International Journal of Science and Engineering Science Research
Volume 2 | Issue 3 | July-September 2026 | ISSN 3049-2793
Peer Reviewed (Referred Journal)
DOI: https://doi.org/10.63671/ijsesr.v2i3.161

Exploration of Rural Road Safety on Basis of Average Accident and Road Geometry: A Case study of Rural Road Kaski, Nepal

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Abstract

Road geometric design in an inappropriate manner leads to road traffic accident which is major aspect to be consider regarding to safety. To ensure safety hazardous location must be identified on basis of accident regarding to road geometric elements. The basic purpose of this research is to examine the critical aspect between road geometric design and traffic safety in the rural mountainous terrain of Kaski, Nepal. Basically, the study aims to identify geometric elements which contribute to accident frequency and quantify their relationship through well calibrated mathematical models.This research assist to develop a framework for identifying design inconsistencies which lead to loss of property and life. This is a case study related to Methlang- Gyarjati rural road where three test curves are selected to collect necessary primary data using mobile sensors and standard survey equipment. Test-retest was conducted to ensure data integrity. The research utilizes a predetermined linear model ($Y=0.03X+0.54$) to estimate average accident numbers based on operating speed (V_{85}) due to lack of consistent historical accident records. The sensitivity of each geometric predictor are establish through statistical analysis using General Linear regression. The findings reveal that shoulder width (S_w) is the most significant predictor of safety, explaining approximately 63% to 65% of the variability in infrastructure-estimated baseline accident risk rather than curve length and radius which fail to meet driver workload demands thus indicating geometric inconsistencies in the study section. The model was formulated as $Y_{av}=1.9084-0.4543Sw$ which mathematically elaborate significant decrease in estimated accident frequency with increase in shoulder width. Thus, it can be said that rural road accidents are tied to geometric deficiencies rather than random factors. The widening of shoulders to at least 1.0m to 1.5m at curve sections must be prioritize which is very sensitive in reducing long term risk. Thus, model develop herein play a vital role for maintaining geometric consistencies, safety audits and hence prevent huge loss of life and property.

Keywords

Average accident number, Rural Road geometry, Safety

1. Introduction

A robust exploration of rural road safety necessitates an integrated analysis of average accident occurrence and road geometry because the physical design elements of non-urban roads are primary determinants of crash risk and severity, often due to older designs and varied cross-sections (Austroads, 2019; Analysis and Modeling of Rural Roads Traffic Safety Data, 2023). The safety profile

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of rural road network really pressing challenges in global scenario of transportation engineering. Statistics consistently shows that rural roads account for a disproportionately high number of fatalities despite of significantly lower traffic volumes. In context of global scenario road traffic accident claim approximately 1.9 million lives annually, remaining the leading cause of death for children and young adults aged 5-29. In context of Nepal for the fiscal year 2024/25, the country reported 28,692 road traffic accidents with a rapid increment from 20,640 in 2020/21.Kathmandu valley accounts for nearly half of national crashes, whereas fatality rates are higher outside the valley ranging from 15% to over 50% per crash due hazardous road geometry and delayed emergency response. Economically this account roughly 7% of the national GDP.

So, it seems that beside reactive safety measures it is essential to quantify the relationship between road geometry and its accident history to meet the critical needs which are justified in this study. The justification are made by addressing geometric inconsistency, evidence-based interventions, predictive modeling $Y=0.03X+0.54$ and engineering accountability such that proper budgetary allocation can be made by Government for widening shoulders and optimizing curve radii in mountainous terrain of Nepal.

So, to sum up this research seeks to validate that accidents are not merely random occurrences but are often the result of geometric inconsistencies between road design and the driver workload demand. Identifying these high risk segments is preliminary aspect towards attainment of safety such that resilient rural road infrastructure can be obtained thus ultimately saving huge loss of life and property in rural Nepal.

Every year several accidents occur in rural road of Kaski which has poor record of safety. Speed on single elements and subsequent elements are major factor pertaining to accident. Rod geometric inconsistencies on the other hand play vital role in accelerating accidents in rural road of Kaski.

The major objectives of the study include:

- To identify major geometric elements related to average number of accident.
- To explore the relationship between average number of accident and calibrated geometric elements.

The study will assist in evaluation of safety at curve section such that inconsistency in design section of the curve can be identified and necessary correction can be made by concerned local authority (DOR).

The analysis of rural road safety is a critical area of study due to the disproportionality high number of fatalities that occur on these roads compared to the urban areas. The structural safety evaluation of rural road network remains an urgent challenge within global transportation sector. Annually, road traffic injuries account approximately 1.19 million fatalities worldwide, which is the leading cause of death for children and young adults aged 5-29(World Health Organization, 2023). Urban networks accommodate higher absolute traffic volumes, non-urban and rural mountainous corridor exhibit a

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disproportionately elevated fatality rate per crash (Austroads,2019; Federal Highway Administration,2023).

Basically, in developing countries like Nepal which is characterized by a rugged terrain, this crisis is amplified by under-engineered infrastructure and rapidly expanding traffic volumes. The traffic safety metrics reveals an alarming trajectory: during the 2024/25 fiscal year, national accident figures surged to 28,692 crashes, up from 20,640 in 2020/21

(Poudel et al., 2024). The single vehicle lane departures frequently result in multi-fatality events which lead to severe macroeconomic toll, costing Nepal approximately 7% of its national gross domestic product(GDP) in infrastructure damage, healthcare, and lost productivity (Poudel et al.,2024)

In mountainous alignments, such as the rural road networks of the Gandaki province, roads are bound by extreme topographic constraints. Consequently, they are frequent characterized by sharp horizontal curves, steep long grades and highly restricted cross-sectional dimensions. Historically, empirical safety evaluation emphasize that non-standard alignment features are the primary predictors of lane departure incidents (Sari et al.,2024). However, conventional safety research often treats geometric variables like curve radius(R), curve length (CL), and longitudinal slope in isolation, failing to account for the transitional dynamics between consecutive alignment elements (AI-Masaeid,2024).

Basically geometric design consistency is achieved when the physical features of the roadway align with driver expectations and cognitive workload capacities(Austroads,2019).When a driver transitions from a high-speed tangent section into an abrupt, sharp horizontal curve a massive spike in driver workload occurs(Banjara & Gautam,2023).Similarly, if the radius of the curve is insufficient, the vehicle's operating speed(V85) will dramatically deviate from the theoretical design speed which force drivers into sudden, unstable deceleration maneuvers (Sharma&Landge,2024).

Nearly, 75% of surveyed horizontal curves reveal that horizontal curves suffer from poor design consistency as per regional evaluations on major hilly corridors in Nepal. (Banjara&Gautam,2023). This indicates an increased frequency of run-off-road and head- on collisions, as explained by the kinematic inconsistency theory. (AI-Masaeid, 2024; Marchesini&Weijermars,2024)

It is obvious that horizontal curvature faces tracking instability, meanwhile the cross-sectional configuration of the roadway determines whether that instability result in a successfully recovery or a fatal crash. This dictates that an well-engineered transport corridor must provide an unobstructed, traversable recovery area adjacent to the travel lane (Federal Highway Administration, 2023). Finally, within this clear zone the structural dimensions and material stability of shoulder width (S_w) play vital role for correcting tracking errors (Zeng & Schrock, 2012)

In mountainous environment, narrow shoulder mean that any minor lane departure immediately leads to catastrophic run-off-road event or an impact with mountain cut-slope wall. A desirable shoulder width provides an immediate recovery zone for driver who get surprise due to geometric features and it also function as buffer zone to avoid head on collision due to narrow, two-lane rural roads where large vehicles frequently encroach in opposite lanes (Sari et al., 2024).Many literature reviews reveals that shoulder width is inversely proportional with accident rates which assist in playing dramatic role in reduction of crash severity. (Zeng&Schrock,2012)

Despite of extensive research on rural road safety in developed nations, there is still lack of localized literature that accounts for extreme mountainous terrain of Gandaki Province. Contemporary localized literature frequently overemphasizes pavement surface distress(such as potholes, or rutting) or driver impairments as the exclusive cause of rural crashes(Sharma&Landge,2024).while these factors are undeniably influential, treating them as the sole causes obscures the underlying role of geometric deficiencies. Most of the models are feasible for rolling and flat terrains which generally fails to predict accident frequencies especially in high grade and sharp curve environment typically of Kaski. Previous literature often analyses geometric elements like radius, curve length in isolation. Recent regional studies also suggest that 75% of curves in Nepal suffer from poor design consistency which means the major problem lies in transition between elements rather than just the element themselves. (Banjara & Gautam,2023).This research aims in bridging the gap by using predetermined linear speed-risk model (Y=0.03X+0.54) which tries to establish a baseline safety risk using field-measured operating speed(V_{85}) across critical curve sections. By pairing this operating speed parameter with specific local geometric elements through general linear regression, this study explicitly isolates and quantifies the sensitivity of the roadway's cross-section. It mathematically demonstrates that shoulder width alone accounts for 63% to 65% of the variation in estimated safety risk(R^2=0.6503,RMSE=0.04123) .It will assist as a mathematical foundation for the Department of Roads to prioritize low-cost, high-yield shoulder widening interventions thus, developing a resilient rural road infrastructure in Kaski, Nepal.

2. Methodology

The basic methodology for analysis includes preliminary survey of geometric features for three pre-test samples of curves. It overall, basically follows a quantitative, cross-sectional design for modeling the safety performance of study area to find the impact of road geometry on accident frequency.

2.1. Study area selection and sampling phenomenon:

The Methlang-Gyarjati rural road was especially selected due to mountainous panorama and poor record of safety for the study. A systematic sampling procedure was implemented to identify three test curve sections with varying degree of horizontal curvature and shoulder availability for model development.

2.2. Field Survey Methods:

At each selected curve points primary data related to road geometry (curve length, radius, and shoulder width) are collected using mobile sensors and standard survey equipment's to ensure reliable precision. The degree of curve (D) was calculated using standard horizontal alignment formula.

Test-Retest method was applied to the survey measurements of some geometric elements at different intervals, which assist in confirming the reliability of the data prior to statistical analysis.

2.3. Use of predetermined model and it's justification:

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It is obvious that basically in rural road of Nepal, a comprehensive and location-specific historical accident data are often under-reported, inconsistent for curve section analysis. Due to gaps in local historical data and under-reporting, this study implement predetermined linear model (Y=0.03X+0.54) to establish a baseline estimated accident frequency using field measured operating speed (V_{85}) data. This model bridges the gap by allowing safety evaluation without relying on flawed historical data.

As this approach rely on infrastructure-induced risk rather than incomplete police data so it is justifiable. Likewise, the operating speed (V_{85}) is calibrated using specific local geometric parameters V_{85}=40.168+0.070R- 0.118 D , where 'R' and 'D' indicate radius and degree of curve respectively.This also assist to ties the predetermined accident model back to the physical terrain characteristics of Kaski. Basically, Local authorities in Nepal traditionally rely on qualitative safety assessments but this mathematical model will assist in providing a quantitative framework for prioritizing infrastructure funding and safety upgrades.

2.4. Data Analysis and Model Formulation:

The relationship between the measured geometric predictors and estimated accident frequency are explored on the basis of General Linear Regression. Statistical Normality test reflect that while curve radius and length varied, shoulder width remained consistently narrow across the road section. The final predictive model are acceptable for safety analysis which are evaluated on basis of coefficient of determination (R^2) and RMSE. Overall, the result provides a quantifiable picture dictating safety on study area.

2.4.1. Statistical Profile of Road Geometry:

The field survey data of three test curve sections demonstrate the variability in horizontal alignment which is elucidated below:

Table 1: Horizontal Alignment Parameters:

Curve Point	Radius(R)/m	Curve length(C_L)/m	Shoulder width(S_W)
1.	38.85	14.90	0.39
2.	24.05	8.81	0.36
3.	73.49	26.92	0.12

The preliminary step regarding to analysis includes field survey for three test horizontal curves with mobile sensor (Table 1)

Table 2: Statistical analysis of Geometric elements:

Geometric elements	Mean	Min^m	Max^m	Range	S.D.
C_L	21.77	8.81	36.46	27.65	6.91
R	66.76	24.05	130.66	106.61	26.65
S_W	0.49	0.12	1.10	0.98	0.24

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From the statistical analysis the normality of the data was obtained with not much variation regarding to shoulder width irrespective of curve length and radius (Table-2) which is taken into consideration to meet the desired objectives. The lack of variation in shoulder width, regardless of the sharpness of the curve suggest a systematic deficiency of recovery zone for drivers in the study area.

2.4.2 Observation of speed and accident:

For each section safety system performance were evaluated by observing (estimation) of speed and accident.

Table 3: Operating Speed and Estimated Baseline Accident Frequency

Curve Point	Speed (Km/h) (V_{85}=40.168+0.070R-0.118D)	**Estimated Baseline/average Accident Frequency**(Y=0.03x+ 0.54)up-to 44km/h
1.	41.57	1.78
2.	38.41	1.69
3.	44.39	1.86

The operating speed for three test curve sections are obtained from predetermined model (Table-3) and estimation of average accident number up-to 44Km/h are made based on standard graph (Figure-1) respectively. The probability of accident also rises as operating speed increase due to larger radii if other safety features like shoulders are not improved.

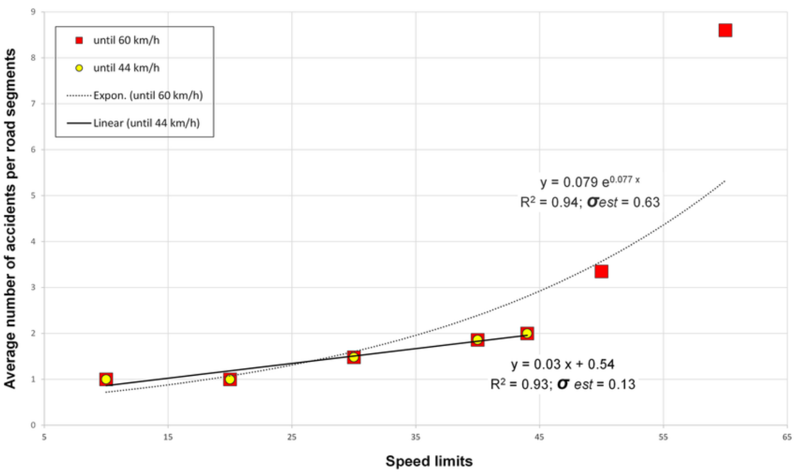

Figure-1: *Relation between speed limits and Average number of accidents per road segments*

The relationship holds good up-to 44 Km/h where average number of accidents per road segments(Curves) are determined using equation as Y=0.03x+0.54 (Figure-1) which confirms the follow of linear regression by accident rate.

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2.4.3 Model Formulation:

This involves the final analysis which established model for predicting accident frequency on the basis of most explanatory variables related to geometric elements.

Table-4: Relationship between average accident number and Geometric elements

Curve Section	Relationship	R^2	Model Formulation	Av.no.of accident predicted	RMSE
1.	Average accident number and curve length	0.9525	Y= 0.009x+1.6247	1.78	
2.	Average accident number and Radius	0.9331	Y= 0.0032x+ 1.6295	1.66	
3.	Average accident number and shoulder width	0.6503	Av. accident at curve (Y)=1.9084-0.4543S_w	1.85	0.04123

Despite the curve length and radius present high mathematical correlations (R^2=0.9525 and R^2=0.331 respectively), still they show structural design inconsistencies relative to operational vehicle speeds. This results the formulation of final predictive model exclusively around the most stable and sensitive geometric element: shoulder width (S_w). This model (Yav.=1.9084- 0.4543Sw) is validated by an R^2 value of 0.6503,which proves that 65% of the infrastructure risk profile on these mountainous curve is directly governed by cross-sectional constraints.

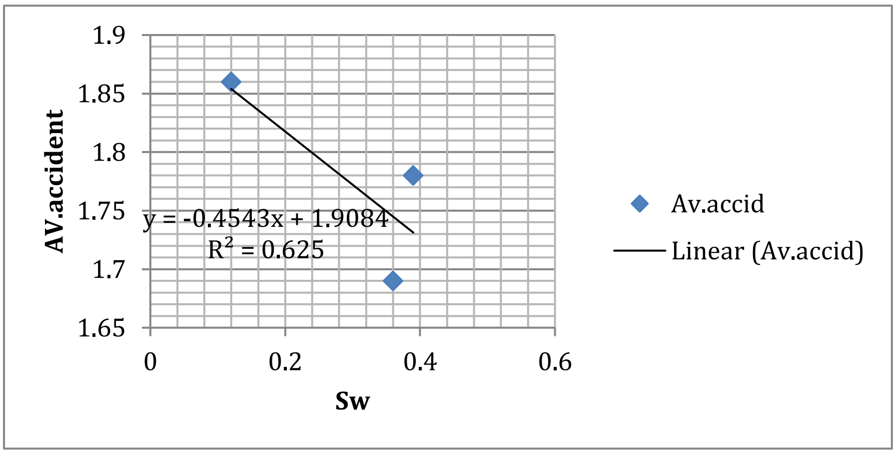

Figure 2: Relation between average accident and shoulder with(Sw)

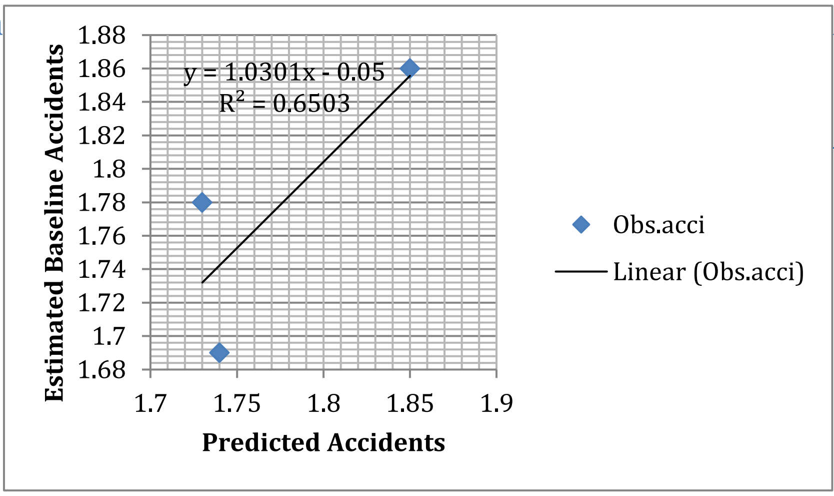

Figure 3:Scattered plot Correlating Speed-Derived Baseline Estimates vs.Geometric Model Predicted Accidents

3. Results and Discussion

The result shows the significant correlation (R^2=0.6503) (Figure.3) between the speed-estimated baseline risk observed and final shoulder-width predicted crash risk. Further, with increase in shoulder width the average accident number seems to be decrease (Figure 2) which assist in design consistency of rural road of Kaski, Nepal. Overall, the analysis reflects that road geometry in kaski are the influencing factors for accident outcomes with shoulder width (S_w) as the most emerging factors.

3.1. Shoulder width(S_w) and it's potential impact:

Results reflect that as shoulder width increases, the average accident number significantly decreases. These findings are also supported in global scenario by international literature which dictate that wider shoulder provides a recovery area for driver who stray from the lane, thus by minimizing the run-off-road accidents.

3.2. Design Consistency and Road geometry:

Thus, curve length showed a high correlation with accident occurrence, it often failed to meet driver workload demand thus, leading to design inconsistency. Especially, curve of radii less than 200 are characterized by high accident frequency and severity.

In the context of Nepal, basically most research made on Narayanghat-Mugling road section reveals that 75% of curve section were poor in consistency which contribute to the significant accident every year.

4. Conclusion

This study generally focused on providing a quantitative evaluation of the geometric safety performance of the Methlang-Gyarjati rural road corridor in Kaski, Nepal. Due to under-reported or missing crash records, the implementation of a predetermined speed-risk model($Y= 0.03X+ 0.54$) assist successfully to establish a baseline for infrastructure-induced safety risks based on vehicle operating speed(V_{85}).The geometry-induced baseline risks are highly applicable and stable due to mathematical calibration for low-speed mountainous environments up-to 44Km/hr.

The risk along the rural curves is the deterministic consequences of measurable cross-sectional deficiencies rather than random occurrences which are justified by the empirical findings. Among geometric predictors evaluated, shoulder width (S_w) was identified as the most critical infrastructure element, explaining 63% to 65% of the total variability

in estimated baseline safety risk (R^2=0.6503).The localized predictive model formulated as $Y_{av.}=1.9084 – 0.4543S_w$ mathematically reflects that increasing the shoulder width

results in a direct quantifiable decrease in the predicted accident index. Conversely, while variation in the curve length showed a high mathematical correlation with accident estimation (R^2= 0.9525), but the existing layout fails to address the physical transition demands of the corridor which illustrate critical design inconsistencies across the road network. This research finally validates that restricted shoulder width (S_w) which average a narrow 0.49m across the surveyed sections are the primary structural source of infrastructure risk on these mountainous curve sections. Thus, to prevent from long term loss of life and property.it require urgent engineering interventions which assist to meet the current deficiencies in rural road network of Kaski. For tangible safety improvements through transformation of these statistical findings

the Department of Roads (DOR) and local municipal authorities must take following actions reforming their plans and policies.

- Prioritize the structural widening of shoulder width with a minimum threshold of 1.0m to 1.5m at all horizontal curves with a radii below 40m, where safety risk profile are high sensitivity to cross-sectional width.
- Re-alignment of curve sections must be emphasis where poor design consistencies are noticed to ensure smooth operation of vehicles.
- The developed model $Y= 0.03X+0.54$ can be utilize as a predictive auditing tools to identify and prioritize high risk geometric "black spots" especially for rural roads in Kaski before accident occurs.
- High-intensity reflective markers and clear signage must be install for better define of existing curve geometry if immediate widening is geographically impossible.

Overall, based upon the present findings following future academic explorations are suggested for considerations:

- The geometric expansion related to vertical alignment elements can be proceeded for future research.
- The initial calibrated model (R^2= 0.6503, RMSE = 0.04123) strongly points to shoulder sensitivity, thus expanding the sample size to include more mountainous road corridors will allow for full multi-variable ANOVA matrices, exact p-value mapping, and robust residual profiling.

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- The traffic volume can be incorporated in the regression models for better predictive accuracy of accident rate.
- Advance modeling technique can be implemented for better understanding between complex road geometry and human behaviour.
- Post-implementation of study should be done on Methlang-Gyarjati road to validate the reduction in accident numbers.

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