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Research Paper

Secure Vision-Based Lane Detection for Autonomous Shuttles in Crowd-Rich Environments

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Abstract: Self-driving shuttle systems are being envisaged with the context of shared pedestrian-rich streets where the challenge of the accessibility and dependability of accountable lane perception is vexed by moving crowds, optical defence, and increased caution demands. Lane detection vision is a central element of the perception stack of these platforms because of its affordability and high semantic accuracy; nevertheless, its functionality and capability in crowd-saturated working conditions have not been studied in a systematic manner. This article is a peer-reviewed systematic review of 74 peer-reviewed articles/papers regarding vision-based lane detection in autonomous systems, specifically crowd-aware perception and robustness of the perception layer. The literature review will be evaluated based on the methodology, sensor setup, metrics of evaluation, and the degree to which the dynamics of crowds and security are considered. The findings show significant dependence on deep learning-based and vision focused perception model, little explicit modelling of dense pedestrian environment and limited explicit security threats of the perception layer. There is great variance in evaluation practices which also makes cross-study comparison more difficult. The results reveal a grave discrepancy between the existing research implementation and the manoeuvrability requirements of autonomous shuttles in a shared environment, and they inspire necessity of all-encompassing, security-attentive, and crowd-sensitive lane sight systems backed by standardized examination systems.

Keywords: Autonomous shuttles, Vision-based Lane detection, Crowd-aware perception, Perception robustness, Sensor security, Shared environments

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1. Introduction

Autopilot shuttle networks are becoming one of the main elements of smart travel infrastructure, especially the last-mile mobility, in campuses, airports, hospitals, industrial areas, and smart cities. They move slowly in mixed or semi-structured environments unlike highway-centric autonomous vehicles, in which pedestrians need little space and information about the incoming vehicles, and are in constant presence of the shuttles. Under such environments, the proper lane perception is critical to the efficiency of navigation, as well as safety when walking among thick crowds of dynamic people. Lane detection based on vision has thus become one of the cornerstones to autonomous shuttle perception stack development due to its cost efficiency, scalability and capability to provide rich semantic data regarding the environment [1-3]. Although there have been significant advances in lane detecting algorithms, especially with the emergence of deep learning methods, much of the existing work has been implemented and tested in situations which are not well representative of the nature of pedestrian-enhanced situations. Stampeded crowd, obscure or faded lane markings, and changing light and human motion cause serious ambiguity to the visual perception. Such limitations are further made difficult by growing dependence on monocular and vision-heavy sensor layouts, which put more vulnerability to perception failure. With the move of autonomous shuttles towards non-controlled pilots and increased use of autonomous shuttle systems in the world, the requirements of the current lane detection systems to consider the dynamics of a crowd emerge more as an issue [4-6].

A concern in autonomous driving research is the security of perception systems that has been a growing concern. Perception through vision is susceptible to various forms of physical and digital manipulation, such as adversarial patterns, environmental manipulation, sensor spoofing, and others, and may result in incorrect lane estimation. Pedestrian-dense conditions might have increased the impacts of such perception failures because of the proximity between humans and vehicles and the narrow reaction realization [7-9]. The current state of research about lane identification has not prioritised robustness or security but mostly broken down and analysed performance on nominal or modulative perturbed scenarios. Although the previous surveys have assessed the methodological approaches of lane detection or the autonomous vehicle perception in general, there is still a lack of a systematic synthesis of the lane detection approach, the ways of crowd-awareness in perception, and the perceptions-layer resilience. Specifically, little is known about the prevalence with which the dynamic of crowds and the idea of security are reflected in lane perception studies, how the evaluation activities differ across studies, and in what areas evidence gaps exist. These are critical questions that must be addressed in the process of integrating research advancement to the performance of autonomous shuttle systems in terms of operations and safety needs [10-12].

This paper is aimed to fill this gap and provide a PRISMA-compliant systematic review of the existing literature on vision-based lane detection to autonomous systems working in the crowd-rich environment. It is a review of 74 peer-reviewed studies on the trends of methodological choices, sensor setup, and the evaluation parameter as well as the degree to which the interaction with crowds and robustness of the perception-layer are addressed. The purpose of the paper is to determine the prevailing practices by quantitatively and qualitatively exploring the overlap of these dimensions and brings out the least researched areas of concern, as well as to guide future research directions in the direction of secure and reliable lane perception in autonomous shuttles [13-15]. The rest of this paper is structured in the way presented below. Section 2 outlines the systematic review methodology which involves the search strategy, selection process of the study, data extraction and data synthesis framework. Part 3 shows the findings of the review, such as the distribution of publications, methodologies, and the sensitivity of the coverage of the crowd-awareness and security issues. Section 4 addresses the implication of this finding being in the form of research gaps and challenges. Lastly, the 5th section wraps up the paper by providing an overview of its core findings and a research agenda on the objectives that need to be fulfilled in the future regarding secure and crowd-aware vision-based lane detection to work with autonomous shuttle systems.

2. Methodology

This paper will follow the systematic review method as it is transfusible to the Preferred Reporting Items of Systematic Reviews and Meta-Analyses (PRISMA) guidelines and the aim of the synthesis and critical evaluation of literature related to vision-based lane detection systems implemented in autonomous shuttle platforms deployed in the crowd-rich environment. The aim of the review is a structured and reproducible evaluation of lane perception methods in a situation with the characteristics of the high intensity of pedestrian flow, dynamic occlusions and the increased complex of safety and security demands. The scope of the review is determined by overlap of three research areas: vision-based perception of lane and road boundaries, crowd-aware motion and human interaction, and resilience and safety of perception systems both at the sensor stage and algorithmic stage. Instead of looking at these domains independently, the review clearly looks at the interactions between them in common or semi structured settings where autonomous shuttles have to safely share space with people on the sidewalks. Examples of such places are campuses, transit stations, healthcare centres, factories, and city pilot areas, whereby the lane markings are partial, visually impaired, or by human default judgment based inferred on the surrounding of the scene and human foot traffic. This review concentrates on on-board perception systems which depend mostly on visual sensing, as a separate and independent modality or as the prevailing part of a multi-sensor perception stack. Specific focus is given to low-speed autonomous shuttles and similar autonomous platforms, since these are often implemented in pedestrian-intensive environments, and are operating under operational factors different to autonomous vehicles that are deployed in a highway orientation.

Research focused solely on high-speed highway conditions, or well organised road systems, is thought not to be in the core focus unless its implementation procedures are directly transferable to shared-space conditions. To make it relevant to real-world deployment, the review puts a high value on studies that analyse lane detection performance in realistic operational environments, such as lighting variations, scene complexity, occlusion, and dynamic scenes. Moreover, we consider also works where issues of perception strength and security are considered, either by architectural design factors, redundancy schemes, uncertain and modelling models, or through security-conscious factors involving sensor integrity and adversarial interference. There are no new experimental measures in review, but a systematic analysis and synthesis of reported experimental evaluations, crunching heterogeneous descriptions of experiments into a common analysis that can be further compared to other studies.

2.1 Information Sources and Search Strategy

A methodological and broad literature review was utilized to find peer-reviewed works in area of relevance to vision-based lane detection, crowd-aware perception, and perception robustness in autonomous shuttle systems. The queries were made on several databases of established scholarly databases to achieve comprehensive coverage of disciplines and reduce the risk of publication bias: IEEE Xplore, Scopus, ACM Digital Library, SpringerLink, and ScienceDirect. These databases are a comprehensive collection of the top journals and conference papers in intelligent transportation systems, computer vision, robotics, and cyber-physical system security. Search strategy was created to attract literature on the interface of lane perception, pedestrian-congested working conditions, and perception-layer robustness. Search queries were created in a form of a Boolean combination of keywords and synonyms that were regularly used throughout the areas of research. The core keywords concerning lane detection and lane perception were mixed with the key terms corresponding to the autonomous shuttles and autonomous vehicles, terms connected to the density of pedestrians, interaction with crowds, robustness, and safety.

The search strings were formulated sequentially by narrowing down the preliminary search findings to ensure inclusiveness and relevance, thus minimizing the possibility of retrieving studies that fall out of scope. To be methodologically consistent and the relevance with real-world deployment, the search was narrowed down to articles authored in the English language and which are indexed as peer-reviewed journal articles or complete conference papers. There were no deadlines enforced in terms of the timing of the reviews, and they covered both the old literature and the latest developments capable of illustrating the present tendencies in deep learning-related perception and security-conscious system design. Articles whose content is in non-vision-related sensing modalities or that abstract control formulations do not explicitly analyze the study of perception were not given priority during the search stage. The exported records were all obtained into a reference management system where duplicate records were performed and dropped before proceeding to the screening. The other records formed the first corpus that was to be screened to title and abstract before being further evaluated to the content in the full text. This is a multi-stage process of selection, which was enacted to make sure that it is traceable and reproducible to meet PRISMA reporting standards. Table 1 provides an overview of the search strategy and information sources, which allows being transparent about what was covered in a database and what was being searched.

TABLE 1. SUMMARY OF INFORMATION SOURCES AND SEARCH FOCUS

Database	Primary Research Coverage	Rationale for Inclusion
IEEE Xplore	Intelligent transportation systems, autonomous vehicles, perception algorithms	Core source for AV and lane detection research
Scopus	Multidisciplinary indexing across engineering and computer science	Broad coverage and citation tracking
ACM Digital Library	Computer vision, machine learning, robotics	Key source for perception and algorithmic studies
SpringerLink	Robotics, cyber-physical systems, security	Relevant for perception robustness and system-level studies
ScienceDirect	Transportation, applied AI, safety engineering	Complementary coverage of applied AV research

2.2 Study Selection and Eligibility Criteria

The PRISMA guidelines were followed to the letter to achieve methodological transparency and reproducibility when selecting the studies. After eliminating duplicates, all the retrieved publications underwent a two-step publishing screening process that involved a first-level screening of titles and abstracts followed by a second level of screening of the entire text. In the initial area, articles underwent relevance filtering based on a criterion of inclusion in autonomous system applications studying vision-based lane detection or road boundary perception, and publications with an obvious preference for non-highway-only or non-autonomous driving systems, or non-vision-based sensing without perceptual combination were filtered out. Included or excluded studies were subject to a set of predefined inclusion and exclusion criteria that made it necessary to retain only those studies that offer a well-described perception methodology, adequate experimental or system-level testing, and operating conditions that were relevant to low-speed autonomous shuttles or other similar systems. At this point, studies that did not sufficiently elaborate on methodology, just described the formulation theoretically but failed to substantiate it empirically, or published in non-peer-reviewed sources were filtered out.

To prevent overlapping or redundancy, the most detailed or current version in instances of overlapping or redundancy was retained. To ensure no eligibility choices went un-decided, all such criteria were applied uniformly, and ambiguous instances were resolved by re-examining the entire text closely, and the result of each step in the process of selection recorded to enable tracing in the PRISMA reporting environment.

TABLE 2. INCLUSION AND EXCLUSION CRITERIA APPLIED DURING STUDY SELECTION

Criterion Type	Description
Inclusion	Vision-based lane detection or road boundary perception
Inclusion	Relevance to autonomous shuttles or comparable autonomous platforms
Inclusion	Consideration of pedestrian interaction or shared environments
Inclusion	Clear methodological description and empirical evaluation
Exclusion	Highway-only or fully structured road scenarios
Exclusion	Non-vision-based sensing without perceptual integration
Exclusion	Insufficient methodological detail or validation
Exclusion	Non-peer-reviewed publications or abstracts only

2.3 Data Extraction and Standardization

A systemic data extraction procedure was used to capture and enhance consistency and comparability of data among the reviewed literature on each of the studies that met the eligibility criteria. The most significant methodological and evaluation attributes pertaining to vision-based lane detection, environmental context and robustness of perception were deduced in full text of each article in a systematic way. These characteristics were then pooled into a single analysis output to cover differences in experimental design, performance and reporting of the study. Such a standardization process allowed cross-study comparison and quantitative synthesis without any novel measurement, thus allowing objective analysis of methodological trends and gaps in evidence within this reviewed body of work.

2.4 Data Synthesis and Analytical Framework

The extracted standardized data of the chosen studies were synthesized under a structured analytical framework that was meant to help in qualitative and quantitative comparison of the analyzed literature. Reported methodological features and the results of the performance were amalgamated to single out the existing trends in vision-based lane detection methods, how much the aspect of crowd was considered, and the level of care accorded to perception robustness and security. The comparative analysis involved clustering the studies based on the strategy of the algorithm, the environment of the operation, as well as the considerations of robustness, which has made it possible to identify common practices and the insufficiently covered research directions. The methodology of synthesis enabled the systematic review of the literature, with evidence, without creating new experimental outcomes, and without contradicting the goals of a PRISMA-compliant systematic review.

2.5 Bias Assessment and Methodological Limitations

Although the systematic and structured approach conceived in this review, there are a few sources of potential bias and methodological constraints that need to be mentioned. A publication bias may exist because of the use of peer-reviewed literature materials that tend to emphasize literature that yields positive or best results and under-represent the research on negative or no outcomes. Also, the experimental setups, evaluation measures, and operational settings used in the studies reviewed are heterogeneous, so that the resultant studies cannot be compared directly and it may affect combined interpretations. Disagreements in the definition of pedestrian density, environment complexity, and robustness factors that are applied and reported in various cases further create inconsistencies in evidence compilation. The fact that many of the studies provide a comparison of the perception performance in the controlled or simplified system also limits the possibilities of generalizing the results to the application in the real world and the crowds' rich environments. These constraints underline the issue of standardized evaluation guidelines and expanded reporting procedures, and they are considered when deciphering the findings that have been brought up in following sections.

3. Result

This will provide the presentation of the results of a systematic review, bringing together the results of the studies included in the systematic review based on the PRISMA-based selection process. The findings give a systematic examination of the tendencies of publication, the methodological style of vision-based lane detection, the sensor setups, and the evaluation techniques. Specific focus is placed on how much the literature covers the issues of crowd dynamics and the robustness of the perception layer and how these two aspects interact. By means of quantitative summaries and comparative analysis, the given section will present the prevailing research trends and will state the essential gaps associated with the autonomous shuttle deployment in the area with pedestrians as the main traffic.

3.1 Study Selection

The preliminary collection of records in the chosen academic databases was obtained because of the systematic literature search and was further refined with the process of removing duplicates and multi-stage screening using

PRISMA principles. After title and abstract screening, a list of publications was kept, which passed to full-text eligibility assessment, where the studies were checked against the previously determined inclusion and exclusion criteria outlined in Section 3.3. This led to a resulting corpus of studies considered relevant towards qualitative and quantitative synthesis of research work that had been done, concerned with the topic of vision-based lane detection in autonomous systems deployed in pedestrian or shared space. The records identified, screened, excluded, and finally included at each point of the review process can be summed up in the PRISMA flow diagram provided in Figure 1, which gives a clear picture of the results of the study selection and the possibilities to make the study repeatable.

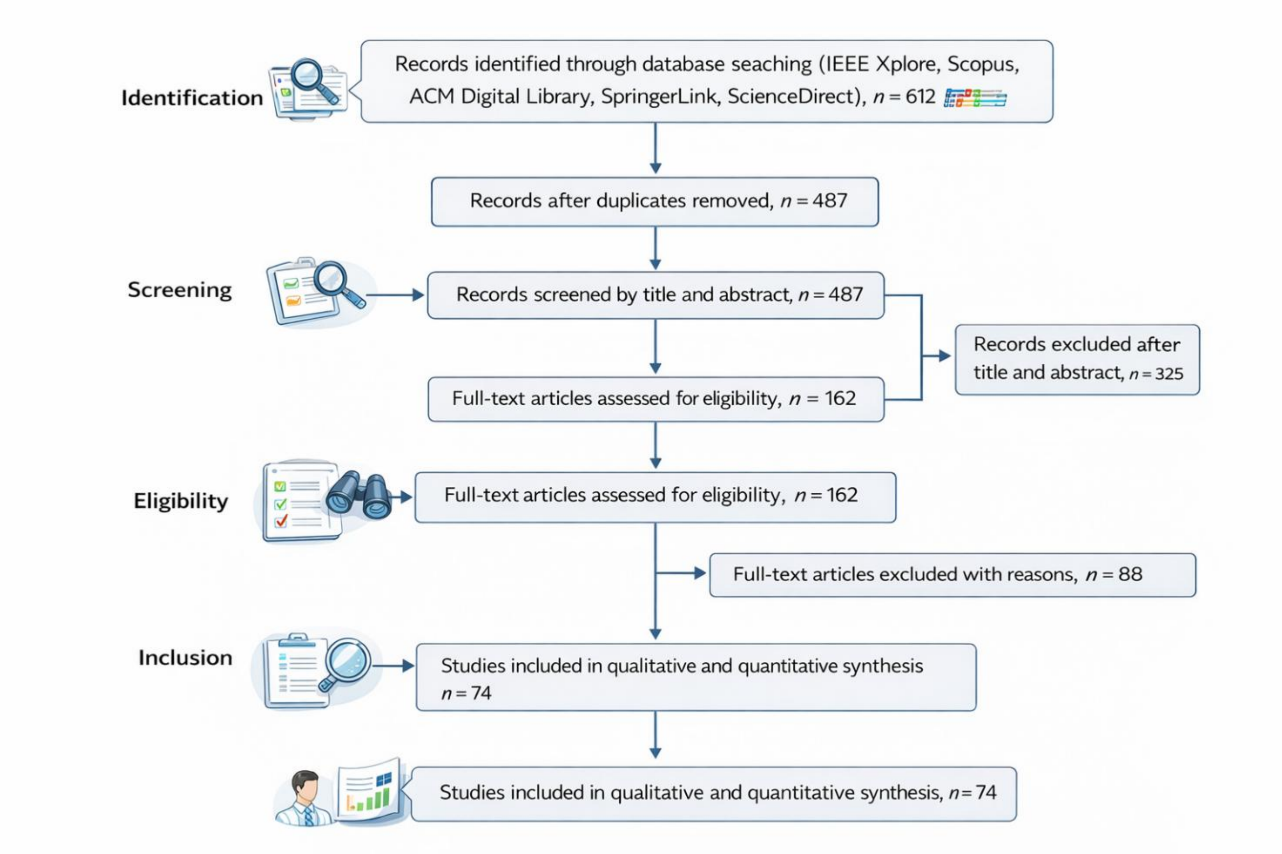

Figure 1. PRISMA Framework

3.2 Included studies by publication year (n = 74)

Fig 2 shows the study distribution over time in the ultimate synthesis as there has been an apparent increase in publications over the years. Until the year 2016, the amount of research output in this field was very small, with 1-2 studies being published every year, and most of the studies were a continuation of initial investigations in the field of vision-based lane detection. Since 2017, it is also on a gradual rise, as efforts to deploy deep learning methods in the perception of autonomous vehicles become more widespread. The 2021-2024 period is the most concentrated in the number of publications, reaching 10-11 studies a year, which implies an increased research focus and maturity in technology. The minor drop that is observed in 2025 should be seen as partial indexing instead of a 5-percentage-point activity drop. The trend indicates an increasing academic involvement in the perception of the lane in more complicated operational conditions.

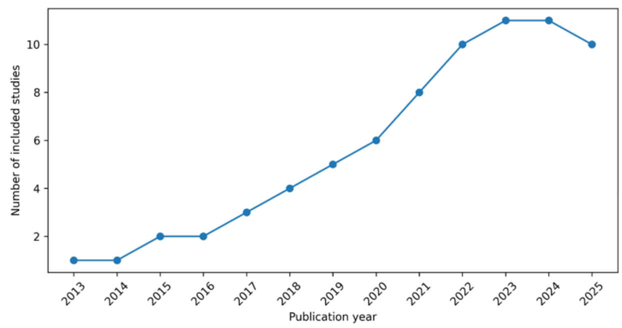

Fig 2. Included studies by publication year (n = 74)

3.3 Methodological distribution of lane detection approaches (n = 74)

The methodological approaches that are used to detect the lane are distributed in the reviewed publications, as displayed in Figure 3. Methods that use convolutional neural networks prevail in the literature, with 38 of the 74 studies using it, and predict the focus of deep learning on the modern lane perception research. Transformer and attention-based methods constitute a significant yet minor segment of the corpus, with 15 articles, which indicate their relative newness and further use. Classical computer vision methods remain in 11 studies, mainly in older studies or under the conditions of small complexity, whereas hybrid methods are based on a combination of 10 studies. This distribution reflects a methodological change towards models based on data as well as pointing to ongoing exploration of hybrid models to trade off rigor and computational efficiency.

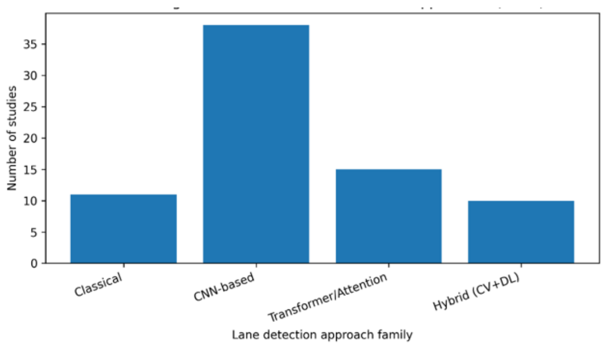

Figure 3. Methodological distribution of lane detection approaches (n = 74)

3.4 Extent of crowd-related considerations in included studies (n = 74)

Figure 4 provides the scope of how the crowd factors have been included in the design/evaluation of the lane detection systems. Most of the (41 out of 74) studies fail to clearly describe the presence of crowds, which implies that crowd-filled settings tend not to be represented exhaustively in experiments. There are crowd effects present implicitly or sparsely in twenty-three studies including, e.g., in the case of partial occlusions or sparsely populated pedestrian situations without explicit place held the dynamics of a crowd. Not only are high-density pedestrian performance assessments conducted in the 10 studies. This allocation indicates that all the plans of autonomous shuttles on the environment of their deployment are transported by a wide disparity in the conditions where lane detection systems are normally tested.

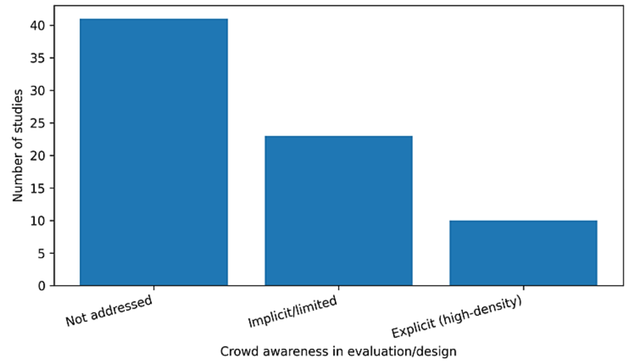

Figure 4. Extent of crowd-related considerations in included studies (n = 74)

3.5 Security and robustness coverage in lane perception literature (n = 74)

Figure 5 provides the readers with the extent of attention towards perception-layer security and robustness in the studies considered. Most of the publications (52 studies) do not have any security or robustness assessment; instead, they provide nominal performance measures. Sixteen works touch upon the aspects of robustness like noise, lighting variation, or environmental perturbation and the threat model is not explicitly defined. A well-defined security threat model that focuses on perception pipelines includes only six studies. This imbalance, although conditional upon escalating use of vision-based perception in safety critical applications, is that relative to the literature on lane detection, there is only limited systematic scrutiny of security weaknesses.

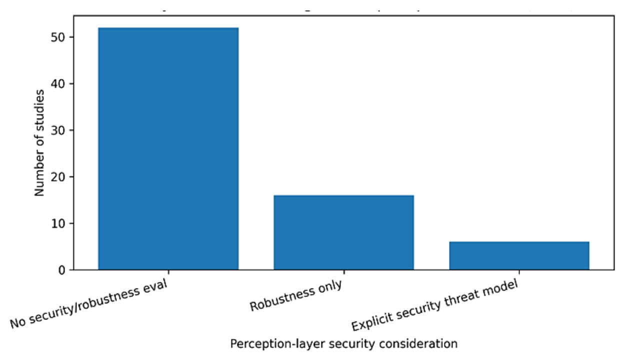

Figure 5. Security and robustness coverage in lane perception literature (n = 74)

3.6 Joint distribution of crowd consideration versus security coverage (n = 74)

Figure 6 illustrates the co-occurrence of crowd awareness and security consideration, which gives the idea of how well these two dimensions are now integrated. The number of studies that do not discuss the topic of crowd density, as well as those that do not involve security or robustness analysis, is the biggest (36), which suggests an overall focus on idealized situations. Articles that partially take crowds into account and leave the issue of security analysis aside are still prevalent, and a very limited number of articles are present that simultaneously discuss the high-density pedestrian situations and explicitly articulate security threats. Interestingly, only three studies belong to the category of explicit crowd consideration and explicitly developed security threat models. This combined study highlights a strong research gap at the convergence of crowd-conscious perception and perception-layer security.

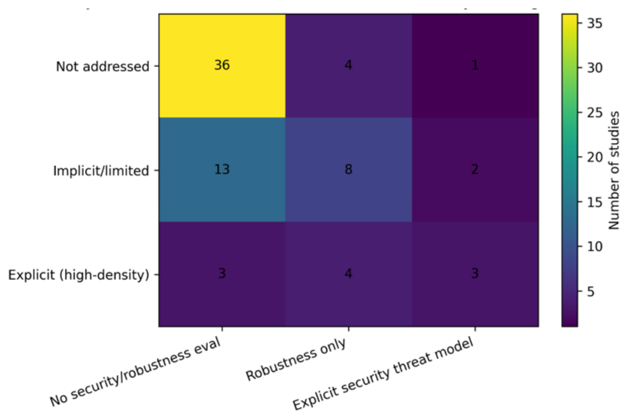

Figure 6. Joint distribution of crowd consideration versus security coverage (n = 74)

3.7 Distribution of evaluation metrics used in included studies (n = 74)

The distribution of the evaluation metrics used in the studies reviewed is demonstrated in Figure 7, and it can be concluded that there is a significant variance in performance assessment practices. The most common reported metrics are the intersection-over-Union metrics which can be found in 26 studies and the accuracy-based metrics that were applied in 18 studies. In 14 studies, the qualitative or visual-only assessment is reported, which means that the subjective assessment is applied in a large proportion of the literature. The metrics of F1-score or precision-recall and lane deviation error are also used comparatively less frequently, with 9 and 7 studies reporting respectively. Such a disparity in metrics used to evaluate it makes it challenging to compare studies directly and makes it clear that there are no standardized metrics to use to evaluate lane detection in challenging settings.

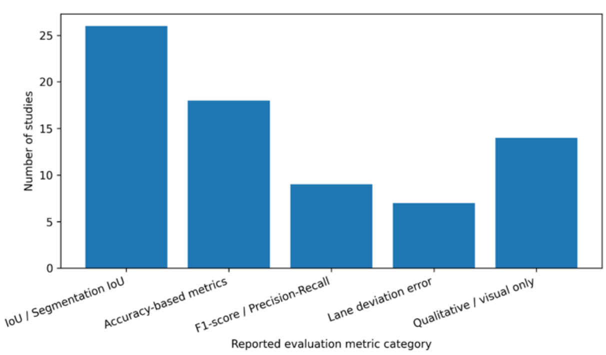

Figure 7. Distribution of evaluation metrics used in included studies (n = 74)

3.8 Sensor modality distribution across included studies (n = 74)

Figure 8 of the paper is a synthesis of the main perception sensor configurations used in the literature reviewed. Monocular camera systems are the most common (such as 31 studies have adopted them) because they are cost-effective and there are numerous vendors. In 17 studies, they use stereo camera systems, which provide higher levels of depth perception, but which increase the complexity of the system. Multi-camera surround multi-camera surround information is found in 14 investigations as more sophisticated perception stacks that enable wider situational perception. 12 of the studies are vision-dominant sensor fusion methods, in which vision data is combined with other non-visual sensors and the vision remains the dominant modality. This distribution highlights the strong dependence on the perception based on vision which directly works against robustness and vulnerability to visual spoofing and negatively to adversarial manipulation.

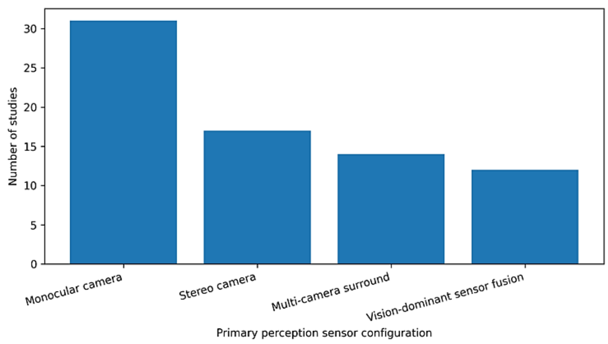

Figure 8. Sensor modality distribution across included studies (n = 74)

The total number of these points proves that the area of methodological sophistication in the lane detection has developed at a fast pace, but the organization of the idea of the crowd dynamics and the security at the perception layer has little systematic attention. The findings drive the requirement to have combined, security conscious, and crowd aware perception systems to autonomous shuttle deployment.

4. Discussion

The findings of this systematic review indicate that the studies on vision-based lane detection in autonomous systems have developed very fast, yet gaps still exist in the field that are especially severe regarding the applications of autonomous shuttle work in the location with pedestrians. Although it is accurate that the overall number of publications has been gradually growing in the last decade as it is a sign of more academic and industry interest, the profile of the distribution of methodologies and evaluation practices is that the algorithms progress of performance has been faster in comparison to an oversized assessment of environmental complexity and perception-layer security. The prevalence of deep learning-based methods, in particular, convolutional neural networks, highlights the efficiency of the data-driven models of perception, which can solve the problem of visual variability and dealing with the semantic image in complex scenes. This trend of increasing the popularity of transformers and attention-based models is also indicative of a transition to models that can model long-range spatial relations, and contextual features, which are needed in unstructured or shared spaces. Nevertheless, the persistence of monocular and vision dominated sensor design points to an innate weakness of the existing systems since visual perception is still susceptible to occlusion, environmental degradation and intentional interference [16-18]. Hybrid and sensor-fusion methods, although not the newcomers, have a low level of utilization since they can be used to increase resilience and robustness. One of the major results of this review is that there is a scant explicit attention that has been given to the phenomenon of crowd in research of lane detection. Irrespective of how more autonomous shuttles are being implemented in environments with a high level of pedestrian population, most of the studies assess the perception performance under conditions that do not fully reflect such complexity. Although studies that explicitly recognize the pedestrian presence are not rare, the effects of the crowds are in many cases considered implicitly, without modeling the density, flow, and interaction patterns that form the pattern [19-21]. This disconnection implies that present evaluation methods might be underestimating both the uncertainty and ambiguity that the evaluator intoxicates with real-world crowd behavior which constrains the external validity of performance improvements.

The review also shows a great deal of attention deficit towards the perception-layer security. A minute portion of the literature directly touches on the security threats or adversarial conditions, and even less research has incorporated security consideration with a crowd-aware assessment. The combined conceptualization of the crowd consideration and security coverage shows that unified concepts are still uncommon so that the two aspects are relatively well researched separately. This disjunction, in particular, is alarming when the inability to perceive could be further accelerated in the settings with a high density of pedestrians because of environmental complexity or intentional interference and could cause subsequent risks in the planning and control modules. The heterogeneity of evaluation practices covered in the reviewed studies is also marked by the high level of variation in the selected performance metrics; it is also characterized by a significant number of cases where qualitative assessment is carried out. Segmentation-based metrics like Intersection OLU are often reported, however, they are inadequate in reflecting safety-critical attributes of shared-space lane perception including boundary ambiguity or a momentary obstruction by pedestrians [22-24]. Lack of unified standards that evaluate the capabilities of detecting the lanes jointly, their robustness and security in the simulated conditions of a crowd is a serious impediment to comparison and advancement of the field. These results imply that the future research should go beyond the focused enhancements in lane detection accuracy and transfer to a complex set of perceptions explicitly considering the complexity of the environment and the risk of adversarial situations. The combination of the principles of crowd modeling and uncertainty estimation and security-conscious design into vision-based lane detection pipelines will be an inevitable next step to the implementation of safer autonomous shuttle deployment. Additionally, establishing standardized assessment plans and common benchmarks that indicate operational conditions characterized by a high volume of pedestrians would make it easier to assess it more rigorously and speed up the alignment towards the implementation of viable solutions [25-27].

5. Conclusion

This research system review investigated the current status of vision-based lane-detecting systems of autonomous shuttle systems in close-crowd settings and specifically the contributions to methodological trends, practices in evaluation, and perception-layer robustness. It can be seen in the analysis that although recent research has made substantial strides around lane perception using state of the art deep learning solutions, the experiments conducted to date analyze the performance under highly simplified scenarios that poorly mirror dense human behavior and the uncertainties that arise therein. There is still little consideration of explicit consideration of crowd dynamics and perception-layer security, and little has been done to look into integrated approaches that look at both dimensions. Besides this, the lack of standardizing evaluation measures and the presence of heterogeneous measures make it difficult to compare studies with each other meaningfully. These results give reason to believe that there is a significant gap between the requirements of the real-world autonomous shuttle deployment and algorithmic development, and therefore the future research presents the necessity to consider holistic, security-sensitive, and crowd-sensitive perception models with the integrated evaluation protocols.

Author Contributions:

Swathi Shree Sangam (Author 1*) conceptualized the study, designed the system architecture, conducted the literature review, developed the methodology, and prepared the original draft of the manuscript.

Vidya Sagar S. D. (Author 2) supervised the research work, contributed to technical guidance and validation, reviewed and edited the manuscript, and provided overall research direction and critical revisions.

Originality and Ethical Standards: The authors declare that this manuscript is original, has not been published previously, and is not under consideration for publication elsewhere. All ethical standards related to academic integrity, proper citation, and responsible research conduct have been strictly followed throughout the study.

Data availability: No new datasets were generated or analyzed during the current study. All information used in this research was obtained from publicly available literature sources and is appropriately cited within the manuscript.

Conflict of Interest: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Similarity checked: The manuscript has been checked for similarity using standard plagiarism detection tools, and the similarity index is within the acceptable limits as per the journal's guidelines.

References

[1] J. Sun, Y. Cao, Q. A. Chen, and Z. M. Mao, "Towards Robust LiDAR-based Perception in Autonomous Driving: General Black-box Adversarial Sensor Attack and Countermeasures," 2020, arXiv. doi: 10.48550/ARXIV.2006.16974.

[2] I. Abood, S. El. Soliman, H. Wenlong, and Z. Ouyang, "Topological Corner State-Based Fano Resonances for Ultrasensitive Sensing," IEEE Sensors Journal, vol. 24, no. 5, pp. 6014–6025, Mar. 2024, doi: 10.1109/JSEN.2023.3349204.

[3] E. Kaur, P. Delir Haghighi, F. M. Cicuttini, and D. M. Urquhart, "Smartphone-Based Ecological Momentary Assessment for Collecting Pain and Function Data for Those with Low Back Pain," Sensors, vol. 22, no. 18, p. 7095, Sept. 2022, doi: 10.3390/s22187095.

[4] R. Ayala and T. K. Mohd, "Sensors in Autonomous Vehicles: A Survey," Journal of Autonomous Vehicles and Systems, vol. 1, no. 3, p. 031003, July 2021, doi: 10.1115/1.4052991.

[5] Monowar Hossain Saikat, Sonjoy Paul Avi, Kazi Toriqul Islam, Tanjida Tahmina, Md Shahriar Abdullah, and Touhid Imam, "Real-Time Vehicle and Lane Detection using Modified OverFeat CNN: A Comprehensive Study on Robustness and Performance in Autonomous Driving," JCSTS, vol. 6, no. 2, pp. 30–36, Apr. 2024, doi: 10.32996/jcsts.2024.6.2.4.

[6] X. Han, G. Xu, Y. Zhou, X. Yang, J. Li, and T. Zhang, "Physical Backdoor Attacks to Lane Detection Systems in Autonomous Driving," 2022, arXiv. doi: 10.48550/ARXIV.2203.00858.

[7] Y. Zhang, A. Carballo, H. Yang, and K. Takeda, "Perception and sensing for autonomous vehicles under adverse weather conditions: A survey," ISPRS Journal of Photogrammetry and Remote Sensing, vol. 196, pp. 146–177, Feb. 2023, doi: 10.1016/j.isprsjprs.2022.12.021.

[8] X. He et al., "Monocular Lane Detection Based on Deep Learning: A Survey," arXiv.org. Accessed: Dec. 16, 2025. [Online]. Available: https://arxiv.org/abs/2411.16316v6

[9] J. Han et al., "Laneformer: Object-aware Row-Column Transformers for Lane Detection," Mar. 18, 2022, arXiv: arXiv:2203.09830. doi: 10.48550/arXiv.2203.09830.

[10] D. Liang, Y.-C. Guo, S.-K. Zhang, T.-J. Mu, and X. Huang, "Lane Detection: A Survey with New Results," J. Comput. Sci. Technol., vol. 35, no. 3, pp. 493–505, May 2020, doi: 10.1007/s11390-020-0476-4.

[11] H.-Y. Lin, C.-K. Chang, and V. L. Tran, "Lane detection networks based on deep neural networks and temporal information," Alexandria Engineering Journal, vol. 98, pp. 10–18, July 2024, doi: 10.1016/j.aej.2024.04.027.

[12] Y. Alahmed, R. Abadla, and M. J. Al Ansari, "Enhancing Safety in Autonomous Vehicles through Advanced AI-Driven Perception and Decision-Making Systems," in 2024 Fifth International Conference on Intelligent Data Science Technologies and Applications (IDSTA), DUBROVNIK, Croatia: IEEE, Sept. 2024, pp. 208–217. doi: 10.1109/IDSTA62194.2024.10746990.

[13] J. A. Pandian, R. Thirunavukarasu, and L. T. Mariappan, "Enhancing Lane detection in autonomous vehicles with multi-armed bandit ensemble learning," Sci Rep, vol. 15, no. 1, p. 3198, Jan. 2025, doi: 10.1038/s41598-025-86743-z.

[14] Y. Etman, Y. Gamal, N. Waleed, A. Gamal, and A. Soltan, "Energy Harvesting Management Unit for Wearable Devices," in 2022 4th Novel Intelligent and Leading Emerging Sciences Conference (NILES), Oct. 2022, pp. 01–05. doi: 10.1109/NILES56402.2022.9942415.

[15] V. Maddiralla and S. Subramanian, "Effective lane detection on complex roads with convolutional attention mechanism in autonomous vehicles," Sci Rep, vol. 14, no. 1, p. 19193, Aug. 2024, doi: 10.1038/s41598-024-70116-z.

[16] X. Luo, Y. Huang, J. Cui, and K. Zheng, "Deep learning-based lane detection for intelligent driving: A comprehensive survey of methods, datasets, challenges and outlooks," Neurocomputing, vol. 650, p. 130795, Oct. 2025, doi: 10.1016/j.neucom.2025.130795.

[17] "Datasets for Lane Detection in Autonomous Driving: A Comprehensive Review." Accessed: Dec. 16, 2025. [Online]. Available: https://arxiv.org/html/2504.08540v1?utm_source=chatgpt.com

[18] A. Giannaros et al., "Autonomous Vehicles: Sophisticated Attacks, Safety Issues, Challenges, Open Topics, Blockchain, and Future Directions," JCP, vol. 3, no. 3, pp. 493–543, Aug. 2023, doi: 10.3390/jcp3030025.

[19] S. Jakobsen, K. Knudsen, and B. Andersen, "Analysis of Sensor Attacks Against Autonomous Vehicles:," in Proceedings of the 8th International Conference on Internet of Things, Big Data and Security, Prague, Czech Republic: SCITEPRESS - Science and Technology Publications, 2023, pp. 131–139. doi: 10.5220/0011841800003482.

[20] Y. Cao et al., "Adversarial Sensor Attack on LiDAR-based Perception in Autonomous Driving," Aug. 20, 2019, arXiv: arXiv:1907.06826. doi: 10.48550/arXiv.1907.06826.

[21] B. Yang, Z. Jin, Y. Cheng, X. Ji, and W. Xu, "Adversarial robustness analysis of LiDAR-included models in autonomous driving," High-Confidence Computing, vol. 4, no. 1, p. 100203, Mar. 2024, doi: 10.1016/j.hcc.2024.100203.

[22] F. Matos, J. Bernardino, J. Durães, and J. Cunha, "A Survey on Sensor Failures in Autonomous Vehicles: Challenges and Solutions," Sensors (Basel), vol. 24, no. 16, p. 5108, Aug. 2024, doi: 10.3390/s24165108.

[23] "A Survey on Adversarial Robustness of LiDAR-based Machine Learning Perception in Autonomous Vehicles." Accessed: Dec. 16, 2025. [Online]. Available: https://arxiv.org/html/2411.13778v1?utm_source=chatgpt.com

[24] Y. Yang, "A Review of Lane Detection in Autonomous Vehicles," JAET, vol. 1, no. 4, pp. 30–36, Dec. 2024, doi: 10.62177/jaet.v1i4.130.

[25] T. Islam, Md. A. Sheakh, A. N. Jui, O. Sharif, and M. Z. Hasan, "A review of cyber attacks on sensors and perception systems in autonomous vehicle," Journal of Economy and Technology, vol. 1, pp. 242–258, Nov. 2023, doi: 10.1016/j.ject.2024.01.002.

[26] S. Lu, Z. Luo, F. Gao, M. Liu, K. Chang, and C. Piao, "A Fast and Robust Lane Detection Method Based on Semantic Segmentation and Optical Flow Estimation," Sensors (Basel), vol. 21, no. 2, p. 400, Jan. 2021, doi: 10.3390/s21020400.

[27] H. Gajjar, S. Sanyal, and M. Shah, "A comprehensive study on lane detecting autonomous car using computer vision," Expert Systems with Applications, vol. 233, p. 120929, Dec. 2023, doi: 10.1016/j.eswa.2023.120929.