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A Review of Uncertainty Management in Vehicular Platooning: Safety and Efficiency in Opportunistic Transport Environments

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Abstract—In recent years, vehicular platooning systems have gained significant attention due to their potential to enhance road safety, fuel efficiency, and traffic flow. However, these systems face several challenges, including external disturbances, communication uncertainties, cyber-attacks, and heterogeneous vehicle dynamics. This paper presents a comprehensive review of state-of-the-art control strategies designed to address these challenges in vehicular platooning systems. The focus is on various control approaches such as adaptive control, model predictive control, and robust control, which offer solutions for maintaining platoon stability despite disturbances and communication failures. We also discuss event-triggered mechanisms, which aim to reduce communication load, and cybersecurity-focused protocols that protect platooning systems from attacks. A comparison of these strategies is presented based on several criteria. The paper concludes with recommendations for future research directions to improve the robustness and real-time applicability of vehicular platooning systems in increasingly dynamic and uncertain environments.

Index Terms—Uncertainty, Adaptive Control, Safety, Vehicular platooning.

I. INTRODUCTION

Vehicular platooning systems, a key component of intelligent transportation systems, have emerged as a promising solution to improve traffic flow, fuel efficiency, and road safety [1]. In a platoon, multiple vehicles travel closely together, coordinated by a

lead vehicle, which significantly reduces aerodynamic drag, improves fuel efficiency, and allows for tighter vehicle spacing without compromising safety. The benefits of platooning are numerous; however, they also introduce new challenges related to vehicle coordination, communication, control, and cybersecurity. These challenges become particularly acute in the presence of uncertainties such as external disturbances, varying communication quality, and heterogeneous vehicle dynamics.

Control strategies for vehicular platoons must address multiple issues simultaneously, including maintaining string stability, ensuring vehicle synchronization, and mitigating the effects of external disturbances such as wind or road friction. Additionally, vehicle-to-vehicle and vehicle-to-everything communication links are critical to platoon coordination but are vulnerable to communication delays, packet losses, and cyber-attacks. Therefore, resilient and robust control approaches that can handle these uncertainties are essential for ensuring the safe and efficient operation of platoons in real-world conditions.

Over the years, various control approaches have been developed to address these challenges. Among them, adaptive control and model predictive control are widely adopted for their ability to manage uncertainty and dynamically changing environments.

Adaptive control strategies modify control parameters in real-time based on the changing conditions of the vehicles and the environment. This is particularly useful in heterogeneous platoons, where each vehicle may have different dynamics and control capabilities. Adaptive control techniques are designed to handle nonlinearities and ensure the stability of the entire platoon under uncertain conditions. Model predictive control has gained prominence in vehicular platoon control, allowing the system to optimize the future behavior of the vehicles while respecting safety and performance constraints.

Despite the advantages of adaptive control and model predictive control, there are still several challenges that need to be addressed. The computational complexity of these methods can limit their real-time applicability, particularly in larger networks. For example, the neural network approximations used in some adaptive control strategies introduce computational overhead, which may hinder their performance in real-time applications. Additionally, model predictive control frameworks often require accurate initial model parameters, and significant deviations from these parameters can affect the overall control performance.

To address these limitations, recent research has explored the use of event-triggered control mechanisms. Event-triggered control reduces the frequency of control updates by activating the control action only when specific conditions are met, thus lowering the communication burden between vehicles. This is particularly beneficial in large-scale platoons where continuous communication may lead to network congestion and delays. Event-triggered control offers a trade-off between communication efficiency and control performance, ensuring that the control system is only updated when necessary, which helps maintain stability while reducing communication load.

Another critical aspect of vehicular platooning systems is cybersecurity. As these systems rely heavily on communication, they are susceptible to cyber-attacks such as denial of service attacks, where malicious actors disrupt communication between vehicles, potentially leading to unsafe conditions. Cybersecurity measures must be integrated

into control strategies to ensure the resilience of platooning systems in the face of such threats. For example, robust control strategies that incorporate cyber-physical security mechanisms can help mitigate the effects of cyber-attacks, ensuring that the platoon remains stable and avoids collisions even when communication is compromised.

In addition to control and cybersecurity, energy efficiency is becoming increasingly important in the design of vehicular platooning systems. By optimizing the speed and distance between vehicles, platooning has the potential to significantly reduce fuel consumption. However, achieving energy efficiency requires sophisticated control strategies that can balance fuel savings with maintaining safe inter-vehicle distances and ensuring platoon stability. Some recent works have proposed hybrid control strategies that integrate both energy management systems and stability control to address this challenge.

The objective of this paper is to provide a comprehensive review of the current state of the art in vehicular platoon control strategies, with a focus on adaptive control, model predictive control, resilient and robust control, event-triggered mechanisms, and cybersecurity. We also present a comparison of these strategies based on key criteria such as scalability, real-time applicability, and energy efficiency. By examining these approaches, we aim to identify the strengths and weaknesses of each method.

This paper is organized as follows. Section II presents a detailed review of the studied solutions, discussing the various approaches used to handle uncertainties, disturbances, and communication issues. Section III offers a comparison of the reviewed methods based on several performance criteria. Finally, Section IV concludes the paper and offering perspectives for future work.

II. STATE OF THE ART

In the realm of vehicular platooning, several approaches have been developed to handle the challenges posed by heterogeneity and uncertainties in communication environments. This section presents a classification of state-of-the-art solutions across various dimensions, including control approaches,

communication resilience, event-triggered strategies, and disturbance management, with a focus on improving vehicular platoon stability, efficiency, and security. The reviewed strategies are illustrated in the taxonomy of Figure 1.

A. Control Approaches for Heterogeneous Systems

Control strategies for heterogeneous and uncertain vehicular platoons aim to ensure that vehicles with varying dynamics can maintain coordinated movement, even under external disturbances or communication uncertainties. Two key approaches in this domain are adaptive control and model predictive control, both of which provide robust solutions for maintaining platoon formation while mitigating the effects of uncertainty and dynamic disturbances.

1) *Adaptive Control*: Adaptive control techniques provide solutions for dealing with the complex, nonlinear dynamics often found in heterogeneous platoons. These approaches use real-time data to adapt the control parameters, ensuring stability despite changes in vehicle dynamics or environmental uncertainties. Recent advancements in this area have leveraged neural network approximations and distributed control laws to ensure synchronization between vehicles, even when direct communication is lost.

Arevalo-Castiblanco et al. [2] have proposed an adaptive control approach for synchronizing heterogeneous vehicle platoons under unstructured uncertainty. They introduce a distributed control law that eliminates nonlinear input uncertainties by employing neural network approximations. Additionally, the work incorporates an input estimator to handle communication loss between agents, ensuring that proper control is maintained even in the absence of direct input communication between vehicles. The method's effectiveness is demonstrated through simulations, which show that all closed-loop signals remain bounded under various operational scenarios. The primary advantage of this work lies in its ability to manage both heterogeneous vehicle dynamics and nonlinear input disturbances. The use of neural network approximations allows the system to estimate and cancel out structured uncertainties ef-

ficiently. Moreover, the input estimator ensures that vehicle synchronization is maintained even when communication between agents is interrupted. One potential drawback is the computational complexity introduced by the neural network approximation and distributed input estimation, which may present challenges for real-time applications in larger networks.

2) *Model Predictive Control*: Model predictive control has become a popular framework for managing the complexities of mixed vehicle platoons, where both autonomous and human-driven vehicles coexist. Model predictive control-based techniques focus on optimizing future vehicle trajectories while accounting for constraints, such as safety distances and fuel efficiency. The use of model predictive control allows for dynamic adaptation to both vehicle model uncertainties and external disturbances, making it suitable for real-time control in highly dynamic environments.

Hua et al. [4] introduce a decentralized tube model predictive control framework specifically tailored for mixed platoons of connected autonomous vehicles (CAVs) and human-driven vehicles (HDVs). By addressing the uncertainties inherent in HDV behavior, their approach ensures smooth platoon formation using a combination of feedforward and feedback control mechanisms. This decentralized method stands out for its explicit focus on HDV unpredictability, making it highly effective in environments with heterogeneous vehicle types. However, while the decentralized nature improves scalability, the increased computational complexity remains a challenge, especially in larger networks. Similarly, Sun et al. [5] also focus on distributed model predictive control for vehicle platoons, but their approach is more generalized to account for mixed disturbances and model uncertainties across all vehicles, not just HDVs. By allowing each vehicle to operate independently while only exchanging limited information, Sun et al.'s method enhances scalability and reduces communication overhead. However, as with Hua et al., there is a reliance on accurate initial model parameters, which can pose challenges if deviations occur.

Building on these ideas, Li et al. [6] take a step

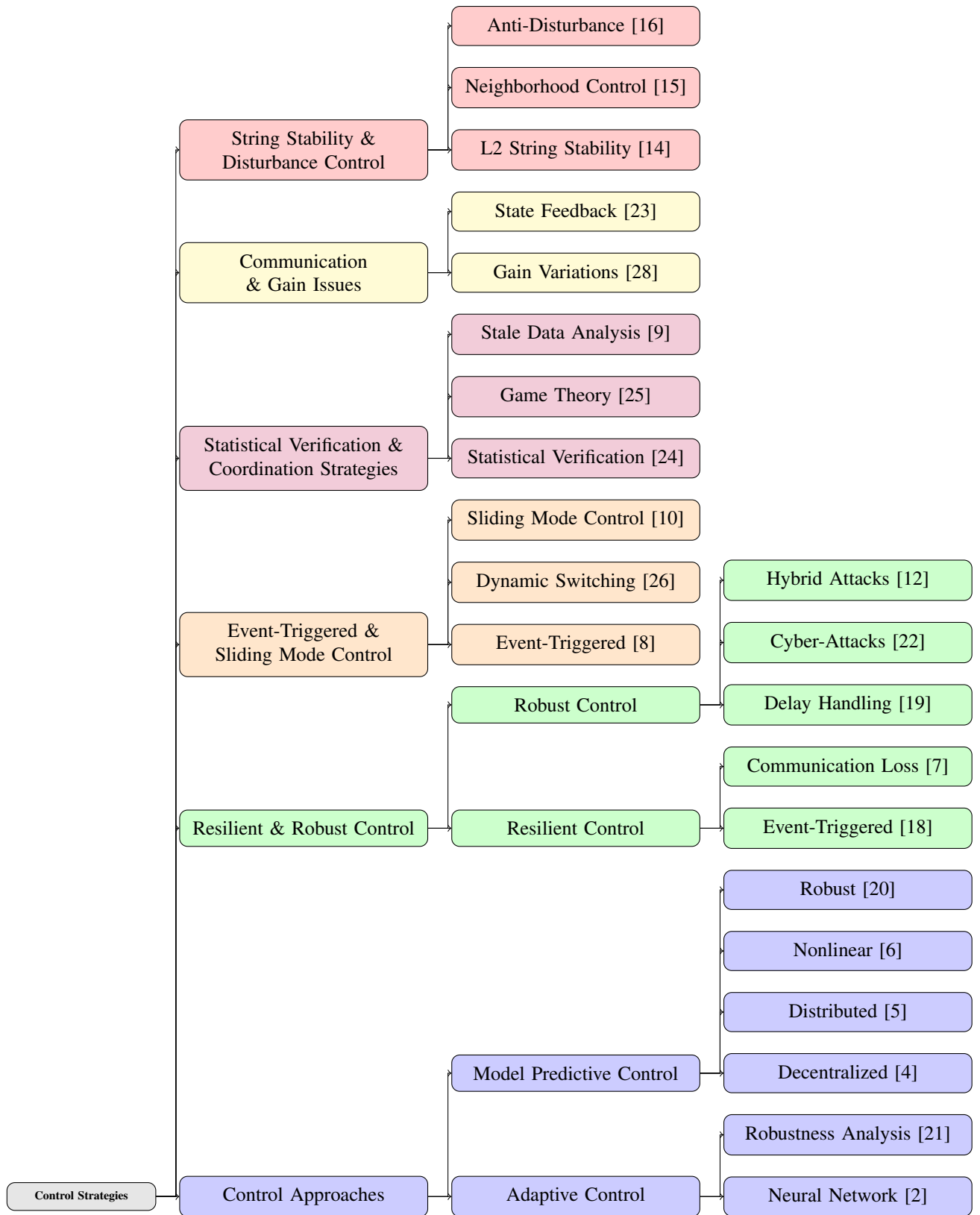


Fig. 1. Taxonomy of Control Strategies for Vehicular Platooning Systems

further by proposing a distributed nonlinear model predictive control framework, aimed at addressing the complex nonlinear dynamics of heterogeneous vehicle platoons. While Hua et al. and Sun et al. focus on linear models or approximations, Li et al. tackle the more challenging case of nonlinear dynamics. This approach ensures greater stability and performance in real-world conditions, especially with varying road surfaces or vehicle parameters. However, like its predecessors, Li et al.'s framework is computationally intensive, which could limit its real-time applicability.

Zhang et al. [20], in contrast, focus more explicitly on the uncertainties and communication challenges in connected platoon systems. Their robust model predictive control approach integrates distributed control to handle both model uncertainties and communication delays, making it particularly well-suited for environments where connectivity may be unstable. This method, like that of Hua et al., aims to reduce the need for centralized decision-making, improving scalability and coordination. However, Zhang et al. also highlight the computational complexity of model predictive control as a limiting factor for real-time applications, a recurring theme across all four studies.

B. Resilient and Robust Control

Vehicular platooning systems rely heavily on stable communication links for exchanging control information between vehicles. However, these communication systems are vulnerable to failures, delays, and cyber-attacks. To address these challenges, resilient and robust control strategies have been developed to ensure that vehicle platoons can maintain performance and safety, even in the face of communication disruptions. These approaches focus on managing uncertainties in vehicle-to-everything (V2X) communication, as well as handling potential cyber-physical attacks that threaten the integrity of the control system.

1) Resilient Control for Uncertain Communication Links: Resilient control methods are designed to ensure stable platoon operation despite intermittent communication or cyber-attacks. These methods often employ event-triggered mechanisms

to reduce communication frequency while ensuring that performance is not compromised.

Chen et al. [7] propose a distributed resilient control approach designed to handle uncertainties in vehicle-to-everything communication links. Their focus is on ensuring the platoon's stability and maintaining safe inter-vehicle distances, even when communication losses and delays occur. This method is particularly effective in real-world autonomous platoons where communication between vehicles can be unreliable. The distributed nature of the control reduces the communication burden, enhancing system scalability while ensuring robust performance. However, a key challenge with this approach is its potential vulnerability under extreme communication disruptions or prolonged data loss, which could compromise safety. The reliance on vehicle-to-everything communication means that additional mechanisms may be required to ensure that the platoon remains stable even in complete communication failure scenarios.

Building on the idea of resilience in communication-challenged environments, Chen et al. [18] focus more specifically on the issue of cyber-attacks and parameter uncertainties, particularly in the context of denial of service attacks. Their resilient event-triggered control method offers a way to ensure stable platoon operation even when intermittent communication failures occur due to cyber-attacks. The key innovation here is the event-triggered mechanism, which reduces the communication load by activating control updates only when necessary. This is an effective way to mitigate the impact of attacks, which are designed to overload communication networks. While the event-triggered mechanism is an advantage in terms of efficiency, it introduces the challenge of accurate event detection. If events are not detected correctly, it could lead to safety risks, particularly in dynamic environments. Furthermore, predefined thresholds for triggering control updates may not always adapt well to changing conditions, potentially limiting the system's performance in highly dynamic environments.

2) *Robust Control in Mixed and Uncertain Scenarios*: Robust control methods play a critical role in addressing uncertainties in vehicle dynamics and external disturbances, such as packet loss and communication delays. Two notable contributions in this direction are made by Wang et al. [19] and Wang et al. [12], both offering robust control frameworks but focusing on different types of uncertainties and threats in vehicle platooning systems.

Wang et al. [19] introduce a robust control strategy specifically designed for mixed vehicle platoons, which include both autonomous and human-driven vehicles. Their method focuses on addressing polytopic uncertainties, communication delays, and packet dropouts, all of which are common challenges in real-world platoon applications. The robustness of this approach lies in its ability to maintain stable platoon formation and safe inter-vehicle distances despite these uncertainties and disturbances. However, as the number of vehicles in the platoon increases, the complexity of the control method also increases, potentially limiting its scalability for very large platoons.

Building on the idea of robust control, Wang et al. [12] focus on a broader range of uncertainties, including parametric uncertainties and hybrid cyber-physical attacks. Their distributed robust control framework is designed to ensure platoon stability while mitigating the effects of cyber-attacks such as denial of service and false data injection. This dual focus on both parametric uncertainties and cybersecurity makes the approach particularly relevant in real-world scenarios where autonomous vehicles are susceptible to malicious attacks. The distributed nature of the framework reduces communication overhead, making the method more scalable for large platoons. However, the success of the approach depends on the accurate detection of hybrid attacks, which could be challenging if attacks are stealthy or difficult to detect.

C. *Event-Triggered and Sliding Mode Control*

Event-triggered control and sliding mode control are two promising techniques aimed at reducing communication overhead. Event-triggered control updates the system only when necessary, while slid-

ing mode control offers robustness by maintaining a stable control regime, even under adverse conditions such as disturbances and uncertainties.

Liang et al. [8] introduced an event-triggered prescribed performance control framework that targets model uncertainty in vehicle platoons. This framework ensures key performance metrics, such as maintaining safe inter-vehicle distances, while also minimizing communication between vehicles by employing event-triggered updates. The main advantage of this approach is its capacity to reduce communication overhead while maintaining necessary control performance, making it particularly suitable for large platoons. However, one challenge lies in event detection accuracy. If event detection is delayed or inaccurate, especially in high-speed scenarios, the performance could deteriorate, posing potential safety risks. More extensive testing is required to verify its robustness in fast-changing, highly dynamic environments.

Similarly, Li et al. [26] presented a switched dynamic event-triggered control method designed to ensure string stability in nonhomogeneous vehicle platoons, with a focus on compensating for uncertainties. By using an event-triggered mechanism, this method reduces the frequency of communication updates while preserving platoon stability, even when uncertainties in vehicle dynamics are present. The benefit of this approach is its scalability, as reducing communication load makes it suitable for larger platoons. Furthermore, the switching control strategy increases robustness in dealing with dynamic uncertainties. However, the complexity of this switching mechanism might create challenges for real-time implementation, and, similar to Liang et al.'s approach, its performance depends heavily on accurate event detection. Delays in triggering control updates could negatively impact overall system performance.

Tang et al. [10] took a different approach by proposing a finite-time second-order sliding mode control framework for vehicle platoons. Their method focuses on addressing uncertainties and external disturbances, such as road friction and wind, to maintain robust platoon stability and tracking performance. Sliding mode control is known for its

ability to handle disturbances effectively, and the finite-time convergence property ensures a fast response, making it suitable for real-time applications. Furthermore, by using second-order sliding mode control, the method reduces the chattering effect commonly associated with traditional sliding mode control, resulting in smoother vehicle behavior. However, the increased computational complexity associated with second-order control designs may limit its applicability in larger platoons. As with the other methods, further real-world testing is needed to assess the control's effectiveness in varying external conditions.

Taken together, these methods highlight the potential of event-triggered and sliding mode controls to balance communication efficiency and robustness in vehicle platooning systems. Liang et al. and Li et al. both utilize event-triggered mechanisms to reduce communication overhead, with each emphasizing scalability and robustness under uncertainty. Meanwhile, Tang et al. provide a complementary approach by focusing on robustness through sliding mode control, particularly in handling disturbances. However, the real-world applicability of all these methods remains dependent on further testing and improvements, especially in terms of event detection accuracy and computational complexity.

D. Statistical Verification and Coordination Strategies

The approaches of this category leverage statistical methods to verify system behavior and employ coordination techniques, such as game theory, to optimize vehicle cooperation. Such strategies are essential in handling uncertainties in vehicle communication, travel times, and the complex interactions between multiple autonomous systems.

1) *Verification and Uncertainty Handling:* Verification frameworks provide a means to assess the reliability of platooning systems under a variety of conditions, including communication failures and external disturbances. Statistical approaches offer a way to bypass the computational limits of exhaustive verification methods by focusing on probabilistic outcomes.

Hyun et al. [24] have proposed a statistical verification framework for a platooning system of systems under uncertainty. The framework leverages statistical model checking techniques to verify the system's behavior under various internal and external uncertainties, such as vehicle accidents and network disconnections. By automatically generating platooning configurations and scenarios, the framework bypasses the state-explosion problem typical of exhaustive verification techniques. The primary advantage of this framework is its ability to efficiently handle the complexities and uncertainties inherent in a platooning system. The statistical approach enables deeper analysis of system failures while significantly reducing computational overhead. However, the framework's reliance on simulation and scenario generation may not capture all real-world conditions. Additionally, the approach primarily addresses system of systems' level uncertainties, with limited consideration of micro-level vehicle behaviors.

St. Louis and Calhoun [9] have explored the impact of data uncertainties in autonomous ground vehicle platooning. The study focuses on analyzing how stale or outdated data in the communication network affects the safety and efficiency of autonomous vehicle platoons. By simulating stale data scenarios, the paper identifies key parameters that influence the risk of collisions. The primary advantage of the study is its focus on data reliability in autonomous systems, a critical factor in real-world implementations of vehicle platooning. The insights gained from the analysis can help improve fault tolerance and data handling in autonomous systems. However, a limitation of the study is that it mainly focuses on one-dimensional platooning models, which may not fully capture the complexity of real-world scenarios. Expanding the analysis to more dynamic, multi-dimensional models would provide a more comprehensive understanding of the problem.

2) *Coordination and Game Theory:* Coordination strategies, often based on game theory, allow autonomous vehicles to cooperate efficiently in uncertain traffic conditions. These strategies help balance the costs of platoon formation, such as

waiting times. In this direction, Johansson et al. [25] have proposed a strategic hub-based coordination approach for vehicle platooning, addressing the challenge of uncertain travel times. The paper introduces a non-cooperative game theory model where vehicles decide on their waiting times at hubs to form platoons, balancing the benefits of platooning with the costs of waiting. The approach is evaluated using both deterministic and stochastic travel times, with feedback solutions allowing vehicles to update their strategies en route. The main advantage of this method is its ability to handle uncertainty in travel times, optimizing platoon formation while minimizing delays. The feedback mechanism significantly improves the overall system benefit in stochastic scenarios. However, the non-cooperative nature of the game may lead to suboptimal outcomes if vehicle strategies are not aligned. Additionally, the model assumes that vehicles can accurately estimate future travel times, which may not always be realistic.

E. Platoon Control with Communication and Gain Issues

Communication delays and gain variations pose significant challenges to maintaining platoon stability. Various control strategies have been developed to compensate for these issues, ensuring that platoons remain robust to communication-induced disturbances and varying vehicle dynamics. These strategies focus on compensating for delays in vehicle-to-vehicle communication and ensuring robust feedback control under varying network conditions.

Xu et al. [28] introduced a robust vehicular platoon control method to address gain variations caused by unreliable vehicular ad-hoc networks (VANETs). Their approach compensates for communication-induced gain variations, ensuring stable platoon behavior even when network connectivity is intermittent. The primary strength of this method lies in its robustness against communication issues, a common challenge in real-world VANETs. By compensating for gain variations, the method maintains platoon stability even when network performance degrades. However, the assumption that

gain variations are bounded may not always hold in highly dynamic network environments, and further large-scale VANET deployment testing is needed to validate its real-world effectiveness.

Similarly addressing communication-related challenges, Sawant and Chaskar [23] proposed a state feedback control approach for vehicle platoons, specifically designed to manage parametric uncertainty and communication delays. Their method offers a detailed analysis of spacing errors and proposes a control scheme that adjusts controller gains to maintain string stability despite these challenges. The ability to simultaneously handle parametric uncertainties and communication delays makes this approach particularly valuable in real-world situations where these factors are unavoidable. However, the effectiveness of this method depends on the accurate estimation of vehicle parameters, and the computational complexity introduced by these estimations may limit scalability in larger platoons.

Xiao et al. [27] proposed a different approach by focusing on output-feedback control strategies for mixed traffic systems, which include both human-driven and autonomous vehicles. Their observer-based design estimates unmeasured states and applies robust control actions to ensure stability and effective disturbance rejection in these mixed environments. The main advantage of this method is its applicability to mixed traffic scenarios, providing robust control for systems where both human and autonomous vehicles coexist. However, the performance of the observer could degrade under severe disturbances or unmodeled dynamics, limiting the system's effectiveness.

Overall, Xu et al. and Sawant and Chaskar both address challenges in communication reliability and uncertainty, with Xu focusing on gain variations in VANETs and Sawant and Chaskar tackling parametric uncertainty and delays. Xiao et al., in contrast, apply their method to mixed traffic systems, offering robust control for the coexistence of human and autonomous vehicles. While each method has strengths in specific scenarios, real-world testing remains a common need across all three approaches to ensure scalability and robustness in dynamic

environments.

F. String Stability and Control of Disturbances

String stability is a crucial aspect of maintaining the safety and efficiency of vehicle platoons. It ensures that disturbances affecting one vehicle do not amplify as they propagate through the platoon. Recent research has focused on developing control mechanisms that maintain string stability while compensating for external disturbances and uncertainties in communication.

Zhao et al. [14] have proposed an L2 string stability analysis method for heterogeneous vehicle platoons, addressing the effects of disturbances and communication delays. The paper focuses on ensuring that the disturbances affecting one vehicle in the platoon do not amplify as they propagate through the following vehicles. The method accounts for both heterogeneous vehicle dynamics and the impact of communication delays in vehicle-to-vehicle networks. The primary advantage of this work is its ability to maintain string stability in the presence of both disturbances and delays, making it suitable for real-world applications in connected and automated vehicles. The L2 string stability criterion provides a robust framework for analyzing the effects of disturbances in heterogeneous vehicle platoons. A potential drawback is the assumption that communication delays are bounded and known, which may not always hold true in real-world scenarios. Additionally, the method primarily focuses on linear models, and extending the analysis to nonlinear vehicle dynamics could provide a more comprehensive solution.

Prayitno et al. [15] have proposed a distributed model reference adaptive control approach using a neighborhood controller-local observer scheme for heterogeneous vehicle platoons. The main goal is to maintain platoon formation with limited output information while dealing with uncertainties in vehicle dynamics. The local observer estimates the full state of each follower vehicle, and the neighborhood controller ensures tracking of the leader's state. The key advantage of this method is its ability to handle heterogeneous vehicle platoons with limited state information, reducing communication

requirements. The use of a local observer simplifies the controller design and improves computational efficiency. However, the method's effectiveness relies on accurate state estimation, which may be challenging in scenarios with severe communication delays or data loss.

Zhang et al. [16] have proposed hierarchical anti-disturbance control framework based on nonlinear least squares for vehicle platoons, specifically addressing time-varying parameter uncertainties. The method aims to ensure robust platoon stability in the presence of disturbances and uncertainties. The hierarchical control structure allows for both local disturbance rejection and global platoon coordination. The main advantage of this method is its ability to handle both local and global disturbances effectively, making it suitable for highly dynamic environments. The use of nonlinear least squares improves the system's disturbance rejection capabilities while maintaining platoon stability. However, the complexity of the hierarchical structure may pose challenges for real-time implementation in large-scale platoons. Additionally, the method's performance under severe communication delays or packet losses remains to be thoroughly evaluated.

III. OVERALL DISCUSSION

The comparison criteria of the reviewed control strategies for vehicular platooning systems are motivated by the specific challenges and requirements inherent in autonomous vehicle systems. These challenges include managing external disturbances, communication overhead, cybersecurity concerns, real-time applicability, scalability, event-triggered control, heterogeneity in platoons, and energy efficiency. These criteria reflect key performance indicators that determine the robustness, adaptability, and practical deployment potential of each method in real-world applications. Table I summarizes the overall comparison of the reviewed approaches.

External Disturbances is an essential criterion since vehicle platoons frequently face environmental factors such as wind resistance, road surface changes, and varying traffic conditions. Methods that can robustly handle external disturbances are crucial for ensuring platoon stability under real-

TABLE I
COMPARISON OF CONTROL APPROACHES FOR VEHICULAR PLATOONING SYSTEMS

Reference	External Disturbances	Communication Requirements	Cybersecurity Focus	Real-Time Capability	Scalability	Event-Triggered	Heterogeneity	Energy Efficiency
[2]	✓	Medium	×	Medium	Medium	×	✓	×
[4]	✓	High	×	Medium	High	×	✓	×
[5]	✓	Medium	×	High	High	×	✓	×
[6]	✓	Medium	×	Medium	High	×	✓	×
[20]	✓	Medium	×	Medium	High	×	✓	✓
[7]	✓	Medium	✓	Medium	Medium	✓	✓	×
[18]	✓	Low	✓	High	High	✓	✓	×
[22]	✓	High	✓	Medium	Medium	×	✓	×
[19]	✓	High	×	Medium	High	×	✓	×
[8]	✓	Low	×	High	High	✓	✓	×
[26]	✓	Low	×	High	High	✓	✓	×
[10]	✓	Medium	×	Medium	High	×	✓	×
[24]	×	Medium	×	High	Medium	×	×	×
[9]	×	Medium	×	Medium	Medium	×	×	×
[25]	×	Medium	×	Medium	High	×	✓	×
[28]	✓	High	×	High	High	×	✓	×
[23]	✓	High	×	Medium	High	×	✓	×
[27]	✓	Medium	×	High	Medium	×	✓	×
[14]	✓	High	×	Medium	High	×	✓	×
[15]	✓	Low	×	Medium	Medium	×	✓	×
[16]	✓	Medium	×	Medium	Medium	×	✓	×

world operating conditions. For example, nearly all reviewed works emphasize handling external disturbances, as evidenced by the high presence of checkmarks in the respective column.

Communication Requirements are central to ensuring effective coordination between platoon members. A system with high communication requirements may struggle in environments with network latency or packet loss, affecting control performance. Therefore, balancing communication load and system performance is critical, particularly for large platoons, where communication delays could propagate and amplify disturbances.

Cybersecurity Focus is increasingly important as vehicular systems become more connected through vehicle-to-vehicle and vehicle-to-everything networks. Cyber-attacks such as denial of service can compromise the safety and stability of platooning systems. Only a few works, such as [7], [18] and [22], explicitly address cybersecurity threats, indicating a gap in the current literature that future research must address.

Real-Time Capability assesses the feasibility of deploying the proposed methods in practical environments. Real-time control is critical in platooning systems, where any delay in decision-making or execution could lead to collisions or loss of stability. Approaches that require extensive computational resources, such as those utilizing complex neural networks or optimization algorithms, may face challenges in real-time applications. The table

shows that most methods offer medium to high real-time capability, although some could struggle with computational overhead.

Scalability evaluates the ability of a control method to function effectively as the size of the vehicle platoon increases. Methods that are scalable ensure that the control strategy remains effective and efficient even as the number of vehicles in the platoon grows.

Event-Triggered mechanisms are used to reduce communication overhead by updating control actions only when necessary, rather than continuously. This reduces the burden on communication networks and computational resources, especially in large-scale systems.

Heterogeneity in platoons refers to the presence of vehicles with differing dynamics and control capabilities, such as a mix of autonomous and human-driven vehicles. Control strategies must adapt to heterogeneous platoons to ensure stability. The table shows that most reviewed methods handle heterogeneity, except for a few that assume homogeneous vehicle types.

Energy Efficiency is increasingly vital due to environmental concerns and the need for sustainable transportation solutions. Energy-efficient control strategies can significantly reduce fuel consumption and emissions. However, energy efficiency is often an under-addressed criterion, with only a few works, such as [20], focusing on this aspect.

IV. CONCLUSIONS AND PERSPECTIVES

In this paper, we have reviewed the state-of-the-art control strategies for vehicular platooning systems, with a focus on adaptive control, model predictive control, resilient and robust control, event-triggered mechanisms, and cybersecurity. Each of these approaches addresses key challenges such as external disturbances, communication uncertainties, and heterogeneous vehicle dynamics. Our comparative analysis has shown that while significant progress has been made, several areas require further exploration and development to enable the widespread deployment of platooning systems in real-world environments.

One of the key conclusions drawn from this study is the need for more efficient real-time control strategies. While adaptive control and model predictive control offer robust solutions for handling uncertainties, their computational complexity poses a challenge for real-time applications, especially in large-scale platoons. Future research should focus on optimizing these control algorithms to reduce computational overhead and improve their scalability in dynamic environments.

Another critical area that requires further attention is cybersecurity. As vehicular platooning systems become increasingly reliant on vehicular communication, they become more vulnerable to cyberattacks, which can have devastating consequences for both safety and system stability. Integrating cybersecurity mechanisms into control frameworks is essential for ensuring the resilience of platooning systems. Future research should explore more advanced cyber-physical security solutions that can detect and mitigate threats in real-time.

Energy efficiency is another aspect that requires further investigation. While platooning inherently offers fuel savings through reduced aerodynamic drag, optimizing control strategies to maximize these savings without compromising safety and stability remains a challenge. Hybrid control approaches that integrate both energy management and stability control should be explored in greater depth to achieve the dual goals of sustainability and safety.

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