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Cooperative Adaptive Cruise Control Platoon Fleet Formation Model Considering Efficiency and Stability

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Abstract: In the existing formation model, vehicles in the same lane or adjacent lane are regarded as the structure, and the driving behavior of vehicles is studied from the perspectives of safety, speed consistency, and stability, and the speed control model is proposed from the perspective of vehicles themselves, to obtain a stable fleet with the same distance and speed. However, in this process, the initial condition of the vehicle, the traffic flow environment, and the efficiency of the fleet formation are less considered. Therefore, based on summarizing the existing fleet building model, this paper puts forward the rapid construction model and algorithm of a cooperative adaptive cruise control platoon fleet. One of the important goals of forming a team is to enter the team with the smoothest trajectory in the shortest time. Therefore, this chapter studies the trajectory optimization of the vehicle formation process from the perspective of vehicle dynamics.

Keywords: Cooperative adaptive cruise control platoon; Fleet stability; Communication rules; Travel time

1. Introduction

Vehicle-road cooperation can obtain real-time information on vehicles and roadsides simultaneously, adjust vehicle speed, guide driving behavior from a global perspective, and coordinate the cooperation relationship between vehicles and human drivers [1]. From the perspective of collaborative control, the main line and ramp can be managed at the same time to quickly form a stable and reliable queue, improve import safety, and reduce the probability of slowing down concessions or stopping and waiting. Select the lane at the entrance according to the destination, contrast with the efficiency of the dedicated lane, reduce the number of lane changes in transit, and so on. Through the similarities and differences between the entrance and the target lane, the traffic flow operation state is predicted to achieve global control and optimization, and the traffic flow oscillation is reduced in the midway and the exit ramp. Most of the control strategies studied in the existing literature are limited to local areas, which often lead to significant adjustments in local traffic flow speed at ramp entry or exit nodes, causing violent shocks. However, this paper starts from the whole road section, considers the vehicle's exit lane demand from the starting point, and systematically optimizes the traffic flow at the starting point, ramp entrance, and destination point according to the time axis. It is of great theoretical and practical significance to reduce traffic flow oscillation and improve traffic efficiency.

The following model of mixed traffic flow based on the unified modeling method can better analyze the stability and improve the control effect of mixed traffic flow. The study by Xie *et al.* shows that human-driven vehicles and autonomous vehicles exhibit similar behaviors, in that both drivers and vehicles make decisions based on factors such as speed, following distance, speed differences, and others [2]. Based on the intelligent driver model, a mixed-flow following model is proposed. Zhang transformed the micro model and the macro model by improving the intelligent driver model and proposed a mixed-flow follower model suitable for human-driven vehicles and autonomous vehicles [3]. Zhou and Zhang took adjustable sensitivity and smoothing coefficients into account in the model [4]. Zong has analyzed the following characteristics of human-driven vehicles and autonomous vehicles, established a comprehensive front and rear vehicle dynamic tracking model based on the full velocity and acceleration difference model, and simulated the vehicle by using actual vehicle data [5]. Wang used the optimal velocity model to describe the human-driven vehicle following behavior and combined the improved adaptive cruise control following model to obtain the steady-state conclusion of traffic flow under two different mixed conditions [6]. Wang showed that the annular hybrid traffic system composed of connected autonomous vehicles and multi-human driven vehicles can maintain good stability under less interference [6]. On this basis, an optimal controller at the level of a hybrid transport system based on structural optimization control technology is proposed to overcome the problem of the limited communication capacity of connected autonomous vehicles.

From the perspective of the development of intelligent connected vehicles, when the penetration rate reaches a certain ratio, the operation efficiency of the cooperative adaptive cruise control platoon fleet will be greatly improved. However, in the optimization strategy of on-ramp inbound or off-ramp outbound, most of the application scenarios are independent optimization of a single intelligent vehicle, and only the information transmission between vehicles in front and behind a certain range is considered. The cooperative cruise driving mode is less considered. Under the operating conditions of a cooperative adaptive cruise control platoon fleet, the objectives and constraints of optimization control will change greatly. The motion trajectory and speed adjustment rule of cooperative adaptive cruise control platoon vehicles are studied in mixed traffic flow. Based on analyzing the driving characteristics of vehicles, the working conditions of the new team formation at the starting point and the split and reorganization of the team in the way were analyzed respectively, and then the vehicle trajectory was planned according to the communication rules and the state of the front and rear vehicles. The single-vehicle trajectory during the team formation was optimized with the goal of the shortest travel time, the least speed shock, and the highest driving comfort.

2. Multi-objective optimization model of fleet formation

The purpose of establishing the formation model is to enable vehicles to enter at different speeds, depending on their state during trajectory planning, and to ensure smooth vehicle formation with minimal cost. Therefore, from the perspective of efficiency, the formation model pursues the shortest duration of speed adjustment, that is, it can ensure the formation of queues quickly. From the stability point of view, the model pursues the minimum speed oscillation amplitude, which means the highest driving comfort.

(1) The formation model pursues the shortest duration of speed adjustment can be obtained by **Equation (1)**.

$$min\, T_i = \sum_j t_{ij}\, , (j = 3) \tag{1}$$

$$min\,T_i = T_i^{\,1} - T_i^{\,0} \tag{2}$$

(2) The smoothness of the driving trajectory can reduce emissions, save energy consumption, and increase passenger comfort while increasing vehicle stability. The driving smoothness is measured by the acceleration difference of adjacent periods. The model is expressed as follows:

$$min\,D_i = (\frac{1}{T_i}\int_0^{T_i}[a_i(t+1) - a_i(t)]^2\,)^{1/2} \tag{3}$$

$$T_i = \sum_j t_{ij} \tag{4}$$

(3) Since the front car has stabilized, the adjustment process of vehicle *i* can be divided into three stages according to the speed condition. Considering the requirements of safe following distance and stable fleet, the following constraints are established: According to the above expression for each stage of vehicle driving, the following constraint set can be obtained for the *i*th vehicle:

$$v_0^i + \sum_{j=1}^{7} \Delta v_i^j = v_s \tag{5}$$

$$L_0^i + v_s(\,t_1 + t_2 + t_3) - x_i = d_s \tag{6}$$

$$a_1,\ |a_3| \le a_{max} \tag{7}$$

$$v_0^i + \sum_{j=1}^{3} \Delta v_i^j \le v_{max} \tag{8}$$

$$L_0^i + v_s t_1 - \sum_{j=1}^{3} \Delta x_i^j \ge T_{safe}(v_0 + \sum_{j=1}^{3} \Delta v_i^j) \tag{9}$$

$$L_0^i + v_s(t_1 + t_2) - \sum_{j=1}^{4} \Delta x_i^j \ge T_{safe}(v_0 + \sum_{i=1}^{4} \Delta v_i^j) \tag{10}$$

3. Examples and analysis of results

The formation process of a cooperative adaptive cruise control platoon on a lane is simulated, which is suitable for the sparse traffic flow at the starting point or the team regrouping after changing lanes in the middle. The steady and constant speed of the front car is 25 m/s, the speed of the rear car is between 15 m/s and 30 m/s, and the acceleration is random in the range of 0 m/s2 to 2.5 m/s^2. The traffic flow distribution follows the Poisson distribution with an average interval of 3 s. According to the total length of the convoy, the trajectory of a convoy of ten randomly entering vehicles is simulated. After the solution sets of decision variables are obtained, the target values corresponding to each group of feasible solutions are obtained, and the ideal optimal solution is obtained.

To show the leading results of multi-objective Pareto more clearly, four out of ten vehicles are selected in **Figure 1** to show the range of target values. The selected vehicles one, four, seven, and eight respectively represent the change of the target value in four states when the vehicle enters the convoy.

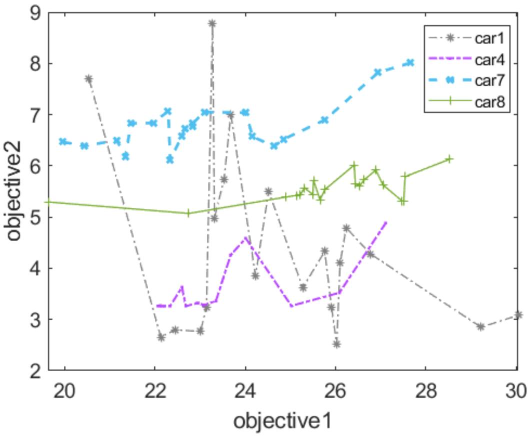

Figure 1. The leading results of multi-objective Pareto

It can be seen from the results that due to the difference in dimensions, the value range of binocular objects fluctuates greatly, and the target value brought by a set of Pareto solutions fluctuates greatly. Weights can generally be set according to the importance of the target value. The weight ratio of the two objectives determined in this paper is 3:1, and the solution set of decision variables corresponding to the optimal solution is obtained. The corresponding acceleration and deceleration values and duration of ten vehicles are shown in **Table 1**.

Table 1. The decision variable

Number	Acceleration (α_1)	Deceleration (α_3)	t_{21} (t_1)	t_{31} (t_2)	t_{41} (t_3)	ΔX_i
1	0.00	-0.67	6.07	13.24	6.00	515.94
2	1.50	-0.36	6.01	8.19	6.59	717.74
3	2.06	-0.60	6.08	8.47	7.74	739.53
4	1.37	-0.04	6.02	10.03	6.02	403.64
5	2.10	-1.02	6.22	8.44	6.71	706.14
6	2.22	-0.67	6.06	8.25	6.32	617.80
7	0.00	-2.99	6.41	8.23	6.51	514.62
8	1.23	-0.33	6.16	8.37	6.23	663.04
9	2.19	-0.87	6.13	8.20	7.40	676.10
10	0.00	-1.00	6.01	12.00	6.00	495.60

According to the optimal solution set solved in **Table 1**, the stage of vehicle acceleration can be judged and the corresponding value a(t) of each 1 s acceleration in the duration can be obtained. According to the solution results, the acceleration, speed, position, and following distance of ten vehicles over time are plotted, as shown in **Figure 2** to **Figure 4**.

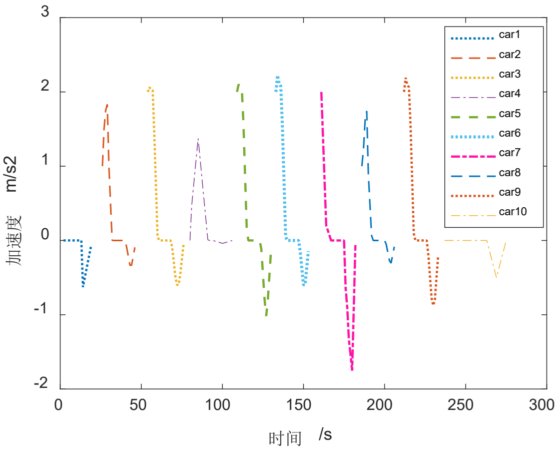

Figure 2. Acceleration over time

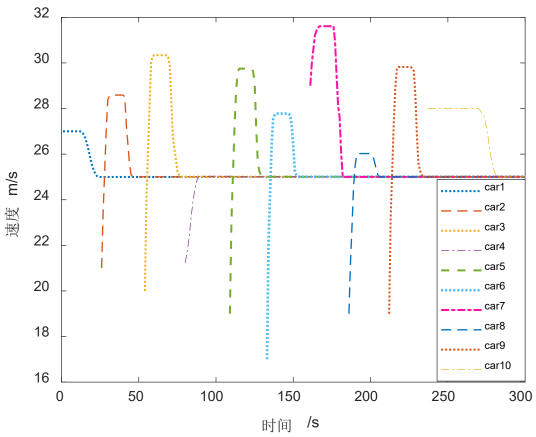

Figure 3. Velocity over time

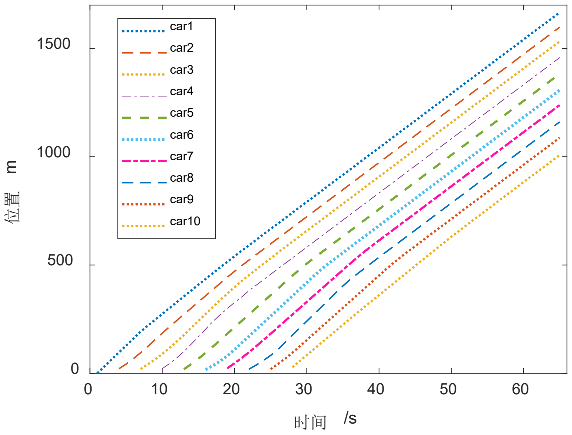

Figure 4. Location over time

As can be seen from **Figure 2** to **Figure 4**, the adjustment time of all ten vehicles is greater than 20 s and less than 30 s. Although the initial state of vehicles is different, the adjustment time of each vehicle is not much different. The total adjustment duration is: 25.31 + 20.7 + 22.29 + 22.07 + 21.37 + 20.63 + 21.15 + 20.67 + 21.73 + 24.01 = 219.66 s.

It can be seen from **Figure 4** that compared with the initial acceleration not equal to 0, the vehicle needs a shorter adjustment distance when the initial acceleration is 0. To sum up, the vehicle speed and following distance can be adjusted in a relatively short time under the premise of ensuring a safe distance, considering the dual objectives of stability time and vehicle smoothness.

4. Conclusion

According to the formation of the vehicle fleet at the starting point and the division and reorganization of the vehicle fleet caused by the lane change, the rules of the vehicle fleet formation and the trajectory planning model of the vehicle under different working conditions are analyzed respectively. This paper mainly studies the stable fleet formation model of the front car. In this paper, the motion characteristics of vehicles in the process of variable acceleration are analyzed, and constraints such as safety distance, vehicle characteristics, and stable vehicle terminal conditions are established during the formation of the convoy. Multi-objective constraints are established with the goal of the shortest time and maximum comfort, and a solution algorithm is given for the model characteristics of the stability of the front vehicle. The results show that the vehicle can be successfully merged into the fleet, forming a stable speed and safe distance cooperative adaptive cruise control platoon fleet, and can guarantee short time and small speed amplitude.

Disclosure statement

The authors declare no conflict of interest.

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