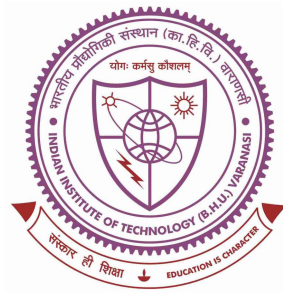


Road Safety Assessment in Heterogeneous and Non-Lane-Based Traffic Using Surrogate Safety Measures and Statistical Modeling



*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**.


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.

Date: 03/07/2024

Place: Varanasi

Ashutosh Kumar
Signature

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

Supervisor
Dr. Abhisek Mudgal
Department of Civil Engineering
Indian Institute of Technology (BHU)
Department of Civil Engineering
Varanasi-221005

IIT (BHU)

Varanasi

03.07.24

Signature of the Head of the Department

(Civil Engineering)
विभागाध्यक्ष/HEAD
जानपद अभियंत्रिकी विभाग
Department of Civil Engineering
भारतीय प्रौद्योगिकी संस्थान (पी.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**.

Date: 03/07/2024

Place: Varanasi

Ashutosh Kumar
Signature

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	xxiii
List of tables	xxv
1 Introduction	1
1.1 Background	1
1.2 Surrogate Safety Measures	2
1.3 Traffic Conflict	4
1.4 Heterogeneous and Non- Lane Based Traffic	6
1.5 Motivation	7
1.6 Research Challenges	8
1.6.1 Challenges in data collection and extraction	8
1.6.2 Defining conflict for non-lane-based traffic	9
1.6.3 Incorporating heterogeneity	10
1.6.4 Inconsistency in conflict segregation	10
1.6.5 Safety assessment models and their validation	11
1.7 Research Objectives	12
1.8 Scope of the Research	13
1.9 Thesis Outline	13

2	Literature Review	15
2.1	Preface	15
2.2	Review of Existing Literature	16
2.3	Analysis of Conflicts Studies	25
2.3.1	Data Collection for conflict studies	25
2.3.2	Defining conflict in non-lane-based traffic	30
2.3.3	Effect of vehicle and site-based heterogeneity	37
2.3.4	Segregating conflicts from normal traffic interactions	39
2.3.5	Methods to estimate thresholds	41
2.3.6	Modeling traffic conflicts	43
2.4	Research Gaps	47
3	Methodology	51
3.1	Preface	51
3.2	Extreme Value Theory	51
3.2.1	Univariate Peak-Over Threshold Model	53
3.2.2	Bivariate Peak-Over Threshold Model	54
3.2.3	Threshold Selection Procedure	56
3.3	Bayesian Modeling Approach	58
3.3.1	Basic theory	58
3.3.2	Bayesian hierarchical inference	59
4	Study Design and Data Collection	61
4.1	Preface	61
4.2	Details of Study Sites	61
4.3	Video Data Extraction	64
4.3.1	Trajectory extraction using Tracker	65

4.3.2	Data Processing	68
4.4	Data Summary	70
5	Defining Traffic Conflict in Non-Lane-Based Traffic Condition	73
5.1	Preface	73
5.2	Suitability of Conflict Indicators in Non-Lane-Based Traffic	74
5.3	Data	75
5.3.1	Extracting conflict indicators	76
5.4	Defining traffic conflicts in non-lane-based traffic	77
5.5	Results and Discussion	79
5.5.1	Dependence Structure between TTC and Gap_{lat}	79
5.5.2	Determining the threshold	81
5.5.3	EVT modeling results	82
5.5.4	Overall model performance	84
5.5.5	Comparison of separate and joint-site models	86
5.6	Chapter Summary	87
6	Effect of Vehicle Size on the Crash Risk	89
6.1	Preface	89
6.2	Crash risk assessment in heterogeneous traffic	90
6.3	Conflict Data	92
6.3.1	Conflict indicators in staggered car-following scenario	93
6.3.2	Dependence structure between TTC and Gap_{lat}	94
6.4	Analysis and Results	95
6.4.1	EVT model results	95
6.4.2	Sensitivity analysis	102
6.5	Discussion	102

6.5.1	Minimum TTC and Gap_{lat} depends upon the L-F vehicle type . . .	103
6.5.2	Comparison of conflicts using L-F based threshold and global threshold model	104
6.5.3	Effect of vehicle size on conflicts and crashes	104
6.6	Chapter Summary	106
7	Incorporating Heterogeneity Through Bayesian Hierarchical Models	107
7.1	Preface	107
7.2	Conflict-based Safety Assessment and Modeling Heterogeneity	108
7.3	Bayesian Extreme Value Modeling	109
7.4	Traffic Conflict Data and Heterogeneity Tests	110
7.5	Bayesian Hierarchical Extreme Value Models	111
7.5.1	Threshold to segregate extreme values	112
7.5.2	Bayesian hierarchical structure	113
7.5.3	Analysis and results	115
7.6	Discussion	123
7.6.1	Conflict Identification in heterogeneous traffic	123
7.6.2	Pooled versus hierarchical model	123
7.6.3	Identification of critical vehicle groups	124
7.7	Chapter Summary	125
8	Conclusions	127
8.1	Preface	127
8.2	Research Findings and Conclusions	128
8.2.1	Defining conflict in non-lane-based traffic	128
8.2.2	Examining the effect of vehicle size on crash risk	130

8.2.3	Incorporating heterogeneity using Bayesian hierarchical modeling framework	131
8.3	Thesis Contributions	132
8.4	Applications and Practical Implications of the Research	133
8.5	Limitations and Direction for Future Research	134
	References	137

List of figures

1.1	Safety pyramid of traffic interactions [5]	3
1.2	Interaction of vehicles in non-lane-based traffic	7
2.1	Traffic conflict data collection	26
2.2	Conflict data collection techniques and sample size	31
3.1	Framework for (a) pooled and (b) hierarchical models	60
4.1	Study sites map (a) location and (b) roadway geometry of study sites.	63
4.2	Camera view of the study sites	64
4.3	Trajectory Extraction using Tracker Software.	66
4.4	Extracting and Cleaning Vehicle Trajectories.	69
4.5	Relationship between derived and observed vehicle speeds.	70
4.6	(a) Vehicle composition and (b) speed variation at different sites.	71
5.1	Conflict and crash in non-lane-based traffic for all site data.	78
5.2	Fisher's chi-plot for test of dependence.	80
5.3	Asymptotic dependence between negated TTC and negated Gap_{lat} .	81
5.4	Threshold stability plot for joint-site model.	84
5.5	Spectral measure plot for joint-site model.	85
5.6	Diagnostic plots for the joint-site model.	86

6.1	Speed of different vehicle types.	93
6.2	Speed of different vehicle types.	95
6.3	Comparison of (a) TTC and (b) Gap_{lat} among L-F pairs	96
6.4	Spectral measure plot for negated TTC vs. negated Gap_{lat}	97
6.5	Threshold stability plot for (a) negated TTC and (b) negated Gap_{lat}	97
6.6	Proportion of conflicts in interactions and proportion of crashes in conflicts.	101
6.7	Comparison of proportion of conflicts in total interactions based on the two modelling approaches (global and L-F).	102
6.8	Sensitivity analysis of crash probability with different thresholds.	103
6.9	Single threshold based conflict segregation.	105
7.1	Variation of MTTC among (a) sites (b) L-F pairs.	111
7.2	Threshold stability plot for the pooled model.	115
7.3	Model parameters: posterior distribution (a) L-F-based models (b) site- based models.	116
7.4	Crash risk with a 95% CI based on hierarchical and pooled models (a) site-based models (b) L-F-based models.	119
7.5	Trace plot for hierarchical models (a) L-F- based models (b) site-based models.	120
7.6	Posterior predictive checks for (a) pooled model, (b) site-based hierarchical model, and (c) L-F-based hierarchical models.	121
7.7	Sensitivity analysis of crash risk (95% credible interval) with different thresholds (a) site-based models (b) L-F- based models.	122

List of tables

1.1	Common conflict indicators	4
2.1	Previous review studies on SSM	17
2.2	Data collection and extraction of conflict indicators from field data	28
2.3	Selection of conflict indicators	32
2.4	Summary of Conflict modeling approaches in reviewed literature	46
3.1	Parametric bivariate extreme value distributions used in the present study	56
4.1	Details of Study sites	65
4.2	Extracted Vehicle Trajectory Data	66
4.3	Vehicle class and their average dimensions	67
4.4	Descriptive statistics of vehicle speeds	72
5.1	Descriptive statistics of conflict indicators (TTC and Gap_{lat})	77
5.2	Correlation between lateral and longitudinal parameters	80
5.3	Estimation results of bivariate threshold excess models	83
6.1	Descriptive statistics of TTC and Gap_{lat}	94
6.2	Threshold for marginal and joint distribution	99
6.3	Model selection based on AIC	99
6.4	Estimation results of BGP model	100

7.1 Threshold estimated from threshold stability plot 117

7.2 Estimation result of hierarchical and pooled model 118