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Bauhaus-Institut für zukunftsweisende Infrastruktursysteme (b.is)

Das Bauhaus-Institut für zukunftsweisende Infrastruktursysteme (b.is) verfolgt das Ziel, die Kooperation der derzeit beteiligten Professuren Siedlungswasserwirtschaft, Biotechnologie in der Ressourcenwirtschaft und Urban Energy Systems zu intensivieren sowie die Honorarprofessur Urbanes Infrastrukturmanagement, um Lehr-, Forschungs- und Beratungssaufgaben auszubauen. So werden beispielsweise die Weiterentwicklung von Studiengängen, gemeinsame Doktorandenkolloquien oder gemeinsame Forschungs- und Entwicklungsaufgaben durchgeführt.

Das b.is will sich deutlich sichtbar im Bereich der Infrastrukturforschung aufstellen. Die Forschung und Lehre in diesem Bereich orientiert sich am medienübergreifenden Modell der nachhaltigen Gestaltung von Stoff- und Energieflüssen sowie ressourcenökonomisch ausgerichteten Systemen, die verbindendes Konzept der Kernprofessuren des Instituts sind. Die Professur Betriebswirtschaftslehre im Bauwesen ist mit dem b.is assoziiert.

Bauhaus-Institute for Infrastructure Solutions (b.is)

The Bauhaus-Institute for Infrastructure Solutions (b.is) aims to strengthen the cooperation of the university´s research teams in Urban Water Management and Sanitation, Biotechnology in Resources Management and Urban Energy Systems in the areas of teaching, research and consultancy work. This encompasses the further development of degree programmes, joint doctorate colloquia and joint research and development activities.

Currently the chair of urban water management and sanitation, the chair of biotechnology in resources management and the chair of urban energy systems as well as the honorary professorship for urban infrastructure management are members of the institute. The chair of construction economics is associated with the institute.

The b.is will increase its visibility in infrastructure research. Education and research are geared to the comprehensive model of sustainable material and energy flows and resource economy oriented systems, which are the linkage of the institute's chairs.

COMPARATIVE ANALYSIS OF ROAD SAFETY AT U-TURNS ON 4-LANE DIVIDED HIGHWAYS IN THAILAND *

by

M. Tech. Inder Pal Meel

A thesis submitted in partial fulfilment of the requirements for the degree of
Doktor-Ingenieur (Dr.-Ing.)

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Glossary of Terms – Quick Reference Guide

Accident (traffic)	An interaction where two road users have collided that results in injury, fatality or property damage
Accident outcome	Consequences of an accident in terms of injury severity, fatality and material 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 categorized as slight, serious or fatal
Adaptive situation	An interaction between road users with lower severity than an accident or a serious conflict
Auxiliary Lanes	The portion of the roadway adjoining the traveled way for speed change, turning, storage for turning, weaving, truck climbing, and other purposes supplementary to through-traffic movement
Average Hourly Conflicts	Refers here to the total number of observed conflicts at a U-turn divided by the number of observation hours
Collision	Impact event between two or more road-users/vehicles, or a road-user (vehicle) and stationary object
Collision course	Unless the speed and/or the direction of the road users changes, they will collide
Conflict	A potentially unsafe interactive event that requires evasive action (braking, swerving or accelerating) to avoid collision
Conflict observation	Method that is used by trained observers to determine objective parameters (Time-to-Accident values etc.) in accordance with the Traffic Conflict Technique or subjective estimation of speed and distance or evasive maneuver of road-users/vehicles that are in a conflict situation
Conflict point	Common spatial location of projected trajectories 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

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
Downstream	The direction of traffic flow
Evasive action/ maneuver	Action taken to diverge from a collision course by changing speed or direction involves braking, accelerating, and/or swerving
Event	Any kind of incident or occurrence in traffic
Event severity continuum or safety hierarchy	Conceptions of unsafeness and severity of an event whereby all interactions are placed on the same scale with safe passages at one extreme and accidents involving fatalities at the other
Fatality	Death resulting from a traffic accident (usually within a 30 day period after the accident occurrence)
Hard traffic conflict	Refers here to a traffic conflict situation where one or more road user(s) use "hard brake" resulting braking sound or skid marks on road to avoid collision
Hourly Conflict Rate	Refers here to the "Average Hourly Conflicts" divided by "Hourly Volume"
Hourly Volume	Refers here to the total number of vehicle entering at a U-turn divided by the number of observation hours
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
Interaction	A traffic event with a collision course where interactive behavior is a precondition to avoid an accident
Light traffic conflict	Refers here to a traffic conflict situation where one or more road user(s) force to reduce speed (without applying brake) and change lane to avoid collision
Loon	Expanded paved aprons opposite a U-turn/ median crossover used to facilitate the larger turning path of commercial vehicles along roadways with narrow medians
Median	The portion of a divided highway separating the traveled ways for traffic in opposing directions
Moderate traffic conflict	Refers here to a traffic conflict situation where one or more road user(s) apply brake (braking light glow) and almost stop to avoid collision

Near-accident	Any circumstance that requires a rapid, evasive maneuver by the participant vehicle, or any other vehicle, pedestrian, cyclist, or animal, to avoid a crash. A rapid, evasive maneuver is defined as steering, braking, accelerating, or any combination of control inputs that approaches the limits of the vehicle capabilities
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
Post-Encroachment Time (PET)	A safety indicator that represents a measure of the time measured from the moment the first road-user leaves the potential collision point to the moment the other road-user enters this conflicting point
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
Safety hierarchy	Conceptions of unsafety and severity of an event. The serious injury accident is at the top
Serious conflict	An interaction where without an evasive action the impression is such that the situation easily could have ended up in an accident instead or event that cross severity threshold value of measuring parameters such as Time-to-Accident or Post-Encroachment Time etc
Severity hierarchy	The safety hierarchy transferred into measurable parameters based on certain presumptions
Shoulder	The portion of the roadway contiguous with the traveled way that accommodates stopped vehicles, emergency use, and lateral support for subbase, base, and surface courses
TCT	Traffic Conflicts Technique(s). TCT is a tool for estimating accident potential at road infrastructure, indirect measurement of safety and indicating methods of reducing hazardous conditions
Time-to-Accident (TA)	Conflict safety indicator measure determined in accordance with the Traffic Conflict Technique. Based on subjective estimation of speed and distance by trained observers for conflicting road-users in relation to a 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

Time-to-Collision (TTC)	A continuous function of time as long as there is a collision course; Safety indicator measure based on an objective measure of speed and distance (usually involves photometric video-analysis) for conflicting road users in relation to their conflict course. The Time-to-Collision measure is recorded continually throughout a conflict course and is not dependent on evasive action by the conflicting road-users
Traffic conflict	An accepted definition is stated as: "an observable situation in which two or more road users approach each other in space and time for such an extent that there is a risk of collision if their movements remain unchanged" (Amundsen and Hydén, 1977)
Traffic safety	Traffic safety refers to methods and measures for reducing the risk of a person/ vehicle using the road network being injured, death or harm and/or damage to material
Underreporting	Term used to describe the fact that many accidents are not reported to the police or concerning agencies and therefore are not represented in accident statistics
Upstream	The direction from which traffic is flowing
Validity	Validity concerns the accuracy with which a measure represents a theoretical construct (assessed often through consensus)
Weaving	The crossing of traffic streams moving in the same general direction accomplished by merging and diverging

Chapter 1

Introduction

1.1 General Background

The road traffic crashes in developing as well as emerging countries tend to be one of the major causes for fatalities and disabilities. In 2010, the United Nations General Assembly unanimously adopted a resolution calling for "Decade of Action for Road Safety 2011–2020". The goal of the decade (2011–2020) is to stabilise and reduce the increasing trend in road traffic fatalities, saving an estimated 5 million lives over the period. The World Health Organization (WHO) report depicted that approximately 1.24 million people were killed on the roads worldwide in 2010 and another 20 to 50 million sustained non-fatal injuries as a result of road traffic crashes (WHO and Others, 2013). This is unacceptably high. The problem appears to be one of the global proportions with traffic fatalities rated as the eighth 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 in third world countries. The worldwide road safety situation has also been described as a "global catastrophe" by the Red Cross organisation.

The road traffic injuries take an enormous toll on individuals and communities as well as on national economies. The middle-income countries which are motorizing rapidly are the hardest hit. These injuries and deaths have an immeasurable impact on the affected families, whose lives are often changed irrevocably as a result of these tragedies, and on the communities in which these people lived and worked. The WHO report suggested for a need of a sound body of scientific evidence behind the road safety interventions.

Road Safety Situation in Thailand

The economic growth in Thailand has resulted in an expanding network of roads and an increasing number of driving people. The growing number of vehicles on the roads, in turn, has contributed to a significant increase in road crashes annually and road traffic crash problem is now regarded as one of the most serious social and health problems. For Thailand, the reported road traffic fatalities were 13766 and estimated GDP loss was about 3% due to road traffic crashes and was placed second with a road death rate of 38.1 per 100,000 inhabitants in 2010 (see Figure 1.1), preceded by Dominican Republic (41.7) and followed by Venezuela (37.2). In contrast, Germany, Netherlands and Sweden have very low fatality rates of 4.7, 3.9 and 3 respectively per 100,000 inhabitants due to road crashes (WHO and Others, 2013).

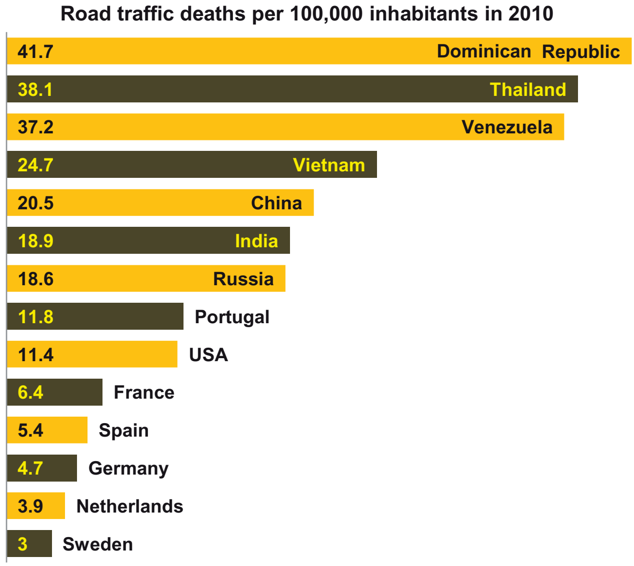


Figure 1.1: Road death rates in 2010

*(**Source:** WHO and Others (2013))*

Although there is a declining trend in the number of traffic crashes in Thailand (see Figure 1.2), yet is still high among South-East Asian countries.

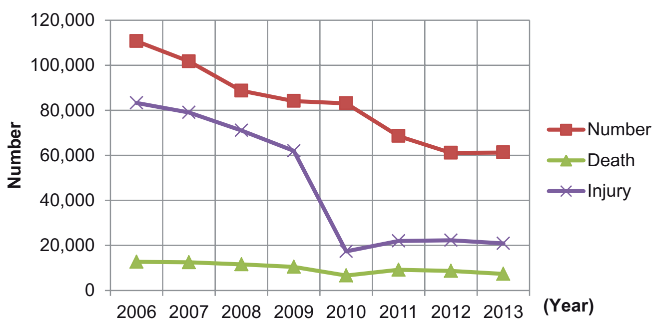


Figure 1.2: The road traffic crashes trend in Thailand

*(**Source:** Prapongsena et al. (2014))*

1.2 Function of U-turns on Thai Highways

The median at-grade U-turn on divided Thai highways is provided for U-turning movements to facilitate road users to join the opposite direction traffic stream. The U-turns are also constructed to reduce the number of at grade T and X-junctions (to avoid direct right turn from highway to minor road and from minor road to highway (for left hand traffic)). The other purposes include reduction of travel time for emergency services, efficient law enforcement and highway maintenance. The distance between U-turn and adjacent minor road is varying (approximately 100 m to 2 km); also no specific guidelines are available for the separation distance between adjacent U-turns. The experts believe that the separation distance between two adjacent U-turns is varying from approximately 1.5 to 3 km on Thai Highways, depending upon the field geography and the local road design practices. The numerous types of layout geometric design practices of U-turn are followed in Thailand, some are standard (as per the design guidelines of the Department of Highways) and rest are non-standard (based on the local design practices). For study purpose, U-turns were classified on the basis of the application of geometric components. The basic functions of median at-grade U-turns on Thai highways is shown in Figure 1.3.

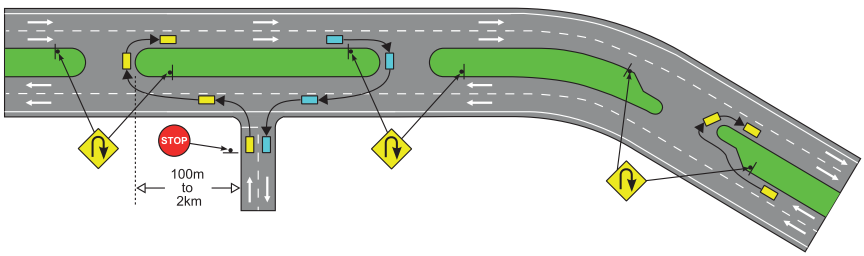


Figure 1.3: Basic functions of median at-grade U-turns

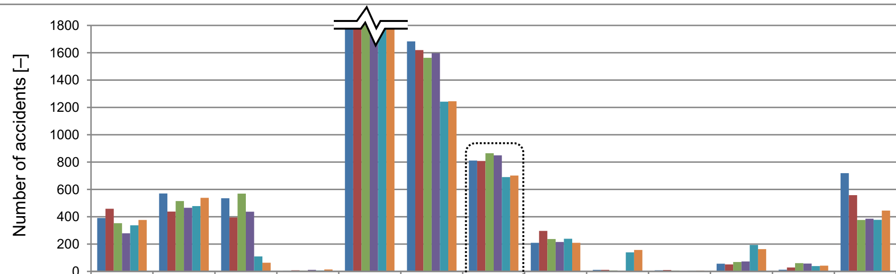
1.3 Need for the Study - RoSCoE

The road traffic crashes are consuming about 2 to 3 percent of the Gross Domestic Product (GDP) of Thailand annually. Over the past few decades, little effort has been made in Thailand to assess the cost of road crashes, owing to the lack of systematic crash data and/or information. Various questions often arise about the crash data collection and management system when road safety strategies are proposed to address the road crash situation in Thailand. In order to get a better insight into the safety effects of the present highway designs, the partner universities of the international scientific network <<RoSCoE: EU-Asia road safety centre of excellence>>* was established to conduct research works on different segments of the rural highway, such as intersection, U-turn, cross section, rail-road junction and grade separated junctions. The main objective of the project was to transfer knowledge in the field of road safety.

*Funded by the European Commission

1.3.1 Road Safety at U-turns

U-turns are considered as the most road traffic crash prone locations after straight and curved sections of Thai Highways, as illustrated in Figure 1.4.



	+ Inter-section	Y or T Inter-section	Other Inter-section	Round-about	Straight	Curve	Median Opening	Bridge	Change Lane Width	Railways Crossing	Highway access	Inter-change	Other
Year 2007	391	570	535	4	8646	1683	811	209	11	8	56	12	719
Year 2008	458	438	395	8	9655	1620	808	296	11	10	51	28	558
Year 2009	353	515	569	6	9048	1563	865	237	7	6	68	60	376
Year 2010	279	466	437	11	7680	1597	849	215	3	2	73	57	385
Year 2011	337	478	110	7	6751	1242	690	239	139	4	194	39	377
Year 2012	376	538	63	14	7054	1245	701	209	157	6	163	42	445

Accident location on highway

Figure 1.4: Crash frequency by the location on Thai highways

(**Source:** *Prapongsena et al. (2014)*)

There are interactions between the through and U-turn traffic streams which cause interruption in the through traffic movements at a significant level. As a result, the drivers experience longer travel and delays.

After arriving at the midblock median opening, the U-turning vehicles wait for a gap large enough to complete U-turn maneuver. As traffic volume increases on the through streams, the U-turning traffic confronts trouble in finding a sufficient gap to enter the other side of the carriageway. The U-turning vehicles often do not wait for a large enough acceptable gap of the through traffic stream before merging. They gradually move onto the conflicting lane to show their intention to go. The through vehicles sometimes do not allow for U-turn by increasing the speed or changing lane or honking vehicle horn or opening headlight. According to the field observation at the U-turn junction, when the U-turn traffic is in a long queue or has waited for a longer time, the U-turn traffic tends to be more aggressive to complete the U-turn maneuver. At the same time, the conflicting through traffic tends to be willing to stop and allows the U-turn traffic to move. In theory, through traffic should get priority over U-turn traffic all the time. The reduction of traffic volume in one stream could increase the movement capacity in the other stream.

The U-turning vehicles affect the through traffic movement in the opposite direction when they merge and when they diverge, stop and create a queue in the same direction. Sometimes, the storage length (in the same direction) at upstream zone provided for

Figure 1.5: Spillback effect by a queue of U-turning vehicles

the U-turning vehicles may get occupied completely; this may lead to a dangerous situation where the queue of vehicles will extend back onto the highway (spill back), impeding the through movement traffic (see Figure 1.5). Even worse, sometimes, a parallel queue of U-turning vehicles is formed at inner through lane.

The drivers and other road users basically determine their movements on the road due to a sense of obligation to adapt their behaviour to the existing traffic regulations and rules, road infrastructures, traffic and weather conditions in accordance with their driving skills and health status. Furthermore, human behaviour itself is influenced by a myriad of elements associated to the individual and his/her ability, skill and experience, current physical and psychical state and perception of the actual traffic and road conditions. The inconsistent geometric design of U-turns influences the perceptibility, recognisability, understandability, drivability and visibility of road-users towards the road environment.

Effects of Geometric Components and Geometric Design Consistency

The layout design of U-turns varies with the application and dimensions of its components, such as auxiliary lanes (acceleration, deceleration and loons). The placement of auxiliary lanes makes it interesting and challenging to study the road safety at Thai U-turns. In contrast to other highway access points and some type of intersections, the acceleration lane for merging and the deceleration lane for diverging are provided adjacent to the inner lanes of highways at U-turns. Therefore, these maneuvers are performed at the inner through lanes. Practically, the inner lanes are used for overtaking and by vehicles moving with a comparatively higher speed. So, merging and diverging maneuvers at inner lanes make U-turns susceptible to traffic crash hazards with a high severity. Also, the length of these auxiliary lanes is not uniform at most of the U-turn locations. The shorter length of these lanes does not provide enough space to make comfortable lane change; this may result in a safety problem for weaving and storage.

Heavy commercial vehicles face difficulty to use inner acceleration lanes due to the requirement of a larger turning radius, so these vehicles either merge into through lanes or use loons (outer paved area). The main reason for placing a loon or an outer-widening is to provide additional space with a larger turning path to facilitate commercial vehicles along narrow medians to negotiate U-turns. With the use of loons, it may be possible to gain the safety and operational benefit of a divided roadway.

Furthermore, the numerous types of U-turn layouts produce inconsistent design characteristics of the road infrastructure. This means that the drivers cannot drive safely at high speeds all the time and everywhere, since changes in the road environment require a constant adaptation in the speed and influence the driver's expectancy. The requirement of adapting speed to suit the environment can increase the opportunity for human error and lead to a higher risk of crash and injury. The posted speed limit at Thai U-turns is the same as the mid-block speed limit (80 kilometers per hour). The higher the speed, the more severe collisions are. Even a small increase in speed can result in a dramatic increase in the forces experienced by crash victims, and it is argued that the probability of sustaining an injury in a crash increases exponentially rather than linearly with the vehicle speed. The conjunction of high speed and varying geometric conditions could be a major factor in crash causation with a high mortality rate.

U-turn Density

The at-grade U-turns, on divided highways, function almost similar to the un-signalised 'at-grade intersections' and 'access points' where merging, diverging and crossing maneuvers are performed by the road users. The increase in the density of U-turns (numbers per unit length of highway) causes frequent lane-changes at highway for merging, diverging and weaving maneuvers. It could disrupt the through traffic flow and, even worse, lead to crashes. Frequent lane-changes could also have a significant bottleneck effects on the overall traffic flow. The practitioners believe that crash frequency augments rapidly when the density of at-grade U-turns (number of U-turns per unit length) rises. This indicates that the number of U-turns should be reduced or another solution is the construction of grade separated U-turns which are meant to create space, to reduce or to eliminate the variety of events to which the driver has to respond. It could be one of the most important factors in the reduction of crashes.

Typical Behaviour of Road Users at Thai U-turns

The maneuvers of motorcyclists for a U-turning movement make the study more complex and challenging. Thai motorcyclists, mostly travel on outer paved shoulders and seldom use inner auxiliary lanes for U-turning movements, so these have to cross all through lanes of both directions and create crossing conflicts. Figure 1.6 shows the typical driving maneuvers of motorcyclists. The arrow with a diamond head-marker (green) is pointing a motorcyclist who is properly using the deceleration lane. The arrow with a triangle head-marker (red) is pointing a motorcyclist who is not using the deceleration lane in a proper way.

Figure 1.6: Typical driving maneuvers by Thai motorcyclists at a U-turn

Similarly, heavy commercial vehicles travel in outer lanes most of the time. Therefore, before entering a U-turn facility, these vehicles have to cross the inner lane(s) and if the length of the deceleration lane is not adequate, these face difficulty during weaving maneuvers (see Figure 1.7).

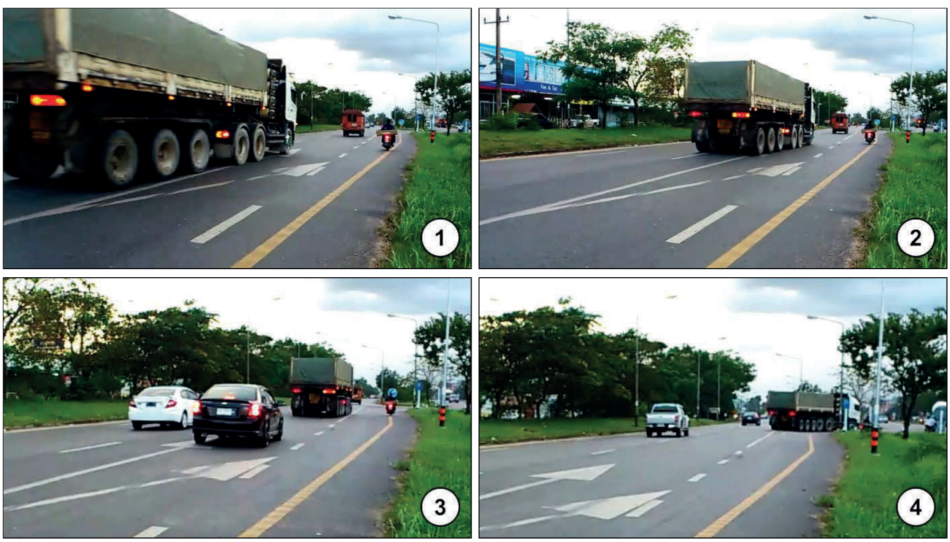


Figure 1.7: Illicit driving maneuver by a heavy commercial vehicle while diverging at a U-turn

These vehicles also have difficulty to use the inner acceleration lane(s) due to the requirement of a larger turning radius, so these vehicles either merge into through lanes or use loons or outer paved area (see Figure 1.8).

Figure 1.8: Crossing maneuver by heavy commercial vehicles

1.4 Road Safety Measurement and Analysis

Road safety refers to the methods and measures for reducing the risk of a person using the road network for being injured or killed, and a vehicle or material for being damaged. The various tools and methods have evolved for road safety assessment such as road safety audit, road safety inspection, crash modelling, conflict studies, monitoring road user behaviour and crash investigations etc. The solutions to road safety problems are often chosen among different geometrical designs and/ or enforcement policies. By modifying the environment, the road user behaviour is influenced and the safety situation is changed.

1.4.1 Crashes Based Safety Analysis

Road safety is commonly measured in terms of the number of road crashes and the consequences of these crashes with regards to their outcome in terms of severity. Traditionally, road safety analysis has been undertaken using historical road traffic collision records (crash frequency and severity). The level of safety of a specific location is measured by its history of rate of consequences (fatal, injury and property damage only) of crashes and the traffic exposure. A location is considered crash-prone when it produces higher consequences of crashes as compared to the other similar road-segments and traffic exposure. This approach to road safety analysis is *reactive* and implying that a significant number of crashes must be recorded before a particular road safety problem is identified and remedied using appropriate countermeasures.

The most common challenge with this approach concerns the quality and the availability of the crash data and the time-period required to statistically validate the success of different safety enhancing measures for random and sparse nature of traffic crashes. As the collisions are rare events, even at collision-prone locations, extended observation periods are required to determine the stable trends. Also, all of the crashes are not reported, and the reporting level can vary from region to region. Therefore, quality and reliability of crash data are the most important factors for providing accurate results.

Need of Crash Data

The availability of road crash data is a prerequisite for each efficient road safety management system. Identification and definition of the relevant problem together with the knowledge of data and parameters describing the problem is essential for its successful solution. Comprehensive, up-to date crash data is needed for the recognition of the scope of road safety problems and for raising public awareness. Reliable and relevant data enables the identification of the contributory factors of the individual crashes, and an unveiling of the background of the risk behaviour of road users. It offers the best way to explore the prevention of crashes and ways to implement measures to reduce crash severity.

The crash data is a crucial element for any road safety intervention, but it is not only the description of crash circumstances that are needed. The contributing factors like the road and traffic characteristics, vehicle parameters and information about the people involved in the crash have to be registered as well.

Data Parameters and Their Quality

To effectively analysis, compare and make informed conclusions from the data, it is necessary to fulfill the following basic requirements:

- Accuracy (to exactly describe the individual parameters)
- Complexity (to include all features within the given system)
- Availability (to be accessible to all users)
- Uniformity (to apply standard definitions)

The last parameter (uniformity) has vital importance for comparisons. Even at the national level, it is important that the local and regional definitions comply with national ones. There are different databases that often exist within a country. These databases may be managed by:

- police
- road administration
- hospitals / health system
- insurance companies

1.4.2 Near-crash Events as an Alternative Approach

A crash is an event where the road users have not managed to react in time to avoid a collision. They are either so close in time or space when they detect danger that the possibilities to avoid a collision have vanished, or they do not detect each other until having collided. The crashes are, fortunately, rare events; usually accidents with the most severe consequences are also the rarest.

It is accepted that under-reporting of road crash data is an international phenomenon. Sometimes, for various reasons, crash data does not exist at all. This is, for instance, the case in countries with no established routines for collecting crash data in a structured way. Or when a totally new measure is to be introduced, there is no historical crash data to indicate possible safety effects of the measure.

If there are shortcomings (limitation of the availability and reliability of crash and traffic data) of collision based safety measures, road safety analysis can benefit greatly from methods that use observable, non-collision interactions. In order to perform an alternative and comprehensive form of safety analysis, and to assess and predict levels of road 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 a short-term without the need of (or in addition to) crash data. Similarly, these alternative safety measures can provide a foundation to estimate the safety impact with a desired level of accuracy and provide a substitute for crash data in places (e.g. less developed countries) where crash data is either non-existent or extremely unreliable.

1.4.3 Traffic Conflict Technique (TCT)

The various non-collision measures or surrogate measures of safety have been proposed and used over the past few decades, leading to the creation of technical observation approaches which are referred as traffic conflict techniques (TCT). The approach is to study traffic conflicts or near miss events which occur more frequently, can be clearly observed and are related to the probability of collisions. The TCT have been advocated as a proactive and supplementary approach to the collision-based road safety analysis. However, there are issues of subjectivity, reliability and cost associated to the use of human observers. The main advantage of such measures is related to their resource-effectiveness given that they occur more frequently than crashes and require relatively short periods of observation in order to establish statistically reliable results.

The beginning of traffic conflict study is usually associated to Perkins and Harris (1967), in which conflicts were identified as readily observable evasive maneuvers taken by the drivers. Examples of such maneuvers include the abrupt changing of lanes or the observation of brake lights and rapid deceleration. A formalized definition of a traffic conflict was later adopted as "an observable situation in which two or more road users approach each other in space and time to such an extent that there is a risk of collision if their movements remain unchanged" (Amundsen and Hydén, 1977), and the observation method was formalized in terms of Traffic Conflict Technique (TCT).

The conflict safety indicators are particularly useful 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 conflict data also make the results sensitive to site-specific elements associated to the roadway design and the dynamic and complex relationships among different traffic variables such as traffic flows, speed and proportions of turning movements (Archer, 2005).

A traffic conflict study can be used to:

– make progress in a safety diagnosis - Traffic conflict studies are particularly useful when crash data suffers from strong limitations (crash reports may be unavailable, the information may be insufficient or unreliable).
– evaluate the effectiveness of a safety treatment - A conflict study can be conducted soon after work has been completed and negative assessment can be made quickly if anticipated benefits have not been achieved (or if unexpected side effects have been created).
– compare the safety performance of different road features or traffic rules.

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

1.5 Pilot Study: Thai Crash Data Management System

Many developing as well as emerging economies still have underdeveloped systems of crash data collection and management. In Thailand, mainly the *Royal Thai Police* and the *Department of Highways* are the responsible agencies for crash data collection and management. At the beginning of the study, the planned methodology was on the basis of crash data records. Although there has been significant improvement in crash data collection and management system in urban areas of Thailand, yet, in rural areas, the system is in underdeveloped conditions. Therefore, to analyse the availability, quality and reliability of crash records in rural areas, a pilot study was conducted. To conduct the pilot study, the crash data from year 2008 to 2011 was gathered and examined for the identified 35 U-turns locations in the Songkla and Phatthalung provinces. The findings of the pilot study endorse that there were strong shortcomings in the requisite characteristics of crash data in rural areas. There were issues of missing reports, under-reporting, non-reliability, poor preservation and limited accessibility of crash data.

1.6 Research Objectives

The goal of this research is to analyse road safety at U-turns on 4-lane divided Thai Highways with focus on their layout designs. The study focuses on the application and use of the *Traffic Conflict Technique* as a method for short-term safety assessment and comparison of road safety at eight types of U-turns. This evaluation and comparison are based on an empirical investigation. More specifically, the objectives of this study consisted of the following parts:

- To assess the possibility of the use of *crash data analysis'* to compare road safety on several U-turn layout designs on 4-lane divided highways of Thailand at the non-built up areas.
- To analyse the availability, reliability and quality of crash data recorded in various responsible agencies (Department of Highways and Royal Thai Police) for rural highways in Thailand.
- To develop a procedure for formulating the *Conflict Indexes*, as: *Severity Conflict Index* and *Relative Conflict Index* at U-turns.
- To evaluate the effect of variation in dimension of layout geometry components (median opening length, auxiliary lanes, loon etc.) of U-turn on road safety related to traffic volume exposure.
- To assess the most appropriate layout design of U-turn for rural divided highways of Thailand with respect to traffic volume exposure, vehicle compositions and road safety aspects among adopted designs.

The relationships between the frequency and severity of conflict indicators and recognised traffic parameters such as traffic flow rates on through and turning streams, and the effect of the operating speed were examined.

1.7 Scope of Study

This study presents the influence of U-turn layout designs on road safety. The study is limited to at-grade U-turns on 4-lane divided highways at the non-built-up areas under the responsibility of the Department of Highways, Thailand. The several goals were identified to achieve, such as:

- To investigate adopted U-turn layout design practices on rural highways of Thailand.
- To investigate the availability, reliability and quality of crash data recorded with various agencies (the Department of Highways and the Royal Thai Police) for rural highways in Thailand.
- To evaluate the effect of variation of layout geometry of U-turns' components (median opening dimensions, auxiliary lanes, loon etc.) on the frequency of type and severity of traffic conflicts.
- To assess the effect of traffic volume exposure on traffic conflicts at U-turns.

The following basic requirements were applied while selecting sites for investigations:

- Outside of built-up areas.
- Physically divided highways having median width between 0.5m to 15m.
- Not to be located at the horizontal curve.
- Not to be located at the crest.
- Not to be a part of T or X-junction.
- Not to be a grade separated design.

– No special design solution.
– Posted/applicable speed limit is 80 kilometers per hour.

For traffic volume and conflict data collection, the following criteria were considered:

– Only on weekdays (Monday to Friday) and during day-light hours.
– Morning/ evening peak hours and afternoon non-peak hours.
– Avoided during extreme (inclement) weather conditions.

Following three indicators were used to judge whether a conflict occurred or not:

– brake light.
– lane changing.
– perceptive deceleration.

1.8 The State of Science

The use of crash data based road safety analysis was not fruitful due to under-reporting and limitations of the availability and reliability of traffic crash data in Thailand. Therefore, the opted methodology was based on *Traffic Conflict Techniques*.

The identified U-turns were classified on the basis of the several combinations of its four geometric components, viz. deceleration lane, acceleration lane, directional-island and outer widening or loon. On the basis of these combinations, eight types of layout geometries of U-turns were identified. The collected data depends on the form of the U-turn being studied and included traffic volumes, U-turning movement counts, using auxiliary lane counts, vehicle compositions, operating speed, geometric data and traffic conflicts.

U-turns have a distinct geometry, longer conflict area in the longitudinal direction and a higher operating speed. Therefore, a subjective approach was opted to measure the severity of traffic conflicts and the complexity of evasive action (braking and sudden lane-change) of road users was considered as an indicator of the conflict occurrence. To put more emphasis on severe crashes than on slight ones, two types of weighting coefficients were computed. First coefficient was based on the subjective judgement of the seriousness of conflict situation assessed by a human observer and the second was based on the relative speed and the angle between conflicting streams. With the use of these coefficients, two types of conflict indexes were assessed, the *Severity Conflict Index* (SCI) and the *Relative Conflict Index* (RCI). The *Product of Through and Turning Volumes* (PTTV) was computed as the traffic exposure to the observed number of conflicts.

To compute SCI, the weighting coefficients were considered for three levels of severity of conflict situations (severity grading), such as slight, moderate and severe, and the values of these weighting coefficients were adopted as 1, 3 and 6 respectively.

To compute RCI, the weighting coefficient as a *Level of Conflict* for diverging, merging and crossing conflicts was assessed by computing the *Speed Adjustment Factor* using the relative speed of conflicting traffic streams and the *Conflict Orientation Factor* which depends on the angle between the conflicting streams.

Limitations of the Study

This study has undergone to use a surrogate and subjective to human judgment approach, which is frequently debated by experts and practitioners for its characteristics of reliability and subjectivity.

1.9 Outline of the Thesis

This thesis consists of seven chapters. *Chapter 1* provides a brief introduction about the background and research objectives of this study. *Chapter 2* describes a summary of past studies conducted in the proposed area and methods. *Chapter 3* explains the methodology employed in achieving the research objectives. *Chapter 4* focuses on the data collection and field procedures. In *chapter 5*, the data compilation procedures, the results of compilations in terms of conflict indexes are described. *Chapter 6* presents the comparison of road safety in relation to traffic volumes, operating speeds and variation in layout geometry of U-turns. Finally, *Chapter 7* provides summaries, major conclusions and recommendations obtained from this research.

1.10 Research Approach and Design

The research approach and design are graphically illustrated in Fig 1.9

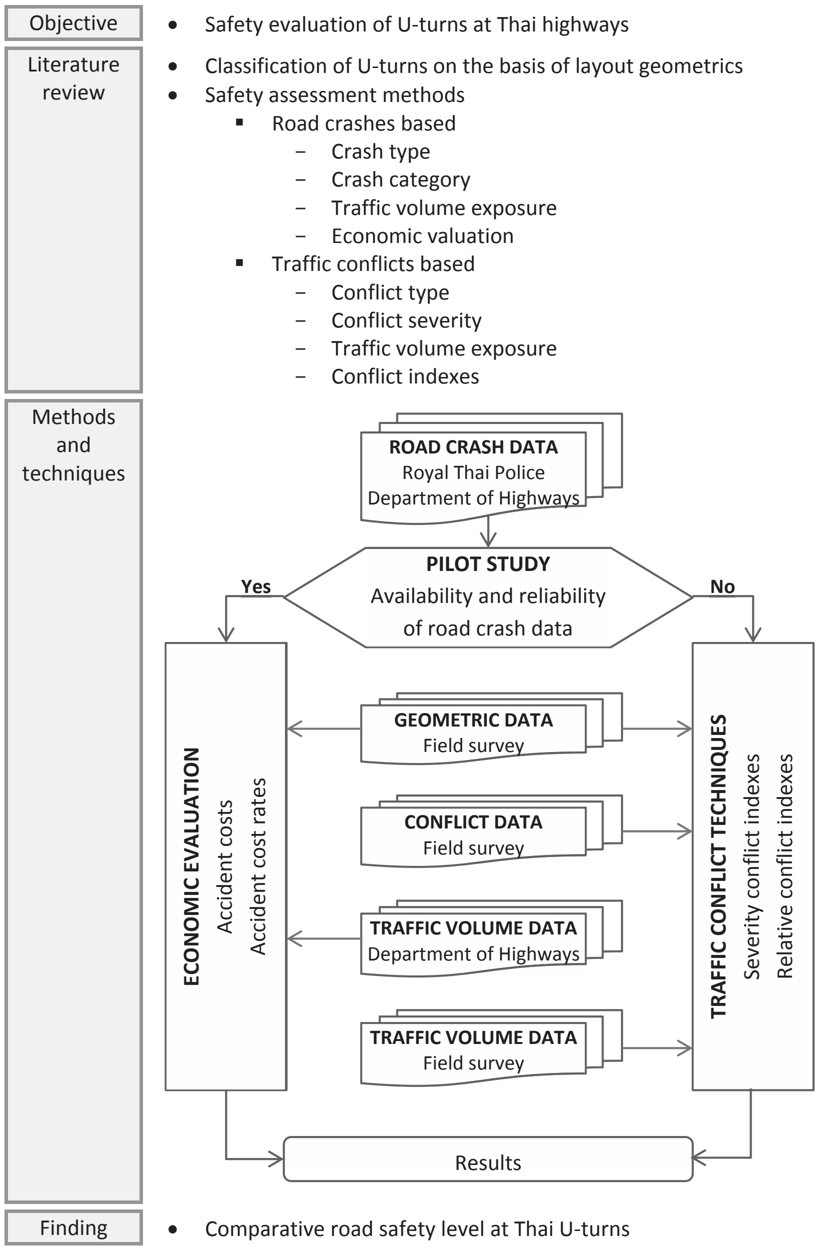


Figure 1.9: A schematic representation of research approach and design

Chapter 2
Literature Review

2.1 General

This chapter presents an overview of the subject areas related to the research topic investigated in this thesis. The objective is to provide context on the current state of the art on which the presented research is based and built upon.

The PIARC* road crash investigation guidelines for road engineers (PIARC Technical Committee, 2007) described that road users basically determine their movements on the road due to a sense of obligation to adapt their behaviour to the existing traffic regulations and rules, to road surfaces, to traffic and weather conditions in accordance with their driving skills and health status. Furthermore, human behaviour itself is influenced by a myriad of elements related to the individuals and their ability, skills and experience, current physical and psychical state, and perception of the actual traffic and road conditions. Many spots or road sections that have similar features show a high frequency of crashes. This means that *the particular road environment instigates inappropriate driver responses or provides misleading stimuli to drivers' perception that creates confusion, and/or delayed reactions*.

2.2 Road Safety and Socio-economic Costs

Road safety refers to the methods and measures that are used to reduce the risks of injury, death and harm to drivers, passengers and pedestrians. Road safety analysis procedures contribute significantly to a better understanding of creating safer standards for roads (Brannolte et al., 2009).

According to the WHO report (WHO and Others, 2013), approximately 1.24 million people were killed on the roads worldwide in 2010 and another 20 to 50 million sustained nonfatal injuries as a result of road traffic crashes. Road traffic injuries take an enormous toll on individuals and communities as well as on the national economy. The middle-income countries, which are motorizing rapidly, are the hardest hit. The negative consequences from road crashes are regarded as socio-economic costs from the viewpoint of the society. Estimates of these socio-economic costs can be used in costbenefit analysis of road investments or for other purposes (Trawén et al., 2002).

Traditionally, it has been suggested as a rule of thumb that road crashes cost a country about 1% of its gross national income, regardless of the level of development, or rate of motorization. The World Bank has recently started to use a figure of 2% of the national

*Permanent International Association of Road Congresses income to indicate the typical magnitude of the cost of road crashes (Elvik, 2000). In Thailand, the problem of road traffic crashes is now regarded as one of the most serious social problems. The total economic losses due to road crashes in Thailand were estimated to be 140,000 million Baht or 2.56 percent of the Gross Domestic Product (GDP) in 2002 (Luathep and Tanaboriboon, 2005). The total traffic cost of crashes for the year 2004 was estimated to be 153,755 million Baht, or approximately 2.37 percent of the GDP (Thongchim et al., 2007). The reported road traffic fatalities were 13766 (2010) and estimated GDP loss due to road traffic crashes was 3 percent (WHO and Others, 2013). Although, according to Prapongsena et al. (2014), there is a declining trend in traffic crashes in Thailand, the number of crashes are still higher among the South-east Asian countries (WHO and Others, 2013).

2.3 Safety at Thai U-turns

Charupa (2011) stated that U-turns are located near the entrance and exit of local village and towns. Most of the divided highways usually have at graded U-turns, some of the U-turns are under the bridge and some of them are U-turn bridges. Often, the various types of U-turn confuse unfamiliar drivers. In many areas, U-turns are closely situated due to the need of service to the local residence. However, in some areas, U-turns are located too far from each-other causing illegal driving, such as driving in the wrong direction to the closest U-turn point.

Figure 2.1: Illicit driving at Thai Highways

*(**Source:** Charupa (2011))*

The problem with U-turns under the bridge is the low clearance height which negates high ceiling-vans and trucks from using the U-turn facility. U-turns developed in the most of network are at grade U-turns, which are inappropriate for heavy vehicles and local traffic mix in the traffic composition. The trucks and buses require a larger turning radius with a lower speed which is causing conflicts with fast moving vehicles in through lanes.

2.4 Layout Designs of U-turn and Road Safety

The safety study of U-turn maneuvers was focused in several projects. Generally, these projects focused either on U-turns at signalized or unsignalized intersections. The NCHRP Project 17-21 was conducted on the subject "Safety of U-turns at Unsignalized Intersections" (Potts et al., 2004).

The NCHRP 524 report focused on the safety of U-turns at unsignalized intersections. This report included an intensive safety evaluation of U-turns by using traffic conflicts and crash rates for different types of median openings and the places of median-openings on major roads. The data, related to the observed conflicts and occurred crashes, was analysed in the report.

2.4.1 Spacing of Median Openings

Potts et al. (2004) stated that increasing the spacing between median openings improves the arterial flow and safety, reduces the number of conflicts and conflict points per mile, provides greater distance to anticipate and recover from turning maneuvers. The spacing of openings should be consistent with criteria of the access management classifications.

2.4.2 Classification of U-turns, their Advantages and Disadvantages

Potts et al. (2004) classified U-turns on the basis of layout designs and presented their merits. The study used the following key factors to classify or describe the design of a U-turn.

- Application of deceleration lanes.
- Application of directional island.
- Application of loons.

Figures 2.2 through 2.7 illustrate these median opening designs and their advantages and disadvantages are described in the following sections.

Advantages and disadvantages of median opening type 1a— conventional mid-block median opening

Advantages

- Midblock access is provided for vehicles to (a) make a U-turn and (b) reach driveways on the opposite side of the street.

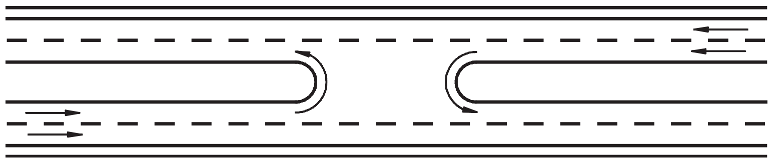


Figure 2.2: Type 1a—Conventional Midblock Median Opening Without Deceleration Lanes

*(**Source:** Potts et al. (2004))*

- Since vehicles making a U-turn only need to enter, but not cross, the opposing roadway, a minimum gap of only 4 to 6 sec will be needed.
- There are only four conflict points.
- Providing median openings for U-turns between intersections reduces the number of turning maneuvers at the intersections.

Disadvantages

- The absence of deceleration lanes increases the potential for rear-end collisions between the U-turn vehicles and the following through vehicles.
- U-turn vehicles forced to stop in the median opening may encroach on adjacent lanes and interfere with through traffic.
- U-turn vehicles entering the through lanes may delay full-speed through traffic.
- Narrow medians may not provide enough space for larger vehicles to negotiate a convenient U-turning maneuver.
- With no directional island, opposing U-turn vehicles may have to overlap.

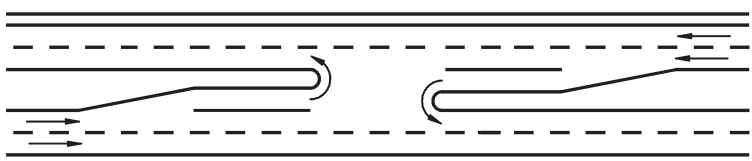


Figure 2.3: Type 1b—Conventional Midblock Median Opening With Deceleration Lanes

*(**Source:** Potts et al. (2004))*

Advantages and disadvantages of median opening type 1b—conventional midblock median opening with deceleration lanes.

Advantages

- The presence of deceleration lanes reduces the potential of rear-end collisions between the U-turn vehicles and the following through vehicles.

- The presence of deceleration lanes mitigates the problem of U-turn vehicles encroaching on adjacent lanes and interfering with through traffic while waiting for a gap in the opposing traffic.

Disadvantages

- U-turn vehicles entering the through lanes may delay full-speed through traffic.
- Narrow medians may not provide enough space for larger vehicles to negotiate a convenient U-turning maneuver.
- With no directional island, opposing U-turn vehicles may have to overlap.

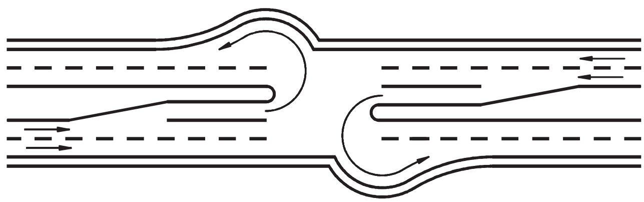


Figure 2.4: Type 1c—Conventional Midblock Median Opening With Deceleration Lanes and Loons

(**Source:** *Potts et al. (2004)*)

Advantages and disadvantages of median opening type 1c—conventional midblock median opening with deceleration lanes and loons

Advantages

- Widening on the far side of the turn makes it possible to make a U-turn without stopping or backing and reduces the interference between U-turn and through traffic, particularly for large vehicles.
- Without performing major reconstruction, additional space can be provided to facilitate larger turning path for heavy commercial vehicles along the narrow medians.
- The presence of deceleration lanes reduces the potential of rear-end collisions between the U-turn vehicles and the following through vehicles.
- The presence of deceleration lanes mitigates the problem of U-turn vehicles encroaching on adjacent lanes and interfering with through traffic while waiting for a gap in the opposing traffic.
- Midblock access is provided for vehicles to (a) make a U-turn and (b) reach driveways on the opposite side of the street.

Disadvantages

- U-turn vehicles entering the through lanes may delay full-speed through traffic.
- With no directional island, opposing U-turn vehicles may have to overlap.
- The presence of loons may make snow removal and other maintenance work more difficult.

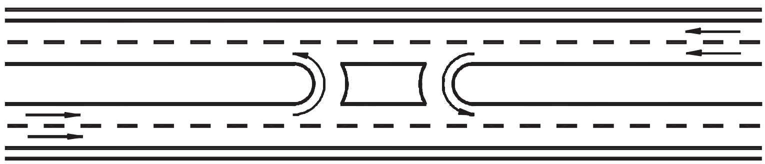


Figure 2.5: Type 2a—Directional Midblock Median Opening Without Deceleration Lanes

(**Source:** *Potts et al. (2004)*)

Advantages and disadvantages of median opening type 2a—directional midblock median opening without deceleration lanes

Advantages

- This design prevents overlapping U-turns.
- Midblock access is provided for vehicles to (a) make a U-turn and (b) reach driveways on the opposite side of the street.
- Since vehicles making a U-turn only need to enter, but not cross, the opposing roadway, a minimum gap of only 4 to 6 sec will be needed.
- There are only four conflict points.
- Providing median openings for U-turns between intersections reduces the number of turning maneuvers at the intersections.
- Accident rates at mid-block median openings are lower than those at three-legged or four-legged median openings.

Disadvantages

- The absence of deceleration lanes increases the potential of rear-end collisions between the U-turn vehicles and the following through vehicles.
- U-turn vehicles forced to stop in the median opening may encroach on adjacent lanes and interfere with the through traffic.
- U-turn vehicles entering the through lanes may delay full-speed through traffic.
- Narrow medians may not provide enough space for larger vehicles to negotiate a convenient U-turning maneuver.

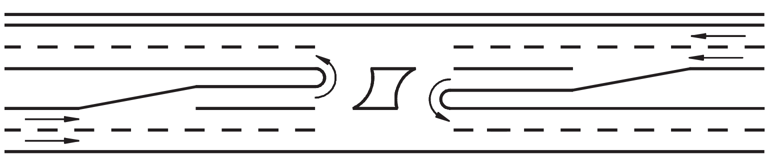


Figure 2.6: Type 2b—Directional Midblock Median Opening With Deceleration Lanes

(**Source:** *Potts et al. (2004)*)

Advantages and disadvantages of median opening type 2b—directional mid-block median opening with deceleration lanes

Advantages

- The presence of deceleration lanes reduces the potential of rear-end collisions between the U-turn vehicles and the following through vehicles.
- The presence of deceleration lanes mitigates the problem of U-turn vehicles encroaching on adjacent lanes and interfering with through traffic while waiting for a gap in the opposing traffic.
- This design prevents overlapping U-turns.
- Midblock access is provided for vehicles to (a) make a U-turn and (b) reach driveways on the opposite side of the street.
- Since vehicles making a U-turn only need to enter, but not cross, the opposing roadway, a minimum gap of only 4 to 6 sec will be needed.
- There are only four conflict points.
- Providing median openings for U-turns between intersections reduces the number of turning maneuvers at the intersections.

Disadvantages

- U-turn vehicles entering the through lanes may delay full-speed through traffic.
- Narrow medians may not provide enough space for larger vehicles to negotiate a convenient U-turning maneuver.

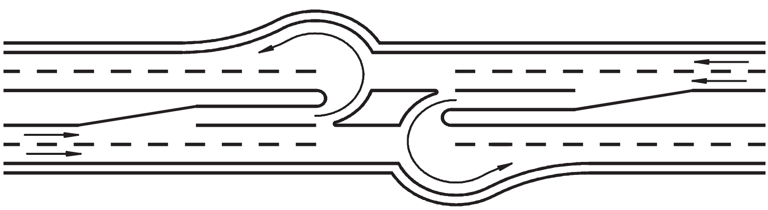


Figure 2.7: Type 2c—Directional Midblock Median Opening With Deceleration Lanes and Loons

(**Source:** *Potts et al. (2004)*)

Advantages and disadvantages of median opening Type 2c— directional mid-block median opening with deceleration lanes and loons.

Advantages

- Widening on the far side of the turn makes it possible to make a U-turn without stopping or backing and reduces the interference between U-turn and through traffic, particularly for large vehicles.
- Without performing major reconstruction, additional space can be provided to facilitate larger turning path for commercial vehicles along narrow medians.

- The presence of deceleration lanes reduces the potential of rear-end collisions between the U-turn vehicles and the following through vehicles.
- The presence of deceleration lanes mitigates the problem of U-turn vehicles encroaching on adjacent lanes and interfering with through traffic while waiting for a gap in the opposing traffic.
- This design prevents overlapping U-turns.
- Midblock access is provided for vehicles to (a) make a U-turn and (b) reach driveways on the opposite side of the street.
- Providing median openings for U-turns between intersections reduces the number of turning maneuvers at the intersections.

Disadvantages

- The presence of loons may make snow removal and other maintenance work difficult.

2.4.3 Median Acceleration Lanes

They provide vehicles a path to accelerate to an appropriate speed before entering through travel lanes on a divided highway. The median acceleration lanes provide both safety and operational benefits that the entering vehicles do not cause vehicles on through travel lanes to decelerate substantially.

In the NCHRP Report 375 (Harwood et al., 1995), four intersections with one or more median acceleration lanes were studied with crash data. These studies found that the median acceleration lanes can enhance the operation of intersections on divided highways. In particular, median acceleration lanes reduce the likelihood that vehicles making a left turn (for right hand traffic) from a crossroad approach will need to stop at the median opening.

Potts et al. (2004) described advantages and disadvantages of median acceleration lanes as follows:
Advantages

- They reduce delays when traffic volumes are high.
- They provide higher merging speeds.
- They are useful if the acceleration lane is long enough to allow a safe merge.
- They may reduce crashes.

Disadvantages

- It is difficult to merge from median acceleration lanes because of the blind spots.
- They are not used properly by the drivers.
- They create anxiety to the through traffic.
- They create conflicts.
- They may be unexpected and unfamiliar to the drivers.
- The benefits of median acceleration lanes do not warrant the construction costs.

2.4.4 Loons or Outer-widening

A common problem associated to the use of U-turns is the difficulty of larger vehicles to negotiate U-turns along cross-sections with narrow medians. This situation often affects the operation and safety of commercial vehicles that typically require more space in order to perform a U-turn maneuver. One possible solution to this problem is the construction of a loon. The loons are defined as expanded paved aprons opposite to a median crossover. Their purpose is to provide additional space with a larger turning path to facilitate for commercial vehicles along the narrow medians.

With the use of loons, it may be possible to gain the safety and operational benefit of a divided roadway. In spite of the benefits of loons at U-turns, the NCHRP Report 524 (Potts et al., 2004) specified the following safety concerns at loons:

- Fixed-object crashes with delineator posts, sign posts (in the median and along the mainline) and guardrail.
- Side-swipe crashes involving vehicles merging into mainline traffic from the loon.
- Commercial vehicles backing up and parking within the crossover.

2.5 Road Safety Measurement Using Historical Crash Data

Traditionally, road safety analysis has been undertaken using historical road traffic collision records (crash frequency and severity). The level of road safety at a specific location is determined by its history of rate of consequences (fatal, injury and property damage only) of crashes and traffic exposure. This is a traditional and long-standing approach that has established the use of crash data as an accepted measure of road safety. Statistical crash data has proved to be useful for a wide range of purposes, including the identification of crash black-spots and problems associated to particular types of facilities or different groups of road-users. 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 the safety programs, strategies and policies at different levels of interest. A location is considered crash-prone when it produces higher consequences of traffic crash than similar road-segments. This approach to road safety analysis is reactive and implying that a significant number of crashes must be recorded before a particular road traffic safety problem is identified and remedied using appropriate safety countermeasures.

There are a number of methods proposed by practitioners to assess road safety using historical crash data. Among these methods, economic valuations (cost-benefit analysis or crash cost analysis) and crash modelling are widely adopted.

2.5.1 Road Safety Analysis and Crash Costing

The estimates of road crash costs have mainly been intended for use in cost-benefit analysis of safety measures. Road safety can be improved substantially if policy priorities are based on costbenefit analysis to a greater extent than they are today (Elvik, 2003).

Crash Category

The outcome of crashes are classified on the basis of the possible damage to human and property (Dietze et al., 2005), such as:

Fatality	– Person who dies due to a crash within 30 days.
Seriously Injured	– Person who has to stay in a hospital for at least 24 hours.
Slightly Injured	– all other injured persons.
Serious PDO	– Serious crash with material damage minimum one vehicle is not roadworthy.
PDO	– Crash with material damage.

Based on these consequences, the following six crash categories were derived:

Category 1 – crash with fatalities.

Category 2 – crash with seriously injured.

Category 3 – crash with slightly injured.

Category 4 – crash with serious material damage.

Category 5 – crash with material damage but without driving while intoxicated.

Category 6 – crash with material damage but with driving while intoxicated.

Crash Costing

The crash costs describe the economic costs caused by road traffic crashes. To determine the costs of road traffic crashes, several practical techniques are available such as the gross output or human capital method, net output method, life-insurance method, court award method, implicit public sector valuation method, and value of risk change or willingness to pay method (Melhuish et al., 2005).

The costs of crashes, comprising fatal and non-fatal damage costs, make up an important part of external costs of traffic. The damage costs include a variety of related expenses. The major cost components associated to road traffic crash are (Dietze et al., 2005):

- Casualties (fatalities, seriously and slightly injured)
- Loss of resources (e.g. damage of capacity to work, invalidity)
- Rehabilitation (e.g. medical rehabilitation)
- Material damage (e.g. repair costs)
- Overhead costs (e.g. administrative expenses)

The road crash data is generally classified into four degrees of severity (fatal, serious, slight, and property damage only). Based on the above mentioned components (for human capital method), the unit cost per casualty due to traffic crashes is estimated. Table 2.1 (on page 26) shows unit costs for road traffic crash in Thailand (Thongchim et al., 2007).

Table 2.1: Average unit cost per casualty or case by severity

Severity	**Average Unit Cost (baht)**
Fatality	3,324,834
Disability	3,470,080
Serious Injury	128,433
Slight Injury	28,091
Property damage only	30,871

*(**Source:** Thongchim et al. (2007))*

Indicators of Crash Analysis

Often, the number of crashes or the number of fatalities is not sufficient to work out the difference and interpret the results, but the crash costs, rates, or densities are more appropriate. The indicators are differentiated as (Dietze et al., 2005):

– Absolute indicators (number of crashes, number of casualties, crash costs)
– Relative indicators (average of casualties per 100 crashes, average of crash costs per 100 crashes, densities, rates)

The absolute indicators can be used to determine general results. For comparisons of roads/ sections according to the geometry, the relative indicators are more appropriate. The crash density represents the incidence of crashes on a road section within a defined time period. The crash density makes it possible to determine areas with significant number of crashes. They are calculated on the basis of the number of crashes/casualties or crash costs.

Crash density (CD) – the average of the number of crashes or casualties which characterizes either a road section of one kilometre length or a defined spot within a defined time period (number/ year)

Crash cost density (CCD) – the average of the economic costs for either a road section of one kilometre length or a defined spot within a defined time period (costs/year)

The crash-rates represent a road user's risk of being involved in a crash. These are calculated by relating to the traffic exposures. Using the exposure based crash rates, instead of traditional crash counts as the dependent variable, has a considerable appeal because crash rates are widely used in crash reporting (Anastasopoulos et al., 2008).

Crash rate (CR) – the average number of crashes at a traffic volume of one million vehicles and one kilometer section length (for spots of only one million vehicles).

Crash cost rates (CCR) – the average of the economic costs at traffic volume of one million vehicle and one kilometer section length (for spots of only one million vehicles).

Generally, road safety related methodologies focus on the traffic exposure, the category of crash and the crash cost within the road network. The crash data and unit cost are statistically examined and different relative crash numbers/rates are obtained and compared. The quality of the road section is described by crash rates and crash cost rates related to road safety (PIARC Technical Committee, 2007).

2.5.2 Limitation of Using Historical Crash Data

The crash analysis involves the use of both quantitative and qualitative data in decision-making. This approach to road safety analysis is reactive and implying that a significant number of crashes must be recorded before a particular road safety problem is identified and remedied using appropriate safety countermeasures.

A further drawback with this approach concerns the quality and availability of crash data and the time-period required to statistically validate the success of different safety enhancing measures for the given random and sparse nature of traffic crashes. However, the reliance on collision data for safety analysis has several shortcomings. As collisions are rare events, even at collision-prone locations, extended observation periods are required to determine the stable trends. Also, all crashes are not reported, and the reporting level can vary from region to region. The quality and reliability of crash data used for analysing safety are the most important factors for providing accurate results (Tanaboriboon et al., 1999).

Another biggest problem while conducting these studies is to determine the exact crash location. Therefore, the availability of a localisation method is a crucial element of any road information system. Without reliable knowledge of the crash localisation and without relevant data, the opportunities for solving the local deficiencies are limited (PIARC Technical Committee, 2007). Each road crash relates to a specific location in the road network. Each road location is described by road number and stationing data uniquely related to each road network. An accurate localisation system should enable the:

– exact localisation of road feature according to localisation data stored in the database.
– storage of recorded data to the appropriate location in the database.

2.6 Traffic Crash Data: Availability, Quality and Reliability

Crash data represents a sort of window on the world of untoward things that happen in the traffic system. The interpretation of this data may lead to a better understanding of operational problems, should enable us to devise countermeasure for those problems, and, in many cases, allow us to evaluate the effectiveness of countermeasure programs. The quality that is the accuracy, precision, timeliness, and completeness of the data used to address these problems is important to arrive at solutions (O'Day, 1993). To effectively analyse, compare and make informed conclusions from crash data, it is necessary to fulfill the following basic requirements:

- Accuracy (to exactly describe individual parameters)
- Complexity (to include all features within the given system)
- Availability (to be accessible to all users)
- Uniformity (to apply standard definitions)

Nevertheless, even a minimal amount of information can offer the ability to identify safety efficiencies in the road environment, and to design possible countermeasures. Three levels of data sets are considered:

- minimum data
- road and traffic data
- additional data

A minimum set of data can provide road engineers with relevant information necessary for basic crash causation investigation. The minimum data can be identified as follows:

- crash identification (a unique number-based system)
- time (date, hour, minute, day of week)
- location (stationing (route km post), main junctions and/ or GPS)
- crash type (driving crash, turning-off crash, etc.)
- vehicles involved (number, type)
- crash consequences (fatalities within 24 hours/30days, injuries, material damage)

Crash data quality (Consistency of reporting):

- In a common form
- Collected by officers with similar training
- Stored in readily accessible computer files
- Collected according to nominal threshold criteria
- Based on national standards.

It is accepted that the under-reporting of road crash data is an international phenomenon (Naji and Djebarni, 2000). The problem in developed countries is limited to property damage or slight injury crash data; however the problem is beyond this level in the developing countries. Unfortunately, a very little work is available in this area for developing countries. A road traffic crash data collection system is satisfactory only if it can produce information that can be used for analysing important road traffic problems. Figure 2.8 (on page 29) shows sources of under-reporting of road traffic crashes.

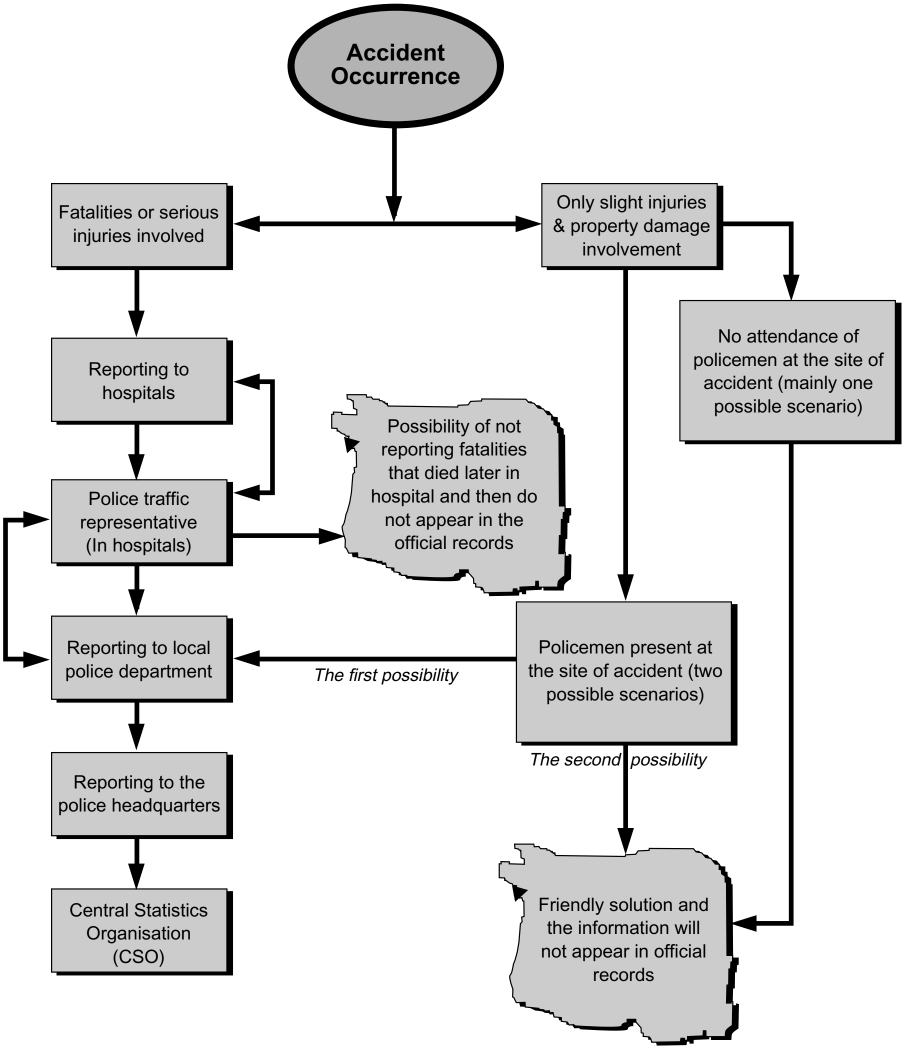


Figure 2.8: The process of crash data collection and reporting system showing the sources of under-reporting

*(**Source:** Naji and Djebarni (2000))*

The availability of road crash data is a prerequisite for each efficient road safety management system. Identification and definition of the relevant problem together with the knowledge of the data and parameters describing this problem is essential for its successful solution. Reliable and relevant data enables the identification of contributory factors of individual crashes, and an unveiling of the background of the risk behaviour of road users (PIARC Technical Committee, 2007).

O'Day (1993) found that a model crash records system should include:

- Competent crash investigation, supported by training and supervision.
- A report form attuned to users' needs.
- Attention to detail in preparation of reports.
- Accurate data entry and process.
- Free-flowing output to interested users.
- Feedback of user comments to induce system improvement.

In many countries, crash reporting is not completed. Hence the actual number of casualties cannot be calculated. This problem can be alleviated if the concern about under-reporting is emphasized. On the other hand, if under-reporting is not recognized, the level of road safety problems is not known or underestimated. This could lead to developing incorrect prioritization of problems, or less efficient and inappropriate countermeasures.

Traffic Crash Data Collection and Management in Thailand

In Thailand, the under-reporting of crash data is widely acknowledged (Srirat, 2008). The principal agencies or organizations such as the *Royal Thai Police*, the *Department of Highways* (DoH) and the *Ministry of Public Health* collect crash data only for their interested purposes and areas of their responsibility. But the integration of databases cannot be found in order to share data among various agencies concerned. Srirats finding shows that 59.3 percent of under-reporting of crash data was found from DoH data while comparing to the police crash data[†], as shown in Figure 2.9

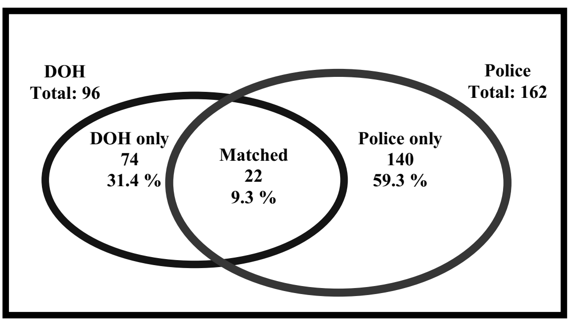


Figure 2.9: The road traffic crash under-reporting between the DoH and the Royal Thai Police

(**Source:** *Srirat (2008)*)

Police mostly focus on legal aspects. As a result, data which is not related to the police investigation is sometimes in poor quality or does not exist. Secondly, unacceptable

[†]Comparing the amount of under-reporting crash data in Nakhon Ratchasima province from DoH database to Police crash data reports.

information is also common, such as missing information related to crash severity, uncertain locations and unknown risk factors. They concentrate only on the cases of fatality involved or not negotiable, so the under-reporting of crash data always exists with non-fatal or injury cases. On the other hand, the hospital data providing information merely about the cases of severity, disability and death of patients admitted to the hospital is reported and the information about the crashes of property damage only and minor injuries is not reported.

Following are some facts about crash data collection and management system in Thailand (Srirat, 2008):

– DoH has a trend of under-reporting during night hours.
– DoH has more under-reporting trend during weekend than during weekdays.
– Crashes between vehicles and objects are almost under-reported by police, but, in other cases, the DoH has a trend of under-reporting.
– Small vehicle crashes' have more tendencies to be under-reported by the DoH than police.
– The hospital data contains only the cases of high severity, disability and death, but does not provide the property damage.

Kowtanapanich (2006) mentioned that since the Royal Thai Police crash data is always kept in the narrative reports and, standardization, consistency, and integrity are poor; also the accessibility to this data is limited to other users; these are the reasons which lead to get incomplete or wrong information. For example, police officer who is responsible for recording the related crash data is not trained for this responsibility. Kowtanapanich (2006) also found that the represented data of crash reports does not cover all cases of the crash occurrence; this shows only the cases of fatality involved and non-fatality cases or the cases of slight injury rarely exist in the descriptive reports of police. Also, with the increase of distance between the crash spot and the police station, there is a higher tendency of under-reporting.

2.7 Surrogate Safety Measures

While the use of road safety assessments on the basis of historical crash data is most common and accepted in traffic engineering today, however there are a number of recognized limitations that are directly related to the quality and coverage of data, and the fact that crashes are rare events that occur randomly in both time and space. The collection of crash data is impractical for short-term safety assessment purposes. Furthermore, this type of data is less useful for determining crash causation since it is rarely recorded with sufficient detail to draw conclusions regarding the complex chain of events that led to a crash occurrence (see e.g. Carsten et al., 1989). Such factors limit the use of crash data for the purpose of determining suitable countermeasures. The road safety assessment on the basis of crash data implies a 'reactive' approach, whereby crashes must actually occur before preventive measures are taken. This approach is regarded by many as unethical.

Surrogate safety measures are any events that can be correlated with crash rates. Since these methods use events that occur at a much greater frequency than crash rates, it is possible to assess the safety of a given location without waiting for a large number of crashes to occur. Additionally, these measures can be used with micro-simulated road networks to assess the safety of proposed roadways and transit projects, experimental roadway designs, or operational strategies before they are built or implemented.

A number of factors have been proposed for use as surrogate safety measures, such as volume, speed, delay, accepted gaps, headways, shock-waves and deceleration-to-safety time. The other potential surrogates are critical events, such as lane merging, speeding and running red lights. The most frequently used surrogate measure is traffic conflict. A traffic conflict is the occurrence of two (or more) road users that have risk of colliding if their course is unchanged.

Surrogate measures are especially useful for evaluating the performance of new roadway designs or comparing road safety for particular type of traffic facilities. These measures are also used in computer simulation models in which the number of conflicts for different designs can be compared to evaluate the overall safety of new roadway.

According to Svensson (1998), the need for surrogate or complementary methods for road safety analysis is consequently high. There is a need to get a more complete picture of the whole safety hierarchy. As a first step towards including less severe events than injury crashes in the hierarchy, the following requirements can be set up:

- The events in traffic that are to be complemented to crash data have to be much more frequent than crashes.
- These events have to be observable in the traffic.
- The utmost requirement is that the complementary events have to have a correlation to crashes (not only a statistical relationship but also a very clear causal relationship to crashes).
- These events must be characterized as being almost crashes. When these events get a location in the severity hierarchy, they must be placed right next to crashes with regards to severity.

The events that fulfil all these preconditions are called traffic conflicts. The development of Traffic Conflict Technique (TCT) has been the first attempt to explore and utilize the severity hierarchy.

2.7.1 Traffic Conflict Techniques (TCT) as an Alternative Approach

With the absence of reliable crash records, traffic conflict technique is a suitable alternative aid to conduct a study of road safety (Ewadh and Neham, 2011). Traffic conflict, like traffic crashes, are produced by interaction between the components of traffic system; road users, vehicles, and the road environment. The main feature of traffic conflicts and crashes is that, they are always preceded by a critical combination of circumstances in traffic (Asmussen, 1984). The original definition of traffic conflicts introduced by Perkins and Harris of General Motors (GM) Research Laboratory 1967 is "a traffic conflict is an evasive action, such as braking or weaving, taken by a driver to avoid a collision" (Brown, 1981). Glauz and Migletz (1980) defines traffic conflict as "a traffic event involving two or more road users, in which one user performs some typical or unusual action, such as a change in direction or speed that places other users in jeopardy of collision unless an evasive maneuver is undertaken". Traffic conflict technique has a long history of development, including research on (Gettman and Head, 2003):

- Data collection methods
- Data collection standards
- Definitions of various types of conflicts
- Severity measures
- Relationship between conflicts and crashes
- Conflicts are related to specific crash types.

A formalized definition of a traffic conflict is given by Amundsen and Hydén (1977) as *"a traffic conflict is an observable situation in which two or more road users approach each other in space and time to such an extent that there is a risk of collision if their movements remain unchanged"*, and the observation method formalized as Traffic Conflict Technique (TCT).

Conflict studies have an inherent advantage over crash studies that conflicts are generally observed simultaneously with the surrounding events and conditions. Crash data, on the other hand, is very rarely collected in real time; normally crash investigation and reconstruction take place post hoc. Conflict studies have been used in a variety of ways (Svensson and Barker, 2007):

- As a research tool to improve understanding of the relationship between behaviour and risk (with conflicts as risk indicators).
- As a method for safety diagnosis – understanding the nature of safety problems at a site or series of sites.
- As a tool for evaluating safety changes, where statistical reliability might require several years of before and after crash data, but where counts of conflicts can provide reliable evaluation with only days worth of data.
- As a substitute for crash data in places (e.g. less developed countries), where crash data is either non-existent or extremely unreliable.

Road traffic conflicts are far more frequent than crashes, and, therefore, can potentially provide reliable information in situations where crash numbers are insufficient. Hyden pyramid is a name given to the hypothesis that events can be ranked in order of increasing severity but decreasing frequency. This idea is often represented graphically with a pyramid divided into horizontal sections, each section representing a class of events. The height of a section from the pyramid's base represents the severity of the corresponding class of events, while the volume of the section represents the relative frequency for that class. For example, fatal crashes are least frequent, so they would occupy the tip of the pyramid. Below fatal crashes might be injury crashes and then non-injury crashes, close calls, and so forth. An indication of the relative frequency of traffic events is shown in Figure 2.10. Undisturbed passages are those situations where there is no interaction between various road users, an example being free-flow traffic.

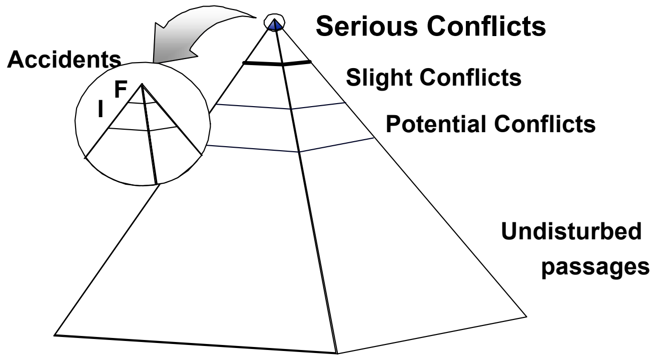


Figure 2.10: The safety pyramid (Hyden, 1987)

Hydns definitions of different events:

Undisturbed passage – Road users pass independently of each other.

Potential conflict – Road users are closer and have to cross each others routes. There is a smooth and very early interaction.

Slight conflict – A situation where road users have a collision course and they start an evasive action. The situation is characterised by being under control and the evasive action is not a type of emergency braking.

Serious conflict – The evasive action starts late and the impression is such that the situation could have easily ended up in a crash instead.

Crash – The evasive action started too late, or there is no time for an evasive action at all - a collision is unavoidable.

The relationship between traffic volumes and conflicts has been another subject for researchers to investigate. Salman and Al-Maita (1995) had a research on three-legged intersections. The summation of all volumes entering the intersection and the square root of the product of volumes that generated the conflicts were used to correlate conflicts and volumes. It was found that the correlation between the conflicts and the square root of the product of volumes was higher than that of the summation of volumes.

The Federal Highway Administration (Gettman et al., 2008) undertook research, which considers the intersection safety evaluation. They developed Surrogate Safety Assessment Model (SSAM) for assessing the safety performance of different types of intersections. In order to do this, they developed software, which supports traffic simulation models including VISSIM, AIMSUN, PARAMICS and TEXAS. The SSAM model can determine the number and severity of conflicts in each conflict point at an intersection. Based on the assumption that the severe conflicts will lead to crashes, they measured the severity of crashes by calculating the speed difference of vehicles in the crash. The severity of conflicts is measured, using Hydén (1996) definition regarding the required braking rate (RBR) for each conflict.

2.7.2 Traffic Event Hierarchy

Safety Hierarchy

All events in traffic are more or less related to safety and it is logical to assume that encounters between road users can be described as events in a safety hierarchy. The conflict technique relies on the concept of *safety hierarchy*, i.e. there is a continuum of all road users interactions with collisions at the top, undisturbed passages or "safe interactions" at the bottom and traffic conflicts in between. The events located next to serious injury crashes in the safety hierarchy must be those events that almost end up as serious injury crashes and so on. A serious conflict is also like A crash, an unexpected event, but here the participants (or at least one of them) are able to take a successful evasive action.

Severity Hierarchy

A safety hierarchy is matched by a *severity hierarchy*, based on *severity indicators* that measure the proximity of an interaction to a collision. It is considered that the inclusion of all interactions and traffic conflicts in particular can be an alternative or complementary approach to analyse road safety from a broader perspective than collision statistics alone. This conceptualization is useful for traffic safety research, providing connectivity between the bottom-up approaches to traffic safety found in behavioural sciences and the macroscopic (top-down) perspective of traffic safety as representing crash frequency and outcome severity. This relationship has been described in many different models over the years, such as that of Von Klebelsberg (1982) illustrated in Figure 2.11

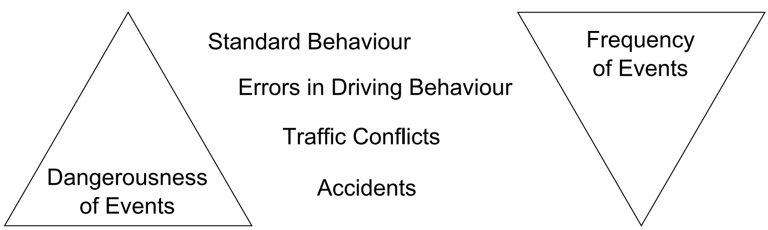


Figure 2.11: Traffic safety and the relationship between errors, standard behaviour, traffic conflicts and crashes

(**Source:** *Von Klebelsberg (1982)*)

2.7.3 Validity and Reliability of TCT

Despite the many advantages associated to the use of TCT, a number of fundamental problems have been identified. The reliability and validity are two issues strongly connected to the usability of TCT. These concern the lack of a consistent definition, their validity as a measure of road 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 conflict safety indicators by road safety analysts.

The main disadvantage of TCT is that the validity is lower than that of crashes. In order to estimate the number of crashes from conflict registration, ratios between the number of conflicts and crashes are used, which means that conflicts can also be regarded as a measurement of exposure as well as an indirect estimate of the number of crashes (Valde and Harri, 1997). The road safety indicators are another even more indirect method to describe or study the road safety situation. These usually have to do with road user behaviour. The advantage is that they have an even higher frequency and are easier to collect than conflict data. The disadvantage is that their validity is normally even lower than that of the conflict technique, (Valde and Harri, 1997).

A number of authors have aimed at validating traffic conflict technique. The reliability and validity of traffic conflict have been a major concern, and there are a number of studies that have tried to address these issues (Williams, 1981; Hauer, 1982; Migletz et al., 1985; Hauer and Garder, 1986). Some empirical studies found that there were clear relationships between traffic conflicts and crashes (Glauz et al., 1985). Despite the concerns about those issues, traffic conflict techniques have been used in various studies to evaluate road safety.

Glauz et al. (1985) aimed at showing a correlation between conflicts and crashes. They collected conflict and crash data at 46 urban intersections, producing tables of daily conflict rates for intersection on the basis of traffic volume and signal control. The validation of traffic conflicts was done for each class of intersections. Within each class, two intersections were randomly selected, and the expected crash rates and their variances were calculated using the tables of conflict rates. The expected crash rates on the basis of conflicts were 18.20, and the total number of crashes that were predicted with traditional means were 20. As a result, the authors concluded that the crash predictions from conflicts are equally valid compared to those predicted from historical crash data.

Sayed and Zein (1999) developed regression prediction models correlating traffic conflicts defined by TTC to traffic volumes and crash rates. Both conflicts and crashes were assumed to follow a Poisson relationship. A statistically significant correlation was found between crashes and conflicts, with an R-square value ranging between 0.70 and 0.77 for signalized intersections. No significant relationship was found at un-signalized intersections, the reason for this difference was believed to be attributable in part to the quality of crash data and the randomness associated with low crash frequency.

Several studies attempting to relate geometry to the safety at un-signalized intersections have been undertaken by measuring and using traffic conflicts in lieu of crash data. Arndt (2003) mentioned that conflicts were found to be extremely volume dependent and could not account for difference in crash when corrected for volume exposure.

For the subjective TCT, the field observers are a source of error while collecting conflict data, due to the subjective nature of decision whether a given driving event is a conflict or not. Each observer is required to judge whether or not a situation is a conflict, resulting in variability in the grading of traffic conflicts by different people. As a result, the human-collected data was not necessarily accurate, especially if multiple observers were used. Nonetheless, traffic conflicts have been shown to have some correlation with the crash frequency, and the consensus is that a higher rate of conflicts correlates to a lower level of road safety (Gettman et al., 2008).

To eliminate the subjectivity from traffic conflict analysis, objective measures are used. Objective measures for traffic conflicts have a higher validity and include a cardinal or ordinal time-proximity dimension in the severity scale. The most common of these measures is time-to-collision (TTC), which is defined as the time until two vehicles on a collision course do collide, if they continue on their current trajectories (Hayward, 1972). As vehicles continue on a collision course, the TTC decreases, so it is the minimum TTC that is critical. Based on this, conflicts can be classified and sorted by severity. A lower/minimum TTC value leaves less time to carry out corrective action and the collision is more severe. Many other objective measures exist, such as Post-Encroachment Time (PET). The PET is the time between two vehicles on a near-collision course passing at a common point (Allen et al., 1978; Van der Horst and Kraay, 1986). As with TTC, a lower PET indicates higher severity, and the minimum value is also the critical value. It became possible to measure traffic conflicts in computer applications. Archer and Kosonen (2000) were among the first to investigate the possibility of using micro-simulation to perform safety analysis. The Federal Highway Administration (FHWA), USA released a report in 2003 entitled Surrogate Safety Measures From Traffic Simulation Models. This report marked the start of a concerted effort to extract surrogate safety measures from micro-simulation models.

Guo et al. (2010) mentioned that there are disadvantages for both traffic conflict techniques and simulation-based studies. The traditional traffic conflict technique relies on the subjective judgment of the observers to decide the severity of the crash or traffic conflict, and inter-observer variability can distort the true situation. The objective measures such as TTC are difficult to obtain in the field. While TTC is relatively simple to obtain in simulation studies, the studies themselves rely on subjective assumptions for the simulation models. Traffic conflict studies typically collect data for only a few days, which makes crash data collection difficult. Single vehicle conflicts (which are difficult to evaluate in either traffic conflict studies or simulation studies) are commonly excluded from both types of analysis.

2.8 Traffic Conflict Indicators and Severity Measurement

Conflict indicators are defined as measures of crash proximity, based on the temporal and/or spatial measures that reflect the 'closeness' of road-users (or their vehicles), in relation to the projected point of collision. The objective evidence of a traffic conflict by NCHRP definition is the evasive action which is indicated by a brake-light or a lane change affected by the offended driver. First definition of conflict was mainly based on brake light indications. Since then a number of different indicators for conflict techniques have been developed in different countries.

A variety of observation methods have been developed to measure traffic conflicts including the observation of driver behaviour and recording the number of near misses or avoidance maneuvers. Broadly, these can be classified into subjective and objective methods. The subjective methods include considerable judgement by the conflict observer and conflict severity taking into account the level of deceleration (weighted deceleration, which included longitudinal-braking and lateral-swerving-deceleration). The objective methods include a cardinal or ordinal time-proximity dimension in the severity scale.

There are mainly three indicators that are widely recognised and discussed to assess the severity of conflict situation, namely *Time to Accident / Speed* (TA/Speed), *Time To Collision* (TTC) and *Post Encroachment Time* (PET).

2.8.1 Time to Accident / Speed (TA/Speed)

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. In the Swedish TCT, this severity scale is accomplished by applying the TA/Speed dimension i.e. the *Conflicting Speed* and the *Time to Accident* value (TA), which presupposes a collision course.

> The **Conflicting Speed** is the speed of a road user taking an evasive action, for whom the TA value is estimated at a moment just before the start of the evasive action.
>
> The **Time to Accident (TA value)** is the time that remains to an accident from the moment that one of the road users starts an evasive action if they had continued with unchanged speeds and directions.

The TA/Speed value is based on the necessity of a collision course and an evasive action. The proximity is estimated from the time and space margin with the help of introducing conflicting speed at a certain point during the approach; at the time of evasive action. An event with a low TA and a high speed value indicates an event with high severity. The speed is a logical choice for a severity measure as it correlates with the collision impact in case of realization of a crash. Besides having a severity scale on the basis of TA/Speed presumption, the Swedish TCT is also characterised by the elaboration of conflicts with different severity.

A major improvement that can be considered to the Traffic Conflict Technique was the introduction of *'uniform severity level'* and *'uniform severity zones'* on the basis of the relationship between Time-to-Accident and approach speed (see Figure 2.12). 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 on the basis of 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.

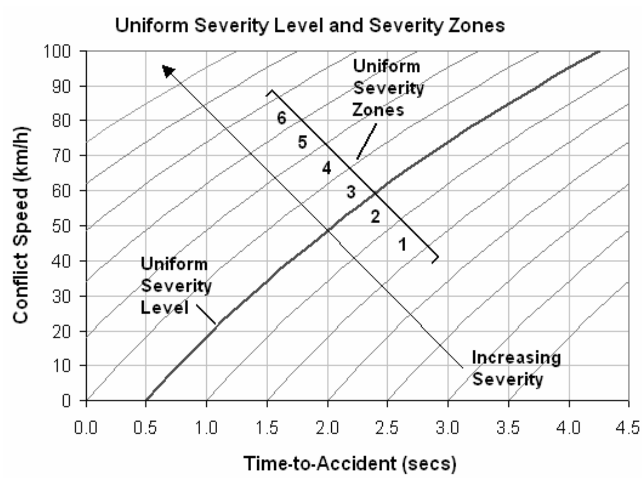


Figure 2.12: Uniform severity level and severity zones according to Hyden

*(***Source:** *Hydén (1987))*

Hydén (1987) investigated crashes and compared the data with conflicts data taking into consideration the important factors such as conflicting speeds and distances to the collision point, type of evasive maneuver and type of road-users involved. This comparison led to the conclusion that conflicts and crashes were based on a common underlying process and had a fundamental similarity.

2.8.2 Time To Collision (TTC)

The Time-To-Collision is usually regarded as a more objectively determined measure of crash proximity in comparison to Time-to-Accident, and generally involves the use of image-processing (video analysis) determined measures. Traffic conflict is defined according to Dutch TCT (DOCTOR - Dutch Objective Conflict Technique for Operation and Research) as:

> 'A conflict is a critical traffic situation in which two or more road users approach each other in such a way that a collision threatens, with a realistic risk of injury or material damage if their course and speed remain unaltered. The available space for maneuver is less than that needed for normal reaction.'

The TTC value is also based on the necessity of a collision course. The proximity is estimated during the approach. TTC is a continuous function of time as long as there is a collision course; the time required for two road users to collide if no evasive action is taken. The TTC_{min} is the specific estimate of TTC during the entire interactive process of the conflict event, rather than the value recorded at the time evasive action is first taken as in the TA/Speed. So, TTC_{min} is the lowest value of TTC in the approaching process of two road-users on a collision course. A lower value of TTC or TTC_{min} indicates an event with high severity.

In safety studies on the basis of use of TTC, a suitable threshold level must also be determined in order to distinguish between serious conflict events, and those events that are not of serious situation. 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 the measures of speed and distance. Several studies estimated that TTC_{min} values less than 1.5 sec indicate a potential dangerous situation at intersection in urban areas. This implies that all TTC-values lower than TTC_{min} 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, can be usefully applied.

Archer (2005) mentioned, that the widespread use of the TTC concept has been largely neglected due to the problems associated to 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 safety study, where conflict events can be difficult to be detected in two-dimensional imagery, and subject to problems related to the relative positioning of the camera and the coverage it provides.

2.8.3 Post Encroachment Time (PET)

A further variation of the Time-to-Collision concept is Post-Encroachment Time (PET). This indicator is used to measure situations in which two road-users that are not on a collision course or an evasive action, pass over a common spatial point or area. The PET value is the time measured from the moment the first road-user leaves the potential collision point to the moment the other road-user enters this conflicting point.

A PET situation measures the closeness in time by the time margins between the road users after the encounter, in contrast to the TTC where the time margin is measured before and during the encounter. Several studies indicate that, for built up areas, PET values that are less than 1 sec are critical. A low PET value indicates an encounter with high severity. An important doubt 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 crashes.

The main difference between PETs and TTCs is the absence of collision course criterion. PETs are easier to extract using photometric analysis than TTC as no relative speed and distance data are needed. The measure represents the difference in time between the passage of "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 regards to data-extraction process, not requiring constant recalculations at each time-step during a conflict event duration.

There are a number of recognized drawbacks with the PET-measure. The 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. The events with similar (final) trajectories better suit 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. The PET-measurement requires a fixed projected point of collision, rather than one that changes with dynamics of a safety critical event (as is the case in an unsafe rear-end or merging interaction) (Archer, 2005).

2.8.4 Strengths and Weaknesses of Conflict Indicators

Each of the indicators has different strengths and weaknesses related to its potential areas of application and suitability for different types of conflicts. The Time-to-Accident measure is distinguished between serious and non-serious conflicts for the purposes of estimating conflict indicators occurrences. The Time-to-Accident measure is the most resource effective conflict indicator with regards to data collection, but it has subjective nature and possibility for error in the estimations of speed and distance. 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 be judged where the conflict point is dependent on the relative speed difference and the distance between vehicles that are in conflict.

The TTC indicator 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 other Traffic Conflict Technique as the measures of speed and distance are derived directly from video-imagery in cases where a collision course actually exists. 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 measuring twice the size of that found for Time-to-Collision.

As already discussed, the PET-safety indicator is not useful for longitudinal conflict trajectories and, of a surety, most useful for safety critical events involving vehicles and vulnerable road-users at pedestrian/cyclist crossings and certain types of vehicle-vehicle interactions. 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 is taken.

For the diverging and merging vehicles, it is often necessary to consider vehicle acceleration/ deceleration in order to estimate where the point of collision would have occurred, had not one of the vehicles taken an evasive action. This situation is complex even for a trained observer, and occurs quite regularly for the U-turning maneuvers. The situations, such as these, should be subject 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 maneuvers may also be more obvious to the observer at U-turn where there are higher levels of speed on the through lanes. When 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 maneuvers 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.

2.9 Severity of Traffic Events

2.9.1 Crash Severity Grading (Category) and Severity Indexes

Road safety assessment based only on the crash frequency (number of crashes) and the rates (crashes for million of vehicles and kilometre) is not considered as appropriate approach. One possibility is to use weights for crash consequences on the basis of socio-economic costs. The purpose of using weights is to put more emphasis on severe crashes than on slight ones. There are several different ways of determining such weights.

Broadly, road crashes, based on their consequences, are divided into three categories namely fatal, injury and property damage only (see *crash category* on page 25).

Truong and Somenahalli (2011) described that without weighted data, it is difficult to know whether high or low clustering exists. The counts of crashes are commonly used to evaluate safety problems at a location. There is a belief that the more severe crashes should have greater weights in identifying unsafe locations on the basis of crash costs. The approach is to give weights to the more severe crashes, but not with extreme high values computed in direct proportion to the crash costs. Truong employs a crash severity weighting system for identifying Pedestrian-Vehicle crash hot-spots in which the basic factor was tow-away crashes and the severity index was computed by the following equation:

$$SI = 3.0 \times X_1 + 1.8 \times X_2 + 1.3 \times X_3 + X_4 \tag{2.1}$$

where:

X_1 – total number of fatal crashes,
X_2 – total number of serious injury crashes,
X_3 – total number of other injury crashes, and
X_4 – total number of property-damage-only crashes

This severity index is used as the criterion for spatial analysis by Truong and Somenahalli (2011).

While using historical crash data for comparison and ranking purposes, the severity of individual crashes at a road section/ infrastructure can be expressed and summed in terms of equivalent property damage only (EPDO) crashes. The concept of this method is that the number of fatal and/or injury crashes at a location or section of highway are given a greater weight than property damage only crashes. This approach assigns a weight to crash injuries and fatalities that is intended to represent their equivalence as a PDO crash. The second approach that is used to quantify and rank the crash severity of a road section/ infrastructure is to weight the different crash injury severities by a cost, i.e. ideally based on socio-economic values.

Luathep (2004) determined the monetary value of road crashes in Khon Kaen Municipality in Thailand and revealed that in terms of crash cost, the costs for Fatal, Injury, and Property Damage Only (PDO), crashes are 3,538,130 Baht, 245,795 Baht and 28,379 Baht respectively. Therefore, the weights for Fatal, Injury and PDO crash are then 125:9:1.

2.9.2 Conflict Severity Grading and Severity Indexes

Interest in grading the severity of conflicts arose relatively early in the development of traffic conflict methods, in connection with difficulties encountered in establishing empirical relationships between conflict counts and observed crash frequencies. If Hydens pyramid relationship is accurate, then it would be expected that establishing the relationship between events in neighbouring levels of the pyramid would be easier than between events at one level and events aggregated over several lower levels. This, in turn, means that objective criteria would be needed for assigning events to their appropriate severity levels.

Severity Scale by Zimolong et al. (1983)

A conflict severity scale on the basis of braking rates was proposed by Zimolong et al. (1983), in which 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 means involves severe use of brakes and/or an abrupt change of lanes; the third level involves emergency braking and fast driver reaction; and the fourth level involves collision.

Braking Rate by Hydén (1996)

In a report by Hydén (1996), the concept of the braking rate severity scale led to the development of video-image processing software that was to be used for the determination of road safety indicator values. In this report, the severity levels, as suggested earlier by Zimolong and colleagues were assigned as deceleration values.

The braking rate definitions were stated in the definition of an alternative near-crash safety indicator – Deceleration-to-Safety (DST). The braking rate values used in association with the DST indicator and the original conflict levels of Zimolong and colleagues are listed in Table 2.2

Table 2.2: 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

TTC by Hayward (1972) and Others

For vehicle-to-vehicle interactions, Hayward (1972) introduced the use of time to collision (TTC) as a measure of conflict severity. At a given instant, TTC is the time at which two road-using entities would collide if each persisted on its present course. Hayward illustrated, while plotting TTC versus time, how TTC would first decrease to a minimal value and then increase after one or more of the involved entities of initiated evasive action. The minimum value of TTC for an encounter was taken as a measure of how close the encounter was to an actual collision.

In the Swedish traffic conflict technique, TTC at the instant a road user initiates an evasive action, rather than the minimum TTC over a time interval, was taken as the measure of conflict severity. In its initial implementations at an urban intersection, the Swedish TTC defined serious conflicts as those with TTC <1.5 seconds. Further attempting to extend this idea to non-built-up area, it was found that the vehicle speed is also needed to be considered. Ultimately leading (Svensson and Hydén, 2006) to grade severity as a function of the ratio of TTC to closing speed (CS),

$$Severity = f(TTC/CS) \tag{2.2}$$

A higher value of TTC/CS indicates conflicts of lower severity. This characterization is especially interesting because TTC/CS is inversely proportional to the minimum deceleration needed to bring the vehicle to a stop in the TTC interval. Svensson and Hyden also advanced the intriguing hypothesis that severe conflicts result from a mismatch between a road users expectations and actual events.

Hauer (1982) noted that if conflicts are treated as crash opportunities, some of which actually result in crashes, then the relationship between conflicts and crash frequency should take the form

$$\begin{aligned} Expected\ no.\ of\ crashes = (Number\ of\ conflicts) \\ \times (crash - to - conflict\ ratio) \end{aligned} \tag{2.3}$$

That is, the number of conflicts is a measure of crash opportunities, while the crash-to-conflict ratio reflects the probability that a given crash opportunity results in a crash.

If conflicts of different degrees of severity have different probabilities of resulting into crashes, then a study that mixes together conflicts of varying severity may find it difficult to identify a stable crash-to-conflict ratio. This leads to the problem of identifying groupings of conflicts having stable ratios. One possible solution is to interpret the crash-to-conflict ratio as the probability that a conflict results in a crash and then allows this probability to vary continuously with a measure of the conflict severity. Another possible solution is weighting higher severity conflict data with respect to lower severity conflict data.

Weighted Conflict Rate by Krivda (2013)

Similar to the *crash severity index*, for traffic conflicts, Krivda (2013) mentioned relative conflict rates and weighted conflict rates for single lane roundabouts. The relative conflict rate is defined as the hourly number of conflict situations per 100 vehicles. It is determine as follows:

$$C_R = \frac{N_{CS}}{V}.100 \tag{2.4}$$

where:

C_R – relative conflict rate [CS/100 veh],
N_{CS} – number of conflict situations (CS) per hour [CS/h],
V – hourly traffic volume [veh/h].

However, the above-mentioned relation does not take into consideration the seriousness of conflict situations. Thus, it is more practical to use the so-called weighted coefficient of the relative conflict rate C_{RW}. The equation for a particular type of conflict situation has the following form:

$$C_{RW} = \frac{N_{CS}.C_{Sj}}{V}.100 \tag{2.5}$$

where:

C_S – coefficient of seriousness[‡] of conflict situations [–], i.e. for example:
– for seriousness of conflict situations of the 1st level ... $C_{S1} = 1$,
– for seriousness of conflict situations of the 2nd level ... $C_{S2} = 3$,
– for seriousness of conflict situations of the 3rd level ... $C_{S3} = 6$.

The equation for all types of conflict situations has the following form:

$$\begin{aligned} C_{RW} &= \frac{\sum_{i=1}^{n} N_{CSi}.C_{Sj}}{V}.100 \\ &= \frac{N_{CS1}.C_{Sj} + N_{CS2}.C_{Sj} + ... + N_{CSn}.C_{Sj}}{V}.100 \end{aligned} \tag{2.6}$$

where:

C_{RW} – Weighted conflict rate [CS/100 veh],
N_{CSi} – number of conflict situations (CS) per hour [CS/h],
C_{Sj} – coefficient of seriousness of conflict situations [–],
i – number of conflict situations of the same type (i = 1,2,3,...n),
j – seriousness of conflict situations (j = 1 or 2 or 3), $C_{S1} = 1$, $C_{S2} = 3$, $C_{S3} = 6$,
V – hourly traffic volume [veh/h].

[‡] In available literature, method or criteria to assess the values of coefficient of seriousness was not mentioned.

The seriousness of conflict situations defined as follows:

- 1st level – potential conflict situations (mere breaking of road traffic rules by a single participant),
- 2nd level – conflict situations when one or more participants are restricted by another participant,
- 3rd level – conflict situations when one or more participants are endangered by another participant,
- 4th level – traffic crash.

Levels of Conflict by Kočárková (2012)

Similarly Kočárková (2012) referred three levels of conflicts for traffic conflicts technique purposes, but the study did not consider weighting factor for levels of conflicts.

- Level 1 – It is assigned to the controlled maneuver without any limitation or just with minor limitation. The example of this level is a conflict between a vehicle, which is standing on the pedestrian crossing because of the traffic jam, and a pedestrian, who would like to use this pedestrian crossing and has to go around the vehicle.
- Level 2 – The difference between level 1 and level 2 is minor. In spite of that, it is necessary to realize that, in some specific situations, it is necessary to sort out this kind of conflict into less severe and more severe categories.
- Level 3 – The conflict level 3 is assigned to such situations, when road users are threatened and sharp maneuver (loud braking supplemented for example with beeping) is necessary to avert traffic crash.

Severity Weights by Conflict Type by Yi and Thompson (2011)

Yi and Thompson (2011) proposes a method to quantify the coupling in hybrid design matrices for traffic intersections by taking into account the presence of coupling, the types of conflicts that coupling may introduce, and the impact that the conflict may have on the intersection. The result is a single numerical value, called the coupling impact index, which can be used to select the safest intersection design for a given situation.

Once the coupling impact index for each traffic intersection has been calculated, the values can be compared to determine which intersection is the most desirable from the perspective of both the Independence Axiom and the traditional traffic conflict theory. The coupling impact index can then be used as part of a formal concept selection process.

Yi used the relationship between traffic conflicts and conflicting volumes. "The total number of traffic conflicts is proportional to the square root of the product of conflicting volumes". This is referred to by Sayed and Zein (1999) as the "product of entering vehicles" (PEV):

$$PEV = \sqrt{(V_1) \times (V_2)} \tag{2.7}$$

where:

V1 and V2 represent the traffic volumes (vehicles/hr) of two conflicting traffic streams.

The impact of coupling on safety of any given intersection as the product of the PEV at each conflict point i multiplied by the severity of the potential collision caused by the presence of that traffic conflict point is summed over all of the traffic conflict points in the intersection.

$$CouplingImpactIndex = \sum_i (PEV_i \times Severity_i) \tag{2.8}$$

Yi estimated the severity by the change in kinetic energy (ΔKE) of a collision caused by each conflict category (crossing, merging and diverging). The severity is greatest in crossing (angle) conflicts, followed by crossing (left-turn), merging, and diverging conflicts, as shown in Table 2.3.

Table 2.3: Severity weights by conflict type

Conflict type	**Severity weight [–]**
Crossing (Angle)	54.35
Crossing (Left-Turn)	15.30
Merging	3.73
Diverging	1

*(**Source:** Yi and Thompson (2011))*

Here, Yi considers that the first vehicle in any potential conflict is assumed to have an initial velocity of 50 km/hour. For crossing (angle) conflicts, the second vehicle is assumed to be travelling at the same velocity and the angle between the two vehicles is assumed to be $90°$. Crossing (left-turn) conflicts are assumed to be equivalent to the turning conflicts and the second vehicle is assumed to be travelling at the speed of 12.5 km/hour. For merging conflicts the angle between the two vehicles is assumed to be $15°$ and the second vehicle is assumed to be travelling at 35 km/hour. Diverging conflicts are assumed to be equivalent to lane changes, the angle between the two vehicles is assumed to be $10°$ and the second vehicle is assumed to be travelling at 45 km/hour.

Conflict Severity Grade by Katamine (2000)

Referring to earlier studies, Katamine (2000) classified four levels of conflict severity grades, as follows:

Slight severity grade (G1) – It includes a precautionary conflict describing vehicles that are waiting for other vehicles to emerge at the intersections, and it also describes vehicles that are experiencing precautionary lane change or anticipatory braking.

Slight severity grade (G2) – It describes vehicles under controlled braking to avoid collisions with adequate time to conduct the maneuver.

Medium severity grade (G3) – It describes lane change or stopping to avoid a collision and a rapid deceleration. This type of conflict results in a near crash situation. Usually, there is no time for a controlled steady maneuver.

Serious severity grade (G4) – It describes very serious incidences and results in near crash situations; occasionally, vehicles touch each other slightly. These may be minor collisions occurred at the intersections, resulting in slight property damage.

Level of Conflict Values by Dixon (2011)

Dixon (2011) used the *potential angle of impact* and the *relative speed of conflicting vehicles* for the grading of severity of conflicts and represented severity in terms of *individual level of conflict values*. The orientation and type of conflict are defined as follows:

Orientation - determines the relative orientation of the vehicle paths at conflict points to determine the angles of impact of conflicting vehicles and to represent the nature of crashes that would occur at the location; and

Type of Conflict - establishes descriptions for the various conflicts (i.e., crossing, merge, diverge, etc.).

The *Level of Conflict*, (LC), is a function of the relative speeds between conflicting vehicles and their angle of impact and the conflict type.

Relative Operating Speed

The kinetic or impact energy for a crash is a factor of the speed (or speed differences) and can be determined from the following well known relationship:

$$KineticEnergy = KE = \frac{1}{2}mS^2 \tag{2.9}$$

where:

m = mass of vehicle and
S = speed (mph)

Dixon considered that the "base" crash as a head-on collision at the speed of 55 mph (88 km/h) or greater [referred to as HO-55 in subsequent discussion]. All other *Levels of Conflict* will ultimately be adjusted to equivalent HO-55 crashes. For the HO-55 crash condition, this equation can be modified as follows:

$$KE_{HO-55} = \frac{1}{2} \times m \times 55^2 = 1512.5 \times m \tag{2.10}$$

A speed adjustment factor, f_{spd}, can be developed by contrasting the kinetic energy for the HO-55 to alternative relative speeds:

$$f_{spd} = \frac{KE_S}{KE_{HO-55}} = \frac{\frac{m}{2}S^2}{1512.5 \times m} = \frac{S^2}{3025} \tag{2.11}$$

where:

S = speed (mph)

If, for example, a vehicle traveling at 40 mph (64 km/h) impacts another vehicle traveling in the same general direction at 30 mph (48 km/h), the relative speed difference would be 10 mph (16 km/h) and this relative speed would be directly associated to the resulting kinetic energy if the vehicles were involved in a crash. As a result, the relative speed for the crash can be used to determine the speed adjustment factor.

Conflict Orientation Factor (c)

In a manner similar to the procedures used for assigning costs to crashes, a severity factor on the basis of crash type and vehicle orientation can be used to represent associated crash risk due to the conflict configuration. This conflict orientation factor, c, defines bicycle and pedestrian-involved crashes as extremely severe ($c = 1.0$) followed by head-on crashes ($c = 0.8$), right-angle crashes ($c = 0.6$), sideswipe crashes ($c = 0.4$) and rear-end crashes ($c = 0.3$). The larger *c* value of 1.0 for bicycle and pedestrian crashes is because these crashes are considered injury-related without any regard to the angle of impact.

Calculating the Level of Conflict, LC

The value of the LC is based on a combination of the speed adjustment factor and the conflict orientation factor:

$$LC = f_{spd} \times c \tag{2.12}$$

where:

f_{spd} = Speed adjustment factor
c = Conflict orientation factor

To demonstrate calculations of LC for a driveway, Dixon considered that the through stream speed is 50 mph (80.5 km/h), diverging vehicle speed is 15 mph (24 km/h), speed vector of diverging vehicle in the direction of through stream is approximately 5 mph (8 km/h), merging vehicle speed is 10 mph (16 km/h) and crossing vehicle speed is 15 mph. The calculated *LC*s are shown in Table 2.4.

Table 2.4: Level of Conflict *calculations by Dixon (2011)*

Conflict Point Type	**Through Stream Speed [mph]**	**Turning Stream Speed [mph]**	**Relative Speed (S) [mph]**	f_{spd} **[–]**	c **[–]**	LC **[–]**
Diverge	50	15 (5**)	45	0.669	0.3	0.201
Merge	50	10	40	0.529	0.4	0.212
Crossing*	50	15	50*	0.826	0.6	0.496

*Use larger speed for kinetic energy calculations

**Speed vector for 15 mph diverging vehicle along arterial at point of exit is approximately 5 mph.

Chapter 3
Methodology

3.1 General

This chapter documents the methodologies that are used to achieve the research objectives of the study. It consists of five sections. The first section explains a pilot study conducted to examine crash data records in Thailand. The second section explains layout designs of the U-turn and their classification. The third section describes the criteria employed during the site selection process. The fourth section describes conflict types recorded at the field and used for analysis. Fifth section of this chapter explains the methodology used to determine the *Severity Conflict Index* and the *Relative Conflict Index*. The last section of this chapter provides brief information about the comparison of *Conflict Indexes* and details about factors influencing these indexes.

3.1.1 Classification of U-turns on Thai Highways

An inventory of 4-lane divided highways with raised medians was conducted in Thailand. The inventory was prepared in the laboratory using satellite imagery from Google Earth computer application.

U-turns were classified on the basis of several combinations of their four layout design components, viz. deceleration lane, acceleration lane, directional island and outer widening or loon as described in Table 3.1 (on the page 54). Based on these combinations, for study purpose, eight types of U-turn layout designs were identified, as shown in Figure 3.1 (on page 53).

3.1.2 The Zones at U-turns

For study purpose, the functional area for a U-turn was considered to be composed of three zones, as shown in Figure 3.2 (on page 55).

Upstream zone: It consists of through lanes, deceleration lane and, sometimes an outer widening is also provided. This zone is used by U-turning road users for perception-reaction maneuver (for deceleration and lane changing), and storage. In this zone, U-turning vehicles diverge from through traffic streams to median opening / deceleration lane. A typical Upstream zone is shown in Figure 3.2a