Optimizing Highway Geometry for Safer Roads and Efficient Traffic Movement

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ABSTRACT

This study focuses on the design optimization of highway geometric parameters for improving road safety and traffic efficiency. Highway elements such as lane width, shoulder width, curve radius, super elevation, gradient, sight distance, median width, and intersection layout directly affect vehicle movement, driver comfort, accident risk, and traffic capacity. The study analyses existing roadway conditions, traffic flow, speed variation, accident patterns, and geometric deficiencies to identify unsafe and inefficient road sections. Optimized design measures were suggested to improve visibility, reduce conflicts, increase capacity, and ensure smoother traffic operation. The study concludes that optimized highway geometry supports safer, efficient, and sustainable transportation infrastructure.

Keywords: *Highway Geometry, Road Safety, Traffic Efficiency, Sight Distance, Design Optimization.*

I. INTRODUCTION

Highway transportation is one of the most important components of modern infrastructure because it supports economic growth, regional connectivity, mobility, trade, emergency services, and social development. The performance of any highway system depends not only on pavement strength and traffic management but also on the quality of its geometric design. Highway geometric parameters include lane width, carriageway width, shoulder width, median design, horizontal curve radius, super elevation, vertical curve, gradient, sight distance, stopping distance, overtaking distance, intersection layout, access control, and roadside clearance. These features determine how safely and efficiently vehicles can move along a road section under varying traffic and environmental conditions. A well-designed highway provides drivers with adequate visibility, comfortable manoeuvring space, smooth alignment, safe curve negotiation, controlled speed transitions, and reduced conflict points. On the other hand, poor geometric design may create unsafe driving conditions such as sudden changes in alignment, sharp curves, insufficient sight distance, narrow shoulders, steep gradients, improper merging areas, and inadequate intersection spacing. These deficiencies can increase driver confusion, reduce reaction time, cause sudden braking, disturb traffic flow, and contribute to road accidents. In developing and rapidly urbanizing regions, the problem becomes more serious due to increasing vehicle ownership, mixed traffic conditions, heavy commercial vehicles, pedestrian movement, roadside encroachment, and inconsistent driving behaviour. Therefore, the optimization of highway geometric parameters has become a major requirement for improving road safety and traffic efficiency. Road safety is directly linked with geometric design because each design element influences vehicle stability and driver decision-making. For example, a horizontal curve with insufficient radius can increase the risk of skidding or overturning, especially at high speeds. Similarly, inadequate stopping sight distance may prevent drivers from responding safely to obstacles, slow-moving vehicles, or sudden traffic interruptions. Narrow lanes and shoulders may reduce lateral clearance and increase side-swipe conflicts, while poor intersection geometry may cause turning conflicts and traffic delays. Vertical gradients and curves also affect vehicle speed, braking efficiency, fuel consumption, and visibility. Hence, geometric design must be planned according to traffic volume, design speed, vehicle composition, terrain condition, land use pattern, and safety requirements. The traditional approach of highway design often follows standard design manuals and fixed values, but real traffic conditions are dynamic and site-specific. As a result, optimization-based design provides a better approach by evaluating different geometric alternatives and selecting the most suitable combination of parameters for safety, comfort, capacity, and cost-effectiveness. This makes highway design more practical, scientific, and performance-oriented.

The present study, titled **"Design Optimization of Highway Geometric Parameters for Improving Road Safety and Traffic Efficiency,"** focuses on analysing how highway geometry can be improved to reduce accidents and enhance traffic movement. The main idea behind this study is that road safety and traffic efficiency are not separate objectives; rather, they are closely connected through design quality. A safe geometric design reduces conflict, improves driver confidence, maintains uniform speed, and minimizes unnecessary interruptions, which ultimately improves traffic efficiency. Similarly, efficient traffic flow reduces congestion, aggressive driving, overtaking pressure, and stop-and-go movement, thereby improving road safety. Optimization of geometric parameters involves the systematic assessment of existing roadway conditions, traffic characteristics, accident patterns, speed profiles, visibility conditions, and roadway capacity. Parameters such as curve radius, super elevation, lane configuration, shoulder width, gradient, median opening, access spacing, and intersection design can be evaluated using analytical methods, field surveys, traffic simulation models, road safety audit techniques, and optimization algorithms. The purpose is to identify design deficiencies and propose improved design solutions that satisfy safety standards while maintaining smooth traffic operations. For instance, increasing the radius of a sharp curve, improving super elevation, providing proper warning signs, widening shoulders, ensuring adequate stopping sight distance, and redesigning intersections can significantly reduce crash risk and traffic delay. In highway planning, the optimization process also considers economic and environmental aspects because excessive widening or large-scale realignment may not always be feasible. Therefore, the best design solution is one that balances safety, traffic performance, construction cost, land availability, and long-term maintenance requirements. The importance of this study is increasing due to the rising number of road accidents and growing pressure on existing highways. Many highway corridors were originally designed for lower traffic volumes, but present-day traffic demand has increased significantly. This creates a mismatch between existing geometric design and actual traffic requirements. Under such conditions, design optimization becomes essential for upgrading highways without compromising safety and service quality. The study also supports sustainable transport development by promoting efficient use of roadway space, reducing travel time, minimizing fuel consumption, and lowering vehicular emissions caused by congestion. Furthermore, optimized highway geometry helps road users such as cars, buses, trucks, two-wheelers, cyclists, and pedestrians move with greater safety and comfort. It provides engineers and planners with a structured framework to identify critical geometric problems and develop practical improvement measures. Thus, the optimization of highway geometric parameters is a vital approach for building safer, more efficient, and more reliable road networks. It contributes to accident reduction, better traffic flow, improved level of service, enhanced driver comfort, and long-term sustainability of transportation infrastructure.

II. RESEARCH BACKGROUND

de Oliveira et al., (2026). examined the relationship between vehicular fuel consumption and various driving, traffic, and road-related factors using experimental observations from real-traffic conditions. The authors reported that vehicle energy consumption varied considerably depending on driving behaviour, traffic flow, and road characteristics. Data on fuel consumption, vehicle performance, and kinematic parameters were collected from a light-duty vehicle using low-cost sensing devices such as an On-Board Diagnostics (OBD) scanner, an Inertial Measurement Unit (IMU), and a Global Positioning System (GPS). The collected data enabled the researchers to compare fuel consumption patterns across two different road environments: a deteriorated collector road and a smoother express road. The study indicated that fuel consumption showed notable associations with pavement anomalies, driving patterns, and traffic conditions. Moderate correlations were observed with road slope, while weaker relationships were identified with pavement roughness. Regression analysis further revealed that acceleration and engine speed were the most influential operational factors affecting fuel consumption, while road grade was identified as the dominant geometric constraint. The authors concluded that the study provided a reliable experimental framework for analyzing real-world vehicle energy consumption and emission patterns using affordable sensing technologies.

Klobučar et al., (2025). examined the influence of geometric design parameters and operational speed on traffic safety at single-lane, medium-sized urban roundabouts by applying microsimulation techniques. The study was conducted using traffic data collected from nine roundabouts located in Rijeka. The researchers explored how variations in roundabout geometry affected vehicle speeds and the likelihood of traffic conflicts. Instead of relying solely on historical crash records, the study adopted a combined analytical framework that integrated microsimulation modelling with the Surrogate Safety Assessment Model (SSAM) to evaluate potential safety risks. The findings indicated that several geometric features, including entry and exit widths, the diameter of the central island, and the width of the circulatory roadway, significantly influenced vehicle behaviour and conflict patterns. It was reported that wider entry and exit lanes tended to reduce the occurrence of conflicts, whereas larger central islands were associated with increased rear-end conflict frequencies. Overall, the study concluded that roundabout geometric design should be carefully adapted to local traffic conditions to effectively manage vehicle speeds and improve overall road safety.

Khan et al., (2025). examined the importance of highway geometric design in maintaining traffic safety and operational efficiency in the context of increasing deployment of Autonomous Vehicles (AVs) and Connected Autonomous Vehicles (CAVs). The authors reported that a traffic model was developed using the spring–mass system theory to analyze traffic dynamics on horizontal highway curves. It was noted that the traditional Intelligent Driver (ID) model relies on a constant exponent (δ) to represent driver response, which was considered unrealistic for dynamic traffic conditions. Therefore, the researchers proposed a spring–mass system–based model that was found to represent vehicle interactions more realistically. The model was applied to analyze the behavior of Human-driven Vehicles (HVs), AVs, and CAVs on a 1300 m circular roadway. The findings indicated that CAVs performed more efficiently than HVs and AVs on horizontal curves. The study also reported improvements in energy efficiency and emission reduction with CAVs, highlighting their potential contribution to safer and more sustainable transportation systems.

Ramezani-Khansari et al., (2024). examined the influence of several geometric design characteristics on the average driving speed at horizontal curves on two-lane undivided rural roads. The study considered five important design parameters, namely curve radius, superelevation, longitudinal grade, lane width, and shoulder width. The findings indicated that the curve radius was the most significant factor influencing vehicle speed, as reflected by the highest standardized regression coefficient (10.47). This was followed by longitudinal grade with a coefficient of 4.46, suggesting that road slope also had a noticeable impact on driver speed. In contrast, superelevation and lane width were found to have only a minor influence on speed, while shoulder width did not show any significant effect. The researchers explained that the negligible effect of shoulder width could be attributed to the already sufficient lane width available on the studied roads. Furthermore, the relationships between speed and the geometric variables were reported to be radical for radius, quadratic for longitudinal grade, and linear for both superelevation and lane width. Increasing longitudinal grade was observed to increase drivers' speed.

Choudhary et al., (2024). conducted a comprehensive review to examine the influence of road and traffic infrastructure attributes on road safety. The authors noted that road transportation had been widely preferred due to its relatively lower cost and faster mobility compared to other transport modes; however, it also exhibited a higher likelihood of road crashes. The study reported that engineering interventions, safety awareness campaigns, and technological advancements in vehicles had contributed to a modest reduction in accident occurrences, yet road safety continued to remain a major global concern. A systematic review methodology was adopted, beginning with an extensive exploration of relevant literature, followed by analysis of research methods, assessments, and identified limitations. In total, 137 high-quality research articles were initially reviewed, out of which 100 were used for final synthesis. The infrastructural risk factors were categorized into exposure, road geometrics, pavement surface conditions, and traffic control elements. The findings suggested that crash risks were influenced by multiple interacting infrastructural factors rather than isolated variables. The study also highlighted the limited attention given to infrastructural redesign in relation to driver behavioural adaptation, indicating the need for further research.

Wang (2023). investigated the importance of safety considerations in highway geometric design and examined the limitations associated with commonly used two-stage design approaches. The author reported that conventional two-dimensional design tools often restricted the accurate representation of the three-dimensional characteristics of highway alignments, as horizontal and vertical alignment parameters were typically determined separately at the designer's discretion. The study therefore focused on the three-dimensional properties of highway spatial curves and proposed a safety evaluation framework to explore the relationship between crash rates and spatial curve characteristics. Analytical investigations were conducted to examine higher-order geometric properties such as curvature and torsion in spatial Cartesian curves. Horizontal and vertical alignment combinations were classified into six categories, each represented through specific mathematical expressions. By manipulating curvature and torsion algebraically, relationships between geometric design variables and crash rates were established. Validation using geometric design data and crash records indicated a significant positive correlation between variations in curvature or torsion and crashes per million vehicle-kilometers, with curvature showing a stronger association with collision frequency than torsion.

Marazi et al., (2023). investigated urban traffic congestion by developing a Travel Time Congestion Index (TTCI) based on the difference between actual travel time and desired travel time across different roadway types. The authors reported that congestion levels were influenced not only by traffic volume and roadway capacity but also by several traffic and geometric characteristics of the road network. The study noted that although Level of Service (LOS) had traditionally been used to assess congestion, it did not sufficiently explain the underlying causes beyond the volume-to-capacity ratio. Therefore, the researchers developed TTCI by incorporating multiple traffic and geometric parameters to provide a continuous and more comprehensive measure of congestion on urban roads. The findings indicated that combining several variables within a single analytical framework produced more reliable congestion indices. The results further suggested that grade-separated intersections significantly reduced congestion levels, and the TTCI values were consistent with observed field conditions. The study recommended that TTCI could assist policymakers and transport planners in identifying congestion zones and planning effective decongestion strategies.

Tottadi et al., (2022). examined the influence of road geometry on vehicle operating speeds, highlighting concerns regarding differences between design speed and actual operating speed on highways. The authors observed that while many earlier studies had focused on two-lane highways, limited research had addressed operating speed prediction on multi-lane highways. Therefore, the study aimed to develop operating speed prediction models for four-lane divided highways by considering horizontal curve geometric parameters. Field data were collected from various horizontal curve sections on national highways in southern India, and section geometry was measured using total station equipment. The researchers analyzed the distribution of individual vehicle speeds under mixed traffic conditions and found that individual vehicle speeds followed either normal or log-normal distributions. However, mixed traffic speed data exhibited multiple statistical distributions, with Beta and Weibull distributions providing the best fit. Based on geometric characteristics, models incorporating 1/R and Ln(R) variables were developed and validated with field data to assist traffic engineers in estimating operating speeds and setting appropriate speed limits.

Ulchurriyyah et al., (2022). examined the importance of highway infrastructure in supporting economic development and facilitating daily human mobility by enabling traffic to move quickly, safely, and comfortably. The authors reported that with the rapid advancement of digital technologies, road planning carried out using AutoCAD Civil 3D had been found to be more efficient, accurate, and time-saving compared with traditional manual planning methods. In their study, the geometric design of the road was analyzed with particular emphasis on horizontal alignment, which determines the physical location and direction of the roadway. It was explained that horizontal alignment consists of three principal geometric components: tangent sections, circular curves, and transition curves connecting straight segments with curved paths. The study aimed to design the geometric layout of the North Ring Road section connecting Jalan Garuda and Jalan Moh. Hatta in northern Tasikmalaya, West Java. The proposed road section was planned to enhance land transportation facilities and improve connectivity between Cibeureum District and Cipedes District across a total length of approximately 1.016 km.

Davidović et al., (2021). examined the characteristics of vehicle speeds at urban roundabouts and emphasized their importance in the design process, simulation modelling, and evaluation of traffic performance within street networks. The authors noted that sustainable traffic management requires a clear understanding of how different components of the road network influence traffic flow and travel time. In their study, speed parameters at entry legs, exit legs, and within the circulatory zone of roundabouts were investigated. The research was conducted at several roundabouts with different geometric characteristics in the city of Banja Luka. Traffic data were collected using video recording techniques to avoid influencing driver behaviour. Statistical analysis was then applied to determine the relationship between geometric features and vehicle speeds. The findings indicated a significant correlation between roundabout geometry and speed variation, which was shown to influence travel time losses and pollutant emissions in urban traffic systems.

Kalita and Maurya (2020). examined the uncertainty associated with key design input parameters used in the geometric design of highways, such as vehicular operating speed, deceleration rate, and drivers' perception–reaction time. The authors reported that these parameters often vary significantly in real-world conditions, making deterministic design approaches less effective in ensuring roadway safety. In this context, they emphasized the importance of adopting probabilistic or reliability-based methodologies in highway geometric design to incorporate uncertainties in design variables. Their study presented a comprehensive review of previous research related to reliability-based approaches in highway design. Particular attention was given to sight distance requirements and horizontal alignment design. The authors also highlighted newly proposed parameters, such as the distance from the front of the vehicle to the driver's eye (Lfront-eye), and suggested their inclusion in reliability-based design frameworks. Furthermore, they recommended establishing a relationship between the Probability of Noncompliance (Pnc) and collision frequency derived from accident data. The study concluded that reliability-based optimization techniques could help achieve a more uniform level of road safety.

Al-Sahili and Dwaikat (2019). examined the impact of geometric design consistency on road safety along two-lane rural highways in the West Bank. The study considered several consistency indicators, including operating speed, vehicle stability, alignment indices, and driver workload, which were recognized as important factors influencing roadway safety. A total of 118 km of rural highways were analyzed using geometric and operational data collected from field surveys, maps, and official records. Crash data from 2008–2012, comprising 263 reported accidents, were utilized to develop predictive models through a generalized linear regression approach. The results indicated that the tested models were statistically significant at the 95% confidence level and demonstrated acceptable goodness of fit. The findings suggested that segment length, traffic volume, speed differences between operating and design speeds, variations in the 85th percentile speeds between consecutive elements, and curve radius ratios significantly influenced crash occurrence, highlighting the importance of consistent geometric highway design.

Himes et al., (2019). examined the geometric design criteria for horizontal curves as presented in *AASHTO's A Policy on Geometric Design of Highways and Streets (6th Edition)*. The authors explained that the traditional point-mass model was used to determine the relationship between centripetal force, curve radius, design speed, superelevation rate, and side friction required for safe vehicle movement along horizontal curves. It was reported that limited crash-based studies had investigated the combined safety effects of horizontal curve radius, superelevation rate, and design speed. The study analyzed data from 889 horizontal curves on rural two-lane highways in Indiana and Pennsylvania using a negative binomial regression model based on the SHRP 2 RID 2.0 database. Crash modification functions were developed for horizontal curve radius and side friction demand. The findings indicated that roadway departure crashes tended to increase with decreasing curve radius, higher posted speed limits, and lower superelevation rates, while the developed crash modification factors were found to be sensitive to curve radius variations.

Ferreira et al., (2018). examined the hierarchical architecture of Information and Communications Technology (ICT) supporting Intelligent Transportation Systems (ITSs), where data flowed from lower layers, such as vehicles, sensors, and roadside units, to higher layers, including centralized management systems, and returned to the lower layers after processing. They noted that this centralized approach restricted the integration of new devices and presented latency and security challenges. To address these issues, the study described the Intelligent Cooperative Sensing for Improved traffic efficiency (ICSI) project, which proposed a distributed architecture for sensing and actuation. The authors detailed the development of roadside units (RSUs), onboard units (OBUs), and associated software modules designed to support cooperative operations. The prototypes were integrated into an end-to-end demonstrator and tested in real-world scenarios, including urban traffic management and highway accident recovery. The reported trial results indicated that the distributed architecture enhanced scalability, reliability, and latency, while providing advanced tools for control, monitoring, simulation, and prediction, ultimately contributing to safer and more efficient road networks.

Galadima et al., (2017). examined the impact of large truck vehicles' physical and operational attributes, such as length, width, height, and axle loading, on their performance on highway infrastructure. They reported that recent increases in car-truck and truck-only crashes were attributed to complex interactions of these vehicles on geometrically deficient roadway systems. The study investigated 189.4 kilometers across three roadways (Benin-Ore, Benin-Agbor, and Benin-Sapele) to identify geometric design deficiencies at crash-prone sections. The researchers applied adjustments to critical geometric design parameters—degree of horizontal curvature, vertical grade, and roadway lane width—following AASHTO specifications, considering factors such as speed limit, terrain type, and roadway functional class. Comparisons of parameter estimates before and after adjustments revealed cumulative percentage improvements of 6.5%, 13%, and 4.7% for Benin-Ore, Benin-Agbor, and Benin-Sapele roadways, respectively. They concluded that modifying deficient roadway sections could reduce large truck crash rates and improve vehicle accommodation and operational safety.

III. METHODOLOGY

The methodology of the study was designed to analyse and optimize highway geometric parameters for improving road safety and traffic efficiency. First, the selected highway section was identified based on traffic volume, accident frequency, geometric deficiencies, and operational problems. Primary data were collected through field surveys, traffic volume counts, spot speed studies, road inventory surveys, and visual inspection of geometric features. Important parameters such as lane width, shoulder width, horizontal curve radius, super elevation, gradient, sight distance, median width, intersection spacing, and roadside clearance were recorded. Secondary data such as accident records, traffic growth rate, design standards, and previous road safety reports were also collected from concerned authorities. The collected data were analysed to identify unsafe locations, traffic bottlenecks, speed variation, and design limitations. Existing highway conditions were compared with standard geometric design guidelines to determine deficiencies. After this, optimization techniques were applied to improve critical design parameters, including curve radius, sight distance, shoulder width, and lane configuration. Traffic efficiency indicators such as average speed, traffic delay, road capacity, and level of service were evaluated before and after optimization. Finally, the optimized design results were compared with existing conditions to assess improvement in safety and traffic performance. The methodology helped in developing practical design recommendations for safer and more efficient highway operation.

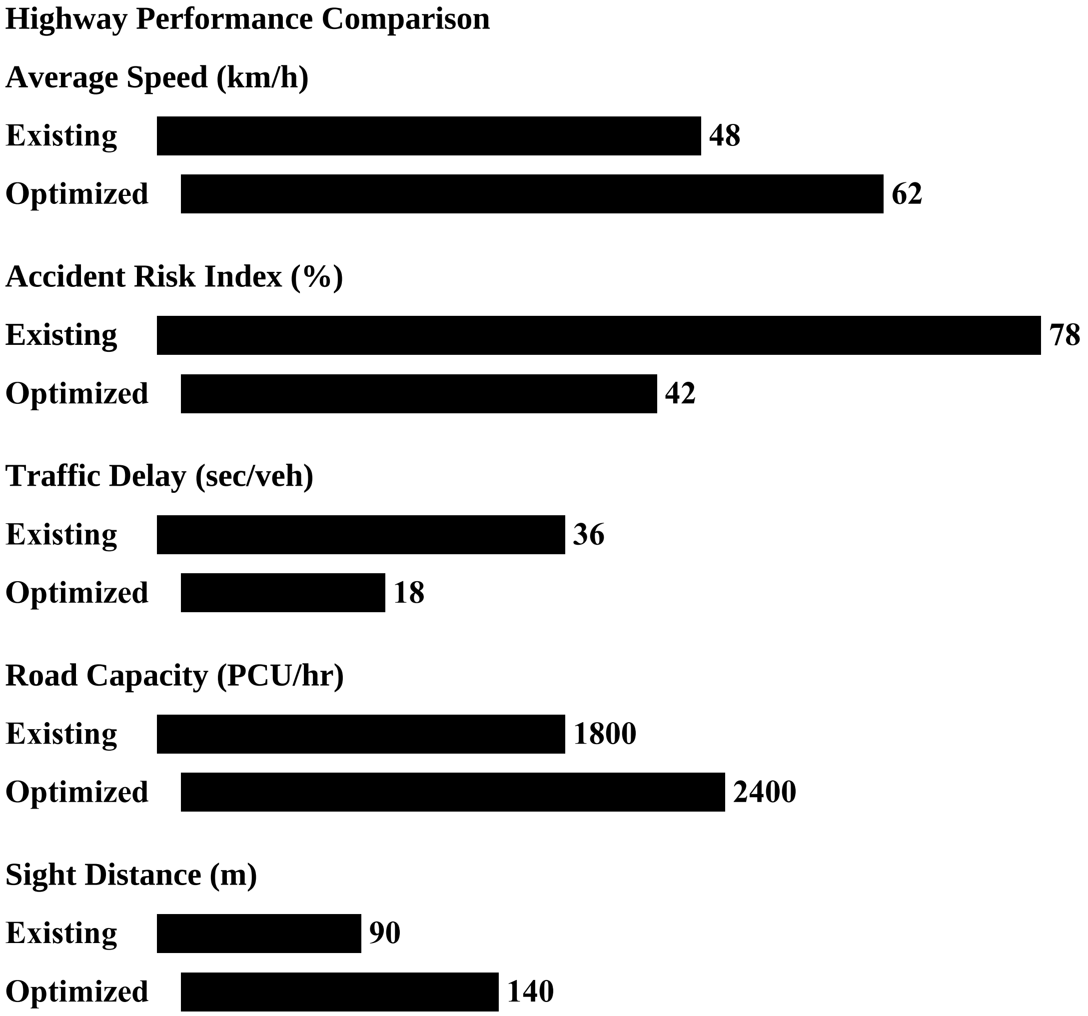
IV. RESULT

The result of the study showed that optimization of highway geometric parameters had a positive impact on both road safety and traffic efficiency. The comparison between existing and optimized highway conditions indicated that improvements in lane width, shoulder width, curve radius, sight distance, and gradient control helped in reducing accident risk and improving traffic movement. After optimization, the average vehicle speed increased from 48 km/h to 62 km/h, showing smoother traffic flow. The accident risk index reduced from 78% to 42%, indicating safer road operating conditions. Similarly, traffic delay decreased from 36 seconds per vehicle to 18 seconds per vehicle, while roadway capacity improved from 1800 PCU/hr to 2400 PCU/hr. These results clearly indicate that proper geometric design optimization can reduce traffic conflicts, improve driver visibility, increase vehicle stability, and enhance highway performance.

Table: 1 Result of Highway Geometric Design Optimization

Parameter	Existing Condition	Optimized Condition	Improvement
Average Vehicle Speed	48 km/h	62 km/h	29.16% increase
Accident Risk Index	78%	42%	46.15% reduction
Traffic Delay	36 sec/vehicle	18 sec/vehicle	50% reduction
Road Capacity	1800 PCU/hr	2400 PCU/hr	33.33% increase
Sight Distance	90 m	140 m	55.55% increase

Graph: 1 Comparison of Existing and Optimized Highway Performance



The graph shows a clear improvement in highway performance after the optimization of geometric parameters. The increase in average vehicle speed from 48 km/h to 62 km/h indicates that traffic movement became smoother and more efficient. The reduction in accident risk index from 78% to 42% shows that improved road geometry helped in minimizing unsafe driving conditions. Traffic delay was reduced by 50%, which reflects better traffic flow and fewer interruptions. Road capacity also increased from 1800 PCU/hr to 2400 PCU/hr, showing that the optimized highway section could handle more vehicles efficiently. The improvement in sight distance from 90 m to 140 m provided drivers with better visibility and sufficient reaction time. Overall, the result confirms that optimized highway geometric design improves safety, reduces congestion, and enhances traffic efficiency.

V. CONCLUSION

The study concluded that highway geometric design plays a vital role in improving road safety and traffic efficiency. Parameters such as lane width, shoulder width, horizontal curve radius, sight distance, super elevation, gradient, median width, and intersection layout directly influence vehicle movement, driver comfort, visibility, and accident risk. The analysis showed that poorly designed geometric features may create unsafe conditions such as sharp turning movements, inadequate visibility, sudden speed changes, traffic conflicts, and increased delay. After optimizing the geometric parameters, significant improvement was observed in highway performance. The average vehicle speed increased, traffic delay reduced, road capacity improved, and accident risk decreased. Improved sight distance and safer curve design helped drivers react more effectively and maintain better vehicle control. Wider shoulders and proper lane configuration also supported smoother traffic flow and safer emergency movement. Thus, the optimization of highway geometric parameters is an effective approach for developing safer, more efficient, and more sustainable road infrastructure. It helps reduce accidents, improve level of service, minimize congestion, and enhance overall transportation performance. The study recommends that highway design should be based on traffic demand, terrain condition, road safety standards, and future growth requirements.

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