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# Effects of Highway Geometric Elements on Accident Modelling: A Case Study from Lucknow, India

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**Abstract**

Road traffic accidents (RTAs) are a major concern for public safety and infrastructure planning, especially in developing countries like India where rapid highway expansion is underway. While driver behavior and environmental conditions have long been studied, the impact of geometric highway design elements remains underexplored in predictive safety models. This research investigates the relationship between key geometric features—such as curve radius, lane width, shoulder width, sight distance, and gradient—and accident occurrence along Faizabad Road (NH-27) in Lucknow, India. Using a combination of field data, traffic police records, Geographic Information Systems (GIS), and regression modeling (Poisson and Negative Binomial), the study identifies significant correlations between geometric deficiencies and crash frequencies. Spatial hotspot analysis further supports these findings by pinpointing high-risk segments. The results underscore the importance of integrating geometric variables into accident prediction models and highway design protocols. The study concludes with actionable recommendations for improving geometric standards to enhance road safety and reduce accident rates.

**Keywords:** Highway Geometry; Road Traffic Accidents (RTA); Accident Prediction Models; Poisson Regression; Negative Binomial Model; GIS Hotspot Analysis; Curve Radius; Lane Width; Intersection Safety; Road Design Standards; India.

## 1. Introduction

Highways play a fundamental role in modern infrastructure, providing critical connectivity for economic growth, transportation of goods, and mobility of people. However, the expansion of highway networks has been paralleled by a concerning increase in road traffic accidents (RTAs), which pose severe threats to life, property, and public health. The World Health Organization estimates that approximately 1.3 million people die annually due to road crashes worldwide, with many such incidents occurring on high-speed highways [1].

While road safety research often emphasizes behavioral, vehicular, and environmental factors, the influence of geometric design elements has not received proportional attention. Key geometric parameters—including horizontal curves, vertical gradients, lane widths, shoulder types, and intersection configurations—have a direct impact on driver perception, vehicle dynamics, and traffic flow. Poor horizontal alignment, for example, can lead to sharp curves that increase lateral forces, raising the risk of run-off-road crashes [2]. Similarly, vertical curves with limited sight distances compromise overtaking visibility, contributing to head-on collisions [3].

This paper aims to analyze the effects of these geometric elements on accident frequency and severity. By applying statistical modeling and spatial analysis techniques to data from Faizabad Road (NH-27) in Lucknow, India, the study seeks to establish a localized understanding of how roadway design influences safety outcomes.

## 2. Problem Statement

Despite considerable advancements in highway engineering, road traffic accidents continue to be a major public safety issue, particularly in developing regions. In India, the burden is especially high, with a significant number of fatalities occurring on national and state highways each year. Although driver behavior and traffic regulation enforcement are critical contributors, geometric deficiencies in road design are increasingly recognized as root causes of traffic incidents.

Existing accident prediction models often emphasize traffic volume and driver error while treating geometric factors as secondary or static. This oversimplification limits their ability to guide effective design improvements. Furthermore, the generalized nature of global models fails to capture regional-specific variables such as heterogeneous traffic flow, road encroachments, or non-standard driver behavior prevalent in India [4].

Research has shown that sharp horizontal curves, narrow lanes, and poorly designed intersections are associated with higher crash rates [5][6]. However, the cumulative and interactive effects of these elements remain underexplored in Indian contexts. There is a pressing need for a contextualized analysis that incorporates local geometric, environmental, and behavioral dynamics to inform more accurate accident prediction and mitigation strategies.

## 3. Objectives

The study is guided by the following objectives:

1. To identify and quantify the impact of specific highway geometric elements (e.g., curve radius, lane width, sight distance, and superelevation) on accident frequency and severity using localized data from Faizabad Road (NH-27), Lucknow.
2. To develop a predictive model that incorporates geometric design parameters for more accurate accident forecasting and risk identification.
3. To recommend design-based interventions aimed at improving road safety, with a focus on geometric improvements tailored to Indian highway conditions.

## 4. Literature Review

Understanding the impact of highway geometric design on road safety necessitates a detailed exploration of past studies and prevailing theories. Geometric design affects several factors influencing traffic accidents, including visibility, vehicle handling, and lane discipline. This section reviews the existing body of literature regarding horizontal and vertical alignments, cross-sectional elements, intersection design, accident prediction models, and the integration of geometric and non-geometric factors.

### 4.1 Horizontal Alignment

Horizontal alignment, particularly the curvature of roads, has been extensively linked to accident occurrence. Fitzpatrick et al. [2] emphasized that sharp horizontal curves increase centrifugal forces on vehicles, especially at high speeds, which often leads to lateral instability and run-off-road incidents. The radius of curvature plays a significant role—accident frequency tends to increase exponentially as curve radius decreases. Hauer et al. [3] established that curves with a radius of less than 300 meters had a much higher crash rate than larger-radius curves. Moreover, superelevation, which counteracts lateral forces, when inadequately designed, further exacerbates accident risk.

### 4.2 Vertical Alignment

Vertical geometry also has critical safety implications, especially in relation to sight distance and vehicle deceleration. Road gradients impact braking effectiveness and visibility, especially on crest vertical curves. Montella [5] demonstrated that locations with insufficient crest curve radii and sharp gradients had a notably higher incidence of head-on and rear-end collisions. Vertical curves impair overtaking visibility, which is especially problematic on two-lane undivided roads. The Highway Safety Manual by AASHTO [7] also outlines specific crash modification factors associated with varying gradient levels, further supporting the role of vertical geometry in accident causation.

### 4.3 Cross-Sectional Elements

Lane and shoulder widths are integral components of road safety. Zegeer et al. [6] found that narrow lanes (less than 3.0 meters) significantly increase the risk of side-swipe and head-on collisions, especially on rural roads. Conversely, excessively wide lanes may encourage speeding. The optimal lane width for safety has been identified around 3.6 meters in high-speed environments. Regarding shoulders, wider and paved shoulders provide recovery space for errant vehicles and reduce the likelihood of severe crashes. Unpaved or nonexistent shoulders not only limit maneuverability but also constrain pedestrian and cyclist movement, particularly in mixed traffic environments [4].

### 4.4 Intersection Design

Intersections inherently introduce multiple conflict points. Poor geometric layout at intersections—such as skewed entry angles, inadequate sight distance, and lack of channelization—can drastically increase crash rates. Chen et al. [8] showed that unsignalized intersections with acute entry angles tend to record more angle and rear-end collisions. Roundabouts, as an alternative to signalized intersections, have been widely praised for reducing crash severity. Montella [5] reported a 40%–50% reduction in fatal and injury crashes following roundabout implementation, contingent on proper design features such as entry curvature and deflection angles.

#### 4.5 Accident Prediction Models

Traditional accident prediction models (APMs) primarily used linear and logistic regression approaches. Hauer et al. [3] developed early regression models that linked geometric parameters to accident frequency. However, these models often suffer from over-dispersion—a situation where crash variance exceeds the mean—making Poisson models less suitable. To address this, Negative Binomial Regression models have been widely adopted for better accuracy [9].

Recently, advanced models using Empirical Bayes (EB) methods and Machine Learning (ML) techniques have emerged. Elvik and Vaa [10] integrated EB models that combine site-specific accident data with historical trends, improving reliability in low-data environments. Zhang et al. [11] applied neural networks and random forests for accident severity prediction, outperforming conventional models. However, the application of such data-intensive techniques is limited in regions like India due to data collection challenges.

#### 4.6 Combined Effects and Regional Studies

Several studies suggest that the safety impact of geometric elements is not isolated but interacts with non-geometric factors like traffic volume, weather, and road user behavior. Harwood and Mason [12] concluded that the safety effects of wider lanes are diminished under conditions of traffic congestion. Similarly, adverse weather such as fog or rain can neutralize the safety benefits of good geometric design. In countries with heterogeneous traffic and limited enforcement, driver behavior can undermine the intended functionality of design features.

Indian studies have also begun to emphasize the need for localized models. Gupta et al. [13] found that geometric standards developed in western countries were not directly applicable to Indian roads, especially those accommodating both motorized and non-motorized users. Tiwari et al. [4] highlighted the need for conflict analysis in mixed traffic streams, where pedestrian and cyclist behavior often contradicts conventional models.

## 5. Methodology

This research adopts a quantitative methodology combining field surveys, statistical modeling, and spatial analysis. The study area is Faizabad Road (NH-27) in Lucknow, a high-speed corridor with a history of frequent accidents. The methodology is structured in five phases: data collection, variable categorization, statistical modeling, GIS-based hotspot analysis, and model validation.

#### 5.1 Data Collection

#### 5.1.1 Sources

Data was obtained from three key sources:

- **Geometric data** from NHAI and PWD project reports, supplemented with Total Station and LiDAR field surveys.
- **Accident data** from the Lucknow Traffic Police and National Crime Records Bureau (NCRB), covering crash frequency, severity, and type over a 3-year period (2020–2023).
- **Traffic volume data**, where available, was sourced from traffic census records and automated traffic counter systems.

#### 5.1.2 Key Variables

The variables are grouped into two primary categories:

- **Geometric Variables:** Curve radius, lane width, shoulder width, gradient, superelevation, sight distance, and intersection geometry.
- **Accident Variables:** Annual frequency, severity (fatal, major injury, minor injury), and crash type (head-on, rear-end, etc.)

#### 5.2 Data Preprocessing

Raw accident records were geocoded using GIS to match with corresponding highway segments. Discrepancies in crash location data were reconciled using FIR narratives and field validations. Missing values in crash reports were imputed using data from hospital and insurance claims where available. Outliers were identified and treated using interquartile range techniques to prevent distortion of model parameters.

## 6. Statistical Modeling and GIS Analysis

To develop an effective accident prediction framework, this study applied **Poisson and Negative Binomial regression models**, commonly used for analyzing count data where over-dispersion is present. Additionally, **Geographic Information Systems (GIS)** were used to spatially map accidents and identify hotspots.

#### 6.1 Model Selection Rationale

Accident counts are discrete and non-negative, making traditional linear regression unsuitable. The **Poisson model** assumes that the mean and variance are equal, which often does not hold true for crash data. Hence, the **Negative Binomial model**—which allows variance to exceed the mean—is also employed.

## 7. Regression Modelling Approach

### 7.1 Model Structure

Let:

- Yi = Expected number of crashes at segment iii
- Xk = k-th geometric variable (e.g., curve radius, lane width)
- βk = coefficient representing the effect of XkX_kXk

The general Poisson regression model is:

$$\ln(Y_i) = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \ldots + \beta_k X_k$$

For the **Negative Binomial model**, a dispersion parameter α\alphaα is introduced to account for over-dispersion:

$$Var(Y_i) = \mu_i + \alpha\mu_i^2$$

### 7.2 Variables Used

| Variable | Type | Description |
|---|---|---|
| Curve Radius (m) | Continuous | Horizontal curve radius |
| Lane Width (m) | Continuous | Distance between lane markings |
| Shoulder Width (m) | Continuous | Paved + unpaved shoulder |
| Gradient (%) | Continuous | Vertical incline of roadway |
| Sight Distance (m) | Continuous | Distance visible to driver in a straight line |
| Intersection Design | Categorical | Type (signalized, roundabout, unsignalized) |
| Crash Frequency | Dependent | Annual number of crashes per segment |

### 7.3 Data Summary (Descriptive Statistics)

| Variable | Mean | Std. Dev. | Min | Max |
|---|---|---|---|---|
| Crash Frequency | 12.3 | 4.7 | 2 | 26 |
| Curve Radius (m) | 190.5 | 60.8 | 75 | 400 |
| Lane Width (m) | 3.15 | 0.28 | 2.8 | 3.75 |
| Shoulder Width (m) | 1.05 | 0.43 | 0.5 | 2.0 |
| Gradient (%) | 2.9 | 1.5 | 0.5 | 6.5 |
| Sight Distance (m) | 110.4 | 35.7 | 60 | 200 |

## 8. Results of Regression Models

### 8.1 Poisson Regression Results

| Variable | Coefficient (β) | Std. Error | p-value | Interpretation |
|---|---|---|---|---|
| Intercept | 1.42 | 0.12 | <0.001 | Baseline crash log-count |
| Curve Radius | -0.0035 | 0.0009 | <0.001 | Crashes decrease as curve radius increases |
| Lane Width | -0.72 | 0.25 | 0.004 | Wider lanes are associated with fewer accidents |
| Shoulder Width | -0.44 | 0.21 | 0.036 | Wider shoulders reduce crashes |
| Gradient | 0.05 | 0.02 | 0.015 | Steeper slopes increase accident likelihood |
| Sight Distance | -0.008 | 0.002 | <0.001 | Greater visibility lowers accident count |
| Intersection (Ref = Signalized) | | | | |
| Unsignalized | 0.38 | 0.14 | 0.007 | Higher crashes in unsignalized intersections |
| Roundabout | -0.22 | 0.11 | 0.044 | Fewer crashes in roundabouts compared to signalized junctions |

### 8.2 Model Fit Statistics

| Model | Log-Likelihood | AIC | Dispersion Test (α) |
|---|---|---|---|
| Poisson | -425.4 | 862.8 | Not applicable |
| Negative Binomial | -407.2 | 828.4 | 0.98 (significant) |

The **Negative Binomial model** yielded better fit and lower AIC values, indicating improved performance due to over-dispersion handling.

## 9. GIS-Based Spatial Analysis

To visualize accident distribution, spatial analysis was performed using **ArcGIS 10.8**.

### 9.1 Hotspot Detection

Using kernel density estimation (KDE), accident hotspots were mapped. High-density zones were primarily located near:

- Tight horizontal curves (radius < 150m)
- Unsignalized intersections
- Areas with inadequate sight distance (< 80m)

### 9.2 Sample Output: Accident Hotspot Map

| Location | Issue Identified | Accident Density (crashes/km²) |
|---|---|---|
| Near Polytechnic Chauraha | Unsignalized intersection | 23.4 |
| In front of High Court flyover | Sharp curve & low sight distance | 27.9 |
| Indira Nagar sector entrance | Narrow lane and poor shoulders | 18.7 |

## 10. Results and Discussion

### 10.1 Key Findings

1. **Curve Radius** was the most statistically significant factor; crash rates decreased as the radius increased. Curves below 150m radius experienced more than double the crashes compared to those above 300m.
2. **Lane and Shoulder Widths** showed strong negative correlations with crash frequency. Wider lanes reduced side-swipe and run-off-road incidents. Similarly, paved shoulders allowed vehicle recovery, especially for two-wheelers.
3. **Sight Distance** had a pronounced effect. Sections with visibility under 100m exhibited higher head-on and overtaking collisions, especially on undivided roads.
4. **Gradient** had a smaller but significant positive effect on crash frequency, confirming earlier studies [3], [7].
5. **Intersection Type** mattered: unsignalized junctions were prone to higher crash counts, while roundabouts helped in minimizing severity and frequency—a trend supported by Montella [5].

### 10.2 Model Application

The validated model provides a predictive framework for:

- **Design screening** of new road segments
- **Risk ranking** of existing corridors
- **Policy formulation** for geometry-based improvements

### 10.3 Practical Design Recommendations

| Geometric Element | Recommended Design Intervention |
|---|---|
| Horizontal Curves | Minimum radius ≥ 250 m for highways >60 km/h |
| Lane Width | Optimal width = 3.5–3.6 m |
| Shoulder Width | Minimum 1.5 m paved shoulder with road edge delineation |
| Vertical Gradient | Avoid >5% gradient for rural highways |
| Sight Distance | Ensure ≥150 m stopping sight distance on crest curves |
| Intersection Design | Replace 3-arm unsignalized intersections with roundabouts |

## 11. Conclusion

This study investigated the relationship between highway geometric design elements and accident occurrence along Faizabad Road (NH-27) in Lucknow, India. Using a combination of field surveys, crash data analysis, GIS mapping, and regression modeling, the research quantified the effects of key variables such as curve radius, lane width, shoulder width, sight distance, and intersection type on accident frequency.

The Negative Binomial regression model emerged as the best-fit analytical tool, accounting for over-dispersion in crash data. Results demonstrated that smaller curve radii, narrow lanes, inadequate shoulders, and low sight distances significantly contribute to higher accident rates. GIS-based spatial analysis further revealed that crash hotspots were commonly associated with these substandard design features.

Overall, this study supports the hypothesis that geometric elements play a critical role in shaping roadway safety outcomes. Findings not only validate international design principles but also emphasize the need for contextualized, region-specific modifications tailored to Indian road conditions and mixed traffic environments.

## 12. Recommendations

Based on the findings, the following design and policy interventions are recommended:

### 12.1 Design Recommendations

| Issue | Recommendation |
|---|---|
| Sharp Curves | Ensure curve radius ≥ 250 m; use spiral transitions when needed |
| Narrow Lanes (<3.0 m) | Adopt standard lane width of 3.5 m on highways |
| Unpaved/Narrow Shoulders | Mandate paved shoulders ≥ 1.5 m with proper drainage |
| Low Sight Distance | Redesign vertical curves to provide stopping sight distance ≥150 m |
| Unsignalized Intersections | Convert to signalized junctions or install modern roundabouts |
| Gradient >5% | Introduce truck escape ramps or reduce gradient with cut-and-fill |

### 12.2 Policy Recommendations

- Integrate geometric safety checks into routine road safety audits (RSAs).
- Incorporate findings into IRC and MoRTH geometric design standards.
- Use accident prediction models during the pre-construction phase for design vetting.
- Establish hotspot monitoring systems using real-time GIS layers and police records.

## 13. Limitations

Despite its comprehensive scope, this study has certain limitations:

1. Data Constraints: Accident data relied on police FIRs, which may underreport non-fatal crashes.
2. Exclusion of Behavioral Factors: Driver fatigue, alcohol use, and speeding behavior were not directly modeled due to unavailability of consistent data.
3. Static Modelling: Traffic volume and vehicle type were treated as fixed, though these vary seasonally.
4. Region-Specific Scope: The model is tailored to Lucknow and may not generalize to hill roads or urban arterials in other states without recalibration.

## 14. Future Scope

The study opens several avenues for further research:

- Integration of real-time traffic and weather data with geometric models using IoT and ITS frameworks.
- Application of machine learning techniques (e.g., XGBoost, Random Forest) for improved model accuracy.
- Longitudinal crash modeling, including before-after studies of design interventions.
- Development of a national-level crash prediction tool incorporating regional traffic heterogeneity.
- Extension to non-motorized road user safety, especially vulnerable users like pedestrians and cyclists.

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## 16. Appendices

### Appendix A: Sample Survey Format for Geometric Data

| Attribute | Measured Value | Unit | Tool Used |
|---|---|---|---|
| Curve Radius | 175 | m | Total Station |
| Lane Width | 3.2 | m | Laser Measure |
| Shoulder Width | 1.0 | m | Visual Tape |
| Gradient | 3.5 | % | Digital Inclinometer |
| Sight Distance | 90 | m | Laser Rangefinder |