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A Review of Collaborative Adaptive Cruise Control for Vehicle Queuing Technology

Zhao An[1,a,*], Hongyun Zhu[2,b]

[1]School of Civil and Hydraulic Engineering, Ningxia University, Yinchuan, Ningxia, 750021, China
[2]School of Mechanical and Electric Engineering, Soochow University, Suzhou, Jiangsu, 215000, China
[a]andy131318@163.com, [b]18395913310@163.com
[*]Corresponding author

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Abstract: With the development of the modern economy, the number of cars on the road continues to increase, leading to escalating problems with traffic congestion. This paper outlines the progression of autonomous driving technology, emphasizing that a single autonomous vehicle is incapable of effectively mitigating traffic congestion. To further enhance the intelligence of traffic systems, this paper explores the potential value and application of Cooperative Adaptive Cruise Control (CACC) within vehicle platooning technology, with an aim to alleviate road congestion and increase traffic efficiency. In terms of the scenarios and potential value involved, this paper highlights the positive impact of vehicle platooning technology on reducing aerodynamic drag, fuel consumption, carbon emissions, and enhancing road throughput. This technology can also improve road safety by reducing collision risks through real-time communication and coordination between vehicles. Moreover, by implementing vehicle platooning, road capacity can be increased, thereby alleviating traffic congestion. The paper also points out some technical difficulties and challenges associated with vehicle platooning technology, including communication reliability, sensor accuracy, automatic control algorithms, and safety assurance. A series of solutions are proposed to address the challenges faced by vehicle platooning technology. Furthermore, potential future trends in vehicle platooning technology are explored, such as experimental verification of larger scale vehicle platoons, and consideration of model uncertainty and interference robustness. In summary, this paper provides a comprehensive exploration of the potential and challenges of vehicle platooning technology in alleviating traffic congestion and enhancing traffic efficiency. By detailing the technical background, application scenarios, potential value, and solutions, this paper offers valuable guidance and research direction for the development of future intelligent traffic systems.

1. Background

With the continuous development of the modern economy, the automotive industry has made significant progress, leading to a reduction in production costs and an increase in the number of vehicles on the road. However, this surge in automobile ownership has resulted in severe traffic congestion issues, particularly in cosmopolitan cities, posing a pressing challenge for future transportation development.

One potential solution lies in the advancement of autonomous driving technology. However, if each autonomous vehicle merely perceives its immediate surroundings and makes independent decisions, it would not effectively alleviate road congestion. Therefore, the application of cooperative autonomous driving technology is essential to enhance the intelligence of the transportation system. A typical application of cooperative autonomous driving is the concept of platooning[1], which represents one of the most promising applications in vehicular networking, as illustrated in Figure 1. It involves a group of vehicles forming a road train without any physical coupling, maintaining short inter-vehicle distances through automation and wireless communication technologies. Research[2] has shown that a vehicle traveling at 80 km/h, following only one lead vehicle at a distance of 25 meters, can reduce aerodynamic drag by 30%, and following two lead vehicles can reduce it by 40%. By maintaining shorter inter-vehicle distances, the "following" vehicles experience reduced air resistance and lower fuel consumption, thereby contributing to the reduction of carbon emissions in the transportation system.

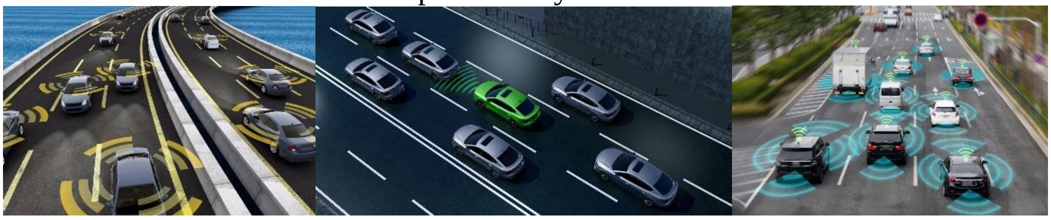

Figure 1: Autonomous vehicle queue

Furthermore, vehicle platooning helps increase traffic throughput on roads, which is crucial for alleviating congestion. For instance, if all passenger vehicles were to form platoons, it could potentially result in a 200% increase in road capacity. Given the urgent need for smooth traffic flow, advancements in autonomous driving, and the desire to reduce fuel consumption, vehicle platooning is poised to become a vital technology in the development of future intelligent transportation systems.

Overall, the adoption of cooperative autonomous driving and the implementation of vehicle platooning hold promise in addressing the challenges posed by increasing traffic congestion. These advancements not only contribute to enhanced efficiency and reduced carbon emissions but also pave the way for a smarter and more sustainable transportation future.

The vehicle platoon control system consists of longitudinal control and lateral control. Longitudinal control aims to regulate the longitudinal motion, while lateral control enables individual vehicles to accurately track the centre of the lane. In this paper, we mainly focus on the longitudinal control of vehicle platoons. Different inter-vehicle spacing strategies are proposed for longitudinal control, such as the constant spacing and variable spacing control strategies. The most popular inter-vehicle spacing control strategies are the constant distance and constant time headway spacing strategies. Compared to the constant distance strategy, the constant time headway spacing strategy improves the scalability and stability of vehicle platoons with different information flow topologies (IFTs) including one-look-ahead, two predecessors following, leader-following, leader-predecessor following, and multiple-look-ahead. In adaptive cruise control (ACC), each vehicle in the platoon utilizes its onboard sensors (e.g., radar-based sensors) to measure the velocity and position of its immediate predecessor, and uses these sensor measurements to maintain a small inter-vehicle distance. Due to limitations of ACC in control performance, e.g., an inherent limitation in progression time, cooperative adaptive cruise control (CACC)[3] has become a more popular technique, as shown in Fig. 2.

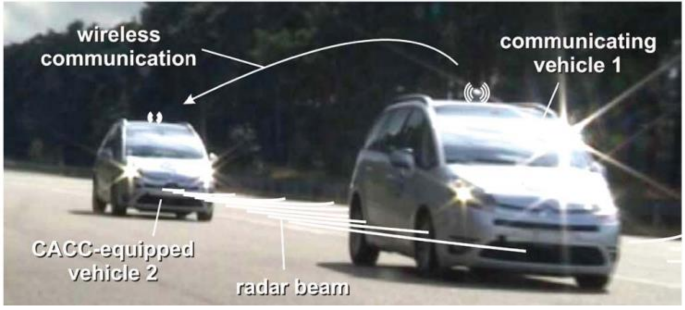

Figure 2: CACC schematic diagram

2. Application Scenarios and Potential Value

2.1. Technical Application Scenarios and Value

(1) Reducing adverse aerodynamic effects and fuel consumption

Vehicle platooning can reduce air drag between vehicles, thereby lowering fuel consumption. Studies have shown platooning on highways can improve fuel efficiency of vehicles by about 10% to 20%. This has significant economic and environmental impacts for the long-haul transportation industry.

(2) Reducing carbon emissions/ Increasing road throughput Promoting (semi)automation

Platoon systems allow vehicles to drive in a more steady and efficient manner, reducing fuel waste and exhaust emissions.

(3) Improving road safety

Vehicles in a platoon are equipped with advanced sensors and communication systems that can monitor the actions of preceding vehicles in real-time and coordinate vehicle speeds consistently. This reduces the impact of speed differentials on traffic flow, enabling vehicles to react faster and reducing collision risks.

(4) Improving utilization of existing road infrastructure

Increasing road capacity: Platooning allows vehicles to maintain smaller gaps while occupying the same road space, allowing more vehicles to fit the same length of road. This increases road capacity, enabling more efficient utilization of road space and reducing possibilities of traffic congestion.

2.2. Technical Challenges

(1) Communication reliability

Vehicle platooning requires real-time communication between vehicles to share position, velocity, and intent information. However, vehicles may travel in environments with blocked or interfered signals, causing communication outages. For example, Vehicle-to-Vehicle (V2V)[6] and Vehicle-to-Infrastructure (V2I) wireless communication technologies are affected by various impairments like channel fading, shadowing, and interference, which inevitably lead to communication delays and packet losses in vehicular communication networks. These impairments affect the quality of wireless communications and thus the performance of vehicle platoon control systems. Therefore, alternative information structures that can improve the scalability and stability of platoons need to be considered.

(2) Sensor accuracy

Vehicle platooning relies on sensors to perceive the surrounding environment information, such as lidars, cameras, and radars. Sensor errors, occlusions, and environmental changes may affect the accuracy of sensor data.

(3) Automated control algorithms

The platoon system requires algorithms to enable cooperative driving among vehicles while coping with dynamic environments. Developing automated control algorithms suitable for different platoon sizes and traffic conditions, taking into account maneuvers like acceleration, deceleration, and steering, needs balancing between performance and stability.

(4) Safety assurance

The platoon needs to ensure safe inter-vehicle distances to prevent collisions and hazardous situations. Developing reliable safety assurance mechanisms like emergency braking systems, collision avoidance algorithms, and vehicle status monitoring, is key to ensuring platoon safety.

(5) Mixed traffic environments

Platoon vehicles need to share roads with conventional vehicles and pedestrians. Therefore, the platoon system must adapt to uncertain behaviors of non-platoon vehicles, like cut-ins, lane changes, and stops, while maintaining platoon stability.

(6) Adopting distributed controller design

As shown in the figure 3, although CACC technology[5] is quite mature, it is still a challenge to be subject to communication failures. Adopting feedforward controller design, the system can readily degrade to a standard ACC system with ineffective or failed wireless communication.

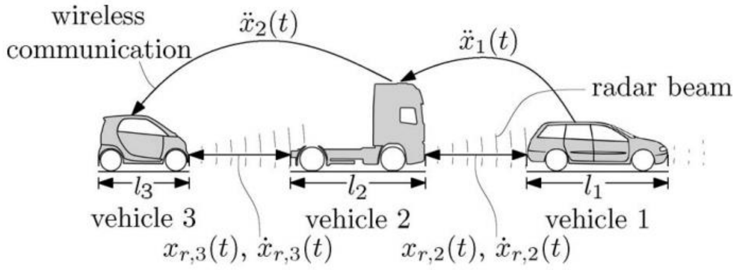

Figure 3: Modeling diagram of a row of vehicles equipped with CACC function

2.3. Solution

When random packet drops exist, a probabilistic packet loss model can be used to characterize the communication impairment on internal stability. This model can compute the probability that the receiver does not receive any data packets within a given time window. If this probability is high, it implies the communication link is unstable, which may affect the performance of vehicle platooning technologies. Therefore, to improve the stability of communication links, some techniques can be adopted, such as forward error correction coding, retransmission mechanisms, multipath transmissions, etc. These techniques can reduce the probability of packet losses, thereby improving the reliability and stability of communication links.

In the presence of communication delays, a distributed control design is utilized, which uses frequency domain methods to define platoon string stability of the vehicle platoon. This design only considers communication with preceding vehicles, and exchanges relative positioning and velocity information of vehicles via wireless communication links. The control design includes a feedforward filter that compensates for communication delays, and ensures vehicles in the platoon maintain constant inter-vehicle distances. Results show that this design can guarantee internal stability and string stability of the platoon even with communication delays.

Under ideal communication environments, there exist gain parameters to guarantee internal stability of vehicle platoons with limited communication ranges, by analyzing the matrix polynomial of the platoon system to obtain the gain parameters, and deriving necessary and sufficient conditions for information flow topology, sampling time, control gains, and internal lags, to ensure internal stability. Specifically, the gain parameters are designed to satisfy the Hurwitz stability criteria, which ensures all eigenvalues of the closed-loop system have negative real parts. The internal stability condition is crucial since it guarantees the platoon system is stable without any oscillations or instabilities that may lead to inter-vehicle collisions.

Chengcheng Zha[4] utilized matrix eigenvalue perturbation theory and blocked matrix polynomials to study internal stability of vehicle platoons. This approach enables more accurate understanding and prediction of platoon behavior under various conditions, thereby providing stronger theoretical support for platoon control. Then, they proved the existence of an upper bound communication delay for time-varying systems, so internal stability of the vehicle platoon can be guaranteed. This is an important finding since it means we can optimize platoon performance by controlling communication delays.

Overall, these solutions provide a comprehensive approach to improve driving performance and stability of vehicle platoons from multiple aspects. By studying communication range, communication delays, matrix eigenvalues, and platoon stability, an in-depth understanding of platoon driving is achieved and a range of effective solutions are proposed, as shown in Fig. 4.

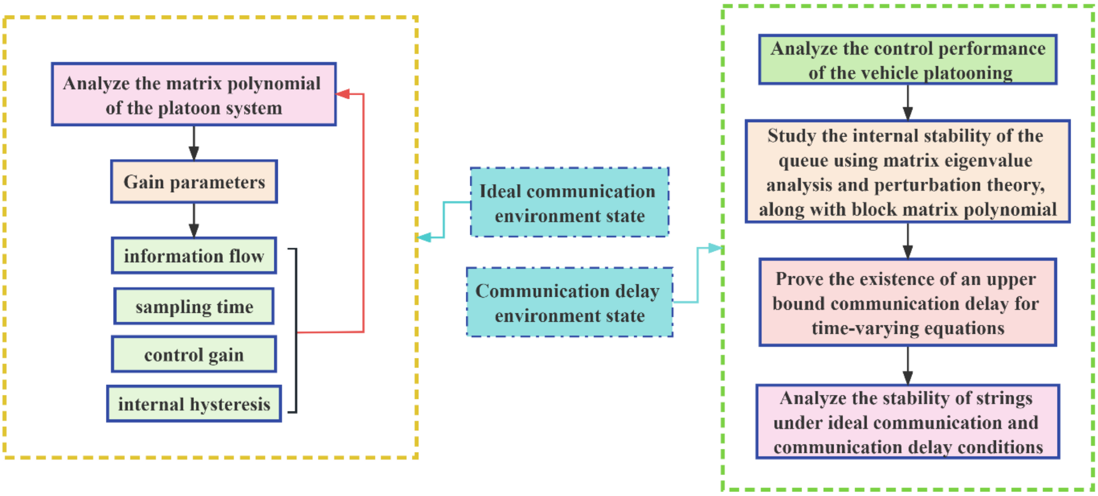

Figure 4: Solution diagram

2.4. Future Trends

However, vehicle platooning technologies have some potential drawbacks, including high implementation costs, requiring dedicated infrastructure, and potential network attacks and hacking. Additionally, there may be legal and regulatory challenges related to liability and accountability in the event of accidents or failures. Meanwhile, vehicle platooning systems require vehicles to share positioning and driving data. This may raise privacy concerns, including leakage and misuse of personal driving information. To mitigate job losses in the freight transportation industry, human intervention is still necessary, although vehicle platooning technologies aim to automate driving, in certain situations like complex traffic environments or system errors, drivers may need to intervene promptly.

Design controllers with safety constraints and perform performance analysis, deal with more accurate system modelling, design distributed collision avoidance controllers under given communication faults, and optimize communication resources.

Further experimental validation of the concept with larger vehicle platoons should be a topic for future research. Additionally, comparing the performance and string stability characteristics of the proposed system setup under different CACC settings is an interesting problem worth further investigation. For example, setups with different communication topologies or different spacing policies could be compared dynamically. Finally, important issues for future research should include robustness to model uncertainties and disturbances in platoon stability analysis, and considerations of the behavior of mixed platoons of CACC-equipped vehicles and unequipped regular traffic.

3. Conclusions

(1) Vehicle platoons have limited communication ranges. Time-varying delays utilizing eigenvalue perturbation analysis. Internal stability with time-varying delays can always be guaranteed given a sufficiently small upper bound. Studied L2 - string stability under ideal constant and uniform constant delays.

(2) Studied how random packet drops affect control performance of multi-predecessor IFT vehicle platoons. Analyzed internal stability and queue stability for different packet drop scenarios.

(3) When the lead vehicle moves at a constant speed, internal stability of the platoon can be viewed as stability of a block companion matrix, which is intractable. Using matrix eigenvalue perturbation theory, derived sufficient conditions on system parameter gains and communication parameters that ensure internal stability of the vehicle platoon, illustrating the impact of communication range limitations on platoon control performance.

(4) Even with high packet drop probabilities, the platoon system can still achieve high reliability when interference variations are stationary. Moreover, it was proven that for time-varying delays, there always exists a sufficiently small upper bound, thereby always achieving internal stability. Studied L2 string stability under ideal and uniform constant delays.

For future work, control design with safety constraints needs to be carried out and dynamic analysis needs to be performed. Additionally, how to utilize more realistic communication simulators to verify platoon performance under limited and non-ideal communication ranges is another important direction. Dealing with model uncertainties using onboard sensor measurements is also an important research problem that needs further investigation.

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