. The use of simulation models allows the user to estimate the potential effects of various new or alternative safety-related measures at an early stage in the research and development process, and to test sensitivity with regard to many other influential parameters.

The simulation study is limited to the study of a single unsignalised T-junction (Täby). Arguably, it would be useful to simulate the traffic conditions at all three of the junctions that were studied and reported in Chapter 7. One of the main reasons for selecting this particular junction is related to the limited number of pedestrians and cyclists using the two pedestrian crossings. Cyclist and Pedestrian behaviour, while possible to emulate in a simulation environment, adds a great deal of complexity to the modelling work.

Given the small number of safety critical events and limited influence these road-users had on traffic performance at this junction, these classes of road-user were excluded from the simulation study. Given the preliminary experimental nature of the present study, it is considered important to minimise complexity and focus specifically on the interactions of vehicle-drivers. The need for studies that pay particular attention to the interactions between vulnerable road-users and vehicle traffic is recognised as an essential component of future safety simulation research and investigation. Further limitations specific to this particular simulation application, are described at a later point in this chapter.

9.2 T-junction data

A micro-simulation model of the Täby T-junction described in detail in Chapter 7 is used for the purposes of this simulation study. The following data is used for the purposes of this study:

- Traffic flow rates, turning percentages and traffic composition data (summarised at 15 minute intervals)
- Measures of speed – average (harmonic) spot speed and standard deviations for priority traffic streams, also free-flow speed distribution data for priority traffic streams (summarised for each two-hour test period)
- Car-following and vehicle arrival (time-gap) data for priority traffic streams (summarised for each two-hour test period)
- Gap-acceptance and rejection data in the form of discrete distributions for each yielding situation (summarised for each two-hour test period)
- Proximal safety indicator data (frequency and severity) for:
- Post-Encroachment Times (PETs)
- Time-to-Collision events (TTCs)
- Time-to-Accident (TAs) representing serious conflicts in accordance with the Traffic Conflict Technique

9.2.1 Traffic flows, compositions, and turning percentages

The traffic flow data, turning percentages and traffic composition data are described in detail in Chapter 7 (Section 7.3.1.2). For simulation purposes, the flow data is summarised in 15 minute intervals for each of the three two-hour simulation scenarios. Turning percentages and traffic compositions are specified individually for each two-hour scenario.

9.2.2 Speed measures

The various measures of speed recorded at the study site are described in Chapter 7 (Section 7.3.1.3). Free-flow speed data is also used for the purposes of defining driver's desired speeds in most simulation models. These free-flow speed distributions are shown below in Figures 9.5(a–c) for each direction of entry on the primary road and the secondary approach road for the three different simulation scenarios respectively. This data was derived from the logging of vehicle passages using pneumatic tubes (loops) at a point 100 metres before the junction. To ensure that the speeds recorded were from free-flowing vehicles a minimum time gap-criteria of six seconds was imposed.

While the free-flow speed data is used as input, it is important to collect data during each simulation run to ensure that the average spot speed and level of variation is consistent with the field data for each of the three simulation scenarios modelled. The interactions between vehicles, particularly turning vehicles, and high traffic volumes will have an effect on measures of spot speed. Ensuring correct speed levels is also a critical factor that determines the frequencies of safety critical events and their outcome severity.

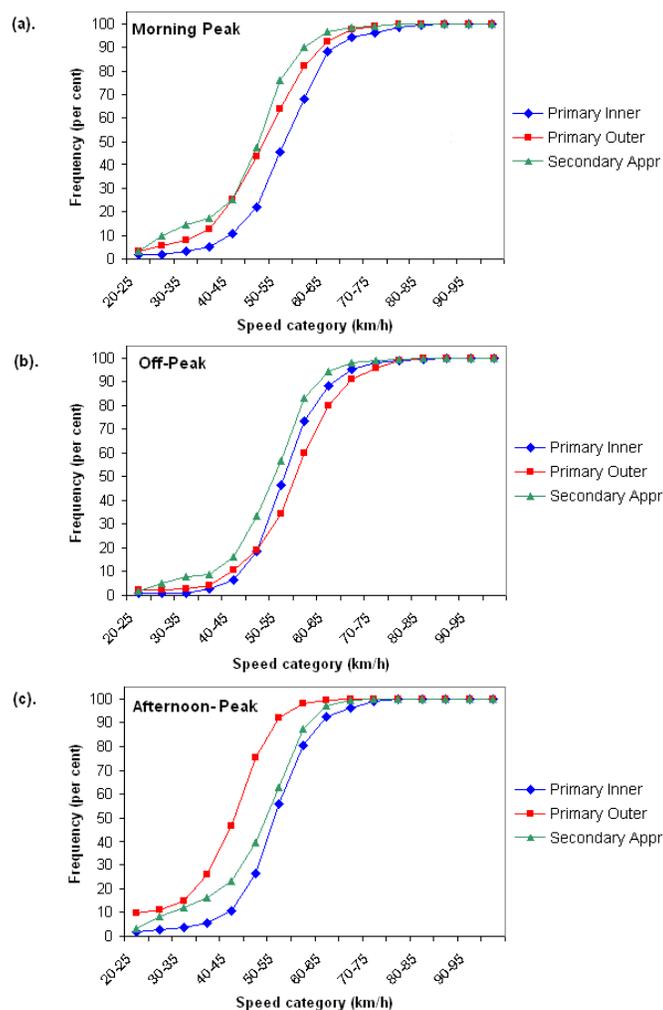


Figure 9.1 a-c Cumulative free-flow speed distributions for the junction approach roads

9.2.3 Car-following and vehicle arrival data

The distributions of car-following time-gaps on each priority approach traffic stream are described in Chapter 7 (Section 7.3.1.4). For the purposes of this study, this data is of great importance in order to provide a similar distribution of gaps to yielding vehicles. A distribution with too many larger or shorter gaps will result in unrealistic gap-acceptance and will undermine the validity of the proximal safety indicator measures recorded during each simulation model runs.

9.2.4 Gap-acceptance data

The probability functions for each yielding situation in each of the three time-periods are shown below in Figures 9.2(a-c).

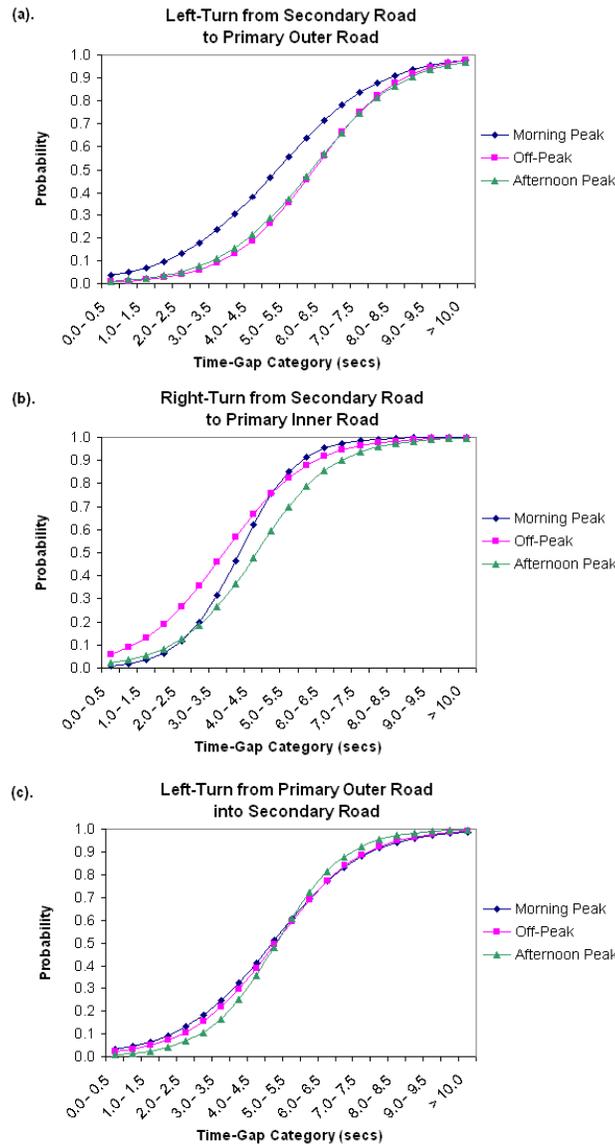


Figure 9.2(a-c) Probability functions for the acceptance of time-gaps in different yielding situations and time-periods

In the simulation model, the lower ends of the probability functions are truncated to the time-gap category containing the lowest observed time-gap. Gap-acceptance and rejection data in relation to each yielding situation is described in Chapter 7 (Section 7.3.1.5). This empirical data has been used as a basis for binary logistic regression analysis to establish probability functions for each yielding situation and each time-period scenario, based on the size of a gap (in tenths of seconds) in an approaching priority traffic stream (see Chapter 7, Section 7.2.10).

9.2.5 Vehicle acceleration and deceleration

Vehicle acceleration and deceleration is also an important issue in this study. Not only the average rates of deceleration and accelerating when stopping or slowing down to yield, or pulling out from a secondary road, but also deceleration behaviour in critical safety situations. In this simulation study, the validity of the safety indicators is dependant on both the reaction of drivers and use of available deceleration power.

Relatively few studies have focused specifically on acceleration and deceleration at vehicle junctions. Some important work in this area has however, been carried out by Akcelik and associates who have stressed the importance of accurately representing acceleration and deceleration in micro-simulation modelling (Akcelik and Besley, 2001a, 2001b; Akcelik and Biggs, 1987). A number of statistical models have been suggested on the basis of empirical data from real-world driving conditions in order to estimate and describe non-linear deceleration and acceleration profiles, average rates, and braking and acceleration distances and the times these processes take.

There are relatively few reports in the literature in relation to emergency braking. An earlier study by Hydén that looked at a safety indicator referred to as “Deceleration Time to Safety” (DST), where braking rates in excess of -6.00 metres/sec² were considered to be a level corresponding to emergency braking (Hydén, 1996). Evans (1991) also reports the possibility of achieving braking levels of around 1 *g*-force (-9.86 metres/sec²).

9.2.6 Safety indicators: TAs (Traffic Conflicts), TTCs and PETs

The proximal safety indicator measures used in the simulation study are the same as those measured by observation in the field, and determined through video-analysis. These include:

- Time-to-Accident measure determined for serious conflicts according to the Traffic Conflict Technique
- Time-to-Collision
- Post Encroachment Time

These proximal safety indicators have been described in detail in Chapter 5. The frequency and severity values for each proximal indicator during the three different time-periods are discussed in detail in Chapter 7 (Sections 7.3.1.6 to 7.3.1.8).

9.3 Simulation modelling

9.3.1 Choice of simulation tool

The VISSIM simulation tool was selected for the purposes of this particular study following a review of existing micro-simulation software, which included practical testing with PARAMICS and an adapted version of HUTSIM. There were a number of reasons for selecting VISSIM. Most of these were directly related to the level of modelling detail and general flexibility of this tool with regard to: roadway design, vehicle performance, and road-user behaviour.

The possibility to define special control functions using the vehicle actuated programming environment (VAP or VisVAP) was also a key issue given the need to accurately represent the process of gap-acceptance. VISSIM was found to be the most suitable modelling environment with regard to the main selection criteria.

The criteria for selection included the following:

- The possibility to define and use different road-user behaviour parameters and sub-models (car-following, gap-acceptance, lane-changing) for different vehicle types and/or links in the same simulation model
- The possibility to define vehicle performance parameters such as desired and maximum braking and acceleration per vehicle type and class
- The possibility to define time-specific traffic input including: input flows, turning percentages or origin-destination matrices, routing, and detailed vehicle compositions
- The possibility to define detailed rules for the interaction of different types of road-users
- The possibility to extract very detailed information for individual road-users at a high time-resolution (one-tenth of a second)
- The possibility to use detectors to record safety relevant data
- An open Application Programmer Interface (API) that allows the user to define added functionality and access objects and data in the model during run-time

9.3.2 The VISSIM micro-simulation tool

VISSIM is a time-based microscopic simulation tool that uses various driver behaviour and vehicle performance sub-models to accurately represent urban traffic and transit. Unlike many other simulation tools, it is not strictly node-link based. There are no predefined intersection types or malls, instead the user builds a network based on one or more aerial photographs or technical drawings, adding objects to the network at the exact point they are needed and where they will have the desired effect on road-users. This object-based solution is one that offers good modelling flexibility. The VISSIM simulation model has been validated against data from various real-world situations (Fellendorf & Vortisch, 2001). Simulation literature suggests that this tool is suited for the modelling of small to medium sized networks that require a high level of modelling detail (see e.g. TfL, 2003).

The flow of traffic in VISSIM is represented as the movement of individual driver/vehicle units. In theory, every driver has stochastically allocated behavioural characteristics and each vehicle has stochastically allocated performance capabilities. Consequently, when a driver is assigned to a vehicle, the driver's behaviour will be adapted to the vehicle performance characteristics. The attributes characterising each driver/vehicle unit include: behaviour of driver/vehicle unit (desired speed, desired acceleration and deceleration, sensitivity thresholds and parameters that determine behaviour); technical specifications of the vehicle (e.g. length, weight, engine power, maximum speed, acceleration and deceleration potential); and, interdependency between vehicles (relative positions of preceding and following vehicles on different lanes, and the positions of other objects).

9.3.2.1 Car-following behaviour in VISSIM

VISSIM uses a psycho-physical car-following model for longitudinal vehicle movement and a rule based algorithm for lateral movement that have been developed by Wiedemann (1974) at the University of Karlsruhe in Germany. Two separate car-following models exist, one (Wiedemann '99) is recommended for inter-urban motorways and the other for urban town traffic (Wiedemann '74). The movement of vehicles according to these models is based on behavioural assumptions regarding desired speed and gap-acceptance (PTV, 2004).

According to Wiedemann's model a driver/vehicle unit can be in any one of four states: free-driving, approaching, following, or braking (see diagram 9.3). In braking for example, a medium to high deceleration rate will be applied if the distance to any preceding vehicle falls below a desired safety distance. Acceleration or deceleration is the result of speed, speed differences, distance, and the individual characteristics of the driver/vehicle unit. Wiedemann suggests that the ability to perceive and estimate speed and distance varies among the driver population; these psychological aspects and physiological restrictions are therefore combined in the psycho-physical car-following model to provide a realistic and representative amount of variation (Wiedemann, 1974).

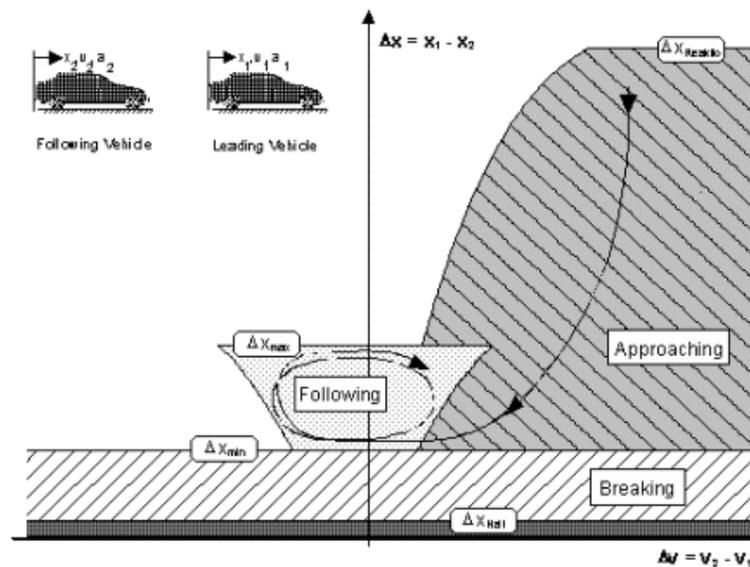


Figure 9.3 The basic principles of the Wiedemann '74 car-following model

In general, the Wiedemann 74 car-following model is simple and effective, and has been thoroughly validated against empirical data in a number of different traffic situations (Wiedemann and Reiter, 1974). The '74 model has two main parameters that are open to the user for calibration purposes in addition to a desired distance between stopped vehicles. Interestingly, the more complex '99 model contains 10 open parameters. The two parameters are described as *additive* and *multiplicative* parts of the desired safety distance BX_{add} and BX_{multi} respectively. Wiedemann recognises that human perception is imperfect and that drivers underestimate safe distances at higher speeds causing risky behaviour, for this reason the relationship between estimated and actual speed is described as a hyperbolic function. The safety distance influencing values can be adjusted to achieve suitable variation in the gap distribution, and are recommended by PTV for the process of calibrating saturation flows at stop lines (PTV, 2004).

9.3.2.2 Gap-acceptance behaviour in VISSIM

Gap-acceptance in VISSIM is determined using so-called '*priority rules*' that define the right-of-way and duty-to-yield behaviour of vehicle drivers and other road-users. These rules are flexible and require the placement of a stop marker on an adjoining road where there is a duty-to-yield, and a conflict marker on the priority road where the road-user has right-of-way. The general concept is similar to that of the '*critical gap*' (a gap that represents equal probability of acceptance and rejection) with no possibility to define suitable levels of variance around a mean gap-value. Thus, all gaps or lags in a priority stream that are less the stated value are rejected, and all gaps or lags that are higher will be accepted. An alternative approach is adopted for the purposes of this study, this includes the use of the Vehicle Actuated Programming (VAP) and probability functions determined using binary logistic regression analysis (see Section 9.3.4 below).

9.3.2.3 Vehicle characteristics in VISSIM

Vehicle characteristics can be specified in considerable detail in VISSIM. There is an object-oriented conceptualisation of vehicles into classes and types that is useful for the specification of technical details and creation of new vehicles. Besides variation in vehicle dimensions, a number of editable functions exist for: maximum acceleration, desired acceleration, maximum deceleration and desired deceleration. Each function is represented by curves indicating minimum, mean and maximum values plotted against speed. This results in a degree of variation between and among vehicle classes and types. Special functionality, is also provided for heavy goods vehicles such as power-to-weight ratios that influence speed on inclines and declines in the roadway.

Acceleration and deceleration patterns derived from studies in urban traffic with a specially instrumented vehicle, suggest that the braking and acceleration profiles fall within the boundaries of the suggested default functions in the VISSIM software (see Chapter 10, Section 10.2.2.8). These were also found to match values predicted by the acceleration and deceleration polynomial model of Akcelik and Biggs (1987). In future studies, it would be useful to perform more detailed validation studies with the instrumented vehicle in relation to safety critical braking to validate the default values suggested in the VISSIM software.

9.3.3 VISSIM, VAP and VisVAP

VAP is an acronym for '*Vehicle Actuated Programming*' and exists as a separate software module that is synchronised with VISSIM at run-time. There is also a '*visual*' version of this software that allows additional functionality to be expressed in flow-charts rather than as program code. This software communicates by extracting information from detectors and returning status control messages to various types of objects in a VISSIM model. The VAP and VisVAP software was originally intended to represent the functionality of signal controllers. VAP and VisVAP do not represent the type of highly flexible Application Programming Interface (API) that is found in PARAMICS, but is useful in some cases for the definition of additional functionality. At the time of writing, there is also the possibility to access VISSIM model objects at run-time through a specially developed COM-interface.

9.3.4 Development of a probabilistic gap-acceptance modelling approach

Gap-acceptance is highly complex driving task and is most commonly oversimplified for the purposes of simulation modelling. There are many factors that contribute to the high level of perceptual and cognitive complexity involved in this task, including the judgement of speed and distance for approaching vehicles in one or several traffic streams, and a simultaneous estimation of own speed and the distance to potential conflict points or yield lines. Furthermore, complex projections are required regarding the time and distance needed for acceleration or braking manoeuvres in order to avoid safety critical situations. Stop situations are slightly less complex to judge, given the stationary position of the vehicle in relation to the approaching traffic streams.

In some cases, yielding requires the driver to identify suitably large gaps or lags in traffic streams. Furthermore, situational complexity experienced by road-users can be reduced by breaking down the yielding manoeuvre into manageable stages. High levels of situational complexity with large number of dynamic objects and several sources of information that are important to the decision-making process, can lead to lapses and errors that greatly increase the risk for accident involvement (as discussed in Chapter 3, see e.g. Rasmussen, 1987; Reason, 1990; Wickens, 1992; Vogel, 2003). Furthermore, research has shown that humans are relatively poor at judging speed and distance (Wiedemann and Reiter, 1992).

In real-world situations, some drivers deliberately '*accept*' gaps that are too short in the knowledge that right-of-way vehicle drivers will adapt their speed accordingly. In other cases, particularly in congested and/or low speed conditions, some priority road vehicles may also perform '*courtesy yielding*' and allow yielding vehicles to enter or pass the priority road. What is often missing in simulation models, with regard to gap-acceptance behaviour is '*representative interactivity*' between drivers. Thus, if a driver in a yielding situation does accept a gap that is too short, this situation will generally be resolved by adaptive behaviour on behalf of the driver that had right-of-way (usually braking or swerving or a combination of both).

In most cases, the occurrence and severity of a safety critical event will be dependant on:

- the speed, acceleration capacity and length of the duty-to-yield vehicle and the distance to the projected point of conflict or conflict zone
- the speed, deceleration capacity and distance of the approaching right-of-way vehicle in relation to the projected point of conflict or conflict zone
- the attentiveness of each driver (i.e. how quickly the danger is perceived)

A probabilistic modelling approach is used to represent gap-acceptance behaviour in this simulation study. When a vehicle in the model arrives at a particular yielding situation, the arrival is recorded by a specially designated ‘arrival detector’. This detector, stretching 6 metres upstream of the yield line, records vehicle speed, type, length and detector occupation time. When the front-end of a vehicle occupies this detector, the process of gap-acceptance is activated. The calculation of a time-gap will include an estimation of the time for the yielding vehicle to reach the yield line, according to the speed and relative distance from this point.

The speeds and distances of approaching vehicles in priority traffic streams are estimated using a series of detectors. This information is used to derive the smallest time-gaps in each relevant traffic stream. For right-turns from the secondary road, and left-turns from the left-turning lane of the priority road into the secondary road there is only one conflicting stream of traffic. For left-turns from the secondary road however, there are two or more conflicting streams of traffic (depending on the existence of turning lanes) and the identification of a suitable time-gap is more complex. For this particular yielding situation, time-gaps are calculated in accordance with an estimation of the time required to reach secondary yield points. In such cases, the defining gap in the acceptance/rejection process will be the one that is shortest bearing in mind the distance to the true yield point.

When a gap has been identified, acceptance or rejection will depend on the probability function determined by binary logistic regression analysis for that particular yield manoeuvre and the time-period scenario in question. Each new gap that passes a position perpendicular to the yield point in a particular traffic stream is assigned a new random value between 0.000 and 1.000, where all values have an equal probability of selection. This random value is then compared to a probability value determined by the binary logistic regression function, if the probability value is greater than the randomly assigned value the gap will be accepted otherwise rejected (see Figure 9.4 below). Larger gaps have a higher probability and therefore are more likely to be accepted than smaller gaps.

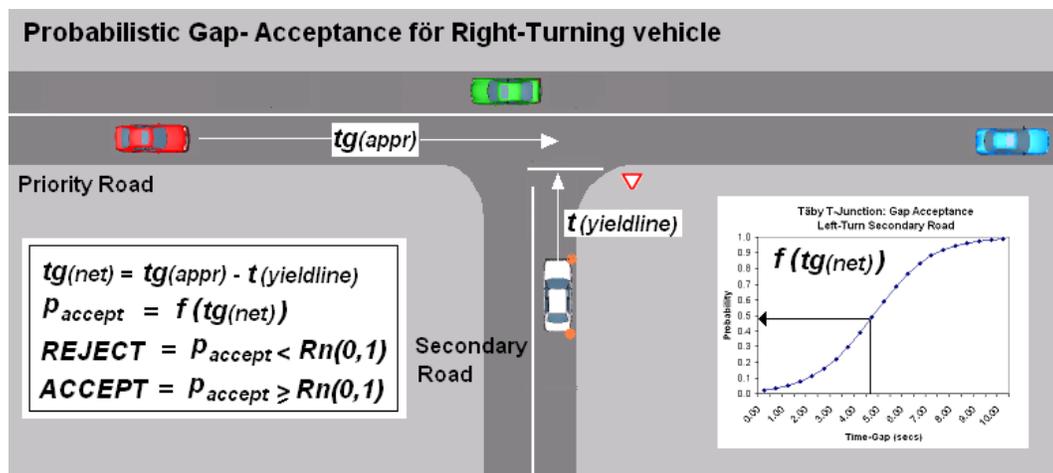


Figure 9.4 Principles of probabilistic gap-acceptance exemplified for right-turning vehicle

As a vehicle approaches in a priority stream, the value from the binary logistic regression function (which is updated upon each 0.10 second update) becomes increasingly smaller and therefore more likely to be rejected. The vehicle is given a time-period of 1.00 second to complete the yield manoeuvre irrespective of the subsequent decreasing probability values. This occurs immediately after a suitably large gap has been identified and the driver accepts it. The size of this '*manoeuvre time-period*' in the simulation application is critical in order to prevent following vehicles to pass without determining their own probability of acceptance. It also prevents unrealistic start-and-stop behaviour.

In addition to each new time-gap being assigned a probability, each new vehicle arrival also causes the time-gap probability for that yielding situation to change. This creates a situation in some cases where vehicles may first reject a gap of a certain size, and then, at a later point in time, accept a similar or smaller gap. In the practical simulation application, the acceptance or rejection of each time-gap or lag is indicated to a yielding vehicle by a specially adapted signal placed at the yield line. Although an internal driver decision-process would be preferred, this is the only alternative using the VAP-module. The effect of the signal is, however, identical to that of an internal representation and allows the process of gap-acceptance or rejection to be visualised. The probability values and gap sizes can also be transferred to an on-line window during simulation for functional verification purposes.

For modelling purposes, it is important to consider the accepted gap-time as consisting of three separate elements including:

- The time taken to reach the conflict zone from the yield line
- The time taken for the vehicle to enter and leave the conflict zone
- A desired safety margin factor that is individual to the driver

Given this conceptualisation, aggressive drivers may have a behaviour where the safety margin is at a minimal level and hard acceleration is applied to reduce the time required to reach and pass a conflict area. This particular type of aggressive behaviour is not directly modelled directly in this study. However, there is a distribution of accepted gaps that includes those that are potentially short and unsafe, and some variation in the levels of desired speed, acceleration and deceleration in the model among different vehicle classes and vehicle types. The safety of the gap-acceptance process is also influenced by the length of the vehicles, this factor is also subject to type and class variation in the model.

The binary logistic functions for gap-acceptance for heavy goods vehicles and buses (all vehicles over 8 metres in length) were incremented by a factor of 1 second to account for slower acceleration rates and longer vehicle lengths.

Reactive behaviour on the part of the vehicle drivers on the priority roads was also implemented through the use of specially designed signals. These warning signals were only activated when there was a vehicle occupying the area between the relevant yield line and the end of the safety zone in question. This was intended to represent the inattentiveness of drivers, causing a variable delay from the time when the yield line was passed, and the activation of the warning signal that caused approaching priority vehicles to brake.

The amount of delay was determined by randomly sampling a Gaussian function with mean 0.50 seconds and standard deviation 0.15 seconds (minimum 0.00, maximum 1.00 seconds). The mean value is slightly lower than the average reaction time of 0.75 seconds (minimum 0.00 to maximum 1.50 seconds) that is often used as a *de facto* standard (see e.g. Bonsall, Liu, & Young, 2001). This is because drivers tend to be more alert (i.e. perceptually primed) when driving through intersections in comparison to situations such as motorway driving.

Observation of the video-data for the T-junction also indicated courtesy yielding in two types of situation. During the afternoon peak hour when there was a queue that extended through the inner-lane of the T-junction, there was a tendency for priority vehicles to allow yielding vehicles to pass into and out from the secondary road. Furthermore, there was also a random tendency for left-turning vehicles from the outer priority road lane to allow left-turning vehicles from the secondary road to assume priority when the vehicle on the secondary road had been waiting for a lengthy period of time (approximately 1 minute or longer). Both types of courtesy yielding were introduced into the model through the VisVAP module by introducing additional rules to control the gap-acceptance signals.

9.3.5 Simulation model limitations

While the aim has been to achieve a high level of representative behaviour, there are a number of recognised limitations and possible error sources that are not catered for:

- overtaking on the approach roads or within the T-junction is not permitted (and occurs very seldom in the real-world)
- no '*unusual*' manoeuvres are implemented such as '*U*' turns
- there is no pedestrian or cycle interference
- there is no restricted vision for drivers that might otherwise affect the gap-acceptance process
- drivers in yielding situations have only knowledge of closest time-gaps on each priority approach, this implies that some risky behaviour may occur in spite of a secondary gap that is larger and potentially safer
- the size of the '*time-gap*' on each priority approach is not subject to any perceptual distortion/variation such that longer gaps are underestimated and shorter gaps overestimated as suggested in the literature

Arguably, with regard to the last point above, the binary logistic functions representing the probability of accepting a gap might be more representative if they were based on speed and distance rather than just a combined time-gap measure. This would then automatically incorporate perception anomalies and the effect of restricted vision in one or more directions for each of the yielding situations. Unfortunately, it was not possible to extract vehicle information over a distance of 30 metres for vehicles approaching from the left on the inner priority road lane from the video-film.

9.3.6 Simulation model output data and post-processing

A series of detectors normally used for signalling were used in the simulation model for the purposes of capturing vehicle events as they occurred over time. The event data was recorded in a special file and used later for post-processing. Data was collected in relation to vehicle yielding and the occupation safety zones. In yielding situations, it was important to establish the time a vehicle arrived at the head of the queue before a yield line, the time it actually passed the yield line, and whether it actually stopped or continued without stopping. For these purposes, an arrival detector was placed immediately before the yield line and a passage detector was positioned immediately after it (see Figure 9.5a).

For the collection of relevant safety data including TAs, TTCs and PETs detectors were used to demarcate common conflict zones at the positions where links crossed each other in order to collect arrival, exit and occupancy data (see Figure 9.5b).

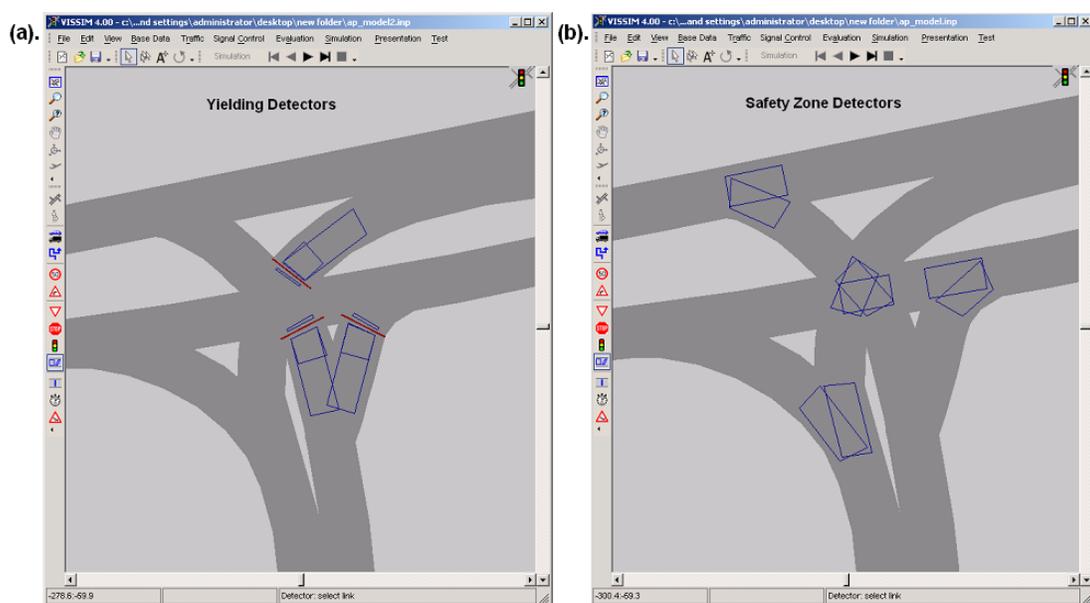


Figure 9.5(a,b) Use of detectors for vehicle arrivals and departures at yielding positions and for the collection of proximal safety indicator data

Besides the event data, a raw-data file containing the variable values for each individual vehicle was generated during each simulation run. The file contained a row of data for each vehicle at each time step during simulation, this included: simulation time, link number, link co-ordinate (distance/position on link), vehicle number, vehicle type, vehicle length, vehicle speed, vehicle acceleration. This 'raw data' was used for post-processing in order to analyse gap-acceptance behaviour and to derive safety indicator values. A special analysis program ('*VISSIM - Safety Analyser*') was written in order to process the large volume of data (3.5 million rows of data per two-hour simulation time-period) and to generate results reliably and consistently.

The result file from the analysis software includes the following information for each simulation run:

- Time-gap distributions for both priority directions measures at a central point in the intersection
- Accepted and rejected gap distributions for each of the three yielding situations
- For each priority road direction:
 - percent vehicles in car-following mode
 - shortest car-following time-gap
 - average speed and speed variation, and average free-flow speed
- Details of each recorded safety event including:
 - time and type of event
 - types of vehicles involved
 - vehicle speeds
 - deceleration rates
 - Time-to-Accident, Time-to-Collision and Post-Encroachment Time Values

9.4 Simulation experiment

The simulation experiment was designed to allow a comparison of the results for the three two-hour time-period scenarios, i.e. morning peak, off-peak and afternoon peak periods. Each simulation scenario is run a number of times with different random number seed numbers. The number of runs for each scenario is determined during the calibration process (see Section 9.5 below). The time-resolution (i.e. update cycle) for all simulation runs was set to 0.10 seconds, (i.e. 10 updates per simulation second) for the VISSIM simulation and for the VisVAP logic module (a special version of VisVAP was used that enabled updates at tenths of a second intervals).

9.5 Model calibration

9.5.1 Number of simulation runs

The number of simulation runs required was calculated in relation to each of the three time-periods using two separate measures, one related to vehicle flows and the other related to the measurement of average speeds for each priority road direction in the simulation model. The method suggested by Hale (1997), and usefully exemplified in a report by Milam and Choa (2000), was used. This method is based on the simulation results from a preliminary number of runs where the mean sample variance is compared to a predetermined confidence interval based on a *t*-distribution. Following a series of further runs, the actual number required can be estimated with good statistical accuracy.

Using this procedure and a 95 per cent level of confidence, the number of runs based on the sample variance of flow rates and average speeds suggested the need for approximately 15 runs per simulation scenario. Given the nature of this study, it was decided to conduct 20 simulation runs for each time-period scenario.

9.5.2 Car-following behaviour and time-gap distributions

A major calibration issue concerned the car-following model and the existence of a representative time-gap distribution. Initially, the comparison between observed and simulated data revealed a poor level of agreement with the standard default car-following parameters in the Wiedemann '74 model. This model has two key parameters for calibration related to the safety distance of vehicles when they are in a car-following state. The time-gap distributions were measured on the priority traffic streams at a point perpendicular to the adjoining secondary road. At the model boundaries, vehicles are generated in accordance with a mathematical function (usually a negative exponential or Poisson distribution function). The gaps between vehicles are influenced directly after generation by the car-following model. When the car-following behaviour of individual vehicles has had sufficient time to stabilise, the time-gap distribution can be measured and compared with observed values.

In this study, it is considered important to ensure that the distribution of gaps between 0.0-10.0 seconds and the number of larger gaps, are representative of recorded values from the real-world site. The distributions provide yielding vehicles in the simulation model with approximately the same opportunities for gap-acceptance as those observed in the field study. Too many or too few time-gaps at different time-intervals in the distribution will result in an unrepresentative gap-acceptance distribution for yielding vehicles in the model, and are likely to have an unwanted influence on the proximal safety indicator measures.

The psycho-physical car-following model of Wiedemann was first used in the simulation models with standard default values. While stable car-following behaviour emerged, the gap-distribution proved distinctly dissimilar in a number of cases to that derived from the real-world site. In most cases, the time-gap distributions *'peaked'* (i.e. were more frequent and less variant) at a point towards the lower end of the distribution. This difference is exemplified by the actual and simulated distributions for the morning peak flow in the outer priority lane as shown in Figure 9.6.

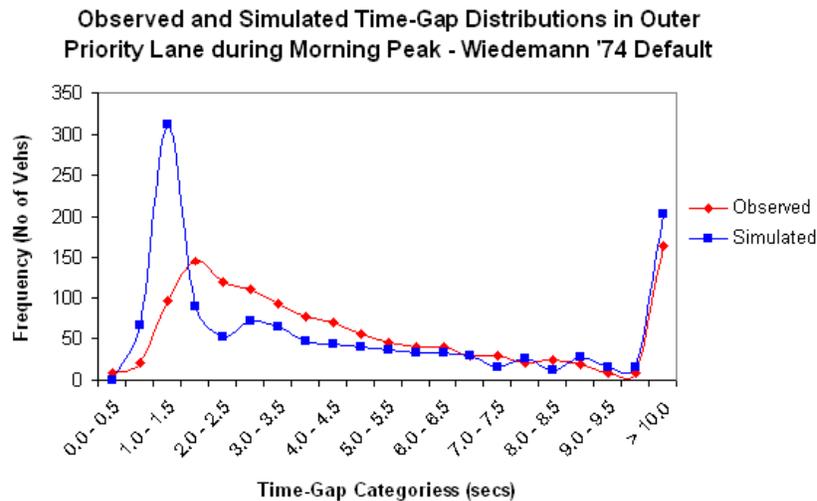


Figure 9.6 Example of differences in observed and simulated time-gap distributions using the Wiedemann '74 model default parameters

In order to calibrate the car-following model, a small study was carried out to test the effects of adjusting the two open parameters of the car-following model representing the additive and multiplicative part of the safety distance. For the example shown above, an far better fit was found by reducing the additive part of the safety distance from its default value of 2.0 to 0.5 and by increasing the multiplicative part of the safety distance from its default value of 3.0 to 8.5. The resulting time-gap distribution is shown in Figure 9.7.

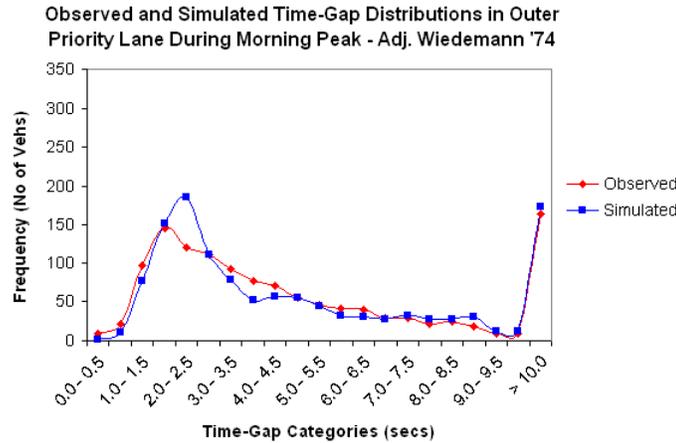


Figure 9.7 Example of differences in observed and simulated time-gap distributions using the Wiedemann '74 model with adjusted parameters

During the process of testing more suitable parameter values were found by identifying the point where an increase in either direction would result in a more inferior fit in accordance with a Chi-2 test. The values of the Chi-2 calculation were, despite continual improvement, overly significant indicating that a good fit had *not* been achieved. The use of the Chi-2 statistic as a goodness-of-fit test is less suitable for these particular distributions due to large amount of random variation in the data. A single divergent value among the 21 time-gap categories was sufficient to cause a significant difference.

The simulated time-gap distribution shown in Figure 9.7 shows some improvement although there is still evidence of an unwanted peak around the 2.0-2.5 time-gap category. This was also evident in the distribution for the inner priority lane during the afternoon peak period. This peak can be interpreted as representing the inability of the Wiedemann '74 model to account for individual variations in the choice of an actual following distance that is not dependent on (desired) speed. In the Wiedemann '74 model, the variation in following distance (headway) is derived from the two safety-distance parameters and speed. The relationship between distance and speed is represented as a parabolic function, to represent the human propensity to underestimate safe distances and drive more erratically at higher speeds (Wiedemann and Reiter, 1992). The basic function for calculating safety distance is shown in Equation 9.1.

$$\text{Safety distance, } ABX = AX + (BX_{add} + BX_{multi} * Rand(i)) * \sqrt{V} \quad \text{(Equation 9.1)}$$

Where: ABX = desired minimum following distance, AX = desired distance for standing vehicles, BX_{add} = the additive part of the desired safety distance, BX_{multi} = the multiplicative part of the desired safety distance, $Rand(i)$ = a random value from a normal distribution (mean 0.5, standard deviation 0.15), and \sqrt{V} = the square root of speed.

While the above relationship characterises an acceptable representation in most driving situations, it does not perform well when the volume and demand of traffic begins to reach the capacity threshold. In these cases, increasing the level of variation will also limit input generation capacity. In order to resolve the car-following problems in the current study, three different car-following models (i.e. different Wiedemann '74 parameter value sets) were used simultaneously in order to represent individual differences without causing too much larger variation in near capacity conditions.

This 'composite' car-following modelling solution, while successful (see Figure 9.8a), was difficult to calibrate (using a process of trial and error) and was only necessary for the outer priority lane during the morning peak and the inner priority lane during the afternoon peak. For all other time-gap distributions, a satisfactory fit could be achieved using a single car-following parameter set. Ideally, the car-following model should incorporate a degree of random safety distance variation that is independent of speed, while at the same time ensuring that a representative distribution of time-gaps is maintained with regard to upper and lower level boundaries and prevailing traffic conditions.

Calibration showed that the use of a parameter value of 0.5-0.8 for the additive part of the safety distance, and a parameter value of 8.5-10.5 for the multiplicative part of the safety distance provided the most representative time-gap distributions in each case for the single car-following parameter sets. For the two multiplicative sets, the three parameter sets were divided equally among only private car types (90 per cent of the traffic composition) and were based on a standard set of parameter values (as above) of 0.3-0.8 for the additive part and 8.5-10.5 for the multiplicative part. Thereafter, small increments were made for the two remaining sets by consistently adding 0.2 to the additive part and 1.0-2.0 to the multiplicative part until a suitable fit was obtained.

The averaged time-gap distributions from the calibration runs for both priority directions and each of the three different time-period scenarios and are shown in Figure 9.8(a-f) below.

As a statistical test to measure the goodness-of-fit between simulated and observed distributions, the categories of the time-gap distributions were transformed to percentage values before being subjected to a Chi-2 test. This conversion removed most of the variation caused by differences in the actual numbers of yielding vehicles among simulation runs and compares the relative forms of the two distributions. Based on a series of 10 simulation runs, averaged time-gap distributions were found to give insignificant differences in comparison to corresponding real-world data (5 per cent level of significance, and 20 degrees of freedom).

A further statistical test for the purposes of this study was derived from the GEH-statistic. The GEH-statistic is designed to distinguish the acceptability of observed and modelled flow rates. In this study, it is used for the comparison of discrete distributions, by first ensuring that the frequency differences in each category (i.e. time-interval) are below an acceptable tolerance limit (in this case a maximum GEH-value of 5.00), and secondly by calculating an average GEH-value for the whole distribution. The averaged value is useful for comparing relative improvements from one simulation run to another. The averaged time-gap distribution values were all found to provide a good match against observed data according to the adapted GEH statistic with values well below the designated maximum.

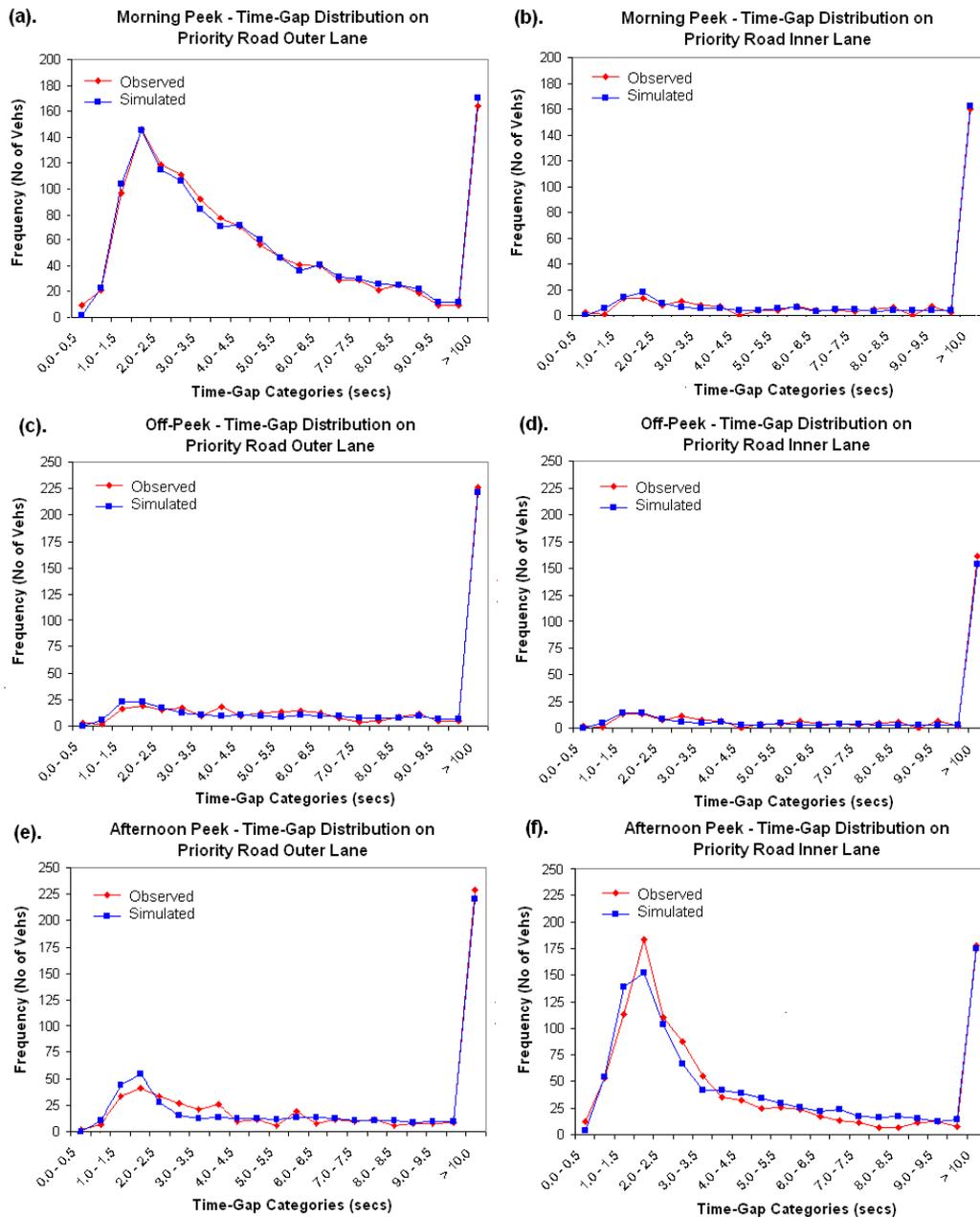


Figure 9.8(a-f) Averaged time-gap distributions in the inner and outer lanes of the priority road during the afternoon peak period

9.5.3 Gap-acceptance behaviour: accepted and rejected time-gaps

In order to validate the gap-acceptance behaviour of drivers, it is necessary to compare the distributions of accepted and rejected time-gaps for each of the three yielding situations (left-turn from secondary road, right-turn from secondary road, and left-turn from priority road) and each time-period scenario. Ensuring the correct number of rejected gaps is more difficult than the corresponding process for accepted gaps, given the probabilistic nature of the modelled gap-acceptance process. A single driver who is more ‘cautious’ may disregard a large number of gaps, whereas other more ‘aggressive’ drivers may find gaps immediately.

The accepted and rejected time-gap distributions for the simulated and observed data for the three different yielding situations in the morning peak scenario are shown below in Figure 9.9(a-f).

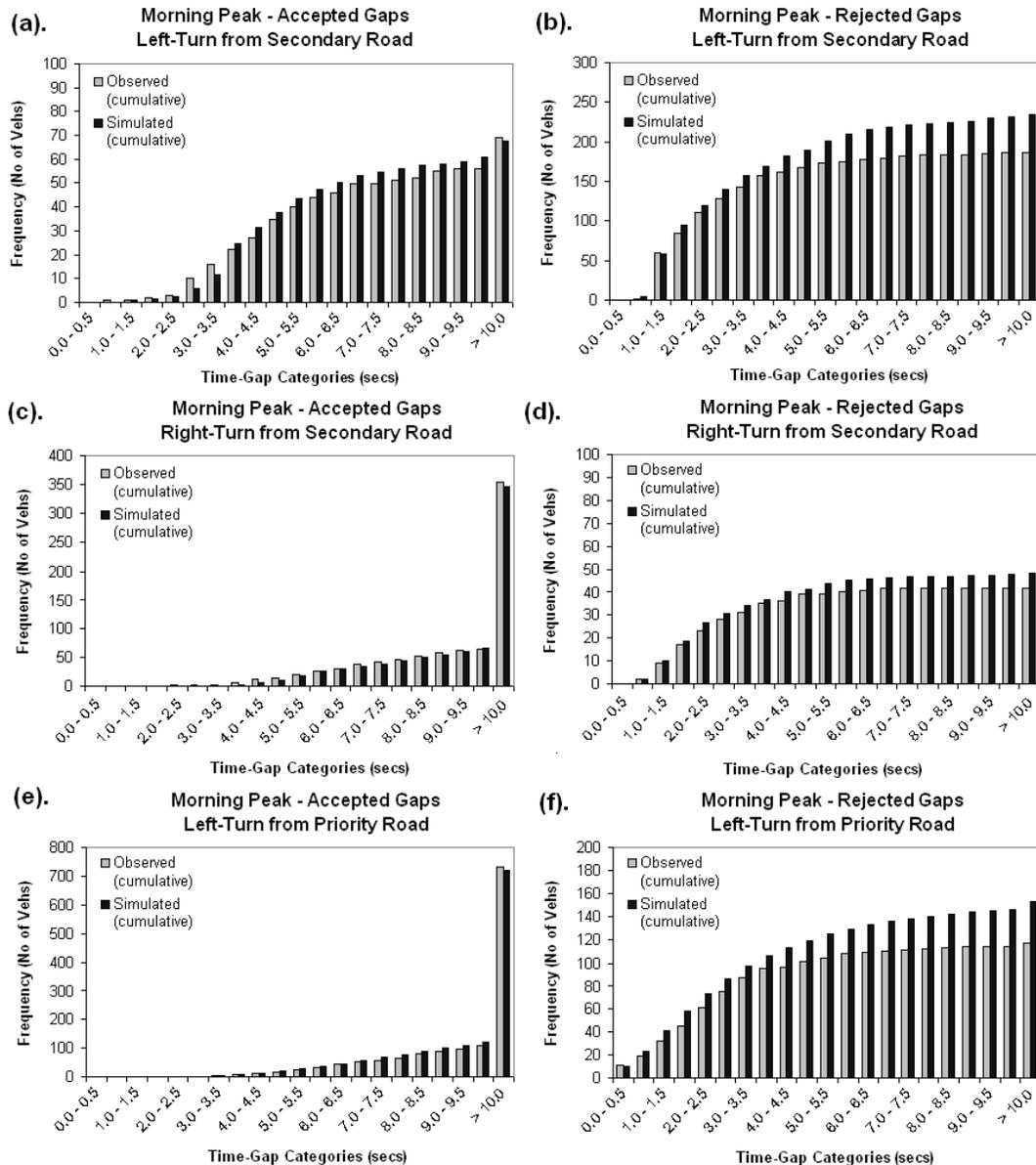


Figure 9.9(a-f) Accepted and rejected time-gap distributions for the three different yielding situations during the morning peak period

During this period, the simulation data for accepted gaps appears to be consistent with the observed data despite the elevated demand during this time-period in the outer priority lane caused by vehicles heading towards the city. The rejected gap distributions are less consistent, with larger numbers of rejected gaps for the two left-turn manoeuvres. This might be expected for the more complex left-turn into the outer-priority lane during congested periods if the gap-acceptance is less aggressive than the real-world situation. Even a slightly less aggressive acceptance of gaps can result in a large accumulation of rejected gaps.

The effect of overly sensitive rejection is found for the left-turn manoeuvres from the priority road. There are however, a far greater number of vehicles performing this particular yielding manoeuvre and the relative numbers of rejected gaps are in comparison quite small. This is in contrast to the other left-turning situation where larger number of gaps are rejected in comparison to those actually accepted.

The accepted and rejected time-gap distributions for the simulated and observed data for each of the three yielding situations in the off-peak scenario are shown in Figure 9.10(a-f).

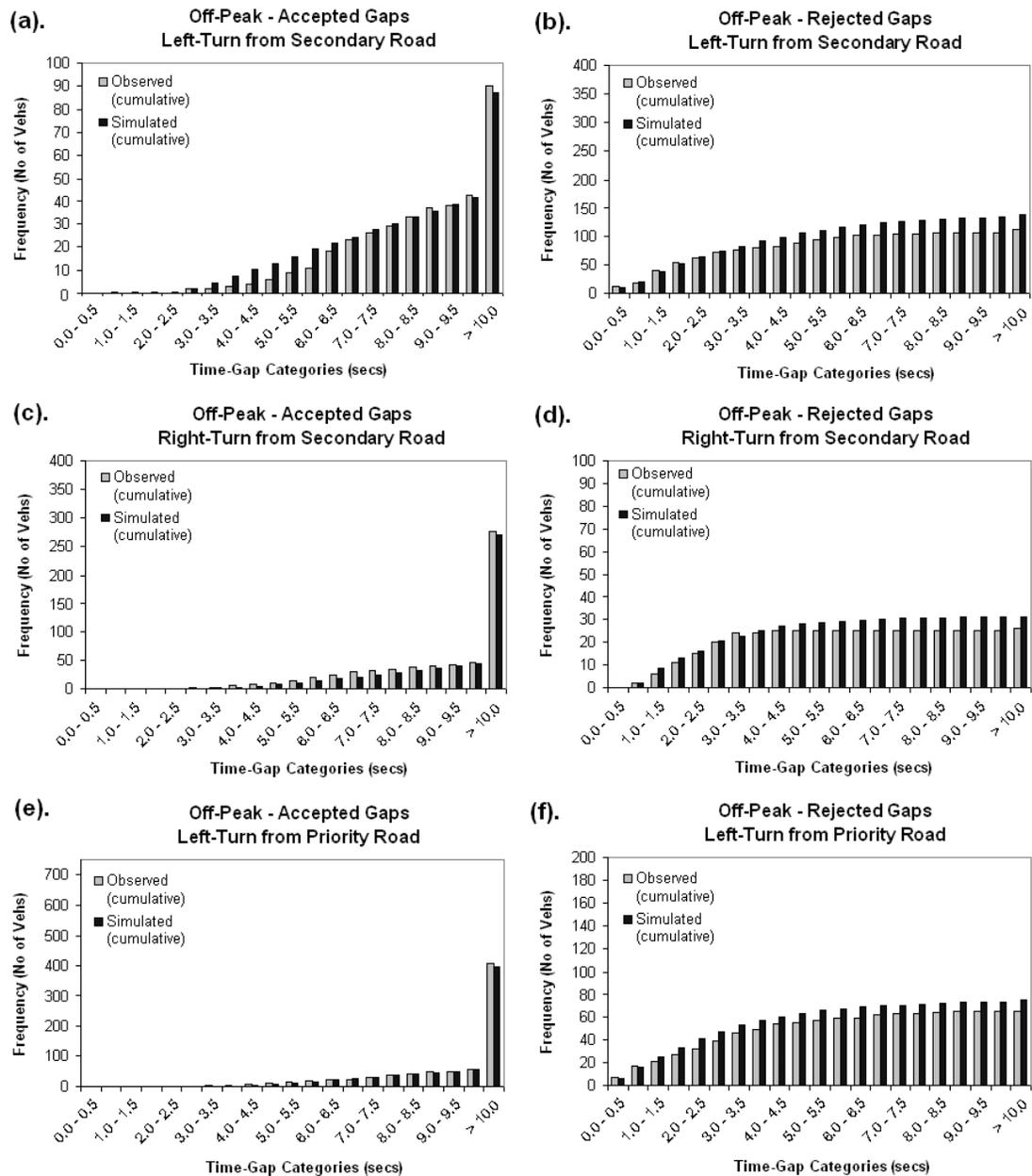


Figure 9.10(a-f) Accepted and rejected time-gap distributions for the three different yielding situations during the off-peak period

Again, the simulated off-peak period data representing accepted gaps is consistent with the observed data. For this time-period scenario, the rejected gap distributions are also quite similar with only a small tendency for over-cautious gap-acceptance behaviour as reflected by the numbers of rejected gaps. This is a direct result of the lower traffic volumes in each priority direction. There is also a slight deviance in the lower categories of accepted gaps for left-turning vehicles from the secondary road. This is most probably the result of the lack of an existing real-world effect whereby drivers are unwilling to accept shorter gaps, when it is known that a larger gap is most likely to appear within a short space of time during periods with low volume and little traffic demand.

The accepted and rejected time-gap distributions for the simulated and observed data for each of the three yielding situations in the afternoon peak are shown below in Figure 9.11(a-f).

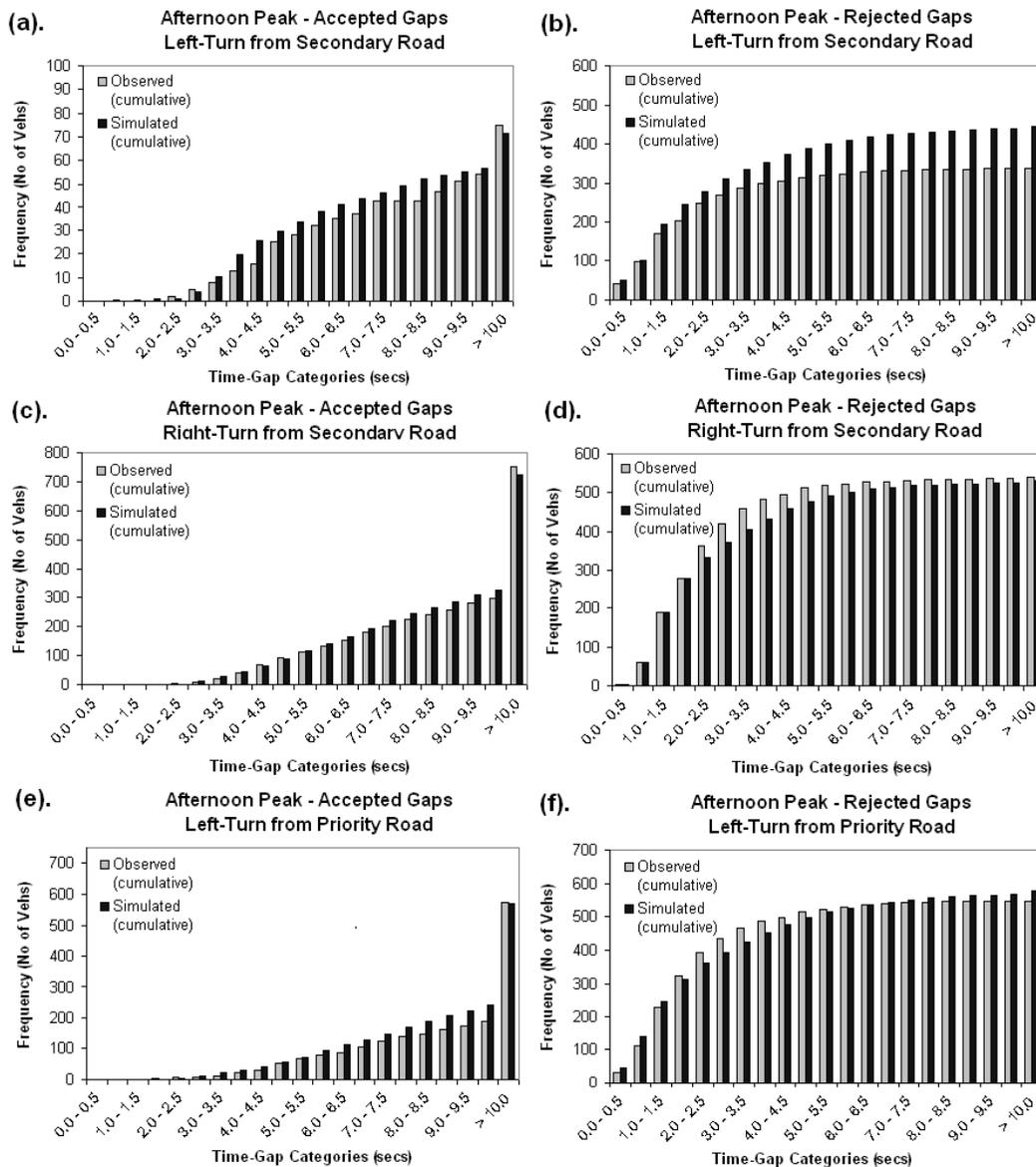


Figure 9.11(a-f) Accepted and rejected time-gap distributions for the three different yielding situations during the afternoon peak period

For the afternoon peak period scenario, there is good consistency between the simulated and observed data for accepted and rejected gaps, despite an elevation in traffic volume and traffic demand in both priority directions and from the secondary road. Again, the rejected gaps for left-turn yielding manoeuvres from the secondary road indicate that drivers in the simulation model were less aggressive than those observed in the real-world situation.

In this scenario, the gap-acceptance distributions from the simulations indicate a marginal tendency for drivers to accept slightly smaller gaps than those observed in the real-world situation. This is also reflected by the number of rejected gaps in all yielding situations except left-turns from the secondary road. The complexity of the left-turn manoeuvre from the secondary road results in a larger number of rejected gaps in all of the simulation scenarios. This is probably the result of an oversimplification in the simulation model of the gap-acceptance process with regard to this particular manoeuvre. In the real-world situation, the gaps in different traffic streams are likely to be valued differently by the driver, such that slightly shorter gaps may be accepted in certain traffic streams depending on the speed and distance values estimated for approaching vehicles, but also assumptions concerning their intent to stop or slow down at the junction.

Given the good level of correspondence for simulated and observed accepted gaps, which are a defining and critical factor for safety, the slight deviancy of the rejected gap distributions is recognised as an issue that requires further research and improvement. However, given that it is generally the larger rejected gaps that are the cause of this problem and that the accepted gap distributions are very similar to those observed in the real-world situation, this problem is not one of vital importance with regard to the generation of safety indicator data.

Some of the difficulties associated with calibration are highlighted here. As mentioned above, even very slightly over-cautious gap-acceptance behaviour drastically increases the number of rejected gaps. Similarly, incorrect time-gap distributions have a noticeable effect on the simulated gap-distributions. Testing with the aim of fine-tuning the gap-acceptance probability functions to achieve a better fit, also proved highly difficult given the sensitive balance of the many numerous parameters such as the flow rates speeds and speed variance.

Statistical tests similar to those performed for the distribution of time-gaps on the priority road were also used to test the level of consistency between observed and simulated time-gap distributions. For statistical testing, the non-cumulative values were used. The Chi-2 test based on percentage values (5 per cent significance level and 20 degrees of freedom), showed no significant differences for any of the distributions of accepted gaps indicating that the distributions are proportionately correct. A comparison based on actual frequency values for the discrete time-gap intervals in the gap-acceptance distributions showed clear significant differences in all comparison cases. Tests using the adapted GEH-statistic (maximum accepted value of 5.00) also indicated a good fit for the gap-acceptance distribution data.

For the rejected gap-distributions, three cases were identified with an unacceptable goodness-of-fit. These included the left-turn yielding manoeuvre from the secondary road into the outer priority lane during the morning and afternoon peak periods, and the left-turn manoeuvre from the outer priority lane into secondary road. These were also identified by the adapted GEH-statistic. The remaining six cases were also found to show an acceptable goodness-of-fit in accordance with the Chi-2 test based on percentage values (5 per cent significance level and 20 degrees of freedom) and the GEH-statistic with a maximum accepted value of 5.00.

9.6 Model validation

9.6.1 Traffic flow rates and turning movements

Traffic flow rates and the numbers of turning vehicles were validated against the original observed data to ensure that the correct amount of traffic was generated in the simulation model. The data for all origin-destination pairs for each of the three simulation time-period scenarios is shown below in Table 9.1. The GEH-statistic is again used as a statistical measure to test the level of agreement between observed and simulated traffic flows.

Table 9.1 Observed and simulated values for traffic flows between all origin and destination pairs for all three time-period scenarios

		Morning Peek			Off-Peek			Afternoon Peek		
		Observ Flow	Sim Flow Mean (St.Dev)	GEH	Observ Flow	Sim Flow Mean (St.Dev)	GEH	Observ Flow	Sim Flow Mean (St.Dev)	GEH
Priority Outer Lane	Str. Ahd	1,230	1,181 (13.87)	1.41	434	426 (14.45)	0.39	536	531 (15.06)	0.22
	Left-Turn	734	719 (15.94)	0.56	407	397 (16.62)	0.50	575	570 (19.34)	0.21
Priority Inner Lane	Str. Ahd	270	277 (8.96)	0.42	252	251 (9.62)	0.06	1,019	1,037 (7.36)	0.56
	Right-Turn	134	137 (8.45)	0.26	102	97 (7.93)	0.50	166	169 (8.92)	0.23
Sec. Road	Left-Turn	69	67 (9.05)	0.24	90	87 (8.79)	0.32	75	72 (8.25)	0.35
	Right-Turn	354	346 (16.59)	0.43	277	270 (15.07)	0.42	751	741 (11.10)	0.37

As anticipated, there were no statistically significant differences in the flow rates between any of the origin-destination pairs. GEH-statistic calculations for all approaches in each time-period showed values well below 1.00 indicating a good match between observed and simulated values. The only exception was found for vehicles travelling straight ahead on the outer priority lane during the morning peak period. This was due to problems generating a desired volume of traffic when the demand approached the capacity limit.

9.6.2 Speed and speed variance

Another very important validation variable is speed and speed variance. Given the desired speeds used as simulation input, it is important to establish correct speed and speed variation levels at a point of measurement near the centre of the junction in both priority lane directions. The speed values from the simulation were compared against those derived from real-world measurements based on video-analysis and loop detector data. The number of vehicles driving faster than the speed limit was also compared, in light of the implications of this measure with regard to safety. This data is shown below in Table 9.2 for both priority directions in each of the time-period scenarios.

Table 9.2 Observed and simulated values for speed, speed variance and numbers of speeders for both priority directions and all three time-period scenarios

	Morning Peak		Off-Peak		Afternoon Peak	
	Outer Priority Lane	Inner Priority Lane	Outer Priority Lane	Inner Priority Lane	Outer Priority Lane	Inner Priority Lane
Observed Average Speed	47.19	51.07	52.12	51.14	47.87	31.60
Sim. Average Speed - Mean (St.Dev)	48.61 (0.33)	50.14 (0.89)	52.90 (0.47)	51.51 (0.85)	48.75 (0.47)	35.47 (0.77)
Observed Speed Variance	6.96	9.15	7.2	9.25	7.58	12.20
Sim. Speed Variance - Mean (St.Dev)	7.03 (0.16)	10.11 (0.72)	7.27 (0.22)	10.43 (0.59)	6.86 (0.22)	12.20 (0.75)
Observed No. of Speeders	40.78	55.35	69.43	67.19	48.42	22.87
Sim. No. of Speeders - Mean (St.Dev)	45.04 (2.27)	51.75 (2.94)	68.05 (3.07)	63.25 (4.90)	44.04 (3.07)	18.59 (1.97)

The data presented in Table 9.2 shows a good level of correspondence for both speed and speed variation for simulated and observed real-world data in the inner and outer priority lanes during the three time-periods. Small differences are found during the afternoon peak period where there were queues that tailed back through the intersection on the inner priority lane (the result of a downstream signalised pedestrian crossing). The number of speeders is also reasonably consistent (within two standard deviations in all cases except the inner priority lane during afternoon peak).

9.6.3 Time-gap distributions on both priority road directions

These main results for the comparison of time-gap distributions are presented and discussed in the calibration section in relation to the car-following models (see Section 9.6.3). The percentages of vehicles in car-following mode (i.e. have a front-to-rear time-gap of less than or equal to 3.50 seconds) are shown below in Table 9.3 for the two priority directions and each of the three different time-periods scenarios.

Table 9.3 Observed and simulated values for the percentages of car-followers for both priority directions and all three time-period scenarios

	Morning Peak		Off-Peak		Afternoon Peak	
	Outer Priority Lane	Inner Priority Lane	Outer Priority Lane	Inner Priority Lane	Outer Priority Lane	Inner Priority Lane
Observed Vehicles in Car-Following State (%)	41.00	17.65	16.59	19.44	26.68	54.70
Simulated Vehicles in Car-Following State - Mean (%) (St.Dev)	41.36 (1.28)	18.40 (1.85)	18.88 (1.85)	19.19 (3.31)	28.56 (1.85)	50.15 (2.13)

Table 9.3 shows a good level of agreement between simulated and observed real-world data with values (within two standard deviations in all but one case). The exception is the inner priority lane during the afternoon peak period. This is probably the result of queues developing, and tailing back through the intersection on this lane as discussed earlier.

9.6.4 Accepted and rejected time-gap distributions

The main results for the accepted and rejected time-gap distributions are presented and discussed in the calibration section (see Section 9.6.4). Other variables of interest for validation purposes include the percentages of vehicles that pass the yield line without stopping, and the average waiting time at the head of a queue for yielding vehicles. This data is presented below in Table 9.4.

Table 9.4 Observed and simulated values for the percentage of non-stopping vehicles and average wait times for yielding vehicles for both priority directions and all three time-period scenarios

	Morning Peek			Off-Peek			Afternoon Peek		
	Left-Turn Sec Road	Right-Turn Sec Road	Left-Turn Prio Road	Left-Turn Sec Road	Right-Turn Sec Road	Left-Turn Prio Road	Left-Turn Sec Road	Right-Turn Sec Road	Left-Turn Prio Road
Observed Non-Stopping Vehicles	21.74	83.33	80.25	36.67	79.78	83.78	26.67	65.73	67.71
Sim. Non-Stopping Vehicles – Mean (St.Dev)	3.56 (2.68)	81.65 (2.53)	78.97 (1.19)	27.61 (6.03)	83.96 (1.36)	80.88 (1.21)	9.38 (2.23)	66.48 (2.31)	63.29 (1.98)
Observed Average Wait Time (secs)	13.57	0.79	0.96	7.08	0.92	0.85	15.30	2.93	3.22
Simulated Av. Wait Time – Mean (secs) (St.Dev)	26.24 (2.21)	0.96 (0.17)	1.59 (0.08)	9.71 (1.27)	0.96 (0.17)	1.28 (0.18)	30.22 (4.26)	3.54 (0.24)	4.51 (0.27)

The data in Table 9.4 indicates a number of differences in the observed and simulated data. This is particularly noticeable with regard to the numbers of vehicles that did not stop when making left-turn manoeuvres from the secondary road in the morning and afternoon peak periods. For the off-peak period, the values for this particular manoeuvre are within the two standard deviations. In addition, the percentage of stopping vehicles for right-turn manoeuvres from the secondary road during off-peak, and left-turns from the priority road during the afternoon peak, are outside the two standard deviation criterion.

These anomalies are probably the result of the ineptitude of simulation model to represent the intrinsic complexity of the left-turn manoeuvre from the secondary road. This complex yielding manoeuvre takes considerably longer in the model than it does in the real-world situation, particularly when there are high volumes of traffic on the inner and outer priority road lanes. Although some provision was made for courtesy yielding and ‘pushing’ in the model, this did not provide completely satisfactory results.

The complexity of the left-turn manoeuvre from the secondary road is also reflected in the results related to waiting time at the head of a queue. A considerably higher value was found for the simulation runs during morning and afternoon peak period, in comparison to those observed in the real-world situation. There are also some small differences in the data for the other yielding situations. The absolute differences in these values are, however, very small in most cases, the exception being the left-turn from the outer priority road during afternoon peak as a result of the queuing on the inner priority road lane.

9.6.5 Validation summary

The validation (and calibration) process revealed a good level of correspondence between observed and simulated data with regard to the time-gap distributions on both priority directions, and the gap-acceptance distributions for the various yielding situations among the different time-periods. A problem that has been noted concerns the excessive number of rejected gaps for left-turning vehicles from the secondary road during the morning and afternoon periods. This problem is also reflected in a larger percentage of non-stopping vehicles and greater average waiting time.

The complexity of this left-turn situation, involving the identification of gaps in as many as three simultaneous streams of traffic, appears to have been underestimated in the modelling approach used. Most probably, this yielding situation would be better represented by a function that considers time and distance rather than the gap size, and which allows drivers to weight the gap sizes in approaching streams differently. These factors while identified, may have an effect on the safety indicator results, and tend to some extent to impinge on model validity. Most importantly, with regard to the investigative nature of this study, the arrival processes and the majority of the gap-acceptance and rejection behaviour is representative, as are the flow rates, turning percentages and levels of speed and speed variance.

9.7 Main results: Safety indicators

The main safety indicator results are related to the frequencies and severities of the proximal safety indicator measures including: Time-to-Accident, Time-to-Collision and Post-Encroachment Time. The severity of the safety critical events is measured using the Required Braking Rate concept described in detail in Chapter 5 (Section 5.3.5). The results are summarised below for the three different time-period scenarios. Each two-hour time-period scenario has been simulated 20 times using different random seed numbers. The results have then been averaged before comparison is made against observed data. The simulated and observed frequencies for the three safety indicators are contrasted in accordance with the type of conflict/safety critical situation (see Figure 9.12 below).

Only conflict types 1 to 5 are recorded during each simulation run, given that these were most frequent in the real-world data observed at the Täby T-junction. Vulnerable road-users are not included in the simulation model and therefore conflict types 9 and 10 are not used. Similarly, all unknown types of conflict are excluded, as these need to be predefined for simulation purposes. Rear-end conflicts were also excluded owing to their low frequency and the considerable amount of extra processing power needed to record their occurrence in and around the junction. In future studies, provision should be made for the recording of all types of conflicts.

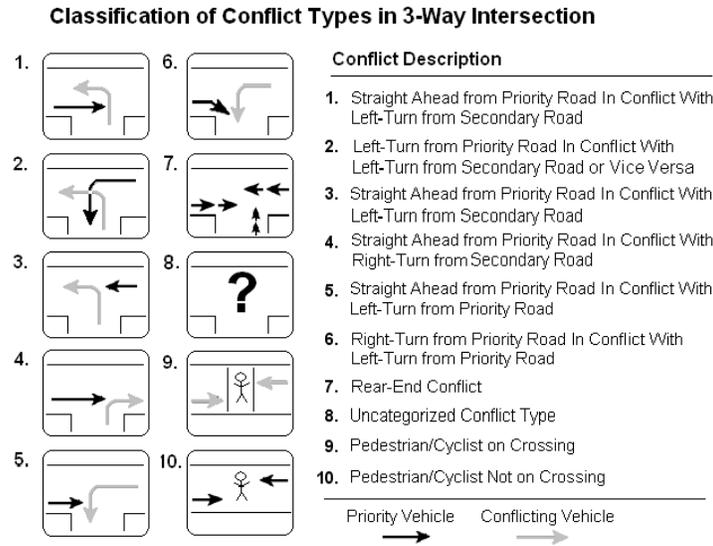


Figure 9.12 Classification of different safety critical event types

9.7.1 Simulated conflict (Time-to-Accident) results

It should be noted that there are a number of important differences in the way in which conflicts are determined in the simulation model, and the way in which they are observed in field studies according to the Traffic Conflict Technique (TCT). In the simulation model, conflicts always require a collision course, whereas the TCT requires road-user behaviour ‘*suggesting*’ a collision course. This is an important difference, and also one that became apparent at a later stage in this work. Furthermore, the TCT defines conflicts at the point where and when evasive action is taken. In the simulation model, the behaviour of road-users is greatly simplified and therefore the defining point was determined where and when the level of deceleration started, provided that it decreased continually thereafter, and reached a level under $-1.50 \text{ metres/second}^2$.

This definition was necessary to distinguish conflicts from regulatory speed control according to the car-following model. Unfortunately, the simplicity of the behavioural models also excluded the possibility of ‘*swerving*’ and ‘*accelerating*’ as types of evasive action. The standard non-linear function that distinguishes serious and non-serious conflicts according to the TCT was used. In the simulation model, non-serious conflicts were also required to have a required average braking rate at the point of definition of less than $-2.00 \text{ metres/second}^2$.

A comparison of the frequencies and severities of simulated and observed Time-to-Accident (TA) events for the different conflict types and time-period scenarios is shown below in Table 9.5. The original real-world frequency and severity values observed at the Täby T-junction have been transformed to provide representative values for each of the two-hour time-period scenarios (the original conflict observation periods for each scenario were longer).

Table 9.5 Comparison of simulated and observed Time-to-Accident data shown according to conflict type for the three time-period scenarios

		Simulated Conflicts (Per 2 Hour Time Period)			Observed Conflicts (Per 2 Hour Time Period)		
Time-Period	Conflict Type	Serious	Non-Serious	RBR Severity	Serious	Non-Serious	RBR Severity
Morning Peak	1	0.05	0.00	0.19	0.50	0.00	2.03
	2	0.20	0.00	2.02	0.00	0.00	0.00
	3	1.05	1.70	6.92	1.00	0.50	3.56
	4	0.05	0.60	0.50	0.50	0.00	3.01
	5	0.00	0.00	0.00	0.00	0.00	0.00
	Total	1.35	2.30	9.63	2.00	0.50	8.60
Off-Peak	1	0.00	0.00	0.00	0.60	0.40	3.03
	2	0.00	0.00	0.00	0.00	0.20	0.00
	3	0.05	0.00	0.17	0.20	0.20	0.90
	4	0.00	0.10	0.00	0.80	0.00	3.91
	5	0.00	0.00	0.00	0.00	0.00	0.00
	Total	0.05	0.10	0.17	1.60	0.80	7.84
Afternoon Peak	1	0.55	0.00	2.59	0.50	0.00	2.10
	2	0.00	0.00	0.00	0.50	0.00	1.99
	3	0.30	0.45	2.12	1.00	0.00	5.63
	4	0.05	1.65	0.18	1.00	0.50	4.92
	5	0.55	0.05	2.53	0.00	0.00	0.00
	Total	1.45	2.15	7.42	3.00	0.50	14.64
Total (6 hour period)		2.85	4.55	17.22	6.60	1.80	31.07

Based on the empirical data, it is possible to estimate confidence intervals around the average numbers of serious conflicts expected during the simulation for each two-hour period. Using the Poisson assumption, and a 90 per cent level of confidence, it would be expected to find at least 4 and at most 10 serious conflicts per simulation run given the average of 6.60 simulated serious conflicts per 6-hour period. Similarly, the probability of obtaining less than 3 serious conflicts (2.85 were found on average in the simulation runs) for a single run is only 4 per cent. This suggests that the aggregated number of serious conflicts from the simulation runs is significantly underestimated. Similar calculations for the morning peak show more favourable results given the 90 per cent confidence interval, where the probability of obtaining less than 2 serious conflicts for a similar average value is approximately 40 per cent. The average numbers of serious conflicts for the other two time-periods fell well outside the projected 90 per cent confidence intervals.

The summated average required braking rates were also greatly underestimated by the simulation model to roughly the same proportions as the frequency data. There is some similarity found for the severity level for the morning peak, however these values were based on very few observations making it difficult to draw any valid conclusions.

A consistent ordering is found among the time-periods with regard to conflict frequency and severity levels for the simulated and observed real-world data. Both sets of data identify the afternoon peak period as that resulting in most serious conflicts closely followed by the morning peak, and finally the off-peak period.

Interestingly, If the simulated severe and non-severe conflict data is summated, a significantly better level of agreement is found for the two sets of data. This is also true for the average RBR-severity levels. This could be interpreted as suggesting a general lack of conflict severity in the simulation runs. In order to check the validity of the severity levels, an average was calculated per conflict based on the data for all simulated serious conflict events. This value was then compared to a similar value for the observed data. The results of this comparison showed that the average RBR-severity level per serious conflict for the simulation runs (mean -5.52 metres/sec², standard deviation 2.32) was slightly lower than that for the observed data (-4.72 metres/sec²). This negligible difference in severity level implies that vehicles in the model are braking slightly harder (and later) than vehicles in the real-world situation. It is however, difficult to make theoretical and statistical comparisons of these differences given the methods of measurement and estimation.

Perhaps the most plausible explanation for the relatively low number of serious conflicts is related to the unrepresentativeness of road-user (driver) behaviour in the simulation model (particularly that in relation to gap-acceptance and car-following). Tests carried out with different distributions of reaction times in relation to the onset of braking for yielding vehicles, showed very little effect on the results. Similarly, changing the braking threshold for identifying the initial evasive action of a conflict (set to -1.50 metres/sec²) also had very little effect on the results. These findings are taken to suggest that the functioning of the model was quite robust, and that when safety critical events do occur their severity is largely determined by the size of the accepted gap and factors related to the initial speed and the dimensions of the vehicles involved.

A further plausible explanation is related to the fact that some serious conflicts observed in the field may not involve (but rather imply) a collision course. The existence of a collision course was a prerequisite in the serious conflict definition used for the simulation experiment. This conceptual difference is of considerable importance and requires careful analysis in later simulation studies involving this particular indicator. It is also possible that the measures of speed and distance determined '*objectively*' from simulation output data are different to those that are '*subjectively*' estimated by observers in the field. Although research has shown that observer estimates are often accurate and reliable, more complex types of conflicts may be subject to greater levels of error (see e.g. Hydén, 1987; Chin and Quek, 1997).

Further comparisons are made with regard to the conflict types. The simulation model runs indicated a similar pattern among the different types of conflicts. Conflict type 2 was represented in the simulation data for the morning peak but not the afternoon peak, whereas the opposite pattern was found for the observed data.

Conflict types 1 and 3 relating to left-turn manoeuvres from the secondary road appear to be represented in the simulation data for morning and afternoon peak periods, and follow the pattern suggested by the observed data. This is also the case for conflict type 4 (right-turns from the secondary road). A further finding is that vehicles turning left from the outer priority lane are sometimes in conflict with vehicles on the inner priority lane in the simulation runs. This is not evident in the observed conflict data, although such conflicts are possible given the gap-acceptance data for this particular yielding situation.

The standard conflict diagram is shown below (see Figure 9.13) for all conflicts generated during the 20 simulation runs for each of the three different time-periods.

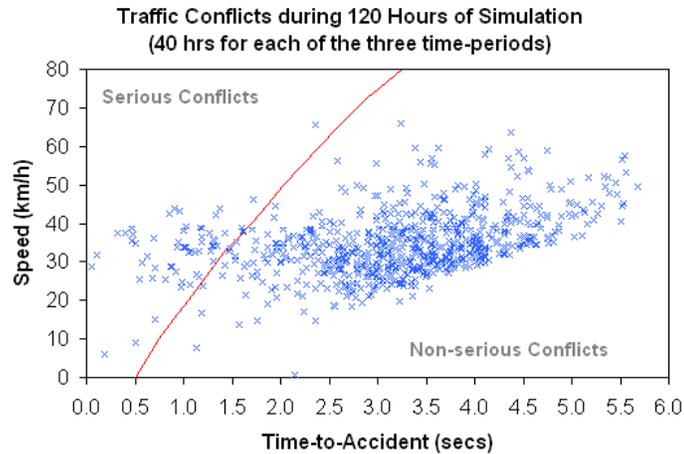


Figure 9.13 All simulated serious traffic conflicts for the three time-period scenarios

The severity of traffic conflicts is also shown below in Figure 9.14 using the Required Braking Rate severity measure (all serious and non-serious conflicts are included).

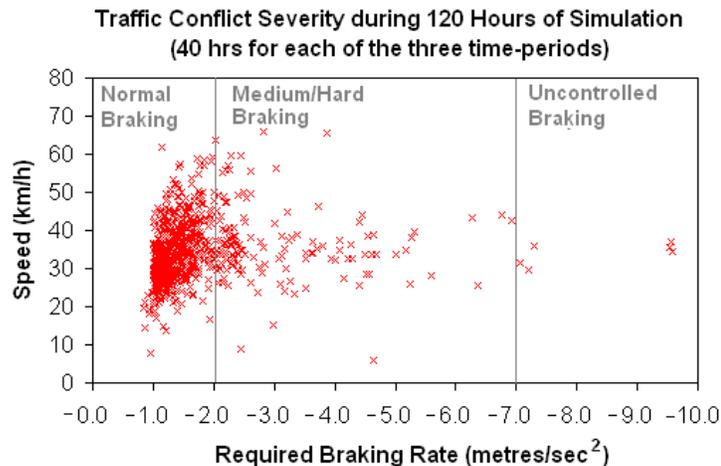


Figure 9.14 Severity of all simulated traffic conflicts for the three time-period scenarios

Statistics in relation to the severity scale indicate that only 20 per cent of all conflict situations involve a required braking rate in excess of -2.00 metres/sec². The vast majority of conflict situations in the simulation model are resolved at an early point in time through controlled reaction and normal braking, as they are in real-world situations.

9.7.2 Simulated Time-to-Collision results

A comparison of the frequency and severities of simulated and observed Time-to-Collision (TTC) events, according to the predetermined conflict types and the three time-period scenarios, is shown below in Table 9.6.

Table 9.6 Comparison of simulated and observed Time-to-Collision data shown according to conflict type for the three time-period scenarios

		Simulated TTCs (Per 2 Hour Time Period)		Observed TTCs (Per 2 Hour Time Period)	
Time-Period	Conflict Type	No of TTCs	RBR Severity	No of TTCs	RBR Severity
Morning Peak	1	0.05	0.20	0.00	0.00
	2	2.00	19.56	2.00	2.67
	3	6.95	18.30	2.00	4.63
	4	1.45	2.66	3.00	9.60
	5	0.00	0.00	0.00	0.00
	Total	10.45	40.72	7.00	16.90
Off-Peak	1	0.00	0.00	0.00	0.00
	2	0.05	0.50	0.00	0.00
	3	0.25	0.44	0.00	0.00
	4	0.15	0.28	2.00	7.32
	5	0.00	0.00	0.00	0.00
	Total	0.45	1.22	2.00	7.32
Afternoon Peak	1	0.60	2.36	0.00	0.00
	2	0.40	4.00	3.00	11.33
	3	1.80	4.89	3.00	7.34
	4	13.85	19.92	12.00	39.81
	5	0.85	4.39	0.00	0.00
	Total	17.50	35.56	18.00	58.48
Total (6 hour period)		28.40	77.50	27.00	82.70

As for serious conflicts, the Poisson assumption was again used to calculate confidence intervals for the expected number of sub-threshold TTC-events found in each simulation run based on the observed frequency. A 90 per cent confidence interval suggested that at least 23, and at most 34, sub-threshold TTC-events per simulation run, would be expected given the observed average of 27 for the six-hour period.

The total number of sub-threshold TTC-events found for the simulation run matches the number of observed real-world events quite well. The standard deviation found among the 60 simulation runs (5.33) was also found to be very similar to that estimated from the observed data using the Poisson assumption (5.20).

The simulated sub-threshold TTC frequencies for morning and afternoon peak periods were also well within 90 per cent confidence intervals calculated using observed frequency values. The number of sub-threshold TTC-events occurring during the off-peak period are underestimated, as they were in the previous case for serious conflicts (TA-values). The severity measures also indicated a good level of agreement for the entire 6-hour period, but were considerably more inconsistent for each individual time-period.

The ordering of the time-period scenarios according to simulated sub-threshold TTC frequencies was found to be consistent with the observed real-world data, and that found for the serious conflicts discussed earlier. Again, most events were found to occur during the afternoon peak period closely followed by the morning peak, and lastly the off-peak period. The ordering between time-periods for total average simulated RBR-severity does not follow the same pattern as the observed data. This is due to the number of high severity conflict type 2 TTC events during the morning peak period.

An average severity level per TTC-event was calculated using the simulated data. A comparison with the corresponding value for the observed data showed that the average severity level from the simulation runs (mean -2.03 metres/sec², standard deviation 1.94) was substantially lower than that for the observed data (-2.97 metres/sec²). This difference is partly explained by the higher level of variation in the simulated data as suggested by the relative size of the standard deviation in comparison to the mean. This difference is the opposite of that found for the serious conflict data.

It is also interesting to note the significantly higher number of safety critical events registered by the minimum TTC indicator, in comparison to the Time-to-Accident frequency discussed in the previous section. This difference is important, given the law of small numbers, and the need for proximal safety indicator frequencies that are substantially higher and more statistically stable than accident frequencies for comparative safety analyses (see e.g. Svensson, 1998).

There are a number of major differences in the Time-to-Accident and Time-to-Accident proximal safety indicator concepts, as pointed out in Chapter 5. An important difference is related to the fact that TTCs are continually measured during a safety critical event while there is a collision course, which places greater emphasis on the modelling of deceleration for simulation purposes. The disparity between the average severity levels per TTC event may suggest that the vehicle performance data used in the simulation model requires further calibration (particularly average and maximum deceleration levels). A similar frequency pattern was found for the different conflict types for simulated and observed sub-threshold TTC events. This was particularly evident in the morning and afternoon peak periods. These frequencies were also found to be consistent with those for the serious conflicts (TAs). Conflict type 3 relating to left-turn manoeuvres from the secondary road is well represented in the simulation data for morning and afternoon peak periods and follows the same pattern as the observed data. Interestingly, no observed data is recorded for conflict type 1 (left-turns in conflict with the inner priority lane traffic stream).

The high frequency of TTCs in relation to conflict type 4 (i.e. right-turns from the secondary road) evident in the observed data for the afternoon peak period, was also found for the simulation data. Furthermore, the afternoon peak shows evidence of TTCs for conflict type 5 (vehicles turning left from the outer priority lane that are in conflict with vehicles on the inner priority lane). This conflict type was not found in the observed data, but is nevertheless possible, given the nature of the yielding situation. The general lack of TTC-data in relation to the off-peak period is (as for the serious conflict data) attributed to the oversimplified behaviour in the simulation model, where lower levels of interactive exposure appear to be more consistent with lower conflict frequency.

The average required braking rate severity levels for all Time-to-Collision events generated during the simulation runs for each time-period scenario, are shown below in Figure 9.15.

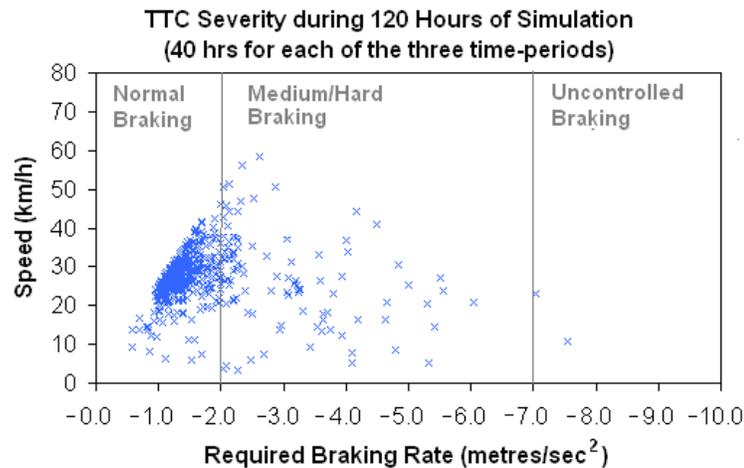


Figure 9.15 Severity of simulated Time-to-Collision events defined by required braking rate for all three time-period scenarios

The simulated severity statistics indicate, in similarity to the serious conflict data, that 80 per cent of all TTC-events result in an average required braking rate less (i.e. closer to zero) than -2.00 metres/sec². This is consistent with the Time-to-Accident data and suggests that most safety critical events in the simulation model are resolved at an early point through controlled reaction and normal braking in a similar manner to interactive events in real-world situations.

9.7.3 Simulated Post-Encroachment Time results

A comparison of the frequency and severities of simulated and observed Post-Encroachment Time (PET) events, according to the different conflict types and time-period scenarios, is shown below in Table 9.7. The PET proximal safety indicator is not suitable for measuring safety critical events where the road-users involved have the same (final) trajectory. As a result, no PET events for conflict types 3 and 4 appear in the data.

Table 9.7 Comparison of simulated and observed Post-Encroachment Time data shown according to conflict type for the three time-period scenarios

Time-Period	Conflict Type	Simulated PETs (Per 2 Hour Time Period)		Observed PETs (Per 2 Hour Time Period)	
		No of PETs	RBR Severity	No of PETs	RBR Severity
Morning Peak	1	0.25	0.79	2.00	9.74
	2	2.85	4.16	0.00	0.00
	5	0.05	0.11	0.00	0.00
	Total	3.15	5.06	2.00	9.74
Off-Peak	1	0.00	0.00	1.00	9.62
	2	1.15	1.56	0.00	0.00
	5	0.00	0.00	0.00	0.00
	Total	1.15	1.56	1.00	9.62
Afternoon Peak	1	1.40	2.84	3.00	12.60
	2	4.10	5.33	4.00	16.03
	5	6.30	13.15	2.00	1.30
	Total	11.80	21.32	9.00	29.93
Total (6 hour period)		16.10	27.94	12.00	49.29

As for the previous cases, the Poisson assumption was used to calculate confidence intervals for the expected number of PET events for each simulation run based on the observed frequency. A 90 per cent confidence interval suggested that at least 8 and at most 17 PET events per simulation run would be expected given an average of 12 for the 6-hour period. The total number of PET events, found for the simulated data matches the number of observed real-world events given the extent of the confidence interval. The standard deviation found among the 60 simulation runs (3.05) is also similar to that estimated from the observed data using the Poisson assumption (3.46). The simulated PET frequencies for each separate 2-hour time-period also fall within the 90 per cent confidence intervals calculated for observed frequency values. Unlike the two previous proximal safety indicators, the simulated average PET frequency for the off-peak period shows a good match against the observed data.

While the simulated and observed frequency data shows a good level of consistency, the severity data measured using summated required braking rate, shows considerable differences, both in terms of the total amount, and that for each individual time-period. The differences for the morning and off-peak periods are due to a number of high severity values in the observed real-world data. High severity values are also found in the afternoon peak period for simulated and observed data in relation to different conflict types.

A consistent ordering was found for the three different time-period scenarios in accordance with PET frequency for the simulated and observed data. This ordering was the same as that found previously for the Time-to-Accident and Time-to-Collision measures. This ordering is less consistent with regard to RBR-severity, due to the relatively low number of cases and the level of variation during the morning and off-peak periods.

The data in relation to different conflict types for each time-period indicates a number of differences. During the morning and off-peak periods, only conflicts of type 1 are noted in the observed real-world data. In contrast, the simulated data suggests that type 2 conflicts (left-turn yielding manoeuvres from the secondary road in conflict with vehicles approaching in the left-turn lane of the outer priority road), are more common during these two time-periods. Similarly, the frequency ordering among conflict types during the afternoon peak period is different between the observed and simulated data. During this time-period, conflict type 5 (vehicles turning left from the outer priority lane in conflict with vehicles on the inner priority lane) appears to represent the biggest problem according to the simulated data. This particular type of conflict was also represented in the simulated data for the other two safety indicators but rarely occurred in the real-world data.

An average severity level per PET event was calculated on the basis of the simulated data and compared to a corresponding value for the observed data. The comparison indicated that the average simulated RBR-severity level per PET-event (mean -1.73 metres/sec², standard deviation 0.88) was lower than that found for the observed data (-2.97 metres/sec²). This is quite a substantial difference, despite the level of variation suggested by the standard deviation. This difference may be due to the modelling approach, whereby vehicles brake after a short reaction delay time whenever a turning vehicle, further downstream, occupies a common conflict area. This causes the level of severity in many simulated PET events to be reduced to a level less than that found in real-world situations, and may also cause some PET events to be averted at an early point before they reach a sub-threshold level (1.50 seconds). In real-world situations, drivers tend not to brake unless the possibility of a collision is readily perceived.

The PET time-value is itself intended to express the level of severity in a safety critical event. The severity of PET-events can be regarded as being directly related to the speed of the second vehicle as it passes the common conflict area (which would have been the impact speed had their been a collision course and no evasive action). In this study, the average required braking rate is calculated using the speed and distance of the second vehicle, at the point when the first vehicle left the common conflict area. Statistics for the average RBR-severity measures indicate that approximately 25 per cent of all PET-events recorded in the simulation result in a required braking rate in excess of -2.00 metres/sec². This represents a slightly higher proportion than the other two proximal safety indicators.

The Required Braking Rate severity levels for simulated sub-threshold Post-Encroachment Time events during the simulation runs for each time-period scenario are shown below in Figure 9.16. The 1.50-second threshold level used for determining 'serious' PET events at different speed levels is clearly noticeable in the diagram by the lack of 'non-serious' PET-notations over and above the speed-threshold boundary.

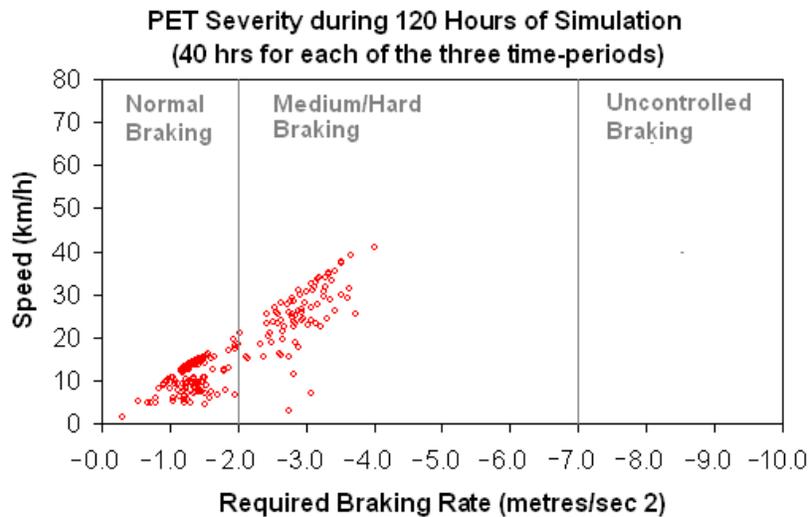


Figure 9.16 Severity of simulated Post-Encroachment Time events defined by required braking rate for all three time-period scenarios

9.8 Discussion and conclusions

The process and results of this simulation experiment indicate many of the problems and limitations associated with this methodology, but also the general potential. A key issue with this study has been to minimise the use of parameters that have no empirically valid basis, and to utilise the full potential of the detailed data set collected and analysed in relation to the real-world T-junction upon which the simulation model is based. The approach also included probabilistic gap-acceptance functionality and composite car-following (i.e. several different parameter sets running simultaneously) in order to accurately represent safety critical aspects of road-user behaviour. These behaviours were also subject to stringent levels of calibration, and validation in accordance with relevant output data variables.

The simulation of safety critical events highlighted a number of difficulties particularly in relation to the Traffic Conflict Technique and the generation of serious (and non-serious) conflicts. The number of serious conflicts was largely and consistently underestimated with regard to both frequency and summated required braking rate severity levels in relation to each of the time-period scenarios. An experimental lowering of the threshold function that distinguishes between serious and non-serious conflicts (from approximately -3.35 to -2.00 metres/sec²) resulted in a higher level correlation between the simulated and observed frequency and severity data. Similarly, a closer examination of the simulation data showed that there was little difference in the average severity level per conflict in comparison to a similar value for the observed data.

A number of plausible explanations are provided with regard to the differences between simulated and observed serious conflict data, and most probably there are elements of truth in each of these. One of the more probable explanations is related to the fact that the interactive road-user behaviour in the simulation model was still too simplistic, most particularly gap-acceptance for left-turning situations from the secondary road. While this fact is undoubtedly true, it is interesting to note that similar levels of underestimation did not occur in relation to the other proximal safety indicators.

A major difference that became known quite late in this study is related to the fact that the TCT does not demand the existence of a collision course, but rather the behaviour of road-users suggesting a collision course. For simulation purposes, the collision course condition was stated as a prerequisite. This conceptual difference, which emphasises the qualitative nature of the Traffic Conflict Technique, may explain part of the differences between the simulated and observed data. Further investigation is required to determine the extent of this difference and to reprogram the conflict definition to include '*conflict behaviour*' in non-collision course serious conflict events. Lastly, it is also possible that some of the differences between simulated and observed data are the result of the measurement methods used and the greater probability of error when subjective estimations of speed and distance are made in the field in more complex conflict situations (see e.g. Chin and Quek, 1997). In the simulation model, the speed and distance measurements are made objectively, although the algorithms used can be questioned with regard to their representativeness.

Importantly, the numbers of simulated serious conflicts were sufficient to identify a similar ordering among the time-periods to that found in the observed data. This ordering suggested that most serious conflicts occur in the afternoon peak, closely followed by the morning peak, and lastly the off-peak period. This ordering was in fact suggested by the simulated and observed data for all three proximal safety indicators. The numbers of simulated serious conflicts in accordance with the five different conflict types were also found to follow approximately the same pattern suggested by observed data, suggesting a degree of validity in the model. Very few simulated serious conflicts were found in relation to the off-peak period in comparison to the number observed. This is taken to suggest a greater level of interdependency between traffic volumes and serious conflicts in the simulation, which again suggests the overly simplistic nature of this modelling approach.

The simulated Time-to-Collision safety indicator measures showed an unexpectedly high level of consistency with the observed frequency data when totalled for all three time-periods. This level of consistency was slightly less evident when the data was examined for each individual time-period, particularly for the off-peak period. The summated average required braking rates, on the other hand, indicated a large degree of variation and were considerably less consistent at the time-period level. The simulated frequencies of sub-threshold TTC-values suggested a similar ordering among the time-periods as that found in the observed data and there was also some consistency with regard to the five different conflict types. Arguably, the TTC-concept (and various derivatives) is better suited for simulation purposes whereby considerably more information for each safety critical event can be extracted and analysed. Unfortunately, TTC-events are difficult to measure in relation to real-world situations thereby making validation a problem.

The Post-Encroachment Time proximal safety indicator also indicated a reasonable level of consistency between observed and simulated data with regard to the totalled frequencies and the frequencies for each individual time-period. As for the TTC data, the summated average required braking rates from the simulation runs showed considerable variation and were less consistent with the observed data. The simulated frequencies of sub-threshold PET-values suggested a similar ordering among the time-periods as that found in the observed data for all of the proximal indicators.

Interestingly, this indicator showed some differences with regard to the five different conflict types, although the frequency levels were too small to draw any general conclusions. The average severity level per TTC event was also found to be significantly lower in the simulation when compared to observed data. This is believed to be due to the manner in which safety critical events are modelled, whereby approaching right-of-way vehicles will brake automatically after a short response delay if there is a vehicle downstream that occupies a common conflict area. In future studies, this type of behaviour will require a higher level of modelling fidelity to accurately represent encroachment events of this complex nature.

A further factor of importance with regard to this study is related to the general level of testing conducted, and the inadequacies of the empirical data set used. The TTC and PET event data represents only six-hours of real-world measurement at the chosen T-junction. This is largely due to the complicated and resource-demanding video-analysis procedures required for deriving actual values. Given the limited measurement period, it is not possible to discount the influence of unusual situations that have the effect of making the data unrepresentative of the traffic conditions during the time-period in question. The Traffic Conflict Technique involved a standard 18 hours of observation, including four hours during morning and afternoon peak periods, and 10 hours during the off-peak period. This data represented a more satisfactory basis for comparison, and was considerably easier to analyse. However, as mentioned above, there appeared to be problems representing the qualitative nature of this technique in a simulation model.

In future simulation studies, a suitable data collection and analysis strategy might involve ensuring the accuracy and validity of data collected in accordance with the Traffic Conflict Technique using several independent observers and procedures involving video-analysis. Similarly, the simulation model and field measurements must share the same definition with regard to conditions such as the existence of a collision course and levels of severity.

With regard to the general methodology, it can be mentioned that the calibration of the simulation model proved particularly difficult and time-consuming. Achieving a representative time-gap distribution through adjustments to the car-following model is considered critical for the accuracy of the gap-acceptance process, and therefore also the validity of the proximal safety indicator data. A particular problem was found during the morning peak scenario, where adjusting the car-following model parameters to increase the variation among drivers had a negative effect on capacity due to the limitations of the Wiedemann '74 model. Adjustments to achieve a suitable proportion of close-following vehicles also resulted in an (unrepresentative) proportion of vehicles with large '*safety-gaps*' that restricted vehicle input at the model boundary.

To overcome problems such as this in the future, it is suggested that modelling environments should allow the definition of more flexible vehicle input functions and that car-following models should incorporate a suitable level of variation that is not entirely dependent on desired or actual speed levels.

Problems in the simulation model application were also found in relation to the probabilistic gap-acceptance functionality. In particular, the left-turn manoeuvre from the secondary road was found to result in too many rejected gaps. This was in spite of the fact that the accepted gap distribution was consistent with observed data.

These problems were also highlighted in the simulation runs by a lower proportion of vehicles that did not stop at the yield line, and a higher average waiting time at the head of the queue, in comparison to the observed data. These problems are probably the result of the overly simplistic nature of the model that does not adequately account for the intricacies and complexities of this particular yielding manoeuvre.

A different gap-acceptance modelling approach based on functions that consider independent measures of speed and distance (rather than time-gap) may resolve these issues and improve the level of representativeness. In addition, the possibility to weight the relative importance of different approaching traffic streams may also contribute to the validity of the model along with the consideration of complex behaviours such as *'pushing'* into queues in congested traffic conditions and various types of courtesy yielding.

Vehicle performance characteristics and modelling, particularly with regard to safety critical events, is another area that requires research to improve the validity of the simulation models aimed at safety estimation in the future. There is also an identified need for research work related to the behaviour and performance of drivers (and other road-users) in safety critical events. This type of research should be carried out with the use of driving simulators and suitably instrumented vehicles in carefully designed experiments.

This type of safety modelling has considerable potential and important implications for transport planning and traffic engineering work in the future. The estimation of safety impact at specific traffic sites, based on micro-simulation and proximal safety indicators, has many advantages over traditional diagnostic and analysis tools. Importantly, factors that have a direct or indirect influence on traffic safety and traffic performance can be taken into account and varied to test the robustness of new and alternative solutions in a safe off-line environment at an early stage in the planning and development process. This type of modelling represents a cost-effective and ethically sound proactive approach to traffic safety. Therefore, it is essential that research be continued in this area.

Case Study 4:

10. Micro-simulation as a method for estimating the safety and performance of an incident reduction function in vehicle actuated signal logic

Summary

This study is concerned with a special incident reduction (IR) function used in standard Swedish vehicle actuated signal control. The IR-function is designed to resolve 'stop-or-go' situations for drivers caught in a 'dilemma zone' following the onset of amber at downstream traffic signals. A simulation experiment based on empirical data from a small suburban intersection was conducted to investigate the effects of the standard IR-function with regard to traffic safety and performance. Safety effects were estimated using Time-to-Collision based measures. The results of the simulation experiment demonstrated a significant safety effect for the IR-function when it was in operation, and a small positive effect on traffic performance.

A further objective of this study was to evaluate the use of micro-simulation as a method with which to test pre-programmed standard Swedish vehicle actuated signalling logic and specially adapted functionality including incident reduction. As a pilot study, important issues regarding calibration and validation were brought to light regarding the use of micro-simulation for safety evaluation. A methodology was also proposed for future work in this area. Although it is difficult to validate safety effects from the simulation environment to those of the real-world situation, it was concluded from this work that micro-simulation is a useful method for the preliminary offline testing of new and improved signal controller based functionality.

The methodology proposed here has now been tested in a further study based at the same intersection. This study investigates the effects of different IR-function logic sets, including the use of speed and headway dependency and situationally adapted detector positioning (Archer and Al-Mudhaffar, 2004). An earlier version of this work has been published in the proceedings of the WCTR Conference in Istanbul 2004 (Archer, Al-Mudhaffar and Cunningham, 2004).

10.1 Introduction

In Sweden as with many other countries today, there is great emphasis on improving the traffic safety situation through the application of Intelligent Transportation Systems (ITS). A very representative type of ITS that is often overlooked due to its long-standing application and use is traffic signalling. Traffic signalling is highly effective for traffic control and system management and provides a fundamental level of safety and accessibility for road-users at intersections. Furthermore, traffic signalling represents an area of considerable research and development and has been a popular ITS area for many years.

A great many signal-controlled intersections in Sweden operate in isolation (approximately 50 per cent) and are adaptive to traffic demand through a system of vehicle actuation. Signal controller logic is essentially adaptive to the needs and demands of the various road-users groups at intersections and associated facilities such as pedestrian and cycle crossings. Achieving an acceptable balance between traffic performance and safety often presents a difficult problem for the signal engineer, where different approaches to enhance safety will typically impose a negative effect on traffic performance, and *vice versa*. In Sweden, there are also specially adapted signal controller logic functions that are used to enhance safety while maintaining a high level of performance. It is this particular type of function that is the focus of this study.

There are a number of international differences in signalling systems throughout the world, a significant difference in Swedish applications is that the controller logic and signalling use a time resolution of less than one-second. Swedish signalling is also *group based* rather than *stage (or phase) based*. In a typical Swedish application, different signal groups *belong* to a phase, although permission to start may be given to a signal group during an earlier phase on the condition that no traffic demand is detected for signal groups with conflicting traffic flows. Traditional Swedish vehicle actuated signal control is based on what has been termed the ‘*time-gap method*’. According to this method decisions are made regarding status changes in a particular signal group based on the demand for green, this in turn depends on whether a vehicle passes a predefined detector position with a recorded time-gap that is greater or shorter than that specified in the controller logic.

As with most vehicle actuated signal control systems, the duration of green time is variable. Thus, when there is demand, green will always be given for a minimum time-period (see Figure 10.1). If there is a continued demand after this minimum period, the duration of green can be extended up to maximum green limit. In a situation where two or more signals groups with non-conflicting traffic flows show an identical signal status within a signal phase, a signal group that has shown green for the minimum period but has no continued demand will be allowed to stay green provided that one of the other groups in the phase has continued demand. This is referred to as *passive green* as opposed to *active green* (SRA, 1991; 2002b).

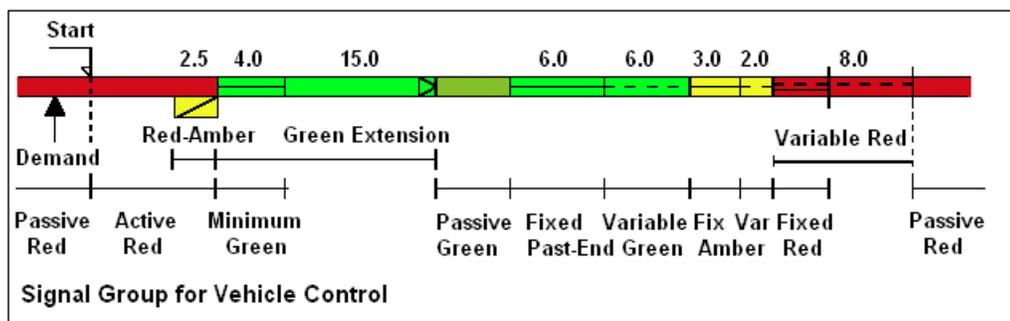


Figure 10.1 Diagram illustrating the different signals and signal status during one cycle for a typical signal group used to control vehicles

The Swedish LHOVRA-technique can be regarded as a further development and complement to the existing signal control functionality. LHOVRA represents a collection of different functions that can be used by the signal engineer to assign variable past-end green, variable amber and variable red times at the signal group level to enhance safety (main priority) and traffic performance. The LHOVRA-technique also introduces improved functionality at the detector level (SRA, 1991; 2002b). Each of the letters in the LHOVRA-acronym (Swedish) represents a different functionality module:

- L** = Heavy Goods Vehicle / Bus Priority
- H** = Mainline Priority
- O** = Incident Reduction
- V** = Variable Amber
- R** = Red-Light Violation Control
- A** = All Red Turnaround

The so-called 'O' (Incident Reduction) and 'R' (Red-Light Violation Control) functions are directed specifically at safety enhancement, while the other five are concerned with traffic performance. While originally developed for rural and sub-urban applications, LHOVRA is today equally applicable to all areas where the posted speed on approach roads does not exceed 70 km/h. The Swedish Road Authority (SRA) states that approximately 70 per cent of all signal applications in Sweden today have some form of LHOVRA functionality.

10.1.1 Traffic safety and the LHOVRA IR-function

The primary objective of the IR-function is to reduce the number of situations where drivers face a decision concerning whether to *stop* or *go* when faced with the onset of amber. The intended effect of the IR-function, according to the definition given by the SRA (1991) is to reduce the number of rear-end collisions and red-light violations without imposing any significant negative effect of traffic performance.

10.1.1.1 Dilemma zone

The area in which drivers face the decision to stop or go is dependent on a number of factors including the current speed of the vehicle and the distance to the stop line, but also certain personal and physical characteristics such as: reaction time, level of driving experience, driving style (aggressive – defensive), sense of urgency, etc. Other situational factors that might also enter into the momentary decision making process include the geometry of the intersection (e.g. slope and curvature of the road), weather conditions, traffic density, the existence of a preceding vehicle, and the probability of being apprehended if a red-light violation occurs. Furthermore, the braking performance potential of the vehicle must also be considered by the driver where larger heavier vehicles require longer distance and greater time to brake than smaller lighter vehicles.

Research related to the dilemma zone can be traced back to the 1970's and beyond in Sweden (see e.g. Alexanderson, Bång and Wretblad, 1964). The dilemma zone was earlier defined as representing the maximum distance from the stop line at which a driver could pass before the onset of red given a constant speed, and the minimum stopping distance. The influence of several traffic variables have been considered including: different amber duration times, driver reaction times and levels of retardation.

A definition of the dilemma zone made by Kell and Fullerton (1990), following research related to the use of traffic detectors, suggests that it starts from the point at which 90 per cent of drivers/vehicles 'go' when faced with a change to amber, and ends at the point where 90 per cent of the drivers/vehicles make the decision to 'stop'.

In the definition of LHOVRA by the SRA, a fixed dilemma zone is identified as existing between 97 and 53 metres before the stop line for a 70 km/h road, and between 56 and 30 metres for a 50 km/h road (SRA, 2002b). These estimates are based on minimum and maximum distances in relation to the posted speed limit (70 or 50 km/h), average braking capacity (0.5 g) and an average driver reaction time (0.75 seconds). However, the SRA considers these dilemma zone distances to be overly conservative for real-world applications given the propensity for drivers to exceed posted speed limits and to frequently pass the stop line on red. This explains the SRA's recommended distances for the outer IR-function detectors (130 metres for 70 km/h roads, and 110 metres for 50 km/h roads).

10.1.1.2 Implementation of the IR-function

In practice, the IR-function is facilitated by detecting vehicles as they enter the dilemma zone and thereafter delaying an imminent change to amber if the conditions and limitations of the IR-function are met. In practice, the implementation of this function is quite complex. The effect of this delay on changing to amber implicitly means that the current green signal is continued. The continued green should however, be interpreted as a delay (rather than an extension) that is imposed on conflicting signal groups that have a recognised demand for green (SRA, 2002b). In effect, the IR function therefore reduces traffic performance. The continuation of green past the end of the normal green extension time is referred to as *past-end green*. This is regarded as an *active* form of green. Signal groups that are in a passive green state can become active again through the implementation of this function. Thus, even while a signal group is in passive green status, potentially dangerous passages can be detected and avoided (see Figure 10.2).

Past-end green is conditional and only given if vehicles are detected within predetermined time-intervals. Furthermore, it is only given up to a maximum predetermined limit. If the past-end green limit is likely to be exceeded, the delay will not be given (controlled by a time-reduction function). This avoids the unwanted effect of having vehicles entering the dilemma zone with no possibility of exiting before a signal change to red. The maximum past-end green limit is set in accordance with the situational conditions of the application.

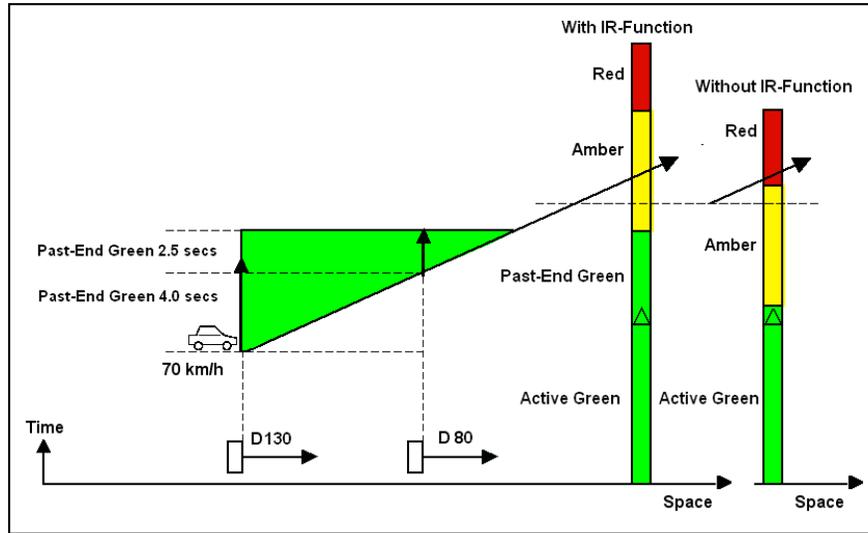


Figure 10.2 The utility of the IR-function in providing safe passage across the stop line in situations where drivers are in the dilemma zone on a change to amber

As a safety countermeasure, the issue of past-end green via the IR-function averts many conflict situations where two vehicles with a short time-gap are caught in the dilemma zone. Such situations are particularly dangerous if the first vehicle decides to brake, and the second vehicle decides to go in response to the onset of amber (see Figure 10.3).

When the IR-function is active and where there is still unused past-end green time available, the possibilities for rear-end collisions to occur are minimised. An exception to this rule occurs during heavy traffic conditions when the maximum past-end green duration time is constantly reached.

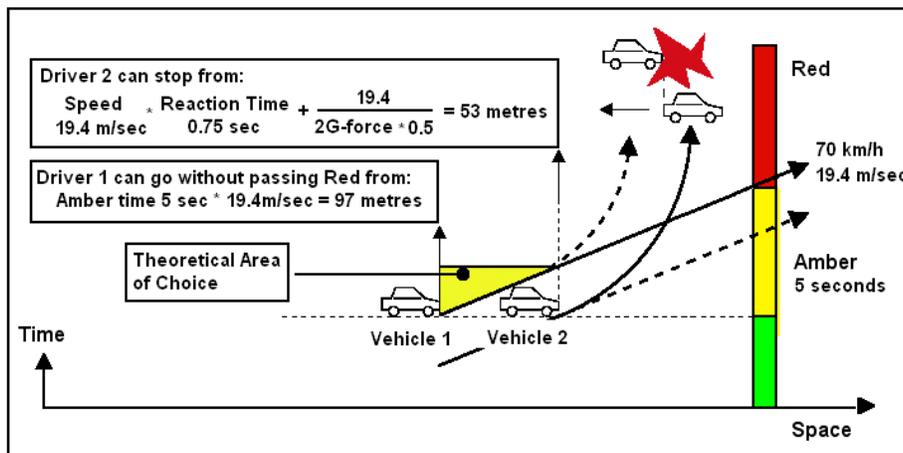


Figure 10.3 Diagram illustrating the propensity for rear-end collisions where vehicles are caught in the dilemma zone on a change to amber

The IR-function uses two detectors to measure time-gaps. On a road with a posted speed limit of 70 km/h, the first detector at 130 metres will often give 4.0 seconds of past-end green and the second detector at 80 metres will update the remaining past-end green time with a 2.5 second period. Similarly, on a road with a posted speed of 50 km/h, the first detector at 110 metres will give 3.5 seconds of past-end green and the second detector at 65 metres will update the remaining past-end green time to 2.5 seconds. In principle, the first detector marks the start of the dilemma zone and is designed to detect potentially dangerous vehicle entries, whereas the second detector is placed well within the dilemma zone boundaries and is used to update the amount of past-end green time needed to pass the stop line safely.

10.1.1.3 Safety and the IR-function

In a traffic safety study related to initial application of the IR-function, Brüde and Larsson (1988) found that the number of accidents at intersections could be reduced from 0.7 to 0.5 per 10^6 incoming vehicles. A closer look at more general safety statistics in Sweden reveals the need for countermeasures aimed at reducing rear-end collisions. Safety statistics reveal that the number of police reported rear-end collisions resulting in fatalities or serious injuries has increased dramatically during the past two decades (from 685 in 1980 to 1807 in 2001). While this accident category has increased, it is notable that all other types of accidents have decreased. Today, rear-end collisions represent approximately 30 per cent of all vehicle-vehicle accidents in Sweden (SIKA, 2003).

A similar finding is reported from Japan where rear-end collisions also account for 28 per cent of all police reported accidents with a total of over 234,000 for 1998 (Hiramatsu & Obara, 2000). The authors state driver inattention as the main cause of this type of accident and make qualified calculations to suggest that:

- the probability of a following vehicle striking a stopped vehicle is about 1 per 600,000 stops
- the probability of a following vehicle striking a decelerating vehicle is about 1 per 1,500,000 stops

This relative increase in rear-end collisions is at least partially due the result of a higher level of traffic signal control and implementation of traffic management strategies in order to cope with increasing number of vehicles in the road network. Another interesting finding suggested by the literature is related to the fact that a high proportion of rear-end collisions result only in property damage and are therefore not reported to the police (SIKA, 2003). As a result, this category of road accident is under-represented in accident statistics, this is particularly the case in Sweden and other countries that have a policy to report only accidents involving injury or fatality to the police authorities.

10.1.2 Suggested improvements to the LHOVRA IR-function

Al-Mudhaffar (2002) has made a number of suggestions regarding the improvement of the IR-function. Firstly, it is stated that slow moving vehicles that receive past-end green at the first detector will fail to receive the intended update of past-end green time at the second detector. In this situation, drivers will find themselves in a new and potentially more dangerous dilemma situation nearer to the stop line. As a solution, Al-Mudhaffar suggests that past-end green should only be given to vehicles that have a high probability of reaching the second detector within the allocated time interval with regard to speed.

This additional functionality can be achieved by introducing speed dependency so that past-end green time is only given to vehicles with a speed greater than a threshold-value when detected at the entry point to the dilemma zone. Suitable speed threshold values can be determined through on-site field observation or by calculations based on the prevailing speed limit, existing detector locations and the amount of past-end green time that is normally allocated after passing a specific detector. While this solution is elegant, it involves installing a further inductive loop in order to enable the collection of speed data.

Al-Mudhaffar (2002) also suggests that the recommended detector distances are often too far from the stop line. The preliminary findings of several field studies at the Royal Institute of Technology concur with the earlier research of Kell and Fullerton (1990) where it suggested: (a) that the first detector should be positioned at around 110 metres from the stop line rather than 130 or 140 metres for approaches with a 70 km/h posted speed limit; and (b) that the second detector should be moved to a position of 65 metres from the stop line rather than 80 or 85 metres. These detector positions bring the practical dilemma zone more in alignment with the theoretical dilemma zone suggested by the SRA.

10.1.3 Testing alternative signal controller logic

The suggested improvements to the incident reduction function represent qualified proposals that are based on literature reviews, practical experience working with vehicle actuated signal control applications and the collection and analysis of field data from a number of representative sites in the Greater Stockholm area. For practical and safety reasons (changing the actual detector locations and introducing new detectors for the acquisition of speed data), it is not possible to test the effects of different solutions at an existing site in a real-world situation.

A suitable off-line test-environment is therefore required that does not compromise safety, and which allows the user to change detector locations and adapt logic easily and effectively. For the test environment to be useful, it must be dynamic and represent the complexities of the traffic system as accurately as possible. The requirements of the off-line test-environment suggest the use of a micro-simulation modelling. While the use of micro-simulation can prove particularly advantageous in providing a suitable off-line test-environment, it also introduces a number of limitations and potential problems that need to be overcome in relation to the performance and validity of the simulation model as an abstract representation of a real-world situation, and how the results may be generalised.

10.1.4 Safety measurement

The incident reduction function is primarily concerned with the prevention of rear-end conflicts and collisions. It is therefore of key interest to measure differences in the number and seriousness of such conflicts in relation to the implementation of different IR-function logic during simulation. Ideally, it would be useful to validate the number of such safety critical events generated during simulation against the number occurring in the real-world situation and the number of police reported accidents.

Rear-end collisions and conflicts are particularly difficult to observe due to the need to estimate absolute and relative speed and distance differences and project the potential point of collision downstream in the direction of travel. This limits the accuracy of safety indicator values obtained using the Traffic Conflict Technique and makes photometric video-analysis difficult and considerably resource-demanding. Furthermore, a great many rear-end collisions do not result in serious injury due to the low speeds involved, and are therefore rarely reported to the authorities. This makes validation of the indicator measures actually obtained from field studies very difficult.

Safety indicators that are suitable for this purposes of comparing the effects of different IR-functionality are the standard Time-to-Collision (TTC) measure proposed by Hayward (1972) and the '*Time Exposed TTC*' and '*Time Integrated TTC*' measures proposed by Minderhoud and Bovy (2001). These measures have been described in detail earlier. A TTC-threshold level of 3.50 seconds has been chosen for this study in accordance with the research of Hirst and Graham (1997) who suggest that this is a suitable limit for discriminating between drivers who unintentionally find themselves in a conflict situation and those who remain in full control.

Another safety indicator that is useful in this study is the frequency of red-light violations. Red-light violations are reported to be one of the main causes of accidents at intersections. Safety statistics reported by the FHWA in USA for 2000 suggest that as many as 106,000 vehicle accidents, 89,000 injuries and 1,036 deaths can be attributed to red-light driving (FHWA, 2004). This type of behaviour is reported to be attributable in many cases to '*being in a rush*', impatience or even thrill-seeking (Porter and Berry, 1999). The effectiveness of red-light cameras has been substantial in many countries including USA, Netherlands, UK and Australia, where 55- 60 per cent fewer violations and approximately 25-30 per cent fewer traffic accidents have been noted (see e.g. Andreassen, 1995; FHWA, 1999)

10.1.5 Scope and objectives

A primary objective of this study is to conduct a micro-simulation experiment based on empirical data to identify the traffic safety and performance potential in relation to the LHOVRA incident-reduction function in its standard application in comparison to an identical traffic situation where the incident-reduction function is disabled. Furthermore, it is aimed to establish and evaluate a methodology for simulation studies of this nature for forthcoming work related to the evaluation and comparison of different vehicle actuated signal controller logic functions such as those suggested by Al-Mudhaffar (2002).

This work also represents an initial validation study with regard to the use and suitability of a particular micro-simulation modelling tool (VISSIM), and a specially developed vehicle actuated signal control logic program (written in VisVAP program that is compatible with VISSIM) that included the additional LHOVRA-functions.

A further objective that is more in alignment with the intentions of this thesis is to evaluate the usefulness of the Time-to-Collision (TTC) safety indicator and the associated Time Extended and Time Integrated TTC measures proposed by Minderhoud and Bovy (2001). It is expected that significant differences will be found in the frequencies of safety critical events (measured by the safety indicator) between the simulation scenario that incorporates the use of the incident-reduction function and that which does not. It is also expected to find a higher frequency of safety critical events during the peak period compared to the off-peak.

It is important at this point to note that the Time-to-Collision data recorded in the simulation experiment will not be validated against real-world proximal safety indicator data. The intention, scope and resources of this study did not allow for Time-to-Collision verification and are instead concerned with establishing the possibilities and potential of using micro-simulation and pre-programmed vehicle-actuated signal controller logic to study traffic safety and performance impact. The work presented here can therefore be regarded as an important and relevant preliminary pilot study for safety and traffic performance estimation.

10.2 Method

10.2.1 Intersection test site

The test site chosen for this study represents a typical suburban intersection in the Greater Stockholm area. Diagrams of the principle intersection test site and technical signal and detector locations and functionality are shown below in Figure 10.4a and 10.4b, respectively. The priority approaches (1 and 3 in Figure 10.4a) connect two major arterials leading to and from central Stockholm. Each priority approach has a separate left-turning lane. The secondary roads (approaches 2 and 4 in Figure 10.4a) lead to residential areas. All approaches have a 50 km/h posted speed limit. The intersection is controlled by seven signal groups, each with a single signal head (numbered 1-7 in Figure 10.4a). The main signal phases are also shown in Figure 10.4a.

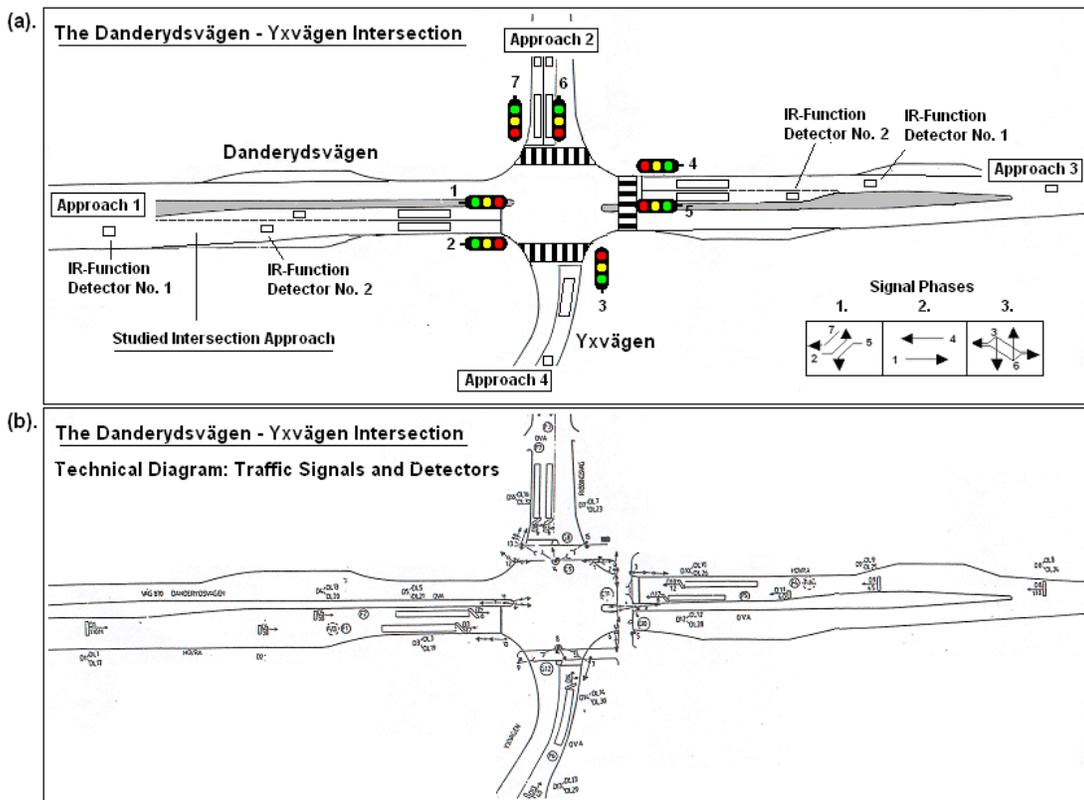


Figure 10.4(a-b) The intersection test site showing signal phases, the approach that is studied, and the positions of signal heads and detectors

The two priority approaches have five vehicle detectors. Two of these are placed at 50 and 30 metres respectively on the left-turn lane. The other three mainline detectors are placed at distances 110, 65 and 30 metres (standard for an approach with a posted speed limit of 50 km/h). The secondary approach roads, including the separate right-turn lane on Approach 2, each have two detectors placed at 40 and 20 metres. The detectors placed closest to the stop line are used in standard signal control and LHOVRA to provide variable amber and red. The detectors further upstream are used to provide green extension time and past-end green.

For the purposes of this study, safety and performance results are mainly considered in relation to Approach 1. Revised IR-function logic is however implemented for both priority approaches. The intersection also had pedestrian crossings on three of four approaches placed in front of the stop lines. These were only occupied sporadically during the study period and therefore are not included in the simulation model.

10.2.2 Data collection and analysis

Test site data was collected on one day during mid-week between 14:00 and 18:00 p.m. to provide a basis for simulation model calibration and validation.

10.2.2.1 Traffic flows, compositions, and turning percentages

The field data was analyzed in order to generate input data for the simulation model at 15-minute intervals. This data is presented below in Figure 10.5, The figure illustrates the relative consistency of the secondary roads and the extent of the main afternoon peak traffic between 16:00 and 17:00 p.m. on the mainline approach roads.

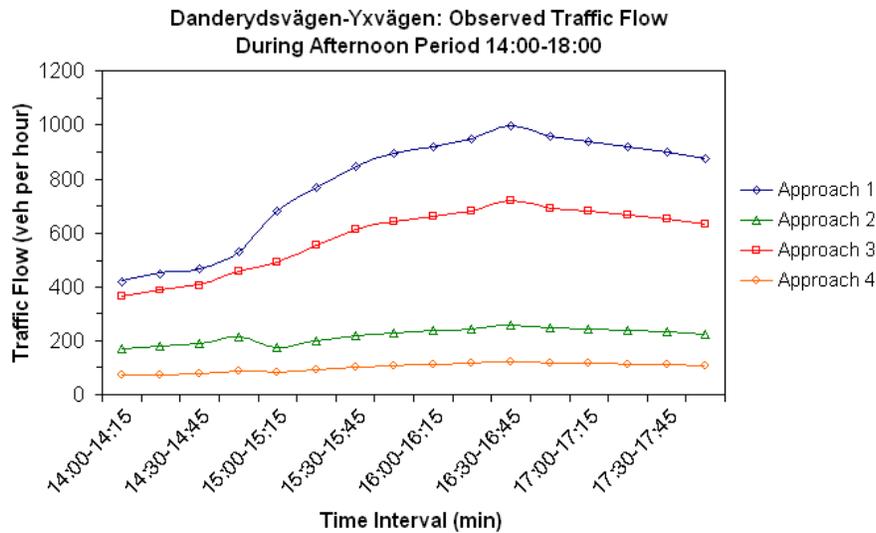


Figure 10.5 Traffic flows/demand for the intersection approach roads

Turning percentages were also derived from the data analysis (see Figure 10.6). No significant differences were found in the turning percentages over the four-hour time-period to make time dependent input necessary in the simulation model.

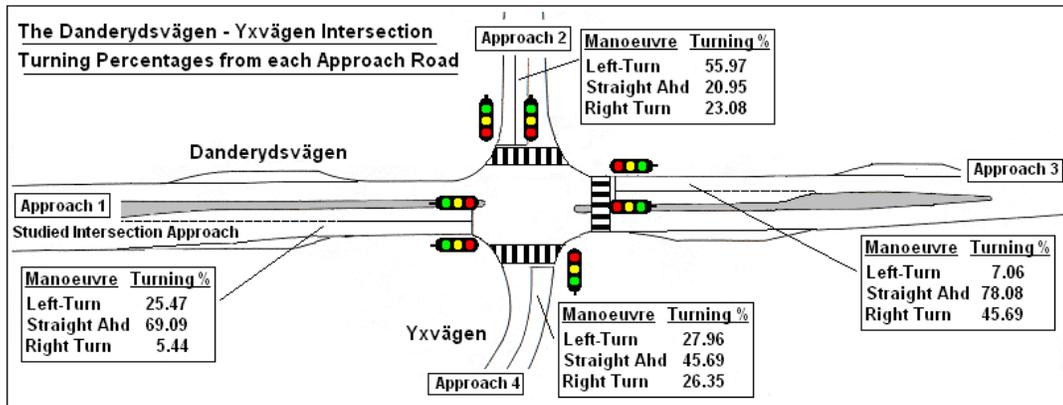


Figure 10.6 Turning percentages for the intersection approach roads during the four hour measurement period

Traffic composition data was also found to be stable throughout the four-hour observation period with only minor differences between priority and secondary approaches. Vehicles were found to account for 85 per cent of the total traffic volume with smaller vans and multi-purpose vehicles (MPVs) accounting for an additional 12 per cent. Furthermore, heavy goods vehicles accounted for slightly more than 1 per cent of the traffic volume and buses approximately 1.5 per cent.

10.2.2.2 Free-flow speed distribution data

A free-flow speed distribution was also derived from a measurement point 150 metres upstream of Approach 1. This was derived for vehicles with a time-gap of more than 5 seconds to a preceding vehicle and used to represent desired speeds on the main approach roads in the simulation model (see Figure 10.7).

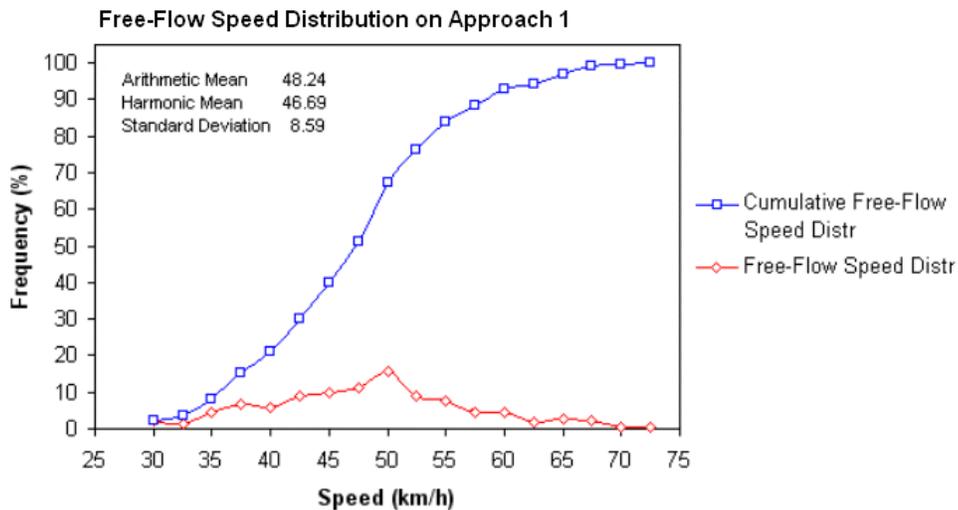


Figure 10.7 Cumulative and non-cumulative free-flow speed distribution for Approach 1

10.2.2.3 Time-gap distribution and car-following data

This study focuses on the effect an incident reduction function has on the frequency of rear-end-collisions and conflicts, it is therefore of critical importance to ensure that the distribution of time-gaps between vehicles on the mainline approach road is accurate (prior to the onset of braking). If the number of short time-gaps in the model is overrepresented when compared to the real-world situation, this will be reflected by a higher and more unrepresentative frequency of rear-end conflicts. Similarly, a lack of shorter time-gaps at the lower end of the distribution is likely to be reflected by a smaller number of conflicts. The time-gap distribution represents an important calibration parameter for the purposes of this simulation study.

The time-gap distributions for Approach 1 (measured 110 metres upstream on the intersection) during the first off-peak hour and the main afternoon peak hour are shown below in Figure 10.8. Measurement data for Approach 1 (measured before the start of the left-turning lane) indicated that approximately 53 per cent of vehicles were in car-following mode (i.e. had a time-headway of less than 3.50 seconds) during the first off-peak hour between 14:00-15:00 p.m. Similarly, 19 per cent of all vehicles had a time-headway greater than 10 seconds. During the main afternoon peak hour between 16:00-17:00 p.m. the proportion of vehicles in a car-following state increased to 74 per cent with only 4 per cent of all vehicles having a time-headway greater than 10 seconds.

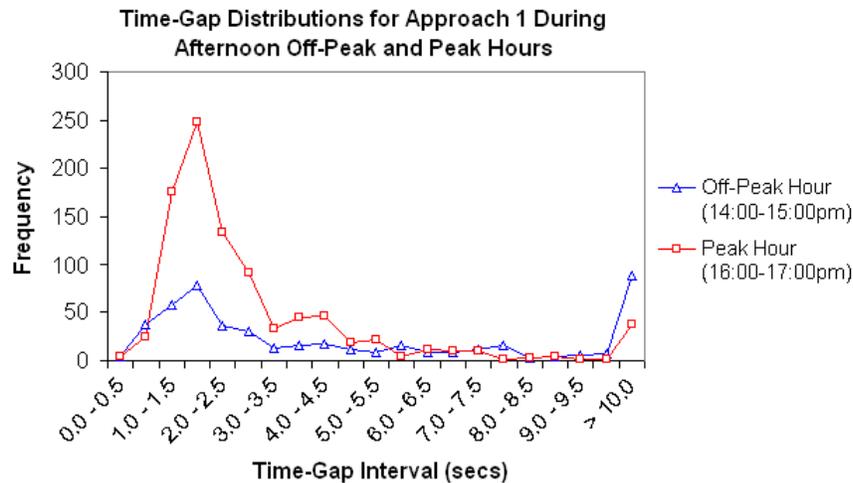


Figure 10.8 Time-gap distributions during off-peak and peak hours

10.2.2.4 Queue lengths

Average and minimum queue lengths were measured by counting the number of stopped vehicles (travelling at a speed of less than 5 km/h) at the time the signals changed from red to red-amber (i.e. 1.5 seconds before the change to green). The average and maximum queue lengths were measured during the first off-peak hour (14:00-15:00 p.m.) and the peak hour (16:00-17:00 p.m.) at the stop line for signal group 1 on approach number 1. During the off-peak hour the average queue-length was 2.6 vehicles and the maximum was 6.0 vehicles. For the peak hour the average queue-length was 7.1 vehicles and the maximum was 18.0 vehicles.

10.2.2.5 Saturation flow

Saturation flow was measured using film analysis for the stop line at Signal Group 1 on Approach 1 in the inner lane (for vehicles travelling straight ahead and turning right). The method used involved recording average discharge rates (i.e. headways) for the third to the eighth vehicle as they passed the stop line and then transforming the averages to hourly saturation flow rates (see e.g. TRB, 2000).

The saturation flow rate calculated from field study during the peak hour was found to be 2,080 vehicles per hour of effective green-time. Studies at other similar but more congested junctions reveal similar saturation flow rates that are also in excess of 2,000 vehicles per hour during peak hour (Sabeti, 1989; Archer & Cunningham, 2004). The saturation flow rate at a particular intersection stop line is an important calibration or validation measure for micro-simulation models that include traffic signals.

10.2.2.6 Number of signal cycles and signal times

In order to verify the functionality of the programmed vehicle actuated signal logic in the simulation model it is important to ensure that the correct number of signal cycles per hour and average green times per cycle were generated in accordance with the traffic demand/flow rates, turning percentages, averages speeds, the arrival pattern and other parameters. The number of signal cycles and signal times were measured during the first off-peak hour (14:00-15:00 p.m.) and the peak hour (16:00-17:00 p.m.) for Signal Group 1 on Approach 1. During the off-peak hour there were 72 signal cycles with an average green time per cycle of 24.90 seconds (maximum 67.28 seconds), the average amber time was 2.23 seconds (variable between 2 and 4 seconds). For the peak hour, there were 44 signal cycles and an average green time per cycle of 49.98 seconds (maximum 72.36 seconds), the average amber time was 3.11 seconds.

10.2.2.7 Driving behaviour in dilemma zone

The decision by drivers to *stop* or *go* when faced with the onset of amber while in the dilemma zone represents an important behavioural aspect of the simulation model. This particular part of the data has been borrowed from another intersection with a similar design and similar traffic conditions. Reactions to amber in the form of stop-or-go decisions have been recorded using a combination of vehicle speed detection logging, signal status logging and film analysis (Moran, 2003). The data included two red light violations during the two-hour data collection period. For the purposes of this study, each case has been plotted in accordance with vehicle speed and the distance to the stop line (see Figure 10.9).

This analysis procedure was first defined by Alexanderson, Bång and Wretblad (1964). Lines denoting the start and end of the dilemma zone are shown. The diagonal straight line indicates the distance that can be covered by a vehicle at its current speed during the normal amber period of 4 seconds on a 50 km/h road, i.e. the start of the dilemma zone. The second (curved) line represents a normal braking distance for a small vehicle (car) with regard to speed and an average deceleration rate during the entire braking event of 2.00 metres per second².

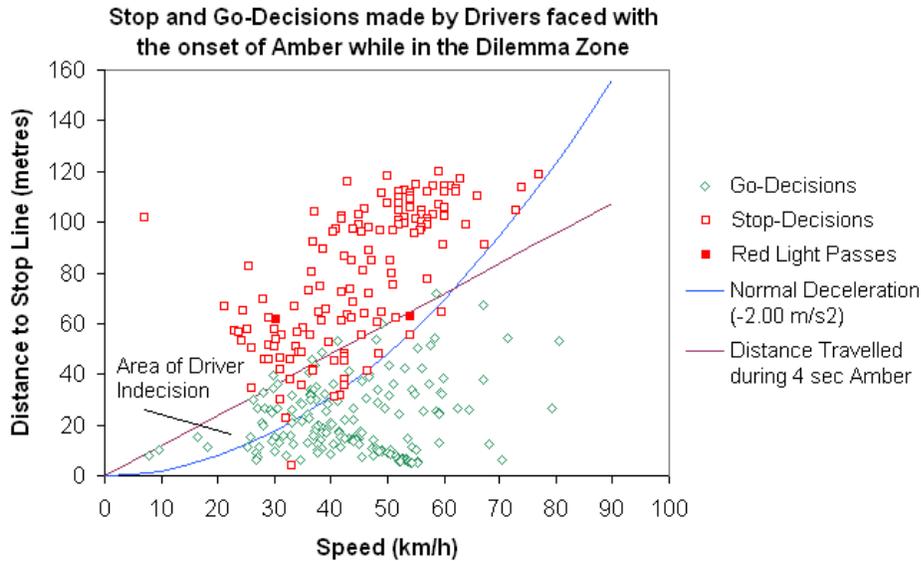


Figure 10.9 Analysis of stop and go-decisions for drivers faced with the onset of amber while in the dilemma zone

These two lines separate the majority of stop and go decisions, and identify an area of behavioural indecision. This area of variant behaviour represents the main safety risk, particularly when a vehicle that decides to *go* is preceded by a vehicle that has decided to *stop*. Interestingly, the go-decisions that are above the line denoting the distance that can be covered during the 4 second amber period would normally result in red-light violations were it not for the frequent and inappropriate behaviour of drivers to accelerate at the onset of amber (presumably to avoid the less desirable alternative of stopping and having to wait if this can be done safely and without violation).

The *stop-go* decision data can be represented in the form of a binary logistic regression function that can be used to estimate the probability of stopping given current speed and distance to the stop line. The binary logistic regression function resulting from the above data is illustrated graphically in Figure 10.10. Binary logistic (logit) regression analysis is useful when the dependent variable (stopping or continuing in relation to the onset of amber) is dichotomous and the independent variables are interval level or categorical (in this case speed and distance). Furthermore, this statistical analysis is not dependent on distributional assumptions such as those used for discriminant analysis. Logistic regression analysis represents a non-linear transformation of linear regression.

The analysis process uses an iterative stepwise procedure to find the best fit. Statistical test can be performed to test the significance of the function parameters, and the Hosmer-Lemeshow statistical test (based on the Chi-2 statistic) can be used as a goodness-of-fit measure. It is also useful to consider the predictive ability of the logistic regression functions, and tests are usually provided for this purpose (e.g. as an average of how well both of the two outcomes of the dichotomous dependent variable are predicted from the original data set). In this study, the SPSS statistical package is used for the purposes of calculating binary logistic regression functions.

The logistic regression function is illustrated for three different speed levels (30, 50 and 70 km/h) in Figure 10.10. The point at which there is an equal probability for stopping and continuing ($p = 0.50$) is shown for each of the three speeds. At 30 km/h, for example, there is an equal probability for stopping and continuing at a distance of approximately 35 metres. Similarly, the distance at 50 km/h is 52 metres, and the distance at 70 km/h is approximately 67 metres. The results of the binary logistic regression analysis used to estimate the probability of stopping when faced with the onset of amber showed statistically significant parameters (at the $p=0.01$ level of significance), and provided a good-fit against the data as indicated by the Hosmer-Lemeshow statistical test ($1 - \alpha=0.05$, significance level). The predictive ability of the model was found to be over 85 per cent in relation to the data.

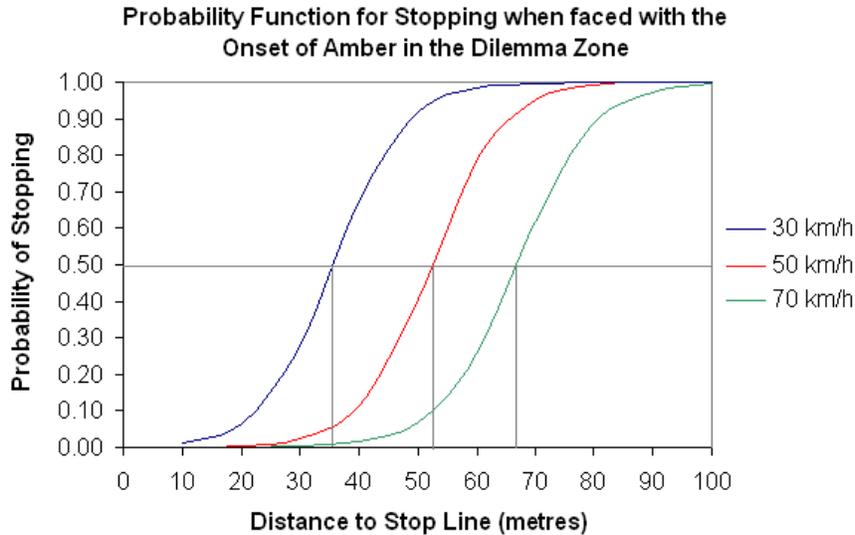


Figure 10.10 Graphical representation of the probabilistic reaction-to-amber logistic regression function for three different speed levels

10.2.2.8 Vehicle deceleration

Vehicle deceleration is also an important issue in this study. Not only the average and maximum rates of deceleration when reacting to a red or amber signal, but also the form of the deceleration curve. Deceleration must be considered to verify the behaviour of driver/vehicle units in the simulation model and therefore the validity of the safety indicator and traffic performance measures. Studies been carried out by Akcelik and associates who stress the importance of accurately representing acceleration and deceleration in micro-simulation modelling (Akcelik and Besley, 2001a, 2001b; Akcelik and Biggs, 1987).

The models of Akcelik and colleagues are based on empirical data from real-world driving conditions and can be used to estimate non-linear deceleration and acceleration profiles, average rates, distances and times. The models reflect the fact that the greatest amount of acceleration is applied during the early part of the acceleration process and similarly that the greatest amount of deceleration occurs during the latter part of the deceleration process. Furthermore, for deceleration average rates increase with higher (initial) speeds.

The polynomial model of acceleration and deceleration is described below:

$$a(t) = r a_m \theta (1 - \theta^m)^2 \quad \text{(Equation 10.1)}$$

$$v(t) = v_i + 3.6 r a_m t_{a/d} \theta^2 \left[\frac{0.5 - 2.0^m}{(m+2)} + \frac{\theta^{2m}}{(2m+2)} \right] \quad \text{(Equation 10.2)}$$

$$L(t) = v_i \frac{t}{3.6} + r a_m t_{a/d} \theta^2 \left[\frac{1}{6} - \frac{2.0^m}{(m+2)(m+3)} + \frac{\theta^{2m}}{(2m+2)/(2m+3)} \right] \quad \text{(Equation 10.3)}$$

where: $a(t)$ = acceleration rate at time t , $v(t)$ = speed at time t , $L(t)$ = distance at time t , a_m = maximum acceleration rate, θ is time ratio, t = time since start of acceleration, $t_{a/d}$ = acceleration time, v_i = initial acceleration speed, and r, m are model calibration parameters.

The polynomial model proves useful for estimating braking profiles including average deceleration rates and the time and distance required to brake from an initial distance and speed to a final distance and speed (see Figure 10.11). Besides additional models for heavy vehicles, there are specific model parameters can be used for calibration against real-world conditions. This makes the model useful for simulation modelling.

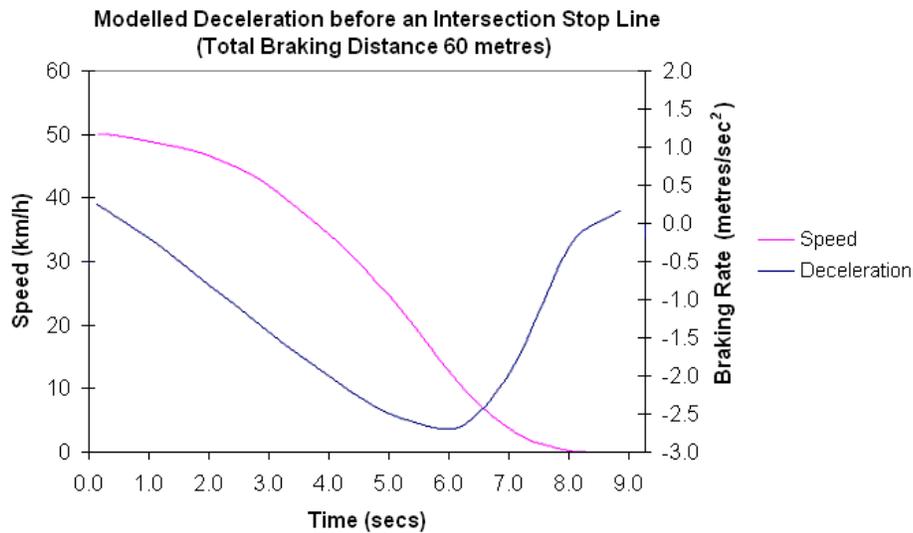


Figure 10.11 Modelled deceleration profile when braking towards a fixed object (e.g. a stop line at a signalled intersection) according to polynomial model of Akcelik and Biggs (1987)

Experiments with a specially instrumented vehicle (see Archer, 2002) have also provided some useful data with regard to deceleration when approaching a signalled intersection on a 50 km/h road (see Figure 10.12). The average deceleration rate for 22 braking events recorded with the instrumented vehicle on an approach towards a traffic signal controlled intersection was found to be -1.49 metres/ sec^2 (standard deviation 0.16, range 33-63 km/h, maximum rate -2.99 metres/ sec^2).

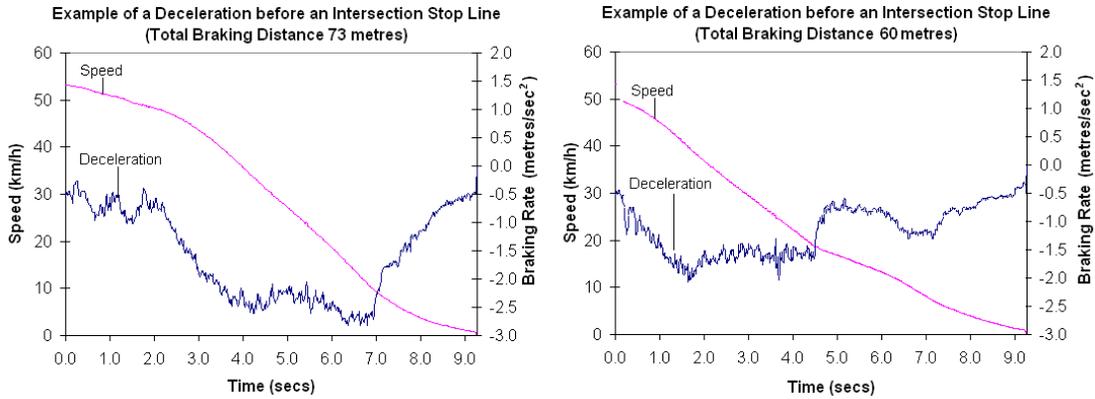


Figure 10.12 Typical deceleration profiles when braking towards a stop line at a signalled intersection (taken from KTH instrumented vehicle)

10.2.2.9 Red-light violations

In total nine red-light violations were observed. Only one occurred during the off-peak hour between 14:00 and 15:00 p.m., while a total of five were observed during the peak between 16:00 and 17:00 p.m. The remaining three red-light violations were outside these two study periods.

10.2.2.10 Vehicle deceleration and safety indicator validity

Even if the braking profiles and the average and maximum braking rates found in the simulation model appear to match those of the real-world, it is still uncertain that the correct safety behaviour will be observed in the micro-simulation model. There are a number of reasons for this, the majority of these are related to the oversimplification of interactive driving behaviour and the absence of important psychological phenomena such as attentional lapses and the delay between perceiving and interpreting potential conflicts and actually taking aversive action.

Hiramatsu and Obara (2000) have, for example, identified driver inattention as a major cause of rear-end accidents. The concept of inattention is rarely incorporated directly in simulation models although reaction delay often exists within the modelled representation of car-following behaviour. The combination of driving too fast and too close in relation to a preceding vehicle is also identified as a major cause for this and particular type of accident in urban areas (Carsten *et.al.* 1989).

10.2.3 Simulation modelling

10.2.3.1 Choice of simulation tool

Following a review of existing commercial and academic micro-simulation software, VISSIM was selected as the model of choice for this simulation study (see e.g. Algiers *et.al.*, 1997; TfL, 2003). There were a number of reasons for selecting this particular simulation tool, including previous experience with this and other commercially available and academic simulation tools including PARAMICS and HUTSIM.

The following criteria were regarded as particularly important selection:

- High level of detail (microscopic) with object based modelling approach rather than node-link based approach
- Possibility to define and test signal controller logic including LHOVRA functionality through the additional VisVAP (Visual Vehicle Actuated Programming) module
- Possibility to define *stop-go* behaviour in relation to the onset of amber at traffic lights (in the form of a binary logistic regression function)
- Possibility to represent and define important vehicle performance parameters such as average and maximum braking and acceleration per type and class
- Open parameters in behavioural sub-models, most importantly the car-following model for the purposes of this study

10.2.3.2 The VISSIM micro-simulation tool

VISSIM is a commercially available micro-simulation tool that is marketed, developed and maintained by PTV in Karlsruhe, Germany (PTV, 2004). A detailed description of this software is outside the scope of this report and the user is therefore referred to independent literature reviews that compare this and other micro-simulation platforms (see e.g. TfL, 2003). For the purposes of this study, the attributes characterising each driver/vehicle unit can be summarised as follows:

- Behaviour of driver/vehicle unit (desired speed, desired acceleration and deceleration, sensitivity thresholds and other parameters that determine car-following and lane-changing behaviour)
- Technical specifications of the vehicle (length, weight, engine power, maximum speed, acceleration and deceleration potential, age of vehicle, etc.)
- Interdependency between vehicles (relative positions of preceding and following vehicles on the same and other lanes, and the positions of other important objects)

10.2.3.3 VISSIM and VisVAP

VisVAP is an acronym for '*visual vehicle actuated programming*' and exists as a separate software program that is synchronised in time with VISSIM and communicates by extracting information from detectors and returning status control messages to signal heads (or other control objects). In effect, VisVAP logic programs represent the functionality of signal controllers.

10.2.4 Modelling signal controller logic and LHOVRA in VisVAP

The standard Swedish signal controller logic including LHOVRA functionality has been programmed in VisVAP. A special pre-release version of VisVAP that operates at a time resolution of one-tenth of a second is used in order to achieve the desired level of functionality and accuracy. The programming of logic has been carried out in accordance with technical documents containing specifications of the controller logic (SRA, 2002b).

Flexibility has been achieved through the use of globally defined signal system parameters at the highest hierarchical level. Parameters have also been added to allow the user to turn off various functions and sub-functions (including the IR-function) to achieve a high level of adaptability and provide a useful test environment.

10.2.5 Simulation model calibration criteria

In simulation, model calibration generally refers to the process through which the individual components of the simulation model are adjusted or tuned so that the behaviour of the model is representative of observations made in the field and the data collected. The components or parameters of a simulation model that require calibration include mainly those related to: traffic control operation, traffic flow characteristics and driver behaviour (see Chapter 8).

With regard to the main purpose of this particular study, model calibration is based on the following variables:

- Number of signal cycles for Signal Group 1 on Approach 1
- Amount of green and amber time for Signal Group 1 on Approach 1
- Car-following behaviour (to ensure that the time-gap distribution between vehicles at the start of the dilemma zone is acceptable)
- Vehicle deceleration (including average and maximum levels)
- Reaction to amber for drivers/vehicles in the dilemma zone

Calibration is carried out using the above parameters in relation to two specific and different (with regard to traffic demand) time-periods, the off-peak hour between 14:00 and 15:00 p.m. and the peak hour between 16:00 and 17:00 p.m.

10.2.6 Simulation model validation criteria

Validation is generally concerned with testing the accuracy of the model by, for example, comparing traffic or safety indicator values generated by the simulation model with observed values. Validation is closely linked to calibration and involves an iterative process where successive adjustments are aimed at improving the ability of a model to replicate qualitative and quantitative aspects of behaviour and performance measured in the field (see Chapter 8).

The following parameters have been identified for model validation:

- Traffic flow rates and turning percentages for all approaches
- For vehicles on Approach 1 only:
 - Vehicle throughput and saturation flow at stop line
 - Time-gap distributions at 110 metres before stop line
 - Average and maximum queue lengths
 - Red-light violations and rear-end conflicts

10.2.7 Simulation experiment and scenarios

The time-period for the simulation was the four-hour afternoon period from 14:00 to 18:00 p.m. An initial 15-minute warm-up period was also included for each simulation run during which no data was collected. A time-resolution (i.e. update-cycle) of 0.10 second was used for the experimental runs. The same basic simulation model with regard to traffic parameters (flows, turning percentages, speeds, etc.) and intersection design is used in each case.

The simulation experiment is based on two scenarios, one with the standard IR-function that represents the existing real-world traffic situation, and a scenario where the IR-function has been deactivated so that no past-end green time is given. Each simulation scenario is run a number of times using different random seed numbers. The number of runs is determined as an integral part of the calibration process.

10.2.8 Simulation output and post-processing

Output data from the simulation model was initially generated in the form of two specially formatted files. The data in these files was then post-processed to extract information relating to traffic performance and safety. The first file contained the exact status of each signal group per simulation update cycle (0.10 seconds). This data was used in order to calculate, amongst others, the amount of green time, past-end green and green extension time given. The second file contained raw data including the speed and position of all vehicles at each update cycle and details regarding any preceding vehicle, and the relative speed difference.

Owing to the large quantities of simulation output data, a special analysis program was designed specifically for the purposes of generating performance and safety results consistently and reliably.

The following output measures were generated from the data for each simulation run:

- Signal Performance Measures - An important part of the comparison of the different simulation scenarios concerns the performance of the signal system with the adjusted signal controller logic. The measures found for this comparison include: number of signal cycles, vehicle throughput, average green time per cycle, and the amount of green extension and past-end green given.
- Traffic Performance Measures - The measures found most suitable for the purposes of this study include: average and maximum queue lengths and saturation flows
- Driver Behaviour in the Dilemma Zone – This includes: numbers and percentages of stop-and-go decisions at the onset of amber and numbers and percentages of stop-and-go decisions for driver vehicle units that are given past-end green
- Safety Indicator Measures - Safety variables are considered in relation to: (a) vehicles that find themselves in the dilemma zone at the onset of amber; and (b) vehicles that are given past-end green. These include the following: average and maximum braking rates, the distance to any preceding vehicle during braking, numbers of red-light violations, details of Time-to-Collision events.

Although the main concern of this thesis is traffic safety and the use of proximal safety indicators, traffic performance measures are also considered here due to the primary objectives of the study, which include developing and establishing a methodology that can be used to test the impact of the IR-function and several other aspects related to vehicle actuated signalling. It is not uncommon to find that safety-related improvements have a negative effect on traffic performance (and *vice versa*). An interesting aspect with regard to the IR-function is that it should provide an additional safety benefit without invoking any tangible negative impact on traffic performance, it is therefore also of interest to investigate the extent to which these two objectives can be achieved in this study.

10.3 Results

10.3.1 Calibration results

An important consideration concerns the number of simulation runs that are required to ensure statistically reliable results in stochastic simulation models. The number of required simulation runs can be determined using averaged values for the mean and variance over a number of simulation runs for one or more chosen variables (Hourdakis *et.al.* 2002). This method has been suggested by Hale (1997) and is exemplified in the report regarding guidelines for calibration and simulation by Milam and Choa (2000). Using the suggested statistical method, runs can be conducted successively until the average mean and standard variation fall within an acceptable confidence interval calculated in relation to the standard *t*-distribution. Using this calculation for the flow rates measured on each approach road at the studied intersection, it was determined that approximately 7-8 simulation runs were necessary in accordance with a confidence interval of 0.95 per cent ($1 - \alpha=0,05$). For the purposes of the simulation experiment, this figure was rounded upwards to 10 simulation runs.

10.3.1.1 Number of signal cycles and signal times

The average number of signal cycles for the off-peak and peak hours were found to be within one standard deviation of the corresponding observed values and therefore within acceptable levels of accuracy for calibration purposes (see Table 10.1 below). A similar comparison also showed that the average and maximum green times were consistent for the off-peak and peak hours.

Table 10.1 Calibration results in relation to the number of signal cycles and average and maximum green signal time on Approach 1

	Off-Peak Hour (14:00-15:00)		Peak Hour (16:00-17:00)	
	Observed	Simulated Mean St. Dev	Observed	Simulated Mean St. Dev
Number of Signal Cycles	72.00	70.61 6.45	44.00	42.46 2.32
Average Green Time (per cycle)	24.90	23.19 2.12	49.98	46.66 1.61
Maximum Green Time (per cycle)	67.28	67.90 7.59	72.36	80.30 8.45

10.3.1.2 Car-following and time-gap distribution at dilemma zone entry

A critical calibration issue concerned the car-following model and the existence of a representative time-gap distribution immediately prior to entry into the dilemma zone (at a point 110 metres upstream on the intersection). Initially, the comparison between observed and simulated data revealed a poor level of agreement with the standard default car-following parameters in the Wiedemann '74 model (Wiedemann, 1974). Adjustments were carried out to the car-following model parameters to provide a better level of agreement between the time-gap distributions for the off-peak and peak hours to those observed in the field.

The adjustments involved changing the car-following model parameter values for the additive and multiplicative parts of the safety distance (see e.g. Wiedemann 1974; Wiedemann and Reiter, 1992; PTV, 2004). The default values for the additive and multiplicative safety distance parameters were changed from 2.00 and 3.00 seconds to 0.50 and 6.50 seconds, respectively, following a calibration process that involved systematic trial and error testing and values suggested from spreadsheet calculations based on the Wiedemann '74 algorithms. Following these adjustments to the car-following model the degree of bunching and level of car-following were found to be considerably more consistent with corresponding observed values.

A comparison of observed and simulation headway time-gap distributions for the off-peak hour is shown below in Figures 10.13. The observed data indicated that approximately 54 per cent of vehicles in the off-peak hour had headway gaps of 3.5 seconds or less (i.e. were in a car-following state) and the simulation runs showed a similar average of approximately 52 per cent. A similar number of vehicles with headway gaps greater than 10 seconds were also found for the observed and simulated data (approximately 20 per cent in both cases).

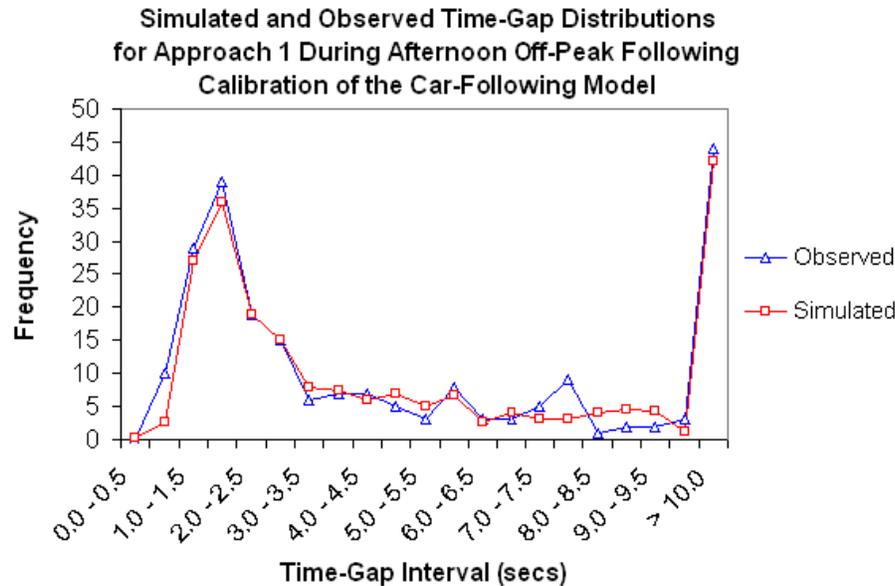


Figure 10.13 Observed and simulated off-peak hour time-gap distributions following calibration of the Wiedemann '74 car-following model

A similar comparison of observed and simulation headway time-gap distributions for the peak hour is shown below in Figures 10.14. For the peak hour, the observed data indicated that approximately 81 per cent of vehicles had headway gaps of 3.5 seconds or less while the simulation runs showed an average of approximately 72 per cent. This disparity was caused largely by the differences at the lower end of the distribution, due to the limitations of the car-following model discussed above. A similar number of vehicles with headway gaps greater than 10 seconds were again found for the observed and simulated data (approximately 4 per cent in both cases).

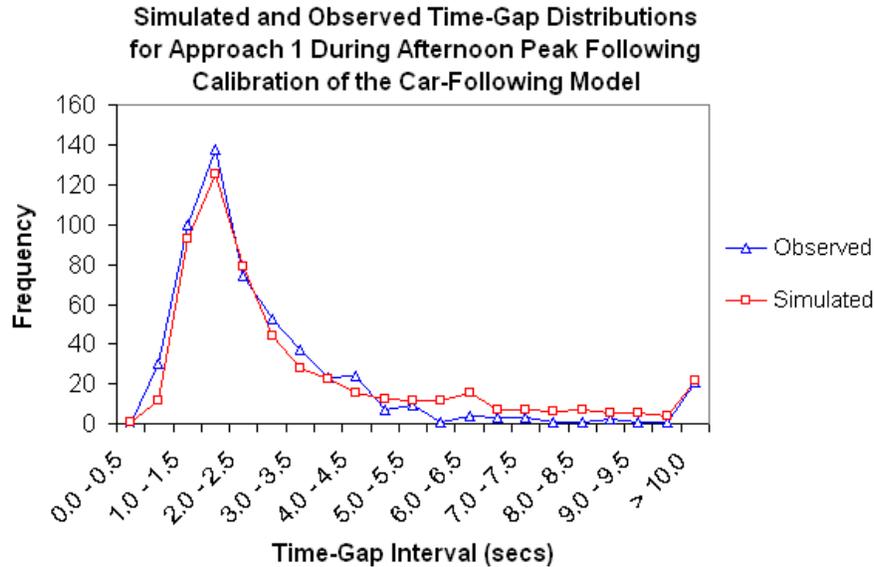


Figure 10.14 Observed and simulated peak hour time-gap distributions following calibration of the Wiedemann '74 car-following model

A minor problem that can be seen in Figures 10.13 and 10.14, is that the number of gaps in the 0.5-1.0 second time category is underrepresented in the simulation model despite adjustments to the two safety-distance parameters. Reducing the parameter value for the additive part of the safety distance to below 0.5 causes more disparity in the overall match for the two curves. This causes unrealistic behaviour in the model due to the level of variation that is included in the car-following model. Adjusting the values is a time consuming but necessary process and requires trial and error in light of the dynamic nature of the effects these adjustments have on traffic processes.

10.3.1.3 Vehicle input at model boundaries

The VISSIM simulation model uses a Poisson distribution to calculate the arrival pattern of vehicles in accordance with a stated hourly vehicle flow rate (i.e. vehicle demand) and time interval during which the flow rate is assumed to be stable. If vehicle entry cannot be made due to queuing the vehicles that are generated but not entered are stored in an internal list or queue at the model boundary and are introduced when conditions in the model are more favourable. The input of vehicles is also restricted by the car-following model such that larger safety gaps will restrict the number of vehicle entries that can be made when the traffic demand approaches the capacity limit.

Adjustments to the car-following model through the use of the safety distance parameter values tend to ‘flatten’ the distribution (i.e. make it more *platykurtic*) causing greater levels of variation. Thus, making changes to the model parameters with the intention of introducing a larger number of shorter gaps may also introduce larger gaps and reduce capacity. Ideally, a simulation modelling environment should allow the user to determine the type and shape of discrete distribution function required for a particular model through the use of various parameters that initially have suitable default values.

There are a number of ways in which arrival patterns can be adjusted to match observed measurements. One alternative is to use input patterns based on observations or measurements in the field to achieve an exact replication. This may not always be useful however, where there signals near the point of entry and where the assignment of desired speed, car-following safety distance and other behavioural parameter values cause a very different pattern of headways or time-gaps further downstream. It is also possible to adjust the lengths of links into which vehicle input is made in order to achieve a reasonably accurate arrival pattern. Longer approaches cause vehicles to group into platoons while shorter approaches retain the same pattern as the input distribution function used. This solution has also limitations and is not suitable in all cases. A great deal depends on the purpose of the modelling and the types of traffic facilities (intersections, motorways, etc.) that are incorporated into the model and how close these are to the vehicle input point.

A further possibility to control model input is to use ‘dummy’ traffic signals, this method is particularly useful if vehicle arrivals in the real-world situation are influenced by signals outside the boundary of the model. Signals are also useful for controlling the otherwise unrestricted flow of vehicles leaving the model. Issues concerning the representation of boundaries in simulation modelling at different conceptual levels have been considered in some detail by Burghout (2004).

For the simulation model used in this study, boundary problems were not an issue. Vehicles were entered at a distance approximately 200 metres upstream of the intersection on each approach road. The generation of vehicles in accordance with the Poisson distribution presented no problems and resulted in a headway time-gap distribution that was calibrated to match the observed distribution at a measurement point further downstream (at 110 metres) using the car-following model.

10.3.1.4 Vehicle acceleration and deceleration

Braking rates in the simulation model were found to vary among vehicles, as expected. The braking rates for cars that stopped when faced with the onset of amber while in the dilemma zone (i.e. distances between 110 metres and 30 metres) revealed an average simulated braking rate of -1.65 metres/sec² (standard deviation = 0.47, range -0.7 to -2.46, number of cases = 116). Given that the average speed prior to braking was slightly less than 50 km/h, the average braking rate tends to be in agreement with the value of 1.7 metres/sec² suggested by the polynomial model of Akcelik and Biggs (1987).

The average braking rate appears to be slightly higher than that based on the data from the RIT instrumented vehicle ($-1.49 \text{ metres/sec}^2$), although the highest level of braking reached in normal conditions was found to be similar to the value ($-2.93 \text{ metres/sec}^2$) obtained from the simulation data. The slightly lower average braking rate from the instrumented vehicle data is probably attributable to the different situational conditions (i.e. urban environment with low traffic demand). Values for emergency braking were extreme, with values approaching $-7.00 \text{ metres/sec}^2$ in the simulation model, this was found to be acceptable given the prevailing literature (e.g. Hydén, 1987,1996; Evans, 1991). In light of these findings, the standard default values for desired and maximum acceleration and deceleration were not adjusted for the purposes of this study.

10.3.1.5 Reaction to amber in dilemma zone

Simulation runs for the off-peak and peak hour indicated that the relative proportions of *stop-go* decisions in the dilemma zone differed to observed values (the values are adopted from a similar intersection). The simulation runs for both the off-peak and peak hours indicated that 80 per cent of all vehicles stopped and that 20 per cent passed while the observed data showed a 60 to 40 per cent *stop-go* ratio. This difference need not imply that the *reaction-to-amber* function used is inappropriate for the studied intersection. Samples taken from the video-recordings for this site reveal an approximate 76 – 24 ratio for driver '*stop-or-go*' decisions, respectively. This suggests that the *reaction-to-amber* function is approximately correct.

The reaction-to-amber function is most probably defined by site-specific factors related to the speed and flow conditions of the approach roads in addition to roadway design and geometry as suggested by Alexanderson, Bång and Wretblad (1964). This is also suggested by the findings of Moran (2003) where variation is attributed to different amber duration time and higher average or posted speed limits

10.3.2 Validation results

10.3.2.1 Traffic flow rates and throughput at the stop line for signal group 1 on approach 1

An important part of the validation process in all traffic simulation modelling involves ensuring that the correct amount of traffic is entering the simulation model. For signalling purposes, it is also important to establish that the correct amount of traffic passes the studied stop lines (Signal Group 1 on Approach 1 in this particular study). A comparison of observed and simulated flows and traffic throughput is presented in Table 10.2 below. The statistical comparisons are based on GEH-statistic calculations (see e.g. UK Highways Agency, 1996; see also Chapter 8 equation 8.3).

GEH-values for the observed and simulated flow rates are shown in Table 10.2 below. The GEH-calculations suggest a very good degree of consistency for all cases.

Table 10.2 Comparison of traffic flow rates on all approach roads and stop line throughput for Signal Group 1 on Approach 1

Flow Rate	Off-Peak Hour (14:00-15:00)		Peak Hour (16:00-17:00)	
	Observed	Simulated Mean (St. Dev)	Observed	Simulated Mean (St. Dev)
Approach 1	549	540.78 (1.92)	1,074	1,064.22 (3.15)
Throughput at Stop Line	418	426.13 (11.46)	821	820.25 (3.15)
Approach 2	222	213.67 (1.12)	269	259.33 (2.24)
Approach 3	462	456.38 (1.22)	721	707.44 (1.94)
Approach 4	99	94.33 (1.41)	138	134.11 (1.54)

10.3.2.2 Turning percentages

In addition to traffic flows, it is important to compare the observed and simulated turning percentages. A comparison of this data is presented below in Table 10.3. The data shows no major differences for the simulated and observed turning data values in either of the two time-periods studied.

Table 10.3 Comparison of turning percentages for all approach roads

Turning Percentages	Off-Peak Hour (14:00-15:00)		Peak Hour (16:00-17:00)	
	Observed LT / SA / RT*	Simulated LT / SA / RT*	Observed LT / SA / RT*	Simulated LT / SA / RT*
Approach 1	7 / 69 / 24	6 / 70 / 24	6 / 71 / 23	6 / 70 / 24
Approach 2	68 / 9 / 23	69 / 13 / 18	55 / 19 / 26	56 / 18 / 26
Approach 3	9 / 86 / 5	12 / 82 / 6	13 / 82 / 5	12 / 83 / 5
Approach 4	32 / 35 / 33	32 / 35 / 33	30 / 38 / 32	30 / 39 / 31

* LT = Left-Turn; SA = Straight Ahead; RT = Right-Turn

10.3.2.3 Saturation flow rates

Saturation flow rates were calculated directly from the simulation data in both the off-peak and peak hours, and compared against the observed value that was determined during peak hour traffic. For the off-peak hour the average saturation flow was 2,035 vehicles per hour (standard deviation 120.84) for the 10 simulation runs. The peak hour average saturation flow rate was 2,091 vehicles per hour of effective green time (standard deviation 76.84). The simulated values are in both cases well within one standard deviation of the observed value and are therefore considered acceptable for validation purposes.

10.3.2.4 Time-gap distributions (110 metres before stop line)

Chi-2 tests were performed in order to statistically verify the goodness-of-fit for the simulated time-gap data distributions against those based on the observed data for the off-peak and peak hours (see calibration section above). The Chi-2 values based on frequency data were both found to be statistically significant (0.05 level of significance, 19 degrees of freedom) indicating a poor fit.

To compensate for the crudeness of this test (which generally reflects the size of the largest value difference in any one category), Chi-2 values were also calculated following a percentage transformation. This transformation implies that the relative proportions of the distribution (in accordance with the 0.5 second time-gap categories) are compared for accuracy against the observed data. Results based on the percentage transformations indicated a non-significant (i.e. reasonably good) fit for both time-periods (0.05 level of significance, 19 degrees of freedom). The transformation used reduced the sensitivity of this test considerably by not allowing singularly deviant frequency values in one category to influence the overall result.

10.3.2.5 Average and maximum queue lengths

In this study, the number of queuing vehicles is considered rather than the actual length of the queue. Results of the comparison between observed and simulated average and maximum queue lengths for the off-peak and peak hours are shown below in Table 10.4.

Table 10.4 Comparison of average and maximum queue lengths at the stop line of Signal Group 1 on Approach 1

Flow Rate	Off-Peak Hour (14:00-15:00)			Peak Hour (16:00-17:00)		
	Observed	Simulated		Observed	Simulated	
		Mean	St. Dev		Mean	St. Dev
Average Queue Length (no. of vehicles)	2.60	2.73	0.54	7.10	6.62	0.98
Maximum Queue Length (no. of vehicles)	6.00	9.00	3.22	18.00	16.50	2.07

A good match was found between the observed and simulated average queue lengths during off-peak and peak hours. In each case, the simulated values are within one standard deviation of observed values. The simulation results for maximum queue lengths are also within one standard deviation of the observed values despite slightly larger deviations from observed values.

10.3.2.6 Red-light violations

The simulation data showed an average of 1.30 red-light violations (standard deviation 1.13) for the off-peak hour, and an average of 6.80 red-light violations (standard deviation 3.05) for the peak hour. These average values are consistent with the observed data for this traffic site (1 red-light violation in the off-peak hour, and 5 during the peak hour).

10.3.2.7 Rear-end conflicts

The simulation data for the off-peak hour showed a mean average of 5.40 safety critical rear-end conflicts with TTC values less than 4 seconds (standard deviation 4.33). For the peak hour, an average of 21.50 rear-end conflicts were recorded with the same TTC threshold (standard deviation 4.81). A 3.5 second TTC-threshold appears to encompass the vast majority (approximately 90 per cent) of the rear-end conflicts that occur in the dilemma zone following the onset of amber (see Figure 10.15). The distribution of TTC-values shown in Figure 10.15 shows that the vast majority of rear-end conflicts result in TTC-values between 1.5 and 3.0 seconds. The form of the distribution is however, dependent on various factors including: the position of the actuating detectors before the stop line, vehicle speeds and the variation in speeds, and the time-gap distribution reflecting the arrival pattern and car-following behaviour of drivers. Given that the average speed on the approach road is likely to be between 40-55 km/h, it can be calculated that TTC-values below 2.50 seconds require braking rates in excess of -3.00 metres/sec² and are therefore quite severe.

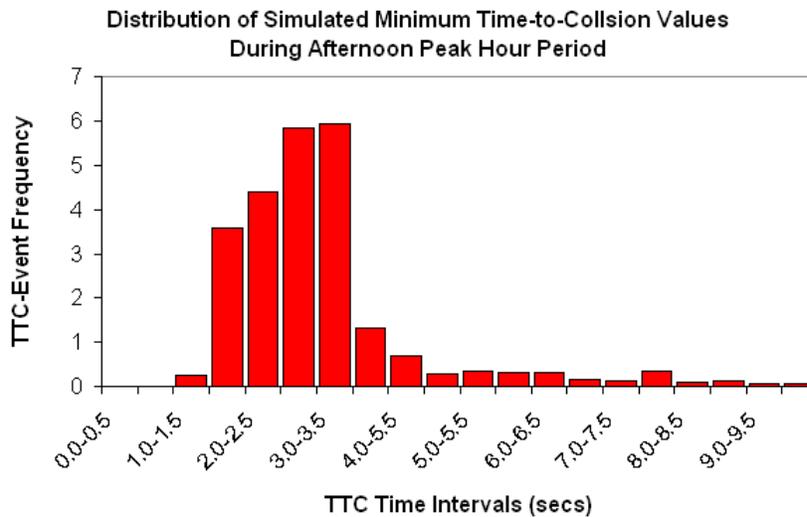


Figure 10.15 Distribution of simulated minimum TTC-values for the peak hour period

Given the difficulties involved in determining safety critical rear-end conflict events through video-analysis and/or conflict observation, strict validation of the Time-to-Collision data obtained from the simulation runs was not possible in this study. It was anticipated that vehicle interactions in the simulation model would result in safety critical events that could be measured using the TTC-safety indicator value, and that these would increase in accordance with traffic volume on the intersection approach studied.

A noticeable difference was also anticipated with regard to the relative frequencies of safety indicator measures for the two experimental scenarios. If the IR-function functions correctly, a significantly lower number of safety critical events should occur in comparison to the scenario where this function was disabled, and the difference should be evident in the relative frequencies of safety indicator measures that are recorded.

10.3.3 Main simulation experiment results

10.3.3.1 Measures of signal performance for signal group 1 on approach 1

The results pertaining to signal performance for Signal Group 1 on Approach 1 are summarised below in Table 10.5. The results show that a consistent number of vehicles passed the stop line during each of the runs for the two simulation scenarios. This implies that the signal performance results are comparable (i.e. use approximately the same traffic volumes and arrival processes during each simulation run).

Results indicate a reduction in the number of signal cycles and a slight increase in standard green time when the IR-function was in operation compared to the scenario without the IR-function. Furthermore, the standard IR-function gives less green extension time. This may be a compensatory effect in relation to the amount of past-end green time given. In total, a greater total amount of green time was given when the IR-function was in operation. Although less green-extension time is wasted with the IR-function in operation, there was also an amount of excess (i.e. unused) past-end green. This was the result of vehicles stopping despite having received past-end green to allow them to safely pass the stop line in the simulation.

Table 10.5 General signal performance data for the two simulation scenarios (4-hour simulation time-period averaged across the 10 simulation runs)

	Without IR-Function		With Standard IR-Function	
	Mean	St.Dev	Mean	St.Dev
No of Stop Line Passages	2,639.90	25.81	2,634.70	26.14
No of Signal Cycles	346.30	8.71	314.80	6.14
Total Standard Green Time (secs)	8,959.54	96.25	9,023.34	71.57
Total Green Ext. Time (secs)	1,238.11	28.75	1,225.70	27.47
Excess Green Extension (secs)	76.44	14.14	65.92	16.91
Total Past-End Green Time (secs)	---	---	226.18	34.01
Excess Past-End Green (secs)	---	---	26.75	9.75

10.3.3.2 Traffic performance measures on signal group 1 on approach 1

Traffic performance should take into consideration the entire intersection including all approaches. However, since the IR-function was implemented only on the two priority road approaches and with regard to the fact that these two approaches had an almost identical roadway design and signal functionality, only the results in relation to the traffic performance of Approach 1 are presented for the two simulation scenarios. All results shown below are based on averages calculated from 10 simulation runs for the four-hour study period.

Queue lengths

The results for the queue lengths in relation to the Signal Group 1 stop line on Approach 1 are summarised below in Table 10.6. The average and maximum queue lengths appear to be marginally smaller in relation to the scenario with the Standard IR-function. This is most probably a direct result of the greater total amount of green time for Signal Group 1 when the IR-function is in operation.

Table 10.6. Comparison of average and maximum queue lengths in the two simulation scenarios measured at the stop line for Signal Group 1 on Approach 1

	Without IR-Function		With Standard IR-Function	
	Mean	St.Dev	Mean	St.Dev
Average Queue Length (metres)	19.97	1.37	19.11	1.09
Average Queue Length (vehicles)	3.03	0.19	2.93	0.16
Maximum Queue Length (metres)	93.18	11.91	83.02	9.91
Maximum Queue Length (vehicles)	13.30	1.64	12.30	1.57

Delay time, number of stops per vehicle and saturation flow

A comparison of the results for average delay times, average number of stops per vehicle, and saturation flows for vehicles passing the stop line for Signal Group 1 on Approach 1 are shown below in Table 10.7. The results shown in Table 10.7 are very similar for the two scenarios. A slightly smaller delay time is noticed for the scenario with the IR-function in operation. This small difference can again be attributed to the greater total amount of green time resulting from this scenario. The saturation flow rates are also very similar for the two simulation scenarios as expected. Changes in signal controller logic should not be found to have any substantial influence on saturation flow as a measure that represents the number of vehicles passing the stop line per hour of effective green time.

Table 10.7 Comparison of average delay, average number of stops per vehicle and saturation flow measured at the stop line for Signal Group 1 on Approach 1

	Without IR-Function		With Standard IR-Function	
	Mean	St.Dev	Mean	St.Dev
Average Delay per vehicle (secs)	8.95	0.51	8.53	0.50
Average Number of Stops (per vehicle)	0.21	0.02	0.19	0.02
Saturation Flow Rate (vehicles per hour of effective green time)	2,010.61	26.35	2,001.80	30.07

10.3.3.3 Driver behaviour in the dilemma zone

Numbers and percentages of stop-and-go decisions

Results concerning the *stop-go* decisions made by drivers in the dilemma zone when a change to amber occurs, or when past-end green is given, and the change to amber is delayed are also of interest in relation to signal group 1 on approach 1. The results for the simulation scenario without the IR-function indicated that the driver chose to stop in 80.00 per cent of cases (161 of 201 *stop-go* decision situations). As expected (given the nature of the ‘*Reaction-to-Amber*’-function in the VISSIM simulation program), the number of drivers that chose to stop when the standard IR-function was activated was very similar (79.52 per cent). However, there were far fewer *stop-go* decision situations in this scenario (166 compared to the 201, when the IR-function not active). From these findings, the effect of the standard IR-function was to reduce the number of *stop-go* decision situations rather than to change the behaviour of drivers (i.e. the relative percentage of stop and go-decisions) is clearly demonstrated.

A further comparison was made in relation to the number of drivers that stopped after having actually received past-end green via the IR-function, (i.e. received past-end green at the first detector but then had insufficient speed to reach the second detector and were therefore being faced with amber again and having to make a secondary stop-go decision at a position much closer to the stop line (and therefore also potentially more dangerous). In total, 24 cases (approximately 35 per cent) were recorded where the driver decided to stop after having received past-end green.

From the simulated data, it can be concluded that the IR-function has been successful in reducing the number of stop-go decision situations for drivers by 45 cases out of the 201 that would have existed had the IR-function not been implemented (approximately 22 per cent). Furthermore, there is potential to increase this number and to make the IR-function more effective by reducing the amount of unused past-end green time by adapting the functionality to the situational demands, as suggested by Al-Mudhaffar (2002).

Number of last passages on green, amber and red in a signal cycle

The results in relation to the signal status faced by the last driver/vehicle to pass the stop line on each cycle for signal group number 1 on approach 1 are summarised below in Table 10.8.

Table 10.8 *Comparison of the signal status seen by the last driver to pass the stop line before the end of the signal cycle*

	Without IR-Function		With Standard IR-Function	
	Mean	St.Dev	Mean	St.Dev
No of Last Passes on Min Green	17.50	5.06	16.90	4.18
No of Last Passes on Max Green	30.08	5.59	28.00	5.52
No of Last Passes on Passive Green	78.90	4.41	70.20	8.60
No of Last Passes on Past-End Green	---	---	8.40	3.31
No of Last Passes on Amber	188.60	9.02	187.20	11.56
No of Last Passes on Red	9.60	3.20	9.20	3.16

The number of last passes for the different signal statuses that involve green are relatively similar between the two scenarios, provided past-end green is also included for the scenario that includes the IR-function. The numbers of last passes on amber and red are also very similar with marginally lower averages when the IR-function was in operation. Last-passes on red (i.e. red-light violations) are discussed in the next section.

10.3.3.4 Safety indicator measures and safety relevant data

Vehicles facing the onset of amber while in the dilemma zone

Results related to the safety of vehicles/drivers facing a signal change from green to amber while in the dilemma zone are summarised in Table 10.9. These results are specific to Signal Group 1 on Approach 1 only.

Table 10.9 Safety related data for vehicles in dilemma zone at signal change to amber while in the dilemma zone

	Without IR-Function		With Standard IR-Function	
	Mean	St.Dev	Mean	St.Dev
Average Brake Rate (metres/sec ²)	-1.68	0.03	-1.66	0.03
Maximum Brake Rate (metres/sec ²)	-4.86	0.46	-4.97	0.93
Closest Distance to Preceding Vehicle during Braking (metres)	1.28	1.28	1.32	0.15
Number of sub-threshold TTC Events	67.50	7.01	52.50	4.70
Total Time Exposed TTC (secs)	262.10	27.76	202.56	18.03
Total Time Integrated TTC (secs)	273.17	34.59	217.44	22.06
No. of Red Light Violations	9.40	3.57	8.80	3.16

The data in Table 10.9 suggests that the average and maximum braking rates remain relatively consistent across the two simulation scenarios. The average rate of -1.68 metres per second² is an acceptable level given normal braking from speeds of around 50 km/h and is consistent with the polynomial model of Akcelik and Biggs (1987) and tests with the KTH-instrumented vehicle. As expected, the maximum deceleration rates recorded in conflict situations are significantly lower than normal braking levels approaching -5.00 metres per second². The IR-function appears to generate a slightly higher degree of variance with regard to maximum braking.

Importantly, the proximal safety indicator data from the simulation runs suggests an average 22 per cent average reduction in the number of sub-threshold TTC-events when the IR-function is in operation. The reduction from 67.50 to 52.50 sub-threshold TTC-events when the IR-function is in operation, represents a statistically significant difference using a *t*-test, (two-tailed, $\alpha=0.01$ with 9 degrees of freedom). Similar *t*-tests calculated on the accumulated levels of Time-Extended TTC and Time-Exposed TTC are also statistically significant at the same level of probability.

This reduction is an important finding with regard to the main purpose of this simulation experiment. A further finding that has implications with regard to experimental validity is that there were approximately three times as many TTC-events during the main peak hour in comparison to the off-peak hours. This suggests that the frequency of rear-end conflicts in the simulation increases in accordance with traffic volume on the signalled approaches as expected. This finding is consistent with real-world situations where increased traffic volume implies shorter time-gaps on average between vehicles and where shorter gaps increase the likelihood for rear-end collisions (see e.g. Hermann *et.al.*, 1959; Evans, 1991; Hiramatsu and Obara, 2000; Brackstone and McDonald, 2003).

The average Time Exposed TTC and Time Integrated TTC values per TTC-event for the scenario without the IR-function (3.88 and 4.05, respectively) are very similar to the corresponding values for the scenario without the IR-function (3.85 and 4.14, respectively according to the data in Table 10.9). This is expected given the fact that there were a number of cases when the IR-function was in operation but where the maximum amount of past-end green had already been allocated. There should however, be differences if the results are considered for *only* those vehicles that received past-end green via the IR-function (these results are presented in the next section).

The data in Table 10.9 also indicates the number of red-light violations in each of the two simulation scenarios. The frequency of red-light violations was found to be slightly smaller when the IR-function was in operation. The six per cent reduction is however, too small to draw any conclusions with regard to the general ability of the IR-function to reduce red-light violations. A further LHOVRA-function exists that is designed specifically for the purpose of reducing red-light driving situations (SRA, 2002b). The number of red-light violations generated on average during the simulation scenarios was found to be reasonably consistent with the frequency actually observed at the intersection during the same time-period (9 cases).

Vehicles that received past-end green

The results in relation to vehicles/drivers that stopped after having received past-end green time while in the dilemma zone are shown below in Table 10.10. Again, these relate specifically to Signal Group 1 on Approach 1. Since past-end green is issued by the IR-function, the results cannot be compared between the two different scenarios. A comparison can be made however in relation to the previously discussed case for vehicles faced with the onset of amber while in the dilemma zone.

The results presented in Table 10.10 are related to vehicles that received past-end green while in the dilemma zone, whereas the results presented earlier in Table 10.9, were related to all vehicles that were faced with the onset of amber while in the dilemma zone irrespective of whether they received past-end green. An important consideration given the nature of the IR-function, is that it is possible for a vehicle to receive past-end green at the first detector and then to be faced with amber several seconds later at the second detector if it is not reached within the allocated time-period. Provided the vehicle reaches the second detector within the time-period allocated, a past-end green update is given that enables it to pass the stop line safely with no possibility to cause a rear-end conflict.

Table 10.10 Safety related data for vehicles in the dilemma zone that stopped after having received past-end green while in the dilemma zone

	With Standard IR-Function	
	Mean	St.Dev
Average Brake Rate (metres/sec ²)	-1.72	0.08
Maximum Brake Rate (metres/sec ²)	-4.76	1.59
Closest Distance to Preceding Vehicle during Braking (metres)	1.65	0.36
Number of sub-threshold TTC Events	7.30	3.30
Total Time Exposed TTC (secs)	26.26	13.51
Total Time Integrated TTC (secs)	25.86	15.88
No. of Red Light Violations	3.00	1.41

The results regarding average and maximum braking rates indicate similar values to those found above in relation to all vehicles faced with the onset of amber. The slight differences are largely the result of variation in the statistics due to the limited number of events per simulation run in which vehicles actually received past-end green. An interesting finding is that the closest distance to a preceding vehicle appears to be slightly higher on average (and therefore potentially safer) for the vehicles that receive past-end green in comparison to the situation for all vehicles faced with amber. More testing is required however, before any statistically sound conclusions can be drawn with regard to this finding.

A closer examination of the simulation data also revealed a number of vehicles that braked and caused rear-end conflicts despite having received past-end green. The average Time Exposed TTC and Time Integrated TTC per TTC-event in relation to vehicles that braked and stopped after having received past-end green are marginally smaller (3.60 and 3.54, respectively) compared to the corresponding values for all vehicles faced with the onset of amber (3.85 and 4.14, respectively). These differences can again be attributed to the relatively small number of cases and the corresponding level of variance in the data.

The scenario that included the IR-function also resulted in three red-light violations for vehicles that received past-end green. This is most probably the result of having insufficient speed to receive past-end green at the second detector, in combination with the decision to continue when faced with the onset of amber. This suggests the need for an IR-function that is correctly adapted to the site-specific traffic situation and signalling parameters (e.g. detector distances, the amount of past-end green time given at each detector, and average speeds through the dilemma zone). A finely tuned speed dependent IR-function would also serve to optimise the effectiveness of the IR-function according to Al-Mudhaffar (2002).

10.4 Conclusions

The results of the simulation experiment provide a clear indication of the effectiveness of the LHOVRA incident reduction function used in standard vehicle actuated signalling in Sweden. The results of the simulation runs showed a statistically significant decrease in the number of safety critical rear-end events measured by the minimum Time-to-Collision and extended TTC proximal safety indicators. Furthermore, the simulation scenario with the IR-function in operation showed no indication of any negative traffic performance impact when compared to the simulation scenario in which the IR-function was disabled.

Although the results presented here are based on a calibrated and validated simulation model with regard to aspects of driving behaviour, traffic performance and signalling, the proximal safety indicator measures were not validated against real-world values. This was not the intention of the study; instead, the focus was placed on methodological issues related to the general use of micro-simulation for the preliminary off-line testing of signal controller functionality. Consequently, this implies that the proximal safety indicator results cannot be generalised to real-world situations. Furthermore, no attempt was made to establish a relationship between the TTC-proximal safety indicator values and accident data at the studied intersection. Generally, the majority of rear-end accidents at intersections such as this, involve insufficient speed to result in injury. As a result, relatively few are reported to the police causing an under-representation in accident statistics.

For the purposes of this study, the proximal indicators represent a useful measures of interactive safety that are easily derived from the simulation of calibrated and validated intersection models. The TTC concept is an existing and established measure that has an accepted or assumed degree of (concurrent) validity when used to indicate levels of ‘*safety*’ at existing real-world traffic facilities. Similarly, the two extended TTC-measures have been provisionally validated in the work conducted by Minderhoud and Bovy (2001). As measures of interactive ‘*safety*’ for simulation modelling purposes, these indicator concepts are useful and reliable as a means of safety comparison. They are however, of less value for validation purposes owing to the difficulty of extracting such data using video-analysis techniques. Arguably, they also display a degree of comparative validity determined by their ability to distinguish between the simulation scenarios and identify the effect of the IR-function in reducing rear-end conflicts.

A lack of construct and process validity is implied by the absolute frequencies of the safety critical events measured by the TTC and extended TTC measures. The average of 67 rear-end TTC-events during a four-hour simulation period for the scenario without the IR-function, suggests an average ratio of 1 conflict for every 5 signal cycles, without taking into consideration the differences between peak and off-peak hours. This frequency is considerably higher than that expected from the corresponding real-world situation and suggests that the TTC-threshold value (3.5 seconds) was too high, or that the processes of car-following and speed adjustment (braking and acceleration) in the simulation model were not representative of those found in the real-world. In future studies, it is important that questions related to proximal safety indicator validity are resolved through the acquisition of suitable field data.

The conceptual definition of the TTC-indicator can also be questioned with regard to the results. As discussed earlier in Chapter 5, TTC-events with similar time-proximity (but different speeds) are considered to have similar levels of severity. Thus, the results may include a number of unrepresentative ‘serious’ or ‘severe’ events with sub-threshold minimum TTC-values but low speed (as a result of spatial proximity). The actual number of such events depends on the threshold value used and various other factors, such as: the type of road-users involved, the roadway layout and geometry, and the type of conflict. These issues lie at the very heart of the proximal safety indicator validity debate (see e.g. Hydén, 1987).

It is also possible that the TTC-threshold value should be adapted specifically for rear-end events. In other words, the very nature of this type of event and the calculation (based here on differential speed and distance) may require a lower-threshold than other types of safety critical events to be representative of ‘serious’ or ‘severe’ incidents and interactions. Although taken from the simulation runs, the relative distribution of TTC-values shown in Figure 10.15 above appears to suggest that the 3.5-second threshold was useful in identifying the main range of safety critical rear-end interactions, and therefore was also useful for the purposes of distinguishing between the safety levels in the two simulation scenarios.

The conceptual nature of the Time-Integrated TTC and Time-Exposed TTC indicators implies that they are a more representative measure of severity than the minimum TTC-value. This is due to the fact that higher initial speeds at the start of a safety critical event are likely to result in longer sub-threshold TTC-event duration (Time Exposed TTC) and greater sub-threshold TTC-levels (Time Integrated TTC). However, while this may be true for individual events, valuable severity information may be lost if these values are aggregated for comparative purposes, or for calculating the probability of involvement in a safety critical event or accident (Minderhoud and Bovy, 2001). Interestingly, there appears to be a consistent linear relationship between minimum TTC-values, Time Extended TTC and Time Integrated TTC, as exemplified by the data from one of the simulation runs in Figure 10.16 below.

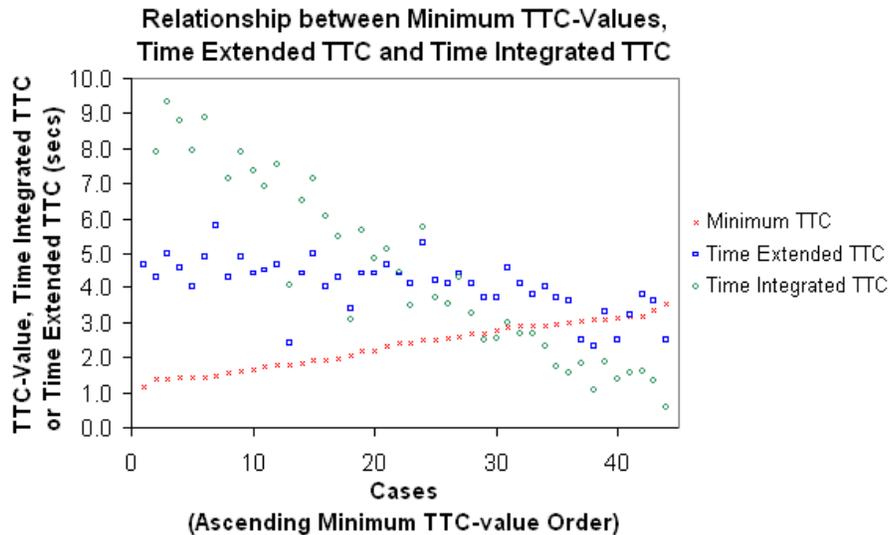


Figure 10.16 The relationship between minimum TTC, Time Integrated TTC and Time Exposed TTC values (results from a single run with IR-function disabled)

With regard to the main results of this study, it is noted that the simulation results imply an optimisation potential for the IR-function. This was evident from the large number of vehicles that continued to stop despite the fact that they were issued past-end green at the first detector. Better adaptation of the IR-function (by for example increasing the amount of time allocated) would allow these vehicles to pass the stop line as intended and would result in less unused green time. The improvements suggested by Al-Mudhaffar (2002), which include: conditional past-end green based on vehicle speed at the first detector to ensure that the second detector would be reached to receive the past-end green update; and better detector placement with regard to the site-specific situation, are likely to further enhance safety and traffic performance.

While the TTC-safety indicator results suggest a safety enhancement potential in conjunction with the use of the IR-function, there appears to be a problem related to the frequency of red-light violations. Again, this suggests the need for a fine-tuning of standard IR-functionality, and a simultaneous adjustment for more general signal control functionality in addition to the special LHOVRA-functions.

An important objective of this study concerned the usefulness of micro-simulation modelling as an *'off-line'* test environment for studies aimed at testing and identifying potential safety and performance effects in relation to vehicle actuated signal control functionality. The methodology adopted for this purpose identified a number of significant aspects in relation to model calibration and validation and important requirements with regard to data collection and analysis. In particular, the calibration of the car-following model was found to be a critical element to ensure that there was a representative time-gap distribution among arriving vehicles. Future models may also include an element of driver inattention or reaction delay, provided that suitable empirical data is available for calibration purposes. Ensuring the correct level and variation of speed on the intersection approaches was also regarded as a critical part of the model calibration and validation process. In addition, it was also found important to consider the representation of vehicle performance in the simulation environment, particularly with regard to vehicle braking.

There is a need for an off-line test-platform among signal engineers for the preliminary evaluation and comparison of alternative signal controller functionality where traffic safety, traffic performance and various measures of signal performance can be measured simultaneously. With some refinement and with more emphasis on proximal safety indicator validation, the general simulation methodology adopted in this study could be useful for this type of work in the future. A great advantage of this methodology is that many different aspects of the traffic system can be investigated with regard to traffic safety and performance. The effects emanating from changes to various traffic parameters and processes and alternative designs and measures can be determined using investigative sensitivity analyses in a safe off-line environment. Although these results of such studies may not be generalised to real-world conditions, they have a considerable value in early transport planning and development work where the main potential and limitations can be identified at an early stage. This type of methodology is therefore both flexible and cost-effective.

PART IV:
SYNTHESIS
AND
CONCLUSIONS

11. Synthesis and conclusions: Safety indicators for traffic safety assessment and prediction

This thesis has been concerned with the concepts, theories and methods related to proximal safety indicators and their effectiveness for short-term traffic safety assessment and prediction. A major part of this work has focused on issues related to the application and reliability of the various measurement methods and analysis techniques used for determining safety indicator values, and similarly the validity and potential of indicative measures as a complement or accepted alternative to traffic accident data.

Studies were carried out with a view to obtaining important knowledge concerning the influence of various traffic parameters and interactive behavioural processes that are assumed to have an influential effect on traffic safety. On the basis of these empirical findings, modelling approaches based on dynamic micro-simulation were developed for traffic safety assessment and prediction purposes. The use of micro-simulation modelling for traffic safety assessment and prediction purposes is quite rare in the prevailing research literature, although the large potential of such a methodology is recognised. The development of a viable safety evaluation methodology based on micro-simulation modelling is of particular interest in the field of transport planning and traffic engineering in the future as a cost-effective and safe 'off-line' platform for the preliminary estimation of traffic system effects related to safety and traffic performance.

11.1 Safety indicators

Road traffic accident statistics are commonly used to assess and predict levels of road safety, and estimate the success of new and existing safety strategies and various types of safety-influencing measures at specific traffic facilities. The significant lack of accurate and reliable accident data has caused many problems for transport analysts and researchers. Furthermore, many of the models that have been developed and implemented for transportation planning purposes are very general in nature, proving less useful for safety analyses at specific locations and facilities where there might be important safety related factors that cannot otherwise be taken into consideration. Largely as a result of such issues the use of proximal safety indicators has been advocated, both as a measure for diagnostic safety analysis purposes, and in order to provide a suitable statistical basis for safety prediction modelling.

Despite the extensive amount of research undertaken in relation to safety indicators and their related methodologies there appear to be a great many issues regarding proximal safety indicator measurement and application that have been misunderstood and even misinterpreted by safety analysts in the past. This has resulted in a general lack of support for methods such as the Traffic Conflict Technique, and has hindered the wider application and development of proximal indicators as potentially useful and resource effective measures of traffic safety in their own right. This has become from research findings that suggest that such measures are equally as effective as accident data for predicting the expected number of accidents at a particular traffic location or facility (see e.g. Migletz *et.al.*, 1985; Svensson 1992).

11.1.1 Validity and the relationship between safety indicators and accident data

Traffic accident and outcome severity data, despite its many limitations, has an established level of construct validity that is the result of a long and complex process of tradition and usage. As a result, alternative measures of safety must now establish their fundamental value by demonstrating an acceptably high level of correlation against this type of data (i.e. show a high level of convergent validity). The discussions concerning the validity of proximal safety indicators remain largely unresolved in light of the many studies that provide evidence for and against the existence of a statistically sound relationship between such measures and traffic accidents (see e.g. Hydén Gårder and Linderholm, 1982; Hauer and Gårder, 1986; Grayson and Hakkert, 1987). Arguably, many of the problems concerning the establishment of a relationship between proximal safety indicators and accident data are attributable to the quality and coverage of the accident data itself.

An early report by Oppe (1986) suggested the necessity of classifying conflicts and accidents according to specific types, and to establish appropriate measures of severity in order to examine the existing relationship consistently. Furthermore, researchers Chin and Quek (1997) in their discussion regarding the Traffic Conflict Technique, propose that establishing a relationship between serious conflicts and accident data may be an unnecessary exercise given the uncertainties of the data sets, and the many confounding effects to which these are subjected. In cases where the Traffic Conflict Technique is used for diagnostic rather than predictive purposes, there appears to be no legitimate reason to establish the extent of the relationship with accident data. The idea of predicting accidents has also been opposed by Hauer (1979) who contends that the greater need in safety studies is to prevent accidents rather than to predict future accident occurrence frequency.

Researchers Grayson and Hakkert (1987) also argue for construct validity rather than product validity, suggesting that measures such as serious conflicts are based on the same underlying processes of causation as accidents, and that any eventual differences in frequencies and severity rates in comparative studies are likely to be the result of the random nature of safety critical event outcomes. The relationship between evasive actions and serious conflicts has also been discussed by Chin and Quek (1997) who propose that if accidents are preceded by conflicts, they must also exist prior to accident occurrence. As evasive actions are absent in many safety critical situations, and because some evasive behaviour is purely precautionary, it is concluded that there may be fundamental differences between serious conflicts and accidents, where conflicts are determined at the point in space and time when evasive action is first taken.

In this thesis, the question of validity has been difficult to investigate given the limited amount of data available for such purposes. This was particularly evident with regard to the study of three T-junctions. In many countries, including Sweden, it is no longer a policy to report accidents that do not result in injury. As a result, there is often little data available, making location-specific safety indicator validation against accident data impossible or at best very difficult task. Arguably, the idea of using accident data is against the principles of traffic safety policies such as the Swedish '*Vision Zero*' which calls for a more active and dynamic approach to traffic safety. Many of the validity problems might also be resolved by the introduction of a conflict database which would yield suitably detailed data for the development of generalized linear models such as those suggested by Sayed and Zein (1999).

The relationship between serious conflicts and police reported traffic accidents at signalised intersections was considered in the Hornsgatan study reported in Chapter 6. This study showed large differences in the numbers of accidents predicted by the CD-Base software based on serious conflict data, and the number of accidents predicted on the base of historical accident data. Furthermore, there were a number of factors that had a complex interactive effect on this serious conflict-accident relationship. The two four-way intersections that were most comparable in terms of design (Hornsgatan-Ringvägen and Hornsgatan-Torkel Knutssongatan) showed contradictory numbers of serious conflicts and accidents largely as a result of differences in traffic signalling and turning regulations.

At the intersection with most serious conflicts, vehicles from opposing directions were allowed to manoeuvre simultaneously causing a large number of conflicts between left-turning vehicles and oncoming traffic streams, and turning vehicles and pedestrians. This was not the case at the other intersection, where all simultaneous left-turn manoeuvres were eliminated by the signalling or regulatory signposting. The second intersection, while showing a considerably smaller number of serious conflicts, indicated a higher number of traffic accidents during the previous six-year period perhaps as a consequence of the higher volumes of traffic and higher speed levels. From this study, it could be concluded that there are many important factors that influence the relationship also between serious conflict frequency and the number of accidents, as suggested earlier by Hydén (1987).

A comparison of accident and serious conflict types at the Hornsgatan intersections also suggested considerable differences. While it can be hypothesised that higher frequencies of particular types of serious conflicts are more likely to be represented in the accident data, this was not found to be the case. In fact, the data suggests that accidents at the intersections occur largely at random, most probably occur as the result of an unfortunate chain-of-events as suggested by Carsten and colleagues (1989), and Elvik (2003). It is also possible that different types of safety critical events and different manoeuvre types have different levels of risk (i.e. probabilities of actually resulting in accidents). While this particular relationship requires a considerably larger data set in order to draw statistically sound conclusions, it is nevertheless feasible that the overall serious conflict frequency and/or severity level at a particular site represents a reasonable predictor of the expected number of accidents.

While the validity problem continues to be a question of much debate, there is evidence that the situation is about to change. Not only is there a rekindled interest in the use of the Traffic Conflict Technique as a qualitative method and diagnostic tool for traffic safety evaluation, there is also an identified need for newer and faster safety evaluation methods to help provide sustainable traffic system development, and meet the aims and goals of long-term safety strategies. This need has manifested itself in many ways, including sponsorship by the Swedish Road Authority for a new project that is aimed specifically at the development of automated video-analysis software for safety analysis purposes. This is likely to have important implications for the validity of proximal safety indicator measures in the future.

11.1.2 Reliability and measurement issues

Besides the problems related to validity and safety indicator definition, there are also important issues related to measurement reliability. Chin and Quek (1997) suggest the importance of considering two main types of reliability: intra-observer reliability related to the variability of conflict recordings made by one particular observer; and inter-observer reliability concerned with the variability among different observers.

Evidence of inter-observer differences was found in Study 1 (Chapter 6) in relation to the study of signalised intersections on Hornsgatan. In this study, one of the observers registered a significantly smaller number of serious conflicts than the other two, at each of the four intersections. Inconsistencies between or within observers are known to occur for a number of reasons including: poor conflict type definition, excessive safety critical event occurrences, the existence of more complex conflict types, fatigue and lack of training (see e.g. Older and Spicer, 1976; Muhrad, 1982). While the serious conflict frequencies differed significantly between observers (as shown by a statistical test), the ordering of intersections according to frequency was found to be reasonably consistent. This situation has also been noticed in earlier studies, including the large-scale conflict study carried out by Grayson and colleagues (1984). Research in relation to the reliability of safety indicators suggests that there is often significant variation among observers, even when safety critical event types are well defined and the observers are well trained (Chin and Quek, 1997).

On-site observations are difficult to verify after-the-fact, whereas measures determined through a process involving video-analysis may be reviewed repeatedly and can be cross-verified by other analysts. Arguably, the analysis of two-dimensional video-imagery represents a poor substitute for on-site observation. The fact that observations are performed on-site allows the observer to carry out a more qualitative analysis, becoming aware of different site-specific safety problems such as: red-light violations, high flow rates, excessive vehicle speeds, large numbers of turning movements, pedestrians that cross at undesignated places or during red signal phases, and other situations that influence road-user behaviour and interaction negatively. This information can also be obtained using video-analysis, but is subject to limitations regarding quality and coverage. Arguably, the '*subjective*' element of on-site conflict observation implies the application and acquisition of safety knowledge and experience in a qualitative approach to safety analysis that is often more informative and resource-effective than most other methods.

11.1.2 Video-analysis and the determination of safety and performance data

Work with the application and development of the SAVA semi-automatic video-analysis software in relation to the study of three T-junctions highlighted the fact that it is more difficult to identify safety critical events recorded on video than it is to observe them on-site. Even the most systematic manual video-analysis is likely to miss some complex and subtle safety critical events. Similarly, automatic detection functions implemented in software applications are only able to detect safety critical events that have been predefined in the program code. Automated and manual detection processes in conjunction with the study of the three T-junctions suggested that an ideal video-analysis methodology should include elements of both for safety critical event detection.

The work conducted in Chapter 7 in relation to the three T-junctions suggested that it is sometimes necessary to understand the implicit intentions of road-users in order to detect safety critical events. These intentions may sometimes be displayed in the form of small momentary lapses of attention or other perceptual or cognitive failures that result in a sudden initiation of action followed by an equally fast revocation, all within a limited spatial area and short time-period. These types of events have a definite accident potential and are likely to be overlooked in automatic safety critical event detection processes.

The study of three T-junctions described in Chapter 7 suggested that Post-Encroachment Time was the easier of the two video-based proximal safety indicator measures to determine, as this involved only a determination of the elapsed time between the passages of two road-users over a common conflict point or area. The PET-safety indicator was however, not found to be suitable for longitudinal conflicting trajectories and revealed a number of conceptual peculiarities regarding the order of passage in potentially unsafe interactions, and the level of control in some potentially safe interactions that generated sub-threshold PET-values. The representativeness of PET-values with regard to severity (as a measure of accident risk) is also a question of some concern, as is the fact that no collision course is required.

A particular problem with regard to the Time-to-Collision safety indicator is related to the complexity and extreme number of calculations that are necessary in order to identify the determining '*minimum*' value. A further consideration concerns ensuring the existence of a collision course (this is not strictly true for serious conflicts according to the Traffic Conflict Technique). The main advantage of the TTC-safety indicator is related to the fact that it is '*objectively*' quantified; usually through processes based on video-analysis. While the objective measurement issue may be important, it must also be remembered that video-analysis procedures often involve a degree of subjective judgement when they are not fully automated. Until fully automated procedures do become readily available, the TTC proximal safety indicator is unlikely to become a method of choice among safety analysts.

The TTC-value is considered a representative measure of severity (i.e. accident risk). Although each TTC value is determined using speed and distance, speed is not considered for the purposes of quantifying the severity of the outcome variable. Thus, two safety critical events with similar TTC-values may be considered to have the same severity level despite significant differences in speed. As a result, there may be events of low spatial proximity that show sub-threshold minimum TTC-values, despite having levels of speed that are insufficient to warrant a '*severe*' classification. This situation raises questions regarding the (process) validity of this measure and whether minimum TTC-values are indeed based on the same fundamental processes as traffic accidents.

The low average severity level per safety critical event, and the lack of correlation between TTC-event frequencies and summated average required braking rate levels across different time-periods and T-junctions also suggested that '*severity*' may be inadequately expressed by TTC-values (see Chapter 7). Despite these findings, the TTC-measure did show good correlation against the extended TTC measures suggested by Minderhoud and Bovy (2001) that are more (but not entirely) representative of safety critical event severity.

11.1.3 Requirements for useful proximal safety indicators

There appear to be problems related to the validity, reliability and definition of all of the proximal safety indicator concepts and their related measurement techniques studied as part of this thesis. The extent of these problems depends on the particular indicator in question and the purpose for which it is used. On the basis of the results and findings of the studies presented as part of this thesis, and the vast amount of previous research in this field, it is possible to suggest a number of criteria that are essential for a proximal safety indicator to be accepted as a useful measure of safety. These are listed below:

- Safety indicator measures should occur with sufficient frequency to provide a basis for statistically sound comparative analysis following a relatively short period of observation and/or video-analysis (as suggested by Svensson, 1998). The length of the study should be extended to meet these statistical requirements, and the study should be repeated (in each experimental condition) in order to establish a level of sampling variability
- Safety indicator measures should be based on temporal and spatial accident proximity where the interaction and/or behaviour of road-users is such that a collision course exists and an accident would prevail if no evasive action were taken by either part
- Safety indicator measures should consider acceleration (positive and negative) for the purposes of determining spatial and temporal proximity and the existence of a collision course
- Safety indicator measures should be related to a suitable scale of severity based on speed and/or acceleration (and where possible even estimations of mass)
- Measurement procedures should include both qualitative on-site field observation and quantitative video-analysis, preferably in a methodology where the values from each are determined independently by different analysts
- Field observation should strive to record as much qualitative information as possible for each safety critical event directly after it occurs
- Manual and automated video-analysis techniques should be used to ensure that the majority of safety critical events are detected
- All safety critical events recorded should be classified according to a standardised classification scheme, but this should not limit or negatively influence the ability of the analyst to detect unusual events that have safety relevance
- Safety critical event data should be compared to existing accident data where this is available, and the comparison should be as detailed as possible with regard to different types of events, and the context in which they occur
- Proximal safety indicators should be used primarily for comparative analyses, for example, to compare the influence of a measure in a before-and-after experimental design
- Accident prediction based on proximal safety indicator values requires extensive longitudinal accident data where calculations consider levels of variance in the data and predetermined levels of statistical confidence calculated in accordance with suitable distributional assumptions that are adapted to the purpose and goals of the study

The future of proximal safety indicators is dependent of their acceptance as a useful and valid measure of traffic safety in their own right, without the implicit need for validation against traffic accident data. One way that this can be achieved is through the development of a national database in which the results of all studies are recorded. Access to this and other traffic data would enable comparisons against accident data and other measures of traffic performance. This would also facilitate, the development of useful and statistically sound predictive models, such as those suggested by Sayed and Zein (1999), for transport planning purposes where cost-benefit analyses based on the estimated costs of accidents involving injury and fatality need to be accurately calculated to justify roadway infrastructure investment. The use of a proximal safety indicator study database would also serve other purposes related to safety analysis, specially if a link can be established to corresponding accident databases, and databases that contain, for example, exposure data or intersection design and regulation information. In the long-term, such a database would establish a solid foundation for the purposes of establishing a general form of construct validity and detailed predictive models.

11.2 Safety assessment methodology

In order to qualify the results and conclusions of any safety analysis, measures related to traffic performance and road-user behaviour must be considered. The reason for this is not only because they have an important influence on safety indicator values, but also because they are important in order to gain a more comprehensive understanding and qualified insight into the safety problems that actually exist, and therefore how they can be resolved practically and effectively without causing an imbalance elsewhere. The use of before- and-after study designs can determine whether or not existing problems been resolved as intended, or if there is evidence of unwanted behavioural adaptation effects.

Many of the measures collected and analysed in the study of three T-junctions (Chapter 7) were useful for a deeper understanding of the prevailing safety situation and underlying causes of safety critical events. These measures included:

- Measures of traffic flow and vehicle composition
- Spot measures of vehicle speeds in and around the junction
- Turning percentages
- Pedestrian/cyclist movements at pedestrian crossings and elsewhere
- Measures related to gap-acceptance for all yielding situations
- Measures related to the arrival patterns of vehicles (time-gap distributions) on priority road lanes near the yielding situations
- Traffic observation to identify potential problems related to the design and geometry of the traffic site
- Measures related to traffic signalling if this form of regulation is used

The majority of these measures are obtained using traditional data-collection techniques such as logging devices, while others require field observation and video-analysis procedures. In all forms of safety analysis, it is also essential to obtain relevant accident history data and to compare this against the various types of data that have been collected and analysed.

The choice of safety indicator is also an important issue. As mentioned above, there are major differences between the different concepts and measurement techniques, and a number of important limitations that must be considered. Most video-based measures tend to be time-consuming and resource-demanding, observation techniques on the other hand, are generally faster and more efficient. They are also equally valid if used correctly, and often add to the qualitative content of a safety analysis.

11.2.1 Quality and quantity

Transport planning and traffic engineering has a tradition as a technical science that is based on fact and cardinal measurement. Until recent years, measures of a more qualitative nature were often dismissed due to the lack of proven statistical validity or measurement reliability given established norms. This situation was exemplified by the rise and fall of conflict measurement techniques in many countries, where analysts could not satisfactorily establish the quantitative and predictive abilities of the various techniques and failed to notice important qualitative contributions that are most often lacking in other forms of analysis.

Today, qualitative measures are becoming more evident in this field, and are considered particularly useful when applied in conjunction with other quantitative measures. Quality and quantity are two important issues in safety analysis, and measures must be taken to ensure that elements of both exist in all forms of safety studies.

11.3 The future of micro-simulation modelling for safety estimation

The results of the simulation experiment based on the Täby T-junction (see Chapter 9) showed contrasting results with regard to the frequencies and severities of the three different safety indicators when compared against field data. The simulation of serious conflicts in accordance with the Traffic Conflict Technique proved only moderately successful with consistent underestimation in each time-period. Reducing the threshold that distinguishes between serious and non-serious conflicts produced a higher level of correspondence between the two data sets, both for conflict frequency and summated severity measured in terms of average required braking rate. These differences were believed to reflect the way in which the serious conflict occurrences were measured, and the fact that the definition used for simulation purposes included a more strict ‘*collision-course*’ requirement.

Although the numbers of serious conflicts emanating from the simulation model representing the Täby T-junction were significantly lower, the relative proportions of conflicts in each time-period were similar suggesting a level of correlation and a similar ordering. Furthermore, there were similarities in the patterns of different conflict types among the time-periods. The severity measure (summated average required braking rate) was also well correlated with the frequency measures, which was also the case for the field data. Similarly, the average severity value per serious conflict was found to be quite similar to the corresponding value based on real-world data. These findings suggest that there are some similarities between the two sets of data, but also that there is a need to verify real-world serious conflict data to enable a more representative and valid comparison.

The simulated Time-to-Collision safety indicator measure showed an unexpectedly high level of consistency, both when totalled over the entire six-hour period, and to a slightly lesser extent among the different time-periods. The simulated frequencies for sub-threshold minimum TTC-values showed a similar ordering among the time-periods as that found for the field data, and also a reasonable level of consistency among the different safety critical event types generated. However, the values for the severity measure indicated a greater degree of variance than that found for the serious conflicts, and corresponded less well with the field data. The average severity value per conflict was also found to be quite low, suggesting that there may be important fundamental issues related to construct validity that require further research.

The Post-Encroachment Time proximal safety indicator also indicated an acceptable level of consistency for observed and simulated data, although the values for the different time-periods were quite variant. The simulated frequencies of sub-threshold PET-values also suggested a similar ordering among the time-periods to that of the observed data. As for the TTC data, the summated average required braking rates from the simulation runs showed some variation, and was less consistent with the observed data. Many of the problems with this particular indicator are related to the representation of driver behaviour, where the approach used in the simulation of driver interaction causes braking as soon as a conflict zone is occupied regardless of the existence of a collision course. In the real-world, drivers tend to be less responsive.

A particular problem with this experiment was the lack of empirical safety indicator data for comparison purposes. The complicated and resource-demanding video-analysis procedure used to derive Time-to-Collision and Post-Encroachment Time values resulted in only six-hours of data at this T-junction. In future safety simulation studies, a great deal more traffic conflict data should be collected, and that the accuracy and validity of this data should be verified in a process that involves different observers/analysts, different video-analysis techniques and software, and experimental designs that are intended to minimise bias and judgemental error.

Calibration and validation of the simulation model highlighted a number of difficulties particular to the simulation approach. Achieving a representative time-gap distribution is critical for the accuracy of the gap-acceptance process. A particular problem was found during the morning peak scenario, where adjusting the car-following model parameters to increase the variation among drivers had a negative effect on capacity due to the limitations of the Wiedemann '74 model. In order to overcome problems such as these in the future, there is a need for the definition the parameters that describe the input function distribution more flexibly with a greater level of detail. Similarly, the car-following models must incorporate a level of variation that is not only dependent on speed, but also on individual driver preference in relation to safety distance.

Problems in the simulation model application were also found in relation to the probabilistic gap-acceptance functions. In particular, the left-turn manoeuvre from the secondary road was found to result in too many rejected gaps despite the fact that the accepted gap distribution was consistent with observed data. These problems were also highlighted in the simulation runs by a lower number of vehicles that did not stop at a particular yield line, and a higher average waiting time at the head of a queue.

These problems are related to a more general lack of representation for the complexity of interactive yielding, particularly in cases where a potential gap must be identified in up to three different streams of traffic simultaneously. A different gap-acceptance modelling approach might be more suitable in the future, that is based on functions that consider both speed and distance values rather than the more simplistic and less informative time-gap concept. Using an alternative approach, it may be possible to have gaps of different lengths that are more or less dependent on speed and distance. Similarly, the use of different values or weightings for the different streams of approaching traffic would most probably improve the representativeness of the modelled gap-acceptance behaviour. In addition, it is also important to include complex behaviours such as '*pushing*' into queues in congested traffic conditions and various types of '*courtesy yielding*'.

The results of the simulation experiment that evaluated the effectiveness of the LHOVRA incident reduction function used in standard vehicle actuated signalling in Sweden, showed some interesting results (see Chapter 10). From a safety perspective, the use of the simulated IR-function showed an average 22 per cent decrease in the number of rear-end conflict events in comparison to a baseline case where the incident-reduction function was deactivated. Safety was measured in accordance with the minimum Time-to-Collision safety indicator. Furthermore, the simulation scenario that incorporated the IR-function showed no significant negative effects on traffic performance for measures including: stop line vehicle throughput, average total green time per cycle, queue lengths and delay times.

Although the results presented are based on a calibrated and validated simulation model with regard to traffic performance and signalling, it was not possible to directly calibrate the safety indicator measures against real-world data. The main intention of the study was not to generalise the findings of the simulation to real-world conditions, but rather to perform a comparison of two different scenarios in order to test the general simulation methodology. Furthermore, no attempt was made to relate Time-to-Collision frequency to the number of accidents at the intersection that was studied. A basic level of validity was found for this simulation approach given that a significant safety impact was found in the direction expected. A good level of reliability was also evident in the results from the different simulation runs.

Importantly, the simulation study showed that there was an optimisation potential for the IR-function. This was evident from the large number of vehicles that continued to stop despite the fact that they were issued past-end green at the first detector. Better adaptation of the IR-function (by for example increasing the amount of time allocated) would allow these vehicles to pass the stop line as intended and would result in less unused green time. The improvements suggested by Al-Mudhaffar (2002), which include time-value adjustments in conjunction with the conditional issue of past-end green based on vehicle speed at the first detector and better detector placing with regard to the site-specific situation, are likely to improve the safety and traffic performance of the IR-function to a greater extent. The general methodology used in this study provided a useful '*off-line*' test environment that is useful for future work in relation to preliminary evaluation and the comparison of alternative or improved signal controller logic functions and their impact on traffic safety, traffic performance and various measures of signal performance.

In both simulation studies, further calibration and validation work and the introduction of new and improved behavioural models and vehicle performance models are also likely to improve the validity of the simulation models in the future. Presently, there is an identified need for research related to quantifying the performance of both drivers and vehicles in safety critical events. Ideally, this should be carried out with the use of driving simulators and suitably instrumented vehicles in carefully designed experimental settings. There are also and great many other areas that require further research before representative safety simulation can become a reality for traffic engineers and transportation planners.

11.4 Final discussion and conclusions

The limitations and potential of the Time-to-Accident, Time-to-Collision and Post-Encroachment Time have been compared and discussed in this work from a theoretical and practical perspective, bearing in mind the need for a reasonably fast, reliable and resource-effective methodology that can be used for active and preventative safety work. This type of methodology is an essential and necessary prerequisite for the achievement of both short and long-term safety strategies, such as the Swedish '*Vision Zero*' aimed at active accident prevention.

The comparisons and analyses that have been performed as part of this work, suggest that the Traffic Conflict Technique is presently the method that shows highest potential for safety analysis. This technique may, however, be succeeded in the future if automated video-analysis techniques for safety assessment purposes become a viable alternative. On-site observation is, and should remain, an important qualitative part of present and future safety analysis methodologies. The work presented here has also pointed to the need for a greater understanding of the relationships between safety indicators and other variables (such as speed and speed variance, traffic flows, traffic compositions, turning percentages) and important behavioural processes (such the gap-acceptance and car-following) in order to ascertain a more comprehensive safety perspective. Such information is also of use for determining effective and sustainable safety solutions. Developing statistical models that adequately predict the number of accidents based on safety indicators will also add to the value of safety analysis work in the future, given the fact that cost-benefit analysis is generally used as a foundation for decision-making in relation to roadway infrastructure investment and development. In order to develop such models, a suitable national database is needed that is accessible to safety analysts and modellers.

The dynamic simulation modelling methodologies presented have provided a useful basis for future work in this field. Most importantly, the modelling approaches adopted have been based as far as possible on empirical data with a minimum of unnecessary assumptions regarding human performance and behaviour. Safety simulation has a great potential for transportation planning related to the estimation of safety impact in the future. Detailed modelling such as this, takes into consideration many important site-specific details, allowing a range of alternative solutions to be tested under different traffic conditions in a safe off-line environment. Investigative sensitivity analyses in relation to safety influencing factors, and the effects these have on other important objectives such as accessibility, capacity and environmental issues, are likely to become an important part of transportation planning work in the future. Presently, however important research is still required in many areas.

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Appendix I: International and national traffic safety policy and the role of the Swedish Road Authority

1.1 European traffic safety policy

Most of the international policy decisions with regard to European traffic are made through the European Union. There are five EU institutions, each with a specific role: the European Parliament, the Council of the European Union, the European Commission (which is the driving force and executive body), the Court of Justice, and the Court of Auditors. There are also a number of other important bodies and agencies closely associated with this system. The aim of the EU is to work together towards peace and prosperity through the pooling of sovereignty, i.e. European integration.

Transport is recognised as one of the key activities of the European Commission where the freedom of movement for people and goods is considered a major issue as is the need for an efficient and safe transport system in order to achieve long-term integration and sustainability. The Commission recognised in their White Paper published in September 2001 that their action and transport policy aimed at improving the road traffic safety situation had been insufficient and therefore proposed the European Road Safety Action Programme for 2003-2010.

The overall objective of this programme is to reduce the number of people killed in traffic by half by the year 2010. The programme focuses on the three main components of the traffic system, i.e. road-users, vehicles and the road infrastructure:

- It is aimed to encourage road-users to behave better by complying more strictly with legislation. There is also a move toward a harmonisation of penalties, and better training for drivers in order to combat dangerous driving.
- It is aimed to make vehicles safer through the harmonisation of passive safety measures and by providing suitable support for technical progress and development. This has led to active support for the European new car assessment programme EuroNCAP
- It is also aimed at improving the road infrastructure through the adoption and identification of 'best practices' and through the elimination of black spots. The Commission has also proposed a framework directive on the safety of the road infrastructure to establish a harmonised management system that includes road safety audits for roads

The Commission recognises human behaviour as one of the main causes of traffic safety problems and aims strategically towards an improvement in a number of identified areas through information and enforcement actions. It is believed that tens of thousands of lives can be saved by restricting excessive and badly adapted speed, driving under the influence of drugs, alcohol or fatigue, and ensuring the proper use of safety devices such as seat belts and helmets.

The EU has identified various means of action for the improvement of road safety including:

- Providing suitable legislation
- Supporting research and technical development projects
- Providing financial support to initiatives aimed at raising awareness among policy makers, professionals and the public through calls for proposals related to safety issues and solutions
- Establishing best practices
- Defining accident investigation methods and the CARE database

While countermeasures of a passive nature have been mentioned in relation to the use of seat belts and helmets, there is also a move toward *active* safety. Today, active safety is largely represented by new on-board information and communication technologies, so-called Intelligent Transport Systems (ITS). The EU, member states and different related industries need to establish an integrated approach to improve the general effectiveness of these new safety technologies. The European Commission sees ITS and the services that this enables as a viable solution to make the movement of people and goods more efficient and safe for all transport modes given the fact that major infrastructure investment is reaching its limits in many member states .

Since the mid-nineties large scale projects with consortia from different EU member states have conducted road related research within the so-called 4th and 5th Framework Programmes. Within these Framework Programmes, there are a number of internationally coordinated projects related specifically to road traffic safety including: ESCAPE, STAIRS, AWAKE, ADVISORS, EBCOS, TRAINER, VIRTUAL, SENSOR, OSSA and PROSPER. A more detailed description of the specific areas of safety research covered by these projects is outside the scope of this thesis. Road traffic safety research in the forthcoming 6th Framework Programme will be concerned with: accident and injury analysis, driver safety training, road infrastructure safety, the enforcement of traffic rules, and the use of acceptability and awareness campaigns

1.2 Safety policy in other countries

Similar traffic safety policies to that of the EU can be found elsewhere. The nation that is most comparable to the EU is perhaps USA. In USA, the Department of Transport (DOT) has developed a strategic plan for safer, simpler and smarter transportation solutions for the period extending from 2003 to 2008. This strategic plan provides a comprehensive vision for the advancement of the transport system in the future, with broad objectives that targets specific performance outcomes and identifies key challenges. In order to operationalise the DOT strategic plan there is also a performance plan that is strongly linked to the budget request, and which defines high-level performance outcome goals, quantifiable measures and specific targets that are to be used for management.

Safety is one of five of the main DOT strategic objectives; others are related to issues concerning mobility, global connectivity, environmental stewardship (i.e. environmental issues), and security. The safety objective is formulated as follows: “*Enhance public health and safety by working toward the elimination of transport-related deaths and injuries*”. Improving the safety of the transportation system is stated as one of the highest priorities where focus is given to reducing the number of highway fatalities. To this aim, the Department has established a goal to reduce the fatality rate to not more than 1.0 per 100 million vehicle miles travelled by 2008 (a figure of 1.7 per 100 million vehicle miles is quoted for 1996).

Other central strategies to improve the road safety situation include measures to reduce alcohol and drug induced driving, and increase the use of safety measures such as seat belts and helmets. The operational goals are similar to those of the European Union. Safety countermeasures include legislation, the use of ITS, increasing the public concern for safety in an attempt to influence behaviour and attitudes, the control of various external factors and the improvement of vehicle safety and infrastructure.

On other continents such as Australia, the development of safety policy and strategies for sustainable traffic safety in the future are comparable to those of the EU and USA. The Australian State Government through the Roads and Traffic Authority (RTA) encourages the safety initiatives and involvement of local government and the local community. The main safety priorities at the community level include raising levels of awareness for safety issues, improving community understanding, increasing the ability of the Local Government to implement initiatives and improve safety at the local level, and to promote greater involvement and better co-ordination with all safety stakeholders. The New South Wales Government in Australia has, for example, committed itself to a safety framework programme that involves halving the fatality rate and saving 2,000 lives by year 2010.

1.3 Socio-economics and traffic safety

The European Union and indeed the transport authorities in most countries, recognise the use of cost-benefit analysis as a tool for policy and planning decisions related to short-term and long-term safety strategies. In a recent paper by the Imperial College Centre for Transport Studies in London, many of the proposed safety initiatives of the EU were analysed prior to their implementation in order to document relative benefits and costs and create a basis for decision-making basis for the European Parliament and Council. This analysis focused on the direct and indirect costs of road traffic accidents.

The socio-economic analysis of investments in the infrastructure require that all of the effects of a certain measure that is of importance to the people that the use the system can be quantified and valued. Effectively, the system-user’s judgements, preferences and willingness to pay decide the value of the effects that are noticed. The evaluated effects then serve as a measure that indicates socio-economic profitability. This form of analysis represents of a useful tool for political decisions related to the transport system. However, this does not always mean that the calculated effects are viable due to, amongst others, ethical and priority allocation reasons associated with objectives such as traffic safety.

In a report on this subject, Elvik (2001) states that the costs related to traffic accidents have three main components. These include: direct costs (related to injuries and property damage, and the use of emergency services), lost production costs (representing the lost contribution to society as a result of death or injury), and human costs (in the form of pain and suffering). Research shows that there are great differences in the methods used to evaluate these costs between different countries. The cost of a fatality in USA represents a value 4.5 times greater than the EUR-15 average, and 66 times greater than that in Portugal. Sweden and the UK are those countries that estimate the greatest socio-economic cost of road accident fatalities, being in the order of twice the EUR-15 average. Elvik (2001), continues his discussion of the issues at stake for accurately representing fatality and injury related costs for the purposes of cost-benefit analysis for traffic safety and road infrastructure investment, pointing to issues related to identifying suitable value-intervals where the uncertainty in these types of assessments are estimated (through statistical sensitivity analyses).

Methods based on socio-economic calculations are used today in many countries to provide a cost-efficient solution to various problems in the public sector including national and local road authorities. Socio-economic analysis of this type has been used in Sweden since the 1960's to prioritise between roadway projects where there is a clear definition of the goals to be achieved and alternative solutions (SRA, 1997)

1.4 Traffic safety policy in Sweden

The Swedish government states that the main goal of the traffic system in Sweden is to: “...provide and ensure a socio-economically effective and sustainable system of transport for the public and private sectors throughout the country” (author's own translation). This goal was clearly defined in a government proposition from 1997 entitled “*Transport politics for a sustainable development*” and was finally accepted in June 1998. The proposal also supported a new direction in Swedish traffic safety through recognition for ‘*Vision Zero*’. Effectively, Vision Zero refers to the long-term goal for traffic safety in Sweden in which no one is killed or seriously injured as a consequence of road traffic accidents (see e.g. SRA, 2003; Tingvall 1995)

The ambitious long-term goal of *zero* fatalities and serious injuries is to be achieved by successively adapting the design and functionality of the road traffic system. As part of this new approach, the responsibility for achieving the traffic safety goals is shared between road-users and system owners, i.e. those responsible for the roadway, vehicle manufacturers, and other authorities, institutions and organisations with an active involvement and vested interest in safety. Furthermore, for a transport system to comply with the more general goal of long-term societal sustainability, there are a number of high-level demands that need to be met with regard to the economical, social and environmental premises.

The major goal for transportation politics in Sweden as for many other countries, is to develop a transport system that is economically, culturally, socially and environmentally sustainable and which eventually can achieve all of the subordinate goals related to accessibility, quality, safety, a good environment, and positive regional development. Many of the goals are intertwined; high levels of quality create growth and employment that leads to the provision of resources to cope with environmental issues. Safety and environmental issues are a prerequisite for traffic system quality and effectiveness.

In order to achieve the political transportation system goals, the concepts of *integration*, *overall perspective*, and *co-operation* have been identified, in addition to the principle of public access to official records and an obligation of service to the public and other authorities and organisations.

1.4.1 The role and organisation of the SRA

The Swedish Road Administration (SRA) is the central administrative agency that is commissioned with the overall (sectoral) responsibility for the road transport system. The SRA works within the framework of current political decisions, the funds that are made available, and the regulations governing its operations. Given the framework of sectoral responsibility, the SRA assumes a leading role in co-ordinating work with other road sector entities. The SRA is also actively bound to uphold the primary goals of the transport system with a primary focus on accessibility, high quality, safe traffic, environmental issues and positive regional development (see e.g. SRA, 2003).

The work of the SRA can be divided into four main segments. The sectoral responsibility mentioned above, includes co-operating and organising clients to drive forward the development of the transport system in what is described as an “*offensive and result-oriented manner*”. This involves providing support, making policy decisions, maintaining traffic related data, contracting services, and initiating research and development. The sectoral responsibility also includes prioritisation. The SRA approach to prioritising various areas, with regard to the ulterior aims and objectives, are to draw up policy documents. Presently, policies exist for road safety, the environment, issues related to disabled persons, information, personnel, safety and security, and total quality.

The second segment of SRA activity, describes the departmental role that is concerned with the generation and application of rules and regulations for vehicles, driver licensing, environmental issues, and professional drivers and transportation. This activity also involves administration of the financial budget allocated by the government. The third segment involves the development and maintenance of the national road network (mostly motorways and A/B-class roads that are not delegated to local authorities). The fourth and final segment of SRA activity describes production, i.e. development projects, construction, repair and maintenance by SRA or contractors.

As an organisation, the SRA is headed by a board of directors appointed by the government. This board is responsible for carrying out the departmental activities in accordance with transport policy. The general director is responsible for carrying out the work at SRA according to board directives and guidelines. The SRA consists of a head-office and seven regional offices across Sweden with four separate business areas and other operational entities.

1.4.2 SRA road safety policy

The current Road Safety Policy that was outlined in August 1998 states that the road transport system should be designed so that no one is killed or seriously injured as a consequence of road traffic accidents. This long-term development requires an adaptation of the traffic system in terms of design and functionality to make it consistent with human ability levels and the level of external trauma the human body can withstand. (see e.g. Tingvall 1995).

The SRA, state that work in this field is based on protecting human life and well-being, and therefore that the main goals are, amongst others, to create a road environment that minimises the risk associated with road-user mistakes and prevents serious injury in work related to the design, operation and maintenance of the state road network. It is also stated that the SRA will analyse all accidents that have resulted in death or serious injury in traffic, and where feasible, to initiate suitable measures to avoid the occurrence of similar accidents in the future.

According to the safety policy, the SRA has overall responsibility for road safety within the road transport system and should monitor and actively promote developments within this area. This responsibility stems from the SRA's role as a central administrative agency for the entire road transport system, as a road manager for construction and maintenance of the roadway, and as an organisation for a large number of internal activities

1.4.3 High-level traffic planning and evaluation

The SRA has a general planning philosophy that is interpreted into a primary strategy to control and drive developmental work related to the road transport system in accordance with political goals. The main strategy is determined from a sectoral perspective, which implies that the SRA has overall responsibility for organising and co-ordinating transport system related work with other concerned bodies. In order to fulfil this responsibility, four strategic areas have been identified and prioritised, these include: the users of the road transport system, traffic co-ordination and organisation, vehicles and fuel, and aspects related to the infrastructure. In order to ensure that the political goals of the transport system are achieved, the government has determined a number of quantifiable stage-related goals. These exist not only for traffic safety, but also for environmental effects, and for some areas related to transport system quality. The SRA has a responsibility to conduct an annual evaluation of their results and to report these to the government (see e.g. SRA, 2003).

In addition to these stage-goals, there are a number of clearly defined and measurable indicators that have been identified to establish the level of development toward the political goals for the transport system. These indicators are qualified by written effect descriptions and subjective evaluations. The government and other authorities have now also called for the development of new methods and measures to determine and evaluate '*goal-achievement*' in relation to the predetermined goals. This requires an improved description of the consequences of different measures that are applied in the road transport system and an increased knowledge on the relationship between measures and their effects.

1.4.4 Towards safer traffic

One of the most central requirements on the transport system of the future concerns the risk for human errors and mistakes and ensuring that these do not lead to fatality or serious injury. This entails redesigning many different parts of the transport system to match the physical limits of the human body to withstand trauma. Primarily this concerns measures related to the infrastructure, vehicles and various transport services, but also other subsystems that are designed for the benefit of road-users including the further development of rules and regulations, driver education, information, enforcement, rescue services, and medical treatment (see e.g. SRA, 2003).

In their strive for safer traffic, the SRA have defined a number of ‘usage-condition’-indicators that are related to the way the traffic system is actually used from a safety perspective and which are controllable and measurable by traffic system administrators. This therefore represents a way for the SRA to strive towards result-oriented traffic safety work. The ‘usage-condition’ measures that are recommended include, amongst others:

- A three-level safety standard classification system for roads based on the proportion of vehicles with excessive speed as a measure of calculated risk for fatality or serious injury.
- Proportion of newly registered vehicles that can be categorised in safety class *high* or *medium*,
- Average level of excessive speed with regard to the prevailing speed limit (30, 50, 70, 90, or 110 km/h)
- Proportion of vehicles that do not maintain a safe gap to preceding vehicles in urban and rural areas
- Average travel speed in relation to posted speed limits in the rural roadway environment
- Proportion of alcohol induced drivers in relation to the number of police controls that have been carried out.
- Proportion of correctly used safety protection devices (e.g. seat belts, helmets) in urban and rural areas.

There are also indicators related to the efficiency of the emergency services and level of first-aid knowledge among the population.

For many of these indicators, work is still required to develop standardised measurement methods. The most important measures have been summarised in a standard checklist for the before-and-after evaluation of effects related to the implementation of a particular safety countermeasure. Similar checklists with suitable indicator values have also been prepared for the other five main goals of the transport system mentioned earlier.

1.4.5 The STRADA database

As part of the political drive for improved traffic safety, the SRA have introduced a new information system called STRADA (Swedish TRaffic Accident Data Acquisition) that is used to record all accidents involving fatality and injury in the Swedish road network. Work with this system has involved co-operation from amongst others, the national police board, the social services, SIKKA and Statistics Sweden (SIKA 2004). The aim is to create a common database that includes information from both the police authorities and hospitals in an attempt to co-ordinate and make effective, the accident recording process and level of detail (see e.g. SRA, 2003).

The STRADA database can be updated and accessed by different users across the country. The SRA have main responsibility for this information system and its implementation and functionality as well as the quality of information and its availability. It is hoped that this new system will eventually fill in a number of important gaps in the data recorded in the previous accident reporting system (VITS) and support traffic safety work and activity at the central, regional and local level.

There STRADA database system has been under continual development since its introduction in order to reach the intended level of service and functionality. In particular, there have been integration problems with other systems such as the National Road Database in Sweden that have undermined the full potential of the accident data.

Appendix II: Software development by the author

A number of software programs, developed by the author and used for the purposes of data-collection and analysis in this thesis are described briefly below. Software development has been carried out in the Borland Delphi Programming Environment. A number of special functions have also been defined in the form of flow charts in the VisVAP (Visual Vehicle Actuated Programming) Environment associated with the VISSIM micro-simulation tool. Both VISSIM and VisVAP are marketed by PTV Solutions, Karlsruhe, Germany.

- 1. Semi-Automatic Video-Analysis (SAVA)** This is a software program designed specifically for the analysis of traffic safety and performance at intersections based on video-recordings. This software allows the user to specify virtual line-markings on a transparent layer over the video-film and to record road-user passages events in accordance with these lines. In addition to line passage, input can be co-ordinate based following an orthogonal calibration procedure that transforms X,Y screen co-ordinates into X,Y,Z real-world co-ordinates. All vehicles are allocated a specific road-user/vehicle type and unique identification number that allows them to be tracked. This software has many special functions for, amongst other things, navigating in the film and for making input easier and faster. The resulting time-event data in relation to the different line-markings or co-ordinates is post-processed using either specially developed software or a statistical software package (e.g. SPSS).
- 2. Axle-Passage Interpreter (API)** This is a software program developed to interpret the raw-data output from a logging device (TMS 007) based on the use of pneumatic tubes and air-pressure sensors. The software allows the user to specify in detail the output data that is required regarding the tubes, tube-distances, directions, standard vehicle type axle-lengths etc. The software also serves as a report generator allowing for the specification of the total and intermediate time-periods for result aggregation.
- 3. VISSIM/VisVAP Standard Swedish vehicle actuated signal control including LHOVRA-functionality.** This functionality has been programmed directly in the VisVAP environment in the form of flow-charts. VisVap communicates with the VISSIM micro-simulation tool and therefore allows for the emulation of standard Swedish vehicle actuated signal control based on input from vehicle detectors in a model application. The so-called LHOVRA functions designed to further enhance safety and traffic performance in relation to vehicle actuated signal control are also represented in the software.

4. **VISSIM/VisVAP Safety indicator measurement and probabilistic gap-acceptance functionality.** Similar to the above, this combined functionality has been programmed directly in the VisVAP environment. Special functions have been designed to record conflicting vehicle movements over common spatial areas with regard to time-proximity and specific safety indicator measurement principles based on speed, time, and distance to a projected point of collision. Probabilistic gap-acceptance functionality is also implemented in the same software module for the different yielding situations at junctions. These probabilistic functions generate variation in the gap-acceptance process whereby gaps of varying size are assigned a probability of acceptance/rejection and are acted upon in accordance with the preferences of the driver.
5. **SAVA Output analysis for safety and traffic performance.** This Windows based software has been developed to specifically process and analyze the large amounts of data generated by Semi-Automatic Video-Analysis (SAVA) software program in relation to safety (different types of safety indicator including Time-to-Collision and Post-Encroachment Time) and traffic performance (spot speed, distance based speed, speed percentiles, minimum and maximum speeds, number of speeders, speed variation, speed distributions, gap-acceptance data at each defined yielding situation, between vehicle time-gap distributions in traffic streams, traffic flow rates, turning percentages, traffic compositions, pedestrian and cyclist movement at pedestrian crossings, and much more). This software uses site-specific definition files to provide flexibility in the analyses and to enable data from different traffic sites to be analyzed consistently and reliably.
6. **VISSIM Output analysis for safety and traffic performance.** Similar to the above, this Windows based software has been developed to specifically process the large amounts of raw-data generated by VISSIM. Raw-data files regarding the position and speed of all vehicles at each time-step during a simulation run are recorded in order to analyze safety and traffic performance. Similar analyses are made to those specified above in relation to the SAVA output. The analysis of this type of highly detailed and specific raw-data is a necessity for safety analyses based on micro-simulation modelling.
7. **VISSIM Output analysis for safety and traffic performance in relation to the dilemma zone and incident-reduction functionality.** This Windows based software has been developed to specifically evaluate Incident-Reduction functionality and aspects related to general signal performance at intersections based on raw-data generated by VISSIM. In particular, the behaviour of drivers/vehicles in the dilemma zone is identified and analyzed in accordance with raw-data files regarding the position and speed of all vehicles and status of different signals at each time-step during a simulation run.