

Impact and controlling strategy of truck platoons in diverging areas under a connected and automated environment

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Abstract: To alleviate the truck barrier effect in diverging areas under a connected and automated environment, a lane-changing model that conforms to diversion characteristics was constructed. The effects of the truck proportion, the arriving flow rate of going-straight vehicles, the arriving flow rate of departing vehicles, the time headway, and the platoon length on the truck barrier effect were analyzed. A truck platoon controlling strategy (TPCS) was proposed and evaluated by integrating a lane change control strategy and platoon length limit strategy. The results show that different combinations of the truck proportion, the arriving flow rate of going-straight vehicles, and the arriving flow rate of departing vehicles are the macroscopic conditions for the formation of truck barriers. From the microscopic aspect, five or more trucks traveling in a platoon with a time headway no more than 2 s will cause the truck barrier effect. In addition, compared to the platoon and non-platoon statuses, TPCS can improve the off-ramp flow by up to 60% and 43%, respectively. Therefore, when the conditions for the formation of the truck barrier are met, traffic managers can implement TPCS to alleviate the truck barrier effect.

Key words: truck platoon; diverging area; truck barrier effect; controlling strategy; traffic simulation

DOI: 10.3969/j.issn.1003-7985.2023.02.005

With the rapid development of transportation systems, traffic congestion and air pollution have become increasingly severe issues. When traditional traffic management cannot provide sufficient support, connected and automated vehicles (CAVs) are the possible solution to these problems. CAVs within the communication range can achieve information sharing and cooperative control, thus improving traffic efficiency and reducing traffic pollution. However, if the distance between CAVs exceeds

the communication range, they will drive in adaptive cruise control mode, which reduces their advantages^[1]. However, according to the characteristics of group errands and uniform routes of trucking, the locations of trucks are relatively centralized, which fits the technical requirements of CAVs. Besides, the fuel consumption of trucks is massive, and advanced technology is urgently needed to reduce it. Therefore, trucks will be preferentially used in the form of CAVs, thus driving as platoons^[2].

The truck platoon shows considerable potential in improving traffic efficiency, reducing traffic pollution, and improving traffic safety. Tsugawa et al.^[3] suggested that platooning two or three trucks in dedicated lanes could increase road capacity by 25%. Shladover et al.^[4] found that truck platoons can reduce the likelihood of driver error, thus reducing the probability of accidents. McAuliffe et al.^[5] conducted field tests on a truck platoon with a following distance of 4 m and found fuel savings of 10%, 17%, and 13% for the leading, middle, and trailing trucks, respectively. In general, the above works have the following features: the study scenarios are mainly basic segments, and the truck platoons are considered to have mainly positive impacts. Thus, how truck platoons perform at bottlenecks such as diverging areas and whether they bring negative impacts deserve further consideration.

Some researchers have noticed that multiple trucks traveling continuously act like a moving wall, making it difficult for vehicles to enter or exit the mainline—a phenomenon known as the truck barrier effect^[6]. With the introduction of truck platoons, trucks are driving faster with shorter following distances and a more uniform driving behavior. The influence of emerging technologies on truck driving behavior appears to facilitate the formation of truck barriers, thereby having a more significant impact on traffic flow. Tabibi^[7] considered that it is difficult for vehicles to find gaps in truck platoons to cross when the truck flow is high. However, the conditions under which the truck barrier occurs have yet to be elucidated. Calvert et al.^[8] extended a dynamic model to examine the impact of truck platoons. It was concluded that the greatest negative impact of truck platoons comes from congestion near ramps, and trucks should platoon only during unsaturated traffic conditions. However, as a critical element, the number of trucks driving continuously has not received sufficient attention.

Received 2022-09-19, **Revised** 2023-03-08.

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Foundation items: The National Natural Science Foundation of China (No. 52002008), the Science and Technology Plan Projects of Beijing Municipal Commission of Transport (No. 11000022210200021338-XM001), the Beijing Municipal Education Commission Science and Technology Program General Project (No. KM202110005002).

Citation: Wen Shangwu, Kong Dewen, Sun Lishan, et al. Impact and controlling strategy of truck platoons in diverging areas under a connected and automated environment[J]. Journal of Southeast University (English Edition), 2023, 39(2): 142 – 152. DOI: 10.3969/j.issn.1003-7985.2023.02.005.

An increasing number of researchers have realized the importance of developing strategies to mitigate the negative impact of truck platoons. Zhao et al.^[9] derived the optimal platoon length (P_L) using a traffic jam identification model, but the specific steps of P_L adjustment were not mentioned. Hsu et al.^[10] designed a maneuvering protocol for platoons, including rules such as splitting, combining, and lane changing. The protocols were a strategy for dynamic adjustment, but the timing of their implementation was not mentioned. Tabibi^[7] proposed to terminate the platoon upstream of the off-ramp. However, this strategy causes CAVs to degrade into human vehicles (HVs), losing all the advantages of CAVs. In summary, the current strategies are proposed from several perspectives, but there are still shortcomings in feasibility and applicability.

For the truck barrier effect in diverging areas, although some researchers have realized the significance of the problem, there are still some gaps in current research. Firstly, the conditions for the occurrence of the truck barrier effect are not clear, and the impact of the effect has not been quantified. Secondly, some strategies have the following shortcomings: 1) The timing of decision-making is not emphasized; 2) The strategies directly sacrifice the advantages of CAVs; 3) The strategies are relatively inflexible. To address the above-mentioned gaps, this study first develops a lane-changing model that conforms to the traffic characteristics of the diverging area. Then, this study examines the effect of truck proportion (T_p), arriving flow rate of going-straight vehicles (A_s), arriving flow rate of departing vehicles (A_D), time headway (T_H), and P_L on the truck barrier effect. Finally, this study proposes a truck platoon controlling strategy (TPCS) and tests its effectiveness. The first contribution of this study is to clarify the critical conditions under which the truck barrier effect appears from macroscopic and microscopic aspects, thus providing a new discriminative method of truck barrier formation for future managers. The second contribution of this study is the innovative combination of two optimization strategies into a dynamically adjusted controlling strategy to mitigate the truck barrier effect. The TPCS mitigates the negative impact of truck platoons, and the advantages of CAVs are guaranteed not to be totally reduced.

1 Simulation Platform

1.1 Configuration for simulation scenario

Based on SUMO, a diverging area of a three-lane free-way with an off-ramp is chosen as the simulation scenario. Meanwhile, as the CAV technology will be preferentially applied to trucks, the simulation scenario is assumed to include only trucks (CAV) and small vehicles (HV), as shown in Fig. 1.

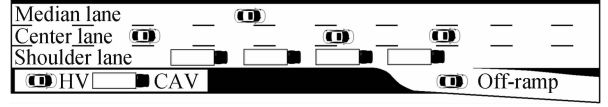


Fig. 1 Simulation scenario

1) To reflect the impact of truck platoons on the diverging area, the simulation scenario should be larger than the diversion impact area^[11]. Therefore, this study sets the mainline including the median lane, center lane, and shoulder lane, the length of each lane is 2 150 m, and the 180 m off-ramp is set at 2 000 m from the starting point of the mainline.

2) Considering the combination of the study scenario and traffic control strategies, this study sets trucks only allowed to drive in the shoulder lane based on the lane restriction strategy. Based on the speed limit strategy, this study sets the maximum speed for the median lane, center lane, shoulder lane, and off-ramp to 120, 110, 100, and 40 km/h, respectively.

3) The vehicle parameters are set by default. For trucks, the size is 16.5×2.55 m, the maximum speed is 110 km/h, the maximum acceleration is 1.1 m/s^2 , and the maximum deceleration is -4 m/s^2 . For small vehicles, the size is 5×1.8 m, the maximum speed is 120 km/h, the maximum acceleration is 2.6 m/s^2 , and the maximum deceleration is -4.5 m/s^2 .

1.2 Car-following models

The scenario will have four types of vehicle combinations based on the difference in vehicle type and vehicle location, as shown in Fig. 2. Parameters such as reaction time differ significantly for different combinations affected by emerging technology. Hence, it is necessary to differentiate car-following models based on different combinations.

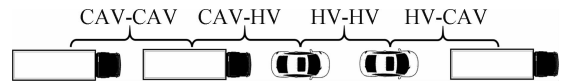


Fig. 2 Vehicle combination types

1.2.1 ACC model

When a CAV follows an HV, or there is no front vehicle, the CAV will drive in ACC mode^[12]. Therefore, the ACC model proposed by PATH is used to describe the driving behavior of the CAV in the above cases^[13]. The equations are given as follows:

$$a_{i,k} = k_1 e_{i,k} + k_2 (v_{i-1,k-1} - v_{i,k-1}) \quad (1)$$

$$e_{i,k} = p_{i-1,k-1} - p_{i,k-1} - L - t_{\text{des}} v_{i,k-1} - d_0 \quad (2)$$

$$d_0 = \begin{cases} 0 & v_{i,k} \geq 15 \\ \frac{75}{v_{i,k}} - 5 & 10.8 \leq v_{i,k} \leq 15 \\ 2 & v_{i,k} < 10.8 \end{cases} \quad (3)$$

where $a_{i,k}$ is the acceleration of vehicle i at time k ; $e_{i,k}$ is

the difference between actual space headway and desired space headway of vehicle i at time k ; $v_{i,k}$ is the speed of vehicle i at time k ; $p_{i,k}$ is the position of vehicle i at time k ; L is the vehicle length; t_{des} is the desired T_H , which is taken as 1.1 s; d_0 is the control difference of space headway; k_1 and k_2 are the control gains.

1.2.2 CACC model

The CACC model proposed by PATH is used to describe the driving behavior of the following vehicle in the CAV-CAV combination^[13]. The equations are given as

$$v_{i,k} = v_{i,k-1} + k_3 e_{i,k-1} + k_4 \frac{d(e_{i,k-1} - e_{i,k-2})}{dt} \quad (4)$$

$$e_{i,k} = p_{i-1,k-1} - p_{i,k-1} - L - t_{\text{des}} v_{i,k-1} - d_0 \quad (5)$$

$$d_0 = \begin{cases} 0 & v_{i,k} \geq 10 \\ -0.125v + 6.25 & v_{i,k} < 10 \end{cases} \quad (6)$$

where k_3 and k_4 are the control gains; t_{des} is the desired T_H , which is taken as 0.6 s.

1.2.3 Krauss model

The Krauss model is used to describe the driving behavior of the following vehicle in the HV-CAV and HV-HV combinations^[14]. The equations are given as follows

$$p_{i,k} = p_{i,k-1} + v_{i,k-1} + \frac{a_{i,k-1}}{2} \quad (7)$$

$$v_{i,k} = \max[0, v_{i,k}^a - \text{rand}(0, \infty \alpha)] \quad (8)$$

$$v_{i,k}^a = \min(v_{i,\text{max}}, v_{i,k-1} + a_{i,\text{max}}, v_{i,k}^s) \quad (9)$$

$$v_{i,k}^s = b_i \tau + \sqrt{(b_i \tau)^2 + v_{i-1,k}^2 - 2b_i g_{i,k}} \quad (10)$$

$$g_{i,k} = p_{i-1,k} - p_{i,k} - L \quad (11)$$

where $v_{i,k}^a$ is the available speed of vehicle i at time k ; α is the random factor; $v_{i,\text{max}}$ is the maximum speed of vehicle i ; $a_{i,\text{max}}$ is the maximum acceleration of vehicle i ; $v_{i,k}^s$ is the safe following speed of vehicle i at time k ; b_i is the comfortable deceleration of vehicle i ; τ is the driver reaction time; and $g_{i,k}$ is the space headway of vehicle i at time k .

1.3 Lane-changing model

The LC2013 model has been proven to be well-adapted for simulating freeway operations^[15]. Furthermore, because of the current technical limitations, CAVs need to switch to a manual driving mode when changing lanes^[16]. Therefore, the LC2013 model was selected as the base lane-changing model for vehicles in this study.

1.3.1 Lane-changing motive

The LC2013 model delineates four types of lane-changing motives, which are described in the literature^[15] for the specific formulation.

Tactical lane-changing is a lane change taken by a vehicle to reach a higher speed when vehicle in the front is slow.

Strategic lane-changing is a lane change taken by a vehicle to ensure successful arrival at the destination when the current lane does not connect to the next edge in the

travel route.

Cooperative lane-changing is a lane change taken by a vehicle to meet the needs of other vehicles to change to the current lane.

Obligatory lane-changing is a lane change that may occur after a vehicle overtakes the front vehicle from the left according to the traffic rule of overtaking on the left and driving on the right.

1.3.2 Safety criteria

To avoid a collision, SUMO will calculate the security gaps and determine whether the vehicle performs lane-changing according to

$$\left. \begin{aligned} d_i^f &\geq d_i^{sf} \\ d_i^b &\geq d_i^{sb} \end{aligned} \right\} \quad (12)$$

where d_i^f is the actual front gap of vehicle i ; d_i^{sf} is the secure front gap of vehicle i ; d_i^b is the actual back gap of vehicle i ; d_i^{sb} is the secure back gap of vehicle i .

The calculation of the security gap is given as

$$d_i^{sf} = T_i v_i + d_i^b - d_{i-1}^b \quad (13)$$

$$d_i^{sb} = T_i v_i + d_{i+1}^b - d_i^b \quad (14)$$

$$\left. \begin{aligned} d_i^b &= v_i n_i - v_i^r \frac{n_i + 1}{2} \\ v_i^r &= b_i t \\ n_i &= \frac{v_i}{v_i^r} \end{aligned} \right\} \quad (15)$$

where t denotes the time step.

1.3.3 Lane-changing rule improvement

In reality, there are significant differences in the lane change position for departing vehicles under different mainline flows (M)^[17]. However, the LC2013 model does not refine the lane-changing rules according to M and cannot show the above differences. Therefore, this study improves the lane-changing rule and develops a lane-changing model based on the divergence characteristics.

Based on the data of the Shanghai-Chongqing Freeway, the starting position of lane change for departing vehicles under different conditions is significantly different^[17].

As shown in Fig. 3, the increase in M will reduce the supply of available gaps, causing the starting position of the lane change to move toward the off-ramp.

To reflect the above patterns, this study introduces the

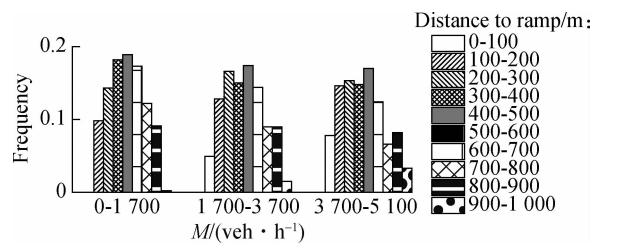


Fig. 3 Frequency of the starting position of lane change for departing vehicles

diversion characteristic coefficient k_{ic} into the strategic lane-changing rule to regulate the urgency of lane changes for departing vehicles,

$$d_e - o < k_{ic} v_f | O_1 | t_f \quad (16)$$

where d_e is the distance from the vehicle to the end of the current lane valid path; o is the traffic density correction constant for the lane; k_{ic} is the diversion characteristic coefficient; v_f is the expected speed of the vehicle to the end of the current lane valid path; O_1 is the offset of the vehicle to the final target lane; t_f is the time required for the lane change.

To further quantify the effect of k_{ic} on diversion characteristics, it is necessary to use the correlation between k_{ic} and the starting position of a lane change for departing vehicles through sensitivity analysis. The obtained quantitative relationship is shown as

$$y = \begin{cases} 0.2x^3 - 13.8x^2 + 282.8x - 3.8 & M \in (0, 1\ 700] \\ 0.2x^3 - 14.5x^2 + 283.5x - 11.2 & M \in (1\ 700, 3\ 700] \\ 0.3x^3 - 17.6x^2 + 294.8x + 43.9 & M \in (3\ 700, 5\ 100] \end{cases} \quad (17)$$

where y is the average distance from the start position of lane changes for departing vehicles; x is the value of k_{ic} ; M is the mainline flow.

The real data is inputted into Eq. (17) to obtain the k_{ic} distribution, as shown in Tab. 1.

Tab. 1 k_{ic} distribution of departing vehicles

$M/(\text{veh} \cdot \text{h}^{-1})$	k_{ic}	Frequency/%
(0, 1 700]	0.56	9.8
	0.94	14.3
	1.34	18.2
	1.75	18.9
	2.18	17.3
	2.64	12.2
	3.12	9.1
	3.62	0.2
(1 700, 3 700]	0.21	4.9
	0.58	12.8
	0.96	16.6
	1.36	15.0
	1.78	17.4
	2.22	14.4
	2.68	9.0
	3.17	9.0
	3.69	1.5
	0.02	7.8
(3 700, 5 100]	0.37	14.6
	0.73	15.3
	1.11	14.8
	1.51	17.0
	1.93	12.4
	2.37	6.6
	2.85	8.2
	3.36	3.3

2 Truck Barrier Judgments

To ensure the efficiency and stability of traffic operations in diverging areas, there is an urgent need to investigate the mechanism of the formation of the truck barrier effect. Current descriptions of the truck barrier effect fall into two main categories^[18]. From a macroscopic perspective, when the T_p , A_s , and A_D reach a certain level, the phenomenon that makes it difficult for vehicles to enter the off-ramp, which leads to a decrease in the off-ramp flow, is called the truck barrier effect. From a microscopic perspective, the truck barrier effect is manifested as multiple trucks driving continuously with a short T_H form a moving “wall” obstructing vehicles from crossing or bypassing, leading to increased difficulty in vehicle diversion.

Based on the above analysis, this study selects T_p , A_s , and A_D as macro factors and T_H and P_L as micro factors of the truck barrier effect. In the simulation, we obtain the changes in off-ramp flow under different conditions by changing T_p , A_s , A_D , T_H , and P_L to propose the criteria for the truck barrier effect in diverging areas.

2.1 Macroscopic aspect

The purpose of this experiment is to determine the flow conditions under which the truck barrier effect appears. When more than a certain number of trucks are platooning in the diverging area, vehicle diversion is impeded, and off-ramp flow decreases. In this case, we simulate the off-ramp traffic operation under the condition that trucks travel in the non-platoon status (Krauss) and platoon status (CACC) separately and compare the differences between them.

As shown in Fig. 4, when $A_D < 0.11$, the off-ramp flows in the platoon and non-platoon statuses increase with the increase in A_D . This indicated that under low diversion demand, whether trucks platoon or not has no effect on traffic efficiency in the diverging area. When $A_D > 0.11$, the off-ramp flow in both statuses decreases as the T_p increases, and it can be assumed that the increase in the truck flow further impedes vehicle diversion, and the impediment appears under a high diversion demand. In addition, the comparison shows that when the T_p and arriving flow rate of vehicles are the same, the off-ramp flow in the platoon status is lower than that in the non-platoon status, indicating that the truck platoon increases the difficulty of vehicle diversion.

This study obtains the difference in off-ramp flow caused by truck platoons to fully reflect the impact caused by the platoons, as shown in Fig. 5. When $T_p = 0.25$ and A_D and A_s fall in the light-colored area in Fig. 5(a), the off-ramp flow decreases by 120 veh/h on average, and the truck barrier effect can be observed. By delineating the light-colored area in Fig. 5, this study

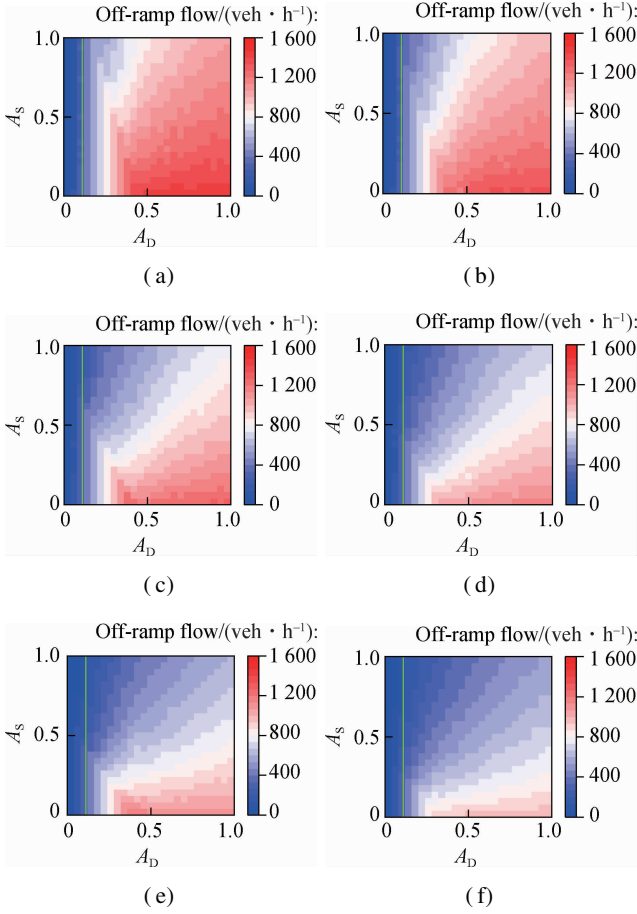


Fig. 4 Off-ramp flow under different traffic demands. (a) $T_P = 0.25$, non-platoon status; (b) $T_P = 0.25$, platoon status; (c) $T_P = 0.5$, non-platoon status; (d) $T_P = 0.5$, platoon status; (e) $T_P = 0.75$, non-platoon status; (f) $T_P = 0.75$, platoon status

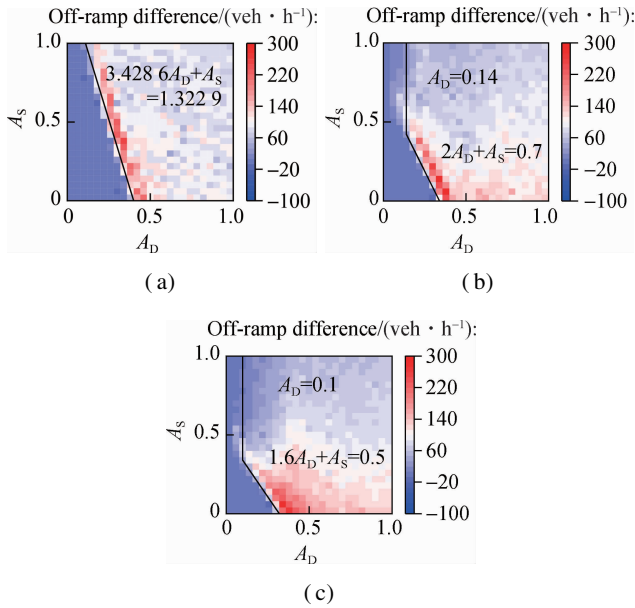


Fig. 5 Off-ramp flow difference. (a) $T_P = 0.25$; (b) $T_P = 0.5$; (c) $T_P = 0.75$

determines the macroscopic conditions for the truck barrier effect to appear as follows:

$$\left. \begin{array}{l} T_P > 0.25 \\ A_S > 0 \\ A_D > 0 \\ 3.428\ 6A_D + A_S > 1.322\ 9 \end{array} \right\} \quad (18)$$

$$\left. \begin{array}{l} T_P > 0.5 \\ A_S > 0 \\ A_D > 0.14 \\ 2A_D + A_S > 0.7 \end{array} \right\} \quad (19)$$

$$\left. \begin{array}{l} T_P > 0.75 \\ A_S > 0 \\ A_D > 0.1 \\ 1.6A_D + A_S > 0.5 \end{array} \right\} \quad (20)$$

2.2 Microscopic aspect

Based on the above works, this experiment selects $A_S = 0.44$, $A_S = 0.72$, and $A_S = 1$ to represent low, medium, and high diversion difficulty, respectively, and sets the T_P to 0.75. The A_D increases from 0 to 1 in a step of 0.04 to simulate various diversion demands. In the simulation, the microscopic conditions for the truck barrier effect to appear are quantified by changing the T_H and P_L of the truck platoon.

2.2.1 Time headway

To investigate the mechanism of the effect of T_H on the truck barrier, this experiment sets the P_L without limitation, and the T_H increases from 0.5 s to 3.0 s with the step of 0.5 s. Fig. 6 shows the variation of the off-ramp flow at different T_H .

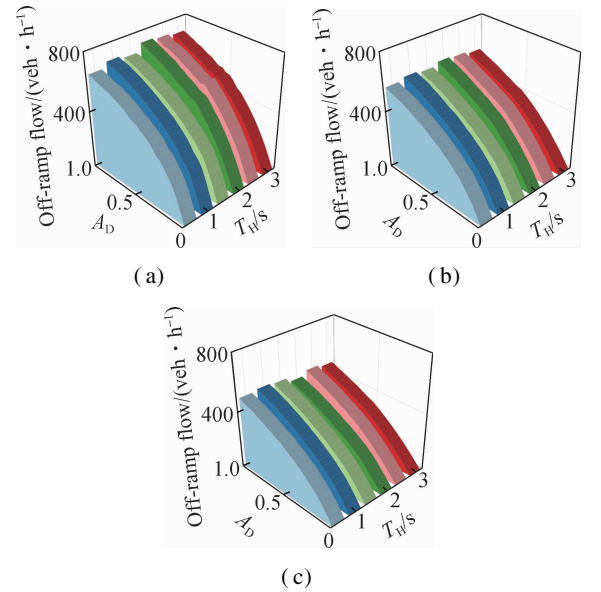


Fig. 6 Off-ramp flow at different T_H . (a) $A_S = 0.44$; (b) $A_S = 0.72$; (c) $A_S = 1$

As shown in Fig. 6, when T_H is shortened, the off-ramp flow under the same traffic conditions shows a trend of rising and then plunging, indicating that when availa-

ble gaps are sufficient, the appropriate shortening of T_H can improve traffic efficiency. However, when the T_H is shortened to a certain value, the available gaps decrease, causing the off-ramp flow to plunge. As shown in Figs. 6 (a) and (b), the T_H of 1.5 s will cause a sudden drop in the off-ramp flow, which can be considered as the formation of the truck barrier effect. As shown in Fig. 6(c), the critical value of T_H for the truck barrier effect becomes 2 s as the A_s increases to 1, indicating that with the increase of M , a longer T_H can trigger the truck barrier effect. In summary, this study concluded that the T_H of 2 s is the threshold for the truck barrier.

2.2.2 Platoon length

To investigate the mechanism of the effect of P_L on the truck barrier effect, this experiment sets the T_H of the truck platoon to 0.6 s and the P_L increases from 1 to 10 in a step of 1. Fig. 7 shows the variation of off-ramp flow under different P_L .

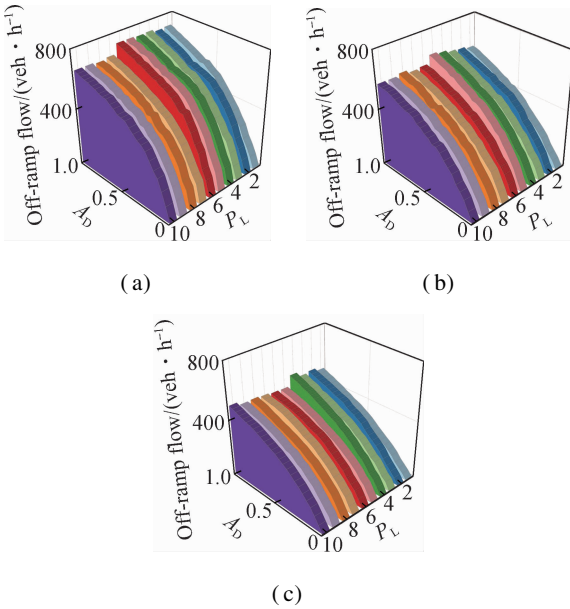


Fig. 7 Off-ramp flow at different P_L . (a) $A_s = 0.44$; (b) $A_s = 0.72$; (c) $A_s = 1$

As shown in Fig. 7, truck platoons of the same P_L will cause different degrees of obstruction to the departing vehicles under different conditions, and this obstruction is more significant compared to that in Fig. 6. As shown in Fig. 7(a), seven trucks in a platoon will lead to a significant reduction in the off-ramp flow, and the truck barrier effect can be observed. As shown in Fig. 7(b), the P_L of six will lead to a significant decrease in the off-ramp flow. As shown in Fig. 7(c), when A_s is 1, P_L reaches 5 will trigger the truck barrier effect. Notably, P_L which is required to form a truck barrier decreases as the A_s increases. In summary, this study concludes that P_L of five or more will cause the truck barrier effect.

3 Controlling Strategy

3.1 Strategy proposal

According to the judgments, corresponding strategies for mitigating the truck barrier effect should be proposed. Regulations and policies have an influence on traffic demand as a macro factor. Therefore, we cannot expect to alleviate the truck barrier effect by controlling traffic demand. However, when the traffic demand reaches the criteria, we can develop corresponding strategies according to the microscopic criteria. Therefore, we propose the TPCS at the micro aspect, which aims to create enough space through a series of controls to allow the departing vehicles to enter the off-ramp smoothly when the truck barrier effect appears.

The TPCS is proposed considering the following two aspects. Firstly, implementing the lane restriction strategy promotes the occurrence of truck barriers in the shoulder lane. We can consider interrupting the lane restriction strategy and shifting the location of truck barriers. Secondly, overlong truck platoons will impede departing vehicles from entering the off-ramp; thus, limiting P_L can be considered. To achieve the above-mentioned functions, TPCS consists of the lane-change control strategy (LCCS) and platoon length limit strategy (PLLS). The former is to control going-straight truck platoons to change to the center lane (see Fig. 8). The latter is to control overlong going-straight truck platoons for splitting (see Fig. 9). Considering that the truck needs to switch to the manual driving mode when changing lanes, this study assumes that the truck executes the PLLS only after completing the LCCS to avoid frequent switching of vehicle driving modes. The TPCS process is shown in Fig. 10.

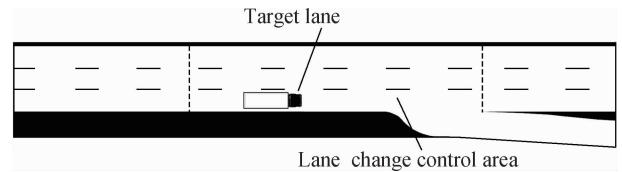


Fig. 8 Schematic of LCCS

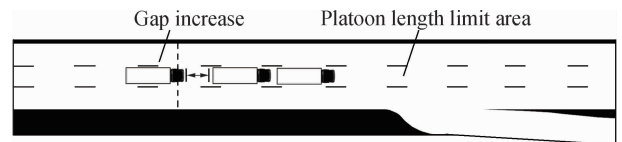


Fig. 9 Schematic of PLLS

3.2 Process for strategy

When the macroscopic conditions of the truck barrier effect are satisfied, TPCS should be implemented.

3.2.1 Process for LCCS

The truck entering the lane change control area will

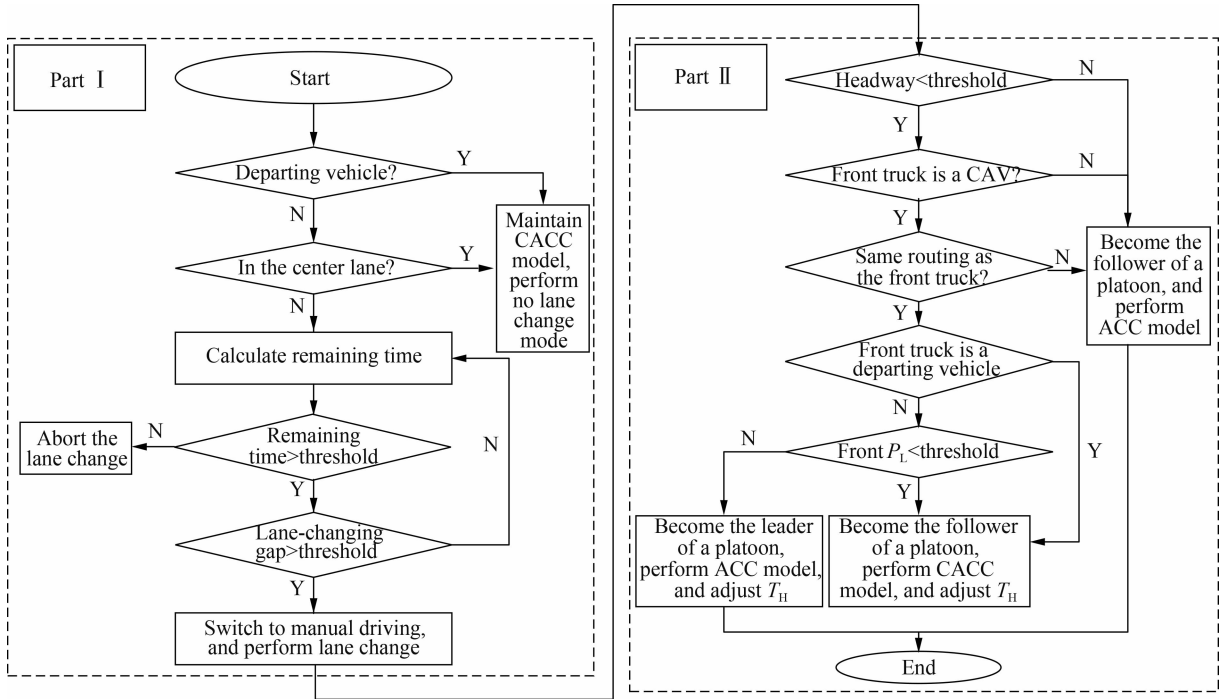


Fig. 10 Process for TPCS

first determine whether it is a departing vehicle. If it is a departing vehicle, the truck will keep the ACC or CACC model and set it to no lane change mode. Otherwise, the truck will detect whether it is in the center lane. If driving in the center lane, the truck will perform the ACC or CACC model and set to no lane change mode, thus staying in the center lane. Otherwise, the truck will change to the center lane within the remaining time. During this remaining time, if there is enough space in the center lane, the going-straight truck will switch to manual driving mode and perform the lane change. Otherwise, the going-straight truck will maintain the previous following state until there is enough space to support lane change.

Note that when the lane change control area is too small, or there is heavy traffic congestion, going-straight trucks may not be able to change to the center lane in the remaining time. In this case, the truck will abort the lane change and stay in the shoulder lane. It can be seen that under the control of the LCCS, the going-straight trucks will change to the center lane as much as possible. When the space in the center lane is insufficient, the going-straight trucks will give up the lane change and continue to drive in the shoulder lane.

For the parameter setting of PLLS, the remaining time refers to the time for the vehicle to travel to the end of the lane change control area at the current speed, and the threshold is set to 0 s; that is, the vehicle is controlled to change to the center lane before reaching the end of the lane change control area. The lane-changing gap is the distance between the vehicle in front and the vehicle behind in the target lane. When Eq. (12) is satisfied, this study considers the lane-changing gap to be greater than

the threshold.

3.2.2 Process for PLLS

According to the second part of the TPCS, the truck entering the platoon length limit area will use sensors to detect the type of vehicle ahead. If there is no front vehicle or the front vehicle is an HV, the truck will become the leader of the platoon and drive in the ACC model. Otherwise, the truck will detect the routing information of the front vehicle. If the front and ego vehicles have different routings, the ego truck will become the leader of the platoon and drive in the ACC model. Otherwise, the ego truck will decide based on the routing information of the front vehicle. If the ego truck is the same departing vehicle as the front vehicle, there is no need to restrict their P_L and T_H as the departing vehicle needs to enter the shoulder lane, and the ego truck will become the follower of the platoon and execute the CACC model. Otherwise, the truck will continue to sense information about the front P_L . To avoid causing the truck barrier effect, if the front P_L exceeds the threshold, the going-straight truck should execute the ACC model by setting the desired T_H to 1.1 s and thus become the leader of the platoon. Otherwise, the going-straight truck will execute the CACC model and become the follower of the front platoon by setting the desired T_H to 2.5 s, thus achieving splitting.

For the parameter setting of PLLS, the threshold of headway is set to 300 m. Furthermore, this study considers the $P_L \geq 5$ and $T_H \leq 2$ s as the microscopic criterion of the truck barrier effect. Therefore, for the departing truck platoon, this study sets the desired T_H of the leader to 1.1 s and that of the follower to 0.6 s. For the going-straight truck platoon, this study sets the desired T_H of the leader

to 1.1 s and that of the follower to 2.5 s, and the threshold of the front P_L is 4.

3.3 Implementation area

To facilitate the implementation of the TPCS, this study assumes that the lane-changing control area and platoon length limit area are of equal length and combines these two areas into the implementation area of the TPCS, which will have an impact on the traffic operation of the diverging area. Early lane changes may result in departing vehicles moving too early into the shoulder lane, reducing traffic efficiency. Late lane changes may result in departing vehicles not being able to enter the shoulder lane to diverge. Furthermore, early splitting may result in the advantages of CAVs not being maximized, and late splitting may result in the continued truck barrier effect caused by truck platoons. Therefore, determining the implementation area is important for applying TPCS.

The following factors must be considered when designing the implementation area. Firstly, because the degree of influence of the truck barrier effect varies under different traffic demands, the implementation area under different traffic demands should be designed differently. Secondly, the departing vehicles need to complete the lane change before the split end of the off-ramp. Therefore, the split end of the off-ramp is selected as the end of the implementation area. Additionally, Tab. 2 shows the simulation parameters. The variation of the off-ramp flow under different implementation area lengths is shown in Fig. 11.

Tab. 2 Parameters of the simulation

Scenario	T_p	A_s	A_D
1a	0.25	0.44	0.44
1b	0.25	0.44	1.00
1c	0.25	1.00	0.44
1d	0.25	1.00	1.00
2a	0.50	0.44	0.44
2b	0.50	0.44	1.00
2c	0.50	1.00	0.44
2d	0.50	1.00	1.00
3a	0.75	0.44	0.44
3b	0.75	0.44	1.00
3c	0.75	1.00	0.44
3d	0.75	1.00	1.00

As shown in Fig. 11, under different traffic conditions, the variation of off-ramp flow with the length of the implementation area shows different patterns. When $T_p=0.25$ and $A_D=0.44$, the off-ramp flow first increases with the increase in length. When the length reaches 3 700 and 4 000 m, respectively, the off-ramp flow peaks and then stays at a certain level. In other scenarios, the off-ramp flow steadily increases with an increase in the length and peaks at a length of about 6 000 m. The above

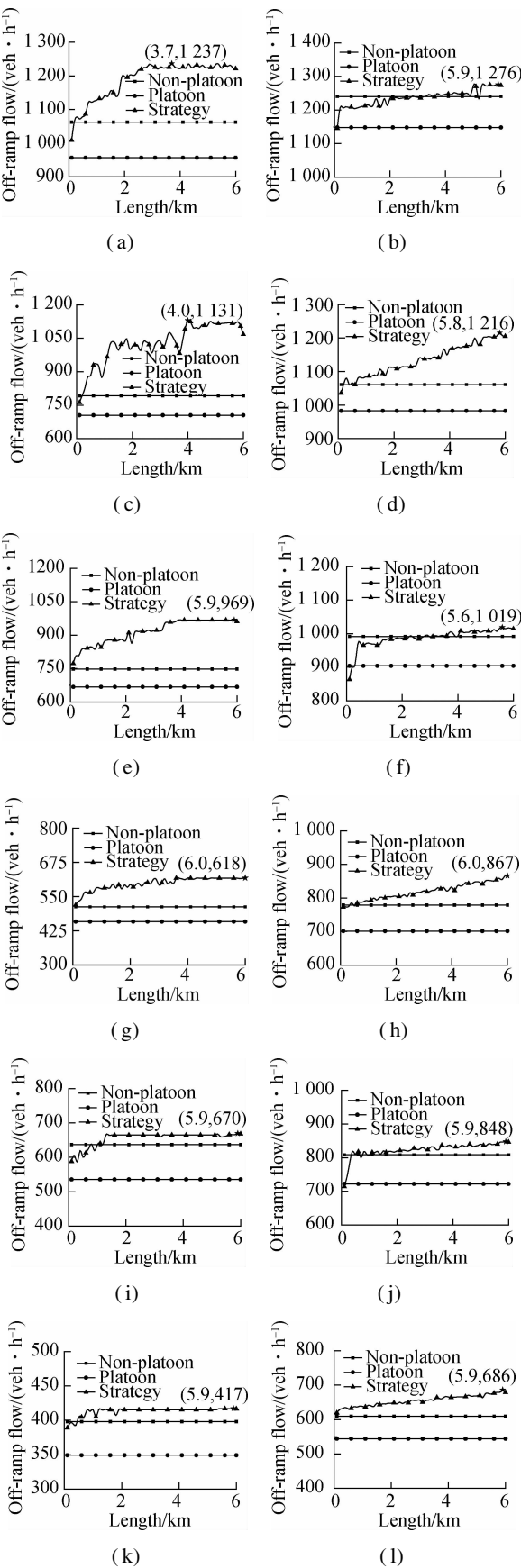


Fig. 11 Off-ramp flow at different lengths of the implementation area. (a) Scenario 1a; (b) Scenario 1b; (c) Scenario 1c; (d) Scenario 1d; (e) Scenario 2a; (f) Scenario 2b; (g) Scenario 2c; (h) Scenario 2d; (i) Scenario 3a; (j) Scenario 3b; (k) Scenario 3c; (l) Scenario 3d

differences indicate that the increase in A_D and T_p will require a sufficient implementation area to meet the demand for lane change and splitting of the truck platoon, so the length corresponding to the peak of the off-ramp flow increases.

In the selection of the implementation area length, this study considers that TPCS is effective, and the corresponding length is desirable when the off-ramp flow after the implementation of TPCS is higher than that in the platoon and non-platoon statuses. Meanwhile, when the off-ramp flow reaches the peak, this study considers that the corresponding length is optimal, as shown in Tab 3.

Tab.3 Recommended lengths of the implementation area

Scenario	Recommended length/m	Promotion ratio of off-ramp flow/%	
		Compared to the platoon status	Compared to the non-platoon status
1a	3 700	29	16
1b	5 900	11	3
1c	4 000	60	43
1d	5 800	24	15
2a	5 900	45	29
2b	5 600	13	3
2c	6 000	35	21
2d	6 000	24	11
3a	5 900	25	5
3b	5 900	17	5
3c	5 900	20	5
3d	5 900	26	13

Tab. 3 shows that when the T_p is 0.25, TPCS can increase the off-ramp flow by up to 43% and 60% compared to non-platoon and platoon statuses, respectively. TPCS can increase off-ramp flow by up to 13% and 26% at a T_p of 0.75. Moreover, the implementation of TPCS is slightly less effective when $T_p=0.25$ and $A_D=0.44$ compared to other traffic conditions. It can be concluded that the implementation of TPCS can effectively mitigate truck barriers, and this effect is especially significant when the T_p and A_D are not low.

4 Strategy Evaluation

Considering that TPCS guides the truck platoons to change lanes and split, the efficiency, stability, and safety of traffic flow in the diverging area will be affected. This section follows the flow methodology of Tab. 2 to compare and analyze the traffic efficiency, safety, and stability of the diverging area with and without TPCS.

4.1 Traffic efficiency

In this study, M is used to verify the effectiveness of TPCS in terms of traffic efficiency. The results are shown in Fig. 12.

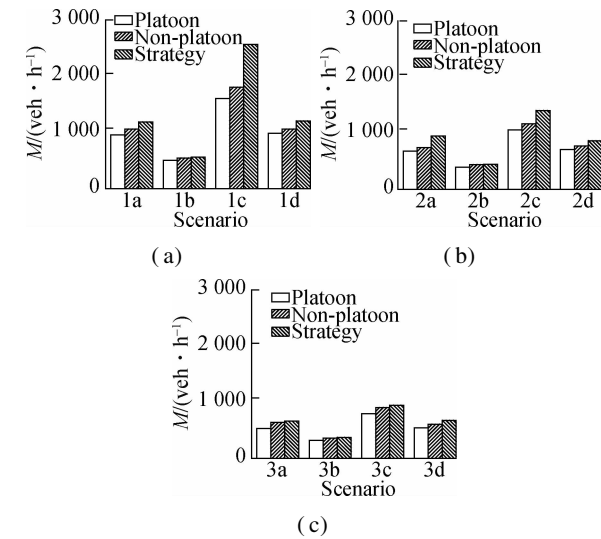


Fig. 12 M in different scenarios: (a) Scenario 1; (b) Scenario 2; (c) Scenario 3

As shown in Fig. 12, after the implementation of TPCS, M in each scenario is higher than that in non-platoon and platoon statuses, indicating that TPCS can improve the traffic efficiency of the mainline while increasing the off-ramp flow. In addition, the advantage of TPCS in improving M decreases with the increase in T_p , indicating that the benefit of TPCS in terms of traffic efficiency decreases with the increase in truck flow, but it is still effective.

4.2 Traffic safety

In this study, the vehicle average conflict time (t_c) was used to verify the effectiveness of TPCS in terms of traffic safety. The results are shown in Fig. 13.

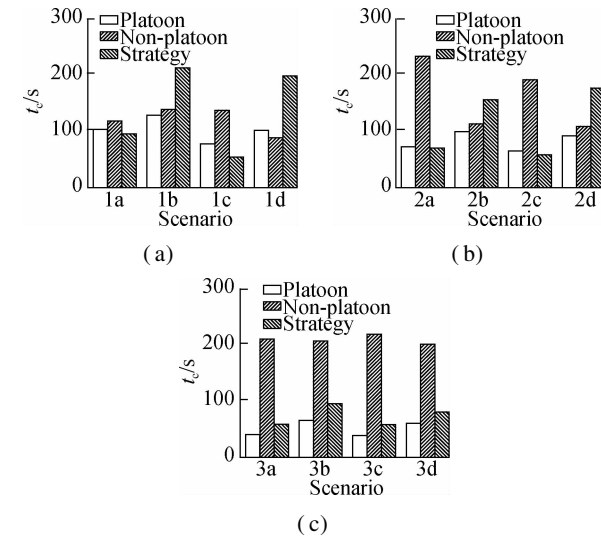


Fig. 13 t_c in different scenarios: (a) Scenario 1; (b) Scenario 2; (c) Scenario 3

As shown in Fig. 13, the effectiveness of TPCS in traffic safety varies depending on traffic conditions. When A_D is high, the safety of TPCS is relatively low, probably because many departing vehicles change to the

shoulder lane at the same time that the truck platoon changes to the center lane, making traffic conflicts more significant. However, in other scenarios, the performance of TPCS in terms of safety is not significantly different from that in platoon and non-platoon statuses.

4.3 Traffic stability

In this study, the speed standard deviation of small vehicles (S_D) is used to verify the effectiveness of TPCS in terms of traffic stability. The results are shown in Fig. 14.

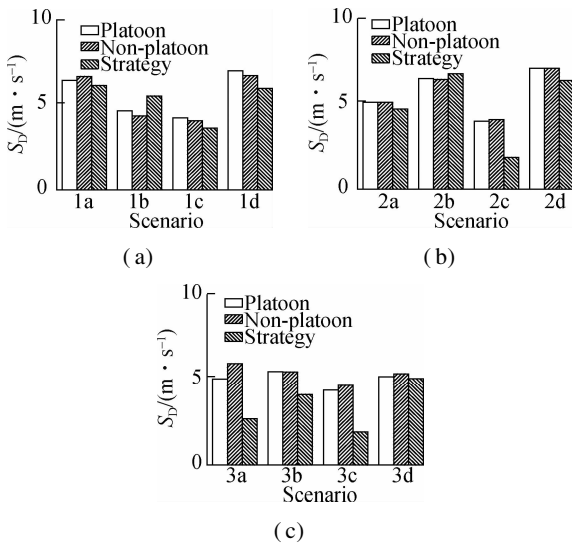


Fig. 14 S_D in different scenarios: (a) Scenario 1; (b) Scenario 2; (c) Scenario 3

As shown in Fig. 14, after the implementation of TPCS, S_D decreases compared to the platoon and non-platoon statuses, indicating that by shifting and splitting the truck platoon, the vehicle layout in the diverging area can be optimized, and traffic flow stability can be effectively improved.

5 Conclusions

1) This study determines the different combinations of T_p , A_s , and A_D when the truck barrier effect appears from the macroscopic aspect and proposes from the microscopic aspect that five or more trucks traveling in a platoon with T_H no more than 2 s are the critical conditions for the truck barrier effect to occur.

2) The implementation of the TPCS can mitigate the truck barrier effect in the diverging area and increase off-ramp flow. Furthermore, the improvement is particularly significant at higher T_p and A_D .

3) The implementation of TPCS can improve M and S_D while safeguarding t_c . Therefore, the effectiveness of TPCS in improving the efficiency, stability, and safety of traffic flow in the diverging area is verified.

References

- [1] Shladover S E, Su D, Lu X Y. Impacts of cooperative adaptive cruise control on freeway traffic flow[J]. *Transportation Research Record*, 2012, **2324**(1): 63 – 70. DOI: 10.3141/2324-08.
- [2] Bhoopalam A K, Agatz N, Zuidwijk R. Planning of truck platoons: A literature review and directions for future research[J]. *Transportation Research Part B: Methodological*, 2018, **107**: 212 – 228. DOI: 10.1016/j.trb.2017.10.016.
- [3] Tsubawa S, Jeschke S, Shladover S E. A review of truck platooning projects for energy savings[J]. *IEEE Transactions on Intelligent Vehicles*, 2016, **1**(1): 68 – 77. DOI: 10.1109/tiv.2016.2577499.
- [4] Shladover S E, Nowakowski C, Lu X Y, et al. Cooperative adaptive cruise control: Definitions and operating concepts [J]. *Transportation Research Record*, 2015, **2489**(1): 145 – 152. DOI: 10.3141/2489-17.
- [5] McAuliffe B, Lammert M, Lu X Y, et al. Influences on energy savings of heavy trucks using cooperative adaptive cruise control [J]. *SAE Technical Paper*, 2018: 1181. DOI: 10.4271/2018-01-1181.
- [6] Garber N J, Gadiraju R. *Effects of truck strategies on traffic flow and safety on multilane highways (abridgment)* [M]. Washington, DC, USA: Transportation Research Board, 1990: 49 – 54.
- [7] Tabibi M. *Design and Control of automated truck traffic at motorway ramps* [M]. Delft, the Netherlands: The Netherlands TRAIL Research School, 2004: 69 – 75.
- [8] Calvert S C, Schakel W J, van Arem B. Evaluation and modelling of the traffic flow effects of truck platooning [J]. *Transportation Research Part C: Emerging Technologies*, 2019, **105**: 1 – 22. DOI: 10.1016/j.trc.2019.05.019.
- [9] Zhao C, Li L, Li J W, et al. The impact of truck platoons on the traffic dynamics around off-ramp regions[J]. *IEEE Access*, 2021, **9**: 57010 – 57019. DOI: 10.1109/access.2021.3072070.
- [10] Hsu A, Eskafi F, Sachs S, et al. Protocol design for an automated highway system [J]. *Discrete Event Dynamic Systems*, 1993, **2**: 183 – 206. DOI: 10.1007/bf01797158.
- [11] Eleftheriadou L A. The highway capacity manual 6th edition: A guide for multimodal mobility analysis [J]. *ITE journal*, 2016, **86**(4): 14 – 18.
- [12] Wang H, Qin Y Y, Wang W, et al. Stability of CACC-manual heterogeneous vehicular flow with partial CACC performance degrading [J]. *Transportmetrica B: Transport Dynamics*, 2019, **7**(1): 788 – 813. DOI: 10.1080/21680566.2018.1517058.
- [13] Xiao L, Wang M, Schakel W, et al. Unravelling effects of cooperative adaptive cruise control deactivation on traffic flow characteristics at merging bottlenecks [J]. *Transportation Research Part C: Emerging Technologies*, 2018, **96**: 380 – 397. DOI: 10.1016/j.trc.2018.10.008.
- [14] Cui J F, Hu B X, Xia H, et al. Comparative analysis of simulation of multi-car-following modes under SUMO platform [J]. *Journal of Chongqing University*, 2021, **44**(7): 43 – 54, 98. DOI: 10.11835/j.issn.1000-582X.2020.250. (in Chinese)
- [15] Erdmann J. SUMO's lane-changing model [C] // *Model-*

ing Mobility with Open Data: 2nd SUMO Conference 2014. Berlin, Germany, 2015: 105 – 123. DOI: 10.1007/978-3-319-15024-6_7.

[16] Liu H, Kan X D, Shladover S E, et al. Modeling impacts of cooperative adaptive cruise control on mixed traffic flow in multi-lane freeway facilities[J]. *Transportation Research Part C: Emerging Technologies*, 2018, **95**: 261 – 279. DOI: 10.1016/j.trc.2018.07.027.

[17] Hou J. *The traffic characteristics and capacity analysis method for diverge influence area on multi-lane freeways* [D]. Nanjing: Southeast University, 2018. (in Chinese)

[18] Sun L S, Zhao S H, Kong D W, et al. Formation conditions and effects of large vehicle barrier on confluence area under automatic driving[J]. *Journal of Beijing University of Technology*, 2022, **48**(8): 851 – 859. DOI: 10.11936/bjutxb2021040021. (in Chinese)

智能网联环境下分流区卡车编队交通影响与控制策略

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摘要:为缓解智能网联环境下分流区的大车屏障效应,构建了符合分流特性的变道模型,分析了卡车比例、直行车辆进入概率、分流车辆进入概率、车头时距与编队规模对大车屏障效应的影响.将变道控制策略和编队规模限制策略相结合,提出并评估了卡车编队控制策略(TPCS).结果表明,卡车比例、直行车辆进入概率与分流车辆进入概率的不同组合是大车屏障效应产生的宏观条件.在微观层面,5 辆及以上卡车以不超过 2 s 的车头时距编队行驶是大车屏障效应产生的临界条件.相较于编队状态与非编队状态,TPCS 可分别将出口匝道流量提高 60% 和 43%.因此,满足大车屏障效应的产生条件时,交通管理者可实施 TPCS 缓解大车屏障效应.

关键词:卡车编队;分流区;大车屏障效应;控制策略;交通仿真

中图分类号:U491