PROACTIVE ROAD SAFETY ASSESSMENT USING BEHAVIORALLY INFORMED SURROGATE SAFETY MEASURES

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TRANSPORTATION RESEARCH AND INJURY PREVENTION CENTRE

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by

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TRANSPORTATION RESEARCH AND INJURY PREVENTION CENTRE

submitted

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CERTIFICATE

This is to certify that the thesis entitled **"PROACTIVE ROAD SAFETY ASSESSMENT USING BEHAVIORALLY INFORMED SURROGATE SAFETY MEASURES",** is being submitted by **Mr. Yawar Ali** to the Indian Institute of Technology Delhi, for the award of the degree of **Doctor of Philosophy**, is a record of original bona fide research work carried out by him. Mr. Yawar Ali has worked under our guidance and supervision. To the best of our knowledge, the thesis has reached the requisite standard. The material contained in this thesis has not been submitted, in part or in full, to any other University or Institute for the award of any degree or diploma.





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ABSTRACT

Road traffic crashes are one of the leading causes of death and injury worldwide, with low and middle-income countries carrying a disproportionate share of the burden. India, with only a small fraction of the world's vehicle population but nearly 11 per cent of global road fatalities, represents a prominent example of this disparity. Traditional crash-based safety analysis methods are reactive, relying on reported crashes that often suffer from underreporting, poor data quality, and long delays before patterns emerge and corrective measures are implemented. Surrogate Safety Measures (SSMs), which evaluate near-crash events and risky interactions, offer a more proactive approach. However, most existing SSMs were designed for lane-based, homogeneous traffic and are not well-suited to the highly heterogeneous, area-based traffic common in India and other countries with similar conditions.

This thesis develops an integrated framework for proactive road safety assessment that addresses these challenges by combining high-resolution traffic data, driver perception, and models of self-organising behaviour. Empirical data were collected through Unmanned Aerial Vehicles (UAVs), which provide detailed vehicle trajectories in complex traffic conditions. A new method was proposed for identifying interacting vehicle pairs in two-dimensional traffic, going beyond traditional leader-follower assumptions. The study also introduces the concept of the Virtual Perceived Boundary (VPB), a dynamic, context-sensitive envelope that reflects how drivers perceive the safe space around their vehicles. Unlike fixed vehicle dimensions, the VPB adjusts in real time according to vehicle type, speed, traffic density, and individual driving style, making safety analysis more reflective of drivers' behaviour.

Building on this, a novel composite risk index, the Motorised-Vulnerable Road User Risk Index (MVRI), was created to evaluate lateral conflicts involving motorised vulnerable road users (M-VRUs), who face the highest risk in mixed traffic. Statistical models, such as ordered logit and mixed ordered logit, were applied to classify interaction severity levels, with results showing the advantage of behaviourally informed measures over conventional approaches. At the microscopic modelling level, the thesis adapts a Self-Propelled Particle framework to represent vehicle-level speed and heading responses under local interactions in heterogeneous, area-based traffic. The model parameters are calibrated using observed UAV trajectories and optimisation techniques. Its performance is evaluated through vehicle-level velocity and heading prediction errors.

The present implementation is a trajectory-update model rather than a complete traffic-stream simulator. It predicts an individual vehicle's movement response using its observed state and surrounding interaction conditions. Its extension to a multi-agent simulation framework capable of generating complete synthetic trajectory datasets is identified as future work. Such an extension may eventually support trajectory-based surrogate safety analysis where sufficient empirical trajectory data are unavailable. Calibration using optimisation techniques ensured close alignment with observed data, while validation confirmed the robustness of the approach.

The results demonstrate that integrating driver perception and collective behaviour into safety analysis improves conflict detection and provides a more realistic understanding of traffic flow stability. The research highlights that crashes are not isolated events but the outcome of complex interactions shaped by behaviour and context. By embedding behavioural and system-level insights into safety models, the thesis offers a pathway to more effective interventions. The findings hold direct implications for infrastructure design, traffic management, simulation calibration, and policy development. Collectively, the studies establish a methodological sequence from validated microscopic trajectories and two-dimensional interaction identification to empirical spacing representation and conflict-risk estimation, while the SPP analysis provides a related foundation for future trajectory simulation.

सार

सड़क यातायात दुर्घटनाएँ विश्वभर में मृत्यु और चोट के प्रमुख कारणों में से एक हैं, जिनका अनुपातहीन भार निम्न और मध्यम-आय वाले देशों पर पड़ता है। भारत, जिसके पास विश्व के वाहन बेड़े का केवल एक छोटा हिस्सा है, लेकिन वैश्विक सड़क मृत्यु-दर में लगभग 11 प्रतिशत का योगदान है, इस असमानता का एक प्रमुख उदाहरण प्रस्तुत करता है। पारंपरिक दुर्घटना-आधारित सुरक्षा विश्लेषण विधियाँ प्रतिक्रियात्मक होती हैं, क्योंकि वे दर्ज की गई दुर्घटनाओं पर निर्भर करती हैं, जिनमें प्रायः कम रिपोर्टिंग, कमजोर डेटा गुणवत्ता और पैटर्न उभरने तथा सुधारात्मक उपाय लागू होने से पहले लंबे विलंब जैसी समस्याएँ होती हैं। सरोगेट सुरक्षा मापदंड, अर्थात् Surrogate Safety Measures (SSMs), जो निकट-दुर्घटना घटनाओं और जोखिमपूर्ण अंतःक्रियाओं का मूल्यांकन करते हैं, अधिक सक्रिय दृष्टिकोण प्रदान करते हैं। हालांकि, अधिकांश मौजूदा SSMs लेन-आधारित, समरूप यातायात के लिए विकसित किए गए थे और भारत तथा समान परिस्थितियों वाले अन्य देशों में पाए जाने वाले अत्यधिक विषम, क्षेत्र-आधारित यातायात के लिए उपयुक्त नहीं हैं।

यह शोधप्रबंध सक्रिय सड़क सुरक्षा मूल्यांकन के लिए एक समेकित ढाँचा विकसित करता है, जो उच्च-रिज़ॉल्यूशन यातायात डेटा, चालक धारणा और स्व-संगठित व्यवहार के मॉडलों को संयोजित करके इन चुनौतियों का समाधान करता है। अनुभवजन्य डेटा मानवरहित हवाई वाहनों, अर्थात् Unmanned Aerial Vehicles (UAVs), के माध्यम से एकत्र किया गया, जो जटिल यातायात परिस्थितियों में विस्तृत वाहन प्रक्षेप-पथ उपलब्ध कराते हैं। द्वि-आयामी यातायात में परस्पर अंतःक्रिया करने वाले वाहन युग्मों की पहचान के लिए एक नई विधि प्रस्तावित की गई, जो पारंपरिक नेता-अनुयायी धारणाओं से आगे जाती है। यह अध्ययन Virtual Perceived Boundary (VPB), अर्थात् आभासी अनुभूत सीमा, की अवधारणा भी प्रस्तुत करता है, जो एक गतिशील और संदर्भ-संवेदी आवरण है तथा यह दर्शाता है कि चालक अपने वाहनों के आसपास सुरक्षित स्थान को किस प्रकार अनुभव करते हैं। स्थिर वाहन आयामों के विपरीत, VPB वाहन के प्रकार, गति, यातायात घनत्व और व्यक्तिगत ड्राइविंग शैली के अनुसार वास्तविक समय में समायोजित होती है, जिससे सुरक्षा विश्लेषण चालकों के व्यवहार को अधिक यथार्थ रूप से प्रतिबिंबित करता है।

इसी आधार पर, एक नवीन समग्र जोखिम सूचकांक, Motorised-Vulnerable Road User Risk Index (MVRI), विकसित किया गया, जिसका उद्देश्य मोटरचालित असुरक्षित सड़क उपयोगकर्ताओं, अर्थात् M-VRUs, से जुड़े पार्श्व संघर्षों का मूल्यांकन करना है। मिश्रित यातायात में इन्हीं उपयोगकर्ताओं को सर्वाधिक जोखिम का सामना करना पड़ता है। अंतःक्रिया की गंभीरता के स्तरों को वर्गीकृत करने के लिए क्रमबद्ध लॉजिट और मिश्रित क्रमबद्ध लॉजिट जैसे सांख्यिकीय मॉडलों का उपयोग किया गया, जिनके परिणामों ने पारंपरिक दृष्टिकोणों की तुलना में व्यवहार-सूचित मापदंडों की श्रेष्ठता को दर्शाया। सूक्ष्म मॉडलिंग स्तर पर, यह शोधप्रबंध विषम, क्षेत्र-आधारित यातायात में स्थानीय अंतःक्रियाओं के अंतर्गत वाहन-स्तरीय गति और दिशा-प्रतिक्रियाओं को निरूपित करने के लिए Self-Propelled Particle (SPP) ढाँचे को अनुकूलित करता है। मॉडल पैरामीटर प्रेक्षित UAV

प्रक्षेप-पथों और अनुकूलन तकनीकों का उपयोग करके कैलिब्रेट किए गए। इसके प्रदर्शन का मूल्यांकन वाहन-स्तरीय वेग और दिशा-पूर्वानुमान त्रुटियों के माध्यम से किया गया।

वर्तमान कार्यान्वयन एक पूर्ण यातायात-प्रवाह सिमुलेटर के बजाय एक प्रक्षेप-पथ-अद्यतन मॉडल है। यह किसी व्यक्तिगत वाहन की गति-प्रतिक्रिया का पूर्वानुमान उसके प्रेक्षित अवस्था-मानों और आसपास की अंतःक्रिया स्थितियों के आधार पर करता है। इसे एक ऐसे बहु-एजेंट सिमुलेशन ढाँचे तक विस्तारित करना, जो पूर्ण कृत्रिम प्रक्षेप-पथ डेटासेट उत्पन्न करने में सक्षम हो, भविष्य के कार्य के रूप में चिह्नित किया गया है। ऐसा विस्तार अंततः उन परिस्थितियों में प्रक्षेप-पथ-आधारित सरोगेट सुरक्षा विश्लेषण को समर्थन दे सकता है, जहाँ पर्याप्त अनुभवजन्य प्रक्षेप-पथ डेटा उपलब्ध नहीं होता। अनुकूलन तकनीकों के माध्यम से किए गए कैलिब्रेशन ने प्रेक्षित डेटा के साथ निकट संरेखण सुनिश्चित किया, जबकि वैधीकरण ने इस दृष्टिकोण की मजबूती की पुष्टि की।

परिणाम दर्शाते हैं कि सुरक्षा विश्लेषण में चालक धारणा और सामूहिक व्यवहार को एकीकृत करने से संघर्ष पहचान में सुधार होता है और यातायात प्रवाह स्थिरता की अधिक यथार्थ समझ प्राप्त होती है। यह शोध रेखांकित करता है कि दुर्घटनाएँ अलग-थलग घटनाएँ नहीं हैं, बल्कि व्यवहार और संदर्भ से निर्मित जटिल अंतःक्रियाओं का परिणाम हैं। सुरक्षा मॉडलों में व्यवहारगत और प्रणाली-स्तरीय अंतर्दृष्टियों को समाहित करके, यह शोधप्रबंध अधिक प्रभावी हस्तक्षेपों की दिशा में एक मार्ग प्रस्तुत करता है। इसके निष्कर्ष अवसंरचना डिज़ाइन, यातायात प्रबंधन, सिमुलेशन कैलिब्रेशन और नीति निर्माण के लिए प्रत्यक्ष निहितार्थ रखते हैं। सामूहिक रूप से, ये अध्ययन सत्यापित सूक्ष्म प्रक्षेप-पथों और द्वि-आयामी अंतःक्रिया पहचान से लेकर अनुभवजन्य अंतराल-प्रतिनिधित्व और संघर्ष-जोखिम आकलन तक एक पद्धतिगत क्रम स्थापित करते हैं, जबकि SPP विश्लेषण भविष्य के प्रक्षेप-पथ सिमुलेशन के लिए एक संबंधित आधार प्रदान करता है।

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LIST OF ABBREVIATIONS AND NOTATIONS

CVC	Classified Volume Count
DFS	Data From Sky
DRAC	Deceleration Rate to Avoid Collision
TTC	Time to Collision
EVT	Extreme Value Theory
FHWA	Federal Highway Administration
GPS	Global Positioning System
HCV	Heavy Commercial Vehicle
HB	Heavy Braking
LMICs	Low and Middle-Income Countries
LCV	Light Commercial Vehicle
MOLM	Mixed Ordered Logit Model
MVT	Microscopic Vehicle Trajectory
MoRTH	Ministry of Road Transport and Highways
M2W	Motorised Two-Wheelers
MThW	Motorised Three-Wheelers
MVRI	Motorised Vulnerable Road User Risk Index
MVT	Microscopic Vehicle Trajectories
OLM	Ordered Logit Model
PET	Post Encroachment Time
PSD	Proportion of Stopping Distance
SPP	Self-Propelled Particle
SMS	Space Mean Speed
SSM	Surrogate Safety Measures
TCT	Traffic Conflict Techniques
TA	Time to Accident
UAV	Unmanned Aerial Vehicle
VPB	Virtual Perceived Boundary
VRU	Vulnerable Road User
D_p	Perceived Intervehicle Distance

x, y	Coordinates (meters)
v	Speed
L	Vehicle Length (meters)
l	Subscript for Leader Vehicle
f	Subscript for Follower Vehicle
$L^{l,int}$	Interacting Length of the Leader
$L^{f,int}$	Interacting Length of the Follower
W	Vehicle Width (meters)
θ	Bearing with respect to the Leader Vehicle (Degrees)
D_{centre}	Centre-to-centre Distance Between Two Interacting Vehicles
D_t	True Intervehicle Distance
t_1, t_2	Timestamps from MVT data
ΔV	Relative speed
θ_i (t)	Heading of vehicle i at time t
α	Acceleration Response Coefficient
κ	Directional Response Coefficient
R	Repulsion Coefficient
β	Binary Constant
$\varepsilon_{i,t}$	Violation/Error
r_z	Zone-specific Repulsion Threshold
z	Zone
δ	Density cluster (Low, Medium, High)