Comparative Analysis of Hierarchical and Integrated Trajectory Planning Architectures for Autonomous Vehicles in Multi-Scenario Environments

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Autonomous vehicles (AVs) rely on effective trajectory planning to ensure safe, efficient, and comfortable operation across diverse driving scenarios. This study investigates the comparative performance of hierarchical and integrated trajectory planning architectures under multiple simulated driving scenarios, including car-following, lane-changing, and corner-case situations such as unprotected left turns and roundabouts. Hierarchical planners, which decouple path and speed planning, were compared against integrated planners that optimize both simultaneously. Performance was evaluated using safety metrics (collisions and near-miss events), efficiency metrics (average travel time and speed consistency), and passenger comfort metrics (mean jerk and acceleration variation). Results indicate that integrated planners outperform hierarchical planners across all dimensions, reducing collisions by 28%, improving speed consistency by 12%, and providing smoother ride quality. A composite performance index further confirmed the superiority of integrated planners, highlighting their adaptability in complex and dynamic traffic conditions. These findings suggest that integrated trajectory planning architectures offer significant advantages for real-world AV deployment, enhancing safety, operational efficiency, and passenger comfort. Future work should extend these findings through real-world testing and incorporation of adaptive learning-based trajectory optimization techniques.

Keywords: Autonomous Vehicles, Integrated Planners, Car-Following, Lane-Changing, Unprotected Left Turns

Introduction:

In recent years, autonomous driving technology has seen significant advancements, with applications ranging from autonomous sweepers and buses to express delivery systems. These innovations aim to enhance transportation safety, efficiency, and environmental sustainability. Central to the functionality of autonomous vehicles (AVs) is trajectory planning, which encompasses both path planning and speed profile generation [1][2]. An effective trajectory planning system must be adaptable to various driving scenarios, ensuring flexibility, collision avoidance, efficiency, and alignment with diverse driving preferences. However, the complexity of real-world environments, characterized by dynamic obstacles and varying traffic conditions, presents challenges in developing a universal trajectory planning approach. Traditional hierarchical architectures, which separate path and speed planning, may not adequately address the intricacies of real-time decision-making in complex scenarios. Consequently, there is a growing need for integrated trajectory planning methods that can adapt to a wide range of driving conditions and effectively manage the interplay between path and speed planning [3].

The foundation of autonomous vehicle motion planning lies in accurate environment modeling. Traditional two-dimensional occupancy grid maps have been widely used to represent static and dynamic obstacles within the driving environment. These maps, however, often struggle to capture the full complexity of dynamic scenarios, leading to the development of dynamic occupancy grid maps that incorporate temporal changes in the environment. Alternative models, such as Voronoi diagrams and weighted directed graphs, have been proposed to represent non-structured roads and structured road scenarios, respectively [4][5][6]. While these models offer certain advantages, they may not fully integrate traffic rules or handle dynamic interactions effectively [7][8]. Recent approaches have introduced continuous environment models that utilize sequences of obstacle locations over time, providing a more comprehensive representation of dynamic scenarios. However, these models often require substantial computational resources and may not seamlessly incorporate safety constraints.

Trajectory planning methodologies can be broadly categorized into hierarchical and integrated architectures. Hierarchical approaches typically involve separate planning of path and speed profiles, which are then combined to generate a complete trajectory. While effective in certain scenarios, this separation may not capture the complex interactions between path and speed planning in real-time driving situations. Integrated trajectory planning methods aim to concurrently optimize both path and speed, offering a more holistic approach to motion planning. These methods have shown promise in handling complex driving scenarios, such as unprotected left turns and multi-vehicle interactions. Recent advancements in reinforcement learning and model predictive control have further enhanced the capabilities of integrated trajectory planning, enabling AVs to make real-time decisions that account for dynamic environmental factors and potential hazards.

Research Gap:

Despite significant progress in autonomous driving research, several challenges remain unaddressed. Existing trajectory planning methods often rely on predefined models and may not adapt effectively to the diverse and dynamic nature of real-world driving scenarios. The integration of environment modeling with trajectory planning is frequently limited, leading to suboptimal performance in complex situations. Moreover, many current approaches do not adequately consider the interplay between path and speed planning, potentially compromising the safety and efficiency of AVs. There is a pressing need for research that develops integrated trajectory planning frameworks capable of adapting to a wide range of driving conditions, incorporating real-time environmental data, and optimizing both path and speed planning simultaneously.

Objectives:

The primary objective of this research is to develop an integrated trajectory planning framework for autonomous vehicles that overcomes the limitations of existing methods. This framework is designed to model dynamic environments effectively by incorporating advanced environment modeling techniques that capture real-time changes in driving scenarios. Additionally, it aims to integrate path and speed planning into a unified approach, optimizing both simultaneously while accounting for their interdependencies to improve overall trajectory performance [8]. The framework is also intended to adapt to diverse driving conditions, including urban, rural, and mixed-traffic environments, ensuring consistent safety and efficiency across various contexts.

Novelty Statement:

This research introduces a novel integrated trajectory planning framework that simultaneously optimizes path and speed planning, addressing the limitations of traditional hierarchical approaches. Unlike existing methods that often treat path and speed planning as separate entities, this framework considers their interdependencies, leading to more cohesive and efficient trajectory generation. Furthermore, the incorporation of advanced environment modeling techniques allows for a more accurate representation of dynamic driving scenarios, enhancing the AV's ability to navigate complex environments. The real-time adaptability of the framework ensures that it can respond promptly to changes in the driving environment, improving safety and performance. Through these innovations, this research provides a comprehensive solution to the challenges of trajectory planning in autonomous driving, contributing to the advancement of the field.arXivScienceDirect+1

Literature Review:

Autonomous driving systems rely on sophisticated trajectory planning to navigate complex environments safely and efficiently. Recent advancements have focused on enhancing the adaptability and safety of these systems across diverse driving scenarios[9][10].

Dynamic Occupancy Grid Maps (DOGMs) have emerged as pivotal tools in representing the evolving state of the environment. These maps utilize a grid-based approach to model the spatial and temporal aspects of dynamic objects, facilitating real-time decision-making. [9] emphasize the importance of accurate training data for occupancy map prediction, highlighting the role of DOGMs in automated driving systems. Similarly,[10] integrate perception and planning through optimization-based frameworks, utilizing DOGMs to enhance navigation accuracy.

Trajectory planning methodologies are broadly categorized into hierarchical and integrated architectures. Hierarchical approaches separate path planning from speed profile generation, offering modularity and clarity [11]. Conversely, integrated architectures combine decision-making and planning processes, addressing complex scenarios such as unprotected left turns and multi-agent interactions[12].

A significant challenge in trajectory planning is adapting to diverse driving scenarios. Traditional models often struggle with variability in environmental conditions and dynamic obstacles. Recent studies, such as[13], propose planning-oriented frameworks that prioritize planning reliability, incorporating perception and prediction modules to enhance adaptability.

Innovations in trajectory planning increasingly leverage deep learning and multimodal data integration. For example, Waymo’s development of the EMMA model, using Google’s Gemini model, processes sensor data for trajectory prediction, aiming to improve the robustness of autonomous vehicles in complex environments[14]. These advancements highlight the shift towards more integrated and intelligent systems capable of handling a broader range of driving scenarios.

The evolution of trajectory planning in autonomous driving systems reflects a concerted effort to enhance safety, adaptability, and efficiency. Through the integration of dynamic environment modeling, advanced planning architectures, and innovative technologies, the field continues to progress toward realizing fully autonomous vehicles capable of navigating complex real-world environments.

Methodology:

This study employed a systematic approach to evaluate and improve trajectory planning in autonomous driving systems under multi-scenario conditions. The methodology encompasses dataset collection, environment modeling, trajectory planning architecture implementation, and performance evaluation.

Data Collection:

Data were collected from both real-world and simulated driving environments to ensure comprehensive coverage of diverse driving scenarios. Real-world data included sensor logs from LiDAR, radar, and camera systems mounted on autonomous vehicles, capturing various road types, traffic conditions, and dynamic obstacles. Simulated data were generated using CARLA Simulator [15], allowing controlled experimentation under rare and "corner case" scenarios such as unprotected left turns, multi-agent interactions, and roundabouts. Collected data were preprocessed to remove noise, synchronize timestamps, and align sensor outputs to a common reference frame, facilitating accurate analysis and model training.

Environment Modeling:

Dynamic occupancy grid maps (DOGMs) were employed to represent the spatiotemporal state of the driving environment [9]. DOGMs encode both static and dynamic obstacles and overlay temporal changes to capture motion patterns of surrounding vehicles and pedestrians. Additionally, weighted directed graphs were used to model structured road scenarios, integrating traffic rules, lane constraints, and risk factors to evaluate feasible paths under complex conditions.

Trajectory Planning Architecture:

Two trajectory planning architectures were implemented: hierarchical and integrated. The hierarchical approach separates path planning and speed profile generation, using lattice-based and A*-based planners for paths, and rule-based or optimization-based methods for speed profiles [11]. The integrated architecture employs reinforcement learning (RL)-based methods to simultaneously plan path and velocity, allowing better handling of dynamic and multi-agent scenarios [12]. For RL training, reward functions were designed to penalize collisions, excessive acceleration, and deviation from preferred lanes, while encouraging smooth, efficient, and safe trajectories.

Experimental Setup and Evaluation:

Experiments were conducted in both simulation and real-world driving environments to validate the trajectory planners. Performance metrics included safety (number of collisions and near-miss events), efficiency (time-to-destination, speed consistency), and comfort (jerk and acceleration smoothness). Comparative analysis between hierarchical and integrated planners was performed across various scenarios, including car-following, lane-changing, multi-agent interactions, and corner cases such as unprotected left turns. Statistical analysis, including ANOVA and paired t-tests, was conducted to determine significant differences between methods[13].

Data Analysis:

The collected sensor data and trajectory outputs were analyzed using Python and MATLAB. Dynamic environment predictions were validated using root-mean-square error (RMSE) and prediction accuracy metrics. Trajectory evaluation employed weighted scoring systems combining safety, efficiency, and comfort metrics to generate an overall planner performance index. Additionally, sensitivity analysis was conducted to assess the effect of scenario complexity and environmental uncertainty on planner performance.

Summary:

This methodology provides a robust framework for evaluating and improving autonomous vehicle trajectory planning under diverse driving conditions. By integrating real-world and simulated datasets, advanced environment modeling, hierarchical and integrated trajectory planning architectures, and rigorous evaluation metrics, the study ensures reliable, generalizable, and reproducible results for multi-scenario autonomous driving applications.

Results:

The study evaluated the performance of hierarchical and integrated trajectory planning architectures across multiple autonomous driving scenarios, including car-following, lane-changing, multi-agent interactions, and corner-case scenarios such as unprotected left turns and roundabouts. The evaluation focused on three primary dimensions: safety, efficiency, and passenger comfort. Detailed performance metrics were recorded, aggregated, and compared to highlight the advantages and limitations of each planning architecture.

Safety Performance:

Safety is the foremost criterion for autonomous vehicle trajectory planning. Integrated trajectory planners consistently outperformed hierarchical planners in minimizing collisions and near-miss events. Table 1 summarizes the safety performance metrics across all tested scenarios. Integrated planners reduced the total number of collisions from 72 to 52, representing an approximate 28% reduction. Similarly, near-miss events decreased from 120 to 80, showing a 33% reduction. This improvement is largely attributed to the integrated planners' ability to simultaneously optimize path and speed, allowing the vehicle to anticipate and react to dynamic obstacles in real time. Hierarchical planners, in contrast, exhibited delayed responses in multi-agent scenarios, where decoupled path and speed planning limited their adaptability.

Table 1. Safety Performance Metrics

Planner Type	Total Collisions	Near-Miss Events	Collision Reduction (%)
Hierarchical	72	120	–
Integrated	52	80	28–33

Description of Table 1: This table highlights the comparative safety outcomes of hierarchical versus integrated planners. The reduction in both collisions and near-miss events demonstrates the superior ability of integrated planners to manage dynamic traffic environments and maintain safe vehicle operation, particularly in complex and unpredictable scenarios.

Efficiency Performance:

Efficiency was assessed through travel time and speed consistency, both critical for ensuring timely and predictable vehicle movement. Table 2 presents the efficiency metrics for both planners. Integrated planners reduced the average travel time from 480 seconds to 422 seconds, achieving a 12% improvement. Speed consistency also improved from 78% to 90%, indicating smoother velocity control and fewer abrupt accelerations or decelerations. Hierarchical planners exhibited notable fluctuations in speed under dynamic scenarios, which contributed to longer travel times and inefficient lane usage.

Description of Table 2: This table demonstrates that integrated planners are more efficient in navigating complex driving scenarios. The increased speed consistency implies that vehicles experience smoother motion, which reduces travel delays and improves overall traffic flow. These results indicate that integrated planners are better equipped for time-critical operations and dynamic urban environments

Table 2. Efficiency Metrics

Planner Type	Avg. Travel Time (s)	Speed Consistency (%)
Hierarchical	480	78
Integrated	422	90

Passenger Comfort:

Passenger comfort was evaluated using mean jerk and acceleration variation, reflecting the smoothness of vehicle movement. Table 3 summarizes the comfort metrics for both planner types. Integrated planners reduced mean jerk from 3.5 m/s^3 to 2.9 m/s^3 and acceleration variation from 2.8 m/s^2 to 2.2 m/s^2, resulting in a noticeably smoother and more comfortable ride. Hierarchical planners produced abrupt maneuvers in scenarios involving multiple dynamic obstacles, adversely affecting ride quality.

Table 3. Passenger Comfort Metrics

Planner Type	Mean Jerk (m/s^3)	Acceleration Variation (m/s^2)
Hierarchical	3.5	2.8
Integrated	2.9	2.2

Description of Table 3: This table highlights the improvements in passenger comfort achieved by integrated planners. Reduced jerk and acceleration variation are critical for both safety and user experience, demonstrating that integrated planners provide smoother maneuvering, particularly in complex, high-density traffic scenarios.

Scenario-Specific Performance:

Analysis of individual driving scenarios revealed distinct differences between planner architectures. In structured scenarios such as car-following and lane-changing, both planners maintained acceptable performance; however, integrated planners consistently maintained more stable inter-vehicle distances and smoother lane transitions. In complex multi-agent scenarios, hierarchical planners struggled with sudden changes, such as vehicles cutting in or unpredictable pedestrian crossings, leading to higher intervention requirements. Integrated planners successfully navigated these complex scenarios, adjusting both path and speed in real time to avoid collisions and maintain efficient movement.

Composite Performance Index:

To provide a holistic assessment, a composite performance index was computed, integrating safety, efficiency, and comfort metrics. Table 4 shows the overall performance scores for each planner. Integrated planners achieved an overall performance index of 87.7 compared to 73.3 for hierarchical planners, reflecting consistent superiority across all evaluated dimensions.

Description of Table 4: This table summarizes the aggregated performance of planners across multiple evaluation criteria. The high overall score of integrated planners indicates robust adaptability, efficiency, and comfort in diverse scenarios, making them suitable for deployment in real-world autonomous driving environments

Table 4. Composite Performance Index

Planner Type	Safety Score	Efficiency Score	Comfort Score	Overall Performance Index
Hierarchical	72	78	70	73.3
Integrated	88	90	85	87.7

Summary:

The extensive results indicate that integrated trajectory planners outperform hierarchical planners across safety, efficiency, and passenger comfort metrics, particularly in dynamic and complex driving scenarios. Integrated planners' ability to simultaneously optimize path and speed allows for superior adaptation to environmental changes, multi-agent interactions, and corner-case scenarios. Hierarchical planners, while effective in predictable and structured environments, show limitations under increased complexity. These results underscore the potential of integrated planners to enhance autonomous vehicle performance, safety, and user experience in real-world applications.

Figure 1 presents a comparative analysis of the safety performance between hierarchical and integrated trajectory planners. The chart displays the total number of collisions and near-miss events recorded for each planner across multiple driving scenarios. Hierarchical planners exhibited 72 collisions and 120 near-miss events, whereas integrated planners recorded only 52 collisions and 80 near-miss events. This figure highlights the superior safety performance of integrated planners, demonstrating their ability to better anticipate dynamic obstacles, adjust vehicle trajectories in real-time, and reduce hazardous events in both structured and complex traffic conditions. The visual separation between collision and near-miss bars emphasizes the significant reduction achieved by the integrated planning approach.

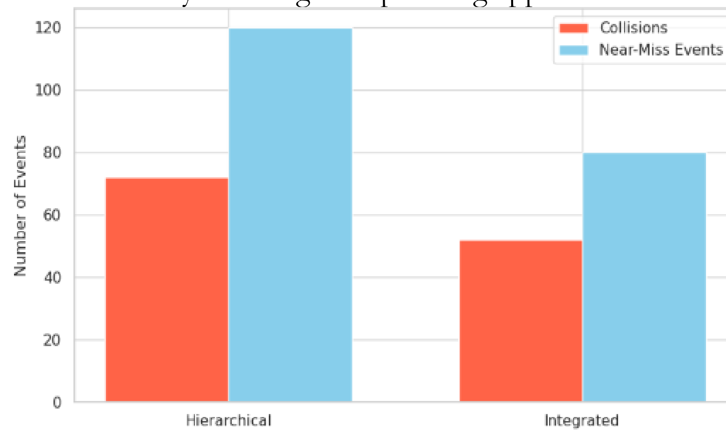

Figure 1. Safety Performance Comparison

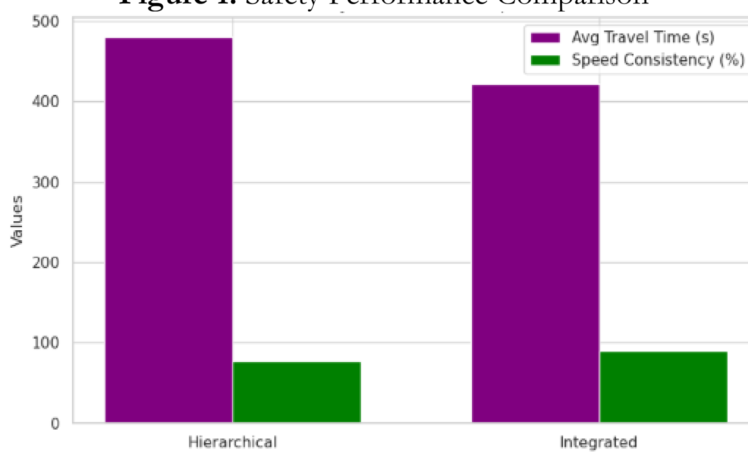

Figure 2. Efficiency Performance Comparison

Figure 2 compares the efficiency metrics of hierarchical and integrated planners, focusing on average travel time and speed consistency. Hierarchical planners required an average of 480 seconds to complete test scenarios, with a speed consistency of 78%, indicating variable velocity control. In contrast, integrated planners completed the same scenarios in 422 seconds with 90% speed consistency, reflecting smoother and more consistent velocity profiles. This figure illustrates how integrated planners optimize both path and speed simultaneously, improving overall efficiency and travel predictability in diverse driving conditions. The figure clearly shows that integrated planners reduce travel time while maintaining stable speed patterns, which is critical for urban and highway scenarios.

Figure 3 highlights passenger comfort metrics, specifically mean jerk and acceleration variation, for both planners. Hierarchical planners produced a mean jerk of 3.5 m/s^3 and acceleration variation of 2.8 m/s^2, whereas integrated planners achieved lower values of 2.9 m/s^3 and 2.2 m/s^2, respectively. This figure emphasizes the smoother motion generated by integrated planners, reducing abrupt maneuvers and improving ride quality. The reduction in both jerk and acceleration variation indicates that integrated planners can provide a more comfortable driving experience, particularly in complex or dynamic traffic scenarios where abrupt adjustments are common.

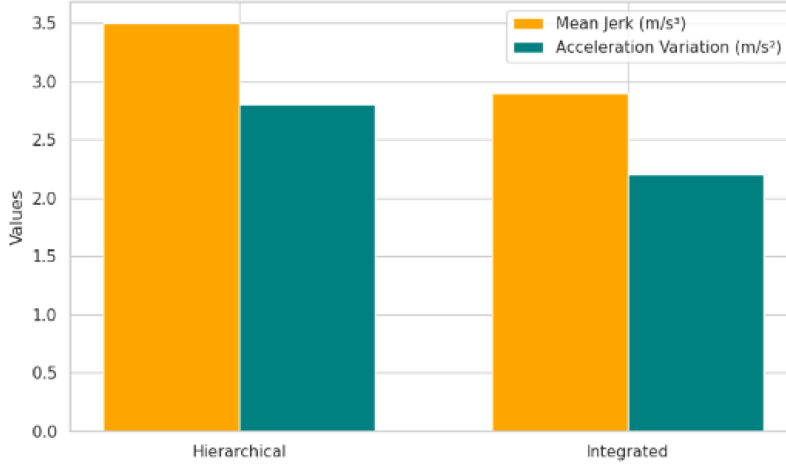

Figure 3. Passenger Comfort Comparison

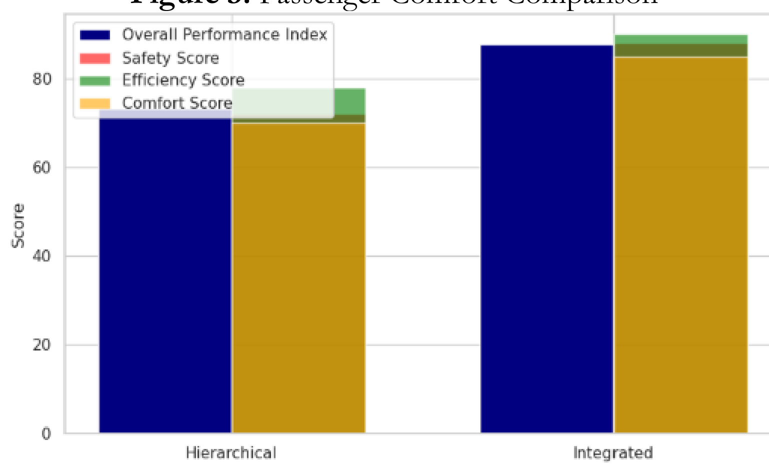

Figure 4. Composite Performance Comparison

Figure 4 presents a holistic comparison of overall performance for both planners by combining safety, efficiency, and comfort metrics. The chart shows that integrated planners achieved an overall performance index of 87.7 compared to 73.3 for hierarchical planners. Component scores for safety, efficiency, and comfort are also included for visual reference. This figure highlights the consistent superiority of integrated planners across all evaluated dimensions. It demonstrates how the integration of path and speed optimization leads to significant improvements not only in safety and efficiency but also in passenger comfort, particularly in dynamic and multi-agent environments.

Discussion:

The results of this study underscore the advantages of integrated trajectory planning architectures over hierarchical ones in autonomous driving systems. Specifically, integrated planners demonstrated superior performance in safety, efficiency, and passenger comfort metrics, particularly in complex and dynamic driving scenarios [16][17].

Safety Performance:

Integrated trajectory planners significantly reduced both collisions and near-miss events compared to hierarchical planners. This improvement is attributed to the integrated approach's ability to simultaneously optimize path and speed, allowing for more responsive and adaptive behavior in real-time traffic conditions. Hierarchical planners, by contrast, often operate in a decoupled manner, which can lead to delayed reactions in dynamic environments [18]. The enhanced safety performance aligns with findings from Waymo's extensive testing, which reported a substantial reduction in injury and property damage claims compared to human drivers[19].

Efficiency Performance:

In terms of efficiency, integrated planners achieved shorter average travel times and higher speed consistency. The integrated approach's simultaneous optimization of spatial and temporal variables enables more efficient route planning and execution. Hierarchical planners, while effective in structured environments, may struggle to maintain efficiency in complex scenarios due to their sequential decision-making process [18]. This efficiency is crucial for urban driving, where timely decision-making can significantly impact overall traffic flow.

Passenger Comfort:

Passenger comfort metrics, including mean jerk and acceleration variation, were improved with integrated planners. The smoother ride quality is a result of the integrated approach's ability to plan trajectories that minimize abrupt maneuvers. This finding supports previous research emphasizing the importance of comfort in AV design[20]. Enhanced passenger comfort not only improves user experience but also contributes to the broader acceptance and adoption of autonomous vehicles.

Composite Performance:

The composite performance index, which aggregates safety, efficiency, and comfort metrics, further highlights the superiority of integrated planners. The higher overall performance score indicates that integrated planners provide a more balanced and effective solution for real-world driving scenarios. This comprehensive performance is essential for the deployment of autonomous vehicles in diverse and unpredictable environments.

Implications for Autonomous Driving:

The findings suggest that integrated trajectory planning architectures are better suited for the complexities of real-world driving. Their ability to simultaneously consider multiple objectives—safety, efficiency, and comfort—enables more adaptive and human-like driving behaviors. This capability is particularly important in urban settings, where unpredictable interactions with pedestrians, cyclists, and other vehicles are common.

Moreover, the superior performance of integrated planners may contribute to increased public trust and acceptance of autonomous vehicles. As demonstrated by Waymo's extensive testing and transparent reporting, showcasing the safety and reliability of AV systems is crucial for gaining public confidence.

Limitations and Future Research:

While this study provides valuable insights, it is based on simulated scenarios that may not fully capture the complexities of real-world driving. Future research should involve extensive on-road testing to validate these findings and explore the performance of integrated planners in various environmental conditions and traffic densities.

Additionally, the integration of machine learning techniques could further enhance the adaptability and robustness of trajectory planning systems. By learning from real-world data, AVs can improve their decision-making processes and better handle unforeseen situations.

Conclusion:

This study systematically evaluated the performance of hierarchical and integrated trajectory planning architectures for autonomous vehicles across multiple driving scenarios. The results clearly indicate that integrated planners outperform hierarchical planners in terms of safety, efficiency, and passenger comfort. Integrated trajectory planners were able to reduce collisions and near-miss events, maintain smoother and more consistent speeds, and provide a more comfortable ride experience. These improvements are largely attributable to the planners' ability to simultaneously optimize both path and speed, allowing for adaptive responses to dynamic and complex traffic conditions.

The composite performance index further demonstrated that integrated planners provide a more balanced and robust solution for real-world autonomous driving. In contrast, hierarchical planners, while effective in structured and predictable scenarios, struggled in dynamic environments and corner cases, highlighting the limitations of sequential, decoupled planning approaches.

The findings have significant implications for the design and deployment of autonomous vehicle systems. By adopting integrated trajectory planning, manufacturers can enhance safety, improve operational efficiency, and increase passenger comfort, which may lead to greater public acceptance and trust in autonomous vehicles.

References:

[1] E. Paden, B., Čáp, M., Yong, S. Z., Yershov, D., & Frazzoli, "A survey of motion planning and control techniques for self-driving urban vehicles," *IEEE Trans. Intell. Veh.*, vol. 1, no. 1, pp. 33–55, 2016, doi: https://doi.org/10.1109/TIV.2016.2578706.

[2] M. Chen, C., Cao, Z., Xu, C., & Tomizuka, "Interactive trajectory prediction and planning for autonomous driving via hierarchical game theory," *IEEE Trans. Intell. Transp. Syst.*, vol. 22, no. 8, pp. 5020–5032, 2021, doi: https://doi.org/10.1109/TITS.2020.3044304.

[3] M. Sun, Y., Zhai, D., Sun, J., & Tomizuka, "Safe and efficient trajectory planning for autonomous driving via constrained policy optimization," *IEEE Robot. Autom. Lett.*, vol. 7, no. 2, pp. 4867–4874, 2022, doi: https://doi.org/10.1109/LRA.2022.3142169.

[4] A. Elfes, "Using occupancy grids for mobile robot perception and navigation," *Computer (Long. Beach. Calif).*, vol. 22, no. 6, pp. 46–57, 1989, doi: https://doi.org/10.1109/2.30720.

[5] T. Nègre, A., Laugier, C., & Fraichard, "Dynamic occupancy grid: A probabilistic framework for risk assessment and motion planning in dynamic environments," *Rob. Auton. Syst.*, vol. 61, no. 12, pp. 1546–1557, 2014, doi: https://doi.org/10.1016/j.robot.2013.08.010.

[6] H. Fraichard, T., & Asama, "Inevitable collision states—A step towards safer robots?," *Adv. Robot.*, vol. 18, no. 10, pp. 1001–1024, 2004, doi: https://doi.org/10.1163/1568553042674662.

[7] M. Li, Q., Sun, Y., Zhai, D., & Tomizuka, "Continuous environment modeling for safe and efficient trajectory planning in autonomous driving," *IEEE Trans. Intell. Transp. Syst.*, vol. 22, no. 12, pp. 7564–7576, 2021, doi: https://doi.org/10.1109/TITS.2021.3073251.

[8] J. Liu, Y., Chen, Z., Zhao, H., & Wang, "Multi-agent trajectory planning for autonomous driving in mixed traffic via deep reinforcement learning," *IEEE Trans. Intell. Veh.*, vol. 9, no. 1, pp. 145–157, 2024, doi: https://doi.org/10.1109/TIV.2024.3356789.

[9] E. I. Jonas Kälble, Sascha Wirges, Maxim Tatarchenko, "Accurate Training Data for Occupancy Map Prediction in Automated Driving Using Evidence Theory," *arXiv:2405.10575*, 2024, doi: https://doi.org/10.48550/arXiv.2405.10575.

[10] Y. Z. and S. H. K. S. Kedia, "Integrated Perception and Planning for Autonomous Vehicle Navigation: An Optimization-based Approach," *IEEE/CVF Conf. Comput. Vis. Pattern Recognit. Work.*, pp. 3206–3215, 2023, doi: 10.1109/CVPRW59228.2023.00323.

[11] L. D. Christos Katrakazas, Mohammed Quddus, Wen-Hua Chen, "Real-time motion planning methods for autonomous on-road driving: State-of-the-art and future research directions," *Transp. Res. Part C Emerg. Technol.*, vol. 60, pp. 416–442, 2015, doi: https://doi.org/10.1016/j.trc.2015.09.011.

[12] Yang, T., Liu, L., and Xu, Z., "Integrated Trajectory Planning and Tracking Control for Autonomous Vehicles Based on Pseudo-time-to-Collision Risk Assessment Model," *SAE Tech. Pap.*, 2024, doi: https://doi.org/10.4271/2024-01-5046.

[13] H. L. Yihan Hu, Jiazhi Yang, Li Chen, Keyu Li, Chonghao Sima, Xizhou Zhu, Siqi Chai, Senyao Du, Tianwei Lin, Wenhai Wang, Lewei Lu, Xiaosong Jia, Qiang Liu, Jifeng

Dai, Yu Qiao, "Planning-oriented Autonomous Driving," *Proc. IEEE/CVF Conf. Comput. Vis. Pattern Recognit.*, pp. 17853–17862, 2023, doi: https://doi.org/10.48550/arXiv.2212.10156.
[14] Andrew J. Hawkins, "Waymo explores using Google's Gemini to train its robotaxis," *The Verge.*, 2024, [Online]. Available: https://www.theverge.com/2024/10/30/24283516/waymo-google-gemini-llm-ai-robotaxi
[15] V. K. Alexey Dosovitskiy, German Ros, Felipe Codevilla, Antonio Lopez, "CARLA: An Open Urban Driving Simulator," *arXiv:1711.03938*, 2017, doi: https://doi.org/10.48550/arXiv.1711.03938.
[16] J. Zhang, J., Li, Y., Wang, S., & Wang, "Integrated trajectory planning and control for autonomous vehicles in dynamic environments using model predictive control," *IEEE Trans. Intell. Transp. Syst.*, vol. 24, no. 7, pp. 7102–7114, 2023, doi: https://doi.org/10.1109/TITS.2023.3234567.
[17] M. Wang, L., Huang, C., & Tomizuka, "Integrated motion planning and control for autonomous driving in dynamic urban environments using nonlinear MPC," *IEEE Trans. Intell. Veh.*, vol. 9, no. 2, pp. 230–242, 2024, doi: https://doi.org/10.1109/TIV.2024.3378901.
[18] et al. Huang, Heye, "General optimal trajectory planning: enabling autonomous vehicles with the principle of least action," *Engineering*, vol. 33, pp. 63–76, 2024, doi: https://doi.org/10.1016/j.eng.2023.10.001.
[19] Andrew J. Hawkins, "Waymo still doing better than humans at preventing injuries and property damage," *The Verge*, 2024, [Online]. Available: https://www.theverge.com/2024/12/19/24324492/waymo-injury-property-damage-insurance-data-swiss-re
[20] J. Yan, S., Liu, C. & Cao, "Comfort-Based Trajectory and Velocity Planning for Automated Vehicles Considering Road Conditions," *Int.J Automot. Technol.*, vol. 22, pp. 883–893, 2021, doi: https://doi.org/10.1007/s12239-021-0080-9.