SAFETY EFFECTS OF PAVED SHOULDERS ON INTERCITY HIGHWAYS IN INDIA

LAXMAN SINGH BISHT

DEPARTMENT OF CIVIL ENGINEERING

INDIAN INSTITUTE OF TECHNOLOGY DELHI

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by

LAXMAN SINGH BISHT

Department of Civil Engineering

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Dedications

To my late grandmother

To my parents

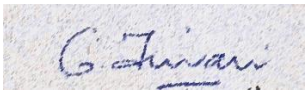
To Professor Geetam Tiwari

Certificate

This is to certify that the thesis entitled ***"Safety Effects of Paved Shoulders on Intercity Highways in India"*** is being submitted by ***Mr Laxman Singh Bisht*** to the Indian Institute of Technology Delhi, India, for the award of the degree of ***Doctor of Philosophy***, is a record of original bona fide research work carried out by him. Laxman has worked under my guidance and supervision.

To the best of my 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.

Dated: October 2022



(Dr. Geetam Tiwari)
Professor and Head
Transportation Research and Injury Prevention Centre (TRIP-C)
Indian Institute of Technology Delhi
New Delhi -110016, India

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गुरुर्ब्रहमा ग्रुरुर्विष्णुः गुरुर्देवो महेश्वरः । गुरुः साक्षात् परं ब्रहम तस्मै श्री गुरवे नमः ॥

(Our creation is that guru; the duration of our lives is that guru; our trials, tribulations, illnesses, calamities, and the death of the body is that guru. There is a guru nearby and a guru that is beyond the beyond. I make my offering to the beautiful remover of my darkness, my ignorance; it is to you I bow and lay down my life.)

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I want to express my gratitude to my parents for everything. I have reached here today because of your relentless effort, sacrifices and faith in me. I wholeheartedly thank my parents today for their blessings and the constant support they have always been for me. There are not enough words to express my gratitude to them for everything they have done for me. I would also like to thank my younger brother for always supporting me, especially in the data collection. I wish you a bright and prosperous future.

Today I am using this opportunity to remember my late grandmother for being with me spiritually all time. Daadi Ji, you may have passed on, but your memories will always live on within me.

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On this journey, there were many gloomy days and unquiet nights. However, you must remember that "*your life is your life; know it while you have it*." Charles Bukowski rightly said that *don't let your life be clubbed into dank submission. Be on the watch, there are ways out. There is a light somewhere. It may not be much light, but it beats the darkness. Be on the watch, and the gods will offer you chances. You can't beat death, but you can beat death in life sometimes. And the more often you learn to do it, the more light there will be. You are marvellous, and the gods wait to delight in you*. With this, I want to thank almighty for helping me through hard times and for giving me the strength to keep going.

Laxman Singh Bisht

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Abstract

This thesis aimed to estimate the effect of paved shoulder width on the number of fatal crashes on intercity highways and to determine the risk factors of fatal crashes on an expressway in India. The objectives of this thesis are as follows (i) to identify road traffic crash (RTC) patterns on the selected intercity highways and expressway stretches of India; (ii) to assess the effect of paved shoulder width on fatal RTCs on the selected intercity highway; (iii) to assess the impact of the paved shoulder width on the selected intercity highway segments having multiple fatal crashes; and (iv) to estimate the role of crash contributory factors in the presence of constant paved shoulder width on segments of an intercity expressway.

Therefore, first, this study analyzed the fatal crash characteristics on the selected intercity highways and an expressway. Subsequently, the effect of paved shoulder width and other crash contributory risk factors were identified on the selected intercity highway segments using the case-control (C-C) method. The C-C method is an observational epidemiological approach used to examine the possible relation of a risk factor to a specific outcome. Whereas, in the case of an expressway with constant paved shoulder width, the crash contributory risk factors were determined with the help of negative binomial random parameter (RPNB) approaches.

The selected intercity highways are part of the national highway (NH), i.e., NH 7 and NH 44, and are open access highways with varying paved shoulder widths. And the Yamuna Expressway (YE) is access-controlled in Uttar Pradesh. In this study, primary data were

collected with the help of surveys, as no central database exists in India. We carried out field surveys on NH 7, and NH 44 as traffic volume, speed, and cross-sectional geometrics data were unavailable during this study's initial data collection stage. Whereas in the case of YE, crash, speed, traffic volume, and geometric data were collected as secondary data. This study employed fatal crashes, traffic volume, operational speed, and geometric and roadside data to develop statistical models.

The crash characteristics revealed that rear-end crashes have a substantial share in total fatal crashes. Vulnerable road users have a high relative risk on the studied highway and expressway stretch. In NH 44, pedestrian fatalities are high. Cars, trucks, and buses are primarily involved as impacting vehicles in fatal crashes. Nighttime crashes have a slightly higher proportion compared to daytime crashes. Next, for NH 7, the estimated odds ratio (OR) shows that paved shoulder widths up to 2.0 m are safe for all users. This finding is consistent for both highway stretches, i.e., NH 7 and NH 44.

In contrast, paved shoulder width of more than 2.0 m has varying effects based on the fatal crash type. The varying impact could be attributed to the roadside context of the highway and prevailing operational speeds. Subsequently, this study explored the C-C method for the applicability of considering multiple crash segments on the selected intercity 6L highways (NH 44). The safety effectiveness of paved shoulder width assessment shows that paved shoulder width of more than 2.0 m is a risk factor for multiple fatal crash segments compared to a paved shoulder width of 1.0 to 1.5 m. In addition, results show that shoulder width between 1.5 to 2.0 m reduces the risk of multiple fatal crashes. Ordinal logistic regression results show that the segments with wider shoulders have less risk of multiple crashes than the narrow shoulder. However, additional studies need to be conducted based on the collision types and locations where multiple fatal crashes have occurred.

In the case of the YE stretch, parsimonious model results revealed that AADT and vertical curve length are significant risk factors for rear-end crashes. AADT and vertical curve

length are the significant random parameters to capture the segment-specific unobserved heterogeneity. The findings indicate that the expressway design should be calibrated as per the local traffic mix and prevailing operational speed characteristics. Further, the results indicate providing bus lay-by and truck drivers' rest areas at regular intervals on the expressway. In addition, the location of the pedestrian underpasses should be determined based on the presence of villages in the vicinity of the expressway.

To sum up, this study was a unique attempt to assess the safety effectiveness of the paved shoulders in case of heterogeneous traffic on divided 4L and 6L highways in India. The study demonstrated that the matched case-control methodology could be an alternative method in the limited data availability scenario to assess the safety effects of the interventions. The outcomes of this study would help the road-owning agencies in India to consider paved shoulders as one of the road safety interventions to improve safety. Especially the provision of the paved shoulder can enhance the safety of vulnerable road users (VRUs), especially motorized-two wheelers (MTW) users. It can also reduce the risk of multiple fatal crashes on multilane highways. However, the results presented in this study are data specific.

In the future, additional studies on various intercity highways using detailed databases would help provide conclusive evidence of the safety effectiveness of paved shoulder width. Besides, this study makes a strong case for developing a rich and centralized database for road safety risk factors in India. Such databases would help researchers to conduct advanced research, eventually promoting research-based findings and safety interventions to reduce crashes and their societal burden. Along similar lines, it is also recommended that a dedicated crash data recording system should be developed within each state's police department. Moreover, the hospital and police databases should be linked and updated on time to deal with the underreporting of crashes.

इस थीसिस का उद्देश्य इंटरसिटी राजमार्गों पर घातक दुर्घटनाओं की संख्या पर पक्की शोल्डर की चौड़ाई के प्रभाव का अनुमान लगाना और भारत में एक एक्सप्रेसवे पर घातक दुर्घटनाओं के जोखिम कारकों का निर्धारण करना था। इस थीसिस के उद्देश्य इस प्रकार हैं (i) भारत के चयनित इंटरसिटी राजमार्गों और एक्सप्रेसवे हिस्सों पर सड़क यातायात दुर्घटना (आरटीसी) पैटर्न की पहचान करना; (ii) चयनित इंटरसिटी राजमार्ग पर घातक आरटीसी पर पक्की शोल्डर की चौड़ाई के प्रभाव का आकलन करना; (iii) कई घातक दुर्घटनाओं वाले चयनित इंटरसिटी राजमार्ग खंडों पर पक्की शोल्डर की चौड़ाई के प्रभाव का आकलन करना; और (iv) इंटरसिटी एक्सप्रेसवे के खंडों पर निरंतर पक्की शोल्डर की चौड़ाई की उपस्थिति में दुर्घटना योगदान कारकों की भूमिका का अनुमान लगाने के लिए।

इसलिए, सबसे पहले, इस अध्ययन ने चयनित इंटरसिटी राजमार्गों और एक एक्सप्रेसवे पर घातक दुर्घटना विशेषताओं का विश्लेषण किया। इसके बाद, केस-कंट्रोल (C-C) पद्धति का उपयोग करके चयनित इंटरसिटी हाईवे सेगमेंट पर पक्की शोल्डर की चौड़ाई और अन्य दुर्घटना योगदान जोखिम कारकों के प्रभाव की पहचान की गई। C-C पद्धति एक अवलोकन संबंधी महामारी विज्ञान दृष्टिकोण है जिसका उपयोग किसी विशिष्ट परिणाम के लिए जोखिम कारक के संभावित संबंध की जांच करने के लिए किया जाता है। जबकि, लगातार पक्की शोल्डर की चौड़ाई वाले एक्सप्रेसवे के मामले में, नकारात्मक द्विपद यादृच्छिक पैरामीटर (RPNB) दृष्टिकोणों की मदद से दुर्घटना अंशदायी जोखिम कारकों का निर्धारण किया गया था।

चयनित इंटरसिटी राजमार्ग राष्ट्रीय राजमार्ग (NH), यानी NH 7 और NH 44 का हिस्सा हैं, और अलग-अलग पक्की शोल्डर की चौड़ाई वाले खुले पहुंच वाले राजमार्ग हैं। और यमुना एक्सप्रेसवे (YE) उत्तर प्रदेश में एक्सेस-नियंत्रित है। इस अध्ययन में, सर्वेक्षणों की सहायता से प्राथमिक डेटा एकत्र किया गया था, क्योंकि भारत में कोई केंद्रीय डेटाबेस मौजूद नहीं है। हमने NH 7, और NH 44 पर क्षेत्र सर्वेक्षण किया क्योंकि इस अध्ययन के प्रारंभिक डेटा संग्रह चरण के दौरान ट्रैफ़िक की मात्रा, गति और क्रॉस-सेक्शनल ज्यामितीय डेटा अनुपलब्ध थे। जबकि YE के मामले में, दुर्घटना, गति, यातायात की मात्रा और

ज्यामितीय डेटा को द्वितीयक डेटा के रूप में एकत्र किया गया था। इस अध्ययन ने सांख्यिकीय मॉडल विकसित करने के लिए घातक दुर्घटनाओं, यातायात की मात्रा, परिचालन गति और ज्यामितीय और सड़क के किनारे के डेटा को नियोजित किया।

दुर्घटना की विशेषताओं से पता चला कि कुल घातक दुर्घटनाओं में रियर-एंड क्रैश का एक बड़ा हिस्सा है। कमजोर सड़क उपयोगकर्ता (VRUs) का अध्ययन किए गए राजमार्ग और एक्सप्रेसवे खंड पर एक उच्च सापेक्ष जोखिम है। NH 44 में, पैदल चलने वालों की मौत अधिक होती है। घातक दुर्घटनाओं में वाहनों को प्रभावित करने वाले मुख्य रूप से कार, ट्रक और बसें शामिल हैं। रात के समय दुर्घटनाओं का अनुपात दिन के समय दुर्घटनाओं की तुलना में थोड़ा अधिक होता है। इसके बाद, NH 7 के लिए, अनुमानित ऑड्स रेशियो (OR) दर्शाता है कि 2.0 मीटर तक पक्की शोल्डर की चौड़ाई सभी उपयोगकर्ताओं के लिए सुरक्षित है। यह खोज दोनों राजमार्ग खंडों, यानी NH 7 और NH 44 के लिए सुसंगत है।

इसके विपरीत, 2.0 मीटर से अधिक की पक्की शोल्डर की चौड़ाई घातक दुर्घटना प्रकार के आधार पर अलग-अलग प्रभाव डालती है। अलग-अलग प्रभाव को राजमार्ग के सड़क के किनारे के संदर्भ और प्रचलित परिचालन गति के लिए जिम्मेदार ठहराया जा सकता है। इसके बाद, इस अध्ययन ने चयनित इंटरसिटी 6L राजमार्गों (NH 44) पर कई क्रैश सेगमेंट पर विचार करने की प्रयोज्यता के लिए CC पद्धति का पता लगाया। पक्की शोल्डर की चौड़ाई के आकलन की सुरक्षा प्रभावशीलता से पता चलता है कि 2.0 मीटर से अधिक की पक्की शोल्डर की चौड़ाई 1.0 से 1.5 मीटर की पक्की शोल्डर की चौड़ाई की तुलना में कई घातक दुर्घटना खंडों के लिए एक जोखिम कारक है। इसके अलावा, परिणाम बताते हैं कि 1.5 से 2.0 मीटर के बीच शोल्डर की चौड़ाई कई घातक दुर्घटनाओं के जोखिम को कम करती है। ऑर्डिनल लॉजिस्टिक रिग्रेशन परिणाम बताते हैं कि चौड़े कंधों वाले सेगमेंट में नैरो शोल्डर की तुलना में मल्टीपल क्रैश का जोखिम कम होता है। हालांकि, टकराव के प्रकारों और उन स्थानों के आधार पर अतिरिक्त अध्ययन किए जाने की आवश्यकता है जहां कई घातक दुर्घटनाएं हुई हैं।

YE के मामले में, पारसीमोनियस मॉडल परिणामों से पता चला कि AADT और ऊर्ध्वाधर वक्र लंबाई रियर-एंड क्रैश के लिए महत्वपूर्ण जोखिम कारक हैं। AADT और ऊर्ध्वाधर वक्र लंबाई खंड-विशिष्ट अप्रमाणित विषमता को पकड़ने के लिए महत्वपूर्ण यादृच्छिक पैरामीटर हैं। निष्कर्षों से संकेत मिलता है कि एक्सप्रेसवे के डिजाइन को स्थानीय यातायात मिश्रण और प्रचलित परिचालन गति विशेषताओं के अनुसार अंशांकित किया जाना चाहिए। इसके अलावा, परिणाम एक्सप्रेसवे पर नियमित अंतराल पर बस ले-बाय और ट्रक ड्राइवरों के विश्राम क्षेत्र प्रदान करने का संकेत देते हैं। इसके अलावा, पैदल यात्री अंडरपास का स्थान एक्सप्रेसवे के आसपास के गांवों की उपस्थिति के आधार पर निर्धारित किया जाना चाहिए।

संक्षेप में, यह अध्ययन भारत में विभाजित 4L और 6L राजमार्गों पर विषम यातायात के मामले में पक्के कंधों की सुरक्षा प्रभावशीलता का आकलन करने का एक पहला प्रयास था। अध्ययन ने प्रदर्शित किया कि हस्तक्षेपों के सुरक्षा प्रभावों का आकलन करने के लिए सीमित डेटा उपलब्धता परिदृश्य में मिलान की गई C-C पद्धति एक वैकल्पिक विधि हो सकती है। इस अध्ययन के परिणाम भारत में सड़क के स्वामित्व वाली एजेंसियों को सुरक्षा में सुधार के लिए सड़क सुरक्षा उपायों में से एक के रूप में पक्के कंधों पर विचार करने में मदद करेंगे। विशेष रूप से पेव्ड शोल्डर का प्रावधान VRUs की सुरक्षा को बढ़ा सकता है, विशेष रूप से मोटर चालित दुपहिया वाहन (MTW) उपयोगकर्ताओं की। यह मल्टीलेन हाईवे पर कई घातक दुर्घटनाओं के जोखिम को भी कम कर सकता है। हालाँकि, इस अध्ययन में प्रस्तुत परिणाम डेटा विशिष्ट हैं। भविष्य में, विस्तृत डेटाबेस का उपयोग करते हुए विभिन्न इंटरसिटी राजमार्गों पर अतिरिक्त अध्ययन से पक्की शोल्डर की चौड़ाई की सुरक्षा प्रभावशीलता का निर्णायक सबूत प्रदान करने में मदद मिलेगी। इसके अलावा, यह अध्ययन भारत में सड़क सुरक्षा जोखिम कारकों के लिए एक समृद्ध और केंद्रीकृत डेटाबेस विकसित करने के लिए एक मजबूत मामला बनाता है। इस तरह के डेटाबेस शोधकर्ताओं को उन्नत शोध करने में मदद करेंगे, अंततः दुर्घटनाओं और उनके सामाजिक बोझ को कम करने के लिए अनुसंधान-आधारित निष्कर्षों और सुरक्षा हस्तक्षेपों को बढ़ावा देंगे। इसी तरह की तर्ज पर, यह भी सिफारिश की जाती है कि प्रत्येक राज्य के पुलिस विभाग के भीतर एक समर्पित क्रैश डेटा रिकॉर्डिंग सिस्टम विकसित किया जाना चाहिए। इसके अलावा, दुर्घटनाओं की कम रिपोर्टिंग से निपटने के लिए अस्पताल और पुलिस डेटाबेस को समय पर जोड़ा और अद्यतन किया जाना चाहिए।

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List of Abbreviations

Abbreviation	Definition
AADT	annual average daily traffic
AASTHO	The American Association of State Highway and Transportation Officials
ADT	average daily traffic
ASA	American Statistical Association
ATCC	automatic traffic counter and classifier
B-A	Before-after
CAGR	compound annual growth rate
C-C	Case-control
CI	confidence intervals
CMFs	crash modification factors
CRPNB	correlated random parameter negative binomial
EASTS	Eastern Asia Society for Transportation Studies
EB	empirical Bayes
FHWA	The Federal Highway Administration
FIR	first information report
FPNB	fixed parameter negative binomial
GBD	Global Burden of Disease
GDP	gross domestic product
GIS	geographic information system

GQ	Golden quadrilateral
GVA	gross value addition
HIC	high-income countries
HSM	The Highway Safety Manual
IHMCL	Indian Highways Management and Corporation Limited
IPC	Indian Penal Code
IRC	Indian Roads Congress
LASER	light amplification by stimulation emission of radiation
LCVs	light commercial vehicles
LHS	left-hand side
LMIC	low-and middle-income countries
MATLAB	MATrix LABoratory
MLE	maximum likelihood estimation
MoRTH	Ministry of Road Transport and Highways
MTW	motorized two-wheelers
MVA	Motor Vehicles Act
M3W	motorized three-wheeler
NB	negative binomial
NCHRP	The National Cooperative Highway Research Program
NHs	national highways
NHAI	National Highways Authority of India
NHDP	National Highways Development Project
NHIDCL	National Highways and Infrastructure Development Corporation Limited
NLOGIT	nested logit

NMV	non-motorized vehicle
OR	odds ratio
PDO	property damaged only
Prob	probability
PS	propensity score
RCTs	randomized control trials
RHS	right-hand side
RTIs	road traffic injuries
ROR	run-off-road
RPNB	random parameter negative binomial
RTCs	road traffic crashes
RTI	road traffic injuries
SDGs	sustainable development goal
SE	standard error
SH	state highway
SPFs	safety performance functions
SVCs	single-vehicle crashes
SW	Shoulder width
TRID	Transport Research International Documentation
UN	United Nations
UP	Uttar Pradesh
US	United States
VKT	vehicle kilometres travelled
VMT	vehicle miles travelled
VRUs	vulnerable road users

WHO	World Health Organisation
YE	Yamuna Expressway
YEIDA	Yamuna Expressway Industrial Development Authority
2L	Two-lanes
4L	Four-lanes
6L	Six-lanes