Chapter 1

Introduction

1.1 Background

Road safety is an emerging concern globally, with approximately 1.19 million road fatalities reported in 2021. Despite having fewer vehicles (only 72% of the world's powered vehicles), developing countries report 92% of total road fatalities [1]. The risk of road fatalities to an individual in low-income countries is three times higher than in high-income countries. Countries of different income level have experienced different trends in terms of road crashes and their ability to reduce road fatalities. Although the global number of road traffic fatalities has decreased with around a 5 percent drop compared to 2010, there is an increase in road fatalities across most developing countries. According to MORTH report in India, road fatalities have increased by 9.2 percent in a year, claiming around 155 thousand lives [6]. Although findings from road safety research can play a crucial role in improving road safety, research on road safety in developing countries is a neglected area [7].

The traditional way of evaluating safety is to investigate the frequency and severity of crashes using historical data. In the past, most researchers have worked to remediate road safety conditions with statistical analysis of crash data, considering traffic crashes as one of the primary measures of traffic safety. Tarko et al. [8] highlighted a number of limitations of this approach:

1. Crashes are rare events and are therefore associated with random variation due to small sample size [9].

2. Safety prediction based on crash data is a reactive approach requiring to wait for several years to observe crashes and identify safety issues.

3.Crash data from accident reports suffer from limited sample size, regression-to-the-mean, error in reports, and reporting bias [10].

1.2 Surrogate Safety Measures

Over the years, the limitations of crash-based studies have given rise to surrogate safety measure (SSM) based road safety assessment. Surrogate means substitute or replacement. By using SSM, we substitute the crash data with observable traffic events that are correlated to crash data. Over the last five decades, researchers have proposed several surrogate safety measures in traffic engineering as mentioned below [8]:

1. Volume, speed, delay, accepted gaps, headways, and shock waves [11].

2. Traffic conflicts [12–15].

3. Aggressive lane merging, speeding, and running on red [16, 17].

SSMs were developed to measure road safety proactively based on a non-crash event. Traffic conflicts are the most used and widely accepted SSM. Conflict (or near crash), a surrogate event to crash, occurs more frequently than a crash and can be quantified more easily. Thus, it can be used for a proactive safety assessment. Traffic conflicts are closely related to Heinrich's triangle also known as the accident triangle. Heinrich [18] proposed a theory to reduce industrial accidents. It has two components:

1. Less severe accidents happen more frequently.

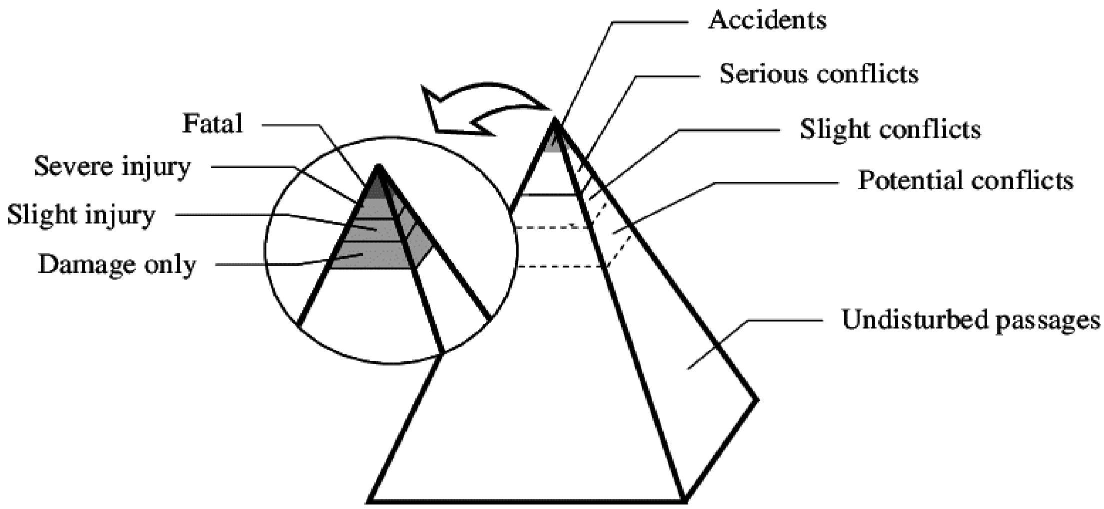

Fig. 1.1 Safety pyramid of traffic interactions [5]

2. The frequency of severe accidents can be reduced by reducing the frequency of minor accidents.

Similar to Heinrich's triangle, Hyden and Linderholm [5] proposed the safety pyramid, where they divided the whole traffic interaction into a sequential chain of events including normal interactions or undisturbed passage, conflicts or near-misses and crashes. Conflicts and crashes can be further divided based on severity level. The safety pyramid depicts that the frequency of conflicts or near-misses is much higher than crashes. Further, from the observed traffic events of different natures, if conflicts are prevented from happening or mitigated in numbers, then crashes can also be prevented or reduced in numbers significantly. The safety pyramid is depicted in Fig.1.1

This approach of safety assessment has several merits over the traditional crash-based approach. First, conflicts are higher in frequency than actual crashes, collecting large sample size is possible in a short duration of time. Since it is based on the observation of non-crash events, which do not lead to any harm to road users. Further, since conflicts are derived from the microscopic traffic parameter, may represent the causal mechanism of crash.

1.3 Traffic Conflict

Traffic conflicts are the most common surrogate to a crash. During the first workshop on traffic conflict techniques in Oslo, Amundsen & Hydén [19] defined traffic conflict as "an observable situation in which two or more road users approach each other in space and time to such an extent that there is a risk of collision if their movements remain unchanged." Since then, utilizing the minimum space, time proximity, and evasive action between road users, numerous conflict indicators have been defined to quantify traffic conflicts. Temporal and spatial proximity are primarily used for quantifying conflicts. In a review of conflict indicators, Mahmud et al. [20] identified that temporal indicators are more appropriate for defining conflict, as they are based on spatial proximity and speed of road users. In past literature, many temporal conflict indicators such as post-encroachment time (PET), time to collision (TTC), and their derivatives such as modified TTC, time exposed TTC, and time-integrated TTC [21–24] have been defined. Among these, TTC is most commonly used and validated for defining conflict in rear-end and lane-changing conflicts [25]. Hayward [21] defined TTC as a minimum time gap before a crash happens between two road users moving on a collision course if both road users maintain the same direction and speed. Few commonly used conflict indicators are presented in Table 1.1.

Table 1.1 Common conflict indicators

Abbreviation	**Indicator name**	**Description**
TTC	Time to collision	The time remaining before the collision if the road users continue with their respective speeds and trajectories [21].

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Abbreviation	**Indicator name**	**Description**
PET	Post-encroachment time	The time between the moment when the first road user leaves the path of the second and the moment when the second reaches the path of the first road user [22].
DR	Deceleration rate	The magnitude of the deceleration action of a driver the moment he or she begins an evasive braking maneuver [26].
TA	Time to the accident	Time to the accident (TA) or time to the point of collision 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 [27].
MTTC	Modified time to collision	Modified TTC incorporates the acceleration and deceleration of vehicle into TTC computation [24].
TDTC	Time difference to collision	The TDTC value at an instant t is defined as the time difference for a pedestrian and a vehicle to travel to the potential conflict point if their speed keeps constant [28].

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Abbreviation	Indicator name	Description
SM	Safety margin	Safety margin in terms of time is defined as the moment at which a pedestrian crosses the virtual conflict zone until the next vehicle reaches the same zone [29].
PSM	Pedestrian safety margin	PSM is the time difference between accepted vehicular time gap with reference to the pedestrian crossing path and pedestrian actual crossing time (based on the field conditions) [30].
ACT	Anticipated collision time	ACT is proposed as the two-dimensional conflict indicator. It is computed as the shortest distance divided by closing in rate in two-dimensional space [31].

Over the last 5 decades, numerous studies have used traffic conflicts as an SSM for road safety assessment in different traffic scenarios. Most of these studies have originated from developed countries where traffic is homogeneous and lane-based. Due to strict lane discipline, vehicular interactions in homogeneous traffic are mostly one-dimensional.

1.4 Heterogeneous and Non- Lane Based Traffic

Traffic in most developing countries is characterized as non-lane-based heterogeneous traffic. The traffic condition is also described as “disordered traffic”, “lane-free traffic”, and “mixed traffic”. The two key component which makes it different from homogeneous

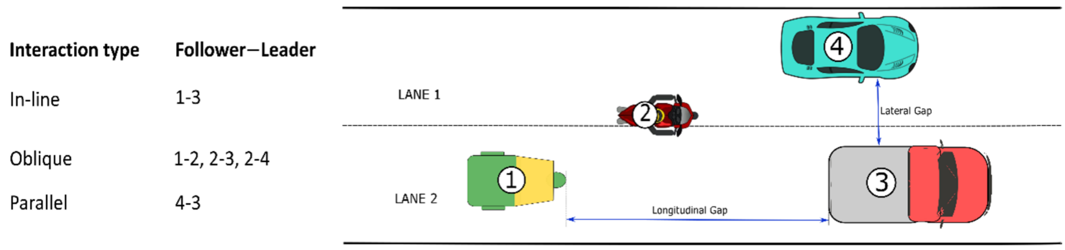

Fig. 1.2 Interaction of vehicles in non-lane-based traffic

traffic is vehicular heterogeneity and non-lane-based vehicular movement. Vehicular heterogeneity refers to the difference in microscopic traffic parameters (space and time headway, lateral gap) resulting from differences in vehicle static and dynamic characteristics. This phenomenon is mostly observed in heterogeneous traffic conditions where the traffic stream comprises different types of motorized and non-motorized vehicles with significantly different static (size, weight) and dynamic (maneuverability) characteristics [2, 32]. Further, in a heterogeneous traffic stream, vehicles do not necessarily travel in the center of the lane and each vehicle is influenced by multiple vehicles, not just the one in the front as assumed in the car following models. Drivers in such conditions try to travel ahead by maintaining lateral gaps without following lane discipline, generating a non-lane-based traffic stream. In such traffic streams, vehicle interaction is multi-vehicle and 2-dimensional in the longitudinal and lateral directions [4, 33]. Fig. 1.2 depicts the vehicular heterogeneity and interactions in non-lane-based traffic in developing countries.

1.5 Motivation

Driver behavior in heterogeneous traffic is considerably different from homogenous traffic [3, 34]. The lane-free vehicular movement in heterogeneous traffic conditions leads to a 2-dimensional conflict scenario, which may lead to rear-end, side-swipe, angled, or head-on collision. In such a traffic stream, it will not be appropriate to use conflict indicators that have been defined primarily for one-dimensional vehicle interactions. Although, few researchers have attempted to fill this research gap by proposing novel conflict indicators, there is still paucity of research in defining conflict in non-lane based 2-dimensional vehicular interactions. Further, most of the surrogate safety measures are derived using space and time proximity between vehicles. Conflict indicators derived using microscopic parameters depend on the vehicle types. There is a need to develop a non-crash-based safety assessment framework which incorporate 2-dimensional interaction and vehicular heterogeneity.

1.6 Research Challenges

The challenges associated with SSM based safety assessment in developing countries are mainly due to heterogeneous and non-lane-based traffic conditions. Traditional conflict measures are defined and validated in lane-based traffic conditions. Application of these measures in non-lane-based traffic may not be appropriate. Based on the literature, several challenges are identified and are discussed in this section.

1.6.1 Challenges in data collection and extraction

In the developing countries, data collection for conflict-based safety assessment is mostly based on roadside sensing using video cameras. Tracking vehicles and capturing conflict indicators from the video data is challenging in a heterogeneous traffic condition due to heterogeneity in vehicles and disordered traffic. Although semi-automated trajectory-based conflict identification is the most common approach for conflict data extraction, it is a tedious and time-consuming task, leading to a small sample size. Computer vision-based automated conflict identification algorithms are mostly developed and trained using datasets such as ImageNet [35] and COCO [36] from lane-based homogeneous traffic. Automated trajectory-based conflict estimation is limited due to the inaccuracy of these algorithms in vehicle identification and tracking in heterogeneous traffic conditions. There is a lot of scope for developing technologies for automated vehicle trajectory extraction and conflict detection in such conditions in order to capture traffic conflicts and develop countermeasures more efficiently.

1.6.2 Defining conflict for non-lane-based traffic

Using single conflict indicators that are derived using temporal proximity are more commonly used to define conflict in the reviewed studies. However, several studies suggest combining proximity and evasive action-based conflict indicators to quantify traffic conflict in heterogeneous traffic. Although many researchers have utilized multiple conflict indicators, including proximity and evasive action-based conflict indicators, mostly these were utilized independently. Multivariate models such as copula and extreme value models may be utilized to integrate multiple conflict indicators. Few researchers have proposed the multivariate EVT modeling framework to aggregate two conflict indicators and thus incorporate 2-D interactions. More research is required to develop and validate multivariate models in these conditions.

In defining the most common conflict indicators such as PET, TTC, MTTC, DRAC and TA, it is assumed that the trajectories of conflicting vehicles overlap at one or more points. These indicators are more suitable for defining conflict in lane-based traffic where trajectories overlap more often. However, in non-lane-based traffic, a conflicting vehicle maintains lateral gap even while following another vehicle. Therefore, to define conflict in the non-collision course, it is important to consider lateral as well as longitudinal movements which include relative proximity, speed, and acceleration in 2-dimension (2-D). To this end, few researchers have modified the existing conflict indicators [37, 38] while other have proposed novel conflict indicators [31, 39, 40] to account for 2-D vehicular interactions. This approach is more appropriate to two-dimensional vehicle interactions.

However, these novel indicators have yet to be applied and validated in different traffic conditions. Future research needs to consider conflict indicators in two-dimensional space.

Further, non-lane-based movement leads to more frequent multi-vehicle interactions. However, existing conflict indicators are mostly defined to quantify conflicts between two vehicles. In heterogeneous traffic, only few researchers have examined multiple vehicle conflicts. Using potential field theory, which is unified model of the crash risks due to all the objects around vehicle [41] defined multi-vehicle conflict between autonomous vehicles at traffic intersections. A similar research methodology could be adopted for defining multi vehicle conflicts in heterogeneous traffic scenarios.

1.6.3 Incorporating heterogeneity

Vehicular heterogeneity is a key component of traffic stream in developing countries. The reviewed studies suggest the microscopic traffic parameters and conflict indicators are dependent on vehicle heterogeneity. However, most reviewed studies have not incorporated the effect of vehicle type in estimating conflict and crash risk. Complete pooled models that ignore vehicular heterogeneity have been utilized in most studies.

Methods such as hierarchical modeling approaches that incorporate heterogeneity in population may be investigated for more accurate crash risk assessment. Few researchers have proposed Bayesian hierarchical modeling framework for incorporating site-based heterogeneity as well [42].

1.6.4 Inconsistency in conflict segregation

In conflict analysis, it is important to identify threshold values of conflict indicators to segregate critical conflicts from risk-free vehicle interactions. Selecting an appropriate threshold value in heterogeneous traffic is challenging since it depends on static and dynamic features of vehicle such as size, speed, acceleration, and braking capability.

Incorrectly selecting the threshold could potentially result in a false estimation of conflicts and consequently impact safety assessments [43]. The threshold values should be suitably estimated based on the conflicting vehicle pairs, local traffic conditions, and driver behavior. Most studies have not accounted for these parameters in selecting the threshold. They have either applied an arbitrary threshold such as 60th, 85th, and 90th quantile or directly utilized threshold values used in previous studies. EVT-based conflict segregation techniques such as threshold stability plots, spectral measure plots, and quantile regression are less explored in heterogeneous traffic conditions and should be further investigated.

In most studies in heterogeneous traffic, a single threshold is set to segregate conflicts. However, applying a single threshold to segregate conflict only represents homogeneous traffic conditions with similarity in road user, vehicle characteristics and different study locations. This approach is prone to error as the conflict indicators derived using microscopic parameters depends on vehicle characteristics [24]. Further, a single threshold fails to account for conflict severity. To resolve this issue, few researchers have proposed variable thresholds based on the diversity of roads and traffic facilities, vehicle type and conflict severity levels.

1.6.5 Safety assessment models and their validation

Traffic crashes are the primary measure of road safety; therefore, deriving a relationship between conflicts and crashes interests many researchers. In the reviewed studies, two modeling approaches have been adopted for conflict-based safety assessment namely (1) crash-conflict model and (2) non-crash models. Due to the unavailability of reliable crash data, crash-conflict models are uncommon in developing countries. Further, although few studies have utilized crash and conflict data for establishing a relationship, these studies utilize conflict and crash data from two different time periods. For example, Tiwari et al. [44] tried to correlate the observed traffic conflicts with 3 years of fatal crash data observed up to nine years ago (from 1989 to 1992). The authors reported a poor correlation between conflict and fatal crashes. In these studies, crashes were observed several years before the conflict data. In addition, a few hours of conflict data are collected with the assumption that similar traffic interactions existed when crashes occurred. However, the traffic conditions could have been altered due to growth in traffic, weather conditions, and time of day. In addition, crash and conflicts are random events subjected to statistical variation. Therefore, fitting a correlation model may be misleading especially when the sample size is small [25].

The second approach is to fit conflict-based safety performance functions. This is the most common modeling approach in reviewed studies where conflict data is utilized to model conflict frequency and severity and to predict crash probability and frequency. Among these, EVT-based conflict models have ability to predict crash probability and even crash frequency over a time period. The unavailability of crash data in developing countries is a major limitation. Although researchers have utilized conflict-based models for safety assessment in different traffic conditions, they are unable to validate the findings in the absence of reliable crash data. This hinders the applicability of SSM-based safety assessment. In the absence of field data, studies on automated vehicle have utilized simulation techniques for model validation. A similar approach may be utilized in heterogeneous traffic conditions. Micro-simulation and driver simulator-based studies, which are less explored, may be utilized for model validation in such conditions.

1.7 Research Objectives

The main purpose of this research work is to develop a non-crash-based safety assessment framework for heterogeneous and non-lane-based traffic. Based on the research gap, three objectives were defined

Objective 1: To define traffic conflict in non-lane-based two-dimensional vehicular interaction.

Objective 2: To investigating the effect of vehicle size on crash risk in heterogeneous traffic condition.

Objective 3: To incorporate vehicular and site-based heterogeneity in safety assessment.

1.8 Scope of the Research

The proposed study aims to provide a safety assessment framework for heterogeneous and non-lane-based traffic scenario. More specifically, this study attempts to define traffic conflict in non-lane-based vehicle following scenario including inline, oblique and parallel interaction. Further, this study attempts to investigate the effect of vehicle sizes on rear-end and side-swipe conflict. Although, this study utilizes data from three-legged traffic intersections, the scope of this research is limited to straight vehicular movement generating a non-lane-based traffic. This study does not include crossing conflict at these traffic intersections.

1.9 Thesis Outline

This dissertation is divided into seven chapters. The chapter wise summary of the dissertation is given below:

Chapter 1 provides the introduction of the research, motivation, research objectives and overview of the dissertation.

Chapter 2 presents a literature review of SSM-based safety assessment in heterogeneous and non-lane-based traffic conditions. The challenges associated with current surrogate safety assessment methodology is highlighted.

Chapter 3 describes the statistical modeling approach utilized in this study. It includes extreme value modeling approaches along with Bayesian hierarchical framework.

Chapter 4 covers the data collection and extraction methodology utilized in this study. It also contains the summary of extracted trajectory data from video.

Chapter 5 introduces a novel framework for defining conflict in non-lane-based traffic condition. The proposed framework incorporates both longitudinal and lateral vehicle interaction while defining traffic conflict.

Chapter 6 investigates the effect of vehicle sizes on crash risk in a heterogeneous and non-lane-based traffic environment.

Chapter 7 presents a hierarchical modeling framework for incorporating site-based and vehicular heterogeneity in the modeling. Further, a comparison is made among pooled modeling approach and hierarchical modeling approach for their suitability in heterogeneous traffic conditions.

Chapter 8 concludes the major findings of this dissertation. It highlights the main contributions of this study and discussed the assumptions and limitations. It also provides the research directions that can be useful for future studies.