Unseen tragedies: analysing accidental deaths in India

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ABSTRACT

Traffic accidents represent a critical public health and socio-economic issue in India. This manuscript examines the critical issue of accidental deaths due to traffic incidents in India, highlighting the alarming trends and underlying factors contributing to rising fatalities. The analysis employs bivariate and multivariate statistical methods, including correlation, time series analysis, multivariate factor and cluster analyses, to explore the relationships between accident severity, fatalities, and injuries. Key findings include significant positive correlations between the year and death rates, as well as between accident severity and fatalities, indicating a persistent increase in road traffic deaths over time. Notably, the severity of accidents is directly linked to higher fatality rates. The analysis identifies two primary clusters: i) time (year) severity and death, and ii) accidents and injuries. The results underscore the need for effective interventions, including improved infrastructure for non-motorized transport, enhanced road safety measures, and stricter enforcement of traffic regulations. By promoting shifts from car travel to cycling and walking, the study advocates for sustainable transportation solutions to mitigate the growing toll of road traffic accidents in India.

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1. INTRODUCTION

Traffic accidents represent a critical public health and socio-economic issue in India. In 2022 alone, India reported 472,467 traffic accidents, including 446,768 road accidents, 2,560 railway crossing accidents, and 23,139 railway accidents. These incidents led to 425,727 injuries and 194,347 fatalities, underscoring the pervasive risk that road traffic accidents (RTAs) pose to public health [1]. The majority of fatalities were associated with road accidents (88%, or 171,100 deaths), followed by railway accidents (10.7%, or 20,792 deaths) and railway crossing accidents (1.3%, or 2,455 deaths) [1]. The States such as Madhya Pradesh, Karnataka, Kerala, Tamil Nadu, and Telangana, with the highest share of accidents and fatalities in 2022, registered an accident severity rate lower than the Indian average. Uttar Pradesh, Maharashtra, Gujarat, Rajasthan, and Andhra Pradesh recorded the top amongst the States in the number of accidents and fatalities, showing accident severity rates higher than the national average [2].

The rise in traffic accidents correlates with rapid motor vehicle ownership in India. In 2011, only 6% of households owned a car; however, ownership has since surged, particularly among high-income households, now exceeding 75% [3]. This shift has coincided with a transformation in transportation modes, moving away from walking, cycling, and public transport (PT) to personal motor vehicles. There were 326 million registered vehicles in India as of March 31st, 2020. The total number of registered motor vehicles in the country grew at a compound annual growth rate (CAGR) of 9.8 per cent between 2010 and 2020. Composition of vehicular population in 2020 shows the highest share of two-wheelers (74.7%) followed by cars, jeeps, and taxis (13.4%), other vehicles (6.9%), goods vehicles (4.4%), and buses (0.7%) [2]. Between 1990 and 2015, the annual growth rate of two-wheelers and cars was approximately 9-10%, effectively doubling the private motorized fleet every 7-8 years [4], [5]. This growth has led to a notable increase in RTAs, with two-wheeler riders comprising 45.5% of road traffic fatalities, followed by car occupants (14.1%), truck/lorry drivers (8.8%), and auto-rickshaw passengers (4.5%) [1].

Globally, RTAs constitute a major public health crisis, resulting in over 1.2 million deaths annually [5], [6]. Despite a global decline in road traffic injury-related mortality from 1990 to 2017, India's share of global road traffic fatalities has risen during this period [7]. Developing countries bear a disproportionate burden, with 93% of RTA deaths occurring in low- and middle-income countries, despite accounting for only 60% of the global vehicle fleet [4], [7]. This economic burden is also significant, with losses from RTAs estimated to account for as much as 5% of GDP in low- and middle-income nations (World Health Organization, 2015) [5]. Young adults, particularly those in economically productive age groups, are especially affected, with RTAs being a leading cause of mortality among individuals aged 15-29 years (World Health Organization, 2010). The loss of life and associated long-term medical costs compound poverty by reducing household income and financial stability [5].

Despite these grave statistics, research reveals notable inconsistencies in official data on pedestrian fatalities in India. While global estimates indicate that pedestrians comprise about 40% of traffic deaths in low-income countries, official Indian reports suggest they account for less than 10%. This stark discrepancy highlights potential underreporting or data collection biases, which obscure the true scale of pedestrian vulnerability. Consequently, the lack of reliable and comprehensive data hampers the development of targeted interventions and evidence-based policies essential for reducing pedestrian-related road traffic fatalities [8], [9].

This study seeks to analyze the scale and impact of traffic accidents in India, addressing both public health and economic implications. Our aim is to propose targeted interventions to reduce the rate of fatalities and injuries resulting from RTAs. Existing approaches to mitigate traffic accidents include improved traffic legislation, enhanced enforcement of traffic laws, and public safety campaigns in countries such as Brazil, Cambodia, China, and Russia [10]-[12]. India reports an alarming number of fatalities and injuries each year, with RTAs being a leading cause of preventable deaths among economically active young adults. Despite efforts to improve road safety, India's rapidly increasing motor vehicle ownership, coupled with inadequate infrastructure and enforcement of traffic regulations, has led to a steady rise in both the frequency and severity of traffic incidents. This issue is compounded by the lack of reliable, disaggregated data, particularly on vulnerable road users such as pedestrians and cyclists, which limits the effectiveness of policy responses. Addressing this urgent public health crisis requires a robust, evidence-based approach to understanding the factors driving RTA trends and formulating targeted interventions for prevention.

However, challenges remain in data accuracy, enforcement, and public awareness. By assessing the effectiveness of existing measures and identifying persistent gaps, this study will propose a comprehensive framework to improve road safety in India. The findings of our research, followed by a discussion on implications for policy and practical interventions, are summarised in this study. This work has contributed to the broader goals of the Global Decade of Action for Road Safety by enhancing data reliability and developing actionable insights for reducing RTAs in India.

2. METHOD

Our study utilized a structured statistical approach to analyze the factors contributing to RTAs in India. This methodology combines both established and advanced analytical techniques, allowing a thorough examination of the relationships and patterns associated with accident incidence. Each analytical approach was selected to ensure a rigorous and reproducible framework for assessing RTA trends and their determinants, thereby facilitating informed conclusions for policy and intervention strategies.

2.1. Data collection and preparation

To ensure data accuracy and completeness, we sourced accident data from the National Crime Records Bureau (NCRB) and other relevant governmental reports, which provide comprehensive and standardized records of RTAs in India. Before analysis, we conducted an extensive data cleaning process, addressing missing values, anomalies, and inconsistencies to achieve a robust dataset. This preparation phase is essential to eliminate potential biases that may arise from incomplete or erroneous data, thus ensuring reliability in subsequent analyses.

2.2. Bivariate correlation analysis

To examine the relationships between various factors and accident rates, we conducted bivariate correlation analysis using Pearson's correlation coefficient. This analysis identifies associations between pairs of variables, such as vehicle type, road conditions, and weather factors, which are hypothesized to impact accident outcomes. Previous research suggests that factors like road quality and traffic density have a significant correlation with accident rates [13]. By analyzing each factor independently, we aimed to isolate potential predictors of accident frequency, setting a foundation for further multivariate analysis.

2.3. Time series analysis

To capture temporal patterns and predict accident rates, we employed time series regression analysis, focusing on the relationship between accident occurrences and independent variables, including population density, vehicle ownership, and infrastructure quality. Regression analysis is a well-established method for examining temporal data, enabling researchers to project future trends based on historical patterns [5]. This analysis also aids in identifying seasonal or annual fluctuations, which are critical for developing targeted road safety initiatives during high-risk periods. This pattern is consistent with studies by Brajesh and Shekhar [14], who found that higher-order models more accurately predicted accident fatalities over time. This increase correlates with factors such as growing vehicle ownership, overcrowded roads, and rising driver negligence, which are major contributors to accident severity in India, as reported in Khorshidi's (2020) study on fatality risk factors [15].

2.4. Multivariate factor analysis

Multivariate factor analysis was performed to uncover latent variables that contribute to RTAs. By analyzing multiple factors simultaneously, this technique helps to reduce the dimensionality of the data and reveal hidden constructs that explain the patterns observed in the dataset. Factor analysis is particularly useful in simplifying complex relationships among contributing factors, which can otherwise be challenging to interpret in isolation [4]. For instance, this analysis allowed us to distil broader categories such as "environmental factors" and "vehicle-related factors" that impact accident rates. These injury trends align with other studies noting that economic and societal disruptions, such as lockdowns, can influence road accident statistics [16].

2.5. Cluster analysis

To classify accident data into distinct groups, we conducted cluster analysis using hierarchical clustering with the correlation coefficient as the similarity index. A dendrogram was constructed to visualize the relationships among clusters, providing a clear picture of how different accident profiles are associated. This classification process helps to identify high-risk regions and demographic groups, enabling targeted interventions and policies aimed at reducing RTAs [6]. Cluster analysis is instrumental in regional RTA profiling, thus informing localized strategies for road safety enhancement.

2.6. Statistical software and analytical tools

For all statistical analyses, we utilized SPSS version 20 and Microsoft Excel. Bivariate correlation and factor analyses were conducted in SPSS, a robust platform known for its capabilities in handling large datasets and complex statistical operations. Excel was employed for time series analysis, given its functionality for regression modeling and ease of use in data visualization. This combination of software ensured precision and reproducibility in our calculations, with each tool selected to maximize accuracy in specific analytical tasks.

The methods outlined above were chosen based on their ability to provide reliable, replicable insights into the factors influencing RTAs in India. Bivariate correlation is a standard preliminary analysis for identifying potential predictor variables, while time series analysis offers a dynamic approach to assessing changes in accident rates over time. Factor analysis allowed us to distill complex datasets into manageable constructs, and cluster analysis further enhanced our understanding by categorizing high-risk profiles. Each method has been previously validated in road safety research, supporting the credibility of our approach [5], [12].

In summary, the selected methodologies enable a comprehensive exploration of the determinants of road traffic accidents (RTAs) and effectively address the key research questions outlined in the Introduction. By integrating bivariate, multivariate, and time-series analyses, this framework enhances the depth, validity, and interpretive power of the findings. Moreover, it reinforces the methodological rigor and provides a transparent, reproducible model that future researchers can adapt to examine RTA patterns, trends, and risk factors in the Indian context or comparable settings.

3. RESULTS AND DISCUSSION

In this section, we present and interpret our findings on the relationships between key parameters affecting road accidents in India. A comprehensive statistical analysis was conducted, including bivariate and multivariate analyses, time series, and cluster analyses, to elucidate the complex dynamics contributing to road accident trends and fatalities. The discussion draws comparisons with similar studies and highlights the broader implications of our findings, including their significance for policy-making and road safety interventions.

3.1. Bivariate analysis

The results of the bivariate analysis reveal significant correlations among key variables in road accident data, as detailed in Table 1. For example, a notable positive correlation was identified between accident severity and the number of resulting fatalities, aligning with previous studies indicating a link between increased accident severity and higher fatality rates [17]-[19]. The analysis also showed strong associations between the total number of accidents, injury rates, and death cases. These findings suggest that variables such as road condition and vehicle density are critical predictors of road accidents in India, supporting similar trends observed in global studies.

Table 1. Actual correlations (above diagonal) and apparent correlations (below diagonal) obtained from the dendrogram between variable pairs

Variable	Year	Accident	Severity	Injury	Death
Year		0.131	0.988*	- 0.159	0.930*
Accident	0.133		0.048	0.933*	0.465*
Severity	0.988	0.133		- 0.241	0.904*
Injured	0.133	0.933	0.133		0.175
Death	0.917	0.133	0.917	0.133	

* Correlation is significant at the 0.05 level

3.2. Time series analysis

To further investigate these relationships, time series regression models were applied. The regression analysis assessed the goodness of fit for different polynomial models. As illustrated in Table 2, the goodness of fit for first-degree (linear) models was generally low, particularly for parameters like accident rates and injury numbers. However, the fit improved significantly with second- and third-degree polynomial models, with F values exceeding critical levels at a 0.05 significance threshold. This pattern is consistent with studies by Shen *et al.*, who found that higher-order models more accurately predicted accident fatalities over time [20]. Our findings confirm the upward trend of accidents and fatalities between 2001 and 2010, followed by a gradual decline and then a marked increase in 2022. This spike likely reflects post-pandemic travel normalization, underscoring the impact of external variables on accident rates in India.

Table 2. Equations of time series lines, their goodness of fit, and 95% confidence intervals

Degree of line	Equation	Goodness of fit (%)	95% confidence interval
Year vs. accident			
First	$y = 44873 – 769.4 x$	1.70	± 92167
Second	$y = 37097 + 20208 x -845.1 x^2$	68.40	± 70431
Third	$y = 36162 + 24606 x – 1312 x^2 + 13.55 x^3$	69.00	± 70244
Year vs. injury			
First	y = 48303 – 1185 x	2.50	± 91483
Second	y = 37966 + 24657 x -1123 x2	75.20	± 46193
Third	y = 35252 + 37424 x – 2481 x2 -39.34 x3	78.00	± 43421
Year vs. death			
First	y = 84401 – 3723 x	86.50	± 18252
Second	y = 67741 + 7888 x - 181 x2	93.10	± 12989
Third	y = 65720 + 8839 x – 282.1 x2 + 2.929 x3	93.10	± 12962
Severity vs. death			
First	y = 6247 – 4357 x	81.60	± 21300
Second	y = 26183 + 23960 x – 345.8 x2	94.40	± 11639

3.3. Accident trends over time

The number of accidents over time is presented in Table 3 and depicted in Figure 1. The ‘F’ value for the first-degree regression line is less than the critical value, indicating a lack of direct relationship between the year and the number of accidents, as shown in Figure 1. However, the ‘F’ values for the second-and third-degree regression lines exceed the critical values at the 0.05 significance level, suggesting that higher-degree polynomial models provide a better fit for the data. Both the second- and third-degree regression lines exhibit upward convexities and are nearly coincident, with comparable goodness-of-fit values as shown in Figure 1. These lines illustrate an increase in the number of accidents from 2001 to 2010, followed by a continuous decline, except for a notable rise in 2022. The observed decline may be attributed to improvements in road infrastructure, such as road widening and the implementation of one-way traffic systems. The decrease in the number of accidents to a minimum of 366,138 in 2020 can largely be attributed to the restrictions imposed during the COVID-19 pandemic. Conversely, the significant increase to 461,312 accidents in 2022 reflects the lifting of travel bans and a return to normalcy. These trends underscore the dynamic nature of road safety in India and highlight the impact of external factors on accident rates.

Table 3. Completed analysis of variance (ANOVA) for the significance of trend lines for year vs. accident

Source of variation	Sum of squares	Degrees of freedom	Mean squares	F-test result
First-degree regression (CSS_{R1})	524195067	1	524195067	$F_1 = 0.216$
First-degree deviation (CSS_{D1})	48647357434	20	2432367872	($F_{\upsilon1=1, \upsilon2=20, \alpha=0.05}$= 4.35)*
Second-degree regression (CSS_{R2})	20763369420	2	10381684710	$F_2 = 6.943^{\S}$
Second-degree deviation (CSS_{D2})	28408183080	19	1495167531	($F_{\upsilon1=2, \upsilon2=19, \alpha=0.05}$=3.52)*
Added by second-degree (CSS_{R2-1})	20239174353	1	20239174353	F_{2-1} =13.536§ ($F_{\upsilon1=1, \upsilon2=19, \alpha=0.05}$=4.38)*
Third-degree regression (CSS_{R3})	20914333696	3	6971444565	$F_3 = 4.441^{\S}$
Third-degree deviation (CSS_{D3})	20914333696	18	1569845489	($F_{\upsilon1=3, \upsilon2=18, \alpha=0.05}$=3.16)*
Added by third-degree (CSS_{R3-2})	150964276	1	150964276	F_{3-2} = 0.096 ($F_{\upsilon1=1, \upsilon2=18, \alpha=0.05}$=4.41)*
Total variation (CSS_T)	49171552500	21		

§F value significant at 0.05 significance level, *Critical values of F are given within brackets

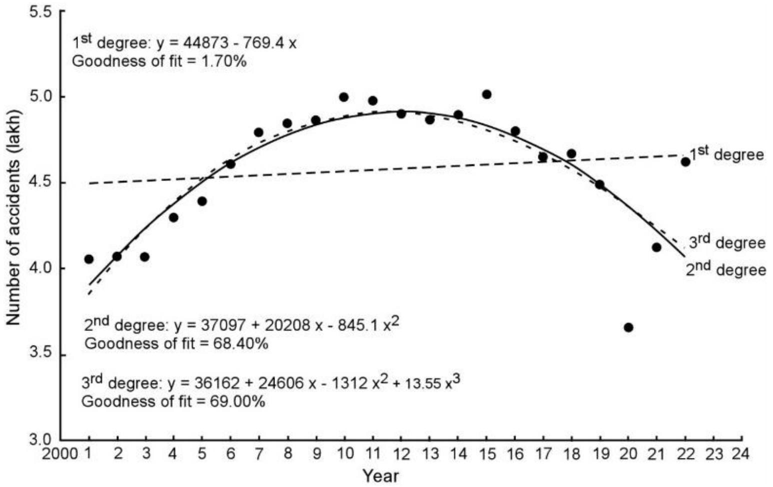

Figure 1. Number of accidents over years

3.4. Injury trends over time

Table 4 and Figure 2 display trends in injuries resulting from road accidents, which closely parallel those observed for accident numbers. The first-degree (linear) model showed low significance, while second- and third-degree models achieved significant fits, as evidenced by their respective F values. A peak in injury rates in 2010, followed by a decline until 2020, highlights the significant role of the COVID-19 lockdowns in reducing accident-related injuries. The subsequent rise in 2022 can be attributed to the resumption of regular travel patterns. These injury trends align with other studies noting that economic and societal disruptions, such as lockdowns, can influence road accident statistics [10].

3.5. Trends in road accident fatalities over time

An analysis of road traffic fatalities over time is shown in Table 5 and Figure 3. The linear and polynomial models indicate a high goodness of fit, with first-degree models achieving an R^2 of 86.5% and second-degree models reaching 93.1%. The significant F values suggest a statistically reliable upward trend in road fatalities. This increase correlates with factors such as growing vehicle ownership, overcrowded roads, and rising driver negligence, which are major contributors to accident severity in India [21].

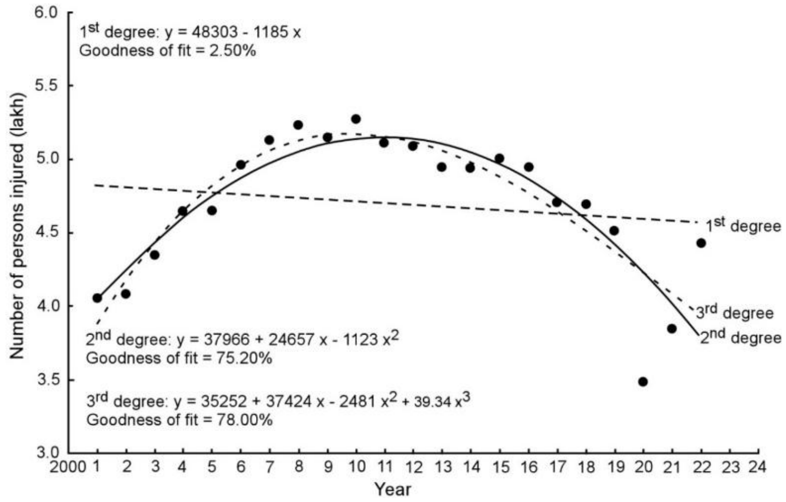

Figure 2. Number of injuries due to road accidents over time

Table 4. Completed analysis of variance (ANOVA) for the significance of trend lines for years vs. injury

Source of variation	Sum of squares	Degrees of freedom	Mean squares	F-test result
First-degree regression (CSS_{R1})	1243441238	1	1243441238	$F_1 = 0.519$
First-degree deviation (CSS_{D1})	47928111263	20	2396405563	$(F_{\upsilon1=1,\ \upsilon2=20,\ \alpha=0.05}= 4.35)$*
Second-degree regression (CSS_{R2})	36951659976	2	18475829988	$F_2 = 28.727$§
Second-degree deviation (CSS_{D2})	12219892525	19	643152238	$(F_{\upsilon1=2,\ \upsilon2=19,\ \alpha=0.05}=3.52)$*
Added by second-degree (CSS_{R2-1})	35708218738	1	35708218738	$F_{2-1} =55.521$§
				$(F_{\upsilon1=1,\ \upsilon2=19,\ \alpha=0.05}=4.38)$*
Third-degree regression (CSS_{R3})	38374361671	3	12791453890	$F_3 = 21.325$§
Third-degree deviation (CSS_{D3})	10797190830	18	599843935	$(F_{\upsilon1=3,\ \upsilon2=18,\ \alpha=0.05}=3.16)$*
Added by third-degree (CSS_{R3-2})	1422701695	1	1422701695	$F_{3-2} = 2.372$
				$(F_{\upsilon1=1,\ \upsilon2=18,\ \alpha=0.05}=4.41)$*
Total variation (CSS_T)	49171552501	21		

§F value significant at 0.05 significance level, *Critical values of F are given within brackets

Table 5. Completed analysis of variance (ANOVA) for the significance of trend lines for year vs. death

Source of variation	Sum of squares	Degrees of freedom	Mean squares	F-test result
First-degree regression (CSS_{R1})	12273675530	1	12273675530	$F_1 = 128.675$§
First-degree deviation (CSS_{D1})	1907696181	20	95384809	$(F_{\upsilon1=1,\ \upsilon2=20,\ \alpha=0.05}= 4.35)$*
Second-degree regression (CSS_{R2})	13215181634	2	6607590817	$F_2 = 129.937$§
Second-degree deviation (CSS_{D2})	966190077	19	50852109	$(F_{\upsilon1=2,\ \upsilon2=19,\ \alpha=0.05}=3.52)$*
Added by second-degree (CSS_{R2-1})	941506104	1	941506104	$F_{2-1} = 18.514$§
				$(F_{\upsilon1=1,\ \upsilon2=19,\ \alpha=0.05}=4.38)$*
Third-degree regression (CSS_{R3})	13219161286	3	4406387095	$F_3 = 82.43$§
Third-degree deviation (CSS_{D3})	962210425	18	53456135	$(F_{\upsilon1=3,\ \upsilon2=18,\ \alpha=0.05}=3.16)$*
Added by third-degree (CSS_{R3-2})	3979652	1	3979652	$F_{3-2} = 0.074$
				$(F_{\upsilon1=1,\ \upsilon2=18,\ \alpha=0.05}=4.41)$*
Total variation (CSS_T)	14181371711	21		

§F value significant at 0.05 significance level, *Critical values of F are given within brackets

3.6. Severity of accidents versus deaths

The ANOVA results, displayed in Table 6 and Figure 4, indicate significant correlations between accident severity and fatalities across polynomial models. Second- and third-degree lines merge, showing that increased accident severity directly elevates death rates. Driver-related factors, including carelessness and substance use, are implicated in the severity of accidents, echoing findings in both domestic and international studies [21]. These results suggest that improving driver education and implementing stricter regulations on road safety can be vital for mitigating accident severity and related fatalities.

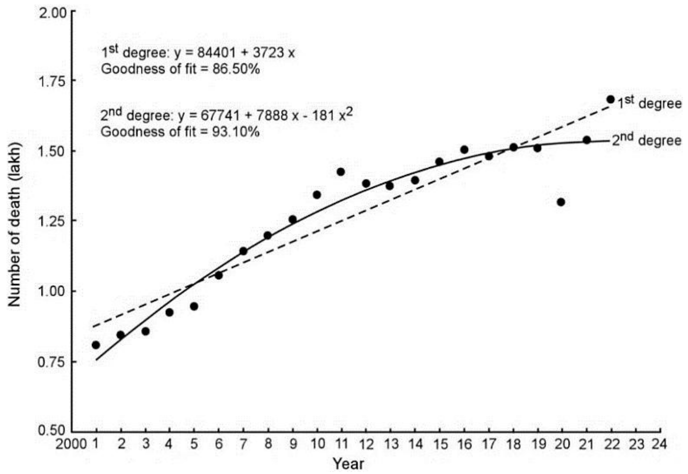

Figure 3. Number of deaths due to road accidents over time

Table 6. Completed analysis of variance (ANOVA) for the significance of trend lines for severity vs. death

Source of variation	Sum of squares	Degrees of freedom	Mean squares	F-test result
First-degree regression (CSS_{R1})	11583148334	1	11583148334	F_1 = 89.162§
First-degree deviation (CSS_{D1})	2598223377	20	129911169	($F_{\upsilon1=1, \upsilon2=20, \alpha=0.05}$= 4.35)*
Second-degree regression (CSS_{R2})	13405552088	2	6702776044	F_2 = 164.153§
Second-degree deviation (CSS_{D2})	775819623	19	40832612	($F_{\upsilon1=2, \upsilon2=19, \alpha=0.05}$=3.52)*
Added by second-degree (CSS_{R2-1})	1822403754	1	1822403754	F_{2-1} = 44.631§ ($F_{\upsilon1=1, \upsilon2=19, \alpha=0.05}$=4.38)*
Third-degree regression (CSS_{R3})	13514704003	3	4504901334	F_3 = 121.632§
Third-degree deviation (CSS_{D3})	666667708	18	37037095	($F_{\upsilon1=3, \upsilon2=18, \alpha=0.05}$=3.16)*
Added by third-degree (CSS_{R3-2})	109151915	1	109151915	F_{3-2} = 2.947 ($F_{\upsilon1=1, \upsilon2=18, \alpha=0.05}$=4.41)*
Total variation (CSS_T)	14181371711	21		

§F value significant at 0.05 significance level, *Critical values of F are given within brackets

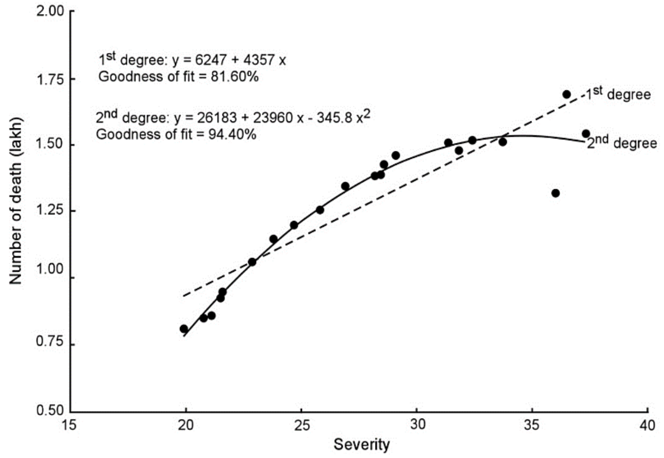

Figure 4. Severity of accidents versus number of deaths in road accidents in India

3.7. Multivariate analysis

The multivariate factor analysis, as shown in Table 7, reveals two main clusters that account for nearly all the variance in the dataset. The dendrogram as shown in Figure 5 supports this structure, with a cophenetic correlation coefficient of 0.92, indicating strong within-cluster similarity. The first cluster includes variables such as time, accident severity, and fatalities, while the second encompasses accident frequency and injuries. These clusters underscore the dual nature of road accidents: while accident frequency correlates with injuries, increasing accident severity is associated with fatalities. This insight aligns with the hypothesis that higher accident severity correlates with fatality trends, as indicated by other studies focusing on vulnerable road users in low- and middle-income countries [22].

Table 7. Factor analysis results of road accidents in India

Parameter	Factors	
	1	2
Year	0.995*	- 0.041
Accident	0.175	0.980*
Severity	0.990*	- 0.125
Injured	- 0.123	0.986*
Death	0.951*	0.301
Eigenvalue	2.923	2.039
% of variance	58.450	40.785
Cumulative %	58.450	99.235

Extraction Method: Principal Component Analysis
Rotation Method: Varimax with Kaiser Normalization
* Significant parameter

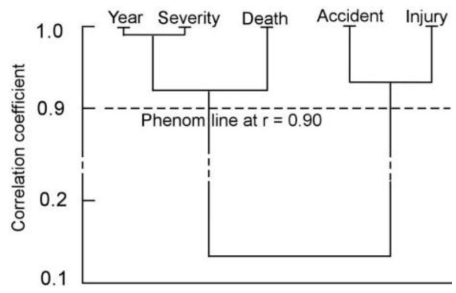

Figure 5. Dendrogram showing clustering of road accident parameters in India

Our analysis affirms that road accident trends in India are multifaceted, influenced by variables including road conditions, vehicle density, and driver behaviour. The observed increase in fatalities over time, even as accidents show a slight decline, suggests that factors related to accident severity are becoming more pronounced. As in high-income countries, where fatalities have declined, similar efforts in India may require better infrastructure, driver education, and regulatory enforcement.

Our methodology identifies RTA determinants and suggests data-driven solutions. Bivariate analysis highlights key predictors like road quality and traffic density, while time series analysis guides interventions during high-risk periods. Factor and cluster analysis refine findings, supporting targeted safety programs to reduce mortality and injury, aligning with national goals.

The findings also underscore the impact of external factors, such as the COVID-19 pandemic, on traffic dynamics and accident rates. The temporary reduction in accident-related fatalities during the lockdown period aligns with global studies observing reduced traffic incidents during similar economic slowdowns [19]. Our study on road traffic accidents (RTAs) in India aligns with and expands upon previous research, revealing both similar and divergent trends in accident and fatality patterns. These comparisons underscore the complex dynamics of RTAs in varying socioeconomic and infrastructural contexts.

A comparative study in China revealed a declining trend in RTA fatalities post-2016 across diverse road types [19]. Consistent with this, our analysis identified a similar downward trend in accident rates in India from 2010 to 2022. This decrease in India appears tied to infrastructural improvements, enhanced traffic regulations, and possibly, temporary reductions in road activity during the COVID-19 pandemic. However, unlike the steady decline in China's RTAs, India witnessed a sharp increase in fatalities and accident severity following the pandemic, likely reflecting the resumption of road usage and insufficient long-term safety protocols. This resurgence indicates a need for sustained intervention beyond external factors such as lockdowns.

In exploring statistical models for forecasting accident-related deaths, Brajesh and Shekhar employed Time Series, Exponential Smoothing, and Auto Regressive Integrated Moving Average (ARIMA) models, observing a long-term upward trend in accidental deaths [14], [20]. Similarly, our study's regression analyses, especially higher-degree polynomial fits, suggest that despite short-term fluctuations, the overall trend in RTA fatalities has an upward trajectory. These findings support the need for predictive models that can accurately capture fluctuating patterns while identifying factors driving these persistent increases.

Risk factors in RTAs have been extensively studied. For instance, Khorshidi's research attributed injuries and fatalities to pedestrian errors, alcohol consumption, and speed, alongside vehicle defects, driver negligence, and excessive loading [23]. Our findings align with these risk factors; specifically, driver carelessness, excessive alcohol use, and failure to adhere to speed limits were key contributors to fatal accidents. Distinct from higher-income countries, low- and middle-income countries like India face more complex road traffic patterns, with high proportions of vulnerable road users. Consequently, road designs and traffic regulations must account for these demographics to improve safety outcomes [18].

Demographic vulnerability analysis in India reveals that males aged 30–59 are at the highest risk of RTA-related fatalities and injuries. It is often due to increased exposure to road usage in this economically active age group. These patterns indicate an opportunity for targeted safety campaigns and stricter regulation enforcement for high-risk groups.

The findings of this study highlight critical areas for intervention, especially given India's unique traffic and demographic landscape. Addressing driver behavior, road infrastructure, and regulatory enforcement could mitigate the severity and frequency of RTAs. Furthermore, the study's alignment with international findings suggests the potential for shared best practices while underscoring the need for country-specific strategies tailored to local conditions.

Our research contributes to understanding RTA trends and factors in India. It has implications for policy formulation, road design improvements, and enforcement practices. While RTAs pose a global issue, this study underscores the need for data-driven, localized approaches to effectively reduce accident rates and fatalities in diverse settings.

This study has significant implications for public safety policies and road infrastructure development. By identifying accident severity and driver behaviour as critical predictors of fatalities, the findings highlight the need for targeted interventions, including improved road safety campaigns, better enforcement of traffic regulations, and increased focus on driver education. Moreover, the clustering analysis emphasizes the importance of addressing both frequency and severity in road safety strategies. Policymakers could use these insights to prioritize high-risk zones and implement strategies that focus on both reducing accident occurrence and managing accident outcomes to enhance road safety in India effectively.

Our findings build on previous research by providing a nuanced analysis of road traffic accidents (RTAs) in India, expanding understanding of both established and emerging patterns in accident severity, injury, and fatality trends. Previous studies, such as those by Khorshidi *et al.* [7], Brajesh and Shekhar [14] and have established the correlation between accident severity, driver-related factors (e.g., alcohol consumption, driver carelessness), and increased fatalities. Our study aligns with these findings but further enhances the discussion by applying advanced polynomial models that reveal more accurate fits for the time series of RTA fatalities, especially noting fluctuations linked to pandemic-related travel shifts. Notably, while prior research has identified general risk factors, our clustering analysis uniquely distinguishes two primary patterns: one related to accident frequency and another to accident severity, offering a fresh perspective on targeting interventions. Additionally, our demographic analysis underscores the elevated vulnerability of specific age groups, which prior studies have mentioned but not examined with a focused clustering approach. This dual-cluster insight provides a new avenue for more targeted road safety measures in India, underscoring the critical need for localized strategies that can directly address both the frequency and severity of road accidents.

The findings of this study carry several implications for research and policy. In light of the rising accident fatalities in India, our study highlights the need for urgent countermeasures, including: i) Enhanced Road Safety Measures: Investments in road design improvements, safety features, and urban planning could significantly reduce accident severity; i) Stricter Traffic Enforcement: Policies that enforce speed limits, address alcohol-related incidents, and penalize negligent driving are essential to curb fatal incidents; and iii) Infrastructure Development and Public Transport: With vehicle ownership on the rise due to increasing per-capita GDP [24]-[26], investments in safe, accessible public transport systems can reduce reliance on private vehicles, lowering accident risks and contributing to safer urban environments [27], [28]. The Government of India had launched major initiatives to upgrade and strengthen National Highways through various phases of the National Highways Development Project (NHDP) and is taking the initiative forward through the umbrella program of Bharatmala Pariyojana Phase-I and other schemes and projects [2].

Implementing measures to encourage non-motorized transport like cycling and walking can enhance road safety by reducing kinetic energy in potential crashes, benefiting vulnerable road users [29]-[31]. Infrastructure improvements, such as dedicated cycling lanes and safer intersections, are essential to facilitate safer conditions and boost cycling adoption [31]. Integrating route planning tools that highlight the shortest, safest routes can align with cyclists' behaviour and improve navigation [32]. Urban planning focused on mixed-use developments may further support shorter trip distances, making cycling more attractive [33]. Regular safety assessments are needed to adapt infrastructure to rising cycling trends and maintain safety [34]. Video monitoring and the presence of uniformed officers have been shown to reduce risky behaviours [35]. Addressing the causes of severe accidents and adopting preventive strategies, particularly in regions with seasonal hazards like North India's winter fog, is crucial for safer roads [36]-[38]. Collectively, these measures aim to create a safer, more sustainable road environment, fostering a culture of responsible and secure transport that can significantly reduce road traffic fatalities.

This study's limitations include potential data inconsistencies due to reliance on secondary sources and underreported accidents. It lacks consideration of contextual factors like weather, socioeconomic influences, and comprehensive multimodal interactions. The analysis may not fully generalize beyond India, and it simplifies driver-related aspects without exploring behavioural nuances. Additionally, the study omits detailed policy effectiveness and socio-demographic insights, limiting targeted intervention strategies. The absence of technological advancements' impact and future projections also restricts the scope of predictive models. Addressing these limitations could enhance future research and policy recommendations.

4. CONCLUSION

Analyses to identify trends, correlations, and key risk factors. RTA fatalities in India continue to rise due to increasing motorization and road usage. Proactive, data-driven, and multifactorial strategies—combining infrastructure, enforcement, and behavioral interventions are essential for building safer, more sustainable road systems. Furthermore, future research could extend this study by examining specific geographic areas, demographic groups, or additional environmental and vehicular factors contributing to RTA fatalities. Integrating new data sources, such as real-time traffic and incident data, may provide more granular insights into accident patterns and enable the development of advanced predictive models.

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C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

Data availability is not applicable to this paper as no new data were created or analyzed in this study.

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