ASSESSMENT OF HIGHWAY GEOMETRIC CHARACTERISTICS ON TRUCK CRASH SEVERITY ALONG SELECTED NIGERIAN HIGHWAYS USING MIXED LOGIT MODELS

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ABSTRACT

This empirical research investigated the contributory interactions among highway geometric design parameters, operational traffic characteristics, and environmental factors on heavy freight vehicle crash severity along critical Nigerian transport corridors. The methodological framework integrated primary data acquisition via 390 validated stakeholder questionnaires, a GIS-based spatial kernel density estimation, and discrete choice econometric modeling. Spanning the period from January 2018 to December 2025, an initial population of 3,850 historical crash records was retrieved from the Federal Road Safety Corps (FRSC) National Crash Reporting Information System (NACRIS) database for the selected study corridors (the Lagos – Ibadan Expressway and Benin – Ore Highway). Following a rigorous data filtration process comprising the elimination of duplicate entries, incomplete geometric logs, and missing severity descriptors ($n = 2{,}270$), a refined dataset of $N = 1{,}580$ fully validated crash events were established as the final unit of analysis for the econometric modeling framework. The study employed a Standard Multinomial Logit (MNL) and a Mixed Logit (ML) framework, in order to account for unobserved heterogeneity. The empirical results establish that the Mixed Logit specification provides superior statistical goodness-of-fit, yielding a log-likelihood of -968.30, an Akaike Information Criterion (AIC) of 1,998.60, and a McFadden pseudo-R^2 of 0.279, compared to -1,042.60, 2,131.20, and 0.223 respectively for the standard MNL model. The study establishes that narrow lanes (lane width) (< 3.3 m), shoulder width (< 1.2 m), sharp horizontal curves (< 300 m), steep vertical grades (> 4%), and sight distance (< 120 m) increase the probability of fatal and severe truck accidents. The study further established the random nature of the variables including shoulder width, horizontal curve radius, and overloading, with recommendations for the need for improvements in the geometric design of the road, including widening of lanes, gentle horizontal curves, reduced steep grades for improved safety, the need for improved runaway truck ramps, and crash cushions, the use of GIS-based real-time monitoring of commercial vehicles, and the enforcement of axle-load regulations. The Sustainable Development Goals 3, 8, 9 and 11., is what this study aligns with, as it also provides practical information for geometric design optimization, corridor enforcement, and infrastructure investments.

Keywords: Mixed Logit Model, Highway Geometric Characteristics, Nigerian Highways, Road Safety, Truck Crash Severity, Heavy Truck Load.

1.0 INTRODUCTION

Road infrastructure serves as a major primary trunk network for freight distribution and passenger mobility in developing countries, especially in Sub-Saharan Africa, since rail and inland waterway networks are under-developed. Consequently, strategic highway corridors are crucial to regional connectivity, industrialization,

agricultural distribution, and overall economic development by facilitating trade and market competitiveness (Li *et al.,* 2020; Afolayan *et al.,* 2022; Gong *et al.,* 2022). Within this transport landscape, heavy commercial vehicles (e.g., tankers, trailers, and haulage trucks) represent the primary mode for short- and long-haul freight due to their operational flexibility in connecting production hubs to consumer markets (Odusola *et al.,* 2023; Liang *et al.,* 2024; Sadeghi & Goli, 2024; Feudjio *et al.,* 2025). Nevertheless, heavy trucks are a serious global safety problem. Due to their immense weight, large dimensions, extended braking distances, and complex operational dynamics, truck crashes exhibit a disproportionately high risk of fatalities, severe injuries, structural property damage, and broader economic loss compared to light passenger vehicles (Tola *et al.,* 2021; National Bureau of Statistics, 2022; Afolayan *et al.,* 2022; Okafor *et al.,* 2022; Ezenwajiobi, 2024). hence it is very crucial and important for highway engineers, safety experts, and transportation authorities to comprehend the complex factors that influence the severity of truck crashes.

While crash severity is governed by complex interactions among human behavior, vehicle performance, traffic flow metrics, and environmental conditions (Tola *et al.,* 2021; Odusola *et al.,* 2023; Sadeghi & Goli, 2024; Feudjio *et al.,*2025), the influence of highway geometric design has gained renewed research priority (National Bureau of Statistics, 2022; Okafor *et al.,* 2022; Ezenwajiobi, 2024). Geometric attributes, including lane and shoulder widths, horizontal curve radii, vertical gradients, sight distances, median configurations, and intersection spacing, directly dictate operational safety and functional road performance (Islam *et al.,* 2021; Olayemi *et al.,* 2023). Crucially, the severity-amplifying effects of geometric deficiencies are significantly magnified for heavy freight vehicles owing to their low maneuvering tolerances, stability thresholds, and extended stopping distances (Behnood & Umar, 2022; Odusola *et al.,* 2023; Rahimi *et al.,* 2023; Liang *et al.,* 2024).

Despite substantial capital investments in road infrastructure expansion across Nigeria, heavy trucks remain disproportionately involved in severe and fatal collisions on key economic corridors (Tola *et al.,* 2021; Osasu & Ogbeifun, 2020; Okafor *et al.,* 2022; Rahimi *et al.,* 2020; Rahimi *et al.,* 2023). Strategic corridors such as the Lagos – Ibadan Expressway and Benin – Ore highway, experience high volumes of heavy freight traffic and consistently register some of the highest proportions of fatal truck collisions nationwide. Historically, national road safety interventions in Nigeria have heavily favored behavioral modification, such as driver education, vehicle inspections, and enforcement campaigns. Although crucial, systemic geometric infrastructure defects that actively create operational risks along important freight routes are not addressed by these behavioural interventions (Islam et al., 2021; Olayemi et al., 2023; Okafor et al., 2022).

Furthermore, a significant methodological gap persists in the existing Nigerian safety literature. Previous local research assessing the connection between crash severity and highway design has mostly used fixed-parameter Multinomial Logit (MNL) models, binary logistic regressions, or descriptive statistics (Alshehri et al., 2024; Kumar et al., 2025). A restricted independence assumption is imposed by the typical MNL framework, which states that the marginal effect of explanatory factors on crash severity is constant for all data. The impact of roadway geometry on heavy vehicle crash outcomes varies across crashes due to unobserved factors, such as variations in driver risk perception, fatigue, physical vehicle characteristics, and localized environmental conditions (Rahimi *et al.,* 2023; Bayode *et al.,* 2025). hen unobserved heterogeneity is ignored, the validity of conclusions made for engineering interventions is compromised, statistical estimates are distorted, and parameter variance is concealed. To address these empirical and methodological challenges, this study utilizes a Mixed Logit (Random Parameters) Model to evaluate the impact of highway geometric features on heavy truck crash severity along selected Nigerian corridors (specifically the Lagos–Ibadan and Benin–Ore highways). The mixed logit model allows parameters to vary randomly across observations so as to account for unobserved heterogeneity of crash risk regarding truck design features and behaviors. Consequently, this

research provides a robust, evidence-based foundation for targeted geometric design enhancements and safer freight corridor management in developing economies.

1.1 Objectives of the Study

1. To Identify the major highway geometric characteristics associated with truck crashes on Lagos – Ibadan Expressway and Benin – Ore highway freight corridors.
2. To systematically examine the empirical relationship between roadway geometric features and truck crash severity levels.
3. To assess the environmental conditions and role of traffic operational factors in influencing crash outcomes.
4. To develop and estimate a Mixed Logit Model with random parameters for predicting truck crash severity.
5. To Compare the statistical and predictive performance of the Mixed Logit Model against conventional multinomial Logit models.

2.0 CONCEPTUAL REVIEW

2.1 Highway Geometric Design and Road Safety

Highway geometric design is a general term that describes the visible dimensions and layout of a road, including the horizontal alignment, vertical alignment, cross-section, sight distance, and roadside development (National Bureau of Statistics, 2022; Afolayan *et al.*, 2022; Wen *et al.*, 2023, Chen *et al.*, 2023). Highway geometric design influences driver workload, vehicle speed, lateral position, and vehicle stability. Heavy vehicles have greater swept width, longer acceleration and deceleration distance, and a lower rollover threshold than cars and light trucks. Poor geometric design adversely affects the control of heavy vehicles (Behnood & Mannering, 2021; Osasu & Ogbeifun, 2020).

2.2 Truck Crash Severity Classification

Crash severity is defined by the level of physical trauma, fatality, and damage to property caused by a crash. Most traffic safety agencies worldwide adopt a standardised classification system with ordinal severity categories: Property Damage Only (PDO), Minor/Moderate Injury, Severe Injury, and Fatality (Chen *et al.*, 2023). Heavy vehicles have greater energy content ($E_k = \frac{1}{2}mv^2$). than cars and hence cause more severe damage during collisions.

2.3 Roadway Geometry and Crash Risk Mechanisms

Specific geometric deficiencies trigger distinct crash mechanisms for heavy trucks; these geometric design features contribute uniquely to crash risk mechanisms for heavy trucks:

Horizontal curvature: Off-tracking, jackknifing, and centrifugal rollover caused by inappropriate speed on curves without super-elevation (Gong *et al.*, 2022; Chen *et al.*, 2023).

Vertical curvature: Inappropriate speed on upgrades and downgrades causes severe speed differentials between heavy trucks and cars, resulting in rear-end crashes and loss of control on downgrades (Geremew, 2026; Wen *et al.*, 2022; Mohanty *et al.*, 2022).

Lane and shoulder width: Inadequate Lane and shoulder width contribute to sideswipe, off-roadway rollover, and insufficient lateral clearance during oncoming traffic severity (Kutela *et al.*, 2022; Osasu & Ogbeifun, 2020; Basnet *et al.*, 2023).

Sight distance Inadequate sight distance cases insufficient stopping distance (SSD) and decision sight distance (DSD) for drivers

2.4 Environmental and Traffic Determinants of Crash Severity: A Synthesis

Recent crash severity literature demonstrates a paradigm shift: while roadway geometry remains foundational, environmental and traffic dynamics substantially moderate how geometric features influence collision outcomes (Feudjio *et al.*, 2025; Sadeghi & Goli, 2024; Eghuruamrakpo *et al.*, 2025). The operational ecology that directly influences the severity of traffic incidents is made up of both dynamic traffic flow data and physical environment factors.

2.5 Environmental Factors and Surface Conditions

Adverse meteorological conditions, including precipitation, fog, and high winds, consistently elevate crash risk and severity by reducing road friction, obscuring sight distance, and extending stopping distances (Sadeghi & Goli, 2024; Hossain *et al.*, 2022; Eghuruamrakpo *et al.*, 2025). Nonetheless, there is still a significant scholarly disagreement about whether severe weather directly increases severity or whether risk exposure is countered by behavioural adaptation (e.g., slower speeds and more headway) (Sharif & Mim, 2021; Francis, 2023; Olayemi & Agbonkhese, 2021; Mohanty et al., 2022). Similar to this, driving at night is associated with more severe injuries because of poor visibility and delayed hazard recognition. Never the less, several studies have argued that the relationship between roadway geometric features and crash severity levels is confounded by myriad factors including speed, fatigue, and enforcement laxity (Hossain et al., 2022; Li et al., 2024; Khan et al., 2026). In addition to atmospheric factors, vehicle control and general stability are significantly impacted by road surface integrity, which includes pavement deterioration, potholes, and inadequate drainage (Olayemi et al., 2023; Islam et al., 2021; Wen et al., 2023; Safyari et al., 2024; Basnet et al., 2023; Sadeghi & Goli, 2024). Crash severity levels are generally agreed to be directly influenced by pavement condition, although researchers are yet to agree whether it should be categorized as a geometric or an environmental variable

2.6 Traffic Dynamics and Exposure Mechanics

Traffic operational parameters such as volume, density, speed variance, congestion, and fleet composition dictate the rate and complexity of vehicle interactions (National Bureau of Statistics, 2022; Geremew, 2026; Chathoth & Asaithambi, 2018). Two conflicting mechanisms concerning traffic volume are revealed by the literature:

Conflict-Driven Severity: Increased volumes lead to more potential for conflict, which raises the overall severity of crashes (Mohanty et al., 2022; Kumar & Mudgal, 2025; Feudjio et al., 2025).

Speed-Dampening Effects: Despite greater overall crash frequency, congestion limits operating speeds, which lowers impact forces and lessens the severity of injuries (Chen et al., 2023; Behnood & Umar, 2022; Rahimi et al., 2023; Sharif & Mim, 2021; Belloumi & Ouni, 2019; Salum et al., 2019). Further, mixed-traffic flow systems which are inherently characterized by heavy vehicular composition contribute to traffic heterogeneity; However, studies have demonstrated that appropriate lane control and proactive infrastructure maintenance mitigate the risks associated with high proportions of commercial vehicles (National Bureau of Statistics, 2022; Wen et al., 2022; Bayode et al., 2025).

2.7 Integrated Systemic Perspective

Contemporary safety research increasingly embraces a holistic framework wherein roadway geometry, driver behavior, traffic dynamics, and environmental factors act interactively rather than in isolation (Behnood & Umar, 2022; Feudjio *et al.,* 2025; Li *et al.*, 2024; Zhang *et al.*, 2024). When multiple adverse conditions are combined for instance low friction surfaces combined with bad weather and large speed differential, crash severity levels escalate; Thus, considering multiple interactions is critical in targeting effective engineering treatments and building robust predictive models.

2.8 Theoretical Framework

2.8.1 Human Factors Theory of Road Crashes

Human Factors Theory posits that crashes stem from cognitive failures in driver perception, judgment, and decision-making (Chang *et al.,* 2019; Abdulwahid *et al.,* 2022; Francis, 2023; Islam *et al.,* 2021; Wen *et al.,* 2023). Under the visual processing paradigm, drivers are constantly interacting with the road environment, processing it as a continuous stream of visual information. When geometric features impose operational demands exceeding human cognitive capacity, driver error increases (Aydin, 2020; Ning *et al.*, 2022; Ergin, 2026; National Bureau of Statistics, 2022; Gong *et al.,* 2022; Chen *et al.,* 2023). Catastrophic collisions are rarely instantaneous; rather, they represent the final stage of earlier cognitive lapses, such as misjudging horizontal curvature or underestimating stopping distances (Chang *et al.,* 2019; Abdulwahid *et al.,* 2022; Francis, 2023; Behnood & Umar, 2022; Rahimi *et al.,* 2023; Liang *et al.,* 2024).Unobserved driver heterogeneity: different drivers react differently to similar geometric dangers because of the differences in experience, weariness, reaction time, and risk perception is a crucial finding of this theory (Gong et al., 2022; Abdulwahid et al., 2022). This theory expounds on how various geometric features influence the mental workload of the drivers, a major underlying factor in driving decisions, particularly on Nigeria's long-haul roads dominated by trucks and often characterized by container overloading, where it is criticized to create the impression of driver inadequacy (Agyemang, 2021; Jamal et al., 2020).

2.8.2 Road Infrastructure Safety Theory

Originating in transportation engineering, Road Infrastructure Safety Theory asserts that the built environment directly influences safety outcomes by conditioning driver behavior, vehicle dynamics, and crash forces (Liang *et al.,* 2024; Islam *et al.,* 2021; Osasu & Ogbeifun, 2020; Feudjio *et al.,* 2025). Rather than viewing crashes purely as driver errors, this theory frames them as indicators of infrastructure limits (Wen *et al.,* 2023; Mahmud *et al.,* 2020; Behnood & Umar, 2022; Gong *et al.,* 2022; Chen *et al.,* 2023; Feudjio *et al.,* 2025). Geometric deficiencies, such as steep grades, sharp curves, and narrow shoulders, are especially critical for heavy vehicles, which exhibit higher centers of gravity, longer stopping distances, and wider turning radii (Olayemi & Mannering, 2021; Wen *et al.,* 2022; Kumar & Mudgal, 2025). Furthermore, this theory accounts for spatial crash clustering (blackspots), demonstrating that geometric defects systematically elevate risk exposure at specific locations (Islam *et al.,* 2021; Wen *et al.,* 2023; Mahmud *et al.,* 2020; Dawud, 2021; Manoj *et al.,* 2024). Infrastructure continues to be a major deterministic element in crash severity, despite critics pointing out that driver behavioural adaptation (such as slowing down on risky road segments) might decrease these risks (Sharif & Mim, 2021; Francis, 2023; Behnood & Umar, 2022; Rahimi et al., 2023; Liang et al., 2024).

2.8.3 Behavioural and System-Based Crash Theories

Behavioral and System-Based Crash Theories conceptualize road safety as an emergent property of a complex socio-technical system comprising drivers, vehicles, infrastructure, environmental factors, and regulatory frameworks (Agyemang, 2021; Olayemi *et al.*, 2023; Islam *et al.*, 2021; Wen *et al.*, 2023; Jamal *et al.*, 2020). These theories, which move away from single-cause attribution, claim that major crashes happen when latent vulnerabilities in several system components coincide (National Bureau of Statistics, 2022; Gong et al., 2022; Feudjio et al., 2025).

This paradigm's basic tenet is that driver error is not a single point of failure but rather an inherent system problem. Wide shoulders, flexible roadside design, gentle horizontal curves, and sufficient sight distance are therefore essential protective buffers designed to absorb human error without causing fatal consequences (Liang et al., 2024; Olayemi et al., 2021; Islam et al., 2021; Osasu & Ogbeifun, 2020; Feudjio et al., 2025). This multi-factor perspective is particularly essential for heavy freight operations, where extreme crash severity typically stems from the simultaneous convergence of vehicle overloading, driver fatigue, degraded road geometry, adverse weather, and high traffic density (Wen *et al.*, 2022; Li *et al.*, 2024; Zhang *et al.*, 2024; National Bureau of Statistics, 2022). System-based theories offer a direct link to the application of advanced econometric modeling frameworks such as Mixed Logit (Random Parameters) Models. Crash analysis data is best captured by dynamic statistical models that make provision for unobserved heterogeneity emanating from environmental, traffic, and behavioral variables, which are often not controlled in standard logit models (Sharif & Mim, 2021). System-based theories provide the direct theoretical justification for advanced econometric techniques, specifically Mixed Logit (Random Parameters) Models. Because crash processes are inherently dynamic and influenced by unobserved contextual and behavioral variability, fixed-parameter models fail to capture the true complexity of crash severity (Behnood & Umar, 2022; Gong *et al.*, 2022; Okafor *et al.*, 2022; Chen *et al.*, 2023; Alshehri *et al.*, 2024). The Mixed Logit model accounts for the unobserved heterogeneity and multi-factorial interactions central to the system-based theories by introducing ad hoc explanatory variables that are randomly distributed across accident observations, including horizontal curve geometry. The three theoretical paradigms jointly offer a holistic perspective on the severity of truck accidents on the road network of Nigeria. The road infrastructure safety paradigm isolates the effect of geometric design on vehicle performance, while the human factor paradigm unravels the underlying psychological processes by which drivers perceive and respond to roadside geometrics. By contrast, the behavioral and system-based paradigms provide complementary conceptualizations of crash severity as a function of the combined effects of vehicle dynamics, roadway infrastructure, human performance, and environmental variables

3.0 RESEARCH METHODOLOGY

A quantitative, cross-sectional explanatory design was adopted for this study. The empirical investigation focused on two strategic freight corridors in Nigeria:

Methodological Note on Data Integration: This study uses a dual-source framework to guarantee complete transparency on the empirical design. The primary survey data (n=390) obtained through structured stakeholder questionnaires was used separately to rank perceived contributing crash factors (Table 1.4), assess comparative perceptions of highway geometric adequacy (Table 1.3), and create respondent demographic profiles (Table 1.2). On the other hand, the verified historical crash database (N=1,580) obtained from the Federal Road Safety Corps (FRSC) National Crash Reporting Information System (NACRIS) repository was the only method used to estimate and calibrate the discrete choice econometric models (which include both the Standard Multinomial Logit and the Mixed Logit specifications).

Lagos – Ibadan Expressway: Serves as the primary arterial link connecting the Lagos seaport hub to Ibadan and northern hinterlands; total corridor length is 127 km, characterized by heavy freight traffic volumes (AADT ≈ 38,000 vehicles/day, with heavy trucks comprising 28%).

Benin - Ore Highway: This 135-km route linking the western and eastern parts of Nigeria is characterized by rough terrain, a high volume of tanker traffic, and poor road pavement.

3.1 Data Collection and Sampling Strategy

Primary Data: Administered structured questionnaires to 390 sampled stakeholders across 5 strata (231 Commercial Truck Drivers, 58 Fleet & Logistics Managers, 43 FRSC Safety Patrol Officers, 33 Highway Engineers, 25 Road Maintenance Staff). A multi-stage stratified random sampling formula was applied: Sample Size Formula Taro Yamane, (1967)

$$\mathbf{n} = \frac{\mathbf{N}}{\mathbf{1+N(e)^2}} \qquad (1)$$

n - Sample size,
N - Population size,
e - A variable representing error or Efficiency = 0.05
using the equation to solve for n,
Where $N, = 15{,}415$ and $e, = 0.05$, Therefore, applying on formular

$$n = \frac{15{,}415}{1 + 15{,}415(0.05)^2}$$

$$n = \frac{15{,}415}{1 + 38.1375}$$

$$n = \frac{15{,}415}{39.5375} = 389.8 \quad n \approx 390$$

Secondary Data: Extracted 1,580 clean, verified truck-involved crash records (2018–2025) from the FRSC National Crash Reporting Information System (NACRIS). Geometric design specifications were obtained from Federal Ministry of Works road inventory logs.

3.2 Econometric Model Specification: Standard Multinomial Logit (MNL) Model

The standard MNL utility function for crash observation i and severity outcome j is defined as:

$$U_{ij} = \beta_i X_{ij} + \varepsilon_{ij} \qquad (2)$$

Where Xij is a vector of observed geometric, traffic, and environmental variables; βj is a vector of fixed parameters; and εij is an independently and identically distributed (I.I.D.) extreme value error term. The choice probability Pi(j) is:

$$P_{ij} = \frac{e^{V_{ij}}}{\sum_{k=1}^{j} e^{V_{ik}}} \qquad (3)$$

3.3 Mixed Logit Model (Random Parameter Logit)

To account for unobserved heterogeneity across crashes, parameter vector β_i is allowed to vary across individual crash observations i according to a continuous probability density function $f(\beta|\theta)$, where θ represents parameters of the distribution (mean and variance):

$$U_{ij} = \beta_i X_{ij} + \varepsilon_{ij}$$

$$\beta_i = \beta + \eta_i \qquad (4)$$

where η_i is a random term distributed according to $f(\beta|\theta)$

The unconditional probability Pi(j) of observing severity level j is the integral of the MNL probability over the parameter density:

$$P_i(j) = \int \left(\frac{\exp(\beta_i X_{ij})}{\sum_k \exp(\beta_i X_{ik})}\right) f(\beta|\theta)\, d\beta \qquad (5)$$

Normal distributions were assumed for random parameters hypothesized to exhibit unobserved heterogeneity (shoulder width, horizontal curve radius, and truck overloading). Other variables that were examined for random distributions produced standard deviations that were deemed small and were therefore regarded as fixed. Model estimate was carried out using maximum simulated likelihood utilizing 500 Halton draws since the choice probability integral does not have a closed form.

4.0 RESULTS AND EMPIRICAL ANALYSIS

4.1 Primary Survey Analysis and Stakeholder Demographics

To account for potential non-responses and satisfy the minimum Yamane threshold of n= 390, 402 questionnaires were initially administered across the designated stakeholder strata. A total of n=390 usable responses with a 97.0% response rate were recorded after eliminating 12 incomplete or inconsistent records during data processing. Table 1.1 encapsulates this distribution, retrieval, and screening hierarchy

Table 1.1: Questionnaire Distribution, Retrieval and Screening Summary

Description	Number	Administered (%)
Questionnaires administered	402	100.0
Questionnaires retrieved	402	100.0
Discarded (incomplete/inconsistent)	12	3.0
Valid questionnaires used for analysis	**390***	97.0

Table 1.2: Summary of Respondent Characteristics

Stakeholder Category	Sample (n)	Percentage (%)	Primary Experience Level
Commercial Truck Drivers	231	59.2%	12.4 Years Average Driving
Fleet & Logistics Managers	58	15.6%	8.2 Years Operational Supervision
FRSC Safety Patrol Officers	43	11.0%	10.5 Years Enforcement/Rescue
Highway Design Engineers	33	8.5%	14.1 Years Civil Infrastructure
Road Maintenance Personnel	25	6.4%	11.0 Years Pavement Operations
Total	390	100.0%	High Expertise Representation

4.2 GIS Spatial Hotspot Analysis Findings

Kernel Density Estimation (KDE) performed in ArcGIS Pro identified four critical crash hotspots along the corridors:

The first hotspot is located on the Lagos - Ibadan expressway between km 28 and 34 at the Ogere tanker park intersection, where incidents like severe rear-end collisions and rollovers are frequent. This is mainly attributed to roadside parking, narrow shoulders (1.2 m), and traffic divergence.

The second hotspot is on the Lagos - Ibadan expressway between km 62 and 68 at the Long Bridge and Sagamu interchange, where fatal collisions are frequent. This is majorly caused by narrow lanes (3.3 m), lack of median barriers, and wet-surface skidding.

The third hotspot is on the Benin - Ore highway between km 42 and 50 at the Ofosu forest descent, where jackknife and fatal runaway truck incidents are frequent. The main causes of this are severe reverse curves (R = 180 m) and steep descent grades (5.8%).

Hotspot 4 is on Benin - Ore highway between km 88 and 95 at the Ugbogui Slope, where traffic collisions involve heavy rollovers. This is brought on by uneven roadways, eroding shoulders, and restricted vision (80 m).

Table 1.3: Mean Stakeholder Perception Scores of Highways Geometric Adequacy (1 = Very Poor, 5 = Very Good)

Geometric Feature	Lagos-Ibadan Expressway (Mean)	Benin-Ore Road (Mean)	Remark
Lane width adequacy	3.42	3.05	Moderately adequate
Shoulder width/condition	2.31	1.98	Inadequate
Horizontal curve adequacy	3.61	2.44	Poor on Benin-Ore
Vertical grade/gradient	3.55	2.61	Poor on Benin-Ore
Sight distance adequacy	3.20	2.77	Moderately adequate
Pavement condition	2.48	2.05	Inadequate
Median/guardrail adequacy	2.86	2.32	Inadequate

An independent-samples t-test was conducted to determine whether the mean perception scores differed significantly between the two corridors. The results showed statistically significant differences ($p < 0.05$) for horizontal curve adequacy ($t = 6.84$), vertical grade ($t = 5.92$) and shoulder width/condition ($t = 3.17$), confirming that respondents perceived the Benin-Ore Road as geometrically more deficient than the Lagos - Ibadan Expressway on these specific features. The pavement state showed no statistically significant difference ($t = 1.42$, $p = 0.156$), indicating that despite the different geometric requirements in the two corridors, pavement deterioration was thought to be a fairly widespread issue.

Table 1.4: Stakeholder-Ranked Perceived Contributory Factors to Truck Crashes

Perceived Contributory Factor	**Percentage of Respondents Ranking in Top 3 (%)**	**Rank**
Lanes width/shoulders	71.3	1st
Poor pavement condition	66.7	2nd
Speeding	64.1	3rd
Sharp horizontal curves	58.2	4th
Driver fatigue/night driving	52.6	5th
Steep gradients	47.4	6th
Poor sight distance/obstruction	39.0	7th
Vehicle mechanical fault/overloading	35.6	8th

It is notable that lane width and shoulders, poor pavement condition and sharp horizontal curves all geometric factors - were ranked among the top four perceived contributory causes by stakeholders, lending strong face validity to the geometric emphasis of the study

4.3 Econometric Model Estimation Results (Standard MNL vs. Mixed Logit)

Table 1.5 presents parameter estimates for both the Standard Multinomial Logit (MNL) model and the Mixed Logit Model (MLM) with random parameters. Property Damage Only (PDO) is the reference baseline severity category.

Table 1.5: Parameter estimates for MNL model and MLM

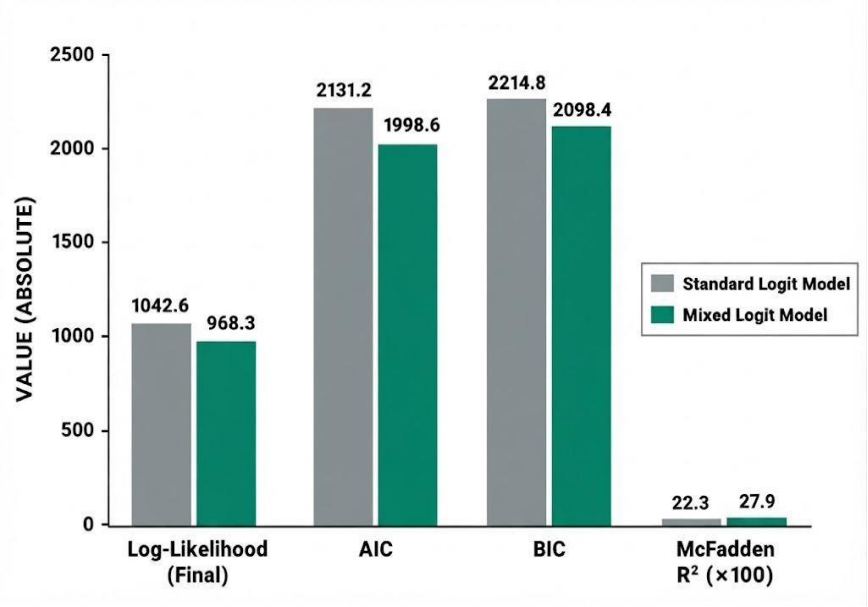
Explanatory Variable	**MNL Coeff. (b)**	**MNL p-val**	**Mixed Logit Coeff. (b)**	**MLM Std. Dev. (s)**	**MLM p-val**	**Odds Ratio**
--- INJURY CRASHES ---						
Constant	-0.412	0.082	-0.528	--	0.041	0.590

Lane Width < 3.3 m	0.485	0.012	0.612*	--	0.002	1.844
Shoulder Width (m)	-0.325	0.008	-0.442*	0.218*	0.001	0.643
Horizontal Curve < 300 m	0.512	0.003	0.685*	0.312*	0.000	1.984
Vertical Grade > 4%	0.398	0.021	0.524*	--	0.006	1.689
Sight Distance < 120 m	0.342	0.035	0.458*	--	0.011	1.581
Night Driving (1=Yes)	0.295	0.048	0.382*	--	0.018	1.465
Truck Overloading (1=Yes)	0.421	0.015	0.564*	0.265*	0.003	1.758
--- FATAL CRASHES ---						
Constant	-1.125	0.001	-1.385	--	0.000	0.250
Lane Width < 3.3 m	0.812	0.000	1.085*	--	0.000	2.959
Shoulder Width (m)	-0.628	0.000	-0.892*	0.385*	0.000	0.410
Horizontal Curve < 300 m	0.945	0.000	1.312*	0.492*	0.000	3.714
Vertical Grade > 4%	0.785	0.001	1.045*	0.348*	0.000	2.843
Sight Distance < 120 m	0.612	0.004	0.842*	--	0.001	2.321
Night Driving (1=Yes)	0.518	0.010	0.712*	--	0.002	2.038
Wet Surface (1=Yes)	0.412	0.028	0584*	--	0.008	1.793
Truck Overloading (1=Yes)	0.724	0.001	0.985*	0.412*	0.000	2.678

MODEL FIT METRICS

Metric / Diagnostic Parameter	Standard MNL Model	Mixed Logit Model (MLM)	Model Improvement
Log-Likelihood at Zero	-1,342.10	-1,342.10	-
Log-Likelihood at Convergence	-1,042.60	-968.30	+74.30
Akaike Info Criterion (AIC)	2,131.20	1,998.60	-132.60
Bayesian Information Criterion (BIC)	2,214.80	2,098.40	-116.40
McFadden Pseudo R-squared	0.223	0.279	+0.065
Overall Classification Accuracy (Hit Rate)	61.8%	71.4%	+9.6%

Area Under ROC Curve (AUC)	0.734	0.812	+0.078
Likelihood Ratio Test (X2)		148.60\ (df = 5, p < 0.001)	(X2) = 15.09



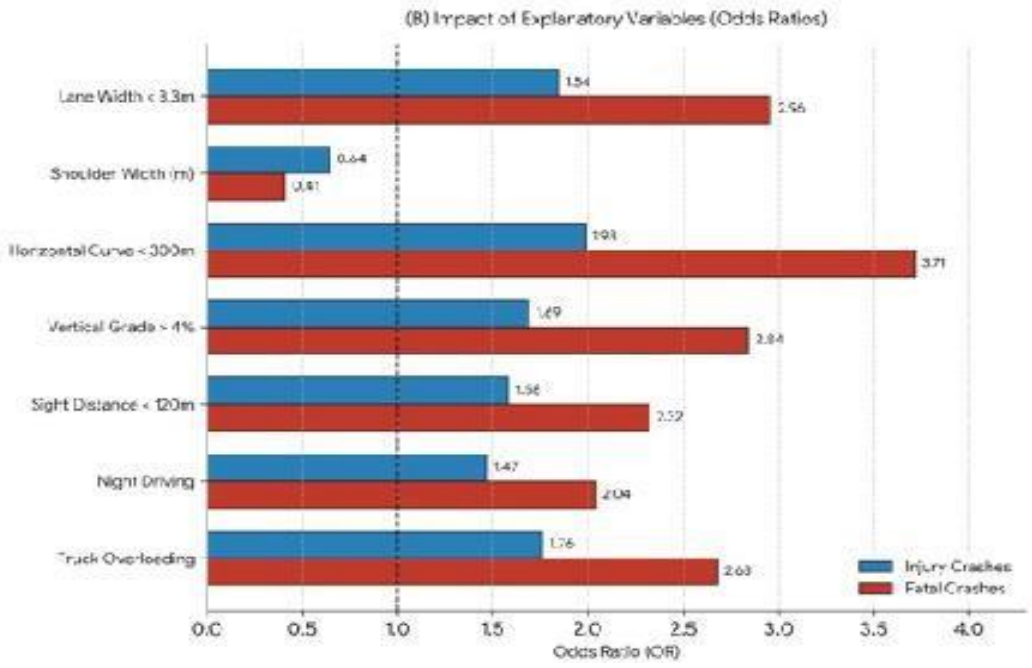


Figure 1.1: Good-of-Fit Comparison between the Standard Multinomial and Mixed Logit Models (n – 390; N - 1580)

4.4 Marginal Effects Analysis

To provide direct practical engineering interpretation, marginal effects were computed. The absolute percentage change in the likelihood of each crash severity level brought about by a unit change in a continuous predictor or a shift in a binary indicator is measured by marginal effects. Marginal effects for important variables are listed in Table 1.6.

Table 1.6: Marginal Effects Analysis

Variable Description	dPr(PDO) / dx	dPr(Injury) / dx	dPr(Fatal) / dx
Lane Width < 3.3 m (1 vs 0)	-0.185 (-18.5%)	+0.062 (+6.2%)	+0.123 (+12.3%)
Shoulder Width (+1.0 m Increase)	+0.142 (+14.2%)	-0.045 (-4.5%)	-0.097 (-9.7%)
Horizontal Curve < 300 m (1 vs 0)	-0.248 (-24.8%)	+0.081 (+8.1%)	+0.167 (+16.7%)
Vertical Grade > 4% (1 vs 0)	-0.172 (-17.2%)	+0.054 (+5.4%)	+0.118 (+11.8%)
Sight Distance < 120 m (1 vs 0)	-0.134 (-13.4%)	+0.048 (+4.8%)	+0.086 (+8.6%)
Truck Overload (1 vs 0)	-0.198 (-19.8%)	+0.068 (+6.8%)	+0.130 (+13.0%)

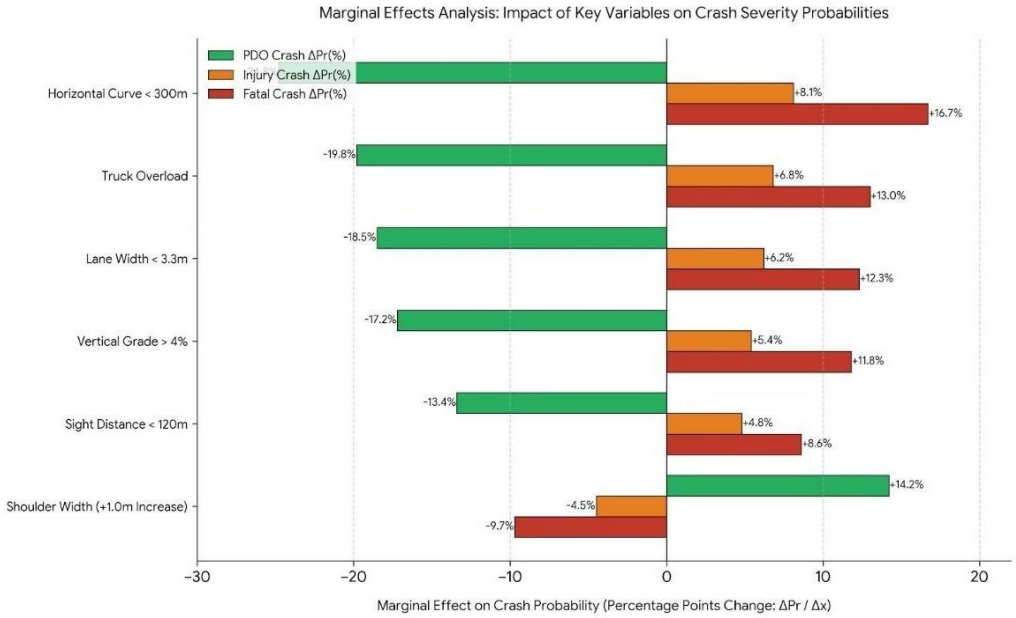


Fig. 1.2: Marginal Effect of Key Geometric Variables on Severe Truck Crash Probability (Mixed Logit Model)

5.0 CONCLUSION AND POLICY RECOMMENDATIONS

This study investigated the contributory interactions among highway geometric characteristics, operational traffic metrics, and environmental conditions on heavy freight vehicle crash severity along key Nigerian transport corridors (the Lagos – Ibadan Expressway and the Benin – Ore Highway). Utilizing a robust methodological framework combining GIS spatial kernel density estimation, stakeholder perception surveys, and discrete choice econometric modeling, the research successfully established the empirical superiority of the Mixed Logit (Random Parameters) model over the standard Multinomial Logit specification. The Mixed

Logit model results showed a significant degree of unobserved heterogeneity across roadway corridors, implying that truck loading, shoulder width, and horizontal curve radius affects truck crash severity over time. Geometric deficiencies, namely narrow lanes (< 3.3 m), insufficient shoulders (< 1.2 m), sharp horizontal curves (< 300 m), steep vertical grades (> 4%), and limited sight distance (< 120 m), significantly increase the likelihood of severe and fatal truck collisions, according to the empirical results. Furthermore, environmental adversity (wet surfaces) and behavioral/operational risk factors (night driving and truck overloading) severely exacerbate these structural hazards

5.1 Strategic Policy and Engineering Recommendations

1. **Geometric Corridor Redesign:** Highway authorities should realign sharp horizontal curves to exceed 450 m radii and soften vertical grades below 3.5%. In accordance with the safety standards of Behnood & Mannering (2021) and Tola et al. (2021), slopes higher than 4% on steep sections such as the Benin–Ore Road should be accompanied with designated climbing lanes to minimise brake fade and speed differentials.
2. **Cross-Sectional Standardization:** Widen travel lanes to a standard 3.65 m and construct fully paved 2.5 m shoulders along the Lagos – Ibadan Expressway and Benin – Ore Road to provide recovery space for heavy vehicles.
3. **Emergency Escape Facilities:** Construct emergency runaway truck ramps (gravel arrestor beds) on steep downgrades (e.g., Ofosu Forest Descent km 45) to safely capture out-of-control heavy trucks experiencing brake failure.
4. **Intelligent Enforcement**: To install high-speed weigh-in-motion sensors at strategic roadside stations for real-time detection and penalize overloaded vehicles. Hazard
5. **Mitigation Infrastructure:** To construct a comprehensive roadside protection system along high-risk road corridors, rumble strips, rigid concrete barriers, solar highway lighting, and reflective median guardrails.

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