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RESEARCH ARTICLE

Impact of highway design on traffic safety: How geometric elements affect accident risk

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***Abstract* -** The study conducted in India using Fuzzy Inference System (FIS) is a novel approach to predicting traffic accident rates on rural highways. By using various highway geometric elements as input data, the study was able to identify risk variables related to roadway features and predict accident rates using FIS. The findings of the study suggest that FIS is a valuable tool for predicting accident rates and can help identify the factors that contribute to accidents. The study also found statistically significant positive connections between geometric elements and accident rates, which highlights the importance of highway design and safety measures. The use of Fuzzy Inference Systems in accident prediction is a promising approach as it allows for a more comprehensive understanding of the complex relationships between various factors contributing to accidents. The model was tested using simulation and data analysis and was found to fit well with real-world data, indicating its potential for practical applications in road safety management. Overall, this study provides important insights into the use of FIS in predicting accident rates on rural highways and can help guide future research in this area. It also highlights the importance of considering various highway geometric elements in designing safer highways and implementing appropriate safety measures to reduce accident rates. However, the road accidents can have significant impacts on ecological cycles, including habitat fragmentation, wildlife mortality, pollution, and climate change.

Keywords - *f*uzzy inference system, fuzzy Logic, traffic accident rate, FCM, K-value

INTRODUCTION

This study aims to use artificial intelligence system modelling to understand and predict how alignment geometric factors affect accidents and accident rates on roads. The study focuses on the horizontal alignment of the road, including the radius and deflection angle, as well as the change in superelevation and the vertical alignment length with its K-value and visibility. The study utilizes a literature review of existing research on accident causal factors, accident prediction, and accident optimization modelling to identify the problems of highway geometry elements in traffic accidents. The study also examines the relationship between horizontal curves on highways and road user safety and concludes that factors such as curve radius, superelevation, extra widening, and sight distance have a significant impact on road accidents. The study also looks at other factors such as traffic volume, geometric parameters of the curve, cross-section profile of the road, roadside hazards, visibility distance, curve direction, road friction, and traffic control devices, all of which had an importance on the safety performance at horizontal curves (Zhang, 2009; Islam et al., 2019; Alghafli et al., 2021). Generally, these road geometry factors affect the safety performance of highways (AlKheder et al., 2022). The reaction of these independent quantities to the accident was examined using negative binomial regression models and achieving "safe-by-design," the study recommends placing attention on issues with three-dimensional (3D) highway design (Kanellaidis et al., 2011). The regression analysis examined the safety implications at various roadway terrain in an accident framework and found when the proposed speed was modified, and different terrain types had an impact on safety. Other studies have also used artificial intelligence modellings such as artificial neural networks (ANN) and fuzzy techniques to investigate the safety impacts of highway geometry on traffic accidents. For example, Cansiz et al. (2011) used ANN models to study the safety impacts of horizontal tangents paired with vertical curves on three-dimensional, two-lane roadways and found that the ANN technique produced better results for estimating the frequency of collisions on horizontal tangents. The effect of roadway and development factors on accident frequency and developing a rural road safety risk index using K-means clustering and the Gaussian model studied by Afandizadeh and Hassanpour (2020). Chang et al. (2012) used a combination of the zero-inflated Poisson and Poisson regression analysis to build a model for detecting accident-prone locations and assessing zero-inflated data sets from traffic crash studies. Driss et al. (2013) conducted a study on a fuzzy logic-based traffic accident prediction system that identifies the degree of experience to road crash risk and assesses the complexity of contributing factors. Further, Arun et al. (2023) consider exceptional circumstances such as crashes and extreme conflicts and integrate severity in the risk estimation framework to provide a comprehensive safety assessment framework. This means that the model considers not only the frequency of accidents but also their severity and other exceptional circumstances. All these studies highlight the importance of using advanced techniques such as artificial intelligence in accident prediction and road safety management, as it helps to enhance the understanding of the importance of highway geometry on accidents and to identify high-risk areas for targeted safety interventions. Hence, understanding of the role of geometric design parameters in road accidents is very important as it can have significant impacts on ecological cycles, including habitat fragmentation, wildlife mortality, pollution, and climate change. It is essential to manage road transport in a way that minimizes these impacts and preserves ecological integrity.

The present study aims to develop a Fuzzy Inference System that can model accident causes variables to identify the crash rate. Based on previous studies, it seems that there hasn't been much use of Fuzzy Inference Systems in accident risk analysis, so the present study aims to address this gap in the literature. A Fuzzy Inference System is a type of artificial intelligence algorithm that uses fuzzy logic to model complex systems. In the context of accident risk analysis, it could be used to identify the factors that contribute to accidents and to predict the likelihood of future accidents based on those factors. By developing this inference system for accident risk analysis, the present study could contribute to a better understanding of the causes of accidents and to the development of more effective accident prevention strategies. To meet this objective, national highway 23 (NH-23) in Central-Eastern, India, which joins Chas in Jharkhand at the crossing of National Highway Number 42 (NH-42) at Banarpal in Odisha, was chosen for this study because of its flat topography.

LOCATION OF COLLECTED DATA

Central-eastern India's NH-23 (fig. 1) has a length of 459 km, which connects the Chas in Jharkhand at NH-42 crossing at Banarpal (Odisha). The research corridor begins at kilometre 338/0 at the community of Pallahara and travels north to south before coming to an end at km 405/0 close to Talcher. This section of the driveway is located in the state of Odisha in-between the latitudes of 21° 25.92' N and 20° 56.84' N and longitudes of 85° 11.21' E and 85° 16.30' E. The study region is shown in Figure 1, and the study corridor has a total length of approximately 67 kilometres.

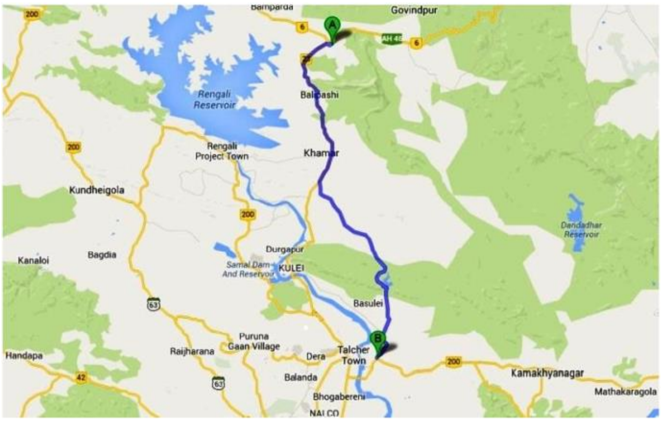


Figure 1: Location Map of NH-23

COLLECTION OF RESEARCH DATA

Topographical investigation. The study described used a combination of field surveys and computer-based tools to analyze the impact of highway geometry on accidents. A topographical (fig. 2 & 3) survey was conducted at the scene of the accident using survey equipment from a Total Station, and the data was managed by a computer-based internal program. The digital data was then downloaded into AutoCAD, a computer-aided design (CAD) tool, for vector entity visualization of the surveying data. Finally, the widely used highway design software MX Road was employed to analyze this data. The study placed 3D topographical points along the road to further understand the accident scene and its relation to the road geometry. These steps provide a detailed and accurate representation of the accident site and its relation to the road design, which can be used to identify potential safety issues and inform design decisions.

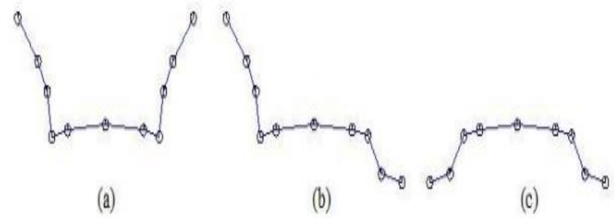


Figure 2: Topographical points on the cross-sectional view

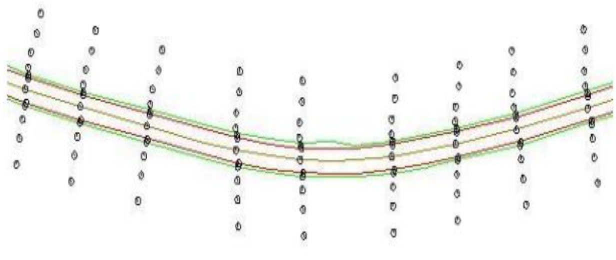


Figure 3: Topographical points on planned interpretation

Accidental records. Records of accidents were gathered from the accident record books of respective police stations. All of these accident-related details were confirmed on-site by police officers and local residents.

Volume of traffic. A long-term (nearly one year) traffic survey at each road location was done to determine the annual average daily traffic (AADT). In order to compare the new data with the old data, the traffic volume has also been gathered from the respective department and validated by a three-day traffic volume survey.

Data extraction. The study used a 3D digital terrain model (DTM) to understand the relationship between highway geometry and accidents. The DTM was created using topographical survey points, road alignment lines, driveway edge, and shoulder border line, which were introduced into the MX Road computer program. This allowed for the determination of the geometric variables of the existing highway. A three-dimensional surface was then used to model the triangulation integrated network (TIN) to further understand the topography of the road. This TIN model was used to retrieve geometric components such as sight distance, angle of deflection, superelevation, vertical curve with alignment, and horizontal curve radius and length. Fig. 4 shows the triangulation integrated network (TIN) or 3D model created throughout the road. This 3D model provides a detailed representation of the road and its geometric components, which can be used to identify potential safety issues and inform design decisions.

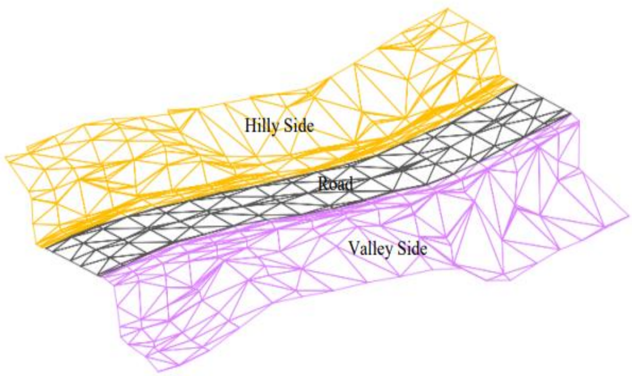


Figure 4: Typical TIN of the existing road

Data extrapolation methodology. The comprehensive research covers a large stretch of country road with different terrain types, such as plain, rolling, and mountainous. A total of 339 accident locations were taken into account on the 297 km stretch of the road. The study gathered data using a 3-D topographical survey of horizontal and vertical alignments, accident statistics, and traffic volume count (Average Daily Traffic). High-precision level software was used to extract the specific details of the highway's geometric features such as the horizontal arc radius, angle of deflection, horizontal arc length, cross fall, change in superelevation, vertical curve and alignment, K-value, and visibility distance. This information will be used to understand the relationship between highway geometry and accidents, identify potential safety issues and inform design decisions to improve road safety.

Horizontal radius. The radius that fits the existing road alignment the best was used to calculate the current radius. The existing center line is fixed with the two tangents in this process, and the radius is fixed with the two tangents to achieve a good fit with the existing alignment. In fig. 5, which was created using AutoCAD, horizontal characteristics that were taken from an existing alignment on an accident spot are shown as an expressive sample.

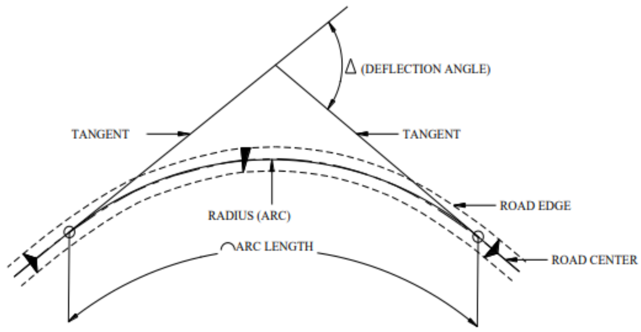


Figure 5: Data extrapolation on the horizontal alignment

Angle of deflection. The present road alignment on curve approaches has fixed tangents. The deflection angle is the collective angle formed by the two tangents, and it has the same measurement. The unit of measurement for the angle of deflection is the degree minutes seconds (DMS), also known as fraction degrees. This information is important in understanding the geometric features of the road and how it relates to the accidents that happen on that stretch of the road. The deflection angle can be used to determine the sharpness of a curve and how it affects the safety of road users. It is also useful in identifying areas where road design improvements are needed to reduce accident rates.

Horizontal curve length. In the study, the length of the arc of the existing road length was calculated using the two tangents that best fit the radius of the curve. The arc length is measured in meters. The curve length can be utilized to find out the length of the arc and how it affects the safety of road users. It is also useful in identifying areas where road design improvements are needed to reduce accident rates. The arc length also is utilized to calculate the radius of the curve, which is an important feature in the observation of the safety of the road section.

Superelevation / Cross fall. This study employed technology to analyze accident locations by creating a cross-section of the current road alignment from the Digital Terrain Model (DTM) at intervals of every 10 meters. The study examined the outer side edge of the roadway in the portion with a horizontal curvature for maximum superelevation. Superelevation is the difference in elevation between the inside and outside edges of a roadway on a curve, measured in percent. This information is important in understanding the geometric features of the road and how it relates to the accidents that happen on that stretch of the road. The superelevation can be used to determine the amount of banking on a curved road and how it affects the safety of road users. It is also useful in identifying areas where road design improvements are needed to reduce accident rates. The superelevation can also be utilized to calculate the radius of the curve, a significant aspect in the determination of the safety of curved road sections.

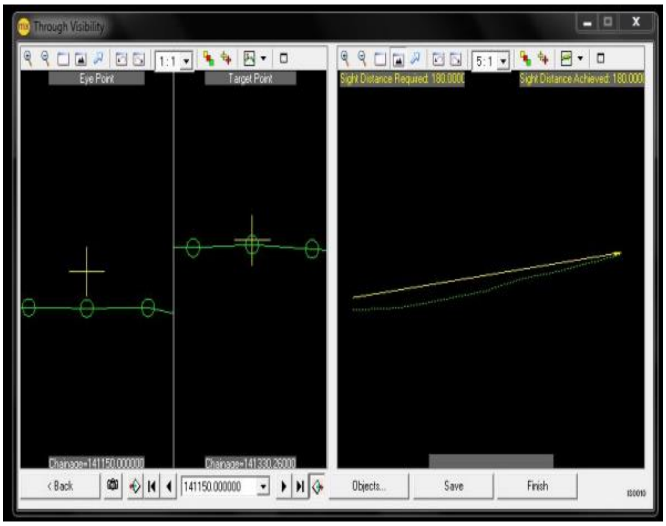
Change in superelevation. The rate of change of superelevation can be used to determine the rate at which the superelevation changes along a curved road and how it affects the safety of road users. It is also useful in identifying areas where road design improvements are needed to reduce accident rates. The rate of change of superelevation can also be used to calculate the radius of the curve, which is a significant aspect in determining the safety of a curved road section.

Vertical gradient. The software analyzed the longitudinal profile of the road at the accident location and determined the maximum vertical gradient. The vertical gradient is the change in elevation over a given distance along the road, measured as a percentage. This information is important in understanding the geometric features of the road and how it relates to the accidents that happen on that stretch of the road. The vertical gradient can be used to determine the steepness of the road and how it affects the safety of road users. It is also useful in identifying areas where road design improvements are needed to reduce accident rates. The vertical gradient can also be used to calculate the radius of the curve, which is an important aspect in the determination of the safety of the curved road.

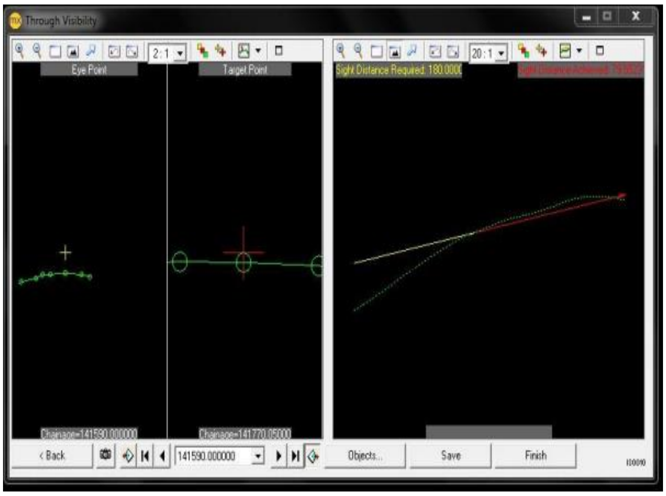
Vertical curve length. The software was used to generate the longitudinal segment of the current road center stripe from the terrain model, after which the existing longitudinal alignment on grade was fitted with the vertical gradient, and the best-fitting parabolic curve was fixed among the two grades. It has been determined how long the best-fitting vertical curve is.

K-value of vertical curve (K). The vertical curve's sharpness or flatness is determined by its K-value or corresponding radius. This is a ratio of the vertical grade change to the length of the parabolic curve. Additionally, this is the horizontal distance needed to modify the gradient by one percent.

Sight Distance. Sight visibility/distance in a 3D coordinate system is a measure of how far ahead a driver can see while driving on a road. It is calculated as a function of the horizontal and vertical alignment of the road. The software can be used to generate the actual sight visibility along the pavement alignment using input values for eye elevation and object height. In this case, the eye elevation is 1.2 meters and the object height is 0.15 meters. Sight distance is typically measured every 10 meters along a road and the minimum sight distance at an accident site is taken into account. Fig. 6 in the provided information illustrates a sample of measuring sight distance throughout the present road.



(a) Achieved on highway



(b) Not achieved on the highway

Figure 6: Sight distance

DATA ANALYSIS AND OBSERVATIONS

Accident analysis is a method used to fix the correlation between the rate of accidents and various highway geometric features. The goal of this analysis is to recognize the specific geometric fundamentals that contribute to accidents and to use this information to develop statistically meaningful models. The horizontal radius, deflection angle, horizontal arc length, superelevation, superelevation changes, vertical gradient, curve length, and K-value with sight distance are some of the geometric components that are typically taken into account in accident analysis. These elements are observed and analyzed statistically to identify patterns and correlations that may contribute to accidents. The information gathered in accident analysis is then used to develop models that can be used to improve highway safety by addressing the specific geometric features that contribute to accidents.

Accident rate. The figure for accidents that occurred in a particular year divided by the number of cars that travelled a certain amount of kilometres during that same year (Table 1) is known as the accident rate. The most common unit of measurement is accidents per million vehicle kilometres.

$$AR = \frac{C\,x100{,}000{,}000}{Vx365xNxL} \qquad \text{Eq.1}$$

Where,
AR = rate of accident expressed in vehicle/km of travel
C = Total number of accidents during the study period
V = Volumes of annual average daily traffic (AADT)
N = Years
L = Length of the carriageway Km

Table 1: Data of accident rate for NH-23

Variables	C	V	N	L	AR
NH-23	165	5093	3	66.5	44.97

Accident rate analysis based on geometric variables. The present geometric elements of NH-23 were analyzed with accident rates.

Accident rate vs horizontal radius. The data for accidents were collected within a certain radius, and then the accident rate was calculated based on that data. The results are presented in fig. 7. From the figure, it is found that when the radius of the horizontal curve increases, the accident rate is decreased. This is because it allows drivers to create a safer and more comfortable driving environment, allowing drivers to navigate the curve with less risk of losing control.

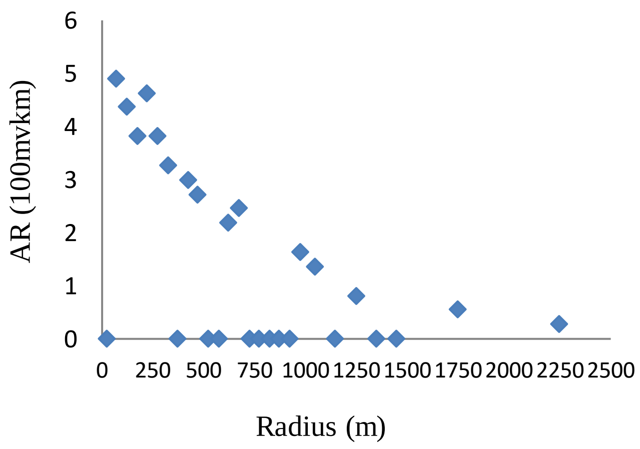


Figure 7: Accident rate vs horizontal radius

Accident rate vs deflection angle. The data for accidents were collected and divided into intervals of 100 angle of deflection, and then the accident rate was observed for each interval and plotted on a graph in fig. 8. This process allows for the analysis of how the accident rate changes with deflection angle. From figure 8, it may find that when the angle of deflection increases the accident risk also tends to increase. This creates a more challenging driving environment, making it harder for drivers to navigate the turn safely. Therefore, it is important to design roadways with appropriate turning angles to minimize the risk of accidents.

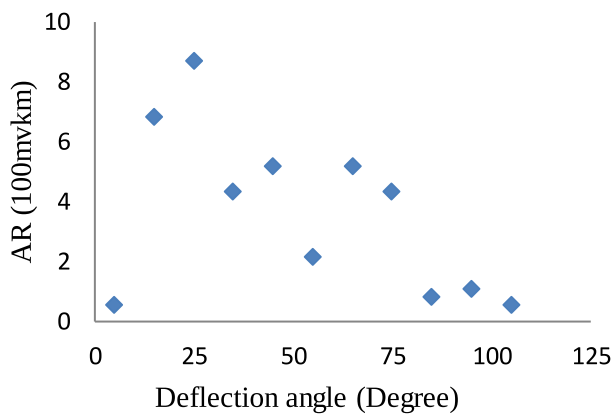


Figure 8: Accident rate vs deflection angle

Accident rate vs curve length. The data for accidents were collected within a certain range of curve length, and then the accident rate was optimized based on that data. The results are presented in fig. 9. This process allows us to identify the connection between the accident rate and the curve length that, as the curve length increases the rate of accident is decreased. The possible explanation for this is that longer curves allow drivers to navigate the turns at a lower speed, reducing the risk of losing control of their vehicle. Whereas, when a curve is too sharp, drivers may need to brake hard or take the turn at a higher speed than is safe, which can increase the risk of accidents. Additionally, longer curves may provide better visibility for drivers, allowing them to see farther ahead and anticipate any hazards or obstacles on the road. This can give drivers more time to react and make adjustments to their speed or position on the road.

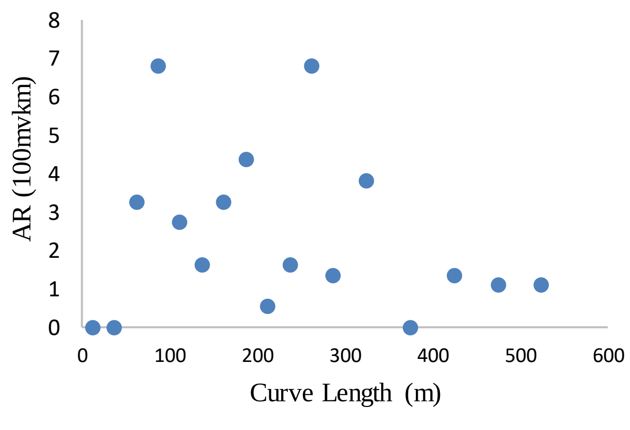


Figure 9: Accident rate vs horizontal curve length

Accident rate vs superelevation. The data for accidents were collected and divided into intervals of 1% superelevation, and then the accident rate was calculated for each interval and plotted on a graph in fig. 10. It is observed from this figure that when the superelevation is increased, resulting in high accidental risks. This may be because of oversteering, understeering, or uneven superelevation. Additionally, high superelevation can exacerbate the effects of wet or icy road conditions, increasing the risk of skidding or sliding. This process allows for the analysis of how the accident rate changes with superelevation. This information could be useful in identifying areas where the superelevation may need to be adjusted to improve safety.

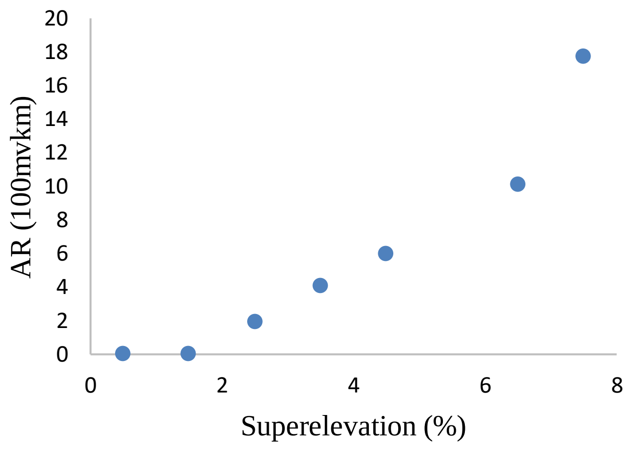


Figure 10: Accident rate vs superelevation

Accident rate vs change in superelevation. The data for accidents were collected within a certain range of change in superelevation, and then the accident rate was observed based on that data. The rate of change of superelevation refers to the slope at which the superelevation changes over a certain distance. The results are presented in fig.11. As, if the change of superelevation is low on the road network, it resulting a high risk of accidents which may recognize in figure 11. This means that a lower change in superelevation on a road curve can increase the risk of accidents, especially for drivers traveling at high speeds or in adverse weather conditions. It could be useful in identifying areas where the change in superelevation may need to be adjusted to improve safety.

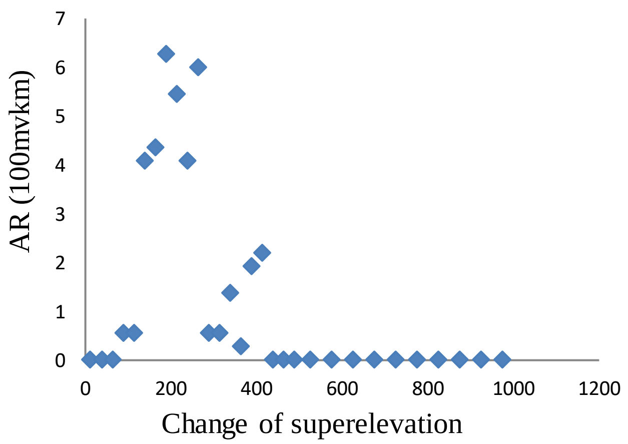


Figure 11: Accident rate vs change in superelevation

Accident rate vs vertical gradient. The data for accidents were collected and divided into intervals of 1% vertical alignment, and then the accident rate was found for each interval and plotted on a graph in fig. 12. This process allows for the analysis of how the accident rate changes with a vertical gradient. From fig. 12, it is observed that, at a lower vertical gradient, the accident risk is more compared to the higher gradient. This is maybe due to when driving downhill on a steep gradient, the vehicle tends to gain speed, which can make it difficult for the driver to control the vehicle. Additionally, braking on a steep downward gradient can cause the brakes to overheat or fail, which can lead to accidents. It could be useful in identifying areas where the vertical gradient may need to be adjusted to improve safety.

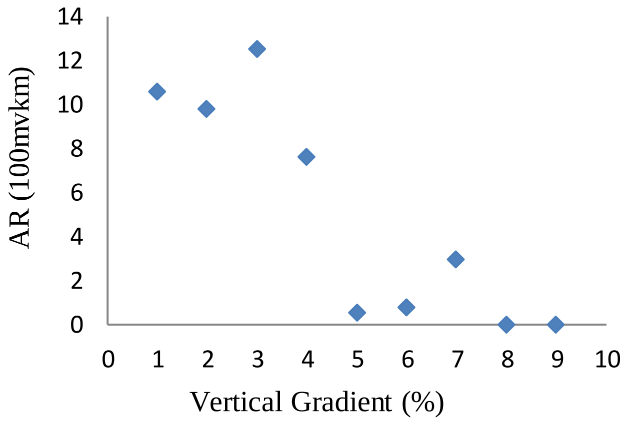


Figure 12: Accident rate vs vertical gradient

Accident rate vs length of vertical curve. The data for accidents were collected and divided into intervals of 25m in the length of the vertical curve, and then the accident rate was determined for each interval and plotted on a graph in fig. 13. This process allows for the analysis of how accidents rate changes with the length of the vertical curve. A vertical curve is a transition between two sloped roadways, allowing for a smooth change in grade. This information could be useful in identifying areas where the vertical curve may need to be adjusted to improve safety.

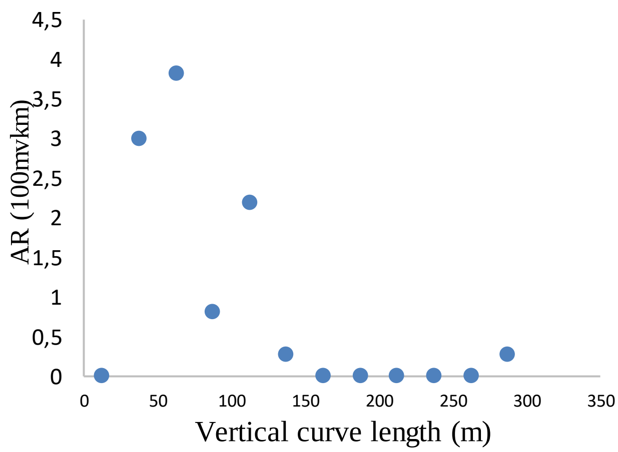


Figure 13: Accident rate vs length of vertical curve

Accident rate vs K-value. The data for accidents was collected in the form of K-value, a measure of vertical alignment of a roadway which is calculated by measuring the radius of a vertical curves, and then the accident rate was calculated based on that data. The results are presented in fig. 14. This process allows us to investigate the connection between the accident rate and the K-value. The K-value is used to design the vertical alignment of a highway and can affect the safety of the road. It could be useful in identifying areas where the K-value may need to be adjusted to improve safety.

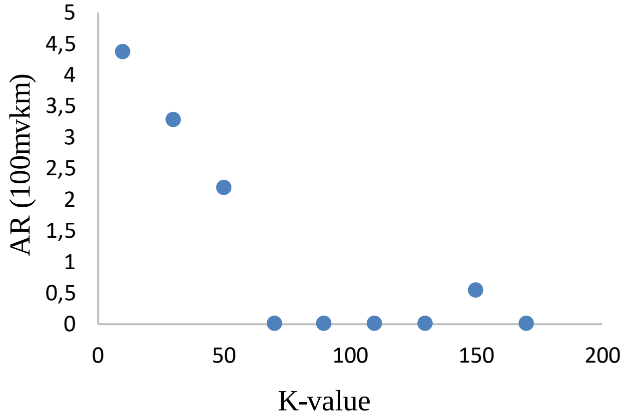


Figure 14: Accident Rate vs K-value

Accident rate vs visibility. The data for accidents were collected and divided into intervals of 10m in sight visibility, and then the accident rate was observed for each interval and plotted on a graph in fig. 15. This process allows for the analysis of how the accident rate changes with sight visibility.

Sight distance is the distance that a driver can see ahead on the road and is affected by factors such as grade, curvature, and obstructions. This information could be useful in identifying areas where the sight distance may need to be improved to improve safety.

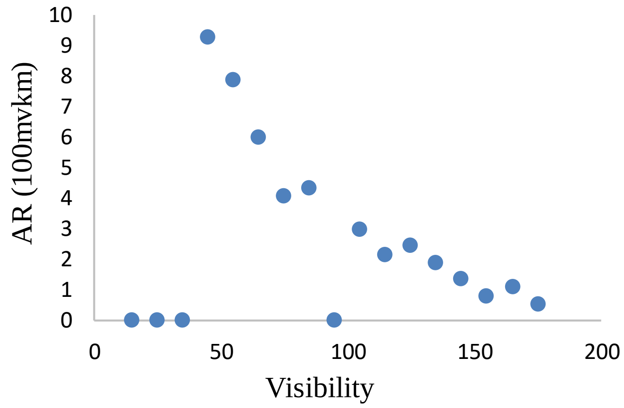


Figure 15: Accident Rate vs Visibility

Statistical analysis of variance. All the geometric elements of the highway were analyzed separately concerning the accident rate using Microsoft Office Excel and the regression analysis method. The result of the analysis of variance (ANOVA) was presented in Table 2. The ANOVA examination is castoff to understand whether there are significant changes between the two or more groups. This process allows us to identify the geometric elements that have an important impact on the accident rate of the highway and could be used to prioritize improvements to improve safety.

Table 2: Analysis of different variances for NH-23

Aspects	R^2	Adjusted R^2	Standard Error	SS	MS	F
Radius	0.86	0.84	0.59	26.99	26.99	76.69
Angle of deflection	0.26	0.17	2.53	19.74	19.74	3.08
Horizontal curve length	0.19	0.12	1.90	10.35	10.35	2.85
Superelevation	0.91	0.88	2.14	141.45	141.45	30.98
Change in superelevation	0.05	-0.01	2.20	3.88	3.88	0.80
Vertical gradient	0.69	0.62	3.03	99.84	99.84	10.88
Length of vertical curve	0.49	0.36	1.19	5.53	5.53	3.87
K-value	0.91	0.86	0.61	7.19	7.19	19.11
Sight distance	0.88	0.87	0.99	81.03	81.03	82.33

Regression analysis. ANOVA analysis reveals that on the flat terrain in NH-23, geometric components of the highway aspects like its radius, superelevation, K-value, and sight distance were important to a source of accidents. Figure 16 shows the results of the regression study used to determine the group influence of highway design elements on the accident rate. From the analysis, the accident rate was found to be the form of

$$AR = [-0.0022\,(RA) + 3.7610\,(SE) - 0.0249\,(K) - 0.0600\,(VB) + 9.4498] \quad \text{Eq.2}$$

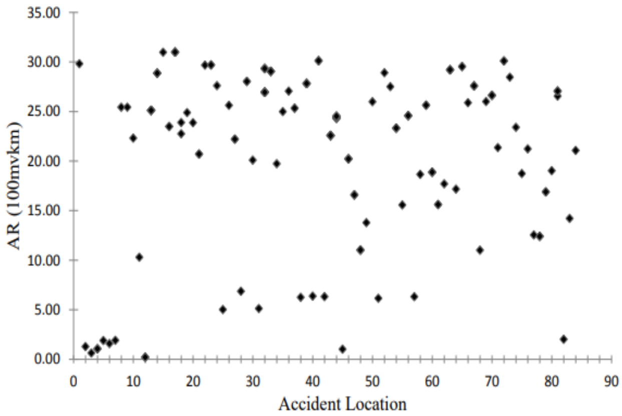


Figure 16: Accident rate on National Highway 23

According to statistical research, several factors are crucial in determining the likelihood that an accident will occur on a highway. In plain terrain, physical elements of the highway alignment including radius, superelevation, and sight distance are particularly important in accident formation. However, K-value was taking a measure role for accidents on highways with flat terrain. According to the studies mentioned above, there were more accidents when the horizontal radius is decreasing, superelevation is higher, visibility is poor, the gradient is sharp, and the K-value of the highway alignment is lower.

PROPOSED MODEL

The research aims to develop an analytical model for predicting the accident rate on rural highways using various geometric aspects of the highway's alignment as underlying variables. The model uses the Fuzzy Inference System (FIS) of the fuzzy logic modeling approach, which is considered appropriate for this purpose due to its ability to handle imprecise or uncertain data and the complexity of the problem. The model is composed of four main components: fuzzification, rules, aggregation, and defuzzification. Fuzzification converts the input data into fuzzy sets, rules are the logical relations between the input and output, aggregation combines the output of the rules, and defuzzification converts the final output back into crisp values. The suggested model is also illustrated in fig. 17.

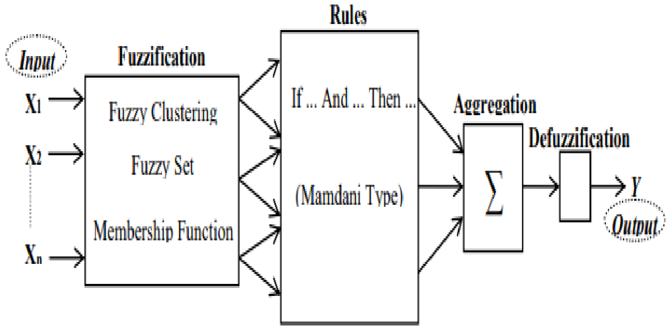


Figure 17: Schematic Illustration of Projected Model

The proposed accident rate prediction model was created using the fuzzy logic toolbox in MATLAB issued R2012b and it is of Mamdani kind fuzzy inference system. The Mamdani kind of fuzzy inference system is based on the concept of linguistic variables and uses the If-Then rules. The model was created to estimate the accident rate as presented in Table 3. This approach allows us to take into consideration the uncertainty and imprecision of the data and model the complex correlation between the geometric parameters of the road and the crash rate. The fuzzy logic toolbox in MATLAB provides a set of functions for designing and simulating fuzzy logic systems, making it a suitable tool for this purpose.

Table 3: Validation of the NH-23 variables

Variable quantity	Minimum	Maximum	Mean	Std. Dev.	Std. Err.
Radius	55	2150	405.81	366.40	30.32
Superelevation	2.60	7.00	5.48	1.19	0.10
K-value	6.15	142.86	29.20	29.80	4.83
Sight distance	41	180	82.24	35.62	2.77
Accident Rate	0.21	31.00	21.78	8.29	0.65

The first phase of the proposed fuzzy logic model, known as "fuzzification," involves creating fuzzy subsets of the input and output variables. Fuzzification has two main stages: describing the variables using natural language and explaining the membership functions for the variables. The membership functions are used to assign a degree of membership for each input value to the corresponding fuzzy set. The input data is then loaded into the Fuzzy Inference System (FIS) and the output results are obtained. The output results are then multiplied by the maximum accident rate under extreme circumstances to obtain the final accident rate. Fig. 18 illustrates the process as a flowchart, and fig. 19 shows a scatter diagram comparing the output of the model with the calculated data for the calibration set group. This process allows us to take into account the imprecision and uncertainty of the data and model the complex correlation between the geometric constraints of the highway and the accident rate.

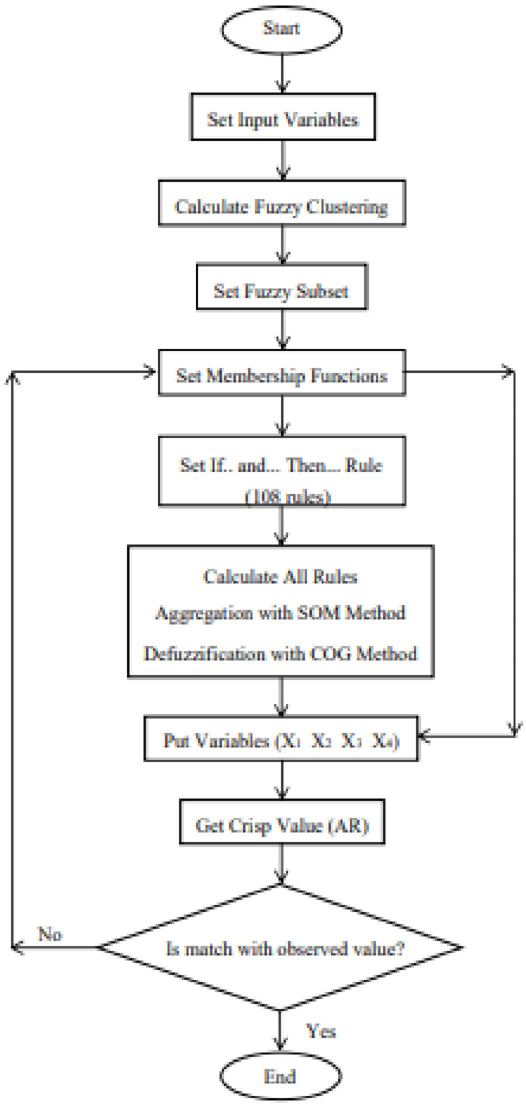


Figure 18: Flow diagram of the proposed model

Conclusion

This present study may help to understand the effect of different geometric design parameters in road accidents which have a significant impact on ecological cycles. The road accidents can cause the death or injury of leaving lifes, which can disrupt ecological cycles by reducing populations and affecting the balance of predator-prey relationships. Similarly, accidents can result in the release of pollutants into the environment, such as fuel or oil spills, which can harm plants and animals and disrupt ecological cycles. Hence, it is essential to manage road transport in a way that minimizes these impacts and preserves ecological integrity. Therefore, the use of fuzzy logic and expert judgment in the FIS model described in the study can help account for the complexity and uncertainty of the problem, and provide a more comprehensive and accurate prediction of accident rates.

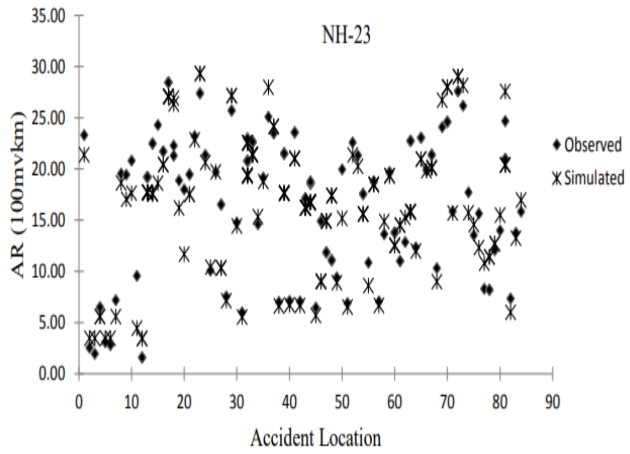


Figure 19: Simulated accident rate (AR) vs accident location for NH-23

The model uses several geometric features of the highway as an input variable and traffic accident rate as a productivity variable. The FIS model has several advantages over conventional algorithms, such as the use of linguistic data sets and the incorporation of expert judgment. The study found that there is a strong association between the geometric characteristics of the highway and the likelihood of accidents. A combination of sharp horizontal radius, high super-elevation, low K-value, and limited sight distance increases the accident rate, while the grouping of a flatter horizontal curve radius, less superelevation, high K-value, and greater visibility reduces the accident crash rate.

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