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Safety impact of application of auxiliary lanes at downstream locations of Thai U-turns☆

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ABSTRACT

To assess the safety impact of auxiliary lanes at downstream locations of U-turns, the Traffic Conflict Technique was used. On the basis of the installed components at those locations, four types of U-turns were identified: those without any auxiliary lane, those with an acceleration lane, those with outer widening, and those with both an acceleration lane and outer widening.
The available crash data is unreliable, therefore to assess the level of road safety, Conflict Indexes were formulated to put more emphasis on severe crashes than on slight ones by using two types of weighting coefficients. The first coefficient was based on the subjective assessment of the seriousness of the conflict situation and the second was based on the relative speed and angle between conflicting streams.
A comparatively higher Conflict Index value represents a lower level of road safety. According to the results, a lower level of road safety occurs if two components apply or if a location is without any auxiliary lane. The highest level of road safety occurs if the layout includes only a single component, either an acceleration lane or outer widening.

1. Introduction

1.1. Road traffic crash trends in Thailand

Road traffic crashes in developing as well as emerging countries tend to be one of the major reasons for fatalities and disabilities. Middle-income countries, which are motorizing rapidly, are the hardest hit. The economic growth in Thailand has resulted in an expanding network of roads and an increased number of drivers. The growing number of vehicles on the road in turn has contributed to a significant increase in road crashes annually. In Thailand, the road traffic crash problem is regarded as one of the most serious social problems. There were 13,766 reported road traffic fatalities in Thailand in 2010, and the estimated GDP loss was approximately 3% due to road traffic crashes [1].

1.2. Road safety at median openings in Thailand

Median openings (including U-turns) are considered the most road traffic crash–prone locations after straight and curved sections of Thai highways, as illustrated in Fig. 1.

Charupa [3] stated that U-turns are frequently located near the entrances and exits of villages and towns. Often, the various types of U-turns confound unfamiliar drivers. In many areas, U-turns are situated close to each other in order to service local residents. However, in some areas, U-turns are located far from each other, causing illegal driving such as driving in the wrong direction to reach the closest U-turn point.

1.3. Function of U-turns on Thai highways

Median at-grade U-turns on divided Thai highways are provided for U-turning to allow drivers to join the traffic stream in the opposite direction. The basic functions of median at-grade U-turns on Thai highways are shown in Fig. 2. U-turns are also constructed to reduce the number of at-grade T- and X-junctions [to avoid direct right turns from highways onto minor roads and from minor roads to highways (for left-hand traffic)]. Other purposes to use U-turns include to reduce travel time for emergency services and to provide for efficient law enforcement and highway maintenance.

☆ Fully documented templates are available in the elsarticle package on CTAN.

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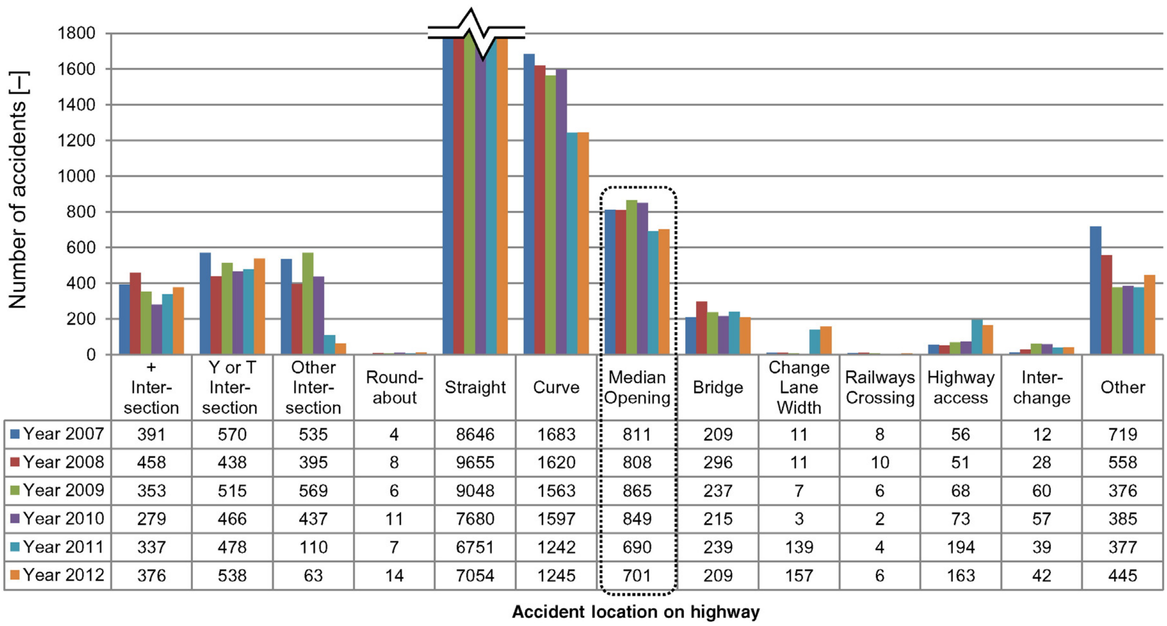

	+ Inter-section	Y or T Inter-section	Other Inter-section	Round-about	Straight	Curve	Median Opening	Bridge	Change Lane Width	Railways Crossing	Highway access	Inter-change	Other
Year 2007	391	570	535	4	8646	1683	811	209	11	8	56	12	719
Year 2008	458	438	395	8	9655	1620	808	296	11	10	51	28	558
Year 2009	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

Fig. 1. Crash frequency by location on Thai highways [2].

1.4. Interaction between U-turning and through-traffic streams

In theory, through-traffic should get priority over U-turn traffic all the time. However, midblock U-turn junctions interrupt the through-traffic movement. There are therefore interactions between through-traffic streams and U-turning traffic streams. After arriving at a mid-block median opening, the U-turning vehicle waits for a gap in the on-coming through-traffic stream large enough to complete the U-turn manoeuvre. As traffic volume increases on the through-traffic streams, the U-turning traffic has trouble finding a sufficient gap to enter the other side of the carriageway, and thus a queue is formed at the deceleration lane, which affects the through-traffic movement in the same direction and, as a result, drivers experience longer delays. The U-turning vehicles also affect through-traffic movement in the opposite direction when they merge. The U-turning vehicles often do not wait for an acceptable gap in the on-coming through-traffic. They gradually move onto the conflicting lane to show their intention to go. Through-traffic vehicles sometimes do not allow for a U-turn by increasing speed, changing lanes, honking the vehicle's horn, or flashing their headlights (visual equivalent of blowing the horn). Eventually, the through-traffic stops and allows the U-turn traffic to move. According to field observations at U-turn junctions, when the U-turn traffic is in a long queue or has waited for a long time, the drivers of U-turning vehicles tend to be more aggressive in making U-turns. At the same time, the conflicting through-traffic tends to be willing to stop and allow the U-turn traffic to go.

1.5. Design consistency of U-turns, road safety, and driver behaviour

Numerous layout design practises of U-turns are followed in Thailand. Some are standard (as per the design guidelines of the Department of Highways) and the remaining are non-standard (based on local design practise). The U-turn layout design varies with the application and dimensions of its components, such as auxiliary lanes (acceleration, deceleration, and loons). The length of these auxiliary lanes is not uniform at most U-turns. The shorter length of some of these auxiliary lanes does not provide enough space to make a comfortable lane change; this may result in safety problems in terms of weaving traffic and queue formation. The numerous types of U-turn layouts produce inconsistent design characteristics of the road infrastructure. For study purposes, U-turns were classified according to their layout components (acceleration lane and outer widening).

In practical terms, inner through-lanes of divided highways are used for passing; they are also dedicated to vehicles moving at high speeds. At U-turns, acceleration (merging) lanes and deceleration (diverging) lanes are provided along the inner lanes of divided highways. So,

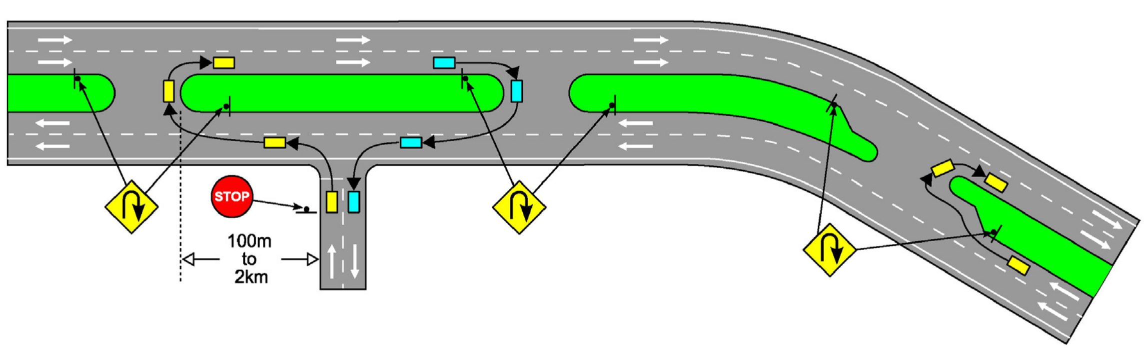

Fig. 2. Basic functions of median at-grade U-turns.

merging and diverging movements are also performed at the inner lanes, which make U-turns susceptible to traffic crashes. Moreover, frequent lane changes on highways at merging, diverging, and weaving traffic areas could disrupt traffic flow and, even worse, lead to crashes. Frequent lane changes could also have significant bottleneck effects on overall traffic flow. Practitioners believe that crash frequency increases rapidly when the density of at-grade U-turns (the number of U-turns per unit length) increases. This means that drivers cannot drive safely at high speed most of the time on mid-block sections of highways because changes in the road environment require constant adjustments in speed and influence driver expectancy. The need to adapt one's speed to suit the environment can increase the opportunity for human error and lead to a higher risk of crashes and injury. The posted permitted maximum speed limit at Thai U-turns is the same as the mid-block speed limit (80 km per hour). Such a high speed increases the severity of a collision. The conjunction of high speed and varying geometric conditions is a major factor in crashes with high mortality rates.

Heavy commercial vehicles travel in outer lanes most of the time. Therefore, these vehicles have difficulty using the inner acceleration lane(s) because they require a larger turning radius, so these vehicles either merge into the outer through-lanes or use loons or outer paved areas (see Fig. 3). The main reason for placing a loon or an outer widening is to provide additional space to facilitate heavy commercial vehicles with a larger turning path along narrow medians to comfortably negotiate U-turns.

1.6. Aims and objectives of the study

The goal of this study was to comparatively analyse road safety downstream of U-turns on rural four-lane divided highways in Thailand on the basis of their layout designs. The study focused on the application and use of the Traffic Conflict Technique (TCT) instead of crash data assessment because the available crash data is unreliable. Short-term field studies were conducted at several U-turn locations to collect traffic volume, speed, conflict, and geometric data. Two diverse traffic conflict approaches were used to reduce bias. First was subjective assessment of the seriousness of the conflict situation and the second was based on the relative speed and angle between conflicting streams. Both approaches produced almost identical results.

2. Literature review

2.1. Road safety measures and traffic events

Road safety refers to the methods and measures adopted for reducing the risk of a driver or passenger being injured or killed or a vehicle or material being damaged. Various tools and methods have been developed for road safety assessment such as road safety audits, road safety inspections, crash modelling, conflict studies, monitoring driver behaviour, crash investigations, and crash cost analysis

An 'event' in a traffic system refers to a crash, near-crash, or incident. The 'event' begins at the onset of the precipitating factor and ends after the evasive manoeuvre. Event severity is a classification of the level of harm or damage resulting from an event, and there are five levels: crash, near-crash, crash-relevant, proximity, and non-conflict events. For an event-based road safety assessment, crash and near-crash events are mostly considered. The operational definitions of a crash and near-crash are presented in Table 1.

2.2. Crash-based safety analysis and its limitations

Road safety is commonly measured in terms of the number of traffic crashes and the consequences of these crashes in regard to their outcome in terms of severity. Traditionally, the level of safety of a specific location is measured by the number and frequency of consequences (fatality, injury, and property damage only) of crashes and traffic exposure. The most common challenge 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 random and sparse nature of traffic crashes. Because collisions are rare events, even at collision-prone locations, extended observation periods are required to determine stable trends. Moreover, not all crashes are reported, and the reporting level can vary from region to region. The quality and reliability of crash data are important factors for obtaining accurate analysis results [5].

2.2.1. Traffic crash data Management in Thailand

In Thailand, the under-reporting of crash data is widely acknowledged [6]. The principal agencies/organizations responsible for investigating crashes such as the Royal Thai Police, the Department of Highways, and the Ministry of Public Health collect crash data for the purposes of their different interests. However, there is no integration of databases in order to share data among the various agencies concerned. Srirat's [6] findings showed 59.3% under-reporting of crash data from the Department of Highways' data as compared to the police crash data in Nakhon Ratchasima province. Kowtanapanich [7] mentioned that standardization, consistency, and integrity are very poor as Royal Thai Police crash data is always kept in the form of narrative reports; moreover, accessibility to this data by other users is limited, which leads to getting incomplete or wrong information.

2.3. Near-crash events as an alternative approach

Because there are shortcomings (limitations in terms of the availability and reliability of crash and traffic data) in collision-based safety measures, road safety analysis can benefit greatly from methods that use observable and non-collision near-crash traffic interactions. In order to perform an alternative and comprehensive form of safety analysis and to assess and predict the levels of road safety at specific types of traffic facilities, the TCT is faster, more informative, and a more resource-effective method that yields valid and reliable safety indicators in the short-term.

Fig. 3. Crossing manoeuvres by heavy commercial vehicles.

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Table 1
Operational definitions of event severity levels [4].

Severity level	Operational definition
Crash	Any contact with an object, either moving or fixed, at any speed where kinetic energy is measurably transferred or dissipated. It includes contact with other vehicles, roadside barriers, objects on or off the roadway, pedestrians, cyclists, or animals.
Near-crash	Any circumstance that requires a rapid, evasive manoeuvre by the participant vehicle or any other vehicle, pedestrian, cyclist, or animal to avoid a crash. A rapid, evasive manoeuvre is defined as steering, braking, accelerating, or any combination of control inputs that approach the limits of the vehicle's capabilities.

2.3.1. Traffic Conflict Technique

The TCT is a method of observing and studying traffic conflicts or near-miss events that occur more frequently, can be clearly observed, and are related to the probability of collisions. The main advantage of such a method is it resource-effectiveness given that traffic conflicts occur more frequently than crashes and thus they require relatively short periods of observation in order to establish statistically reliable results. A formalized definition of a traffic conflict is 'an observable situation in which two or more drivers approach each other in space and time to such an extent that there is a risk of collision if their movements remain unchanged' [8].

Conflict safety indicators are particularly useful in assessing and comparing safety-enhancement measures at specific traffic facilities and, in some cases, the interactions between specific categories of drivers. The methodologies used to collect conflict data take into account site-specific elements related to the roadway design. They also take into account the dynamic and complex relationships among different traffic variables, such as traffic flow, speed, and proportion of turning movements [9].

2.3.2. Validity and reliability of TCT

The reliability and validity of TCT are two issues strongly associated with the usability of TCT. These issues concern the lack of a consistent definition of TCT, its validity as a measure of traffic safety, and the reliability of its associated measurement techniques. A number of studies have tried to address these issues [10–13]. Some empirical studies found clear relationships between traffic conflicts and crashes [14]. Despite the concerns about these issues, traffic conflict techniques have been used in various studies to evaluate road safety [15–18].

Using TCT, field observers are a source of error while they are collecting conflict data due to the subjective nature as to 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 variations in the grading of traffic conflicts by different people. As a result, human-collected data is not necessarily accurate, especially if multiple untrained observers are used. Nonetheless, traffic conflicts have been shown to have some correlation with crash frequency, and the consensus is that higher rates of conflicts correlate to lower levels of road safety [19].

2.3.3. Traffic conflict indicators and conflict severity measurement

Conflict indicators are defined as measures of crash proximity based on the temporal and/or spatial measures that reflect the 'closeness' of drivers (or their vehicles) in relation to the projected point of collision. The objective evidence of a traffic conflict by the NCHRP definition is the evasive action taken, which is indicated by the observance of brake lights or a lane change affected by the offended driver. The original definition of a conflict was mainly based on brake-light indications. A variety of observation methods have been developed to measure the severity of traffic conflicts, including the observation of driver behaviour and recording the number of near-misses or avoidance manoeuvres. These observation methods can be classified into subjective and objective methods. Subjective methods include judgement by the conflict observers and an assessment of conflict severity, taking into account the level of deceleration (weighted deceleration, which includes longitudinal braking and lateral-swerving deceleration). To eliminate subjectivity from the traffic conflict analysis, objective measures are used. The objective measures for traffic conflicts, which have higher validity, include a cardinal or ordinal time-proximity dimension in the severity scale.

Three indicators are widely used to assess the severity of a conflict situation: Time to Accident/Speed, Time To Collision, and Post-Encroachment Time.

2.3.3.1. Time to Accident/Speed (TA/Speed). The TA/Speed conflict indicator is determined at a point in time and space when evasive action is first taken by one of the conflicting drivers [20]. The TA/Speed value is based on the necessity of a collision course and the need to take evasive action. The Time to Accident value (TA value) is the time that remains to an accident from the moment that one of the drivers starts evasive action if they had continued with unchanged speeds and directions. The Conflicting Speed (CS) is the speed of the driver taking evasive action for whom the TA value is estimated, just before the start of the evasive action. An event with a low TA and a high speed value indicates an event with high severity.

2.3.3.2. Time to collision (TTC). 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 drivers to collide if no evasive action is taken. The TTC_{min} is the lowest value of TTC for two drivers on a collision course. A lower value of TTC or TTC_{min} indicates an event with high severity [21].

2.3.3.3. Post-encroachment time (PET). PET is the time between two vehicles on a near-collision course passing at a common point [22,23]. To measure PET, a collision course or an evasive action from the driver(s) is not necessary. As with TTC, a lower PET value indicates higher severity; the minimum value is also the critical value.

2.3.4. Grading of severity of conflicts

A conflict severity scale based on braking rates was proposed by Zimolong [24], in which four different conflict severity levels were specified: the first of these suggests a controlled use of brakes or a controlled lane change to avoid collision; the second involves a severe use of brakes and/or an abrupt lane change; the third level involves emergency braking and fast driver reaction; and the fourth level involves a collision.

2.3.5. Severity grading using 'weighted coefficient'

Krivda [15] reported the use of a relative conflict rate and a weighted conflict rate for single-lane roundabouts. A relative conflict rate is defined as the hourly number of conflict situations per 100 vehicles. The relative conflict rate does not take into consideration the seriousness of conflict situations. Thus, using the so-called Weighted Coefficient of the Relative Conflict Rate (C_{RW}) is a rational and justified approach. The equation for all types of conflict situations has the following form:

$$C_{RW} = \frac{\sum_{i=1}^{n} N_{CSi} \times C_{Sj}}{V} \times 100 = \frac{(N_{CS1} \times C_{S1}) + (N_{CS2} \times C_{S2}) + (N_{CS3} \times C_{S3})}{V} \times 100 \quad (1)$$

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 ($i = 1,2,3,\ldots n$)
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].

The seriousness of conflict situations are 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.

2.3.6. Severity grading using 'Level of Conflict' (LC)

Dixon [17] used the potential angle of impact and the relative speed of conflicting vehicles in order to grade the severity of conflicts, and he represented the severity in terms of individual LC values. The orientation and type of conflict are defined as follows:

Orientation: determines the relative orientation of the paths of vehicles 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.
Type of conflict: establishes descriptions for the various conflicts (i.e., crossing, merging, diverging).

The LC is a function of the relative speed between conflicting vehicles, their angle of impact, and the conflict type.

2.3.6.1. Speed adjustment factor. The kinetic or impact energy of a crash is a factor of the speed of a driver or the difference in speed between two or more drivers, and it can be determined from the following well-known relationship:

$$\text{Kinetic Energy(KE)} = \frac{1}{2} \times m \times S^2 \quad (2)$$

where

m mass of vehicle
S speed [mph]

Dixon considered a 'base' crash to be a head-on collision at a speed of 55 mph (88 km/h) or greater (referred to as HO-55 in subsequent discussions). All other LC will ultimately be adjusted to be equivalent to HO-55 crashes. For the HO-55 crash condition, the Eq. (2) can be modified as follows:

$$\text{KE}_{\text{HO}-55} = \frac{1}{2} \times m \times 55^2 = 1512.5 \times m \quad (3)$$

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

$$f_{spd} = \frac{\text{KE}_S}{\text{KE}_{\text{HO}-55}} = \frac{\frac{m}{2} \times S^2}{1512.5 \times m} = \frac{S^2}{3025} \quad (4)$$

2.3.6.2. Conflict Orientation Factor (COF). In a manner similar to the procedures used for assigning costs to crashes by using the value of a human life (ex. Human Capital Approach), a severity factor based on the crash type and vehicle orientation can be used to represent associated crash risk due to the conflict configuration. This COF defines bicycle- and pedestrian-involved crashes as extremely severe, COF = 1.0, followed by head-on crashes, COF = 0.8, right-angle crashes, COF = 0.6, sideswipe crashes, COF = 0.4, and rear-end crashes, COF = 0.3. The larger COF value of 1.0 for bicycle and pedestrian crashes is because these crashes are considered injury-related without regard to the angle of impact.

2.3.6.3. Assessing the LC. The value of LC is based on a combination of the speed adjustment factor and the Conflict Orientation Factor and is given as follows:

$$\text{LC} = f_{spd} \times c \quad (5)$$

2.3.7. Traffic exposure

Salman and Al-Maita [25] researched 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.

Yi and Thompson [26] used the relationship between traffic conflicts and conflicting volumes at intersections to state that 'the total number of traffic conflicts is proportional to the square root of the product of the conflicting volumes'. This is referred to by Sayed and Zein [16] as the 'Product of Entering Vehicles' (PEV).

$$\text{PEV} = \sqrt{(V_1) \times (V_2)} \quad (6)$$

where

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

3. Methodology

3.1. Classification of U-turns on Thai highways

U-turns were classified on the basis of several combinations of their layout components, viz. deceleration lane, acceleration lane, and outer widening. Based on these combinations, for this study, four types of U-turn layout designs were identified and are shown in Fig. 4 and Table 2.

3.2. Downstream zones at U-turns

The downstream zone of a U-turn consists of through-lanes, either an acceleration lane, an outer widening, or a combination of both (see Fig. 4). This zone is used by U-turning vehicles for accelerating to an adequate speed before merging into through-traffic streams. A typical layout of downstream zones at a U-turn is illustrated in Fig. 5.

3.3. Types of traffic conflicts at downstream zones of U-turns

Traffic conflict points are areas formed by conflicting movements in the traffic flow. The placement of conflict points at U-turns is shown in Fig. 6. The separation between conflict points increases with increasing length of the auxiliary lanes (deceleration, acceleration, and outer widening). A greater separation between conflict points simplifies the weaving and turning manoeuvres. This, in turn, generally leads to lower frequencies of conflicts and crashes, lower vehicle delay, and a higher level of road safety. Traffic conflicts at downstream zones are classified into two basic types in which the degree of severity varies, as described in the following sections.

3.3.1. Merging conflicts

Merging conflicts are caused by the joining of two traffic streams when the U-turning vehicles enter the through-lanes from an acceleration lane and begin to accelerate at the downstream zones. If the length of an acceleration lane is too short, the merging vehicles do not have enough space to accelerate to the operating speed of through-traffic,

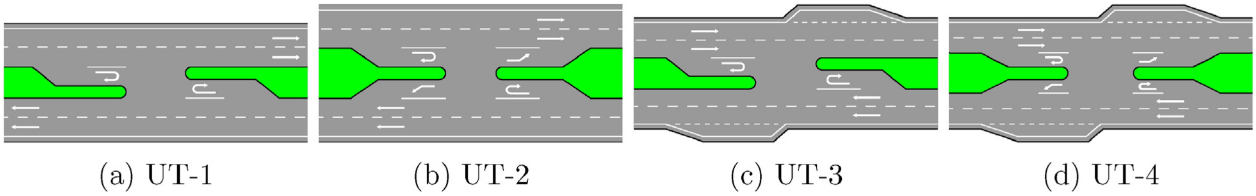

Fig. 4. Layout designs of U-turns on Thai highways.

increasing the potential for collisions. The most common types of crashes due to merge conflicts are side swipes and rear-end crashes.

3.3.2. Crossing conflicts

Crossing conflicts are caused by the intersection of two crossing traffic streams. At U-turns, these conflicts occur when a U-turning vehicle makes a manoeuvre from a median opening to an outer lane, a loon, or an outer shoulder. These manoeuvres are mostly performed by motorcyclists and heavy commercial vehicles. These conflicts are more severe than merging conflicts and are most likely to involve injuries or fatalities. Typical crash types as a result of crossing conflicts are right-angle crashes and head-on crashes.

3.4. Selection of conflict severity indicators

U-turns have a distinct geometry, a longer conflict area in a longitudinal direction, and a higher operating speed. They make it difficult to judge the speed and spacing between conflicting vehicles and to measure the severity of a conflict. This study focused on U-turns in non-built-up areas where elevated locations were unavailable to install a camera so as to obtain an aerial view. Therefore, the use of the indicators TA, CS, and TTC were not practically viable for this study. At U-turns, the majority of conflicting events take place due to merging and diverging manoeuvres, and PET is only suitable for measuring crossing-conflict events. Therefore, the indicator PET was not used in this study.

Two distinct approaches were used to assess Conflict Indexes due to the abovementioned constraints, as described in the following sections.

3.5. Severity of a conflict using severity indicator

The complexity of the evasive actions of drivers was considered as an indicator of conflict, and a subjective approach was considered to measure the severity. For a comparative safety assessment, it is a justified approach to give weights (relative importance) to conflict events having a higher level of seriousness. The purpose of using weights was to put more emphasis on severe conflicts than on slight ones. To give weights to the conflict events, the values of Coefficient of Conflict Severity (CCS) were adopted from Krivda [15], which were used to calculate Severity Conflict Indexes (SCI). As mentioned in Section 2.3.5, three levels of severity (seriousness) of traffic conflicts were adopted, as presented in Table 3, which were used to calculate the SCIs.

3.6. Severity of a conflict using LC

To give the relative importance of specific types of conflicts, a weighting coefficient as a LC was assessed. The LC takes into account the type of conflict and the relative speed of the conflicting vehicles. The potential angle of impact of the conflicting vehicles represents the nature of the crash that would occur due to a conflicting situation, and the type of conflict is classified on the basis of the potential angle of impact between the conflicting vehicles in various traffic streams, which are merging and crossing conflicts.

3.6.1. Relative speed and speed adjustment factor

The relative speed of the conflicting vehicles is defined as the speed difference between the 'speed of a vehicle in a through–traffic stream' and the 'speed vector of a vehicle turning in the direction of the through–traffic stream'. The speed of the vehicles in turning streams and the angle between the paths of vehicles in the turning stream and the through stream were adopted from Yi [26], as shown in Table 4. These values also resemble the observed values during the field investigation. The speed vector is calculated as

$$\text{Speed vector} = S \times \cos(\theta) \tag{7}$$

where

S speed of vehicle in turning stream
θ angle between vehicles in turning stream and through stream

The kinetic or impact energy of a crash is given as in Eq. (2).

At Thai U-turns, the maximum legal speed limit is 80 km/h. Therefore, for a head-on (HO-80) crash condition, this equation can be modified as follows:

$$\mathrm{KE}_{\mathrm{HO-80}} = \frac{1}{2} \times m \times 80^2 = 3200 \times m \tag{8}$$

As mentioned in Section 2.3.6, a speed adjustment factor (f_{spd}) can be developed by contrasting the kinetic energy for HO-80 to alternative relative speeds:

$$f_{spd} = \frac{\mathrm{KE}_{\Delta S}}{\mathrm{KE}_{\mathrm{HO-80}}} = \frac{\frac{m}{2} \times (\Delta S)^2}{3200 \times m} = \frac{(\Delta S)^2}{6400} \tag{9}$$

where

ΔS relative speed of conflicting vehicles (km/h)

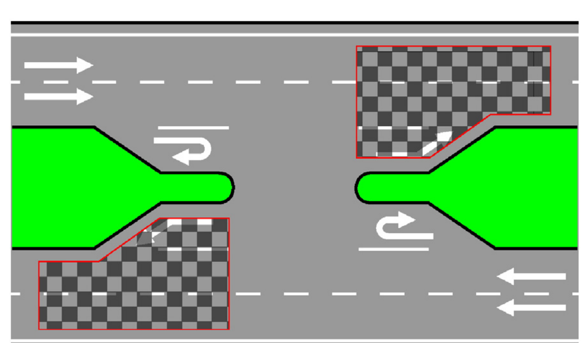

Fig. 5. Downstream zones at a U-turn.

Table 2
Classification of U-turn types on Thai highways.

U-turn type	Application of deceleration lane	Application of acceleration lane	Application of outer widening
UT-1	Yes	No	No
UT-2	Yes	Yes	No
UT-3	Yes	No	Yes
UT-4	Yes	Yes	Yes

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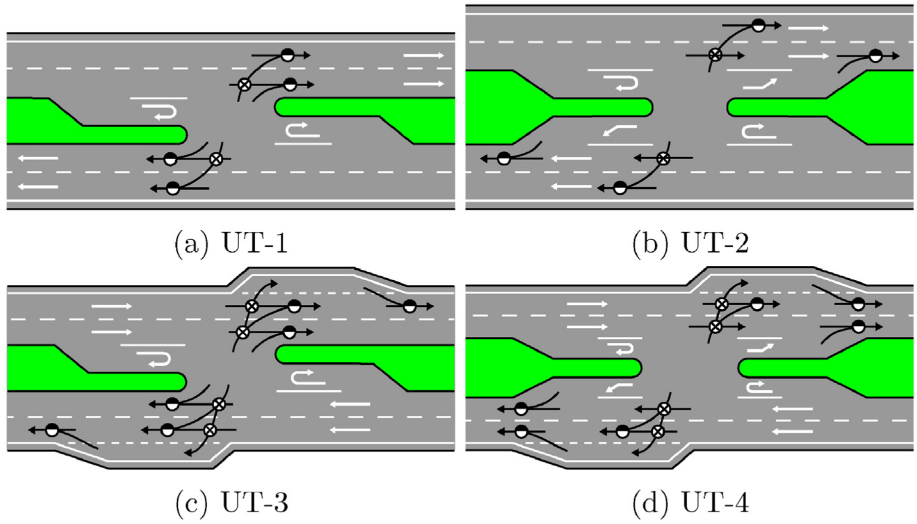

Fig. 6. Conflict points downstream of U-turns. Legends: ◓ — Merging conflict ⊗ — Crossing conflict.

3.6.2. Application of the COF

A description of the COF was given in Section 2.3.6. Here, we apply the factor to the specifics of the current study. In a manner similar to the procedures used for assigning costs of crashes using the value of a human life (ex. Human Capital Approach), a severity factor based on the conflict type and the vehicle orientation can be used to represent the associated risk of severe consequences of crash due to the conflict configuration [17]. For road safety assessment at downstream zones of U-turns, the COFs were assessed for the merging and crossing conflicts to calculate the Relative Conflict Index (RCI).

For a merging conflict, the value of the COF is moderate as these conflicts are typically the most moderate of all conflicts. The collision types that may occur are side-swipe and rear-end collisions. The relative speed of the conflicting vehicles for this type of conflict is lower than that for crossing conflicts.

For a crossing conflict, the value of the COF is higher as this type of conflict is typically the most severe of all conflicts because it involves a possible right-angle collision type, which most frequently involves injuries or fatalities. The relative speed of the conflicting vehicles for this type of conflict is also higher than that of other types of conflicts. Table 5 shows the COFs for various conflict types.

3.6.3. Conflict severity as LC

Value of LC represents the severity of a conflict situation. LC is calculated using the Eq. (5).

Table 3
Conflict severity indicators and severity coefficients.

Severity	Indicators	CCS
Slight	Sudden lane change or light braking	1
Moderate	Intense deceleration and vehicle almost stops	3
Severe	Hard braking or skid marks or braking sound	6

Table 4
Speed vector of vehicles in turning stream.

Turning stream	Angle (θ)	Operating speed [km/h]	Speed vector [km/h]
Merging	15°	35.0	33.81
Crossing	90°	12.5	0

3.7. Product of conflicting volumes for downstream zones

The product of conflicting [through and turning (merging)] volumes (PCV_{dn}) was computed for the downstream zones of U-turns as a traffic exposure to the observed conflicts for calculating the conflict rates. PCV_{dn} is defined as 'the square root of the product of (average hourly) traffic volumes of the conflicting streams (through and turning)'.

3.8. Conflict number

3.8.1. Hourly traffic conflict number (HCN)

The HCN is defined as the number of observed conflicts at a zone divided by the number of observation hours for that zone. Several HCNs were computed based on classification of the severity of conflict situations as slight, moderate, or severe and the type of conflict (merging and crossing).

3.8.2. Average hourly traffic conflict number (AHN)

Each U-turn has two downstream zones and two locations were investigated for each U-turn type. Therefore, for the downstream zones of a group of particular U-turn types, the AHN is defined as the summation of HCNs at the downstream zones divided by the number of downstream zones in that group. Furthermore, AHNs were classified on the basis of the severity of the conflict situation as slight, moderate, or severe and the type of conflict (merging and crossing).

3.9. Severity Conflict Index at downstream zones (SCI_{dn})

The values of CCS from Table 3 and Section 2.3.5 were used as coefficients for assigning relative weightiness (importance) to the conflict events and for assessing the SCI_{dn}.

SCI_{dn} is defined as the ratio of the summation of the product of the AHNs (slight, moderate, or severe) and their respective CCS values to the PCV_{dn} values. A higher value of SCI_{dn} at a traffic facility represents a comparative lower level of road safety. The SCI value for the

Table 5
COF for various types of conflicts.

Conflict type	COF [−]
Merging	0.4
Crossing	0.6

downstream zone of U-turns was computed using the following equation:

$$\mathrm{SCI_{dn}} = \frac{(CSS_{sl} \times AHN_{dn-sl}) + (CSS_{mo} \times AHN_{dn-mo}) + (CSS_{se} \times AHN_{dn-se})}{PCV_{dn}} \quad (10)$$

where

CSS_{sl} coefficient of seriousness of slight conflict = 1
CSS_{mo} coefficient of seriousness of moderate conflict = 3
CSS_{se} coefficient of seriousness of severe conflict = 6
AHN_{dn-sl} average hourly slight traffic conflict number
AHN_{dn-mo} average hourly moderate traffic conflict number
AHN_{dn-se} average hourly severe traffic conflict number

3.10. Operating speed

The legal maximum speed limit for the identified U-turns was 80 km/h, the same speed limit for the mid-blocks of highways. However, the operating speeds varied due to spatial influencing factors. Spot speed surveys were conducted at the U-turns for the through-traffic of both sides and an 85th percentile speed was considered the operating speed.

3.11. Sample calculation of LC

Table 6 illustrates a sample calculation of LC for traffic flow from the southwest to the northeast at one of the U-turn locations, UT-1.

3.12. Relative Conflict Index for downstream zone (RCI_{dn})

The RCI is defined as the ratio of the summation of the product of the AHNs (merging and crossing) and their respective value of LC to the PCV_{dn}. A higher value of the RCI at a traffic facility represents a comparatively lower level of road safety. The RCI_{dn} values were computed using the following equation:

$$\mathrm{RCI_{dn}} = \frac{(AHN_{dn-me} \times LC_{dn-me}) + (AHN_{dn-cr} \times LC_{dn-cr})}{PCV_{dn}} \quad (11)$$

where

LC_{dn-me} value of Level of Conflict for merging conflicts
LC_{dn-cr} value of Level of Conflict for crossing conflicts
AHN_{dn-me} average hourly merging traffic conflict number
AHN_{dn-cr} average hourly crossing traffic conflict number

3.13. Comparison of SCI_{dn} and RCI_{dn}

Table 7 shows a comparison of the Conflict Indexes.

Table 6
A sample calculation of LC.

U-turn type: UT-1; Site location ID: A; Direction: SW to NE		
	Merging	Crossing
Operating speed (S_o) [km/h]	84	84
Speed of vehicles in turning stream (S) [km/h]	35	12
Angle of impact (θ)	15°	90°
Speed vector ($S_v = S \times \cos\theta$) [km/h]	34	0
Relative speed ($\Delta S = S_o - S_v$) [km/h]	50	84
Speed adjustment factor ($f_{spd} = (\Delta S)^2/6400$) [−]	0.394	1.103
Conflict Orientation Factor (c) [−]	0.4	0.6
Level of Conflict ($LC = f_{spd} \times c$) [−]	0.157	0.662

Table 7
Comparison of Conflict Indexes.

Measure	SCI_{dn}	RCI_{dn}
Conflict indicators	Severity of conflict situation on the basis of complexity of evasive action such as lane change, deceleration, skid marks, and sound of braking.	Type of conflict event as diverging, merging, and crossing.
Relative speed	Not taken into account.	Used to measure the impact of kinetic energy in terms of the Level of Conflict.
Angle of conflicting streams	Not taken into account.	Used to represent the associated crash risk due to conflict configuration and measures in terms of the Conflict Orientation Factor.
Exposure	Measures in terms of product of through and turning volumes.	Measures in terms of product of through and turning volumes.
Bias	Subjective to human judgement.	Sensitive towards producing higher values for crossing conflicts.

4. Data type and data collection

The data gathered relied on the form of the U-turn being studied and included traffic volumes, U-turning movement counts, auxiliary lane movement counts, traffic compositions (traffic mix), geometric data, and traffic conflicts. For the classified four groups of U-turns, two locations for each group were selected and investigated throughout Thailand. The physical locations of the selected U-turns are presented in Table 8.

The following basic requirements were applied to the selection of sites for the investigation:

- Located on four-lane divided highways
- Located outside built-up areas
- Physically divided highways having median widths between 0.5 and 15 m
- Not located at a horizontal curve
- Not located at a crest or sag curve
- Not part of a T- or X-junction
- Not a grade-separated design
- No on-street parking
- No pedestrian or bicycle traffic
- No special design solution
- Permitted legal speed limit is 80 km/h

4.1. Recognition of traffic conflicts

Traffic conflicts, unlike accidents, do not have consequences after they occur. Traffic does not stop and the vehicles continue to flow after a conflict has occurred. The driver has to decide on an evasive manoeuvre in an instant of time and the observer has to recognize the conflict when it occurs.

Table 8
Physical locations of selected U-turns.

U-turn group	Site	Location	Latitude	Longitude
UT-1	A	Hat Yai, Songkhla	7.023115°	100.439300°
	B	Hat Yai, Songkhla	7.039420°	100.460800°
UT-2	A	Chang Wat Chai Nat	15.175760°	100.142200°
	B	Phra Nakhon Si Ayutthaya	14.155340°	100.291100°
UT-3	A	Phatthalung	7.741714°	99.979680°
	B	Phatthalung	7.650726°	100.033800°
UT-4	A	Hat Yai, Songkhla	7.054027°	100.479400°
	B	Hat Yai, Songkhla	7.066093°	100.489600°

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Indicators of conflicts are applying brakes, swerving, and noticeable deceleration of vehicles. Brake application is frequently used to recognize conflicts. Observers should not only be aware of the vehicles' brake lights but also the speed of the vehicles and the conditions in order to judge a conflict occurrence. Swerving is a complicated indicator of a traffic conflict. Drivers may change the direction of vehicle or the lane in which they choose to travel instead of applying brakes to avoid a collision. Swerving does not occur as frequently as brake application because drivers might put themselves into another conflict situation by swerving. Brake application is usually safer than swerving because the driver does not have time to check the side lanes in case of a conflict. The conflicts were observed and recorded in accordance to the indicators mentioned in Table 3 and the type of conflict (merging or crossing).

The traffic conflicts were recorded by video cameras in the field on working days during daylight hours (2 h in the morning/evening and 2 h in the afternoon) while avoiding adverse weather conditions. A total of 16 h of video of traffic operations data were recorded at each U-turn group. The recorded data was later reviewed in the laboratory to obtain traffic operations data.

5. Results

5.1. Traffic volumes

At downstream locations of U-turns, there are two types of traffic streams, viz. through and merging. The observed Average Hourly Through volumes (AHThV), Average Hourly Merging Volumes (AHMeV), and Average Hourly Merging Volumes of Heavy Commercial Vehicles (AMeCv) are presented in Table 9. UT-1 had the highest value of AHThV, followed by UT-4. UT-1 also had the highest value of AHMeV, followed by UT-3. UT-4 had the lowest AHMeV.

where

PCV_{dn} product of conflicting volumes $= \sqrt{AHThV \times AHMeV}$
PMeV percentage of the hourly merging volumes $= \frac{AHMeV}{AHThV+AHMeV} \times 100$
PCv percentage of heavy commercial vehicles $= \frac{AMeCv}{AHMeV} \times 100$

The volume of merging vehicles is a major variable influencing the conflict frequency. PMeV is defined as the ratio of the AHMeV to the summation of the AHThV and the AHMeV. PMeV was highest for UT-3 and lowest for UT-4 (see Table 9). Similarly, the volume of heavy commercial vehicles in a merging traffic stream also influences the number of conflicts. PCv was highest for UT-4 and lowest for UT-3.

5.2. Severity conflict indexes

The assessed SCI_{dn} and the application of auxiliary lanes at downstream zones of U-turns are illustrated in Table 10 and Fig. 7. The value of SCI_{dn} was lowest for UT-3 and highest for UT-1, followed by UT-4. The values of SCI_{dn} for UT-2 and UT-3 were below the average.

where

AAL application of acceleration lane
AOW application of outer widening

Table 9
Various traffic volumes at downstream zones of U-turn locations.

U-turn type	AHThV [veh/h]	AHMeV [veh/h]	AMeCv [veh/h]	PCV_{dn} [veh/h]	PMeV [%]	PCv [%]
UT-1	1321	174	7	479	11.7	4.0
UT-2	875	139	8	349	13.7	5.8
UT-3	702	164	4	339	18.9	2.4
UT-4	1197	116	12	373	8.8	10.3

Table 10
Severity Conflict Indexes and application of auxiliary lanes at downstream zones.

U-turn type	AHN_{dn-sl} [−]	AHN_{dn-mo} [−]	AHN_{dn-se} [−]	SCI_{dn} (×100) [conflicts/veh]	AAL	AOW
UT-1	50.6	1.8	0.0	11.66	No	No
UT-2	23.5	0.9	0.0	7.56	Yes	No
UT-3	21.2	0.2	0.0	6.40	No	Yes
UT-4	30.6	1.7	0.0	9.58	Yes	Yes

5.3. Relative conflict indexes

The assessed RCI_{dn} and the application of auxiliary lanes at downstream zones of U-turns are illustrated in Table 11 and Fig. 8. The value of RCI_{dn} was lowest for UT-2 and the highest for UT-4, followed by UT-1. The values of RCI_{dn} for UT-2 and UT-3 were below the average.

6. Discussion and conclusions

A comparatively higher Conflict Index value represents a lower level of safety at a U-turn location.

6.1. SCI_{dn} at downstream zones

Because no auxiliary lanes are applied at downstream zones of UT-1, this type yielded the highest value of SCI_{dn}. The layout design of this U-turn produced the lowest level of road safety, as expected.

The UT-2 type has only one auxiliary lane (acceleration lane) at the downstream zone. Although this location had a higher percentage of merging traffic volume (PMeV) than UT-1 and UT-4 (see Table 9), it yielded a somewhat lower average value of SCI_{dn}, and thus a medium level of road safety is expected. The literature survey revealed that merging into an inner lane from an acceleration lane is a difficult traffic manoeuvre due to the blindspots (areas of the road that cannot be seen while looking forward or through either the rear-view or side mirrors of the vehicle).

The UT-3 type has only one auxiliary lane (outer widening). Although it had the highest percentage of merging traffic volume (19%), it yielded the lowest value of SCI_{dn} and the highest level of road safety. Therefore, based on the results of the value of SCI_{dn} of this study, it can be concluded that UT-3 is the safest U-turn type among the four types identified.

The UT-4 type yielded above average and comparatively higher values of SCI_{dn} than U-turn types UT-2 and UT-3, although the percentage of merging volume was the lowest for this U-turn type (see Table 9). The possible reason for this result could be the application of an acceleration lane and outer widening at the downstream zone, which could provide a larger area for conflict interactions in the through and

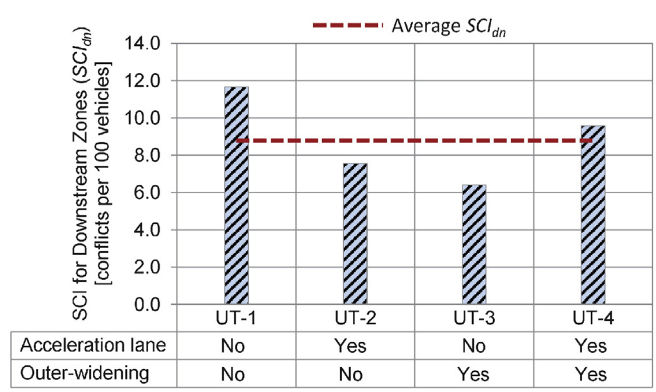

Fig. 7. The relationship between SCI_{dn} and auxiliary lanes.

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Table 11
Relative Conflict Indexes and application of auxiliary lanes at downstream zones.

U-turn type	RCI_{dn} (×100) [conflicts/veh]	AAL	AOW
UT-1	2.64	No	No
UT-2	1.84	Yes	No
UT-3	2.39	No	Yes
UT-4	3.00	Yes	Yes

merging streams, creating additional opportunities for undesirable driving behaviour. This type could also make it difficult for drivers of the conflicting vehicles to judge the manoeuvres of the other drivers.

6.2. RCI_{dn} at downstream zones

Because no auxiliary lanes are applied at the downstream zone of UT-1, this type yielded an above average value of RCI_{dn}, and thus a lower level of road safety is expected at this U-turn type.

The UT-2 type has only one auxiliary lane (acceleration lane) at a downstream zone. Although it had a higher percentage of merging traffic volume than UT-1 and UT-4 (see Table 9), it yielded the lowest value of RCI_{dn}, and thus the highest level of road safety is expected. RCI_{dn} is susceptible towards crossing conflicts because of a much higher value of LC for this type than other conflict types. Few crossing manoeuvres were observed at UT-2 because of its layout configuration. The other safety concern is (as the literature survey revealed) that merging into an inner lane from an acceleration lane is a difficult traffic manoeuvre due to the blind-spots.

The UT-3 type has only outer widening, and it yielded a comparatively medium value of RCI_{dn}. A moderate level of road safety is expected, even though it had a highest percentage of merging traffic volume. Outer widening influences the behaviour of U-turning drivers because most users tend to complete the U-turn manoeuvre by crossing the through-lanes before merging into through-traffic streams.

The UT-4 type yielded the highest value of RCI_{dn}, although the merging traffic volume was lowest for this U-turn type (see Table 9). The possible reason for this result could be the larger size of this U-turn type and its effect, as described in Section 6.1.

6.3. SCI_{dn} versus RCI_{dn}

As shown in Fig. 4, there are 2, 3, 3, and 4 parallel lanes at downstream locations of UT-1 (2 through-lanes), UT-2 (2 through-lanes and 1 acceleration lane), UT-3 (2 through-lanes and 1 outer widening lane), and UT-4 (2 through-lanes, 1 acceleration lane, and 1 outer widening lane), respectively. Increases in the number of parallel lanes caused more opportunities for crossing conflicts by U-turning vehicles. As mentioned in Section 3.13, RCI_{dn} is sensitive towards crossing conflicts due to the angle of impact. Therefore, the value of RCI_{dn} was higher for UT-3 than for UT-2, in contrast to SCI_{dn}. Similarly, the value of RCI_{dn} was higher for UT-4 than for UT-1.

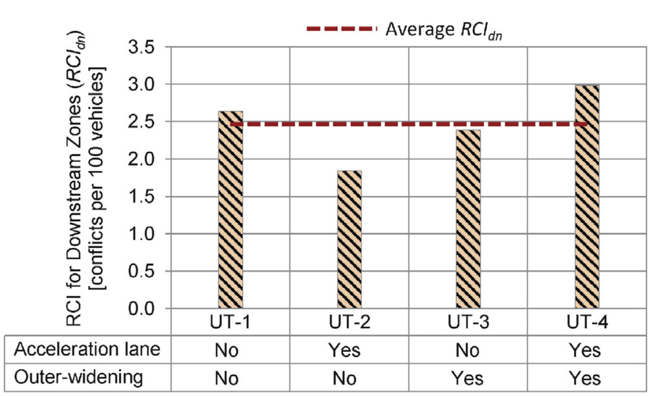

Fig. 8. The relationship between RCI_{dn} and auxiliary lanes.

7. Recommendations

U-turn types UT-1 and UT-4 have the lowest level of road safety; therefore, these should be modified as early as possible and should not be applied to future projects. Selection of the U-turn type among UT-2 and UT-3 should be based upon the local practise of drivers using the auxiliary lanes and the volume of heavy commercial vehicles in U-turning traffic streams because narrow medians may not provide enough space for larger vehicles to negotiate a convenient U-turn manoeuvre.

There are some areas of this research that need to be improved in future studies. The methodology used was based on the subjective approach of the TCT. Several objective methods for measuring the levels of conflict severity, such as Time-to-Collision and Post-Encroachment Time should be considered as important factors for predicting conflict severity and reducing dependency on human judgement. Moreover, due to limitation of financial resource for this study, the sample size was only two locations per each U-turn type, and the data was collected on working days only during daylight hours.

For future assessment of comparative road safety at U-turns, in contrast to subjective TCT, micro-simulation software and programmes are advanced technological tools that could be used to produce results with higher levels of accuracy, reliability, and validity.

In addition, there is a very serious need for the establishment of a well-structured and systematic traffic crash data system in Thailand for improving road safety strategies to ensure timely and quality results. This study used an alternative and subjective human judgement approach, which is frequently criticized by experts and practitioners in terms of its reliability and subjectivity.

Abbreviations

AHN	Average Hourly Traffic Conflict Number
CCS	Coefficient of Conflict Severity
CI	Conflict Index
COF	Conflict Orientation Factor
CS	Conflicting Speed
f_{spd}	Speed Adjustment Factor
HCN	Hourly Traffic Conflict Number
LC	Level of Conflict
NCHRP	National Cooperative Highway Research Program
PCV_{dn}	Product of Conflicting [Through and Turning (Merging)] Volumes
PET	Post-Encroachment Time
RCI	Relative Conflict Index
SCI	Severity Conflict Indexes
TA/Speed	Time to Accident/Speed
TCT	Traffic Conflict Technique
TTC	Time to Collision

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