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Evaluating Sight Distance Limitations and Accident Risks on Horizontal Curves: A PRISMA-Based Systematic Literature Review

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ABSTRACT

Sight distance is a fundamental parameter in roadway design, as insufficient visibility along horizontal curves often leads to higher accident risks and reduced driver performance. Despite ongoing efforts in road safety research, the evidence concerning sight distance limitations remains dispersed, making it challenging to consolidate effective strategies for mitigating crash likelihood. This study addresses this gap by conducting a systematic literature review to synthesize the current state of knowledge on the relationship between sight distance and accident risk. The review followed the PRISMA protocol, with data retrieved from two major databases, Scopus and ScienceDirect, applying strict inclusion and exclusion criteria to ensure relevance and quality. After the screening process, 29 primary studies were selected for detailed analysis. The findings were categorized into three central themes. The first theme, Sight Distance, Visibility & Lighting, highlights how roadway geometry, lighting design, and visibility enhancements directly influence hazard perception and driver safety margins. The second theme, Reliability, Design Consistency & Optimization, demonstrates the importance of reliability-based design measures, consistency evaluation, and optimization frameworks in predicting crash risks and guiding safer roadway alignment. The third theme, Automation, Connected Vehicles & Human Factors, emphasizes the role of intelligent speed adaptation, connected-vehicle technologies, and driver behavioral responses in enhancing safety, particularly under adverse conditions. Collectively, the evidence suggests that addressing sight distance limitations requires not only traditional geometric and lighting considerations but also integration with modern reliability-based approaches and automation-driven safety systems. The study concludes that future roadway safety improvements should adopt a multidisciplinary perspective that combines engineering design, system reliability, and human–technology interaction to reduce accident risks associated with limited sight distance.

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1. Introduction

Horizontal curves are an essential component of roadway alignment and are commonly associated with higher crash rates than tangent sections. Compared with straight road segments, horizontal curves introduce limitations related to driver visibility and vehicle control, which may negatively affect driving performance. Among these factors, sight distance is a key design element because it defines the length of roadway that can be observed by drivers and determines the time available to detect hazards and respond appropriately.

When sight distance is insufficient on curved alignments, drivers may face unexpected obstacles or roadway conditions with limited reaction time, increasing the potential for accidents. Although numerous studies have examined safety issues on horizontal curves, research specifically focusing on sight distance is scattered across different areas, including geometric design, driver behavior, and advanced evaluation methods. As a result, a clear and integrated understanding of the relationship between sight distance limitations and accident risk has not yet been fully established.

In addition, differences in data sources, analytical techniques, and evaluation criteria across studies limit the direct application of research findings to design standards and safety policies. These challenges are particularly important under varying traffic conditions, environmental influences, and the increasing presence of automated and connected vehicle technologies. To address these issues, this study conducts a systematic literature review following the PRISMA protocol to examine sight distance limitations and accident risks on horizontal curves. The review is organized into three themes: sight distance, visibility and lighting; reliability, design consistency and optimization; and automation, connected vehicles and human factors. The objective is to summarize existing knowledge, identify research gaps, and support more consistent and informed approaches to roadway design and safety assessment.

2. Literature Review

2.1 Accident Risks on Horizontal Curves

Horizontal curves are associated with a higher frequency of severe accidents compared to straight road sections. Horizontal curves account for more than 25 percent of fatal crashes and the average crash rate for curves is approximately three times higher than tangent segments [1]. The risk of accidents on these curves is influenced by several factors, including the radius of the curve, the length of the curve, the presence of spiral transition curves, super-elevation, and the distance to adjacent curves [2] [3] [4]. Studies have shown that sharper curves and shorter distances between curves can increase accident risk, although roads with frequent sharp curves may not necessarily have higher overall risk compared to roads with fewer, widely spaced curves [2] [5].

2.2 Sight Distance Limitations

Sight distance on horizontal curves can be restricted by various obstructions such as buildings, barriers, and natural features like mountain slopes or trees [6][7][8][9]. These obstructions can significantly reduce the available stopping sight distance (SSD), which is the distance required for a driver to perceive and react to an obstacle and bring the vehicle to a stop safely. Current design guidelines often fail to account for the three-dimensional nature of roadways, leading to potential underestimation of sight distance limitations [6][7][8][10][11].

2.3 Design and Safety Considerations

Several studies have highlighted the limitations of current design approaches and proposed new methodologies to improve sight distance calculations and enhance safety on horizontal curves. For instance, a reliability-based methodology was developed to calculate horizontal sight offset (HSO) on 3D alignments, considering variations in design parameters [6]. Additionally, software tools and 3D virtual models have been used to evaluate sight distance and identify potential safety issues on curves with overlapping vertical alignments [7][8][10].

2.4 Driver Behavior and Curve Negotiation

Driver behavior, including speed selection and lateral positioning, is significantly influenced by the geometric characteristics of horizontal curves and the visibility of the curve's arc. Studies using driving simulators have shown that reduced visibility on curves leads to lower speeds and increased lateral movement towards the centerline, which can compromise safety [5] [12][13]. Furthermore, the proximity of adjacent curves affects approach speeds, with closer curves resulting in lower approach speeds but higher speeds while negotiating the curve itself [5].

2.5 Mitigation Strategies

To mitigate the risks associated with sight distance limitations on horizontal curves, several strategies have been proposed. These include:

i. Improving Pavement Surface: Ensuring a high-friction surface can reduce the likelihood of skidding and improve vehicle control on curves [3].
ii. Adjusting Curve Radius: Increasing the radius of horizontal curves can enhance sight distance and reduce accident risk, although this may not always be feasible due to spatial constraints [14][15].
iii. Implementing Road Markings and Signage: Low-cost measures such as road medians and horizontal warning signs have been shown to reduce speeds and improve lateral positioning on curves [12].
iv. Using Advanced Design Tools: Employing 3D modeling and reliability-based design approaches can provide more accurate assessments of sight distance and inform safer roadway designs [6][7][8][10][11][15].

Among the factors related to sight distance in horizontal curves and mitigation strategies as shown in Table 1. On the other hand, Figure 1 illustrates the structure of the literature related to the research topic “Sight Distance Limitations and Accident Risks on Horizontal Curves,” which can be categorized into three primary areas: safety performance, modeling techniques, and accident analysis. Safety performance emphasizes how limited sight distance influences overall roadway safety, linking to studies on sensitivity analysis, driver risk perception, crash modification factors, and risk assessment methods. Modeling techniques highlight the analytical tools used to study the problem, such as structural equation modeling to examine relationships between geometric, behavioral, and safety variables, and regression analysis to predict crash risks based on sight distance and roadway geometry. Accident analysis focuses on empirical crash data, particularly accident frequency and crash characteristics, to evaluate the real-world effects of limited visibility on curved roads. Collectively, the figure shows that research on sight distance limitations is multidimensional, combining engineering design, statistical modeling, driver psychology, and empirical crash evaluations to provide a comprehensive understanding of how horizontal curve geometry influences accident risks.

In conclusion, sight distance limitations on horizontal curves significantly contribute to accident risks. Addressing these limitations through improved design methodologies, driver behavior interventions, and strategic roadway modifications can enhance safety on these critical sections of roadways.

Table 1
Mitigation Strategies and Impact on Accident Risk of Accident factors

Factor	Impact on Accident Risk	Mitigation Strategies
Curve Radius	Smaller radii increase risk	Increase radius where feasible [14] [16]
Sight Distance	Limited sight distance increases risk	Use 3D modeling for accurate assessment [6][7][8][10][11]
Driver behavior	Higher speeds and improper lateral positioning increase risk	Implement road markings and signage [12]
Proximity of Curves	Closer curves affect approach speeds	Design consistent curve spacing [5]
Pavement Surface	Poor surface increases skidding risk	Ensure high-friction surface [3]

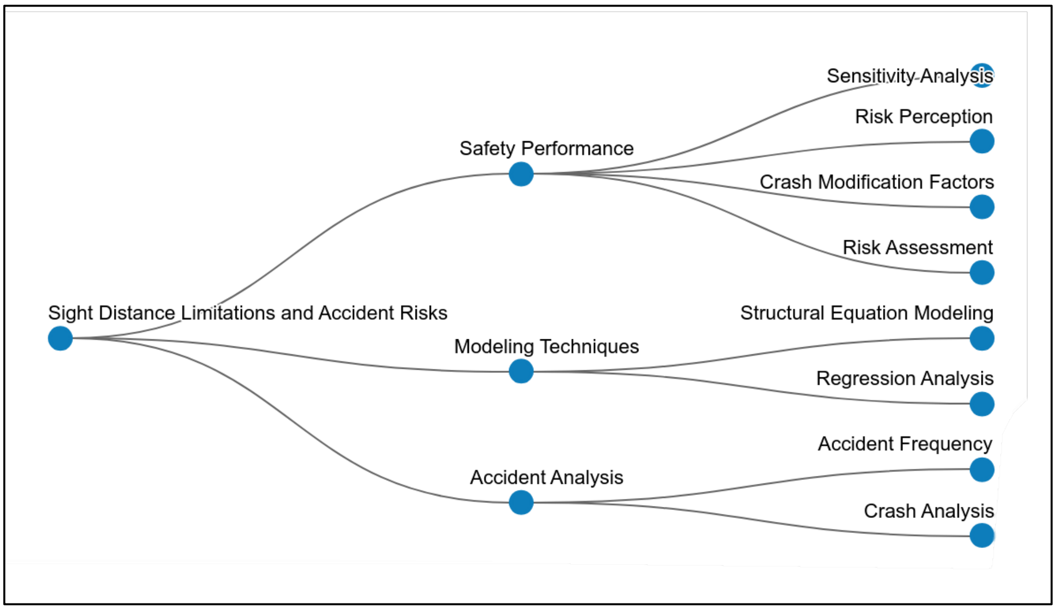

Fig. 1. Conceptual framework linking sight distance limitations to accident risks.

3. Methodology

3.1 Research Question

Formulating research questions constitutes a critical step in conducting a systematic literature review (SLR), as these questions establish the foundation and direction for the entire process. Clearly defined research questions delineate the scope and focus of the review, guiding the inclusion and exclusion of studies and ensuring that the evidence gathered remains directly relevant to the topic of interest. By structuring the literature search around well-specified questions, the review becomes exhaustive and systematic, thereby minimizing bias and ensuring a comprehensive representation of existing knowledge. Research questions further enable the categorization, organization, and synthesis of data, providing a coherent analytical framework that facilitates the generation of meaningful insights and actionable conclusions. In addition, they enhance clarity and transparency, reducing ambiguity and improving reproducibility, which allows subsequent researchers to validate findings or extend the review. Ultimately, well-formulated research questions align the review with its objectives, whether identifying knowledge gaps, assessing the effectiveness of interventions, or evaluating emerging trends thereby serving as the backbone of a rigorous and impactful SLR.

In this study, specifying the research questions (RQs) was considered the most crucial component of the planning phase, as it shaped the review methodology [17]. Given that the primary aim of this review was to identify and analyze the state of the art in horizontal curve safety, the PICo framework was employed to support the development of the RQs. The PICo framework, originally proposed by [18], is a mnemonic that helps structure research questions systematically, particularly in qualitative research. By applying the PICo framework, this study developed research questions that are both structured and comprehensive, ensuring a clear analytical pathway for exploring horizontal curve safety. This study achieved three research questions as below;

i. RQ1: How do different visibility treatments (adaptive headlamps, tunnel lighting regimes, and retroreflective guidance) affect drivers' hazard detection distances and crash-risk proxies on horizontal curves?
ii. RQ2: Which reliability-based design-consistency metrics and optimisation frameworks best predict and reduce safety risk on horizontal curves across mixed traffic and environmental conditions?
iii. RQ3: To what extent do connected-vehicle warnings, intelligent speed adaptation, and in-vehicle advisory systems improve driver performance and reduce collisions on horizontal curves when accounting for human perception and workload?

3.2 Material and Methods

The PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) framework, developed by Page et al.[19], is a globally recognized standard for conducting systematic literature reviews, ensuring transparency, methodological rigor, and reproducibility throughout the review process. By following PRISMA guidelines, researchers are able to systematically identify, screen, and include studies with greater precision, thereby enhancing the credibility and reliability of their findings. The framework emphasizes the importance of using structured protocols and flow diagrams to clearly document each phase of the review, while also recognizing the value of including randomized studies, given their ability to minimize bias and strengthen the overall quality of evidence. In this study, two comprehensive and authoritative databases which are ScienceDirect and Scopus were selected for data retrieval due to their extensive journal coverage, multidisciplinary scope, and inclusion of high-impact, peer-reviewed publications. Their use reinforces the robustness of the search strategy and ensures that the literature included reflects the most relevant and rigorous research available within the field.

The PRISMA approach is a methodical, four-stage process: identification, screening, eligibility, and data abstraction. In the identification phase, exhaustive searches across databases are conducted to capture all pertinent studies. The screening phase rigorously evaluates these studies against strict criteria to exclude irrelevant or substandard research. In the eligibility phase, the remaining studies undergo a comprehensive review to confirm their alignment with inclusion standards. Finally, the data abstraction phase extracts and synthesizes key data, forming the foundation for robust and reliable conclusions. This systematic framework ensures the review is executed with precision, yielding results that are both credible and actionable, providing a solid foundation for advancing research and practice.

3.2.1 Identification

In the Identification phase of the Systematic Literature Review (SLR) process, an extensive search was conducted using Scopus and ScienceDirect databases, focusing on sight distance and horizontal curve in transportation engineering. The Scopus search yielded 208 records, while ScienceDirect contributed 886 records, resulting in a total of 1,094 identified studies. This extensive search across two leading academic databases was crucial for ensuring a broad and comprehensive pool of relevant literature, given that ScienceDirect tends to focus on applied sciences, particularly in engineering, which explains the higher yield from this source. However, the disparity in record numbers also raises questions about the scope and overlap between the two databases, as well as the specificity of search terms. While the large volume of results may initially seem promising, it necessitates careful filtering in the subsequent screening phase to ensure that only high-quality, relevant studies are included. Ultimately, this rigorous identification process lays a solid foundation for a robust and representative synthesis of literature, ensuring the systematic review is comprehensive and trustworthy.

Table 2
The search string

Scopus	TITLE-ABS-KEY (("sight distance" AND "horizontal curve") OR (visibility AND "horizontal curve") OR (visibility AND "road curve")) ("sight distance" AND "horizontal curve") OR (visibility AND "horizontal curve") OR (visibility AND "road curve") Date of Access: 19 September 2025
Science Direct	("sight distance" AND "horizontal curve") OR (visibility AND "horizontal curve") OR (visibility AND "road curve")") Date of Access: 19 September 2025

3.2.2 Screening

The screening phase, as the second critical step in the Systematic Literature Review (SLR) process, focuses on refining the initially identified records to ensure that only the most relevant and high-quality studies proceed to further analysis. From the 1,094 records identified in the identification phase, a total of 942 records were excluded based on predefined inclusion and exclusion criteria designed to maintain both the relevance and academic rigor of the review. Specifically, studies were removed if they were non-English, published prior to 2020, categorized as conference papers, book chapters, or review articles, labeled as "in press", or published in fields outside engineering. These criteria are justified on several grounds: the exclusion of non-English literature ensures consistency and interpretability in data extraction; focusing on studies from 2020 onward guarantees the inclusion of the most recent and relevant advancements in the field; and removing non-peer-reviewed or non-journal content like conference proceedings and book chapters helps ensure the scientific rigor of the sources as shown in Table 3. After this rigorous screening, 152 studies remained including 39 from Scopus and 113 from ScienceDirect, indicating a substantial narrowing of the literature to a manageable and focused set of articles. Following this, a duplicate check was conducted to eliminate redundant entries across the two databases, resulting in the removal of 18 duplicate records. This careful process reduced the dataset to a final 134 unique studies, forming a curated and high-quality foundation for the subsequent eligibility assessment. The significant reduction from 1,094 to 134 papers not only demonstrates the stringency and transparency of the screening process but also reinforces the importance of applying well-defined exclusion criteria to eliminate irrelevant, outdated, or lower-impact studies. This meticulous approach ensures that the SLR maintains a high standard of credibility and relevance, ultimately enabling the derivation of meaningful insights and recommendations that are grounded in the most authoritative and up-to-date research within the domain of transportation engineering.

Table 3

The selection criterion is searching

Criterion	Inclusion	Exclusion
Language	English	Non-English
Time line	2020 – 2025	< 2020
Literature type	Journal (Article)	Conference, Book, Review
Publication Stage	Final	In Press
Subject	Engineering	Besides Engineering

3.2.3 Eligibility

In the Eligibility phase of the Systematic Literature Review (SLR), a total of 134 articles were thoroughly examined to ensure alignment with the study's objectives and methodological standards. During this critical evaluation, 105 studies were excluded for specific reasons, including being outside the relevant field, insignificant titles, or abstracts not aligning with the research focus on sight distance and horizontal curves. These exclusion criteria were essential to maintain the analytical depth, contextual relevance, and quality of the review. Ultimately, 29 high-quality studies were retained for qualitative synthesis, representing a refined and reliable body of evidence. This rigorous selection ensures that only the most pertinent and methodologically sound research informs the final analysis, thereby enhancing the credibility, focus, and impact of the review's conclusions in the context of transportation engineering.

3.2.4 Data abstraction and analysis

In this study, an integrative analysis approach was employed as a robust qualitative assessment strategy to examine and synthesize findings from a diverse range of research designs within the 29 selected studies. This method was particularly well-suited for the study's objective which is to uncover and organize relevant themes and subthemes related to sight distance on horizontal curves by allowing the integration of varied methodologies and perspectives across the selected literature. The process began with systematic data collection, wherein each study was meticulously reviewed to extract statements, findings, and contextual details directly relevant to the research questions. As illustrated in Figure 2, the authors conducted an in-depth examination of all 29 articles, focusing on the methodologies, key findings, and thematic relevance of each study. Table 4 on the other hand shows the details of primary studies database. Particular attention was paid to the alignment of research objectives, study design, and outcome measures to ensure consistency and relevance across the data set. This comprehensive approach enabled the identification of recurring patterns, which were then translated into preliminary themes. In the theme development phase, the primary author collaborated closely with co-authors, ensuring that multiple perspectives informed the analytical process. This collaboration helped enhance inter-rater reliability, as differences in interpretation were openly discussed and resolved through critical dialogue. A detailed logbook was maintained throughout the analysis to capture evolving interpretations, analytical decisions, uncertainties, and emergent ideas, serving as both an audit trail and a reflexive tool. Importantly, the authors performed a comparative consistency check to ensure the themes were conceptually coherent and empirically supported. Where disagreements arose, the team engaged in reflective discussion to refine or reconcile differing viewpoints, ensuring a rigorous and transparent analytical process. The justification for employing this integrative approach lies in its ability to synthesize a complex body of literature into a cohesive narrative while accommodating methodological variation, thereby enhancing the depth, reliability, and validity of the findings. This ensures that the resulting themes are not only grounded in the evidence but also reflective of the broader academic discourse surrounding sight distance in the context of horizontal road curves.

3.3 Quality of Appraisal

According to the guidelines proposed by Kitchenham and Charters [17], the quality of the selected primary studies was assessed to enable a systematic evaluation and quantitative comparison of the evidence. The quality assessment framework adopted in this review is based on the approach proposed by Anas Abouzahra et al. [46], which comprises six quality assessment (QA) criteria. Each study was evaluated against these criteria using a three-level scoring scheme. A score of 1 was assigned when a criterion was fully satisfied (“Yes”), a score of 0.5 was assigned when the criterion was partially satisfied but exhibited certain limitations (“Partly”), and a score of 0 was assigned when the criterion was not satisfied (“No”). This structured assessment ensured consistency in evaluating study quality and supported the reliability of the synthesized findings.

i. QA1. Is the purpose of the study clearly stated?
ii. QA2. Are the interest and the usefulness of the work clearly presented?
iii. QA3. Is the study methodology clearly established?
iv. QA4. Are the concepts of the approach clearly defined?
v. QA5. Is the work compared and measured with other similar work?
vi. QA6. Are the limitations of the work clearly mentioned?

The table outlines a quality assessment (QA) process used to evaluate a study based on specific criteria. Three experts assess the study using the criteria listed, and each criterion is scored as "Yes" (Y), "Partly" (P), or "No" (N).

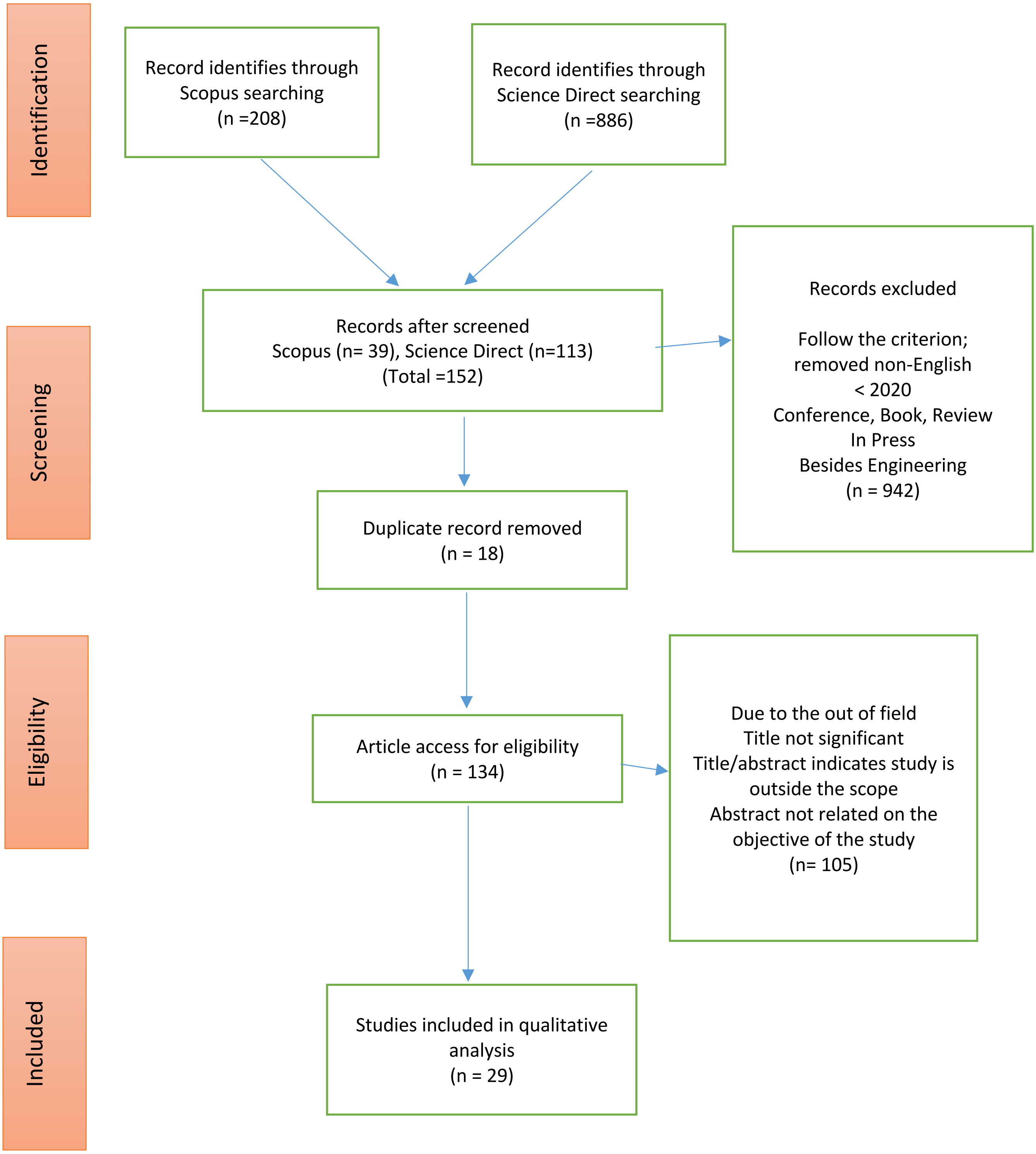

Fig. 2. Flow diagram of the proposed searching study [1]

Table 4
Number and details of Primary Studies Database

No	Authors	Title	Year	Journal	Scopus	Science Direct
1	S., Wang, Shuyi; J., Zhang, Jiakun; Y., Ma, Yang; Y., Zheng, Yuan; B., Yu, Bin; F., Jiao, Fangtong; Y., Lai, Yuanwen[20]	Sight distance analysis of vehicles with driving automation on horizontal curves of as-built highway tunnels	2025	Tunnelling and Underground Space Technology	/	/
2	A.G., Ramesh, Anjana G.; J., Goyani, Jaydip; S.S., Arkatkar, Shriniwas Shrikant; S.M., Easa, Said M.[21]	System Reliability Evaluation of Expressway Horizontal Alignment Design Considering Trucks and Passenger Cars	2025	Transportation Research Record	/	
3	H., Ge, Hongcheng; C., Song, Cancan; D., Jing, Difei; W., Li, Wei; Z., Shi, Ze; Z., Guo, Zhongyin; F., Zhang, Fangyan [22]	Analysis of the effect of highway extra-long tunnel Accompanying vehicle lighting on driving behavior in horizontal curve – A driving simulation study	2025	Tunnelling and Underground Space Technology	/	/
4	S., Rankavat, Shalini; A., Garg, Akanksha[15]	Reliability Analysis for Horizontal Curves with Crashes: Case Study in New Delhi, India	2024	Journal of Transportation Engineering Part A: Systems	/	
5	D.T., Godumala, Dharma Teja; K.V., Ravi Shankar, K. V.R.[23]	Geometric Design Consistency Model for Evaluating Safety at Horizontal Curves on Two-Lane Rural Highways Under Mixed Traffic Conditions	2024	Journal of The Institution of Engineers (India): Series A	/	
6	A., Hazoor, Abrar; A., Terrafino, Alberto; L.L., Di Stasi, Leandro Luigi; M., Bassani, Marco[24]	Intelligent speed adaptation for visibility technology affects drivers' speed selection along curves with sight limitations	2024	Journal of Traffic and Transportation Engineering (English Edition)	/	/
7	S., Wang, Song; Z., Li, Zhixia; Y., Wang, Yi; Q., Zheng, Qi; Z., Liu, Zhengxin [25]	Effectiveness of connected-vehicle-based curve speed warning systems with considerations of heads-up display language type's effects on driver behavior	2023	Transportation Research Part F: Traffic Psychology and Behaviour	/	/
8	V., Matragos, Vassilios; F., Fotos, Fotios; K., Apostoleris, Konstantinos; S., Mavromatis, Stergios[26]	Sight distance assessment on left horizontal curves over crest vertical curves on divided highways through reliability-based analysis	2023	Advances in Transportation Studies	/	
9	S.A., Ghalehni, Sajad Asadi; A.M., Boroujerdian, A. M.[27]	Model of encroachment into opposite lanes in horizontal curves of rural roads	2023	IATSS Research	/	/
10	F., Jiao, Fangtong; Z., Du, Zhigang; Y.D., Wong, Y. D.; J., Mei, Jialin; F., Sun, Feng [28]	Design and evaluation of visual guiding facilities along urban road tunnel horizontal curves based on vision and speed perception	2023	Tunnelling and Underground Space Technology	/	/

11	G., Cantisani, Giuseppe; G., Loprencipe, Giuseppe; L., Moretti, Laura[29]	Median design to provide stopping sight distance along horizontal curves in urban freeways	2022	Advances in Transportation Studies	/	
12	A.R., Alozi, Abdul Razak; M.G., Khalil, Mohamed Gamal; C., Qi, Chao; M., Hussein, Mohamed[30]	A Reliability-Based Framework to Assess the Impacts of Increasing Freeways' Posted Speed Limits	2022	Journal of Transportation Engineering Part A: Systems	/	
13	A.K., Bakhshi, Arash Khoda; M.M., Ahmed, Mohamed M.[31]	Driving Simulator Trajectory-Level Analysis of Truck Drivers' Behavioral Alteration in Connected Vehicles Environment Under Fog with Complex Roadway Geometry	2022	Transportation Research Record	/	
14	A., García, Aifredo; D., Pastor-Serrano, Daniel[32]	Determination of minimum horizontal curve radius for safe stopping sight distance of vehicles overpassing truck platoons	2022	Computer-Aided Civil and Infrastructure Engineering	/	
15	M., Gamal Khalil, Mohamed; M., Hussein, Mohamed[33]	A Risk-Based Multiobjective Optimization Framework to Enhance the Safety of Horizontal Curves with Limited Sight Distance	2022	Journal of Transportation Engineering Part A: Systems	/	
16	K., Habib, Karim; M.H., Tawfeek, Mostafa H.; K., El-Basyouny, Karim[34]	A system to determine advisory speed limits for horizontal curves based on mental workload and available sight distance	2022	Canadian Journal of Civil Engineering	/	/
17	X., Ye, Xinchen; X., Wang, Xuesong; S., Liu, Shuang; A.P., Tarko, Andrew P.[35]	Feasibility study of highway alignment design controls for autonomous vehicles	2021	Accident Analysis and Prevention	/	/
18	J., Vos, Johan; H., Farah, Haneen; M.P., Hagenzieker, Marjan P.[36]	How do dutch drivers perceive horizontal curves on freeway interchanges and which cues influence their speed choice?	2021	IATSS Research	/	/
19	A., Shalkamy, Amr; S.A., Gargoum, Suliman A.; K., El-Basyouny, Karim[16]	Towards a more inclusive and safe design of horizontal curves: Exploring the association between curve features, reliability measures, and safety	2021	Accident Analysis and Prevention	/	/
20	A., Sahaf, Ali; A., Abdoli, Ali; A., Mohamadzadeh Moghaddam, Abolfazl[9]	Calculating TIN-Based 3D Sight Distance and Its Evaluation on Drivers Free-Flow Speed	2021	Shock and Vibration	/	
21	N.M., Joseph, Neena M.; M., Harikrishna, M.; M.V.L.R., Anjaneyulu, Matha Venkata Lakshmi Ranga[37]	Safety evaluation of multiple horizontal curves using statistical models	2021	International Journal of Vehicle Safety	/	

22	M., Zolali, Mehdi; B., Mirbaha, Babak; M., Layegh, Maziyar; H.R., Behnood, Hamid Reza[38]	A Behavioral Model of Drivers' Mean Speed Influenced by Weather Conditions, Road Geometry, and Driver Characteristics Using a Driving Simulator Study	2021	Advances in Civil Engineering	/	
23	A., Shalkamy, Amr; K., El-Basyouny, Karim[39]	Multivariate models to investigate the relationship between collision risk and reliability outcomes on horizontal curves	2020	Accident Analysis and Prevention	/	/
24	A., Shalkamy, Amr; K., El-Basyouny, Karim; H., Xu, Haiyang[40]	Voxel-Based Methodology for Automated 3D Sight Distance Assessment on Highways using Mobile Light Detection and Ranging Data	2020	Transportation Research Record	/	
25	N., Stamatiadis, Nikiforos; B., Psarianos, Basil; K., Apostoleris, Konstantinos; P., Taliouras, Philippos[41]	Nighttime versus Daytime Horizontal Curve Design Consistency: Issues and Concerns	2020	Journal of Transportation Engineering Part A: Systems	/	
26	K., Habib, Karim; M., Gouda, Maged; K., El-Basyouny, Karim[42]	Calibrating Design Guidelines using Mental Workload and Reliability Analysis	2020	Transportation Research Record	/	
27	Y., Ma, Yang; Y., Zheng, Yubing; J., Cheng, Jianchuan; S.M., Easa, Said M.[43]	Analysis of dynamic available passing sight distance near right-turn horizontal curves during overtaking using LiDAR data	2020	Canadian Journal of Civil Engineering	/	/
28	R., Alsaleh, Rushdi; T.A., Sayed, Tarek A.; K., Ismail, Karim; F.S., Al-Rukaibi, Fahad S.[44]	System reliability as a surrogate measure of safety for horizontal curves: methodology and case studies	2020	Transportmetrica A: Transport Science	/	
29	César De Santos-Berbel, Maria Castro[45]	Effect of vehicle swiveling headlamps and highway geometric design on nighttime sight distance	2020	Mathematics and Computers in Simulation		/

4. Result and Findings

Background of selected study: based on quality assessment, table 5 shows the result of assessment performance for selected primary studies. The quality assessment of the 29 primary studies (PS1–PS29) reveals a generally strong level of reporting, with an average score of 4.52 out of 6 (75.3%) and a median score of 4.5. This indicates that the majority of studies fall within a moderate-to-good quality range, with most clustering between 66% and 76%. A notable strength across the collection is the consistency with which authors present the purpose, usefulness, and methodology of their work. Every abstract assessed clearly articulated its research aim (QA1), explained its importance (QA2), and described the methodology used (QA3), which reflects a strong standard of clarity and transparency in communicating the core elements of the research. In addition, nearly 80% of the studies provided sufficiently clear definitions of key concepts (QA4), although some still relied heavily on technical jargon without adequate clarification, resulting in partial scores. These findings suggest that in terms of presenting the motivation and methods, the field demonstrates a high level of rigor and accessibility.

However, the analysis also highlights significant weaknesses in how studies contextualize and qualify their findings. Only 7 studies explicitly compared their work to similar research (QA5), while the majority provided only partial reference to prior work, limiting the ability of readers to situate new findings within the broader body of knowledge. The most critical shortcoming is observed in QA6 (limitations), where no study fully acknowledged its limitations in the abstract, and only 7 made partial mention of constraints such as scope, assumptions, or future work. This omission reduces transparency and may hinder replication or critical appraisal of the results. The top-performing studies (PS12, PS15, PS19, PS23, PS26, and PS28) achieved scores of 5.5 out of 6 (91.7%), reflecting strong clarity, contextualization, and at least some acknowledgment of limitations, while PS8 followed closely with 5.0 (83.3%). By contrast, PS1 scored the lowest at 58%, primarily due to the absence of comparative context and omission of limitations. Overall, the assessment demonstrates that while studies in this area excel at presenting objectives and methods, they often fail to adequately position their contributions within the literature or discuss potential weaknesses. This pattern suggests an opportunity for improvement in abstract writing practices, particularly in explicitly stating limitations and benchmarking against prior research, which would enhance transparency, critical evaluation, and the cumulative development of knowledge in the field.

Table 5
Quality assessment performance of selected primary studies

Author	Title	QA1	QA2	QA3	QA4	QA5	QA6	Total Mark	%
PS1	Sight distance analysis of AV in tunnels	Y	Y	Y	P	N	N	3.5	58.3
PS2	System reliability of expressway alignment	Y	Y	Y	P	P	N	4	66.7
PS3	Tunnel lighting & driving behavior	Y	Y	Y	Y	P	N	4.5	75
PS4	Reliability analysis of curves in Delhi	Y	Y	Y	P	P	N	4	66.7
PS5	Geometric design consistency model	Y	Y	Y	P	P	N	4	66.7
PS6	Intelligent speed adaptation (V-ISA)	Y	Y	Y	Y	P	N	4.5	75
PS7	Connected vehicle curve speed warning	Y	Y	Y	Y	P	N	4.5	75
PS8	Sight distance on combined curves	Y	Y	Y	P	Y	P	5	83.3
PS9	Lane encroachment model	Y	Y	Y	P	P	N	4	66.7
PS10	Visual guiding facilities in tunnels	Y	Y	Y	Y	P	N	4.5	75
PS11	Median design for SSD	Y	Y	Y	P	P	N	4	66.7

PS12	Speed limit reliability framework	Y	Y	Y	Y	Y	P	5.5	91.7
PS13	CV truck driver behavior under fog	Y	Y	Y	Y	P	N	4.5	75
PS14	Truck platoons & sight distance	Y	Y	Y	P	P	N	4	66.7
PS15	Risk-based optimization framework	Y	Y	Y	Y	Y	P	5.5	91.7
PS16	Advisory speed limits with mental workload	Y	Y	Y	Y	P	N	4.5	75
PS17	Feasibility of AV alignment design controls	Y	Y	Y	P	P	N	4	66.7
PS18	Dutch drivers' perception of curves	Y	Y	Y	P	P	N	4	66.7
PS19	Inclusive & safe design of curves (SEM)	Y	Y	Y	Y	Y	P	5.5	91.7
PS20	TIN-based 3D sight distance	Y	Y	Y	Y	P	N	4.5	75
PS21	Safety of multiple horizontal curves	Y	Y	Y	P	P	N	4	66.7
PS22	Simulator study: speed, weather & geometry	Y	Y	Y	Y	P	N	4.5	75
PS23	Collision risk & 3D sight distance	Y	Y	Y	Y	Y	P	5.5	91.7
PS24	Voxel-based 3D ASD using LiDAR	Y	Y	Y	Y	P	N	4.5	75
PS25	Night vs day curve design consistency	Y	Y	Y	P	P	N	4	66.7
PS26	Design guidelines, workload & reliability	Y	Y	Y	Y	Y	P	5.5	91.7
PS27	Dynamic APSD near curves using LiDAR	Y	Y	Y	Y	P	N	4.5	75
PS28	Reliability of horizontal curves (multi-mode)	Y	Y	Y	Y	Y	P	5.5	91.7
PS29	Swiveling headlights & night sight distance	Y	Y	Y	Y	P	N	4.5	75

A total of twenty-nine articles were selected after applying the screening and eligibility process, forming the basis for addressing the research questions. From the synthesis of these studies, three overarching themes emerged to structure the review: (1) Sight Distance, Visibility & Lighting, which highlights the role of geometric design, roadway illumination, and visibility treatments in shaping drivers' ability to perceive hazards and maintain safe operation on horizontal curves; (2) Reliability, Design Consistency & Optimization, which focuses on reliability-based approaches, alignment consistency, and optimization frameworks to evaluate safety performance and reduce accident risks under diverse roadway and traffic conditions; and (3) Automation, Connected Vehicles & Human Factors, which explores the integration of intelligent speed adaptation, connected-vehicle technologies, and human-centered considerations such as workload, perception, and behavioral responses in improving safety on curved segments. These themes provide the structural foundation for the subsequent detailed analysis, where the evidence within each category is examined comprehensively.

4.1 Sight Distance, Visibility & Lighting

Three-dimensional sensing and modelling approaches have improved the representation of available sight distance on horizontal curves. Studies by Sahaf et al. [9], Shalkamy & El-Basyouny [39], and Shalkamy et al. [40] demonstrate that terrain-interpolated meshes, voxelized point clouds, and LiDAR-based methods more effectively capture occlusions and relief than planar assessments. Their findings indicate that dynamic assessments, which account for vehicle motion and time-varying sensor updates, provide more realistic estimates of available sight compared to static evaluations [43] [9][40]. Discussions in these works highlight trade-offs between improved fidelity and increased computational requirements, emphasizing the need for validation against field performance to connect geometric outputs with safety outcomes [9] [39][40].

Lighting conditions and visual guidance also play a critical role in maintaining visibility and safety in tunnels and transition zones. Wang et al. [20], Ge et al.[22], and Jiao et al. [28] show that optimized tunnel illumination and guiding facilities enhance driver control by stabilizing scanning behavior and reducing adaptation delays. Their findings reveal that abrupt luminance transitions at tunnel portals impair recognition distances, affecting stopping sight distance and increasing safety risks. This effect extends to automated perception systems, which may experience reduced accuracy under conditions of glare and contrast variability [20][22] [28]. These results suggest that integrated approaches to lighting, reflective guidance, and sensor calibration are necessary to support consistent human and automated system performance [22][28][20].

Nighttime driving conditions introduce further challenges for curve safety, particularly when design is based on daytime sight distance standards. Stamatiadis et al. [41], De Santos-Berbel & Castro [45], and Wang et al. [20] report that adaptive lighting systems, such as swiveling headlights, improve curve visibility but must address glare and consistency across multiple road users. Comparative analyses by Stamatiadis et al. [41] and De Santos-Berbel & Castro[45] suggest that nighttime sight margins are often inadequate on curves designed for daytime conditions, making speed adjustments or supplemental lighting necessary. Discussions across these studies recommend a combined strategy of vehicle-based lighting innovation, roadway illumination, and reflective treatments to maintain reliable sight distances at night [45] [41][20]

Geometric complexity, combined curves, and the presence of heavy-vehicle platoons amplify visibility limitations and raise accident risks. Matragos et al. [26], García & Pastor-Serrano [32], and Shalkamy & El-Basyouny [39] show that compound curves and truck platoons significantly restrict overtaking and following sight distance, creating frequent high-risk zones. Ma et al. [43] and Shalkamy et al. [40] further demonstrate that three-dimensional LiDAR-based models are effective in pinpointing visibility hotspots caused by vehicle-induced shadowing or curvature overlap. These findings suggest that countermeasures such as roadside clearing, variable speed limits, or curve geometry adjustments can mitigate risks in sections prone to restricted visibility [26] [32][43].

4.2 Reliability, Design Consistency & Optimization

Three-dimensional sensing and modelling approaches have improved the representation of available sight distance on horizontal curves. Studies by Sahaf et al. [9], Shalkamy & El-Basyouny [39], and Shalkamy et al. [40] demonstrate that terrain-interpolated meshes, voxelized point clouds, and LiDAR-based methods more effectively capture occlusions and relief than planar assessments. Their findings indicate that dynamic assessments, which account for vehicle motion and time-varying sensor updates, provide more realistic estimates of available sight compared to static evaluations [43] [9][40]. Discussions in these works highlight trade-offs between improved fidelity and increased computational requirements, emphasizing the need for validation against field performance to connect geometric outputs with safety outcomes [9] [39][40].

Horizontal-curve design is moving from deterministic checks toward reliability-based assessment. Ramesh et al. [21] frame alignment evaluation as a system-reliability problem, showing how probability-based failure metrics reveal vulnerable alignment elements; Rankavat & Garg [15] report that field calibration in Delhi exposes discrepancies between fixed stopping-sight thresholds and observed operating speeds; Godumala & Shankar [23] develop a geometric design consistency model that links curvature and cross-section variability to speed dispersion and conflict likelihood. The common finding is that single-value design criteria underrepresent operational variability. The discussion in these studies recommends formal incorporation of reliability targets into design standards so that alignment checks reflect distributions of vehicle performance, sight conditions, and driver behaviour rather than idealized assumptions.

Lane-level mechanisms and multi-user interactions produce localized failure modes that aggregate into corridor risk. Ghalehni & Boroujerdian [27] show how probabilistic lane-encroachment models identify lateral excursion processes that precede run-offs and sideswipes. Alsaleh et al. [44] extend reliability assessment across multiple modes, evidencing differential vulnerability for passenger cars, heavy vehicles, and vulnerable road users. Joseph et al. [37] demonstrate that sequences of horizontal curves concentrate perceptual and control demands, producing hotspots not apparent from isolated-curve analysis. Findings across these studies indicate that lane-encroachment probabilities and multi-mode reliability indices are complementary: lane-level metrics detect immediate lateral threats while multi-mode indices support corridor prioritization. The studies discuss integration of lane-level outputs into corridor reliability pipelines for targeted mitigation.

Design elements, speed policy, and human workload interact to determine effective stopping and avoidance margins. Cantisani et al. [29] finds that median geometry and cross-section details materially affect available stopping distance and head-on exposure. Alozi et al. [30] proposes a speed-limit reliability framework where posted speeds are set to achieve prespecified reliability levels under uncertain sight and compliance; empirical results show reduced exceedance rates when probabilistic criteria drive speed setting. Habib et al. [34] argue for embedding workload and perceptual limits into design guidelines so that geometry and speed together produce manageable task demands. The studies conclude that combining physical measures (medians, clear zones) with reliability-based speed policy and workload-aware guidance yields stronger safety outcomes than geometry changes alone.

Optimization and decision-support approaches translate reliability metrics into implementable interventions under resource constraints. Gamal Khalil & Hussein [33] present a risk-based optimization framework balancing crash-reduction benefits against construction and maintenance costs using reliability constraints to bound acceptable failure probabilities. Ramesh et al. [21] illustrate embedding reliability targets directly into alignment optimization to avoid fragile alignments with high sensitivity to disturbance. Alozi et al. [30] show stochastic approaches for advisory speed setting that prioritize robust performance across scenarios. Findings emphasize usefulness of sensitivity analysis and scenario testing to identify interventions with highest marginal safety return. Discussion sections recommend that optimization outputs include robustness diagnostics and be presented in practitioner-interpretable form, with explicit constraints for constructability and maintenance.

Empirical calibration and validation are essential to make reliability models transferable across contexts. Rankavat & Garg [15] provide field-derived parameters that diverge from standard assumptions in mixed-traffic urban settings; Joseph et al. [37] document crash patterns on curve sequences that expose model-data mismatches; Godumala & Shankar [23] report validation exercises showing that consistency indices correlate with observed speed variance but require local tuning. The recurrent finding is that uncalibrated models risk misleading prioritization in regions with different vehicle mix, behaviour, or roadside conditions. Discussions in these studies call for expanded empirical datasets, routine performance monitoring, iterative recalibration of indices, and pilot deployments so that model recommendations remain robust and applicable.

4.3 Automation, Connected Vehicles & Human Factors

Active and advisory speed-management systems consistently reduce speed dispersion on horizontal curves but require careful calibration to remain effective in real operation. Hazoor et al. [24] report that an intelligent speed adaptation scheme (V-ISA) narrows the speed distribution and reduces exceedance of advisory thresholds, though effectiveness depends on alert timing and acceptance. Wang et al. [25] find that connected-vehicle curve speed warnings lower approach speeds and smooth braking patterns, with reduced benefit when false-alarm rates increase. Habib et al. [34] show that driver mental workload moderates response to advisory speeds: well-timed, low-cognitive-load messages improve compliance, while overly frequent or complex alerts may hinder performance. Simulator evidence from Zolali et al. [38] supports these points by demonstrating sensitivity of compliance and control to message modality and environmental complexity and suggests that adaptive thresholding and nuisance-filtering logic improve sustained effectiveness [24][25][34][38].

System resilience under degraded visibility and heavy-vehicle conditions is limited unless sensor and message logic are adapted to context. Bakhshi & Ahmed [31] observe that fog substantially delays driver reaction and that connected warnings partially mitigate delay only when latency and message relevance are controlled. Zolali et al. [38] show in simulation that adverse weather increases false positives for some sensing modalities and elevates task load, which in turn reduces the probability of correct driver response. Ye et al. [35] discuss alignment design controls for automated vehicles and emphasize that perception reliability under low visibility should guide feasibility assessments; conservative operational bounds for heavy vehicles and degraded vision conditions are recommended [31] [38][35].

Human perception, workload, and inclusivity substantially mediate the success of automation and advisory systems on curves. Vos et al. [36] report that subjective perception of curve risk varies across driver cohorts, influencing preferred speed and acceptance of automated prompts. Shalkamy et al. [16] use structural equation modelling to show that perceived clarity and risk perception mediate compliance with curve warnings, implying that interface simplicity and message framing are crucial. Habib et al. [34] document that elevated mental workload reduces ability to process additional advisory messages, recommending prioritized and minimal-cognitive-load alerts to maintain compliance across diverse driver groups [36] [16] [34].

Feasibility and system-level integration studies emphasize co-design of roadway geometry, roadside infrastructure, and in-vehicle systems before large-scale deployment. Ye et al. [35] argue that alignment design controls intended for automated platforms require verification for sensor line-of-sight and redundancy under varying weather and traffic mixes. Hazoor et al. [24] recommend pilot implementation with performance metrics that include driver acceptance and false-alarm incidence to guide tuning of V-ISA parameters. Wang et al. [25] advise staged roll-out of connected warnings combined with monitoring of human–system interactions so that alert policies can be adjusted to minimize workload and maximize safety benefits [35][24][25].

5. Discussion and Conclusion

This study sets out to systematically review the relationship between sight distance limitations and accident risks on horizontal curves, with the aim of consolidating existing evidence and identifying critical directions for safer roadway design. By applying the PRISMA protocol across Scopus and ScienceDirect, 29 high-quality primary studies were identified, representing the most recent and relevant contributions in this area. The analysis was structured around three main themes: sight distance, visibility, and lighting; reliability, design consistency, and optimization; and automation, connected vehicles, and human factors. Collectively, the review underscores that sight distance is not simply a matter of geometric compliance, but a multidimensional factor shaped by roadway design, driver behavior, environmental conditions, and the integration of new technologies. Key findings indicate that visibility improvements through lighting and guidance facilities remain essential, yet insufficient when considered in isolation. Reliability-based approaches provide a more realistic evaluation of design safety compared to deterministic criteria, particularly under mixed traffic and complex environmental conditions. At the same time, the emergence of intelligent speed adaptation and connected-vehicle systems demonstrates that future roadway safety must integrate automation and account for human perceptual and cognitive limits to be effective.

The contributions of this review extend beyond synthesizing existing findings, as it provides a structured framework for understanding how sight distance interacts with reliability assessments and automation technologies to influence safety outcomes. From a practical standpoint, the evidence suggests that design standards should transition toward reliability-based thresholds, incorporate three-dimensional and dynamic sight distance assessments, and align speed policies with probabilistic safety margins. Automation technologies should be deployed with careful attention to driver workload, perception, and inclusivity, ensuring that warnings and advisory systems enhance safety rather than overwhelm users. However, the review also highlights notable limitations in the field, such as insufficient empirical validation of reliability models, underreporting of study limitations, and limited exploration of multi-modal safety outcomes. Future research should address these gaps by expanding empirical datasets, validating models across diverse contexts, and exploring the interaction between human factors and automation in greater depth. In conclusion, sight distance limitations represent a persistent and multifaceted risk factor in roadway safety. Addressing this challenge requires an integrated approach that combines geometric and lighting improvements with reliability-based evaluations and human-centered automation strategies. Such an approach offers the most promising pathway toward reducing accident risks on horizontal curves and advancing the development of safer transportation systems.

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Conflicts of Interest
The authors declare that they have no conflicts of interest to report regarding the present study

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