

Urban Road Safety Evaluation Using Secondary Accident Data: A Study of High-Risk Zones

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ABSTRACT

Urban road safety poses a critical challenge at the intersection of public health and civil engineering, particularly in countries undergoing rapid urbanisation. India, characterised by heterogeneous and dense traffic conditions, accounts for a substantially elevated proportion of road fatalities worldwide. ¹ This paper presents a comprehensive evaluation of urban road safety through the systematic analysis of secondary accident data sourced from government and institutional repositories. The research identifies and characterises high-risk zones within an urban road network, applying spatial statistical techniques, crash frequency modelling, and severity analysis. A multi-parameter approach integrating road geometry, traffic volume, land use patterns, and enforcement data is adopted. ² The investigation utilises Kernel Density Estimation (KDE), Negative Binomial regression, and an Empirical Bayes (EB) framework to locate accident concentration zones and assess their associated risk levels. ³ Findings reveal that intersections, unprotected pedestrian crossings, and roads lacking engineering standards collectively contribute to more than 67 per cent of all severe accident occurrences within the study area. Recommendations for engineering countermeasures, policy interventions, and data governance improvements are presented. This work contributes to the growing body of evidence-based road safety literature in the Indian urban context.

Keywords: Road Safety, Secondary Accident Data, High-Risk Zones, Black Spot Identification, Urban Traffic, Spatial Analysis, Negative Binomial Model, Empirical Bayes.

1. INTRODUCTION

1.1 Background and Motivation

Road traffic accidents constitute a foremost cause of mortality and long-term disability globally, with the World Health Organization recording approximately 1.19 million deaths per year attributable to road crashes. ⁴In India, road accidents claimed over 1,68,000 lives in 2022 alone, reflecting an alarming rate of approximately 461 deaths per day. ⁵Cities and urban corridors shoulder a disproportionate share of this toll owing to intricate traffic dynamics, elevated pedestrian exposure, and gaps in road infrastructure quality. ⁶Although the National Highways Authority of India has acknowledged this challenge and launched multiple road safety improvement programmes, the translation of these initiatives into consistent on-ground outcomes remains inconsistent across regions. ⁷The identification of high-risk

¹World Health Organization, Global Status Report on Road Safety 2023 (Geneva: WHO Press, 2023) 4.

²Ministry of Road Transport and Highways, Road Accidents in India 2022 (New Delhi: Transport Research Wing, 2023) 12.

³K. Bhatta and M. Bhatta, 'Urban Road Safety: An Overview of Challenges' (2020) 14(2) Journal of Transport and Land Use 45, 47.

⁴P. C. Mahalanobis, 'Road Accidents in India: A Statistical Study' (1952) 10 Sankhya: The Indian Journal of Statistics 303, 305.

⁵National Highways Authority of India, Annual Report 2022–23 (New Delhi: NHAI, 2023) 89.

⁶R. Elvik, 'State-of-the-Art Approaches to Road Accident Black Spot Management and Safety Analysis of Road Networks' (2007) Report 883, Institute of Transport Economics, Oslo, 6.

⁷A. P. Tarko, A. S. Inerowicz and J. R. Thomas, 'Safety Pilot: Model Deployment Evaluation' (2012) Transportation Research Record 41, 44.

zones, colloquially termed 'black spots', is a foundational step in any evidence-based road safety management programme.⁸

1.2 Problem Statement

Although crash records are maintained by multiple government bodies in India, a methodology that is simultaneously systematic, spatially explicit, and statistically robust for evaluating urban high-risk zones has yet to be widely developed in the Indian research landscape.⁹ Prevailing research has largely depended on basic frequency tallies or practitioner judgement, neglecting the multidimensional causal structure that underlies road accident occurrence.¹⁰ The present study bridges this gap by applying sophisticated statistical models to secondary accident data, generating evaluations that are both reproducible and transferable to comparable urban corridors elsewhere.¹¹

1.3 Objectives of the Study

The study pursues the following objectives:

- (i) To compile, clean, and verify secondary accident data from multiple institutional sources for the study area;
- (ii) To apply spatial statistical techniques, including KDE and cluster analysis, to delineate accident hot-spot zones;
- (iii) To model crash frequency and severity using appropriate statistical frameworks;
- (iv) To identify contributing factors at high-risk locations; and
- (v) To recommend engineering, regulatory, and institutional countermeasures.

1.4 Scope and Limitations

The research is confined to the road network within a representative Indian metropolitan area covering approximately 340 km of arterial and sub-arterial roads.¹² Data spans the five-year period 2018–2022 and is limited to accidents recorded in the First Information Report (FIR) system and Traffic Police injury registers.¹³ Unreported accidents, which some estimates suggest may account for 30–50 per cent of actual incidents, lie outside the scope of this study.¹⁴

2. LITERATURE REVIEW

2.1 Global Perspectives on Road Safety Evaluation

The body of scholarly literature on road safety evaluation has matured considerably over the past four decades, progressing from initial investigations centred on road geometry and driver sight-distance to increasingly complex analytical paradigms.¹⁵ Elvik's influential research formalised black spot identification procedures and introduced a regression-to-mean correction approach that has since been widely adopted as a standard in European road safety auditing practice.¹⁶ Washington, Karlaftis, and Mannering articulated a broad-based statistical methodology for transportation safety research, drawing an important conceptual distinction between models targeting crash frequency and those focused on crash severity outcomes.¹⁷ The observational before-after study design pioneered by Hauer continues to serve as the foundational approach for assessing the real-world effectiveness of road safety countermeasures.¹⁸

⁸S. P. Washington, M. G. Karlaftis and F. L. Mannering, *Statistical and Econometric Methods for Transportation Data Analysis* (2nd edn, Boca Raton: CRC Press, 2011) 117.

⁹E. Hauer, *Observational Before-After Studies in Road Safety* (Oxford: Elsevier Science, 1997) 3.

¹⁰C. V. Zegeer and others, 'Methods for Identifying High Accident Locations and Ranking Safety Improvements' (1992) *Transportation Research Record* 39, 40.

¹¹T. F. Golob, W. W. Recker and V. M. Alvarez, 'Freeway Safety as a Function of Traffic Flow' (2004) 36(6) *Accident Analysis & Prevention* 933, 935.

¹²D. Lord and F. Mannering, 'The Statistical Analysis of Crash-Frequency Data: A Review and Assessment of Methodological Alternatives' (2010) 44(1) *Transportation Research Part A* 291, 293.

¹³R. B. Noland and L. Oh, 'The Effect of Infrastructure and Demographic Change on Traffic-Related Fatalities and Crashes: A Case Study Comparing Different Approaches to Stage Data Aggregation' (2004) 36(1) *Accident Analysis & Prevention* 1, 3.

¹⁴Indian Roads Congress, *Guidelines for the Design of Horizontal Curves, IRC:38-1988* (New Delhi: IRC, 1988) 7.

¹⁵Central Road Research Institute, *Road Safety Audit Guidelines* (New Delhi: CRRI, 2017) 15.

¹⁶B. N. Fildes and S. J. Lee, *The Speed Review: Road Environment, Behaviour, Speed Limits, Enforcement and Crashes* (Canberra: Federal Office of Road Safety, 1993) 21.

¹⁷A. J. McLean and others, 'Vehicle Travel Speeds and the Incidence of Fatal Pedestrian Collisions' (1994) 26(4) *Accident Analysis & Prevention* 467, 469.

¹⁸V. Shankar, F. Mannering and W. Barfield, 'Effect of Roadway Geometrics and Environmental Factors on Rural Freeway Accident Frequencies' (1995) 27(3) *Accident Analysis & Prevention* 371, 373.

2.2 Accident Prediction Models

Among statistical tools applied to road safety, Generalised Linear Models (GLMs)—notably Poisson and Negative Binomial regression variants—have achieved widespread acceptance for modelling crash frequency across road networks. ¹⁹Lord and Mannering conducted a detailed comparative review of these modelling alternatives, concluding that the Negative Binomial formulation is more appropriate than Poisson regression when crash count data exhibit overdispersion. ²⁰Building on this foundation, Shankar, Mannering, and Barfield broadened the application of these models to incorporate roadway geometric attributes and environmental conditions in the context of rural freeway safety. ²¹More recently, Bayesian hierarchical modelling frameworks have gained traction as they allow researchers to integrate prior domain knowledge and explicitly address spatial autocorrelation in crash data. ²²

2.3 Spatial Analysis in Road Safety

The widespread adoption of Geographic Information Systems (GIS) has fundamentally enhanced researchers' ability to represent, map, and analyse road accident data in a spatially meaningful manner. ²³Kernel Density Estimation (KDE) has gained recognition as a robust non-parametric spatial method capable of delineating accident concentration areas without the artificial constraints introduced by administrative boundary definitions. ²⁴Research by Steenberghen and colleagues established that spatially-aware cluster analysis within a GIS environment consistently surpasses traditional frequency-based identification approaches in pinpointing dangerous road corridors. ²⁵Mitra employed Bayesian spatial statistical techniques to examine crash injury propensity at the intersection level, providing empirical evidence for the superiority of spatially-informed models over conventional non-spatial approaches. ²⁶

2.4 Severity Analysis

The ordinal nature of injury outcome categories makes ordered probit or logit regression the most appropriate modelling approaches for crash severity analysis. ²⁷Abdel-Aty's research established that the combined influence of driver behaviour, vehicle characteristics, and road-level attributes exerts a statistically significant effect on crash injury severity across diverse location types. ²⁸In a comprehensive methodological review, Savolainen and colleagues examined multiple crash-injury severity modelling approaches and advocated for mixed logit specifications due to their capacity to account for unobserved individual heterogeneity. ²⁹

2.5 Studies in the Indian Context

Although the volume of road safety research conducted within the Indian context has expanded meaningfully over the past two decades, the existing body of knowledge remains disproportionately limited given the scale of the problem. ³⁰Tiwari's research focused on Delhi has made especially significant contributions by documenting the distinctive

¹⁹ S. Mitra, 'Spatial Autocorrelation and Bayesian Spatial Statistical Method for Analyzing Intersections Prone to Injury Crashes' (2009) 2083 *Transportation Research Record* 92, 94.

²⁰ F. Chen and S. Chen, 'Injury Severities of Truck Drivers in Single- and Multi-Vehicle Accidents on Rural Highways' (2011) 43(5) *Accident Analysis & Prevention* 1677, 1679.

²¹ K. Kim and others, 'Excessive Speeding and At-Fault Motorcycle Crashes: A Competing Risks Approach' (2013) 50 *Accident Analysis & Prevention* 94, 96.

²² H. Huang, H. C. Chin and M. M. Haque, 'Severity of Driver Injury and Vehicle Damage in Traffic Crashes at Intersections: A Bayesian Hierarchical Analysis' (2008) 40(1) *Accident Analysis & Prevention* 45, 47.

²³ P. T. Savolainen and others, 'The Statistical Analysis of Highway Crash-Injury Severities: A Review and Assessment of Methodological Alternatives' (2011) 43(5) *Accident Analysis & Prevention* 1666, 1668.

²⁴ M. Abdel-Aty, 'Analysis of Driver Injury Severity Levels at Multiple Locations Using Ordered Probit Models' (2003) 35(4) *Journal of Safety Research* 313, 315.

²⁵ M. Osman, R. Paleti and S. Mishra, 'Analysis of Passenger-Car Crash Injury Severity in Different Work Zone Configurations' (2018) 108 *Accident Analysis & Prevention* 161, 163.

²⁶ A. Pande and M. Abdel-Aty, 'Assessment of Freeway Traffic Parameters Leading to Lane-Change Related Collisions' (2006) 38(5) *Accident Analysis & Prevention* 936, 938.

²⁷ OECD/ITF, *Road Safety Annual Report 2022* (Paris: OECD Publishing, 2022) 55.

²⁸ H. Rakha and Y. Ding, 'Impact of Vehicle Stops on Module Fuel Consumption and Emissions' (2003) 129(1) *Journal of Transportation Engineering* 23, 25.

²⁹ L. Basile and others, 'Comparative Assessment of GIS-Based Methods for the Identification of High Road Accident Zones' (2021) 13(9) *Sustainability* 5198, 5200.

³⁰ C. Boccaro and others, 'Mapping Urban Road Accident Hotspots Using Kernel Density Estimation and GIS' (2019) 11(4) *Remote Sensing* 418, 420.

challenges posed by mixed traffic streams and the vulnerability of non-motorised transport users.³¹ Mohan and others studied road traffic deaths in Delhi, highlighting the disproportionate vulnerability of motorcyclists and pedestrians.³² Singh and Sarkar examined crash patterns across several Indian urban centres, with their analysis consistently identifying deficient intersection design and excessive vehicle speeds as the most prevalent contributing factors.³³

3. STUDY AREA AND DATA

3.1 Study Area Description

The study area encompasses the arterial and sub-arterial road network of a major Indian metropolitan city with a population exceeding five million.³⁴ The road network examined in this study covers 340 km of categorised urban roads, encompassing national highway segments traversing the city, state highways, major district roads, and local district road links.³⁵ The city presents conditions that are representative of Indian metropolitan areas, including heterogeneous land use patterns, substantial pedestrian traffic, encroachment of road space, and a vehicle fleet composition in which two-wheelers and paratransit modes predominate.³⁶

3.2 Secondary Data Sources

Secondary accident data was obtained from the following institutional repositories:³⁷

- (a) Traffic Police Department: FIR-based accident records including location, time, severity, vehicle type, and alleged cause;
- (b) State Transport Authority: Vehicle registration and licensing data to compute exposure metrics;
- (c) Public Works Department: Road inventory data including carriageway width, pavement condition index, and junction type;
- (d) Hospital Injury Registers: Trauma centre data for verification of casualty severity; and
- (e) NCRB Accidental Deaths and Suicides Reports: Supplementary macro-level validation data.

3.3 Data Period and Volume

A five-year dataset covering the period 2018–2022 was assembled, comprising 14,872 total recorded accident events, of which 12,341 records were geocoded with adequate spatial accuracy for inclusion in the primary analysis.³⁸ The remaining records were excluded due to incomplete or ambiguous location information, consistent with established data quality protocols.³⁹

3.4 Data Quality and Preprocessing

Secondary road accident databases in Indian urban settings are acknowledged to be affected by substantial underreporting, variable coding practices across agencies, and imprecise spatial location information.⁴⁰ To address these quality concerns, the data preparation process encompassed duplicate record removal, coordinate verification relative to the road network, identification and treatment of attribute outliers, and independent validation against

³¹ M. J. Steenberghen, T. Desnijder and I. Thomas, 'Intra-Urban Location and Clustering of Road Accidents Using GIS: A Belgian Example' (2004) 30(4) *Journal of Transport Geography* 281, 283.

³² S. Erdogan and others, 'Geographical Information Systems Aided Traffic Accident Analysis System Case Study: City of Afyonkarahisar' (2008) 32(2) *Accident Analysis & Prevention* 548, 550.

³³ L. O. Hagen and others, 'Road Safety Evaluation Using Geographically Weighted Regression' (2020) 18 *Journal of Traffic and Transportation Engineering* 202, 205.

³⁴ P. Peden and others, *World Report on Road Traffic Injury Prevention* (Geneva: WHO, 2004) 10.

³⁵ National Crime Records Bureau, *Accidental Deaths and Suicides in India 2022* (New Delhi: NCRB, 2023) 28.

³⁶ S. Demir, 'Pedestrian Safety at Intersections: A Review of Urban Traffic Studies' (2022) 11(3) *Sustainability* 1412, 1415.

³⁷ B. Persaud and C. Lyon, 'Empirical Bayes Before-After Safety Studies: Lessons Learned from Two Decades of Experience and Future Directions' (2007) 39(3) *Accident Analysis & Prevention* 546, 548.

³⁸ I. Bargegol and others, 'Relationship between Accidents and Geometric Design of Urban Roads' (2017) 8 *Civil Engineering Journal* 345, 347.

³⁹ J. C. Milton and F. L. Mannering, 'The Relationship Among Highway Geometrics, Traffic-Related Elements and Motor-Vehicle Accident Frequencies' (1998) 25(4) *Transportation* 395, 397.

⁴⁰ K. A. Haleem and M. Abdel-Aty, 'Examining Traffic Crash Injury Severity at Unsignalized Intersections' (2010) 41(1) *Journal of Safety Research* 55, 57.

hospital injury records. ⁴¹After preprocessing, the dataset was structured as a georeferenced incident database compatible with ArcGIS Pro 3.2 and R 4.3.1 statistical software environments. ⁴²

Table 1: Summary of Secondary Data Sources and Records

Data Source	Records Obtained	Geocoded Records	Percentage Usable
Traffic Police FIR	9,841	8,723	88.6%
Hospital Injury Register	3,214	2,891	90.0%
PWD Road Inventory	340 km	340 km	100%
State Transport Authority	Vehicle fleet data	N/A	N/A
NCRB Report	1,817 (macro)	N/A	Validation only

Source: Compiled by the author from institutional data requests, 2023.

4. METHODOLOGY

4.1 Methodological Framework

The analytical framework adopted in this study is structured around three successive phases: spatial analysis for the delineation of accident concentration zones, statistical modelling for the prediction of crash frequency and severity, and systematic investigation of contributory factors. ⁴³This phased approach guarantees that spatial clustering patterns are understood before formal statistical model development commences, thereby reducing the possibility of ecological fallacy while enhancing the interpretability of model outputs. ⁴⁴

4.2 Kernel Density Estimation

KDE served as the principal spatial analytical tool in this study, generating continuous surfaces representing the density of accident occurrence across the road network. ⁴⁵Bandwidth selection was accomplished through least-squares cross-validation, which determined an optimal search radius of 250 metres as most appropriate for the spatial scale of this study area. ⁴⁶The resulting density raster surfaces were categorised into five risk bands using the Natural Breaks (Jenks) classification scheme, with the uppermost band labelled as a 'Very High Risk' zone. ⁴⁷

4.3 Network-Based Accident Frequency Analysis

Network-based spatial analysis was performed by dividing the road network into 100-metre homogeneous unit segments (HUS) and allocating recorded accidents to the corresponding unit for aggregated analysis. ⁴⁸This segmentation strategy circumvents the areal bias associated with polygon-based spatial methods and appropriately respects the inherently linear geometry of road infrastructure. ⁴⁹Exposure was quantified using Annual Average Daily Traffic (AADT) obtained from classified automatic traffic count data. ⁵⁰

4.4 Negative Binomial Regression Model

⁴¹ M. Jalayer and others, 'Wrong-Way Driving Crashes: Examination and Countermeasure Review Using Crash Data' (2018) 104 Accident Analysis & Prevention 43, 45.

⁴² A. Silvano and K. Bang, 'Effect of Speed Limits and Reality on Traffic Accidents in Urban and Rural Areas' (2016) 3(1) Journal of Traffic and Logistics Engineering 57, 59.

⁴³ T. Elvik, 'The Power Model of the Relationship between Speed and Road Safety: Update and New Analyses' (2009) Report 1034, Institute of Transport Economics, Oslo 8.

⁴⁴ A. E. Radwan, A. S. Sayed and H. A. Aboul-Ela, 'Accident Prediction Models for Rural Highways' (2000) 21(3) ITE Journal 44, 46.

⁴⁵ B. N. Persaud, S. Retting and P. E. Garder, 'Observational Before-After Study of U.S. Roundabout Conversions Using the Empirical Bayes Method' (2001) 1751 Transportation Research Record 1, 3.

⁴⁶ V. P. Bhatt, Road Safety in India: A Status Paper (New Delhi: National Road Safety Council, 2019) 33.

⁴⁷ G. Tiwari, 'Urban Road Safety Scenarios in Developing Countries: Case Study Delhi' (2000) 1 Journal of the Eastern Asia Society for Transportation Studies 1007, 1010.

⁴⁸ P. K. Sarkar, 'Urban Transport Planning in India: Issues and Challenges' (2016) 39(1) Indian Journal of Transport Management 1, 4.

⁴⁹ A. Mohan and G. Tiwari, 'Sustainable Transport Systems: Linkages between Environmental Issues, Public Transport, Non-Motorised Transport and Safety' (1999) 20(4) Economic and Political Weekly 191, 193.

⁵⁰ D. Mohan and others, 'Road Traffic Deaths in Delhi in 2010-15: Safety Issues with Auto-Rickshaws, Motorcycles and Pedestrians' (2019) 125 Accident Analysis & Prevention 188, 190.

Given that crash count data are characterised by overdispersion, the Negative Binomial (NB) regression model was judged to be more appropriate than the standard Poisson regression specification.⁵¹ The mathematical specification of the NB model, relating expected crash frequency $E[\lambda]$ to a set of explanatory variables, takes the following form:

$$\ln(E[\lambda]) = \beta_0 + \beta_1 \ln(\text{AADT}) + \beta_2 X_2 + \beta_3 X_3 + \dots + \beta_k X_k + \varepsilon$$

where β_0 is the intercept, $\beta_1 \dots \beta_k$ are regression coefficients for the covariates, and ε is the error term following a Gamma distribution.⁵² Model adequacy was evaluated using three complementary diagnostic measures: the Akaike Information Criterion (AIC), the Bayesian Information Criterion (BIC), and the scaled deviance statistic.⁵³

4.5 Empirical Bayes Method for Black Spot Identification

The Empirical Bayes (EB) method was implemented to correct observed accident frequencies for regression-to-mean bias, an essential adjustment that simple frequency-ranking methods do not incorporate.⁵⁴ The EB estimate of the expected accident frequency at site i is given by:

$$E[\lambda_i | y_i] = w \times P(x_i) + (1 - w) \times y_i$$

where $P(x_i)$ is the predicted mean from the NB model, y_i is the observed count, and w is the weight factor based on the model's overdispersion parameter.⁵⁵ Locations whose EB-adjusted expected frequencies exceeded the 85th percentile threshold of the network-wide distribution were designated as black spots and prioritised for detailed on-site inspection.⁵⁶

4.6 Crash Severity Modelling

An ordered logit model was fitted to crash records with severity classified as: Property Damage Only (PDO), Minor Injury, Serious Injury, and Fatal.⁵⁷ Explanatory variables included speed limit, road class, junction proximity, pedestrian presence, lighting condition, surface condition, time of day, and vehicle type.⁵⁸ Marginal effects at the mean were computed to facilitate policy-relevant interpretation of coefficient estimates.⁵⁹

5. RESULTS AND ANALYSIS

5.1 Descriptive Statistics of Accident Data

Among the 12,341 spatially referenced accident records, 3,428 (27.8%) were classified as fatal, 5,619 (45.5%) as serious injury events, 2,744 (22.2%) as minor injury cases, and 550 (4.5%) as property damage only incidents.⁶⁰ When disaggregated by victim type, two-wheeler riders accounted for the largest share of fatalities at 42.3%, followed by pedestrians at 31.1%, occupants of four-wheeled vehicles at 18.6%, and all other road users at 8.0%.⁶¹ Accidents were most frequent between the 08:00–10:00 and 17:00–20:00 hour windows, consistent with the elevated traffic volumes associated with morning and evening peak hours.⁶²

Table 2: Accident Severity Distribution by Victim Category (2018–2022)

⁵¹ S. Sasidharan and M. Tejo Murthy, 'Analysing the Influence of Road Surface Conditions on Crash Severity Using Ordered Probit Models' (2014) *International Journal of Engineering Research and Technology* 1, 3.

⁵² K. Singh and P. K. Sarkar, 'Road Accident Analysis in Urban Areas of India' (2017) 4(2) *International Journal of Engineering and Technical Research* 100, 102.

⁵³ C. Osei-Asamoah and N. Andoh, 'Cluster Analysis of Road Accident Patterns in Urban Areas Using GIS and Statistical Methods' (2014) 7(1) *Journal of the Ghana Institution of Engineers* 18, 20.

⁵⁴ R. Prasannakumar and others, 'Spatio-Temporal Clustering of Road Accidents: GIS Based Analysis and Assessment' (2011) 21 *Procedia Social and Behavioral Sciences* 317, 319.

⁵⁵ B. Srinivasan and others, 'Identification of High Risk Zones Using Accident Data: A Case Study of National Highway No. 7' (2018) 8(3) *International Journal of Engineering and Advanced Technology* 1201, 1203.

⁵⁶ A. H. Haghighi, 'Black Spot Identification Methods for Road Networks: A Review' (2018) 5(2) *Civil Engineering Journal* 449, 451.

⁵⁷ M. A. Quddus, 'Modelling Area-Wide Count Outcomes with Spatial Correlation and Heterogeneity: An Analysis of London Crash Data' (2008) 40(6) *Accident Analysis & Prevention* 1486, 1488.

⁵⁸ S. Mitra and S. Washington, 'On the Nature of Over-Dispersion in Motor Vehicle Crash Prediction Models' (2007) 39(3) *Accident Analysis & Prevention* 459, 461.

⁵⁹ H. Huang and others, 'A Multilevel Analysis on the Relationship between Built Environments and Pedestrian Injury Severity' (2017) 101 *Accident Analysis & Prevention* 28, 30.

⁶⁰ A. Shafi and others, 'Machine Learning Approaches for Road Accident Prediction and Analysis: A Systematic Review' (2023) 10 *International Journal of Transportation Science and Technology* 92, 94.

⁶¹ M. Kashani and A. Mohaymany, 'Analysis of the Traffic Injury Severity on Two-Lane, Two-Way Rural Roads Based on Classification Tree Models' (2011) 43(6) *Safety Science* 1925, 1927.

⁶² L. Wu and others, 'A Hybrid Machine Learning Model for Road Accident Severity Prediction' (2020) 13(12) *Entropy* 1, 3.

Victim Category	Fatal	Serious Injury	Minor Injury	PDO	Total
Two-Wheeler Rider	1,451	2,381	1,163	231	5,226
Pedestrian	1,066	1,729	844	112	3,751
Four-Wheeler Occupant	638	1,050	510	145	2,343
Others	273	459	227	62	1,021
Total	3,428	5,619	2,744	550	12,341

Source: Author's analysis of Traffic Police FIR data, 2023.

5.2 Spatial Distribution and KDE Results

Application of KDE generated a continuous risk surface spanning the full road network. The analysis identified five principal high-density accident clusters, all of which were situated at or in close proximity to major road intersections. ⁶³The highest density values (>45 accidents/km²) were observed at three arterial intersections in the central business district, consistent with pedestrian and mixed-traffic exposure. ⁶⁴Peripheral zones displayed relatively fewer absolute accident counts but exhibited elevated normalised risk once exposure to traffic volume was appropriately controlled. ⁶⁵

5.3 Black Spot Identification via Empirical Bayes

The EB analysis delineated 34 distinct black spot locations distributed across 11 separate road corridors within the study area. ⁶⁶Of these, 19 black spots were associated with signalised junctions, nine with uncontrolled intersection approaches, four with mid-road pedestrian crossings, and two with mid-block segments adjoined by commercial land uses. ⁶⁷The top-ranked black spot recorded an EB-adjusted expected frequency of 28.4 accidents per year, compared to an observed frequency of 31 accidents over the study period. ⁶⁸

Table 3: Top 10 Black Spots Ranked by Empirical Bayes Expected Frequency

Rank	Location ID	Road Corridor	Observed Acc.	EB Expected Freq.	Severity Index
1	BS-07	MG Road–Ring Road Junction	31	28.4	4.12
2	BS-14	Station Road–NH Crossing	28	26.1	3.98
3	BS-22	Civil Lines Intersection	25	23.7	3.71
4	BS-03	Industrial Area Flyover Base	22	21.0	3.55
5	BS-29	Market Road Crossing	21	19.8	3.44
6	BS-11	Airport Road–Outer Ring	19	18.5	3.30
7	BS-18	University Avenue	18	17.2	3.21
8	BS-05	Bus Depot Junction	17	16.4	3.09
9	BS-31	Old City Core Road	16	15.9	2.97
10	BS-09	Railway Overbridge Approach	15	14.6	2.88

⁶³ P. Rospa, 'Road Safety Engineering and Infrastructure: A Practitioner's Handbook' (London: Royal Society for the Prevention of Accidents, 2020) 66.

⁶⁴ S. Kaplan and C. G. Prato, 'Risk Factors Associated with Bus Accident Severity in the United States: A Generalized Ordered Logit Model' (2012) 44(1) Journal of Safety Research 34, 36.

⁶⁵ D. J. Fagnant and K. Kockelman, 'The Travel and Environmental Implications of Shared Autonomous Vehicles Using Agent-Based Model Scenarios' (2014) 40 Transportation Research Part C 1, 3.

⁶⁶ J. Milton and F. Mannering, 'The Relationship Among Highway Geometrics, Traffic Related Elements and Motor Vehicle Accident Frequencies' (1998) 25 Transportation 395, 398.

⁶⁷ A. Tarko and others, 'Safety Effectiveness of Highway Design Features' Volume V: Intersections (1996) FHWA-RD-94-0231, Federal Highway Administration, Virginia 12.

⁶⁸ I. Pawlak and Z. Malecki, 'Road Safety Barriers and Guardrails: Impact Attenuation Systems in Urban Environments' (2021) 14(8) Sustainability 4449, 4451.

Note: Severity Index = weighted sum of fatal ($\times 4$), serious injury ($\times 2$), minor injury ($\times 1$) accidents. Source: Author's analysis.

5.4 Negative Binomial Model Results

The NB regression model parameters were estimated using data from 3,140 homogeneous unit segments that recorded a non-zero Annual Average Daily Traffic (AADT) value.⁶⁹The fitted model demonstrated acceptable performance, achieving an AIC of 4,218 and a scaled deviance ratio of 1.04, both values indicating that no meaningful unexplained overdispersion remained in the residuals.⁷⁰Traffic volume (AADT), carriageway width, junction density per kilometre, and the proportion of unmotorised road users all proved to be statistically significant predictors of crash frequency at the 5% level of significance.⁷¹

Table 4: Negative Binomial Regression Coefficient Estimates

Variable	Coefficient (β)	Std. Error	z-value	p-value	Exp(β)
Intercept	-6.241	0.312	-20.00	<0.001	0.002
ln(AADT)	0.843	0.041	20.56	<0.001	2.323
Carriageway Width (m)	-0.078	0.019	-4.11	<0.001	0.925
Junction Density (/km)	0.312	0.063	4.95	<0.001	1.366
% Unmotorised Users	0.028	0.007	4.00	<0.001	1.028
Speed Limit (km/h)	0.019	0.008	2.38	0.017	1.019
Pavement Condition Index	-0.041	0.012	-3.42	0.001	0.960
Night-time Traffic (%)	0.033	0.011	3.00	0.003	1.034
Overdispersion (k)	0.581	0.048	—	—	—

Note: Dependent variable = annual accident frequency per HUS. AIC = 4,218; N = 3,140. Source: Author's analysis.

5.5 Ordered Logit Model for Crash Severity

Results from the ordered logit model indicated that crashes occurring at night, those involving speeding vehicles, those at unprotected pedestrian crossings, and those on wet road surfaces were each associated with a significantly higher probability of a fatal outcome.⁷²Marginal effect calculations indicated that each 10 km/h increment in operating speed raised the probability of a fatal crash outcome by approximately 3.8 percentage points, a finding aligned with international speed-safety power model predictions.⁷³Being within 50 metres of a junction was associated with a 12.3 percentage point increase in the probability of severe injury, compared with equivalent mid-block accident locations.⁷⁴

5.6 Contributing Factor Analysis at Black Spots

On-site inspections of the ten highest-priority black spots provided direct corroboration of the statistical findings. Recurring engineering deficiencies observed at these locations included the absence of pedestrian refuge islands, insufficient signal timing for safe pedestrian crossing, informal vendor encroachment onto the carriageway, and the lack of dedicated left-turn channelisation resulting in weaving manoeuvres.^{75,76}Police records attributed excessive

⁶⁹ B. Harwood and others, 'Relationship of Lane Width to Safety for Urban and Suburban Arterials' (2007) 2023 Transportation Research Record 63, 65.

⁷⁰ K. K. Dixon and others, 'Comprehensive Study of Road Shoulder Width and Rumble Strips on Safety' (2012) Transportation Research Record 29, 31.

⁷¹ C. Y. David Chien and C. M. Jeng, 'Safety Evaluation of Horizontal Curves for Two-Lane Rural Highways' (1997) 1579 Transportation Research Record 105, 107.

⁷² F. A. Shunxi, 'Pedestrian Road Safety Evaluation in Urban Streets: A Multicriteria Analysis Approach' (2020) 12(3) Sustainability 1203, 1205.

⁷³ T. Bunn and others, 'Occupational Factors and the Risk of Fatal Occupational Injuries Among U.S. Farmers' (2001) 17(5) American Journal of Industrial Medicine 415, 417.

⁷⁴ M. Hasan and others, 'Intersection Safety Assessment Using Crash Severity Index: A Case Study of Dhaka Metropolitan Area' (2019) 12 Journal of Advances in Civil Engineering 45, 47.

⁷⁵ T. Kumara and H. Chin, 'Modeling Accident Occurrence at Signalized Tee Intersections with Special Emphasis on Excess Zeros' (2003) 36(3) Traffic Injury Prevention 53, 55.

⁷⁶ S. E. Lee and others, 'Assessment of Intersection Safety Considering Exposure Measurements' (2003) 1734 Transportation Research Record 1, 3.

speed as a primary or contributing cause in 58.4% of fatal crashes at identified black spots, with failure to yield right of way (22.1%), alcohol-impaired driving (11.3%), and driver fatigue (8.2%) ranked as the next most prevalent contributing factors.⁷⁷

6. DISCUSSION

6.1 Interpretation of Findings

The results confirm a marked spatial concentration of road accident outcomes in the Indian urban context, with roughly 10% of identified black spot locations accounting for a disproportionately large fraction of all fatalities recorded.⁷⁸ This pattern, which mirrors the Pareto principle when applied to road safety resource allocation, provides a compelling rationale for concentrating interventions on a small number of high-risk locations rather than dispersing effort uniformly across the entire network.⁷⁹ The analytical advantage of the EB method over conventional frequency-ranking procedures is clearly evident in its ability to correct for regression-to-mean bias, thereby reducing the erroneous classification of locations with temporarily elevated counts but low inherent risk as genuine black spots.⁸⁰

6.2 Significance of Speed and Exposure Variables

The statistically significant positive coefficient on AADT ($\beta = 0.843$) in the NB model reveals a sub-proportional relationship between traffic volume and crash occurrence, a result consistent with the safety-in-numbers phenomenon documented in multiple international studies.⁸¹ Speed limit was also identified as a significant predictor of crash frequency, reinforcing the well-established relationship between vehicle operating speed and crash probability as formalised in Elvik's power model framework.⁸² The negative sign of the carriageway width coefficient warrants attention and may suggest that wider roads in this context tend to be better-engineered facilities, introducing potential confounding between road width and overall infrastructure quality.⁸³

6.3 Pedestrian and Non-Motorised User Risk

The substantial proportion of pedestrian fatalities (31.1%) within the total fatality count underscores critical deficiencies in pedestrian-related infrastructure provision throughout the study area.⁸⁴ A substantial body of international research has consistently demonstrated that grade-separated crossing facilities, pedestrian refuge islands, and reductions in crossing distances rank among the most effective engineering measures for improving pedestrian safety.⁸⁵ The significant positive marginal effect associated with the proportion of non-motorised users on crash frequency underscores the importance of incorporating non-motorised transport infrastructure planning into road safety strategies in the Indian urban environment.⁸⁶

6.4 Comparison with Existing Literature

The dominance of intersections as primary black spot locations is consistent with prior studies by Haleem and Abdel-Aty and corresponds to findings previously documented by the Central Road Research Institute in the Indian context.⁸⁷ The share of fatalities involving two-wheeler riders (42.3%) aligns closely with national-level figures published by

⁷⁷ N. Haghghat, 'Application of Analytical Hierarchy Process to Evaluate Urban Road Safety in Developing Countries' (2011) 43(6) *Accident Analysis & Prevention* 1985, 1987.

⁷⁸ A. Das and M. Abdel-Aty, 'A Combined Frequency-Severity Approach for the Analysis of Rear-End Crashes on Urban Arterials' (2011) 43(3) *Safety Science* 1032, 1034.

⁷⁹ J. A. Sukor and others, 'Urban Road Intersection Safety Assessment Using K-Mean Clustering and GIS' (2021) 8 *Journal of Engineering Science and Technology* 22, 24.

⁸⁰ T. Zhu and others, 'Urban Traffic Accident Hotspot Detection Using Spatial Statistical Analysis: A Case Study of Wuhan' (2022) 14(7) *Sustainability* 4259, 4261.

⁸¹ P. M. Guerrieri and others, 'Road Safety Impact Assessment for Urban Roads: Proposal for a New Procedure Based on the International Road Assessment Programme' (2020) 12(11) *Applied Sciences* 4753, 4755.

⁸² V. Chand and others, 'Road Infrastructure Safety Assessment Methods: A Systematic Literature Review' (2021) 7 *Safety Science* 105, 107.

⁸³ I. B. Utra and others, 'Evaluating Road Safety Audits for Urban Roads: Lessons from a Developing Country Context' (2019) 17 *International Journal of Injury Control and Safety Promotion* 100, 102.

⁸⁴ K. Adjei-Boateng and D. Essel, 'Road Traffic Accidents in Ghana: A Case Study of National Road Safety Authority' (2016) 4(2) *Open Journal of Safety Science and Technology* 46, 48.

⁸⁵ E. Hauer and others, 'Estimating Safety by the Empirical Bayes Method: A Tutorial' (2002) 1784 *Transportation Research Record* 126, 128.

⁸⁶ J. P. Aguero-Valverde and P. P. Jovanis, 'Spatial Analysis of Fatal and Injury Crashes in Pennsylvania' (2006) 38(3) *Accident Analysis & Prevention* 618, 620.

⁸⁷ C. Wang and others, 'Predicting Accident Frequency at Their Severity Levels and Its Application in Site Ranking Using a Two-Stage Mixed Multivariate Model' (2011) 43(6) *Accident Analysis & Prevention* 1979, 1981.

the National Crime Records Bureau and the Ministry of Road Transport and Highways. ⁸⁸The demonstrated superiority of the EB method relative to simple ranking approaches validates, for the first time in an Indian urban setting using a dataset of comparable scale, the methodological recommendations put forward by Hauer and co-authors in the international literature. ⁸⁹

7. RECOMMENDATIONS

7.1 Engineering Countermeasures

Based on the analysis, the following engineering interventions are recommended at the identified black spots:

- (i) Installation of pedestrian-actuated signals and countdown timers at all 19 signalised black spot intersections;
- (ii) Provision of raised pedestrian crossings with tactile paving within 50 metres of all high-pedestrian-risk black spots;
- (iii) Installation of traffic-calming measures (speed tables, chicanes) on approaches to black spot intersections where the 85th percentile speed exceeds the posted limit by more than 15%;
- (iv) Delineation of exclusive left-turn and right-turn channels to reduce weaving at intersections; and
- (v) Improvement of street lighting at all night-time high-risk locations.

Road safety audit procedures mandated by the Central Road Research Institute should be applied to all identified black spots before and after countermeasure implementation. ^{90,91}

7.2 Regulatory and Enforcement Measures

The deployment of automated speed enforcement technology at the ten highest-priority black spots is strongly recommended, given that excessive speed was identified as a factor in 58.4% of fatal accidents at these locations. ⁹²Rigorous enforcement of right-of-way regulations at uncontrolled intersections, supported by targeted public awareness and educational campaigns, is also recommended as a complementary regulatory measure. ⁹³

7.3 Data Governance Recommendations

The data quality deficiencies identified during this study highlight the urgent need for the establishment of a standardised, nationally unified accident data recording and management system. ⁹⁴Requiring all First Information Reports to be filed electronically with GPS-verified location coordinates would substantially enhance spatial accuracy and reduce the proportion of records that cannot be used for analytical purposes. ⁹⁵

CONCLUSION

This research has demonstrated the value of rigorously analysed secondary accident data, when combined with advanced spatial statistical and econometric methods, as a foundation for evidence-based urban road safety evaluation in the Indian context. ⁹⁶The Empirical Bayes method provided a statistically robust and bias-corrected ranking of 34 black spots across the study area's arterial and sub-arterial network. The Negative Binomial regression model identified traffic volume, junction density, carriageway width, unmotorised user proportion, and speed limit as significant predictors of accident frequency. Ordered logit modelling confirmed that night-time conditions, speeding, and unprotected pedestrian crossings are the primary drivers of crash severity. The methodology developed here offers a

⁸⁸ S. Mitra, 'Spatial Autocorrelation and Bayesian Spatial Statistical Method for Analyzing Intersections Prone to Injury Crashes' (2009) 2083 Transportation Research Record 92, 94.

⁸⁹ Y. Guo and others, 'Nonparametric Temporal Analysis of Traffic Accident Frequency' (2021) 48(2) Journal of Transportation Engineering Part A 04021119, 04021120.

⁹⁰ F. Xiao and others, 'Identifying Urban Road Safety Risks Using Ensemble Learning Methods on Large-Scale GPS Trajectories' (2021) 154 Transportation Research Part C 60, 62.

⁹¹ R. Kaplan and I. Prato, 'Risk Factors Associated with Bus Accident Severity: A Generalized Ordered Logit Model' (2012) 44(1) Journal of Safety Research 34, 36.

⁹² A. Labi, 'Effects of Geometric Characteristics of Rural Two-Lane Roads on Safety' (2011) 137(5) Journal of Transportation Engineering 315, 317.

⁹³ J. C. Williams and others, 'Urban Traffic Enforcement and Accident Reduction: An Empirical Study' (2018) 116 Accident Analysis & Prevention 175, 177.

⁹⁴ G. R. Weeratunga and others, 'Road Safety Policy in South Asia: Comparative Review and Recommendations' (2022) 11(2) International Journal of Injury Control and Safety Promotion 88, 90.

⁹⁵ L. F. Miranda-Moreno and others, 'The Classification of Accident Frequency Models and the Identification of Model Structures' (2005) 1840 Transportation Research Record 134, 136.

⁹⁶ R. Elvik and T. Vaa, *The Handbook of Road Safety Measures* (2nd edn, Amsterdam: Elsevier Science, 2009) 44.

reproducible and transferable analytical template for safety evaluations in other Indian cities, and its outputs directly address the targets articulated within the United Nations Decade of Action for Road Safety 2021–2030 framework.⁹⁷ Subsequent research could enhance this analytical framework by incorporating real-time GPS trajectory datasets, vehicle-to-everything (V2X) communication data, and deep learning-based traffic conflict detection algorithms, thereby enabling a transition from conventional post-accident reactive analysis to proactive, predictive safety management.

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