A platoon-based cooperative merging ecological control framework under connected environment

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Abstract

Platooning is a main connected and automated vehicle (CAV) application that can significantly enhance traffic efficiency and decrease ecological impacts. In the merging scenario, the advantages of platooning are generally impaired by the lane-changing behaviors of the on-ramp vehicles. This paper proposes a platoon-based cooperative ecological merging control framework, which adopts centralized decision-making and distributed control. More specially, this framework includes a strategy layer and a control layer. The strategy layer aims to predict the future status of both mainline and on-ramp platoons and develops a sequencing game to determine an optimal merging sequence and speed-adaption time instant to minimize the total carbon emission and delay. The control layer designs a platoon controller based on Distributed Model Predictive Control, which solves the local optimization problem of each vehicle in the platoon. Thus, the framework is not limited to the number of vehicles in the scenario and achieves a system-optimal objective while being optimal for a single vehicle. The proposed control framework is compared against the existing first-in-first-out rule and cooperative three-player game. Our numerical experiments demonstrate a better performance of the proposed framework.

1 Introduction

In recent years, the issue of global warming has caused widespread concern and intense debate across society. Road travel alone accounts for three-quarters of transportation emissions, which in turn contribute 21% to the total global emissions (IEA, 2022). As traffic demand continues to rise, the challenges facing the highway system are escalating. Enhancing efficiency has consistently been a primary objective in managing highway transportation. Research into low-carbon driving has emerged as an essential focus within highway traffic control and management. In particular, merging bottlenecks are one of the leading causes of reduced highway efficiency and increased carbon emissions.

As connected and automated vehicle (CAV) technology advances, platooning is a primary method used to improve traffic efficiency (Jia and Ngoduy, 2016; Ngoduy, 2013) and emissions (Ma et al., 2021; Raparthi, and Phuleria, 2022). It is widely applied to highway scenarios and has become an important method in highway traffic control and management in connected environments (Yao et al., 2023). Compared to self-organized traffic, vehicles in the platoon have smaller following distances between them, and travel at higher speeds (Jia and Ngoduy, 2016; Ngoduy, 2013), which means that the negative impacts of traffic safety, efficiency, and emission caused by inappropriate merging solutions of the platoon are much more severe as the platoon passes through the merging zone.

In particular, the merging problems, depending on the level of participation in decision-making, are mainly solved in two ways. One approach involves the entire on-ramp platoon merging to the mainstream platoon (Uno et al., 1999; Lu et al., 2004). Another approach considers the conflict and game of the platoons, focusing on the two or three vehicles around the merging point, and framing it as either a two-player or three-player game (Yang et al., 2023; Hang et al., 2022). The former method considers the platoon as a whole, overlooking individual benefits. This can lead to situations when one or several vehicles experience high energy consumption and delays, resulting in a "short-board effect" that reduces the platoon's overall

durability. The latter one focuses the decision-making on a few vehicles and tends to ignore the total system cost. This can lead to isolated decision-making by the vehicles both in front of and behind the platoon. Small changes in decision-making by leading vehicles can accumulate along the platoon, increasing the minimum cost of decision-making for vehicles at the back of the platoon. Neither approach is well suited to address the platoon-based merging problem.

To solve the aforementioned problem, the platoon-based cooperative merging ecological control framework is proposed. The framework adopts centralized decision-making and distributed control, structured into two layers: the strategy layer and the operational layer. The strategy layer constructs the merging process into a sequencing game, determining a merging sequence that minimizes the cooperation costs for each participant. This approach solves the problem of either sacrificing certain vehicles for overall maximum benefits or causing a decline in overall benefits to equalize individual gains. Meanwhile, the strategy layer using a sequencing game also solves the problem of a fixed number of participants in a multi-player game, and finally obtains the optimal sequence and speed-adaption time. In contrast, the operational layer designs a platoon controller based on a distributed model predictive control (DMPC) method. This controller manages both the mainstream and on-ramp platoons to complete the merging process according to the optimal sequence and speed-adaption timing. This approach avoids the constraints of complex communication topologies and centralized control, thereby improving driving efficiency. The proposed framework is numerically compared against the first-in-first-out (FIFO) method and a cooperative three-player game (CTPG) method to verify its superiority.

1.1 Literature review

The platoon-based merging research has been conducted for more than 20 years. Uno et al. (1999) proposed the concept of virtual platooning for autonomous merging control (Uno et al., 1999). This concept envisions a virtual vehicle or platoon driving within the mainline platoon, in which the platoon is pre-spaced in advance of the actual arrival of the on-ramp vehicle or platoon. Subsequently, Lu et al. further developed virtual platooning (Lu and Hedrick, 2000; Lu et al., 2004). However, this method requires a large enough space for virtual vehicles or platoons, which are usually placed in front of or behind the platoon. In order to minimize costs while mitigating merging conflicts, there's a growing consideration for adopting the cooperative merging method to determine the sequence for platoon-based merging.

The specific rules in the rule-based merging approach are often designed to heuristic rules such as FIFO and fuzzy control rules (Schemidt and Posch, 1983; Posch and Schemidt, 1983). Furthermore, rules are also designed according to vehicle behaviors and traffic states. According to (Gao et al., 2022), several control modes of cooperative adaptive cruise control (CACC) are devised based on different headways. Vehicles in different positions of the mainline platoon are controlled by various control modes to provide lane-changing gaps when an on-ramp vehicle creates merging incentives. (Gao et al., 2022) defined different lane-changing rules in different lanes before determining the optimal multi-lane merging sequence.

In an optimization-based approach, the objective function is constructed to enhance traffic efficiency, improve comfort, reduce fuel consumption, and ensure traffic safety. Chen et al. designed an MPC controller aimed at optimizing the merging sequence to minimize efficiency loss while adjusting the acceleration of on-ramp vehicles (Chen et al., 2021). Hereafter, they established the optimal sequence by minimizing generated traffic disturbance and developing speed adjustment strategies for mainline vehicles (Chen et al., 2022). (Liu et al., 2023) focused on the coordination of three vehicles and constructed the optimal control problem to solve the merging order by maximizing the time and fuel efficiency. Therefore, the rule-based approach focuses on designing the controllers and their merging rules are often simple, while the limitation of the optimization-based approach is that the decision-making is one-sided, and the optimized objects are either mainline vehicles or ramp vehicles. They cannot fully analyse and

discuss the trade-off of all affected vehicles in the merging zone; thus, the obtained results are usually locally optimal or non-optimal (Fang et al., 2022).

When there is one on-ramp vehicle or discontinuous vehicles that need to merge, the above two methods can usually get good individual results, but the overall gains cannot be guaranteed. Unlike these, the platoon-based cooperative merging not only requires the two platoons to minimize the overall and individual costs of the merging process while complying with traffic rules but also reduces the negative impacts of the platoon characteristics on cooperative merging, including tighter spacing and high speeds (Fang et al., 2022; Yang et al., 2023). For platoon-based merging, the conflict between individual and overall benefits is more obvious, and the change of any vehicle in the platoon will have an obvious chain reaction.

Existing studies on platoon-based merging sequences usually adopt a two- or three-player game including two or three vehicles around the merging point. (Hang et al., 2021) considered a mainline vehicle and an on-ramp vehicle and adopted a two-player non-cooperative game to make a merging strategy. Subsequently, they introduce a coalition game theory to give four-player merging sequences in four typical multi-lane merging scenarios (Hang et al., 2022). (Fang et al., 2022) employed the cooperative game among 6 vehicles surrounding the merging point to obtain a locally optimal merging sequence for multiple objectives based on a centralized ramp control. These previous findings indicate that employing a cooperative game for the merging process is advantageous for the overall merging zone. CAVs are particularly suited to enhance this method due to their rationality and information exchange capabilities, which can prevent players from falling into a zero-sum game. Although much effort has been made to consider more decision-making participants, most studies still use the restriction of a fixed number of game participants. This constraint is not suitable for a real platoon because there is no guarantee that the number of vehicles will be unchanged over time. Meanwhile, it usually leads to two dilemmas; one is to adopt a two- or three-player game, which can be applied to more scenarios but cannot guarantee the global optimal merging sequence, and the other is to adopt a multi-player game, which can obtain the global optimal solution but has strict requirements on the number of participants and the relative spatial relationships of the vehicles. Therefore, the platoon-based cooperative merging problem needs a solution that is not limited by the number of vehicles.

Eco-driving is a vehicle control research aimed at minimizing the environmental impact (Huang et al., 2018; Zhou et al., 2016). (Zhao et al., 2018) proposed an Eco-driving model for the platoon mixed with automated and human-driven vehicles which control the mixed platoon through the signalized intersections with better fuel economy. (Yao et al., 2023) designed an ecological CACC method to control the CAV platoon to drive through signalized intersections. However, the current research on eco-driving is less focused on the on-ramp scenario (Jiang et al., 2017; Zong and Yue, 2023). In fact, the merging area is also one of the bottlenecks with frequent disturbances and serious negative environmental impacts (Ma et al., 2021), and is also an important area for ecological driving research (Noroozi et al., 2023). Eco-control solutions for the merging problem can be divided into merging sequence and motion planning (Fang et al., 2022). The merging sequence assigns priority to mainstream and on-ramp vehicles passing through the merging point, and then the vehicles subsequently plan their trajectories accordingly. Therefore, the core of the ecological merging control problem is the merging sequence which has minimal environmental impacts.

1.2 Knowledge gap

In the vast literature reviewed above, platoon-based cooperative ecological merging emerges as a crucial direction for addressing on-ramp scenarios in a connected environment. Coalition game theory has proven effective in tackling issues related to platoon-based merging sequences. However, the number of participants involved in the merging-sequence game is usually fixed, limiting their applicability to specific scenarios and struggling to balance overall system benefits with individual benefits. Simultaneously, they overlook key characteristics of platoons, failing to account for their unique dynamics compared to self-organized traffic, where

vehicle spacing is tighter and interactions are more pronounced. They are addressed in isolation and weaken or even impair the advantages of platooning. Therefore, to fill these gaps, we propose a platoon-based ecological merging control framework. This framework is designed to determine the platoon-based merging sequence to enhance ecological driving and efficiency simultaneously.

1.3 Contribution

The major contributions of this paper are summarized as follows:

- The sequencing game is proposed to solve the platoon-based merging sequence dilemma. It determines the merging sequence aimed at minimizing the cooperation cost for each participant. This approach resolves the issues of sacrificing certain vehicles to maximize overall benefits or equalizing individual benefits at the expense of overall benefits.
- The proposed method addresses the problem of a fixed number of game participants by improving the determination of the participants in the game and can be applied to the merging problem of two platoons of arbitrary sizes.
- A hierarchical merging framework is proposed, which adopts the centralized decision-making and distributed control. In this framework, vehicles within the platoon execute the merging strategy individually at the speed-adaption time. This approach avoids the limitations of complex platoon communication topology and improve the adaptability to real-world scenarios.

1.4 Paper organization

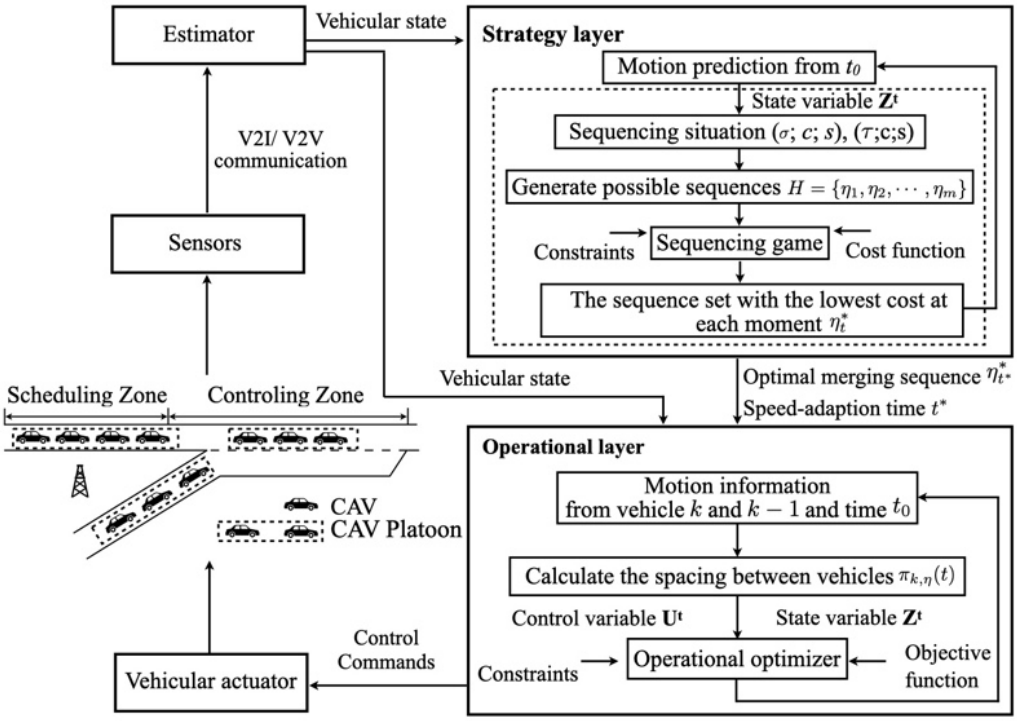
The rest of the paper is organized as follows. Section 2 presents the platoon-based cooperative merging eco-control framework and elaborates on the cooperative strategy layer based on the sequencing game and the operational layer controller, respectively. Section 3 introduces the simulation experiments and analyzes the results. Finally, we conclude the paper in Section 4.

2 Cooperative merging control framework

A cooperative merging eco-control framework is designed to organize the vehicle in the control zone to finish ecological and efficient merging, as shown in Figure 1. Vehicles are assumed to be equipped with estimators which can provide the control center with accurate information detected by sensors. The vehicular information includes position, velocity, and acceleration of CAVs, etc., which are defined as the state variable vector Z^t. The framework includes a strategy layer and an operational layer. The strategy layer adopts centralized decision-making and obtains the optimal merging sequence $\eta_{t^*}^*$ and speed-adaption time t^* by constructing the sequencing game. In future possible merging sequences, the optimal sequence and speed-adaption time are determined based on the cost function. The results of the strategy layer are to maximize the overall ecology and efficiency benefits of two platoons, and they are sent to the operational layer as a command.

The platoons use a distributed control and are controlled by the distributed MPC controller. When the mainline platoon drives into the scheduling zone and accepts the command from the strategy layer, the vehicles travel in a tight formation before the speed-adaption time t^*. Thereafter, in the mainline and on-ramp platoons, the vehicles selected by the optimal sequence $\eta_{t^*}^*$ start to adjust their speeds in preparation for merging. When the on-ramp vehicles drive into the acceleration lane, they can directly merge into the ready space before the end of the acceleration lane. If the on-ramp platoon cannot finish the lane-changing process, the remaining vehicles in the mainline platoon accelerate and pass quickly, while the part of the ramp platoon that fails to merge decelerates and follows them.

Figure 1: The platoon-based cooperative merging eco-control framework



2.1 Strategy Layer: Merging Sequence Scheduling

In this section, according to the merging process, we define the sequencing game situation and establish the sequencing game model to present the decision-making of the merging sequence and determine the optimal merging sequence and speed-adaption time.

2.1.1 Formulation of Sequencing Game

Definition 1 (Sequencing situation) In a sequencing situation, the queue consists of n customers who are waiting to be served. The customers are denoted by $N = \{1,2,\cdots,n\}$, and the place of a customer in one permutation σ is subject to some constraints. Specifically, $\sigma(i) = j$ indicates that the i^{th} customer in the queue is in the j^{th} position. The server provides the service time s_i for each customer, $s_i > 0$. Each customer i has a cost function c_i which expresses its waiting cost. Formally, a sequencing situation is an ordered triple $(\sigma; c; s)$, where $\sigma \in \Pi_N$ which is a set of all permutation of N customers, $c_i: \mathbb{R}_+ \to \mathbb{R}$, $s_i \in \mathbb{R}_+^n$ for every $i \in N$.

Remark 1: In the merging scenario, the order of vehicles on the main lane and on-ramp lane is limited by traffic regulations and road conditions. These vehicles cannot change position but they can adjust the arrival sequence through the merging point. The merging point and the cost of the vehicle before it reaches the merging point can correspond to the server and the waiting cost of customers in the sequencing situation, and the lane-changing time gap is the service time. Hence, the mainline platoon and the on-ramp platoon can be defined as sequencing situations $(\sigma; c; s)$, $(\tau; c; s)$ here σ and τ are one permutation of the mainline and on-ramp platoons, respectively, and they form a merging sequence κ to pass the merging point; c is the cost function of vehicles that join the merging process; s originally denotes the time the consumer is served by the server, but it can be used to represent the lane-changing duration of on-ramp vehicles in the on-ramp area, which can be set to a constant because of the controllability and homogeneity of the CAVs. Therefore, if the two platoons generate a merging sequence κ, the total cost of the merging sequence is calculated as follows:

$$C_\kappa := c_1\left(\sum_{i\in P(\kappa,1)} s_i + s_1\right) + c_2\left(\sum_{i\in P(\kappa,2)} s_i + s_2\right) + \cdots + c_n\left(\sum_{i\in P(\kappa,n)} s_i + s_n\right) \quad (1)$$

where C_κ is the total cost of platoons with a merging sequence κ. $P(\kappa, i) \coloneqq \{j \in N | \kappa(j) < \kappa(i)\}$ represents the set of preceding vehicles in front of vehicle i in the sequence κ. s_i is the lane-changing duration of vehicle i. The total cost can be decreased by rearranging the merging sequence. The total cost is minimal according to the decreasing individual cost, i.e. the vehicle with the highest individual cost first, then the vehicle with the second highest individual cost, and so forth.

Remark 2: If vehicle i and vehicle j in the platoon are neighbors and vehicle i is in front of vehicle j, the total costs change which is equal to $c_j - c_i$ after switching them.

Definition 2 (Sequencing game) Let $N = \{1, 2, \cdots, N_1, N_1 + 1, \cdots, N_1 + N_2\}$ be a set of all vehicles in the scheduling zone called the *Grand Coalition*, N_1 is the number of vehicles in the mainline platoon, N_2 is the number of vehicles in the on-ramp platoon. Nonempty subsets S of N are called *Coalitions*, $S \subset N$. The proposed cooperative merging problem is constructed into a sequencing game $< N, \Theta >$ based on the coalition game theory. Θ: $2^N \to R$ is a characteristic function, which is the set of all possible coalitions of players to a set of payoffs that satisfies $\Theta(\emptyset) = 0$.

Remark 3: In a sequencing game, an original merging sequence needs not to be given, and a nonempty subset S generally has fewer possibilities to change the sequence, and the set of predecessors for the vehicle i is usually constrained.

Moreover, in centralized decision-making, in order to maximize the overall payoff, the optimal sequence given by the sequencing game may result in some vehicles having less payoff. CAVs are typically considered complete rational, which makes a decision by machine not human driver. Besides, the high efficiencies caused by the platoon driving need to be maintained by each vehicle, so vehicles will favor platoon interests over individual interests in decision making. Nevertheless, it is crucial to ensure that they do not reject the cooperation due to the perceived lower gain than expected.

Prior to the construction of a sequencing game for the merging scenario, it is necessary to identify the participants in the game. One current method is that all vehicles in the platoons are taken into account. However, as the number of vehicles increases, the computational load of this method becomes larger. The other method is that only a fixed number of participants are considered. Although this method can yield locally optimal decisions, as the platoons drive, the strategy of the previous group may not necessarily enhance the subsequent group's strategies. Consequently, a novel method is required to dynamically adjust the decision-making participants to ensure global optimization while avoiding excessive computational burden.

Remark 4: To determine the participants in the sequencing game, we propose a method based on the future states of the platoons. It predicts that vehicles in both platoons are driving at the maximum allowed speed, and vehicles that will conflict at the end of the acceleration lane are the participants of the sequencing game. The reason for considering vehicles at the maximum allowed speed is that platoons usually travel at high speeds for greater efficiency. On this basis, the trajectories generated by each conflict vehicle in the mainline platoon at the maximum and minimum allowed speed are predicted. The differences between trajectories are the merging space that can be provided by the mainline platoon for the on-ramp platoon. The platoon on the main road begins to drive at the maximum and minimum speeds its speed at time t_0, respectively. The on-ramp platoon maintains the maximum allowable speed. This is because the on-ramp maximum allowable speed is lower than that of the main road and the carbon emission per kilometer is higher. If the on-ramp platoon decelerates, it will result in a greater increase in carbon discharge and a loss of efficiency. The space of conflicting vehicles on the main road can be provided to accomplish a cooperative merging. Therefore, the vehicles can be determined to be the players in the sequencing game.

2.1.2 Cost Functions

In the proposed framework, the two main goals of the merging sequence decision-making are low carbon emissions and high traffic efficiency. When the vehicle enters the scheduling zone,

the costs of each vehicle begin to be calculated. The total costs of each sequence in the sequencing game are calculated by (1). In (1), the cost c_q of vehicle q consists of emission cost and efficiency cost.

$$c_q = \alpha_{ce} C_{\kappa(q),ce} + \alpha_e C_{\kappa(q),e} \quad (2)$$

In this paper, we use the carbon emission to express environmental impacts. Although connected and automated vehicles are generally considered to be powered by electricity, the main source of electricity currently and for a long time to come is thermal power generation. In fact, emissions from electric vehicles are transferred to the process of generating the electricity consumed rather than actually disappearing. At the current stage, the real environmental impacts of electric vehicles have not yet been expressed accurately.

However, it has become possible to establish an accurate representation of the relationship between vehicle movement and carbon emissions, and to model the representation of this relationship after decades of research. The emission cost of vehicle q is designed using the emission factor method in (DfT, 2009), and written as

$$C_{\kappa(q),ce}(t_p) = \sum_{t=t_p}^{T_p} \frac{\left(a + bv_q + cv_q^2 + dv_q^3 + ev_q^4 + fv_q^5\right)}{v_q} \quad (3)$$

where $C_{\kappa(q),ce}(t_p)$ denotes the carbon pollution exhausted by the q^{th} vehicle in platoons with a merging sequence κ at the possible speed-adaption time t_p, v_q is the velocity of the q^{th} vehicle, T_p is the prediction horizon of the platoons at the time t_p, N_1 and N_2 are the number of the vehicles in the mainline and on-ramp platoon, $a, b, c, \cdots, f$ are the coefficients.

Additionally, the efficiency cost of vehicle q is calculated by traffic delay and described as

$$C_{\kappa(q),e}(t_p) = \sum_{t=t_p}^{T_p} t_q^f - t_q^V \quad (4)$$

where $C_{\kappa(q),e}(t_p)$ denotes the delay caused by the q^{th} vehicle in the platoons with a merging sequence κ compared to the platoons remaining at a constant speed at the possible speed-adaption time t_p, t_q^f is the travel time of the vehicle with a merging sequence, t_q^V is the travel time of the vehicle q^{th} at a maximum allowable speed.

2.1.3 Constraints of Sequencing Game

In terms of traffic regulation, safety and efficiency, vehicles need to satisfy the following constraints:

- Traffic regulations. The minimal and maximal allowed speeds of vehicles on both lanes are

$$v_{main}^{min} \le v_{main,\sigma(i)} \le v_{main}^{max};\ v_{ramp}^{min} \le v_{ramp,\tau(j)} \le v_{ramp}^{max}$$

- Acceleration. Vehicles avoid driving risks from excessive changes in acceleration

$$a^{min} \le a_{\sigma(i)}, a_{\tau(j)} \le a^{max}$$

- Position. Restricted by road conditions, vehicles in the two platoons should maintain their original order to avoid the traffic chaos caused by overtaking.

$$\sigma(N_1) < \cdots < \sigma(2) < \sigma(1);\ \tau(N_2) < \cdots < \tau(2) < \tau(1)$$

2.2 Operational layer: Platoon Control

In this section, the operational layer controller is designed to control vehicles in the platoons to provide an available headway based on the optimal sequence $\eta_{t^*}^*$ and the speed-adaption time t^* from the strategy layer. The distributed MPC method is adopted to design the operational layer controller, as it can decompose the platoon optimization problem into the optimization problem of individual vehicles and has good adaptability and robustness.

2.2.1 Vehicle Dynamics

In the operational layer controller, the vehicle dynamic is modeled by the nonlinear third-order model (Yu *et al.*, 2020)

$$\begin{cases} \dot{x_k} = v_k \\ \dot{v_k} = a_k \\ \dot{a_k} = f_k(v_k, a_k) + g_k(v_k)\delta_k \end{cases} \quad (5)$$

where δ is the engine input. The f_k and g_k are expressed as

$$f_k(v_k, a_k) = -\frac{-2C_{dk}}{m_k} v_k a_k - \frac{1}{\alpha_k(v_k)}\left[a_k + \frac{C_{dk}}{m_k} V_k^2 + \frac{d_{mk}}{m_k}\right] \quad (6)$$

$$g_k(v_k) = \frac{1}{m_k \alpha_k(v_k)} \quad (7)$$

where C_{dk} denotes the aerodynamic drag coefficient, m_k is the vehicle's mass, α_k is the time constant of engine, and d_m is the mechanism drag.

In this nonlinear system, a nonlinear control law is adopted and described as

$$\delta_k = mu_k + C_{dk} v_k^2 + d_{mk} + 2\alpha_k C_{dk} v_k a_k \quad (8)$$

where u_k is the control input, which is generally the acceleration of the vehicle.

Additionally, this paper adopts the predecessors-following topology, the vehicle obtains the motion information from the preceding vehicle.

2.2.2 Platoon Modeling

In the operational layer controller, the safety distance is defined as the distance between two consecutive vehicles to pass the same location. We start adjusting the inter-vehicle spacing to provide the merging clearance for the on-ramp vehicle at the speed-adaption time t^*. Based on the optimal merging sequence $\eta_{t^*}^*$, we can calculate the number of on-ramp vehicles between two neighboring mainline vehicles, and to avoid destabilizing the platoon with drastic changes in speed, we need the change in safety distance to be gradual. So, the safe distance is calculated as follows.

$$\pi_{k,\eta}^{total} = d_k n_{k,\eta} + v_k n_{k,\eta} t_{lc} \quad (9)$$

$$\pi_{k,\eta}(t) = \begin{cases} d_k + \dfrac{\pi_{k,\eta}^{total} - \pi_{k,\eta}(t-1)}{T_p - t^*}(t - t^*) \\ d_k + t_{hw} v_k \end{cases} \quad (10)$$

where $\pi_{k,\eta}^{total}$ is the total safe distance that needs to be provided by the vehicle k under the sequence η, d_k is the minimal distance between vehicles when the platoon stops, $n_{k,\eta}$ is the number of vehicles that will merge in front of vehicle k according to the optimal merging sequence $\eta_{t^*}^*$, t_{lc} denotes the lane-changing duration of a vehicle in the merging process, which is a constant, $\pi_{k,\eta}(t)$ is the safe distance that needs to be provided by the vehicle k under the sequence η at time t, h_{tw} is the headway of the vehicle which is a constant.

The state variable vector is defined as $Z_k \coloneqq [e_{sk}, e_{vk}, a_k]^T$, then the following model is obtained:

$$\dot{Z_k} = \widehat{A_k} Z_k + \widehat{B_{2k}} u_k + \widehat{B_{1k}} a_{k-1} \quad (12)$$

with $\widehat{A_k} = \begin{bmatrix} 0 & 1 & -t_{hw} \\ 0 & 0 & -1 \\ 0 & 0 & -\tau^{-1} \end{bmatrix}$, $\widehat{B_{1k}} = \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix}$, $\widehat{B_{2k}} = \begin{bmatrix} 0 \\ 0 \\ \tau^{-1} \end{bmatrix}$, where e_{sk} and e_{vk} are the distance difference and the speed difference between two adjacent vehicles

2.2.3 Objective Functions

The distributed MPC decomposes the whole system into individual subsystems and solves their optimization problem at the same time and the updated information is shared with their neighbors. In order to minimize emission generation and accurately execute the optimal

sequence, the control objective is to minimize disturbance generation. Define $\widetilde{Z_k} \coloneqq [e_{sk}, e_{vk}, a_k - \overline{a_k}]^T$

$$\min_{U_k(t)} \sum_{j}^{P-1} \left|\left|\widetilde{Z_k}(t+j)\middle|t\right|\right|^2 Q + \left||u_k(t+j|t)|\right|^2 R \quad (13)$$

where P is the prediction horizon, Q and R are positive definite matrices, $\overline{a_k}$ is the predicted acceleration of the preceding vehicle $k-1$

The constraints of the objective function are as follows

$$0 \le x_{k-1}(t) - x_k(t) - L_k \le e_s^{max},\ k \ge 2,\ t \ge 0 \quad (14)$$

$$e_{vk}^{min} \le e_{vk}(t) \le e_{vk}^{max},\ k \ge 2,\ t \ge 0 \quad (15)$$

$$a_k^{min} \le a_k(t) \le a_k^{max},\ k \ge 2,\ t \ge 0 \quad (16)$$

where L_k is the length of the k^{th} vehicle. e_s^{max} is the allowed maximum distance between vehicles in the platoon, e_{vk}^{min} and e_{vk}^{max} are the permissible maximum and minimum speed differences between two adjacent vehicles, a_k^{min} and a_k^{max} are the maximum and minimum acceleration that are set, respectively.

3 Simulation results and discussion

In this section, we design the numerical simulations to verify the effect of the proposed method on carbon emission and efficiency. Section 3.1 presents the performance comparison with the baseline FIFO method (Uno et al, 1999) and the CTPG method in (Jing et al., 2019). Section 3.2 analyzes the sensitivity of the proposed method to platoon sizes and 121 platoon size combinations are considered. Based on the conclusions in Section 3.2, the different lengths of the on-ramp area and the scheduling zone are compared in Section 3.3. It should be pointed out that the same controller is used to ensure that the comparison results are fair.

- **Simulation setup:** In the proposed framework, there are many common parameters with the same values that are used to represent the maximum and minimum speed limits of the road, the length of the vehicle, the maximum and minimum acceleration, and so on. We therefore refer to other experimental designs and set some parameters as follows: $v_{main}^{min} = 16.7m/s$, $v_{main}^{max} = 25m/s$, $v_{ramp}^{min} = 11.1m/s$, $v_{ramp}^{max} = 16.7m/s$, $k_1 = 0.45$, $k_2 = 0.25$, $\pi_k = 2m$, $P = 10\,s$, $a_k^{min} = -3m/s^2$, $a_k^{max} = 3m/s^2$, $a = 2532.35791$, $b = 118.337652$, $c = -0.4316693$, $d = 0.00667756$, $Q = \begin{bmatrix} 200 & 0 \\ 0 & 100 \end{bmatrix}$, $R = 1$. The length of the main road in each experiment is 2500 m, the start positions of the on-ramp lane, scheduling zone and acceleration lane are 350 m, 900 m, 1500 m, the lenggth of the acceleration lane is 200 m, and the simulation duration ends when the platoon leaves the main road.
- **FIFO strategy:** This section adopts the FIFO strategy, which is used in where its effectiveness is recognized, as the baseline method for comparison. The decision-making process is that the mainline platoon imagines the position and required spacing of the virtual on-ramp CAVs according to the arrival order of vehicles in the on-ramp platoon, and then the vehicle in the on-ramp platoon merges into the mainline platoon in order of arrival.
- **CPTG strategy:** The proposed method, as a game theorical method, also needs to prove its superiority by comparing it with a game-based method in addition to a commonly used basic strategy like FIFO. The strategy requires that the vehicle in the on-ramp platoon plays a cooperative three-player game with two vehicles in the mainline platoon around the merging point when it drives in the decision-making area. It is a common cooperative game method which is used to solve cooperative merging problems.

3.1 Performance comparison

In this section, the proposed method is compared with the FIFO method and CTPG method. They are compared in the same scenario with three different platoon lengths where the mainline platoon size is 12 and on-ramp platoon sizes vary: 5, 10, and 15. Figure 2 only presents the trajectories of the platoons when the number of the mainline and on-ramp platoon are 12 and 15 due to space constraints. Table I illustrates that the proposed method outperforms the other two methods in terms of efficiency and emissions when the mainline platoon size is 12. The efficiency of the proposed method is significantly better than the other two methods in three cases. When the on-ramp platoon size is 5, the emissions generated by the proposed method are 0.07% higher than the FIFO method and 0.1% higher than the CTPG method respectively. The main reason for this phenomenon is the reduction of conflicting vehicles. In this case, the on-ramp platoon can drive directly to the rear of the mainline platoon without cooperation. But when the on-ramp platoon sizes are 10 and 15, the proposed method exhausts significantly less carbon emissions than the other two methods.

As shown in Figure 2, the trajectories of the platoon controlled by the proposed framework can reduce speed reduction while providing sufficient merging space. Vehicles' speed controlled by the proposed method is more stable than other two methods, they don't change frequently and increase or decrease dramatically. Furthermore, the speed of vehicles controlled by the proposed method is more often in the low carbon speed range than the other two methods.

Figure 2 The trajectories of the platoons when the number of the mainline and on-ramp platoon are 12 and 15

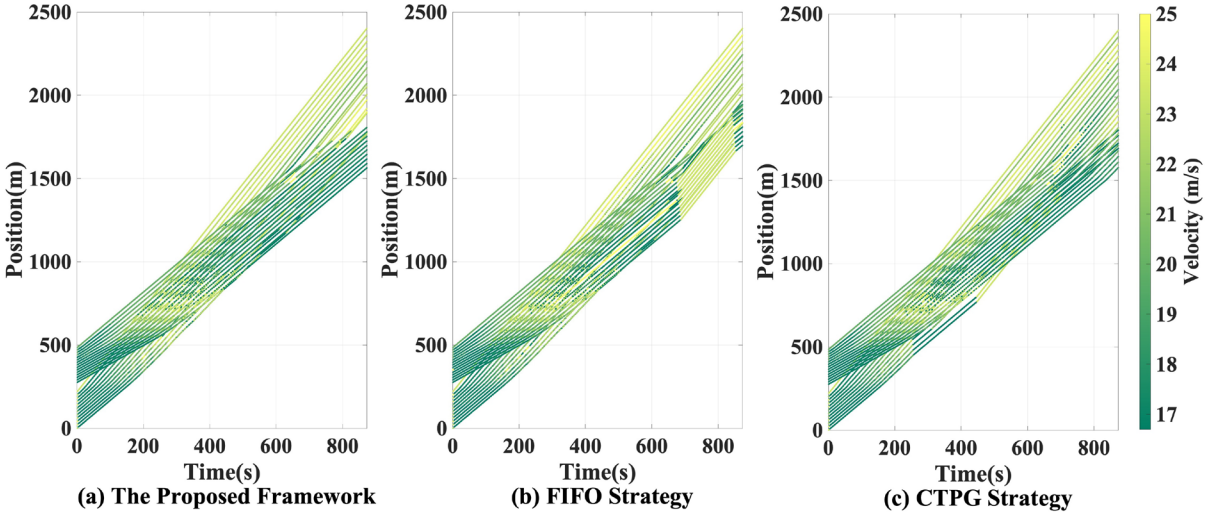


Table 1 Performance comparison results

Platoon Size	Delay(s)			CO_2 Emissions(kg)		
	Framework	FIFO	CPTG	Framework	FIFO	CPTG
12-5	85.79	87.30 (+1.76%)	87.93 (+2.49%)	5574.86	5570.75 (-0.07%)	5569.03 (-0.10%)
12-10	111.05	112.83 (+1.60%)	129.18 (+16.33%)	7015.53	7021.93 (+0.09%)	7893.02 (+12.51%)
12-15	155.46	156.12 (+0.42%)	195.03 (+25.45%)	8406.48	8431.60 (+0.30%)	10560.54 (+25.62%)

3.2 Sensitivity analysis of platoon sizes

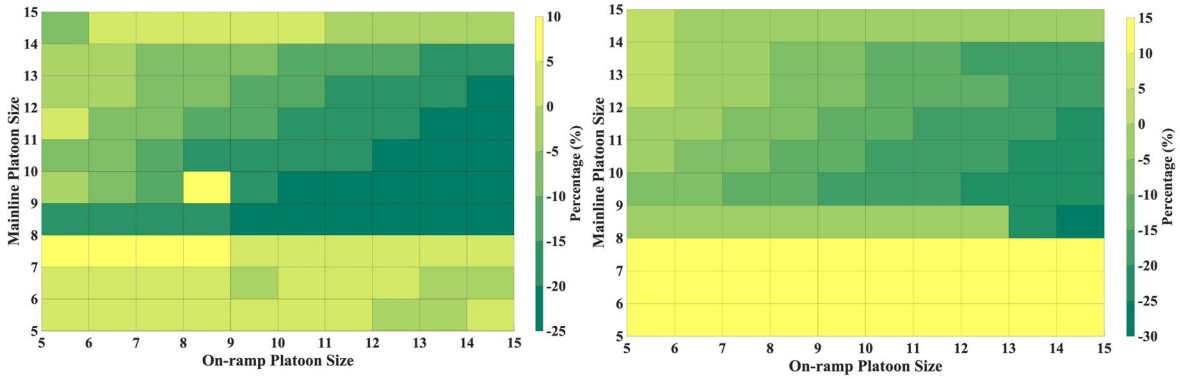
In this section, the sensitivity of the platoon sizes for the mainline and on-ramp platoons is analyzed. 121 combinations of platoon sizes are compared, and the delay and emission

differences of the proposed method compared to the FIFO strategy are calculated and shown in Figure 3, and the results compared to the CTPG strategy are shown in Figure 4.

As shown in Figure3, when the mainline platoon size is from 8 to 14, the delay and carbon emissions generated by the proposed framework are significantly less than the FIFO method. Compared with the CTPG method, when the mainline platoon size range is 8-14 in Figure 4, both the delay and emissions of the proposed method perform better than those of the CTPG method, however, when the mainline platoon has 15 vehicles, the proposed method produces less carbon emission but more delay than the CTPG method. Furthermore, in Figure 3 and Figure 4, when the platoon in the main road consists of 8-14 vehicles, with the number of vehicles in the on-ramp platoon increasing, the reduced delay and emission caused by the proposed method is smaller than those of the other two methods.

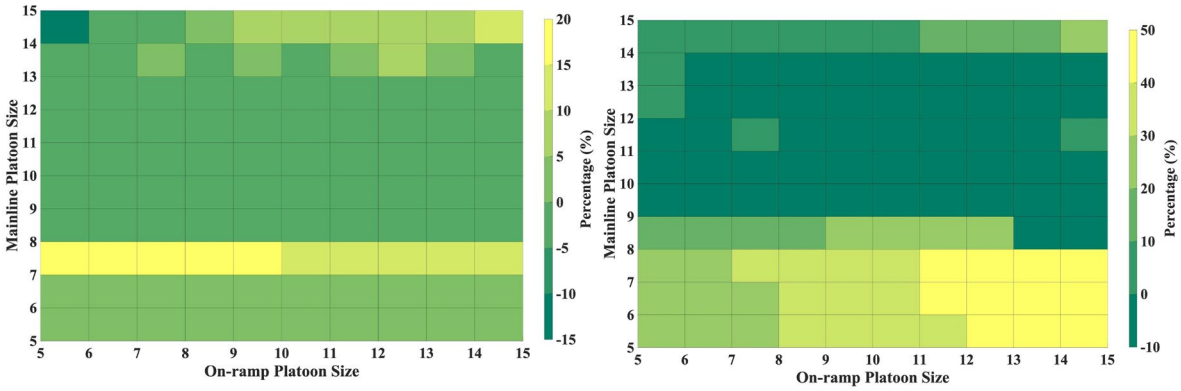
Comparing Figure 3 and Figure 4, we find that the improvement of the proposed method over the FIFO method is less than that of the CTPG method. The FIFO method controls vehicles according to the first-come-first-merged rule. When platoons enter the scheduling zone, it only needs to control the vehicles in the mainline platoon to prepare enough space for every on-ramp vehicles. Decelerating to provide space is incremental along the mainline platoon and is not applied to all vehicles. The CTPG method determines the game between the on-ramp vehicle and the two adjacent mainline vehicles to determine the local optimal merging sequence. Although the local optimum can be obtained, the optimal strategy of the proceeding on-ramp vehicle may not improve the decision-making payoff of the rear on-ramp vehicle. The effect of the GTPG method may not be better than that of the FIFO method in platoon-based merging. This is also the reason why the proposed method has less improvement compared to the FIFO method

Figure 3 Percentage change in delay and emission for the proposed method compared to the FIFO strategy



(a) Efficiency Difference (b) Emission Difference

Figure 4 Percentage change in delay and emission for the proposed method compared to the CTPG strategy



(a) Efficiency Difference (b) Emission Difference

Furthermore, an obvious phenomenon is that when the number of vehicles in the platoon on the mainline is less than 8, the delay and emissions produced by the proposed method are greater than those produced by the other two methods. As the number of vehicles on the on-ramp lane increases, the delay produced by the proposed method reduces, while the emissions increase. The main reason for this phenomenon is the reduction of conflicting vehicles. When the number of vehicles on the mainline is less than 8, the number of conflicting vehicles reduces or even eliminates. In this case, the on-ramp platoon can drive directly to the rear of the mainline platoon without cooperation. However, the proposed method tries to control and finish the possible cooperative merging thus increasing the delay and emissions.

Another phenomenon is that when there are 15 vehicles in the mainline platoon and more than 9 vehicles in the on-ramp platoon, the proposed method generates more delays and emissions than the other two methods. The main reason for this phenomenon is that, when the end point of the on-ramp lane is fixed, the increase in the platoon size means that the first vehicle in the on-ramp platoon enters the scheduling area earlier, and the number of vehicles in the mainline platoon that needs to participate in the cooperative obviously increases, and the costs also increase significantly. Furthermore, because of the small inter-vehicle spacing in the platoon, the vehicles cannot provide enough space at once or for a short time, which requires the platoon to brake gradually along the platoon in advance. The increase in the number of vehicles in the platoon means an increase in the total clearance that needs to be provided, making this task more difficult to accomplish.

As a result, the proposed method in this paper is more applicable to large-scale platoon merging scenarios with the mainline platoon and on-ramp platoon sizes greater than 8, but the length of the scheduling area needs to be increased as the platoon sizes increase so that the platoons have sufficient operable space for speed adjustment.

3.3 Analysis of the length of the scheduling zone and on-ramp area

Based on the analysis in Section 3.2, as the platoon size increases, both the length of the designed on-ramp area and the scheduling zone have an impact on the results of the proposed method. In this section, we design the experiment and analyze the effects of these two factors. The impacts of the on-ramp area is first discussed. The length of the scheduling zone is 600 m which is the same as the original experiment. Based on the initial scenario, the start point of the scheduling zone and acceleration lane and the road length increase by 100 m, 200 m, 300 m, and 400 m, respectively. The size of both platoons is 15. The comparison with itself and the two baseline methods is shown in Table 2.

Table 2 Percentage change in delay and emission for the proposed method compared with itself and the two baseline methods when the length of the on-ramp area increases

Increased length	Variations(vs. self) (%)		Variations(vs. FIFO) (%)		Variations(vs. CTPG) (%)	
	delay	emission	delay	emission	delay	emission
0	0	0	21.26	22.38	21.26	-0.65
100	-7.42	3.68	20.20	20.32	-3.71	-6.22
200	-12.96	7.83	-4.79	17.78	-22.10	-1.73
300	-19.84	11.82	-27.96	15.42	-33.90	2.39
400	-26.42	15.85	-42.64	13.04	-46.96	6.86

As shown in Table 2, there is a significant increase in the efficiency of the proposed method as the on-ramp area becomes longer, which correspondingly leads to an increase in carbon emissions. Compared to the two baseline strategies, the proposed method can significantly improve the efficiency of the platoon. In terms of carbon emission, the carbon emission generated by the proposed method is gradually decreasing compared to the FIFO strategy, increasing compared to the CTPG strategy. When the increased length is greater than 200 m, the carbon emission of the proposed method starts to be more than the carbon emission of the CTPG strategy. The results illustrate that the distance between the first vehicle in the

platoon and the acceleration lane affects the results of the proposed method, which can be balanced by distance settings for different objectives.

Besides, the length of the scheduling zone is also a potential factor that affects the outputs of the proposed method. In order to verify the effect of the length of the scheduling zone, we still set the two platoon sizes to 15, the length of the on-ramp area is increased by 400 m compared to the initial scenario. The length of the scheduling zone is increased by 100 m, 200 m, 300 m, and 400 m , respectively. The comparison with itself and the two baseline methods is shown in Table 3.

According to the results in Table 3, the change of the scheduling zone does not affect the results of the proposed method, and only when the length of the scheduling zone is increased by 100 m, there is a small improvement in the output results. Combining the results in Table 2 and Table 3, in the proposed method, the length of the scheduling zone does not affect the output results, but the distance between the first vehicle in the platoon and the acceleration lane can significantly affect the results. There are two main reasons for this phenomenon. One is that vehicles need to decelerate in order to provide merging gaps, and the effect of deceleration will be transmitted backward along the platoon, which requires sufficient manoeuvrable space at the back of the platoon. The other is that the effect of the length of the scheduling zone is weak, and the optimal sequence given is still mainly affected by the manoeuvrable space of the platoons. The distance between the first vehicle and the merging point should be set to the scheduling zone of the proposed method depending on the platoon size.

Table 3 Percentage change in delay and emission for the proposed method compared with itself and the two baseline methods when the length of the scheduling zone increases

Increased length	Variations(vs. self) (%)		Variations(vs. FIFO) (%)		Variations(vs. CTPG) (%)	
	delay	emission	delay	emission	delay	emission
0	0	0	-42.64	13.04	-46.96	6.86
100	-0.91	-0.08	-43.15	12.56	-47.44	6.77
200	0.09	0.11	-42.58	13.17	-46.91	6.97
300	0.10	0.11	-42.58	13.17	-46.91	6.97
400	0.10	0.11	-42.58	13.17	-46.91	6.97

4 Concluding remarks

This paper introduced a cooperative merging ecological control framework based on platoons. This framework oversees the platoons to achieve both global and individual optimal cooperative merging. The proposed framework adopts centralized decision-making and distributed control. Its strategy layer predicts the future status of platoons, introduces and constructs the sequencing game to solve the cooperative platoon-based merging problem, and then outputs the optimal merging sequence and speed-adaption time. The operational layer accepts the command from the strategy layer and uses a distributed MPC controller that can be optimal for the single vehicle while optimal for the overall.

The proposed framework was compared with the FIFO strategy and the CTPG strategy by simulation experiments. The results showed that the vehicles controlled by the proposed method can prepare the merging gaps in advance and more often keep their speed in a low-carbon speed range and generate fewer and weaker disturbances. Furthermore, the proposed method leads to reduced delays and emissions and optimizes efficiency more significantly as the platoon size increases, and is not constrained by platoon sizes. In practice, the proposed method can be applied not only to the on-ramp area, but also to the off-ramp and platoon merging in two adjacent lanes. In the future research, we will improve the computational efficiency when the platoon sizes increase and delve into multi-lane merging scenarios and

cooperative merging involving heterogeneous traffic to enhance its adaptability across various scenarios.

References

Chen N., B. V. Arem, T. Alkim, and M. Wang (2021) "A Hierarchical Model-Based Optimization Control Approach for Cooperative Merging by Connected Automated Vehicles." IEEE Transactions on Intelligent Transportation Systems.

Chen N., B. V. Arem, and M. Wang (2022) "Hierarchical Optimal Maneuver Planning and Trajectory Control at On-Ramps with Multiple Mainstream Lanes," IEEE Transactions on Intelligent Transportation Systems.

Department for Transport (DfT) (2009). Road vehicle emission factors 2009: regulated. https://www.gov.uk/government/publications/road-vehicle-emissionfactors-2009.

Fang Y., H. Min, X. Wu, W. Wang, X. Zhao and G. Mao (2022) "On-Ramp Merging Strategies of Connected and Automated Vehicles Considering Communication Delay." IEEE Transactions on Intelligent Transportation Systems.

Gao Z., Z. Wu, W. Hao, K. Long, Y. J. Byon, and K. Long (2022). "Optimal Trajectory Planning of Connected and Automated Vehicles at On-Ramp Merging Area." IEEE Transactions on Intelligent Transportation Systems.

Godbole D. and J. Lygeros (1997). "Longitudinal Control of The Lead Car of a Platoon." University of California, Berkeley.

Hang P., C. Lv, Y. Xing, C. Huang, and Z. X. Hu (2021). "Human-Like Decision Making for Autonomous Driving: A Noncooperative Game Theoretic Approach." IEEE Transactions on Intelligent Transportation Systems.

Hang P., C. Lv, C. Huang, Y. Xing, and Z. Hu (2022). "Cooperative Decision Making of Connected Automated Vehicles at Multi-Lane Merging Zone: A Coalitional Game Approach." IEEE Transactions on Intelligent Transportation Systems.

Huang Y. H., E. C. Y. Ng, J. L. Zhou, N. C. Surawski, E. F. C. Chan, and G. Hong (2018). "Eco-driving Technology for Sustainable Road Transport: A Review." Renewable & Sustainable Energy Reviews.

International Energy Agency (IEA) (2022). Greenhouse Gas Emissions from Energy Data Explorer, https://www.iea.org/data-and-statistics/data-tools/greenhouse-gas-emissions-from-energy-data-explorer.

Jia D. and D. Ngoduy (2016). "Platoon based Cooperative Driving Model with Consideration of Realistic Inter-vehicle Communication," Transportation Research Part C-Emerging Technologies.

Jiang H. F., J. Hu, S. An, M. Wang, and B. B. Park (2017). "Eco Approaching At An Isolated Signalized Intersection Under Partially Connected And Automated Vehicles Environment." Transportation Research Part C: Emerging Technologies.

Jing S. C., F. Hui, X. M. Zhao, J. Rios-Torres, and A. J. Khattak (2019). "Cooperative Game Approach to Optimal Merging Sequence and on-Ramp Merging Control of Connected and Automated Vehicles." IEEE Transactions on Intelligent Transportation Systems.

Liu H., W. Zhuang, G. Yin, Z. Li, and D. Cao (2023). "Safety-Critical and Flexible Cooperative On-Ramp Merging Control of Connected and Automated Vehicles in Mixed Traffic." IEEE Transactions on Intelligent Transportation Systems.

Lu X. Y. and K. J. Hedrick (2000). "Longitudinal Control Algorithm for Automated Vehicle Merging." Proceedings of the 39th IEEE Conference on Decision and Control.

Lu X. Y., H. S. Tan, S. E. Shladover, and J. K. Hedrick (2004). “Automated Vehicle Merging Maneuver Implementation for AHS.” Vehicle System Dynamic.

Ma F. W., Y. Yang, J. W. Wang, X. C. Li, G. P. Wu, Y. Zhao, L. Wu, B. Aksun-Guvenc, and L. Guvenc (2021). "Eco-driving-based cooperative adaptive cruise control of connected vehicles

platoon at signalized intersections." Transportation Research Part D: Transport and Environment.

Milanés V., S. E. Shladover, J. Spring, C. Nowakowski, H. Kawazoe, and M. Nakamura (2014). "Cooperative Adaptive Cruise Control in Real Traffic Situations." IEEE Transactions on Intelligent Transportation Systems.

Ngoduy D. (2013). "Platoon-based macroscopic model for intelligent traffic flow." Transportmetrica B: Transport Dynamics.

Posch B. and G. Schmidt (1983). “A Comprehensive Control Concept for Merging of Automated Vehicles under A Broad Class of Traffic Conditions,” IFAC Proceeding Volumes.

Raparthi N., and H. C. Phuleria (2022). "On-road vehicular emission characterization from the road-tunnel measurements in India: Morphology, emission factors, and sources." Environmental Research.

Schmidt G. and B. Posch (1983). “A Two-Layer Control Scheme for Merging of Automated Vehicles.” Proceeding 22nd IEEE Conference Decision and Control.

Stankovic S. S., M. J. Stanojevic, and D. D. Siljak (2000). "Decentralized Overlapping Control of a Platoon of Vehicles." IEEE Transactions on Control Systems Technology.

Uno A., T. Sakaguchi, and S. Tsugawa (1999). “A Merging Control Algorithm Based on Inter-Vehicle Communication.” Proc. IEEE/IEEJ/JSAI International Conference on Intelligent Transportation System.

Yang, L., J. H. Zhan, W. L. Shang, S. Fang, G. Y. Wu, X. M. Zhao and M. Deveci (2023). "Multi-Lane Coordinated Control Strategy of Connected and Automated Vehicles for On-Ramp Merging Area Based on Cooperative Game." IEEE Transactions on Intelligent Transportation Systems.

Yao Z., Y. Wu, Y. Wang, B. Zhao, Y. Jiang (2023). "Analysis of The Impact of Maximum Platoon Size of CAVs on Mixed Traffic Flow: An Analytical and Simulation Method." Transportation Research Part C: Emerging Technologies.

Yao Z. H., H. R. Jiang, Y. S. Jiang, and B. Ran (2023). "A Two-Stage Optimization Method for Schedule and Trajectory of CAVs at an Isolated Autonomous Intersection." IEEE Transactions on Intelligent Transportation Systems.

Yu, S. Y. et al. (2020). Nash optimality based distributed model predictive control for vehicle platoon. 21st IFAC World Congress on Automatic Control - Meeting Societal Challenges, Electr Network.

Zhao W. M., D. Ngoduy, S. Shepherd, R. H. Liu, and M. Papageorgiou (2018). "A Platoon Based Cooperative Eco-Driving Model for Mixed Automated and Human-Driven Vehicles at A Signalized Intersection." Transportation Research Part C: Emerging Technologies.

Zhou M., H. Jin, and W. S. Wang (2016). "A review of vehicle fuel consumption models to evaluate eco-driving and eco-routing." Transportation Research Part D: Transport and Environment.

Zong F., and S. Yue (2023). "Carbon Emission Impacts of Longitudinal Disturbance on Low-penetration Connected Automated Vehicle Environments." Transportation Research Part D: Transport and Environment.