Road Safety Assessment in Heterogeneous and Non-Lane-Based Traffic Using Surrogate Safety Measures and Statistical Modeling

Thesis submitted in partial fulfilment
for the Award of

DOCTOR OF PHILOSOPHY (PHD)

in

CIVIL ENGINEERING

by

ASHUTOSH KUMAR

DEPARTMENT OF CIVIL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY (BHU)
VARANASI - 221005, INDIA

ROLL NUMBER
18061005

YEAR OF SUBMISSION
2024

Certificate

It is certified that the work contained in this thesis entitled **"Road Safety Assessment in Heterogeneous and Non-Lane-Based Traffic Using Surrogate Safety Measures and Statistical Modeling"** by **Ashutosh Kumar**, Roll Number **18061005** has been carried out under my supervision and that this work has not been submitted elsewhere for a degree.

It is further certified that the student has fulfilled all the requirements of Comprehensive Examination, Candidacy and SOTA for the award of **Ph.D. Degree** in **Civil Engineering**.

Abhisek Mudgal

Supervisor

Dr. Abhisek Mudgal

Department of Civil Engineering

Indian Institute of Technology (Banaras Hindu University)

Varanasi-221005

Supervisor
Department of Civil Engineering
Indian Institute of Technology,(BHU)
Varanasi-221005

Declaration

I, **Ashutosh Kumar**, certify that the work embodied in this thesis is my own bonafide work and carried out by me under the supervision of **Dr. Abhisek Mudgal** from July 2018 to July 2024 at the **Department of Civil Engineering, Indian Institute of Technology (BHU), Varanasi**. The matter embodied in this thesis has not been submitted for the award of any other degree/diploma. I declare that I have faithfully acknowledged and given credits to the research workers whenever and wherever their works have been cited in my work in this thesis. I further declare that I have not wilfully copied any others' work, paragraphs, text, data, results, etc., reported in journals, books, magazines, reports dissertations, theses, etc., or available at websites and have not included them in this thesis and have not cited as my own work.

Ashutosh Kumar

Date: 03/07/2024 Signature

Place: Varanasi Ashutosh Kumar

Certificate by the Supervisor

It is certified that the above statement made by the student is correct to the best of my knowledge.

Abhisek Mudgal

Supervisor

Dr. Abhisek Mudgal

Department of Civil Engineering

IIT (BHU)

Varanasi

Supervisor
Department of Civil Engineering
Indian Institute of Technology (BHU)
Varanasi-221005

03.07.24

Signature of the Head of the Department

(Civil Engineering)

विभागाध्यक्ष/HEAD
जानपद अभियांत्रिकी विभाग
Department of Civil Engineering
भारतीय प्रौद्योगिकी संस्थान (बी.एच.यू.)
Indian Institute of Technology (BHU)
वाराणसी-221005/Varanasi-221005

Copyright Transfer Certificate

Title of the Thesis :**Road Safety Assessment in Heterogeneous and Non-Lane-Based Traffic Using Surrogate Safety Measures and Statistical Modeling**

Name of the Student : **Ashutosh Kumar**

Copyright Transfer

The undersigned hereby assigns to the Institute of Technology (Banaras Hindu University) Varanasi all rights under copyright that may exist in and for the above thesis submitted for the award of the **Doctor of Philosophy"** in **Civil Engineering**.

Ashutosh Kumar

Date: 03/07/2024 Signature

Place: Varanasi Ashutosh Kumar

Note: However, the author may reproduce or authorize others to reproduce material extracted verbatim from the thesis or derivative of the thesis for author's personal use provided that the source and the Institute's copyright notice are indicated.

Dedicated to

My loving parents . . .

Acknowledgements

I would like to express my sincere gratitude to my mentor and supervisor, **Dr. Abhisek Mudgal**, for his exceptional guidance, support, and unwavering belief in me throughout my research journey. His insightful advice and encouragement during challenging times have been invaluable. Working with him has been an honor and a life-changing experience.

I am also deeply thankful to the members of my Research Progress Evaluation Committee (RPEC), **Prof. S. K. Gupta** from the Department of Mining Engineering, Indian Institute of Technology (BHU), and **Dr. Ankit Gupta**, Associate Professor in the Department of Civil Engineering, IIT (BHU), for their insightful comments and suggestions. My gratitude extends to **Dr. Agnivesh Pani** and **Dr. Anshuman Sharma** for their valuable feedback during my presentations. I also express my sincere thanks to the other faculty members and staff of the Department of Civil Engineering at IIT (BHU) for their direct or indirect support during my research.

Additionally, I am grateful to **Dr. Satyajit Mondal** and **Ankit Kumar Singh** for their immense support during the data collection phase of my research. I would also like to thank my friends and colleagues for their enormous support during my stay at IIT (BHU). Without their contribution, this thesis would not have been possible.

I sincerely express my gratitude to my brothers, **Ashish** and **Santosh** for their unconditional love, encouragement, and unwavering support throughout all my endeavors. Last but not least, I want to express my heartfelt gratitude to my parents for their relentless effort, sacrifices, and unwavering faith in me. There are not enough words to express how grateful I am for everything they have done for me.

If I have inadvertently omitted anyone, please accept my heartfelt thanks as well.

–Ashutosh Kumar

Abstract

Road crash is the leading cause of death for young people (5 – 29 years old) across the world. This problem is even more serious in developing countries where despite having only 72% of the world's powered vehicles, 92% of all road fatalities occur [1]. Quantifying these crashes/fatalities and investigating the causes behind them is essential for developing appropriate countermeasures. In general, crash data is required for such safety assessment. However, in the absence of crash data, surrogate safety measures (SSMs) have been widely accepted for proactive safety assessment. Despite such a merit, SSMs have not been explored enough for safety assessment in developing countries.

Traffic stream in developed countries is characterized as lane-based traffic where vehicle composition is homogeneous, and strict lane discipline is followed. In contrast, traffic in many developing countries (e.g., China and India) is characterized by vehicular heterogeneity and multi-vehicle interactions resulting from non-lane-based vehicular movement. This traffic condition is also described as "disordered traffic," "lane-free traffic," and "mixed traffic." The two key components that make it different from homogeneous traffic are 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 static and dynamic characteristics of a vehicle [2]. Further, in a heterogeneous traffic stream, vehicles do not necessarily travel at the center of the lane. 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 maintain lateral gaps without following lane discipline [3]. In such traffic streams, vehicle interaction is generally multi-vehicle and 2-dimensional with both longitudinal and lateral interactions [4].

The aim of this study is to develop a non-crash-based safety assessment framework for heterogeneous and non-lane-based traffic. Review of existing surrogate safety studies in heterogeneous traffic conditions highlight the salient features and challenges associated with SSMs-based safety assessment in developing countries. These challenges include conflict data collection in non-lane-based traffic, suitability of various conflict indicators for defining conflict in non-lane-based 2-dimensional interaction, the effect of vehicular size on conflict and crash risk, and lack of methodology for incorporating site-based and vehicular heterogeneity while safety assessment.

Based on these research gaps, three research objectives were defined. In the first objective, this study proposes a framework for defining traffic conflict using video-based vehicle trajectory in non-lane-based traffic scenario. A two-dimensional conflict indicator is proposed to incorporate two-dimensional vehicular interactions. In the second objective, the effect of vehicle size on crash risk is investigated using a bivariate extreme value approach. In the third objective, a Bayesian hierarchical framework for safety assessment in heterogeneous traffic conditions is proposed. To fulfill the above research objectives, traffic video data was recorded at four unsignalized T-intersections, identified as black spots on divided highways in India. Vehicle trajectories were extracted from the recorded video data using a semi-automated tool. A total of 8326 vehicles were tracked for an approximate trap length of 60 m. Conflict indicators were estimated using the extracted vehicle trajectories.

Most of the previously defined conflict indicators are only suitable for one-dimensional vehicle interactions, such as in lane-based traffic. For example, rear-end conflicts can be quantified using TTC in lane-based traffic, where vehicles are moving in strict lane discipline, generating inline interactions. However, it is not appropriate to use such conflict indicators alone to define conflict when vehicles move in non-lane-based traffic, leading to a 2-dimensional vehicular interaction. For defining conflicts in such traffic streams, this study considers lateral along with longitudinal interactions. A Bivariate EVT model was proposed for crash risk assessment using Lateral gap and TTC. The results show that incorporating lateral and longitudinal conflict indicators together into the bivariate models can significantly improve the conflict-based risk assessment in non-lane-based traffic.

A proper threshold value of a conflict indicator must be used to segregate conflicts from normal interactions. While research shows that this threshold depends on vehicle size, it has not been studied before. This study utilizes bivariate conflict indicators to define conflict in two-dimensional interaction. In addition, the effect of vehicle size on crash risk was examined for different leader-follower pairs. Bivariate extreme value modeling was used to relate crash risk with vehicle size. Results show that interactions involving cars and light commercial vehicles were riskier than interactions involving motorized two-wheelers and motorized three-wheelers. This is significantly different from what was found using a global threshold of conflict indicators. The proposed framework can be used for a more accurate risk assessment in heterogeneous traffic conditions.

Extreme value theory (EVT) has been extensively used to assess road safety with traffic conflicts. However, most studies used pooled models that do not account for site-based and vehicular heterogeneity. Literature suggests that minimum spacing and microscopic conflict indicators depend upon the leader-follower (LF) pairs. As traffic streams in heterogeneous traffic consist of multiple subgroups, vehicular heterogeneity should be incorporated in estimating crash risk. A completely pooled model will lead to a biased estimate of crash risk, while the separate model for individual LF reduces the sample size. To address this research gap, this study proposes a risk assessment technique for rear-end crashes incorporating site-based and vehicular heterogeneity using a hierarchical model framework. Conflicts were estimated using modified time-to-collision (MTTC) derived from extracted trajectories as the conflict measure for rear-end crashes. Both pooled and hierarchical models were fitted to compare the crash risk among subgroups. If there is heterogeneity (LF-based model) in the population, the pooled model leads to a biased estimate. In contrast, for the homogeneous case (site-based model), the hierarchical and pooled model leads to comparable crash risk. Further, the pooled model leads to the same crash risk across all vehicle types. In contrast, the hierarchical model revealed that crash risk varied across leader-follower pairs. Interactions involving cars and light commercial vehicles with other slow-moving vehicles are more likely to lead to a rear-end crash.

The novelty of this study is in defining conflict and crash risk considering two-dimensional vehicular interactions in mixed traffic environments. The methodology presented in this study may be used to define conflict in traffic that does not follow lane discipline. Further, this study demonstrates the importance of incorporating vehicle type as well as 2-dimensional interactions in safety assessment. This approach can be used for a more accurate risk assessment in a traffic stream with vehicle size heterogeneity and lane-free movements. In addition, a Bayesian hierarchical framework is proposed to incorporate site-based and vehicular heterogeneity in safety assessment. The proposed safety assessment framework can be used to define critical safety events required in vehicle warning systems for heterogeneous and non-lane-based traffic conditions.

Table of contents

List of figures

List of tables