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The Impact of Truck Platoons on the Traffic Dynamics Around Off-Ramp Regions

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ABSTRACT The platooning technique has shown potential to bring pronounced benefits to road traffic, including higher safety, better fuel economy, and greater comfort. However, an overlong platoon may jeopardize the overall traffic efficiency because of the unintentional obstruction to other traffic participants. Hence, this paper proposes an advance adjustment strategy for the truck platoon in the off-ramp scenarios to reduce the impact on the predictable lane changes of other vehicles. We derive the appropriate platoon length with an analytic method and verify the effectiveness of conclusions via simulations. Both theoretical calculation and simulation experiment results prove that controlling the platoon length within a reasonable range can significantly improve traffic efficiency near a ramp. This study highlights the importance of truck platoon length management on traffic dynamics and provides a valuable reference for future researchers.

INDEX TERMS Traffic dynamics, off-ramp regions, congestion control strategy.

I. INTRODUCTION

Platoon refers to autonomous vehicles travel compactly and steadily with a short inter-vehicle distance. Since this technology enables the vehicles to maintain high speeds with less aerodynamic drag, the improvement is noticeable for the homogeneous fleets of heavy-duty trucks [1], [2].

Some pioneering projects, such as CHAUFFEUR [3], [4], SARTRE [5], [6], PATH, GCDC [7], SCANIA platooning, and Energy ITS [8]–[10], regard the truck platoon as a feature of modern intelligent transportation systems. With the aid of Vehicle-to-Vehicle communication (V2V) [11] and Cooperative Adaptive Cruise Control (CACC) [12], [13], the truck platoon has shown potential to bring pronounced benefits to road traffic, including higher safety, better energy consumption, and greater comfort [14]–[16]. Some research has proven that when driving in platoons at 80 km/h, the leading truck will reduce fuel consumption by approximately 5%, while the following trucks will experience reductions of 10% to 15% [17].

However, the practical application of truck platooning technology still has many challenges waiting to be resolved. For example, how to further optimize the effect of distributed control with ecological cooperative adaptive cruise control (Eco-CACC) [18]–[22]; how to model the conduction of information flow within a platoon with topological methods [23]–[25]; how to effectively reduce the time delays caused by perception and communication for a steadier operation [26]–[28]. To summarize, these studies are devoted to the internal improvement of platooning technology to provide theoretical and technical support for its promotion.

However, an increasing number of researchers are noticing that road traffic is a complex system. The management of truck platoons should not be isolated from the actual environment and traffic dynamics [29], [30]. From a perspective of traffic authority, the platooning systems shall not only have benefits for themselves but guarantee efficient traffic operations at the macro level as well. The next question needs to be answered: *given certain scenarios, how to accomplish a better balance between the efficiency of environmental traffic and the efficiency of truck platoon itself.*

Since heavy trucks are uncommon in urban roads, such studies generally focus on highway scenarios [31]. Among them, the congestion and accidents mostly occur in the ramps, which often become bottlenecks of the whole highway with paramount implications for safe and efficient operations.

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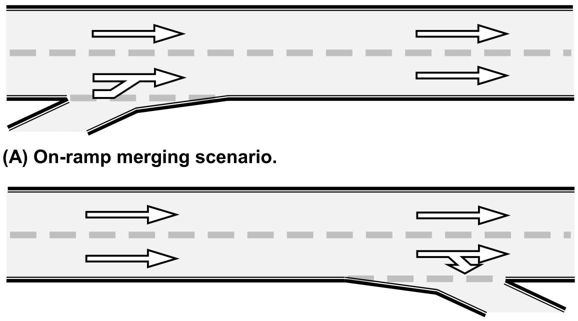
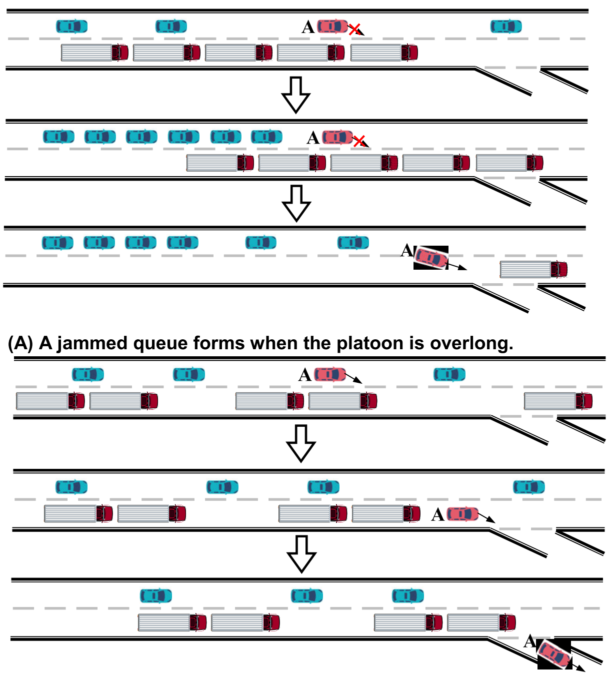


(A) On-ramp merging scenario.

(B) Off-ramp separating scenario.

FIGURE 1. Two typical ramp scenarios on a highway.



(A) A jammed queue forms when the platoon is overlong.

(B) A jammed queue will not occur when the platoon is short.

FIGURE 2. The length of the truck platoon has an evident influence on the environmental traffic condition.

Most of the studies are centered on the on-ramp merging scenario (as shown in Figure 1A), aiming to guide truck platoons safely into the highway through dynamic interaction with environmental vehicles [19], [32]–[34]. Yet the off-ramp separating scenarios (see Figure 1B), as another typical highway scenario, has not received enough attention. We found that the problem of trajectory intersection between the going-straight truck platoons and other departing vehicles is valuable to study.

For less fuel consumption, forming a longer platoon seems like a feasible choice [16]. On the highways near ports and factories, platoons of more than ten trucks are common. Unfortunately, an overlong platoon may severely obstruct the movement of other traffic participants, as shown in Figure 2A. There are two lanes for vehicles, while trucks are usually only allowed to operate in the slow lane (the right one).

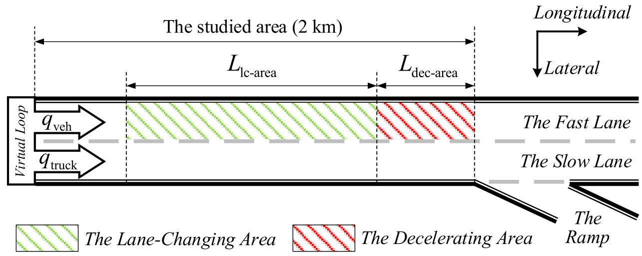


FIGURE 3. Geometry setting of the studied scenario.

Meanwhile, most small vehicles prefer the fast lane (the left one) to avoid truck platoons for a faster expected speed. However, when approaching the ramp, the vehicles aiming to exit the highway must merge to the slow lane within a limited area, called the mandatory lane change (MLC) behavior in traffic research [35]. As shown in Figure 2A, if vehicle A is close enough to the ramp but still has not found a suitable opportunity to merge, its only option is to decelerate or even stop for a sufficient space of the slow lane. However, the traffic flow behind A is continuous during this period, which may result in a jammed queue with a high probability. Obviously, the longer the platoon is, the longer A will wait, and the heavier the congestion will form. Conversely, if the length of platoons can be limited within a reasonable range, A can easily grasp an opportunity to change lane flexibly, as shown in Figure 2B.

Based on a theoretical calculation, this paper proposes an advance adjustment strategy for the truck platoon in the off-ramp scenarios to reduce the impact on the predictable MLC behaviors of other vehicles. Specifically, the paper first establishes a physical model to describe the formation of congestion, and then explains how to calculate the effective boundary of the platoon length. Second, sets of simulation experiments are conducted under varied parameters to investigate the effect of different queue lengths on macroscopic traffic flow. Both theoretical calculation and simulation experiment results prove that controlling the length of the platoon within a reasonable range can significantly improve traffic efficiency near a ramp. This study highlights the importance of truck platoon length management on traffic dynamics and provides a valuable reference for future researchers.

To better explain our findings, the rest of this paper is organized as follows. *Section II* elaborates on the studied scenario and the process of congestion generation. *Section III* introduces the simulation framework as well as the parameter settings used in this paper. *Section IV* provides the numerical simulation results to verify the effectiveness and superiority of the method. Finally, the whole work and its contributions are concluded in *Section V*.

II. ANALYSIS OF JAMS CAUSED BY LONG PLATOONS

A. NOMENCLATURE

The nomenclature of this paper is listed in Table 1.

TABLE 1. Nomenclature.

Symbol	Meaning	Symbol	Meaning
a	Acceleration	l_{veh}	The length of one small vehicle
d	Deceleration	l_{truck}	The length of one truck
i	Index of the small vehicles	$N_{platoon}$	The number of trucks in a platoon
j	Index of the possible jammed queues	N_{hinder}	The number of hindered vehicles
K_{delay}	Evaluation index of congestion severity	N_j	The number of vehicles in the j th jammed queue
K	The slope of $(t_{travel})_i$	q_{veh}	Arriving flow rate of small vehicles
k	The certain correction parameter of K	q_{truck}	Arriving flow rate of trucks
$v_{platoon}$	The speed of the platoon	h_{veh}	The following distance of small vehicles
v_{veh}	The speed of small vehicle	h_{truck}	The following distance of trucks
$L_{lc\text{-}area}$	The length of the lane-changing area	$P_{off\text{-}ramp}$	The probability of a vehicle going off-ramp
$L_{dec\text{-}area}$	The length of the decelerating area	$\bar{t}_{travel}$	The average travel time of all small vehicles
$L_{platoon}$	The length of the platoon	ρ_{veh}	The reaction time lag of small vehicle
$t_{overtake}$	The time required to overtake the platoon	ρ_{truck}	The reaction time lag of truck

B. OFF-RAMP SCENARIOS

In this paper, the off-ramp scenario is modeled as shown in Figure 3, consisting of two one-way lanes and a ramp connected to the slow lane. We select the area 2 km from the ramp as the studied target and focus on the traffic dynamics within this range. According to the maneuvering process of MLC, the studied area near the ramp can be divided into two sections: *lane-changing area* and *decelerating area*. The former refers to the area where lane changes can be implemented without deceleration, and the latter refers to the area deceleration is necessary [36]. *Section III* introduces more detailed parameter settings.

In the experiment, both vehicles and trucks are generated with random probability at the starting point of the scenario, and their arrival rate are labeled as q_{veh} and q_{truck}. In real traffic, those values can be accurately measured by the infrastructures like virtual loop installed on the side of the road [37]–[40]. While if the road environment does not have infrastructure-level measurement conditions, it can also be estimated by on-board-level method only relies on the on-board sensors, which is detailed in Appendix A.

To reduce the computational complexity, the major assumptions involved in the following:

1) We assume that there are only two sizes of traffic participants: trucks and small vehicles. it is reasonable to ignore other types because their size difference is much smaller than the following distance.
2) only the small vehicles in the fast lane are considered. this is because other small vehicles are not blocked by the truck platoon and can enter the ramp freely.

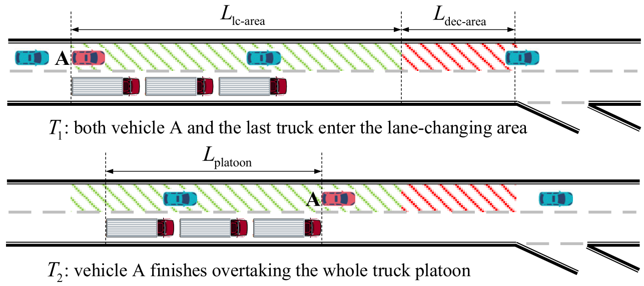


FIGURE 4. The timing sequence diagram, showing two critical situations in the lane-changing scenario.

3) To simulate real traffic, the MLC intentions of small vehicles are random and independent, the probability of which is described by a constant $P_{off\text{-}ramp}$.
4) Due to the existence of V2V and virtual loop, the autonomous trucks have the ability to obtain traffic information within the perception range, including the arrival rate locations, speeds, etc., which is the basis for the following calculations.

C. CONDITIONS REQUIRED TO AVOID CONGESTION

Figure 4 visualizes a timing sequence diagram about congestion generation. We assume that vehicle A aims to go ramp, and both it and the last truck of a platoon enter the lane-changing area at time T_1. To enter the ramp, there are two choices for A at this time point: (a) slow down and wait for the platoon to pass; (b) overtake the whole platoon at time T_2. Since there may be blocking vehicles in front of A, only the general case where it cannot accelerate significantly needs to be considered.

If A chooses (a), the following vehicles have to decelerate too, and then congestion occurs. Conversely, if A chooses (b), the time required for A to overtake the platoon can be obtained as

$$t_{overtake} = T_2 - T_1 = \frac{L_{platoon}}{v_{veh} - v_{platoon}} \tag{1}$$

where $L_{platoon}$ represents the length of the platoon.

To reserve enough time for the lane-changing behavior, A must complete the overtaking process before entering the deceleration area. Thus, we can express this condition as:

$$\begin{aligned} L_{platoon} &= \left(v_{veh} - v_{platoon}\right) \cdot t_{overtake} \\ &< \left(v_{veh} - v_{platoon}\right) \cdot \frac{L_{lc\text{-}area}}{v_{veh}} \end{aligned} \tag{2}$$

where $L_{lc\text{-}area}$ represents the length of the lane-changing area.

In this case, the vehicles following A will not be blocked, while the vehicles leading A just have a shorter space to overtake. In other words, when the above condition is met, every vehicle will be given the opportunity to change lanes, and congestion will not form.

D. CONDITIONS REQUIRED TO AVOID SEVERE CONGESTION

Yet, the above condition is often too difficult to meet in real traffic. The more practical approach would be to block the

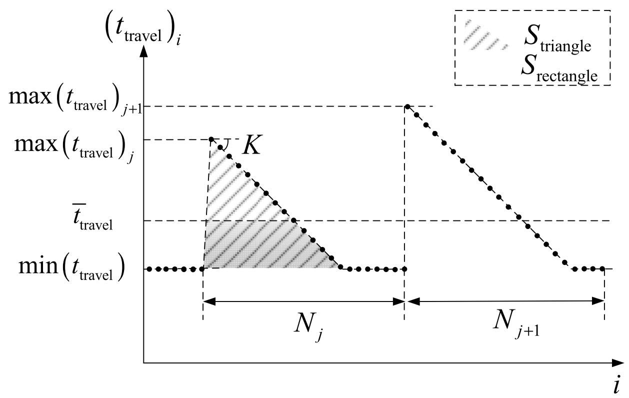


FIGURE 5. **Model of the travel times of all small vehicles in the *j* th jammed queue period.**

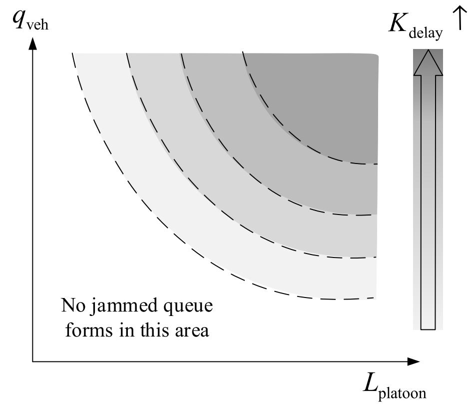


FIGURE 6. **An illustration of the predicted $L_{platoon}$-versus-q_{veh} phase diagram.**

transmission of unavoidable congestion, and prevent it from evolving into severe congestion, which is defined as: one jammed queue does not have enough time to dissipate before the next one forms.

For presentation clarity, we label small vehicles with the index i $(i = 1, 2, \ldots)$ and denote the travel time of the vehicle i to pass through the studied area as $(t_{travel})_i$. The average value of all $(t_{travel})_i$ can evaluate the overall traffic efficiency, which is denoted by $\bar{t}_{travel}$.

Similarly, the possible jammed queues are labeled with the index j $(j = 1, 2, \ldots)$. Each j represents a queue consisting of all the vehicles involved in congestion, as shown in Figure 5. In ideal conditions, the travel time of small vehicles varies like a sawtooth wave [41], [42]. Each peak value of the sawtooth wave may differ because of random factors that will be discussed later.

When severe congestion does not form (the jammed queue does not propagate upstream), $\bar{t}_{travel}$ of one period should be equal to the value calculated by all periods, which is determined by four parameters:

1) K: This parameter represents the slope of t_{travel} and can be calculated by

$$K = k \big/ q_{veh}^2 \tag{3}$$

where k represents a certain correction parameter, determined by the following distance.

2) N_j: The number of small vehicles passing through the studied area in the j th jammed queue is N_j, whose expectation can be calculated by

$$\begin{aligned} E\left(N_j\right) &= \frac{N_{platoon}}{q_{truck}} \cdot q_{veh} \cdot P_{off\text{-}ramp} \\ &= \frac{L_{platoon} \cdot q_{veh} \cdot P_{off\text{-}ramp}}{(l_{truck} + h_{truck}) \cdot q_{truck}}. \end{aligned} \tag{4}$$

where $P_{off\text{-}ramp}$ denotes the probability of a small vehicle going off-ramp.

3) $\min(t_{travel})$: If congestion does not form, t_{travel} of the small vehicles will be $\min(t_{travel})$, which can be calculated by

$$\min(t_{travel}) = (L_{lc\text{-}area} + L_{dec\text{-}area}) \big/ v_{veh}. \tag{5}$$

4) $\max(t_{travel})_j$: Similarly, this is the longest travel time of the small vehicle in the j th jammed queue. Because it has randomness, we use its expectation instead

$$E\left(\max(t_{travel})_j\right) = L_{platoon} \big/ v_{platoon} + \min(t_{travel}). \tag{6}$$

More details on this equation are provided in the Appendix B.

To this point, the relationship between t_{travel} and i can be summarized as Figure 5. The shaded area can be calculated by

$$S_{triangle} = \frac{\left[E\left(\max(t_{travel})_j\right) - \min(t_{travel})\right]^2}{2K}. \tag{7}$$

The area of $S_{rectangle}$ shown in Figure 5 is given as

$$S_{rectangle} = \left[\bar{t}_{travel} - \min(t_{travel})\right] \cdot E\left(N_j\right). \tag{8}$$

According to the definition of $(t_{travel})_i$, the shaded triangular area represents the sum of $(t_{travel})_i$ of the jammed queue. Moreover, the gray rectangular area represents $\bar{t}_{travel}$, which is the average value of $(t_{travel})_i$. Setting $S_{triangle}$ equal to $S_{rectangle}$, we can derive $\bar{t}_{travel}$ as

$$\begin{aligned} \bar{t}_{travel} = \frac{q_{truck}\,(l_{truck} + h_{truck})}{2 v_{platoon} \cdot k} \cdot L_{platoon} \cdot q_{veh} \cdot P_{off\text{-}ramp} \\ + \min(t_{travel}). \end{aligned} \tag{9}$$

Here, K_{delay} denotes the ratio of $\bar{t}_{travel}$ to $\min(t_{travel})$, describing the degree of congestion. We have.

Combining Equation (2) and (10), as shown at the bottom of the next page, the $L_{platoon}$-versus-q_{veh} phase diagram can be obtained as shown in Figure 6. The increase of either $L_{platoon}$ or q_{veh} may lead to the increase of congestion degree K_{delay}. In the left part, no jammed queue will form. While in the right part, a jammed queue will form and quickly propagate upstream, resulting in noticeable varying of $(t_{travel})_i$.

When approaching the ramp, truck platoons can assess the impact of different lengths on environmental traffic through the above calculation process and implement effective dynamic adjustment in advance. We believe this method will reference the platoon length determination under the fixed road geometry structure.

III. SIMULATION

To observe the influence of the platoon length on congestion and verify the above conclusions more intuitively, we conduct a simulation experiment on the Vissim platform. This section introduces the dynamic model, the implementation process, and parameter setting adopted in the simulation, and detailed numerical results are provided in the next section.

A. FOLLOWING MODEL OF SMALL VEHICLES

Because the movement in the fast lane is similar to natural traffic flow, we utilize the Newell following model [43], [44] to update the longitudinal speed of small vehicles. When it is in the free driving state (i.e., not in a jammed queue), the optimal speed $v_i(t)$ at time t can be calculated as:

$$v_i(t) = \hat{v}\left\{1 - \exp\left[-(\Delta x_i(t) - h_{\text{veh}})\big/\left(\hat{v}T_{\text{veh}}\right)\right]\right\}. \quad (11)$$

where $\hat{v}$ represents the expected speed. $\Delta x_{\text{i}}(t)$ denotes the distance between the i th and $i+1$ th vehicles. T_{veh} represents the safety headway for high-density traffic flow conditions. h_{veh} represents the safe distance between vehicles. According to our previous work [45], T_{veh} and h_{veh} can be calculated as:

$$T_{\text{veh}} = \frac{l_{\text{veh}} + h_{\text{veh}}}{\hat{v}}, \quad (12)$$

$$h_{\text{veh}} = \left[v_f \rho_{\text{veh}} + \frac{v_f^2}{2d_f} - \frac{v_l^2}{2d_{\max}}\right]^+, \quad (13\text{-}1)$$

where

$$d_f = d_{\min} + \frac{v_f}{\hat{v}_f}(d_{\max} - d_{\min}). \quad (13\text{-}2)$$

ρ_{veh} denotes the reaction time lag (1 s for human-driven vehicles), v_f denotes the speed of the following vehicle, and v_l denotes the speed of the leading vehicle.

B. FOLLOWING MODEL OF TRUCKS

Equipped with V2V communication and a *Cruise Control System*, an automatic truck platoon can effectively improve the decision delay in emergencies. Therefore, the following distance of a truck platoon h_{truck} is significantly shorter than that of traditional traffic flows. In the truck platoon, v_f and v_l are equal and cancel each other out; thus, h_{truck} can be calculated as:

$$\begin{aligned} h_{\text{truck}} &= \left[v_f \rho_{\text{truck}} + \frac{v_f^2}{2d_{\text{truck}}} - \frac{v_l^2}{2d_{\text{truck}}}\right]^+ . \\ &= v_{\text{platoon}} \rho_{\text{truck}} \end{aligned} \quad (14)$$

where ρ_{truck} denotes the reaction time lag of autonomous trucks, including the measuring delay of sensors, the communication delay, the breaking/throttle delay, etc. Usually, those delays are stochastic and various, but the upper boundary can be reasonably estimated based on the Distributed Control Protocols. According to [27], [28], ρ_{truck} is set as 0.3 s in the following experiments.

C. LANE-CHANGING MODEL

Since our control object is the truck platoon, the whole lane-changing process of small vehicles should be considered continuous and uninterruptible for safety reasons [46]–[48]. For them, the necessary conditions to achieve a safe lane-changing maneuver can be summarized as: i) The vehicle should have reached the lane-changing area of the fast lane. ii) No trucks or other vehicles should be within the target area of the slow lane.

For the small vehicles within the lane-changing area, the entire merging behavior from the fast lane to the slow lane can be approximated as an oblique uniform motion lasting 4 s [36]. Therefore, it should be judged as feasible only when sufficient distance (more than the longitudinal motion distance of the small vehicle under 4 s) is provided between the truck platoons. If the lane change is completed within this area, the subsequent merging behavior to the ramp will basically cause no impact on the truck platoons. This scheme can be considered as the ideal case with the least disturbance on the overall traffic efficiency.

The small vehicles entering the decelerating area need to experience two consecutive mergings to enter the ramp, and we conservatively assume that this process lasts 8 s. In other words, a truck platoon needs to reserve 8 s for a small vehicle with little longitudinal speed to complete the lane-changing maneuver in the least desirable case. Furthermore, if the blocking queue has been formed, the following vehicles do not need to wait until the leading vehicle completes the lane change. We can still use the following model described in *Section III A* to describe the lane-changing queue of the small vehicles. At this point, it is the responsibility of newly arriving trucks to wait until the congestion is relieved.

D. SIMULATION FRAMEWORK

To ensure the timeliness, the simulated time interval is set to 0.1 s. The framework of our simulation system can be summarized as four steps executed in each iteration:

1) VEHICLE-GENERATING PROCESS

When q_{veh} and q_{truck} are given, the simulation system will generate small vehicles and truck platoons accordingly. Each small vehicle has probability $P_{\text{off-ramp}}$ to go off-ramp.

2) SPEED-UPDATING PROCESS

In each time interval, the model will check whether each vehicle is in the free driving state or not and update its speed based on the model from *Section III B* and *D*.

$$\begin{aligned} K_{\text{delay}} &= \bar{t}_{\text{travel}}\big/\min(t_{\text{travel}}) \\ &= \frac{q_{\text{truck}} \cdot v_{\text{veh}} \cdot (l_{\text{truck}} + h_{\text{truck}}) \cdot L_{\text{platoon}} \cdot q_{\text{veh}} \cdot P_{\text{off-ramp}}}{2 \cdot v_{\text{platoon}} \cdot k \cdot (L_{\text{lc-area}} + L_{\text{dec-area}})} + 1 \end{aligned} \quad (10)$$

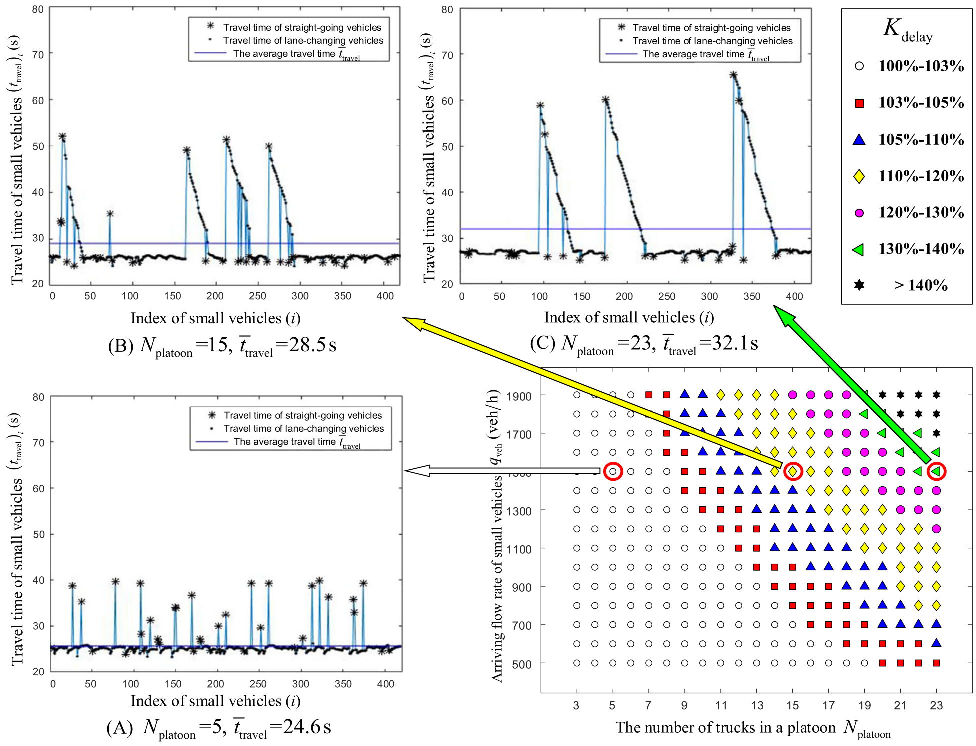


FIGURE 7. N_{platoon}-versus-q_{veh} **phase diagram under different** N_{platoon}. **(a)** $N_{\text{platoon}}=5$; **(b)** $N_{\text{platoon}}=15$; **(c)** $N_{\text{platoon}}=23$.

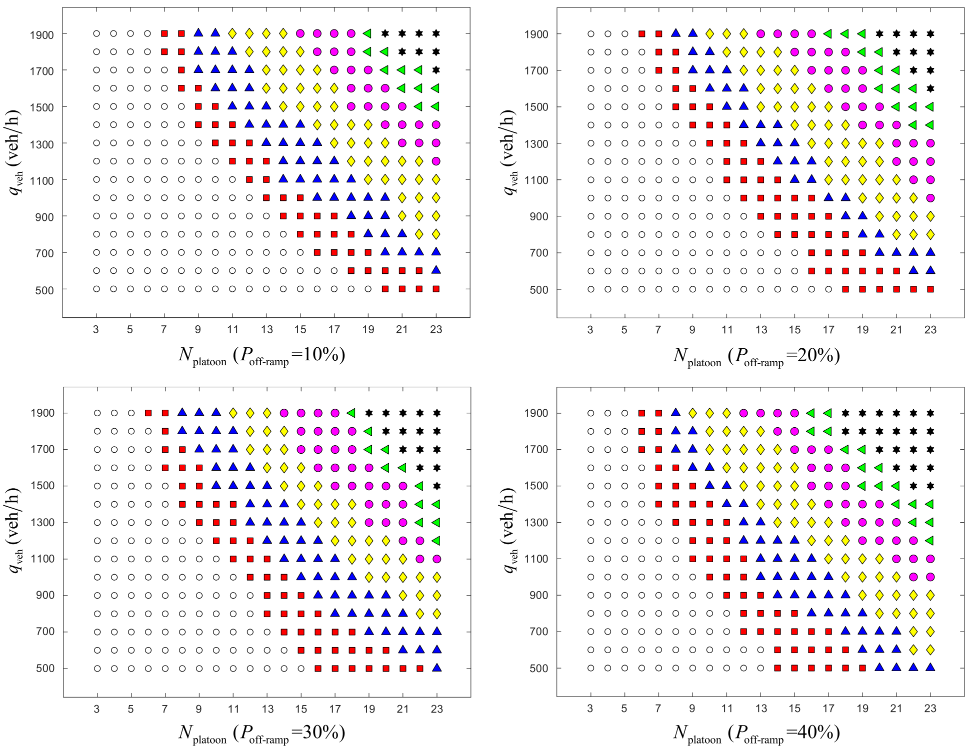


FIGURE 8. N_{platoon}-versus-q_{veh} **phase diagram under different** $P_{\text{off-ramp}}$**, varied from 10% to 40%.**

3) STATE-UPDATING PROCESS

The model will calculate the locations of each vehicle for the next time interval.

4) DRIVING DECISION-MAKING PROCESS

Based on the surrounding traffic conditions, all lane-changing vehicles will judge whether it is possible to change lanes at

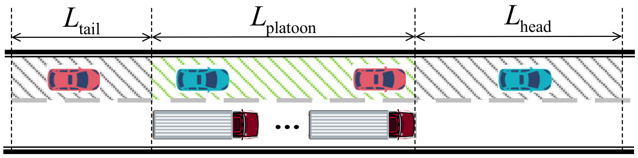


FIGURE 9. The detection range in the on-board-level flow rate measuring method.

that moment. then, the model will record the states of all vehicles and enter the next time interval.

E. SIMULATION EXPERIMENT SETTINGS

In our simulation, the length of each truck l_{truck} is set as 15 m, and the length of each small vehicle l_{veh} is set as 5 m. According to the SAE [49] and FMVSS135 [50] standards, the maximum acceleration a_{max} is limited to 2.5 m/s^2, and the deceleration d is limited within $[-2, -6]$ m/s^2. We set the normal speed as 25 m/s for small vehicles, and 15 m/s for trucks. Since the ramp signs are generally set up 500 m before [51], $L_{lc\text{-}area}$ and $L_{dec\text{-}area}$ are set as 600 m (considering the visual distance) and 100 m (the shortest distance to complete the lane-changing behavior at the initial speed).

In addition, we have conducted several sets of experiments to demonstrate that variation of these parameter settings may change specific results but not affect the effectiveness of the method. In practical applications, the calculation can be adapted to the actual conditions.

IV. NUMERICAL TESTING RESULTS

For the intuitiveness of observation, we select $N_{platoon}$ and q_{veh} as the control variables. In the experiments, $N_{platoon}$ varied from 3 to 23 and q_{veh} varied from 500 to 1900 veh/h.

In the first experiment, we set q_{truck} as 500 veh/h and $P_{off\text{-}ramp}$ as 10%. For better stability, the whole experiment lasted one hour and only the last 30 minutes of data were recorded. Figure 7 records the $N_{platoon}$-versus-q_{veh} phase diagrams for different levels of K_{delay}. The results corroborate the theoretically predicted results from Figure 6. When $N_{platoon}$ is set as 5, no jammed queue will form and $\bar{t}_{travel}$ is 24.6 s ($K_{delay} = 102.5\%$). At this point, the deceleration is only the individual behavior of lane-changing vehicles, indicating that the truck platoon only has little impact on traffic efficiency. When $N_{platoon}$ becomes larger as Figure 7(B), jammed queues appear and $\bar{t}_{travel}$ increases obviously, leading to sawtooth-wave-type variations of $(t_{travel})_i$. Moreover, Figure 7(C) demonstrates that as $N_{platoon}$ increases further, more congestions are caused, and more vehicles are involved. Some vehicles even take 60 s to pass, which is equivalent to their average speed is less than 10 m/s.

With $P_{off\text{-}ramp}$ goes up, the problem becomes worse. In the second simulation, we adjust $P_{off\text{-}ramp}$ from 10% to 40% and record the resulting impacts as shown in Figure 8. The results show that with the increase in q_{veh}, controlling the length of the truck platoon is necessary. When more vehicles have merging intentions, congestion will become more common and faster to accumulate. Unlike other road

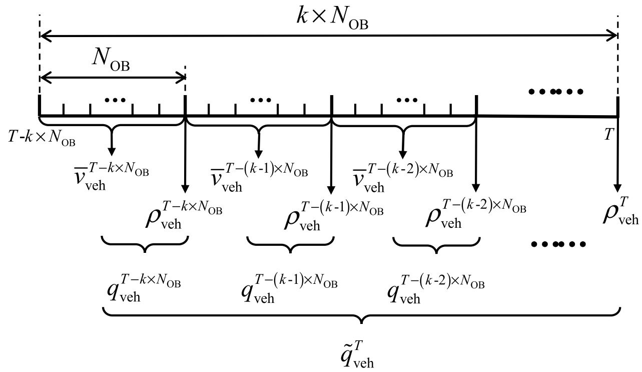


FIGURE 10. The Time intervals sequence to measure the flow rate of time *T*.

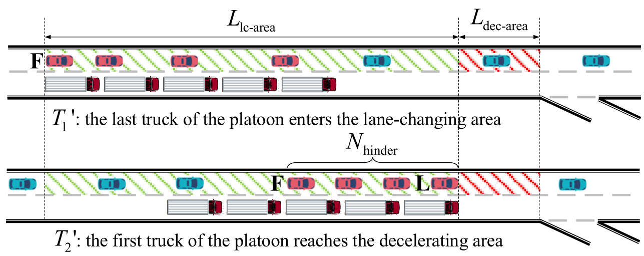


FIGURE 11. The formation process of a jammed queue.

information, $P_{off\text{-}ramp}$ is usually hard to obtain accurately in real traffic, which requires that the platoon length should be assessed with a higher $P_{off\text{-}ramp}$ and adjusted conservatively.

V. CONCLUSION

This paper analyses how the truck platoon affects traffic efficiency in off-ramp scenarios, and proposes a method to determine the length range based on environmental traffic information. The experimental results show that when the arriving flow rate is high, an overlong platoon will form a marked impact on the overall traffic efficiency, as well as the passage time of all vehicles. However, as long as the platoons are reshaped to reasonable lengths to accommodate the lane-changing behavior between them, congestion can be decreased or avoid effectively. To choose the best platoon length, several essential influencing factors should be taken into account, e.g., the flow rate of small vehicles, the flow rate of trucks, the proportion of off-ramp vehicles, and the platoon speed. When the above road information is obtainable or estimable, the upper boundary of the platoon length can be calculated in real-time with our method.

In the next step, we plan to implement more simulations within a larger distance scale and a higher scenario complexity to improve the method proposed in this paper. For example, how to dynamically adjust the length of the truck platoons in a multi-lane situation to coexist harmoniously with the ambient traffic is an interesting topic. We believe that an environmentally friendly, easy-to-calculate, and high-efficiency truck platoon controlling strategy is an essential prerequisite for the application of automatic trucks. Hence, joint efforts by researchers in this field should be directed toward this goal.

APPENDIX A

Instead of using infrastructure like virtual loops, this section introduces an on-board-level method that only relies on the on-board sensor to measure the surrounding flow rate of the truck platoon. Because of the differences in the average speeds of truck platoons and other vehicles, we can approximate the traffic flow rate based on changes in density over time within the detection range.

Specifically, the truck platoon takes only vehicles within $[0, L_{\text{tail}} + L_{\text{platoon}} + L_{\text{head}}]$ into account, as shown in Figure 9, and collects the surrounding vehicle numbers $n_{\text{veh}}^{(t)}$ and average speed $\bar{v}_{\text{veh}}^{(t)}$ every N_{OB} time steps. The local estimation of the flow rate can be calculated by

$$\begin{aligned} q_{\text{veh}}^{(t)} &\approx \bar{v}_{\text{veh}}^{(t)} \times \rho_{\text{veh}}^{(t)} \\ &= \bar{v}_{\text{veh}}^{(t)} \times n_{\text{veh}}^{(t)} \Big/ \left(L_{\text{tail}} + L_{\text{platoon}} + L_{\text{head}}\right) \end{aligned} \tag{A1}$$

where $\rho_{\text{veh}}^{(t)}$ denotes the surrounding vehicle density of the truck platoon. Finally, the sequence of $q_{\text{veh}}^{(t)}$ within a window of length k can be obtained to calculate the flow rate estimation of time T, like

$$\tilde{q}_{\text{veh}}^{T} = \frac{1}{k} \sum\nolimits_{i=0}^{k} q_{\text{veh}}^{T-(k-i)N_{\text{OB}}} \tag{A2}$$

The whole process is shown in Figure 10.

Because the difference between $\tilde{q}_{\text{veh}}^{T}$ and q_{veh}^{T} can be controlled within an acceptable range [52], it could be used to timely estimate the traffic conditions around and achieve comparable results as the infrastructure-level method.

APPENDIX B

The formation process of a jammed queue can be described by Figure 11. Both vehicle F and the last truck of the platoon entered the lane-changing area at time T_1'. As proved above, if the condition of Equation (2) is not met, F cannot overtake the platoon. At time T_2', the first truck of the platoon reached the decelerating area. The first small vehicle hindered by it is labeled as L, and the number of all the hindered vehicles between L and F is denoted by N_{hinder}.

In Figure 11, the hindered vehicle L aiming to go off-ramp has to wait for a long time, and its travel time can be expressed as

$$(t_{\text{travel}})_{\text{L}} = L_{\text{platoon}}/v_{\text{platoon}} + \min(t_{\text{travel}}). \tag{B1}$$

with the probability $P_{\text{off-ramp}}$. If none of the hindered vehicles before L go off-ramp, $(t_{\text{travel}})_{\text{L}}$ is given by

$$(t_{\text{travel}})_{\text{L}} = \left(\frac{1}{v_{\text{platoon}}} - \frac{1}{v_{\text{veh}}}\right) \cdot L_{\text{lc-area}} + \min(t_{\text{travel}}). \tag{B2}$$

with the probability $(1 - P_{\text{off-ramp}})^{N_{\text{hinder}}-1} P_{\text{off-ramp}}$. N_{hinder} can be given as

$$\begin{aligned} N_{\text{hinder}} = &\left[\left(\frac{1}{v_{\text{veh}}} - \frac{1}{v_{\text{platoon}}}\right) \cdot L_{\text{lc-area}} + \frac{1}{v_{\text{platoon}}} \cdot L_{\text{platoon}}\right] \\ &\cdot q_{\text{veh}}. \end{aligned} \tag{B3}$$

To summarize, the expected value of $\max(t_{\text{travel}})_j$ can be calculated by (B4-1), as shown at the bottom of this page, where

$$P_i = (1 - P_{\text{off-ramp}})^{i-1} \cdot P_{\text{off-ramp}}. \tag{B4-2}$$

Combining Equations (B3) and (B4), we can obtain the relationship between $E\left(\max(t_{\text{travel}})_j\right)$ with q_{veh} and L_{platoon}. When N_{hinder} becomes large, the accurate estimation of $E\left(\max(t_{\text{travel}})_j\right)$ can be expressed as

$$E\left(\max(t_{\text{travel}})_j\right) = L_{\text{platoon}}/v_{\text{platoon}} + \min(t_{\text{travel}}). \tag{B5}$$

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$$E\left(\max(t_{\text{travel}})_j\right) = \sum_{i=1}^{N_{\text{hinder}}} \left\{P_i \left[\frac{N_{\text{hinder}} - i}{N_{\text{hinder}} - 1} \cdot \frac{L_{\text{platoon}}}{v_{\text{platoon}}} + \frac{(i-1)\,L_{\text{lc-area}}}{N_{\text{hinder}} - 1}\left(\frac{1}{v_{\text{platoon}}} - \frac{1}{v_{\text{veh}}}\right)\right]\right\} + \min(t_{\text{travel}}) \tag{B4-1}$$

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